MADHA
Expertise | Empathy | Excellence
ENGINEERING COLLEGE

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE3503- CONTROL SYSTEMS

SEMESTER V

REGULATIONS 2021

NOTES

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QUESTION BANK

EE3503 CONTROL SYSTEMS LT P C3 0 0 3

COURSE OBJECTIVES:

- To make the students to familiarize with various representations of systems.
- To make the students to analyze the stability of linear systems in the time domain and frequencydomain.
- To make the students to analyze the stability of linear systems in the frequency domain.
- To make the students to design compensator based on the time and frequency domainspecifications.
- To develop linear models: mainly state variable model and Transfer function model

UNIT I MODELING OF LINEAR TIME INVARIANT SYSTEM (LTIV)

Control system: Open loop and Closed loop – Feedback control system characteristics – First principle modeling: Mechanical, Electrical and Electromechanical systems – Transfer function representations: Block diagram and Signal flow graph.

UNIT II TIME DOMAIN ANALYSIS

Standard test inputs – Time response – Time domain specifications – Stability analysis: Concept ofstability – Routh Hurwitz stability criterion – Root locus: Construction and Interpretation. Effect of adding poles and zeros

UNIT III FREQUENCY DOMAIN ANALYSIS

Bode plot, Polar plot and Nyquist plot: – Frequency domain specifications Introduction to closed loopFrequency Response. Effect of adding lag and lead compensators.

UNIT IV STATE VARIABLE ANALYSIS

State variable formulation – Non uniqueness of state space model – State transition matrix –Eigen values – Eigen vectors - Free and forced responses for Time Invariant and Time Varying Systems –Controllability – Observability

UNIT V DESIGN OF FEED BACK CONTROL SYSTEM

Design specifications – Lead, Lag and Lag-lead compensators using Root locus and Bode plot techniques –PID controller - Design using reaction curve and Ziegler-Nichols technique- PID control in State Feedback form.

TOTAL: 45 PERIODS

COURSE OUTCOMES:

Upon the successful completion of the course, students will be able to:

CO1: Represent simple systems in transfer function and state variable forms.CO2: Analyze simple systems in time domain.
CO3: Analyze simple systems in frequency domain.
CO4: Infer the stability of systems in time and frequency domain.
CO5: Interpret characteristics of the system and find out solution for simple control problems.

TEXT BOOKS:

1. Benjamin C. Kuo, “Automatic Control Systems”, 7th edition PHI Learning Private Ltd, 2010.
2. Nagarath, I.J. and Gopal, M., “Control Systems Engineering”, New Age InternationalPublishers 2010.

REFERENCES:

1. Richard C.Dorf and Bishop, R.H., “Modern Control Systems”, Education Pearson,
2. John J.D., Azzo Constantine, H. and Houpis Sttuart, N Sheldon, “Linear Control SystemAnalysis and Design with MATLAB”, CRC Taylor& Francis Reprint 2009.
3. Katsuhiko Ogata, “Modern Control Engineering”, PHI Learning Private Ltd, 5thEdition, 2010
4. NPTEL Video Lecture Notes on “Control Engineering” by Prof.S.D.Agashe, IIT Bombay.

UNIT I – SYSTEM COMPONENTS AND THEIR REPESENTATION

A system is arrangement of components or devices connected together to perform a specific function. A control system is a type of system, which for a specific input gives corresponding output.

BASIC STRUCTURE OF A SYSTEM

The system consists of various components such as

Input: flow of energy or material that causes process to react or respond. **Manipulated Input** is a input which is subjected to control. **Disturbance Input** is an undesirable and unavoidable input to the plant, also known as Disturbance or Noise.

Command Input: The external input which is independent of the feedback control.

Reference Input Element: This element estimates the relationship between the command and reference input.

Error Detector: Also known as comparator, it compares the reference input with feedback signal.

Controller: This element is responsible for suitable control action. **Control Signal** is the output of the controller.

Error Signal: Output of error detector.

Final Control Element: Actuator element block.

Controlled System: Process, in which a particular condition is to be controlled.

Disturbance Input: Variable which designer has no control or little information is available on magnitude or function or time.

Controlled Variable: It is influenced by both manipulated variable and disturbance.

Feedback : It is a function of controlled variable. It is Used to correct the nonlinear in the controlled system.

CLASSIFICATION OF CONTROL SYSTEM

1. Open loop and closed loop system
2. Linear and nonlinear system
3. Time Invariant and Time Variant system
4. Continuous and Discrete system
5. SISO and MIMO system.
6. Lumped parameter and Distributed parameter system
7. Deterministic and Stochastic control system
8. Static and Dynamic system

Open loop and closed loop system

Open Loop Control System: A control system in which the control action is totally independent of output of the system. Any physical system which does not automatically correct the variation in its output or control system in which the output quantity has no effect upon the input quantity are called open-loop control system. This means that the output is not feedback to the input for correction.

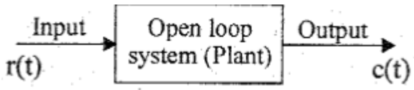


Fig: Open loop system.

In open loop system the output can be varied by varying the input. But due to external disturbances the system output may change. When the output changes due to disturbances, it is not followed by changes in input to correct the output. In open loop systems the changes in output are corrected by changing the input manually.

Example:

1. Light Switch : Lamp glows whenever light switch is ‘ON’ irrespective of light is required or not.
2. Volume of Stereo System: Volume is adjusted manually irrespective of output volume level.

3. Man walking on road with closed eyes. It is very difficult to walk on the desired path.

Merits:

1. System are simple in construction and design.
2. Easy to maintain
3. Economical
4. Stable

Demerits:

1. Systems are inaccurate and not reliable
2. Recalibration of the controller is necessary time to time
3. Changes in output due to external disturbance are not corrected automatically.

Closed Loop Control System: Control systems in which the output has an effect upon the input quantity in order to maintain the desired output value are called closed loop systems.

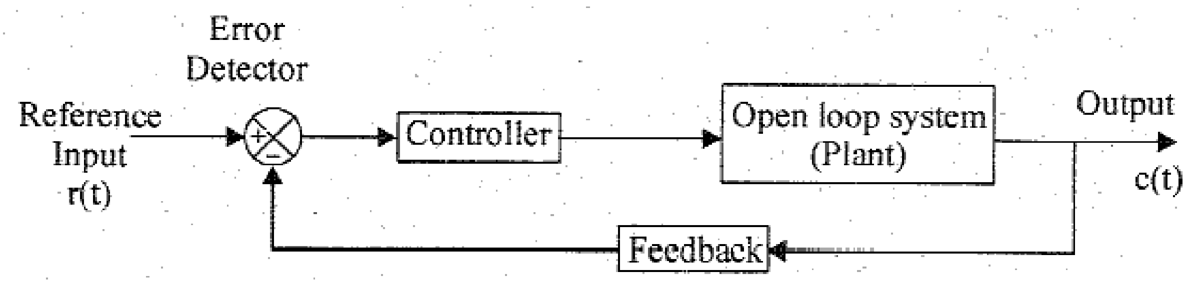


Fig: Closed loop control system.

The open loop system can be modified as closed loop system by providing a feedback. The provision of feedback automatically corrects the changes in output due to disturbances. Hence the closed loop system is also called automatic control system. The general block diagram of an automatic control system is shown in fig.

It consists of an error detector, a controller, plant (open loop system) and feedback path elements. The reference signal (or input signal) corresponds to desired output. The feedback path elements samples the output and converts it to a signal of same type as that of reference signal. The feedback signal is proportional to output signal and it is fed to the error detector.

The error signal generated by the error detector is the difference between reference signal and feedback signal. The controller modifies and amplifies the error signal to produce better control action. The modified error signal is fed to the plant to correct its output.

Example:

1. Automatic electric Iron: Heating element are controlled by output temperature of the iron.
2. Air Conditioner: It's function depends on the temperature of the room.
3. Water Level Controller: Input water is controlled by water level of the reservoir.
4. Man walking with eyes open in a road, eye performs as error detector, compares actual path of the movement with prescribed path and generates error signal. This error signal transmits the corresponding control signal to the legs to connect the actual movement to desired path.

Merits:

1. The closed loop systems are accurate and reliable
2. Reduced effect of Nonlinearity and disturbance.
3. Operating frequency zone is high.
4. Senses the environmental changes and external disturbance and accordingly takes necessary control action.

Demerits:

1. The closed loop systems are complex and costly.
2. The feedback in closed loop system may lead to oscillatory response.
3. The feedback reduces the overall gain of the system.

SNO	**Open Loop Control System**	**Closed Loop Control System**
1.	Feedback is absent	Feedback is always present
2.	An error detector is not present	An error detector is always present
3.	Stable	It may become unstable
4.	Easy to construct	Complicated in construction
5.	It is an economical	It is costly.
6.	Has small bandwidth	Has large bandwidth
7.	It is inaccurate.	It is accurate
8.	Less maintenance	More maintenance
9.	It is unreliable	It is reliable
10.	Examples: Hand drier, tea maker	Examples: Servo voltage stabilizer, perspiration

Linear and Nonlinear system: Linear system obeys law of superposition. The principle of superposition states that the response produced by simultaneous application of two different forcing functions is the sum of individual responses.

If r(t) is input and y(t) is the output, and $r_1(t) \rightarrow y_1(t)$ for $t \geq 0$ and $r_2(t) \rightarrow y_2(t)$ for $t \geq 0$, if the input $r(t) = ar_1(t) + br_2(t)$: for $t \geq 0$,

then for a linear system the output must be $y(t) = ay_1(t) + by_2(t)$, for $t \geq 0$.

Time Invariant and Time Variant system:

For a time invariant system the parameter does not vary with time, response of such system is independent of time at which input is applied.

For time variant the response depends on time. For example, in the space vehicle control system the mass of the vehicle reduces as time increases and fuel decreases.

Continuous and Discrete system

If all the elements of the describing equation is define for all time, then the system is continuous time (Differential Equation).If as in sampled date system, some elemental equation are define or used only at discrete time points, then the system is discrete time system (Difference Equation).

SISO and MIMO system

Single input – Single output and Multi input and multi output system.

Lumped parameter and Distributed parameter system

In Lumped Parameter system the significant variable of the system are lumped at some discrete point, hence they are described by ordinary differential equation. When the significant variables are distributed with respect to space and time, they are described by partial fraction with time, with variables as independent variables.

Deterministic and Stochastic control system

In deterministic system the response is predictable, whereas in Stochastic system the variables and parameters are random and the response is not predicable.

Static and Dynamic system

In a dynamic system the present output depends on present and past inputs. In a static system the present output depends on only the present input.

MATHEMATICAL MODELS

Mathematical modelling of any control system is the first and foremost task that a control engineer has to accomplish for design and analysis of any control engineering problem. It is nothing but the process or technique to express the system by a set of mathematical equations (algebraic or differential in nature).

Analysis means the process of finding the response or output of a system when it is excited by an input or excitation provided we know the mathematical model of the system. On the other hand, **design or synthesis** means we have to find out the system equations or the arrangement of the components, provided we know the output of the system for an input.

Commonly used mathematical models are-

1. Differential equation model.
2. State space model.
3. Transfer function model.

Transfer Function. The transfer function of a linear, time-invariant, differential equation system is defined as the ratio of the Laplace transform of the output (response function) to the Laplace transform of the input (driving function) under the assumption that all initial conditions are zero.

$$G(s) = \frac{\mathscr{L}[\text{output}]}{\mathscr{L}[\text{input}]}\bigg|_{\text{zero initial conditions}}$$

The applicability of the concept of the transfer function is limited to linear, time-invariant, differential equation systems. The transfer function approach, however, is extensively used in the analysis and designs of such systems are as follows.

1. The transfer function of a system is a mathematical model in that it is an operational method of expressing the differential equation that relates the output variable to the input variable.
2. The transfer function is a property of a system itself, independent of the magnitude and nature of the input or driving function.
3. The transfer function includes the units necessary to relate the input to the output; however, it does not provide any information concerning the physical structure of the system. (The transfer functions of many physically different systems can be identical.)
4. If the transfer function of a system is known, the output or response can be studied for various forms of inputs with a view toward understanding the nature of the system.
5. If the transfer function of a system is unknown, it may be established experimentally by introducing known inputs and studying the output of the system. Once established, a transfer function gives a full description of the dynamic characteristics of the system, as distinct from its physical description.

BLOCK DIAGRAMS

Block diagram of a system is a pictorial representation of the functions performed by each component and of the flow of signals. Such a diagram depicts the interrelationships that exist among the various components. Differing from a purely abstract mathematical representation, a block diagram has the advantage of indicating more realistically the signal flows of the actual system.

In a block diagram all system variables are linked to each other through functional blocks. The *functional* block or simply *block* is a symbol for the mathematical operation on the input signal to the block that produces the output. The transfer functions of the components are usually entered in the corresponding blocks, which are connected by arrows to indicate the direction of the flow of signals. Note that the signal can pass only in the direction of the arrows. Thus a block diagram of a control system explicitly shows a unilateral property.

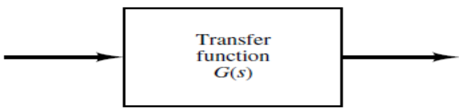
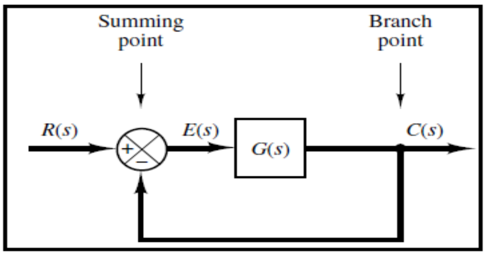


Figure above shows an element of the block diagram. The arrowhead pointing toward the block indicates the input, and the arrowhead leading away from the block represents the output. Such arrows are referred to as *signals.*

The dimension of the output signal from the block is the dimension of the input signal multiplied by the dimension of the transfer function in the block. The advantages of the block diagram representation of a system are that it is easy to form the overall block diagram for the entire system by merely connecting the blocks of the components according to the signal flow and that it is possible to evaluate the contribution of each component to the overall performance of the system.

In general, the functional operation of the system can be visualized more readily by examining the block diagram than by examining the physical system itself. A block diagram contains information concerning dynamic behaviour, but it does not include any information on the physical construction of the system. Consequently, many dissimilar and unrelated systems can be represented by the same block diagram.

It should be noted that in a block diagram the main source of energy is not explicitly shown and that the block diagram of a given system is not unique. A number of different block diagrams can be drawn for a system, depending on the point of view of the analysis.

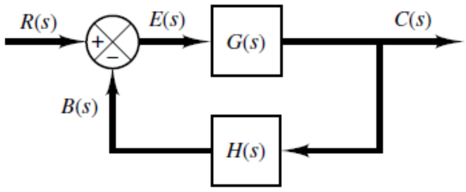


Summing Point. Referring to Figure, a circle with a cross is the symbol that indicates a summing operation. The plus or minus sign at each arrowhead indicates whether that signal is to be added or subtracted. It is important that the quantities being added or subtracted have the same dimensions and the same units.

Branch Point. A *branch point* is a point from which the signal from a block goes concurrently to other blocks or summing points.

Block Diagram of a Closed-Loop System. Figure below shows an example of a block diagram of a closed-loop system. The output C(s) is fed back to the summing point, where it is compared with the reference input R(s). The closed-loop nature of the system is clearly indicated by the figure. The output of the block, C(s) in this case, is obtained by multiplying the transfer function G(s) by the input to the block, E(s).Any linear control system may be represented by a block diagram consisting of blocks, summing points, and branch points.

When the output is fed back to the summing point for comparison with the input, it is necessary to convert the form of the output signal to that of the input signal. For example, in a temperature control system, the output signal is usually the controlled temperature. The output signal, which has the dimension of temperature, must be converted to a force or position or voltage before it can be compared with the input signal. This conversion is accomplished by the feedback element whose transfer function is H(s). The role of the feedback element is to modify the output before it is compared with the input.



For the system shown in Figure, the output C(s) and input R(s) are related as follows:

$$C(s) = G(s)E(s)$$

$$E(s) = R(s) - B(s)$$

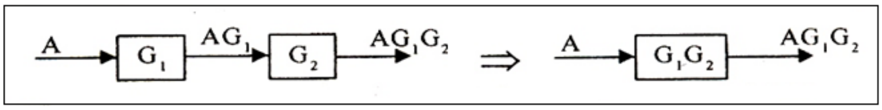
$$E(s)= R(s) - H(s)C(s)$$

$$C(s) = G(s)[R(s) - H(s)C(s)]$$

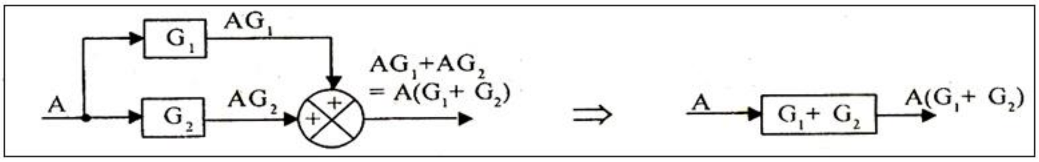
$$\frac{C(s)}{R(s)} = \frac{G(s)}{1+G(s)H(s)}$$

RULES FOR REDUCTION OF BLOCK DIAGRAM

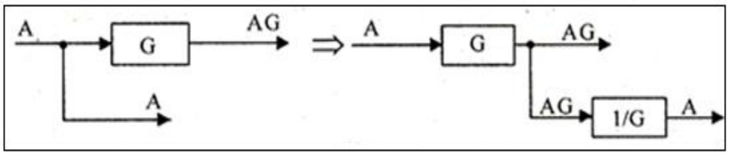
Rule 1: Combining blocks in series or cascade:



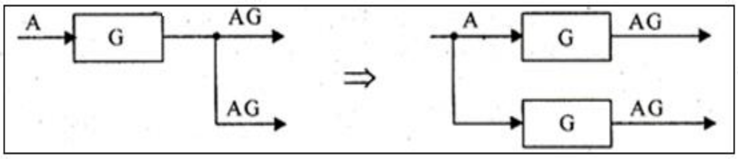
Rule 2: Combining blocks in parallel:



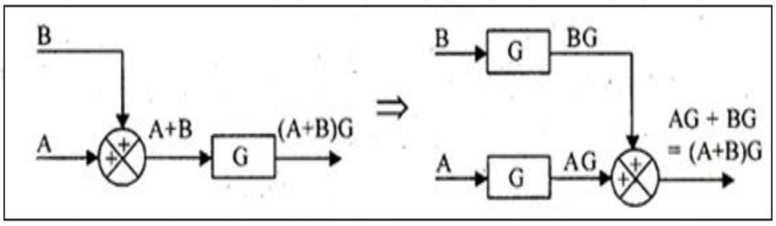
Rule 3: Moving take off (Branch Point) ahead of the block:



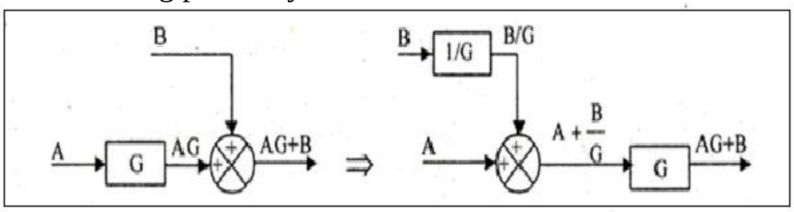
Rule 4: Moving take off (Branch Point) beyond the block:



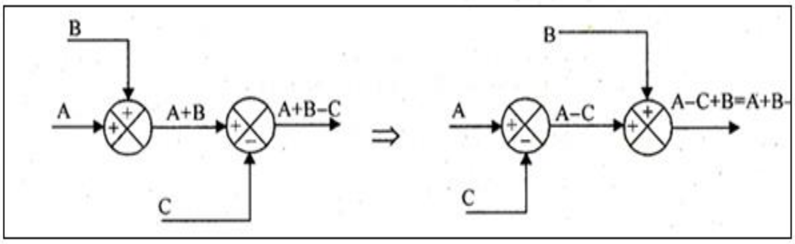
Rule 5: Moving the summing point ahead of the block:



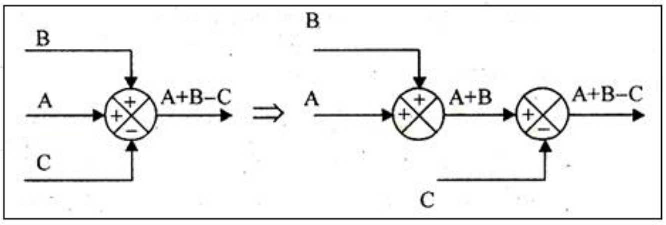
Rule 6: Moving the summing point beyond the block:



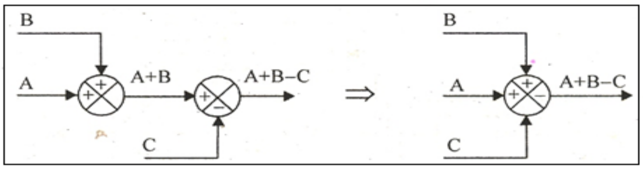
Rule 7: Interchanging Summing Points:



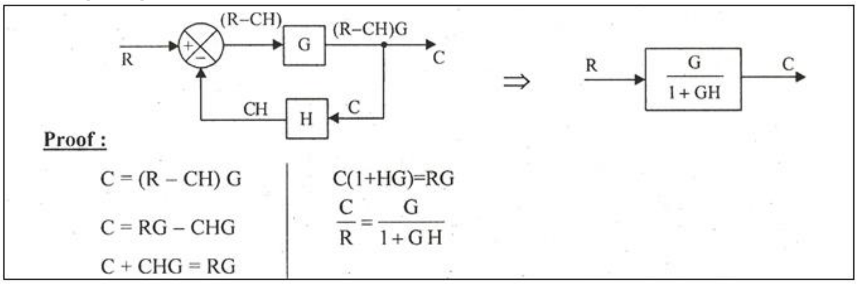
Rule 8: Splitting Summing Points:



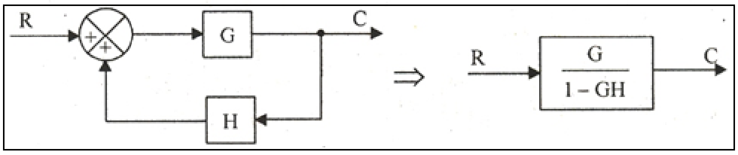
Rule 9: Combining Summing Points:



Rule 10: Eliminating negative feedback:

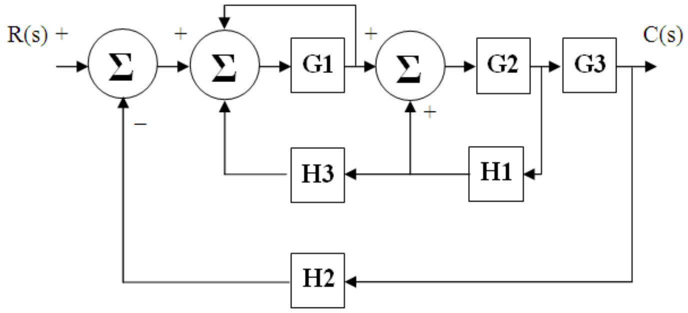


Rule 11: Eliminating positive feedback:

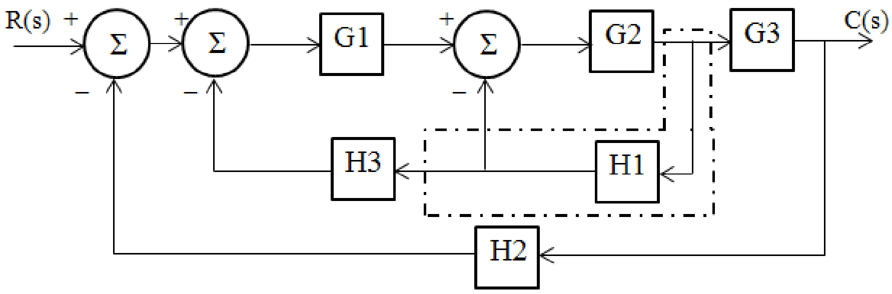


Examples:

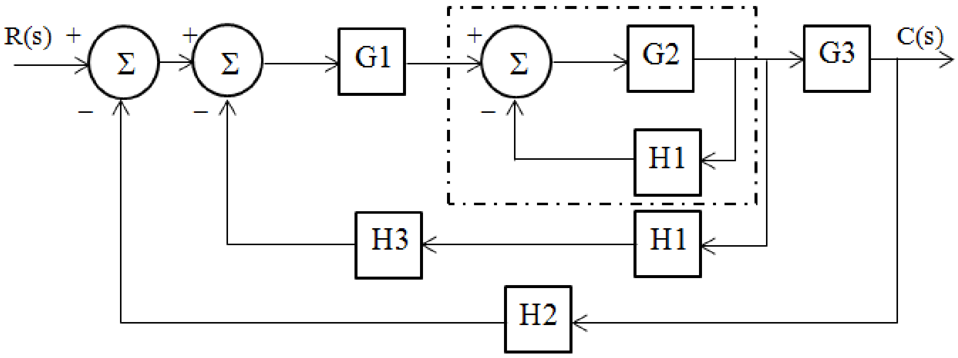
1. Find the transfer function of the system shown in the fig. using block diagram reduction technique and signal flow graph technique.



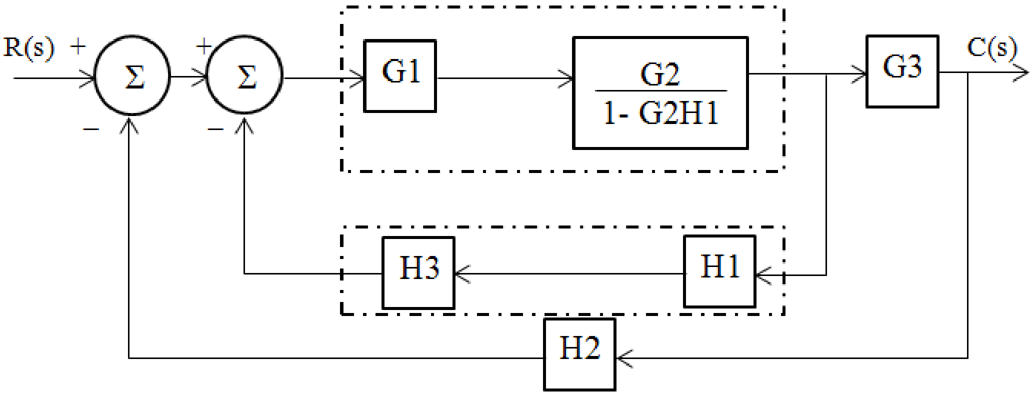
Step 1: Re arranging the branch points.



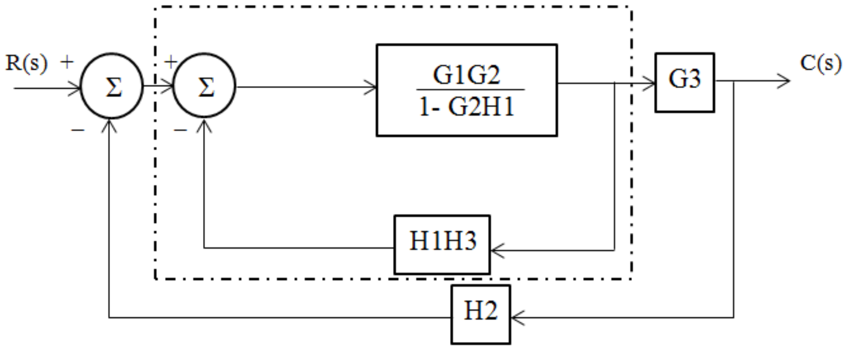
Step 2: Eliminating the feedback paths.



Step 3: Combining the blocks in cascade.



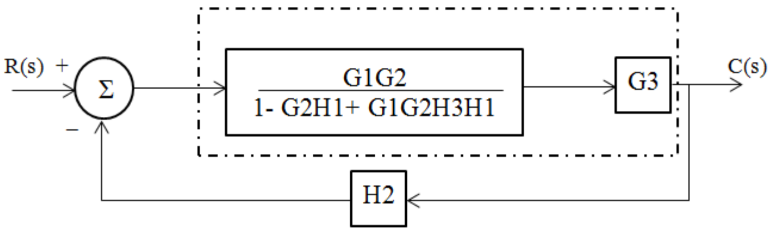
Step 4: Eliminating the feedback path



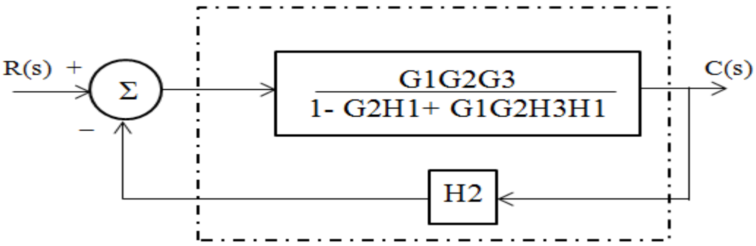
$$= \frac{\dfrac{G2G2}{1-G2H1}}{1+\dfrac{G1G2}{1-G2H1}\times H3H1}$$

$$= \frac{G1G2}{1-G2H1+G1G2H3H1}$$

Step 5: Combining the blocks in cascade.



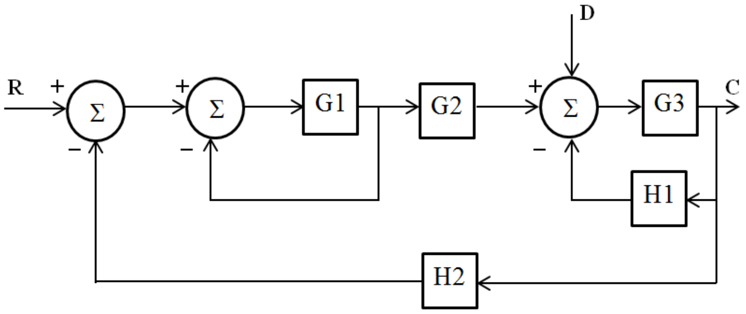
Step 6: Eliminating the feedback path



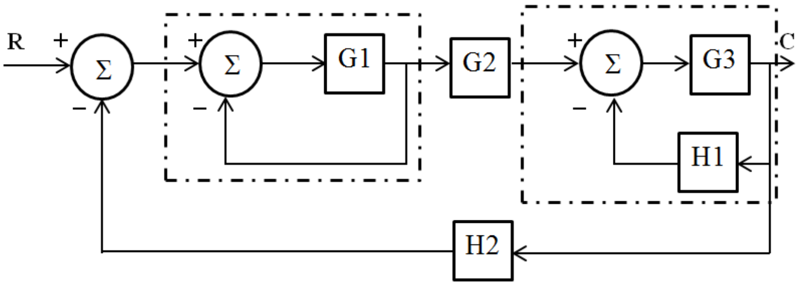
$$= \frac{\dfrac{G1G2G3}{1-G2H1+G1G2H3H1}}{1+\dfrac{G1G2G3}{G2H1+G1G2H3H1}}$$

$$= \frac{C(s)}{R(s)} = \frac{G1G2G3}{1-G2H1+G1G2H3H1+G1G2G3H2}$$

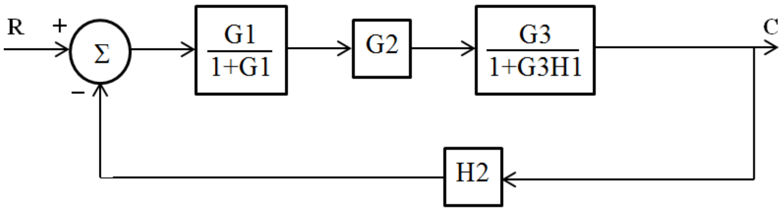
2. For the block diagram shown below, find the output C due to R and disturbance D.



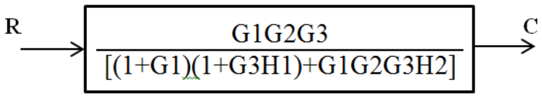
Step 1: Assuming D = 0, the block diagram becomes as shown in the figure below.



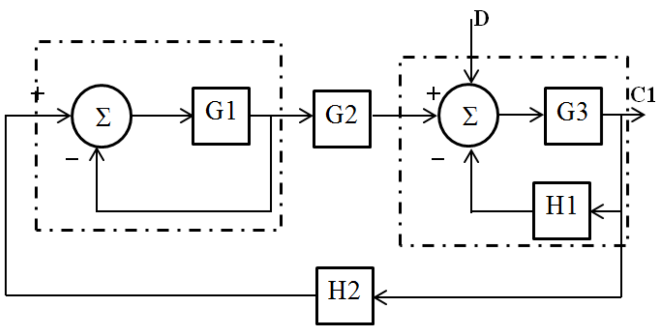
Step 2: Eliminating the feedback paths.



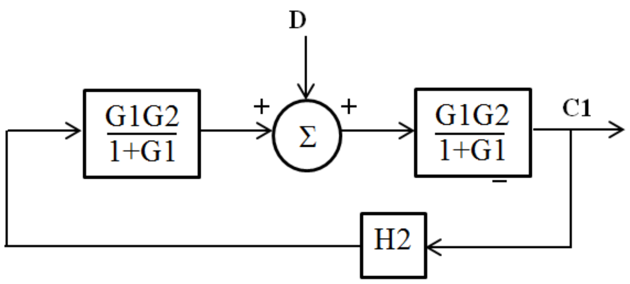
Step 3: The three forward path blocks and the feedback block is combined to give the transfer function.



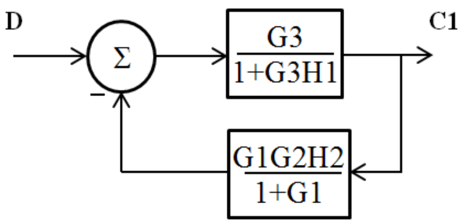
Step 4: Assuming R = 0 the block diagram in the question becomes



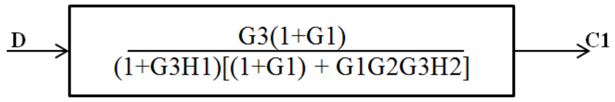
Step 5: The two feedback loops are eliminated.



Step 6: The block diagram can be redrawn as



Step 7: The block diagram can be reduced to give the transfer function as shown.



Step 8: When D = 0 output is C and is given below

$$C = \frac{RG1G2G3}{[(1+G1)(1+G3H1)+G1G2G3H2]}$$

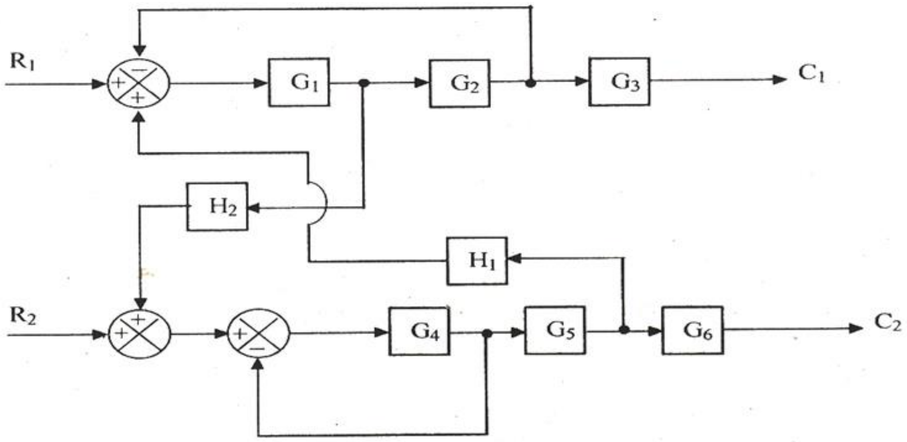
When R = 0 the output is C1 and is given by

$$C1 = \frac{DG3(1+G1)}{[(1+G1)(1+G3H1)+G1G2G3H2]}$$

When R and D are simultaneously present the output is O = C + C1

$$O = \frac{G3[RG1G2+D(1+G1)]}{[(1+G1)(1+G3H1)+G1G2G3H2]}$$

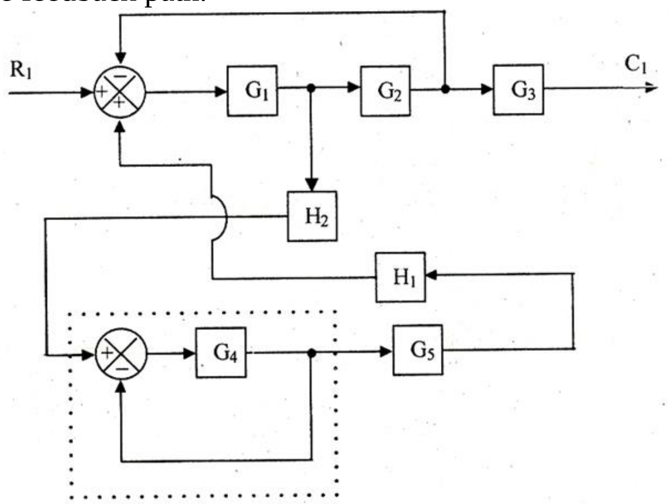
3.For the system represented by the block diagram shown in figure, Determine the transfer function C1/R1 and C2/R1.



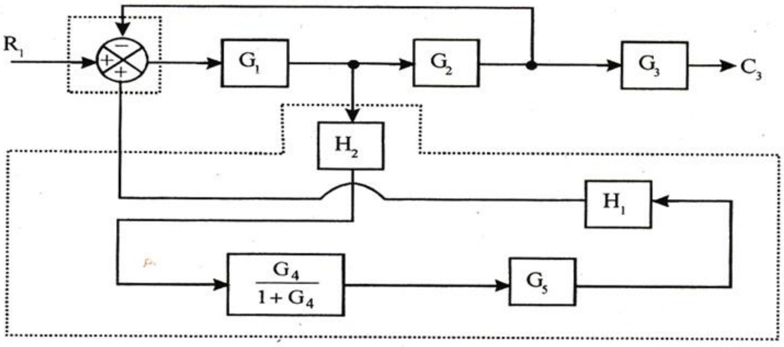
Solution:

Case 1: To find C_1/R_1. Consider R2 and C2 to be zero.

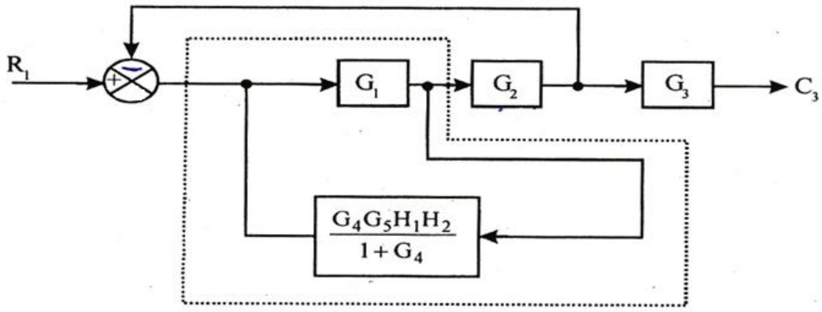
Step 1: Eliminate the feedback path.



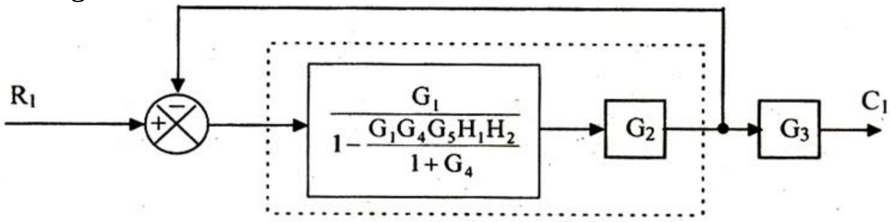
Step 2: Combining blocks in cascade and the summing point.



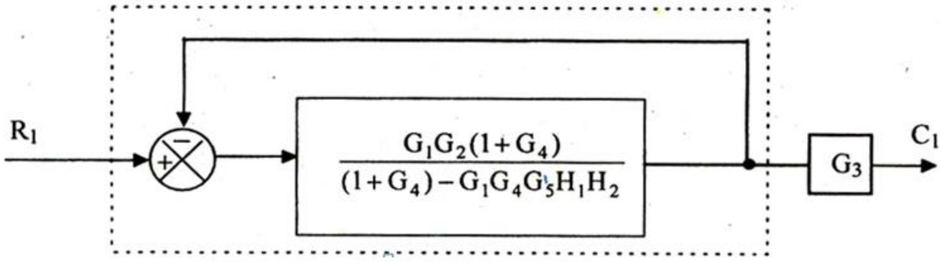
Step 3: Eliminate the feedback path.

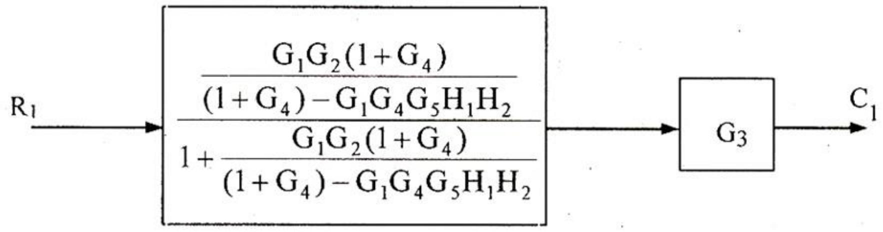


Step 4 : Combining the blocks in cascade

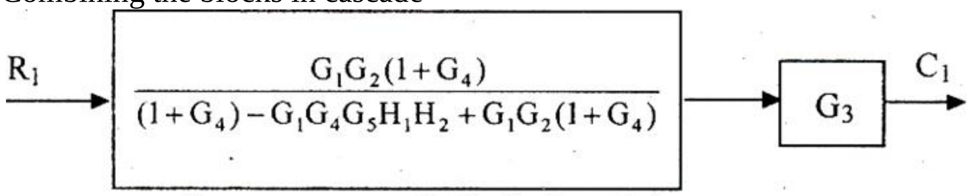


Step 5: Eliminate the feedback path.





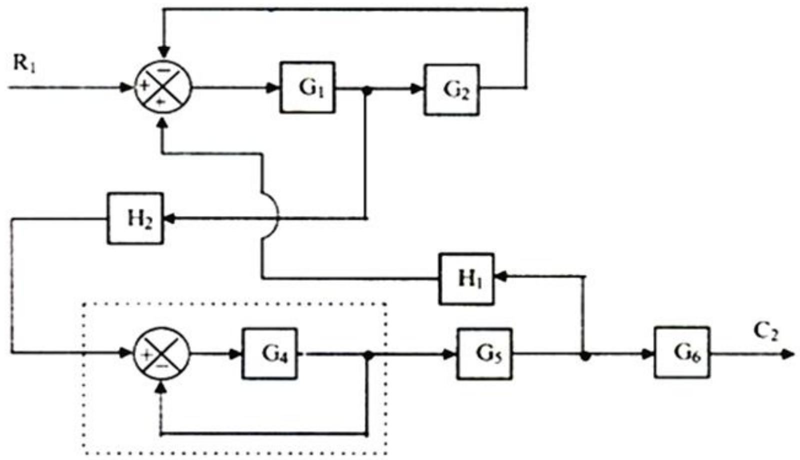
Step 6 : Combining the blocks in cascade



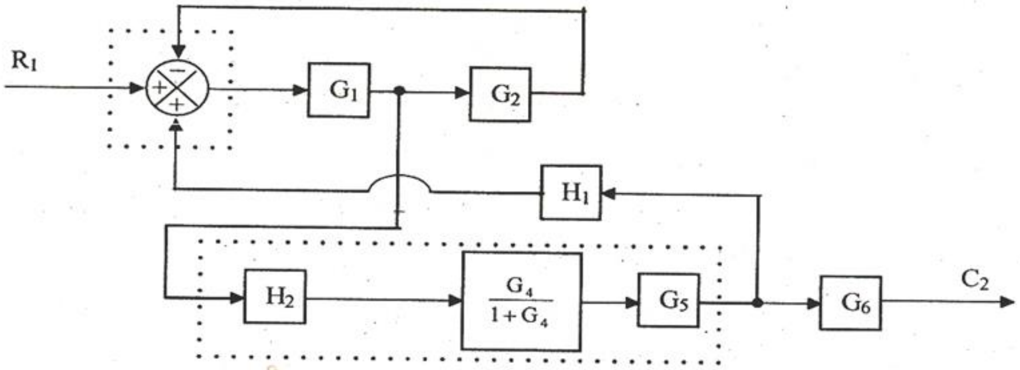
$$\frac{C_1}{R_1} = \frac{G_1G_2G_3(1+G_4)}{(1+G_1G_2)(1+G_4) - G_1G_4G_5H_1H_2}$$

Case 2: To find C_2/R_1. Consider R2 and C1 to be zero

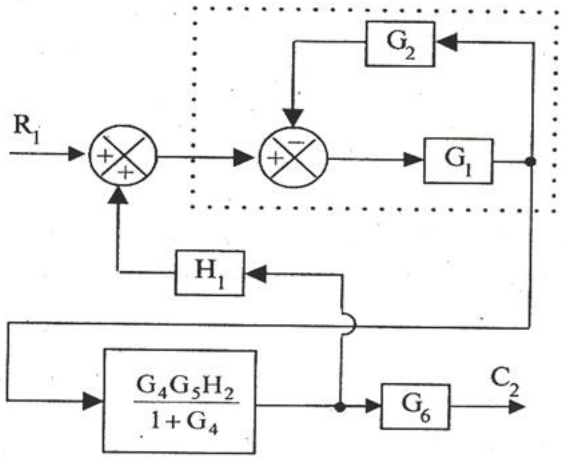
Step 1: Eliminate the feedback path.



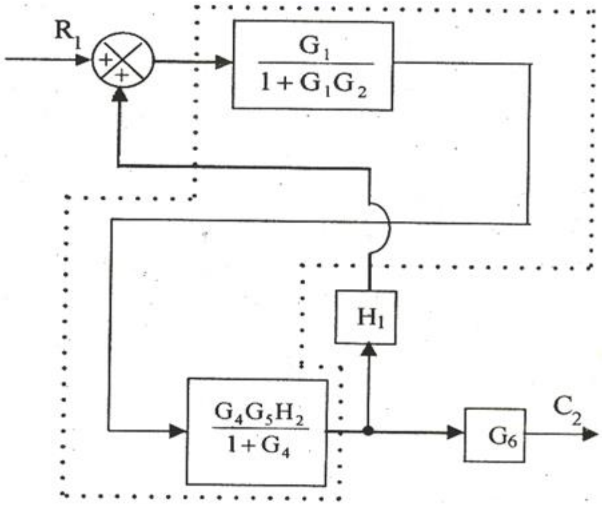
Step 2: Combining blocks in cascade and the summing point.



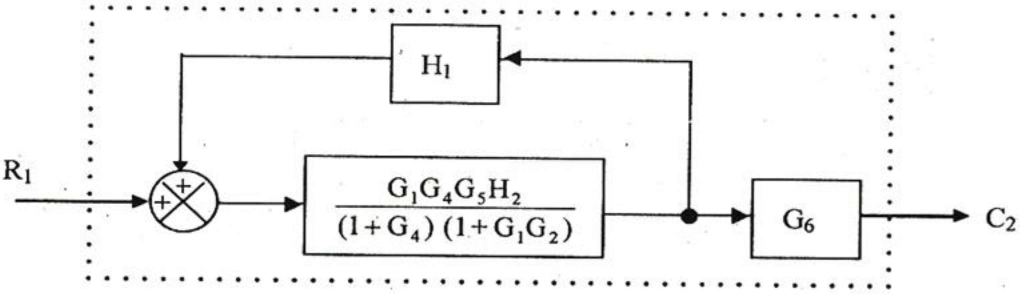
Step 3: Eliminate the feedback path.

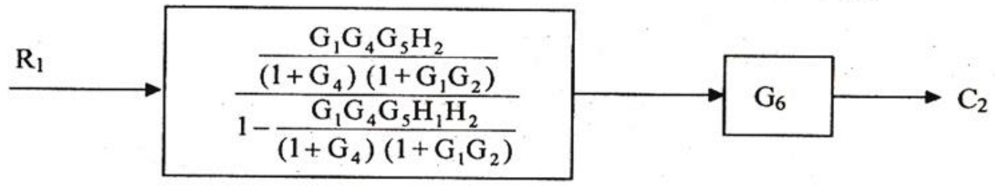


Step 4 : Combining the blocks in cascade

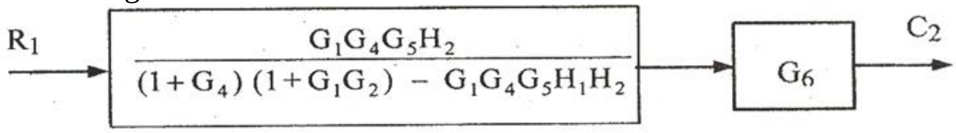


Step 5: Eliminate the feedback path.





Step 6 : Combining the blocks in cascade



$$\frac{C_2}{R_1} = \frac{G_1G_4G_5G_6H_2}{(1+G_4)(1+G_1G_2) - G_1G_4G_5H_1H_2}$$

SIGNAL FLOW GRAPH

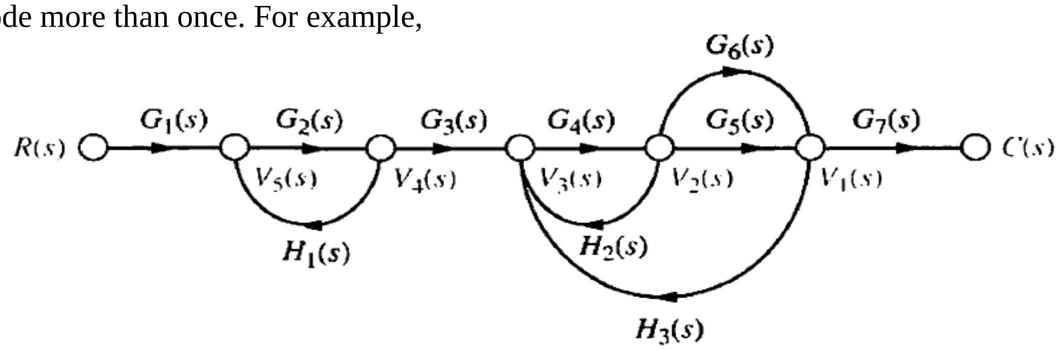
Signal-flow graphs represent transfer functions as lines, and signals as small circular nodes. Summing is implicit. Thus, the main advantage signal-flow graphs over block diagrams, is that they can be drawn more quickly, they are more compact, and they emphasize the state variables.

Signal-flow graphs are an alternative to block diagrams. Unlike block diagrams, which consist of blocks, signals, summing junctions, and pickoff points, a signal-flow graph consists only of *branches,* which represent systems, and *nodes,* which represent signals.

Mason's rule for reducing a signal-flow graph to a single transfer function requires the application of one formula. The formula was derived by S. J. Mason when he related the signal-flow graph to the simultaneous equations that can be written from the graph *(Mason, 1953).* In general, it can be complicated to implement the formula without making mistakes.

Specifically, the existence of what we will later call nontouching loops increases the complexity of the formula. However, many systems do not have nontouching loops. For these systems, you may find Mason's rule easier to use than blockdiagram reduction. Mason's formula has several components that must be evaluated. First, we must be sure that the definitions of the components are well understood. Then we must exert care in evaluating the components with example then discuss the Mason’s Gain formula.

Loop gain. The product of branch gains found by traversing a path that starts at a node and ends at the same node, following the direction of the signal flow, without passing through any other node more than once. For example,



The loop gains are:

1. *G2(s)H_1(s)*
2. *G4{s)H2{s)*

3. *G4(s)G5(s)H3(s)*
4. *G4(s)G6(s)H3(s)*

Forward-path gain: The product of gains found by traversing a path from the input node to the output node of the signal-flow graph in the direction of signal flow.

1. *G1(s)G2(s)G3(s)G4(s)G5(s)G7(s)*
2. *G1(s)G2(s)G3(s)G4(s)G6(s)G7(s)*

Non touching loops : Loops that do not have any nodes in common. Loop G2(s)H1(s) does not touch loops G4(s)H2(s), G4(s)G5(s)H3(s) and G4(s)G6(s)H3(S)

Mason's Rule

The transfer function, T=*C(s)/R(s),* of a system represented by a signal-flow graph is

$$overall\ gain, T = \frac{1}{\Delta}\sum_{K} P_k\,\Delta_k$$

T= T(s) = Transfer function of the system

K= Number of forward path

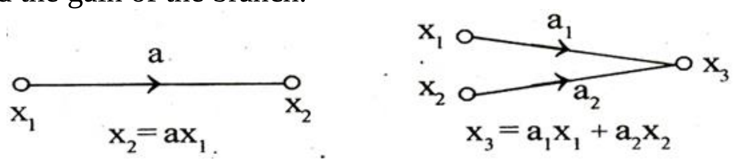
$P_k =$ Forward path gain of k^{th} forward path

$$\Delta = 1 - \begin{bmatrix} sum of individual \\ loop gains \end{bmatrix} + \begin{bmatrix} sum of gain products of all possible \\ combinations of two non-touching loops \end{bmatrix} - \begin{bmatrix} sum of gain products of all possible \\ combinations of three non-touching loops \end{bmatrix} + \cdots$$

$$\Delta_k = \Delta\ for\ that\ part\ of\ the\ graph\ which\ is\ not\ touching\ K^{th}\ forward\ path$$

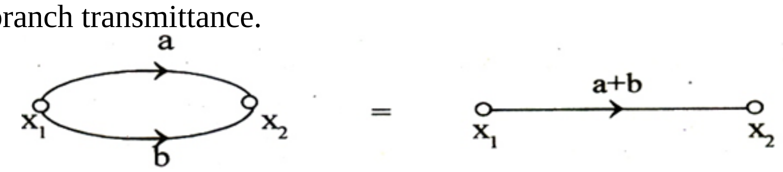
Signal Flow Graph Algebra

Rule 1: Incoming signal to a node through a branch is given by the product of a signal at previous node and the gain of the branch.

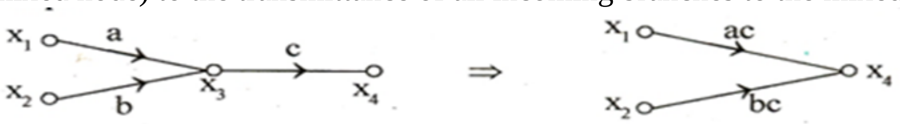


Rule 2: Cascade branches can be combined to give a single branch whose transmittance is equal to the product of individual branch transmittance.

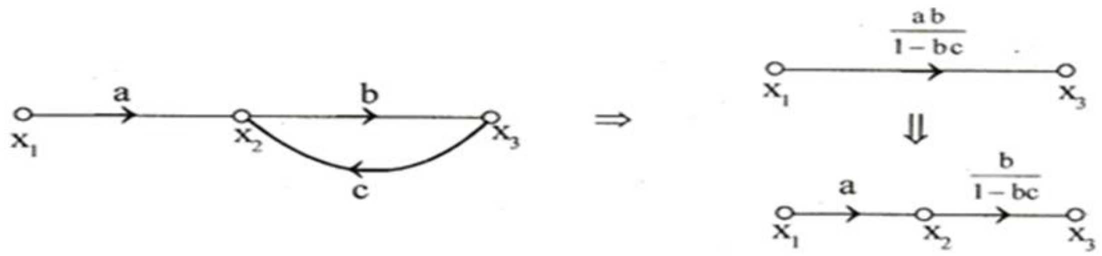
Rule 3: Parallel branch may be represented by single branch whose transmittance is the sum of individual branch transmittance.



Rule 4: A mixed node can be eliminated by multiplying the transmittance of outgoing branch (from the mixed node) to the transmittance of all incoming branches to the mixed node.



Rule 5: A loop may be eliminated by writing equations at the input and output node and rearranging the equation to find the ratio of output to input. This ratio gives the gain of resultant branch.



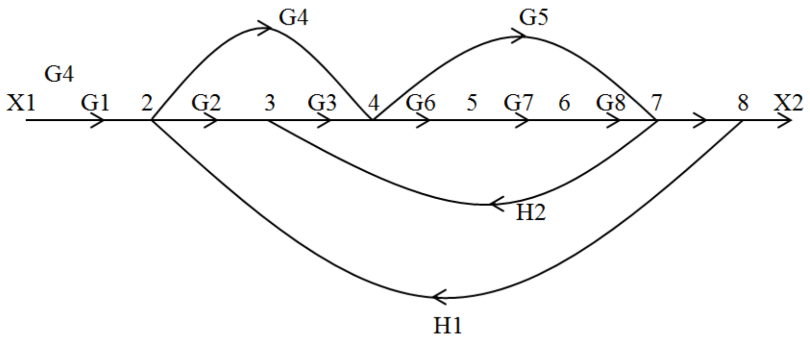
Steps to construct the Signal Flow Graph:

The Signal flow graph is constructed from its describing equations, or by direct reference to block diagram of the system. Each variable of the block diagram becomes a node and each block becomes a branch. The general procedure is

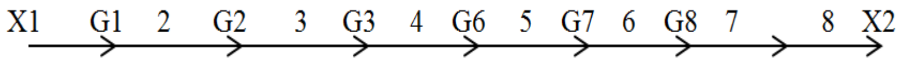
1. Arrange the input to output nodes from left to right
2. Connect the nodes by appropriate branches,
3. If the desired output node has outgoing branches, add a dummy node and a unity gain branch.
4. Rearrange the node and/or loops in the graph to achieve pictorial clarity.

Examples:

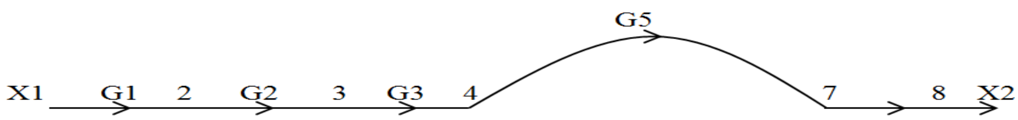
1. Determine the transfer function of the system using Mason's Gain formula.



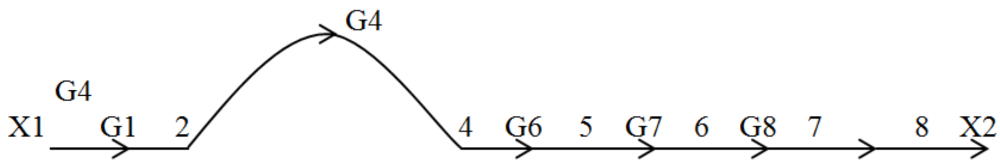
Step 1: There are four forward paths P1, P2, P3, P4; K = 4.



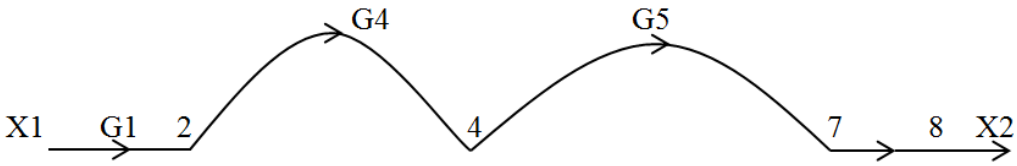
P1 = G1G2G3G6G7G8



P2 = G1G2G3G5G8

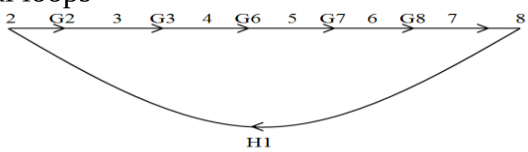


P3 = G1G4G6G7G8

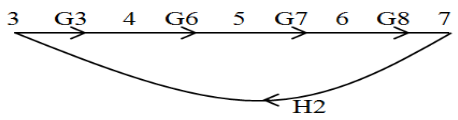


P4 = G1G4G5G8

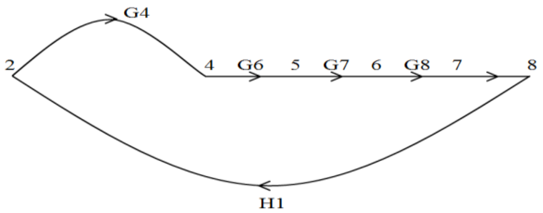
Step 2: There are 5 individual loops



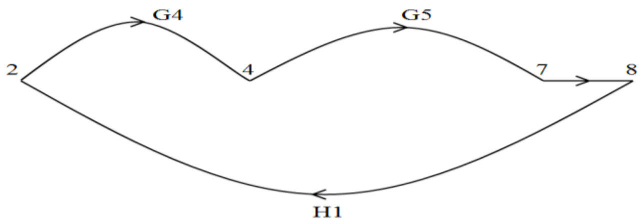
P11 = G2G3G6G7G8H1



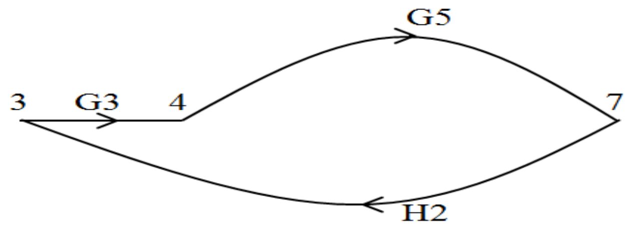
P21 = G3G6G7H2



P31 = G4G6G7G8H1



P41 = G4G5G8H1



P51 = G3G5H2

Step 4: There are no combination of two non-touching loops.

Step 5: Calculation of Δ and ΔK

$\Delta = \quad 1 - (P11 + P21 + P31 + P41 + P51)$

$= 1 - (G2G3G6G7G8H1 + G3G6H7H2 + G4G6G7G8H1 + G4G5G8H1 + G3G5H2$

There is no part of the graph touching with 1st forward path; $\Delta 1 = 1$

There is no part of the graph touching with 2nd forward path; $\Delta 1 = 1$

There is no part of the graph touching with 3rd forward path; $\Delta 1 = 1$

There is no part of the graph touching with 4th forward path; $\Delta 1 = 1$

Step 5: Determination of transfer function.

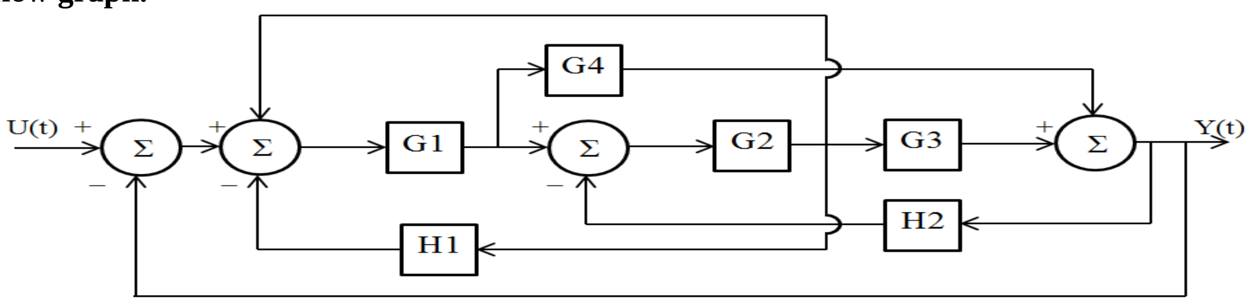
By Masons gain formula the transfer function is given by

$$T = \frac{1}{D}\sum_{K} PKDK$$

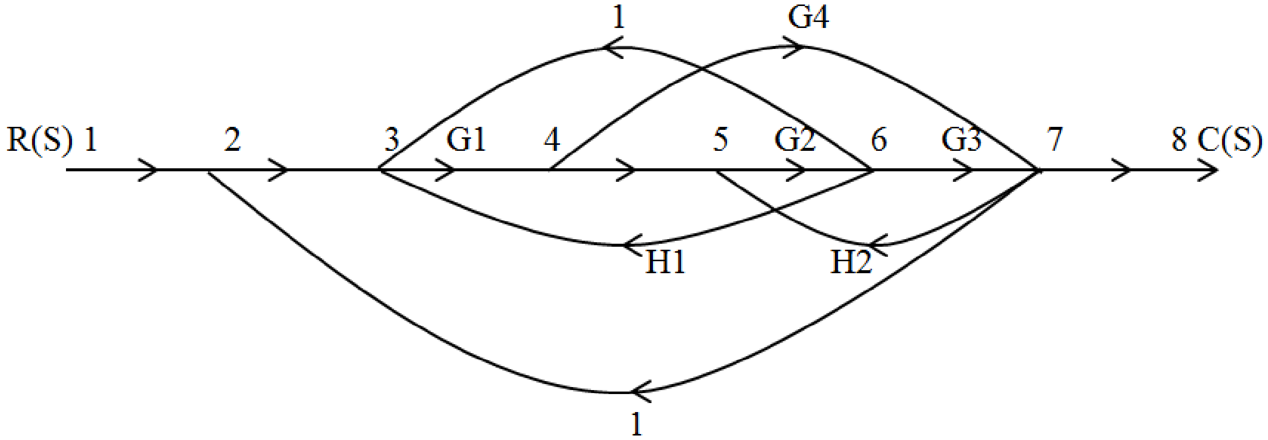
$$= \frac{1}{D}(P1D1 + P2D2 + P3D3 + P4D4)$$

$$= \frac{G1G2G3G6G7G8 + G1G2G3G5G8 + G1G4G6G7G8 + G1G4G5G8}{1 - G2G3G6G7G8H1 + G3G6H7 + G4G6G7G8H1 + G4G5G8H1 + G3G5H2}$$

2.Use Masons gain formula to obtain C(S)/R(s) of the system shown below by using signal flow graph.

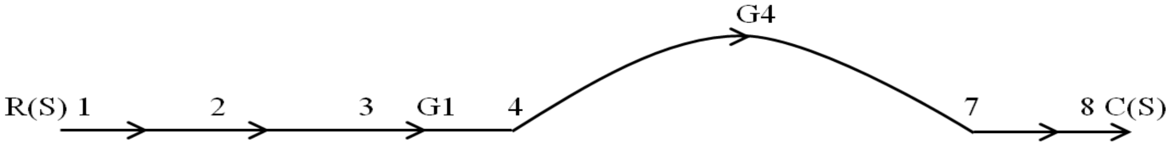


Step 1: The equivalent signal flow graph is given by



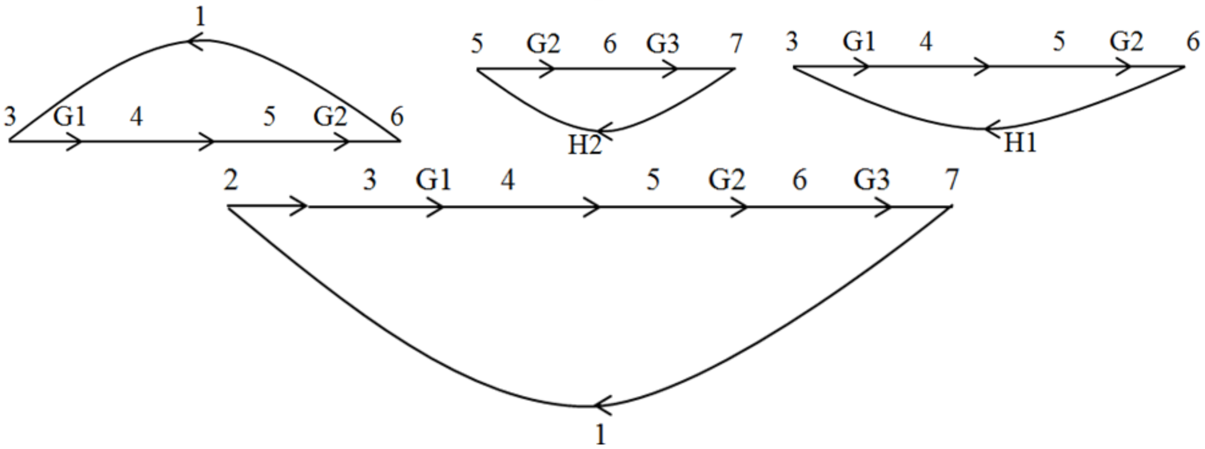
Step 2: There are two forward paths P1 and P2; K = 2

P1 = G1G2G3



P2 = G1G4

Step 3: There are 4 individual loops. Let the four loops be P11, P21, P31, P41



P11 = G1G2 P21 = G2G3H2

P31 = G1G2H1 P41 = G1G2G3

Step 3: Gain product of 2 non touching loops

There are no 2 non touching loops.

Step 4: Calculation of Δ and ΔK

$\Delta = 1 - (P11 + P21 + P31 + P41)$

$\Delta = 1 - G1G2 - G2G3H2 - G1G2H1 - G1G2G3$

$\Delta1 = 1 - 0 = 1$

$\Delta2 = 1$

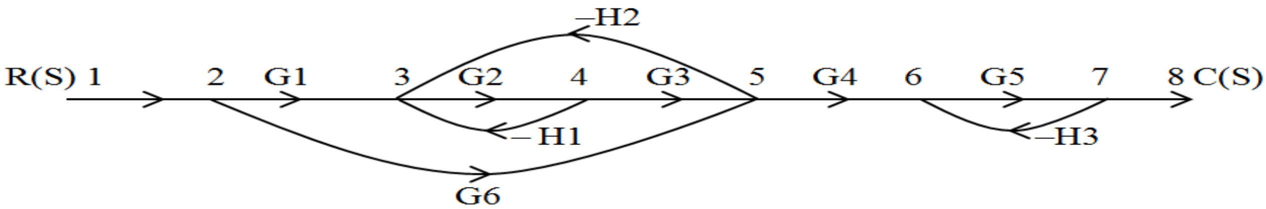
Step 5: Determination of transfer function

$$T = \frac{1}{\Delta}\sum_{k} PK\Delta K$$

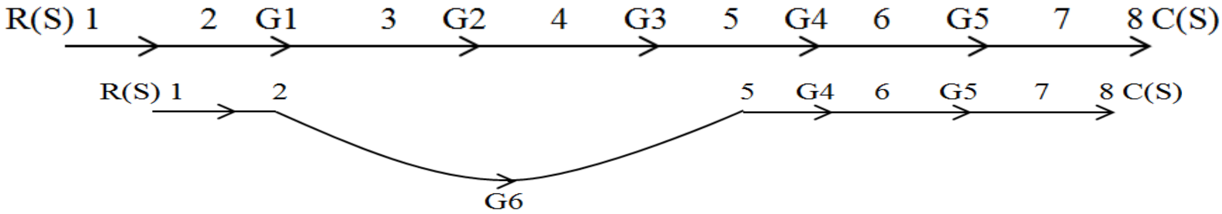
$$= \frac{1}{\Delta}\left(P1\Delta1 + P2\Delta2\right)$$

$$= \frac{G1G2G3 + G1G4}{1 - G1G2 - G2G3H2 - G1G2H1 - G1G2G3}$$

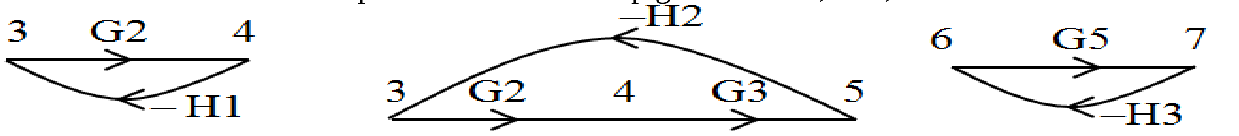
3.The signal flow graph for a feedback control system is shown in the figure. Determine the closed loop transfer function C(s)/R(s).



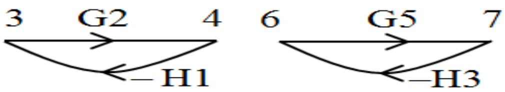
Step 1: Forward path gains
There are two forward paths K = 2
Let forward path gains be P1 and P2



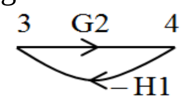
Gain forward path 1 = P1 = G1G2G3G4G5
Gain forward path 2 = P2 = G4G5G6
Step 2: Individual loop gain
There are three individual loops. Let individual loop gains be P11, P21, P31



Loop gain of individual loop 1 = P11 = –G2H1
Loop gain of individual loop 2 = P12 = –G2G3H2
Loop gain of individual loop 3 = P31 = –G5H3
Step 3: Gain products of two non-touching loops
There are two combinations of two non-touching loops. Let the gain products of two non-touching loops be P12 and P22.



Gain product of 1^{st} combination of two non-touching loops
P12 = P11P31 = (–G2H1)(–G5H3) = G2G5H1H3
Gain product of 2^{nd} combination of two non-touching loops
P22= P21P31= (–G2G3H2)(–G5H3)= G2G3G5G3H2H3
Step 4: Calculation of Δ and ΔK
Δ = 1– (P11 + P21 + P31) + (P12 + P22)
= 1– (–G2H1–G2G3H2–G5H3) + (G2G5H1H3 + G2G3G5G3H2H3)
= 1 + G2H1+G2G3H2+G5H3 + G2G5H1H3 + G2G3G5G3H2H3
$\Delta 1$ = 1, since there is no part of the graph which is not touching with first forward path
The part of the graph which is not touching with the second forward path is shown below.



$\Delta 2$ = 1–P11 = 1 – (– G1H1) = 1+G2H1
Step 5: Transfer function T
By Mason’s gain formula the transfer function T is given by,

$$T = \frac{1}{\Delta}\sum_{k} PK\Delta K$$

$$= \frac{1}{\Delta}\left(P1\Delta 1 + P2\Delta 2\right) \text{ No of forward path is 2, K = 2}$$

$$= \frac{G1G2G3G4G5+G4G5G6(1+G2H1)}{1+G2H1+G2G3H2+G5H3+G2G5H1H3+G2G3G5H2H3}$$

$$= \frac{G1G2G3G4G5+G4G5G6+G4G5G6G2H1)}{1+G2H1+G2G3H2+G5H3+G2G5H1H3+G2G3G5H2H3}$$

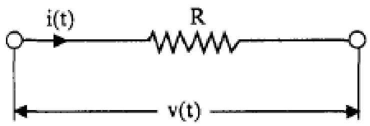
$$= \frac{G2G4G5[G1G3+G6/G2+G6H1]}{1+G2H1+G2G3H2+G5H3+G2G5H1H3+G2G3G5H2H3}$$

ELECTRICAL AND MECHANICAL SYSTEMS

Electrical Systems:

Most of the electrical systems can be modelled by three basic elements : Resistor, inductor, and capacitor. Circuits consisting of these three elements are analysed by using Kirchhoff's Voltage law and Current law.

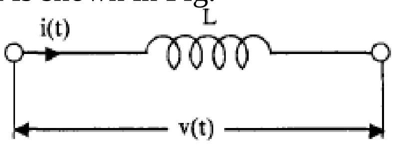
Resistor*:* The circuit model of resistor is shown in Fig.



The mathematical model is given by the Ohm's law relationship,

$$V(t) = i(t)\,R$$
$$i(t) = V(t)/R$$

Inductor: The circuit representation is shown in Fig.



The input output relations are given by Faraday's law,

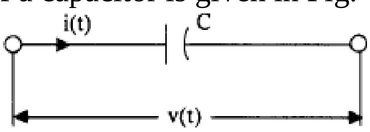
$$V(t) = L\,di(t)/dt$$

$$i(t) = \frac{1}{L}\int v\,dt$$

where Integral of v dt is known as the flux linkages. Thus

$$i(t) = \frac{\Psi(t)}{L}$$

Capacitor: The circuit symbol of a capacitor is given in Fig.



$$v(t) = \frac{1}{C}\int i dt$$

$$i(t) = C\,\frac{dv}{dt}$$

In eqn. idt is known as the charge on the capacitor and is denoted by *'q'*. Thus

$$q = \int i dt$$

$$v(t) = \frac{q(t)}{C}$$

Mechanical System

There are two types of mechanical systems based on the type of motion.

- Translational mechanical systems
- Rotational mechanical systems

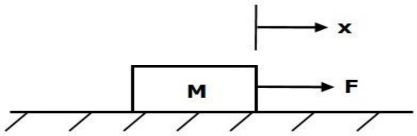
Modeling of Translational Mechanical Systems

Translational mechanical systems move along a **straight line**. These systems mainly consist of three basic elements. Those are mass, spring and dashpot or damper.

If a force is applied to a translational mechanical system, then it is opposed by opposing forces due to mass, elasticity and friction of the system. Since the applied force and the opposing forces are in opposite directions, the algebraic sum of the forces acting on the system is zero. Let us now see the force opposed by these three elements individually.

Mass

Mass is the property of a body, which stores **kinetic energy**. If a force is applied on a body having mass **M**, then it is opposed by an opposing force due to mass. This opposing force is proportional to the acceleration of the body. Assume elasticity and frictions are negligible.



$$F_m \propto a$$

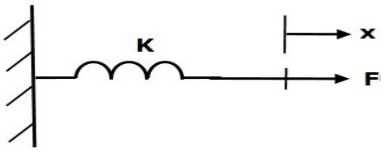
$$\Rightarrow F_m = Ma = M\frac{d^2x}{dt^2}$$

$$F = F_m = M\frac{d^2x}{dt^2}$$

- **F** is the applied force, $\mathbf{F_m}$ is the opposing force due to mass, **M** is mass, **a** is acceleration
- **x** is displacement

Spring

Spring is an element, which stores **potential energy**. If a force is applied on spring **K**, then it is opposed by an opposing force due to elasticity of spring. This opposing force is proportional to the displacement of the spring. Assume mass and friction are negligible.



$$F \propto x$$

$$\Rightarrow F_k = Kx$$

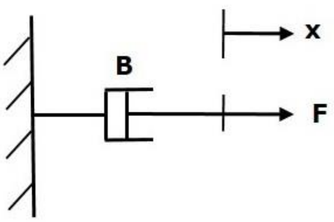
$$F = F_k = Kx$$

F is the applied force, $\mathbf{F_k}$ is the opposing force due to elasticity of spring, **K** is spring constant

- **x** is displacement

Dashpot

If a force is applied on dashpot **B**, then it is opposed by an opposing force due to **friction** of the dashpot. This opposing force is proportional to the velocity of the body. Assume mass and elasticity are negligible.



$$F_b \propto \nu$$

$$\Rightarrow F_b = B\nu = B\frac{dx}{dt}$$

$$F = F_b = B\frac{dx}{dt}$$

- $\mathbf{F_b}$ is the opposing force due to friction of dashpot, **B** is the frictional coefficient, **v** is velocity
- **x** is displacement

Modeling of Rotational Mechanical Systems

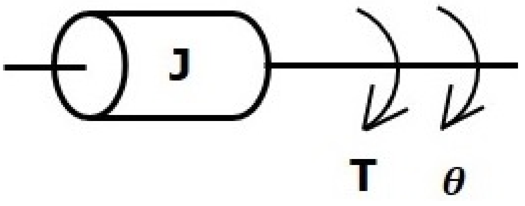
Rotational mechanical systems move about a fixed axis. These systems mainly consist of three basic elements. Those are **moment of inertia, torsional spring** and **dashpot**.

If a torque is applied to a rotational mechanical system, then it is opposed by opposing torques due to moment of inertia, elasticity and friction of the system. Since the applied torque and the opposing torques are in opposite directions, the algebraic sum of torques acting on the system is zero. Let us now see the torque opposed by these three elements individually.

Moment of Inertia

In translational mechanical system, mass stores kinetic energy. Similarly, in rotational mechanical system, moment of inertia stores **kinetic energy**.

If a torque is applied on a body having moment of inertia **J**, then it is opposed by an opposing torque due to the moment of inertia. This opposing torque is proportional to angular acceleration of the body. Assume elasticity and friction are negligible.



$$T_j \propto \alpha$$

$$\Rightarrow T_j = J\alpha = J\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2}$$

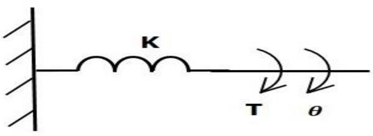
$$T = T_j = J\frac{\mathrm{d}^2\theta}{\mathrm{d}t^2}$$

- **T** is the applied torque, $\mathbf{T_j}$ is the opposing torque due to moment of inertia, **J** is moment of inertia
- **α** is angular acceleration, **θ** is angular displacement

Torsional Spring

In translational mechanical system, spring stores potential energy. Similarly, in rotational mechanical system, torsional spring stores **potential energy**.

If a torque is applied on torsional spring **K**, then it is opposed by an opposing torque due to the elasticity of torsional spring. This opposing torque is proportional to the angular displacement of the torsional spring. Assume that the moment of inertia and friction are negligible.



$$T_k \propto \theta$$

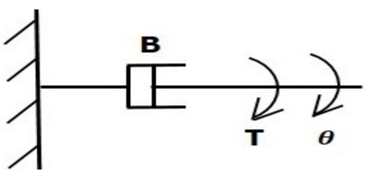
$$\Rightarrow T_k = K\theta$$

$$T = T_k = K\theta$$

- **T** is the applied torque, $\mathbf{T_k}$ is the opposing torque due to elasticity of torsional spring, **K** is the torsional spring constant, **θ** is angular displacement

Dashpot

If a torque is applied on dashpot **B**, then it is opposed by an opposing torque due to the **rotational friction** of the dashpot. This opposing torque is proportional to the angular velocity of the body. Assume the moment of inertia and elasticity are negligible.



$$T_b \propto \omega$$

$$\Rightarrow T_b = B\omega = B\frac{\mathrm{d}\theta}{\mathrm{d}t}$$

$$T = T_b = B\frac{\mathrm{d}\theta}{\mathrm{d}t}$$

- T_b is the opposing torque due to the rotational friction of the dashpot, **B** is the rotational friction coefficient, **ω** is the angular velocity, **θ** is the angular displacement

Two systems are said to be **analogous** to each other if the following two conditions are satisfied.

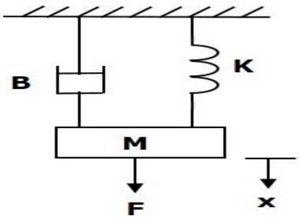
- The two systems are physically different
- Differential equation modelling of these two systems are same

Electrical systems and mechanical systems are two physically different systems. There are two types of electrical analogies of translational mechanical systems. Those are force voltage analogy and force current analogy.

Force Voltage Analogy

In force voltage analogy, the mathematical equations of **translational mechanical system** are compared with mesh equations of the electrical system.

Consider the following translational mechanical system as shown in the following figure.

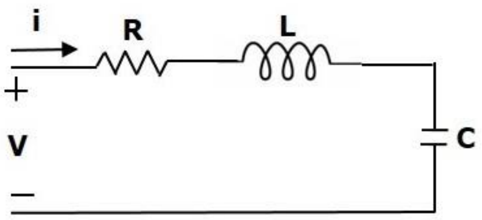


The **force balanced equation** for this system is

$$F = F_m + F_b + F_k$$

$$\Rightarrow F = M\frac{d^2x}{dt^2} + B\frac{dx}{dt} + Kx$$ **(Equation 1)**

Consider the following electrical system as shown in the following figure. This circuit consists of a resistor, an inductor and a capacitor. All these electrical elements are connected in a series. The input voltage applied to this circuit is VV volts and the current flowing through the circuit is ii Amps.



Mesh equation for this circuit is

V=Ri+Ldi/dt+1/c∫idt **(Equation 2)**

Substitute, i=dq/dt in Equation 2.

$$V = R\frac{dq}{dt} + L\frac{d^2q}{dt^2} + \frac{q}{C}$$

$$\Rightarrow V = L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \left(\frac{1}{c}\right)q$$ **(Equation 3)**

By comparing Equation 1 and Equation 3, we will get the analogous quantities of the translational mechanical system and electrical system. The following table shows these analogous quantities.

Translational Mechanical System	Electrical System
Force(F)	Voltage(V)
Mass(M)	Inductance(L)

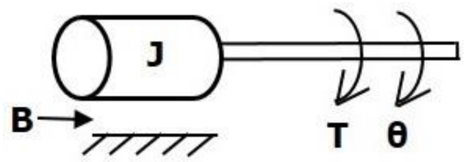
Frictional Coefficient(B)	Resistance(R)
Spring Constant(K)	Reciprocal of Capacitance (1c)(1c)
Displacement(x)	Charge(q)
Velocity(v)	Current(i)

Similarly, there is torque voltage analogy for rotational mechanical systems. Let us now discuss about this analogy.

Torque Voltage Analogy

In this analogy, the mathematical equations of **rotational mechanical system** are compared with mesh equations of the electrical system.

Rotational mechanical system is shown in the following figure.



The torque balanced equation is

$$T = T_j + T_b + T_k$$

$$\Rightarrow T = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + k\theta$$ **(Equation 4)**

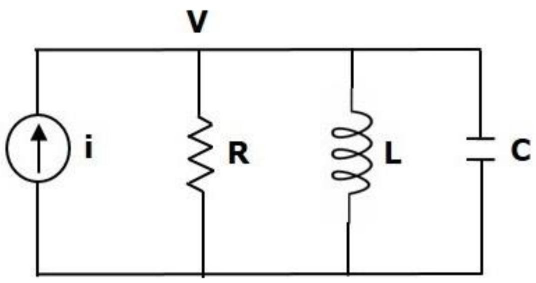
By comparing Equation 4 and Equation 3, we will get the analogous quantities of rotational mechanical system and electrical system. The following table shows these analogous quantities.

Rotational Mechanical System	Electrical System
Torque(T)	Voltage(V)
Moment of Inertia(J)	Inductance(L)
Rotational friction coefficient(B)	Resistance(R)
Torsional spring constant(K)	Reciprocal of Capacitance (1c)(1c)
Angular Displacement(θ)	Charge(q)
Angular Velocity(ω)	Current(i)

Force Current Analogy

In force current analogy, the mathematical equations of the **translational mechanical system** are compared with the nodal equations of the electrical system.

Consider the following electrical system as shown in the following figure. This circuit consists of current source, resistor, inductor and capacitor. All these electrical elements are connected in parallel.



The nodal equation is

$$i = \frac{V}{R} + \frac{1}{L}\int V dt + C\frac{\mathrm{d}V}{\mathrm{d}t}$$ **(Equation 5)**

Substitute, V=dΨ/dt in Equation 5.

$$i = \frac{1}{R}\frac{\mathrm{d}\Psi}{\mathrm{d}t} + \left(\frac{1}{L}\right)\Psi + C\frac{\mathrm{d}^2\Psi}{\mathrm{d}t^2}$$

$$\Rightarrow i = C\frac{\mathrm{d}^2\Psi}{\mathrm{d}t^2} + \left(\frac{1}{R}\right)\frac{\mathrm{d}\Psi}{\mathrm{d}t} + \left(\frac{1}{L}\right)\Psi$$ **(Equation 6)**

By comparing Equation 1 and Equation 6, we will get the analogous quantities of the translational mechanical system and electrical system. The following table shows these analogous quantities.

Translational Mechanical System	Electrical System
Force(F)	Current(i)
Mass(M)	Capacitance(C)
Frictional coefficient(B)	Reciprocal of Resistance(1R)(1R)
Spring constant(K)	Reciprocal of Inductance(1L)(1L)
Displacement(x)	Magnetic Flux(ψ)
Velocity(v)	Voltage(V)

Similarly, there is a torque current analogy for rotational mechanical systems. Let us now discuss this analogy.

Torque Current Analogy

In this analogy, the mathematical equations of the **rotational mechanical system** are compared with the nodal mesh equations of the electrical system.

By comparing Equation 4 and Equation 6, we will get the analogous quantities of rotational mechanical system and electrical system. The following table shows these analogous quantities.

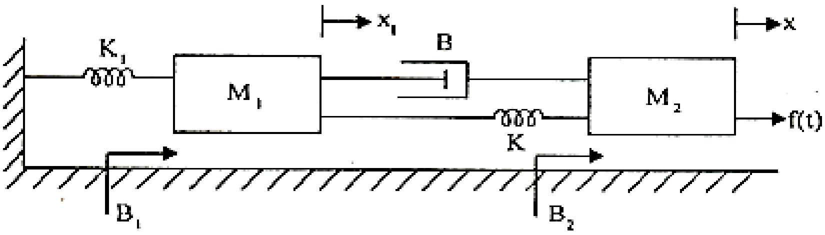
Rotational Mechanical System	Electrical System
Torque(T)	Current(i)
Moment of inertia(J)	Capacitance(C)
Rotational friction coefficient(B)	Reciprocal of Resistance(1R)(1R)
Torsional spring constant(K)	Reciprocal of Inductance(1L)(1L)

Angular displacement(θ)	Magnetic flux(ψ)
Angular velocity(ω)	Voltage(V)

These analogies are helpful to study and analyze the non-electrical system like mechanical system from analogous electrical system.

Examples

1. Write the differential equations governing the mechanical system shown in fig .And determine the transfer function?



Solution

In the given system, applied force f(t) is the input and displacement X is the output

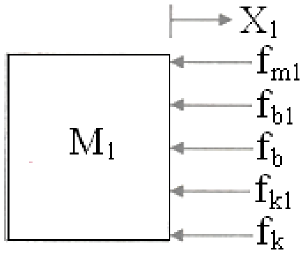
Let, Laplace transfer of f(t)=£{f(t) = F(s)}

Laplace transfer of x =)=£{X} = X(s)

Laplace transfer of X_1= £{X_1} = $X_1(s)$

Hence the required transfer function is $\frac{X(s)}{F(s)}$

At node 1(M1)



By Newton's second law,$f_{m1} + f_{b1} + f_b + f_{k1} + f_k = 0$

$$M_1 \frac{d^2X_1}{dt^2} + B_1 \frac{dX_1}{dt} + B\frac{d}{dt}(X_1 - X) + K_1X_1 + K(X_1 - X) = 0$$

On taking Laplace transform of above equation with zero initial conditions we get,

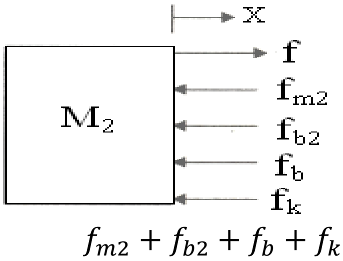
$$M_1s^2X_1(s) + B_1sX_1(s) + Bs[X_1(s) - X(s)] + K_1X_1(s) + K[X_1(s) - X(s)] = 0$$

$$X_1(s)[M_1s^2 + (B_1 + B)s + (K_1 + K)] - X(s)[Bs + K] = 0$$

$$X_1(s)[M_1s^2 + (B_1 + B)s + (K_1 + K)] = X(s)[Bs + K]$$

$$\therefore X_1(s) = X(s)\frac{Bs + K}{M_1s^2 + (B_1 + B)s + (K_1 + K)} \dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

At Node 2 (M2)



By Newton's second law, $f_{m2} + f_{b2} + f_b + f_k = f(t)$

$$M_2 \frac{d^2X}{dt^2} + B_2 \frac{dX}{dt} + B\frac{d}{dt}(X - X_1) + K(X - X_1) = f(t)$$

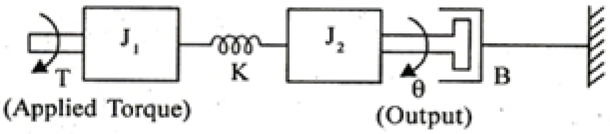
On taking Laplace transform of above equation with zero initial conditions we get,

$$M_2s^2X(s) + B_2sX(s) + Bs[X(s) - X_1(s)] + K[X(s) - X_1(s)] = F(s)$$
$$X(s)[M_2s^2 + (B_2 + B)s + K] - X_1(s)[Bs + K] = F(s) \ldots\ldots\ldots\ldots\ldots..(2)$$
Substituting $X_1(s)$ from equation (1) in equation (2) we get,
$$X(s)[M_2s^2 + (B_2 + B)s + K] - \frac{(Bs + K)^2}{M_1s^2 + (B_1 + B)s + (K_1 + K)} = F(s)$$

$$X(s)\left[\frac{[M_1s^2 + (B_2 + B)s + K][M_2s^2 + (B_1 + B)s + (K_1 + K)] - (Bs + K)^2}{M_1s^2 + (B_1 + B)s + (K_1 + K)}\right] = F(s)$$

$$\therefore\ \frac{\mathbf{X(s)}}{\mathbf{F(s)}} = \frac{\mathbf{M_1s^2 + (B_1 + B)s + (K_1 + K)}}{\mathbf{[M_1s^2 + (B_1 + B)s + (K_1 + K)][M_2s^2 + (B_1 + B)s +] - (Bs + K)^2}}$$

2. Write the differential equations governing the mechanical rotational system as shown in fig, obtain the transfer function of the system.

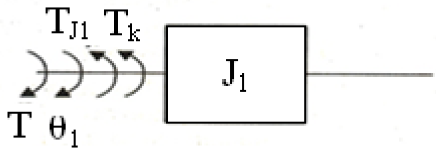


SOLUTION

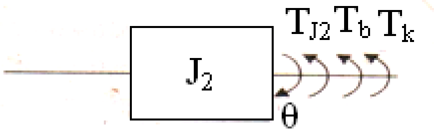
In the given system, applied force f(t) is the input and displacement X is the output.
Let, Laplace transfer of T =£{T} = T(s)
Laplace transfer of x =)=£{θ} = θ(s)
Laplace transfer of X_1= £{θ_1} = θ_1(s)
Hence the required transfer function is $\frac{\theta(s)}{T(s)}$
The system has two nodes and they are mass $J_1$and J_2, the differential equations governing the system are given by torques balance equations at these nodes.

Let the displacement of mass J_1 be θ_1 .The free body diagram of J_1 is shown in fig. the opposing forces acting on $J_1$are marked as T_j, and T_k.

Free body diagram-1



By Newton's second law,$T_{j1} + T_k = T$
$$J_1\frac{d^2\theta_1}{dt^2} + K(\theta_1 - \theta) = T$$
On taking Laplace transform of above equation we get,
$$J_1s^2\theta_1(s) + K\theta_1(s) - K\theta(s) = T(s)$$
$$(J_1s^2 + K)\theta_1(s) - K\theta(s) = T(s) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(1)$$
Free body diagram-2



By Newton's second law,$T_{j2} + T_b + T_k = 0$
$$J_2\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + K(\theta - \theta_1) = 0$$
On taking Laplace transform of above equation we get,
$$J_2s^2\theta(s) + Bs\theta(s) + K\theta(s) - K\theta_1(s) = 0$$

$$(J_2s^2 + Bs + K)\theta(s) - \theta_1(s) = 0$$

$$\theta_1(s) = \frac{(J_2s^2 + Bs + K)}{K}\theta(s) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.(2)$$

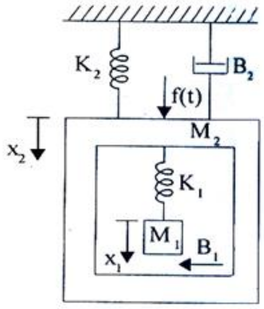
Substitute $\theta_1(s)$from equation 2 in equation 1 we get,

$$(J_1s^2 + K)\frac{(J_2s^2 + Bs + K)}{K}\theta(s) - K\theta(s) = T(s)$$

$$\left[\frac{(J_1s^2 + K) + (J_2s^2 + Bs + K) - K^2}{K}\right]\theta(s) = T(s)$$

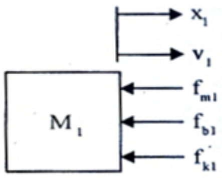
$$\boxed{\frac{\boldsymbol{\theta(s)}}{\mathbf{T(s)}} = \frac{\mathbf{K}}{\mathbf{(J_1s^2 + K) + (J_2s^2 + Bs + K) - K^2}}}$$

3. Write the differential equations governing the mechanical system shown in fig. draw the force current electrical analogous circuit.



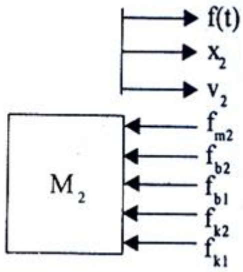
Solution:

Node-1



$$M_1\frac{d^2x_1}{dt^2} + B_1\frac{d(x_1 - x_2)}{dt} + K_1(x_1 - x_2) = 0$$

Node-2



$$M_2\frac{d^2x_2}{dt^2} + B_1\frac{d(x_2 - x_1)}{dt} + B_2\frac{dx_2}{dt} + K_1(x_2 - x_1) + K_2x_2 = f(t)$$

<u>Force- Current analogous circuits</u>

The electrical analogous is given by:

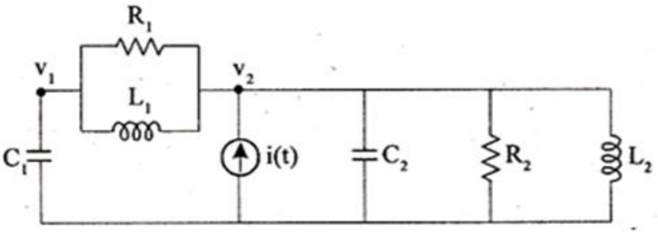
$f(t) \rightarrow i(t)$	$v_1 \rightarrow v_1$	$M_1 \rightarrow C_1$	$B_1 \rightarrow 1/R_1$	$K_1 \rightarrow 1/L_1$
	$v_2 \rightarrow v_2$	$M_2 \rightarrow C_2$	$B_2 \rightarrow 1/R_2$	$K_2 \rightarrow 1/L_2$

Thus the systems equations are:

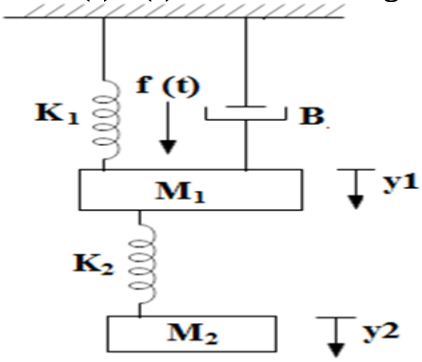
$$C_1\frac{dv_1}{dt} + \frac{1}{R_1}(v_1 - v_2) + \frac{1}{L_1}\int(v_1 - v_2)\,dt = 0$$

$$C_2\frac{dv_2}{dt} + \frac{1}{R_2}v_2 + \frac{1}{L_2}\int v_2 dt + \frac{1}{R_1}(v_2 - v_1) + \frac{1}{L_1}\int(v_2 - v_1)dt = i(t)$$

And the circuit is given by



4.Determine the transfer function $Y_2(s)/F(s)$ of the shown fig.



Solution:

Let Laplace transform of f(t) = L{f(t)} = F(s)

Let Laplace transform of y_1 = L{y_1} = $Y_1(s)$

Let Laplace transform of y_2 = L{y_2} = $Y_2(s)$

The system has two nodes and they are mass M_1 and M_2.

The differential equations governing the system are the force balance equations of at these nodes.

Consider Mass M_1,

Free Body diagram of M_1,

$f(t) = M_1\frac{d^2Y_1}{dt^2} + B\frac{dY_1}{dt} + K_1Y_1 + K_2(Y_1 - Y_2)$ 1

on taking Laplace Transform of equation (1) with zero initial conditions,

$M_1S^2Y_1(s) + BsY_1(s) + K_1Y_1(s) + K_2[Y_1(s) - Y_2(s)] = F(s)$

$Y_1(s)[M_1S^2 + Bs + (K_1+K_2)] - Y_2(s)K_2 = F(s)$ 2

Consider Mass M_2,

$M_2\frac{d^2Y_2}{dt^2} + K_2(Y_2 - Y_1) = 0$ 3

On taking Laplace Transform of equation (3) with zero initial conditions,

$M_2S^2Y_2(s) + K_2[Y_2(s) - Y_1(s)] = 0$ 4

$Y_2(s)[M_2S^2 + K_2] - K_2Y_1(s) = 0;$

$Y_1(s) = \frac{M_2S^2+K_2}{K1};$ 5

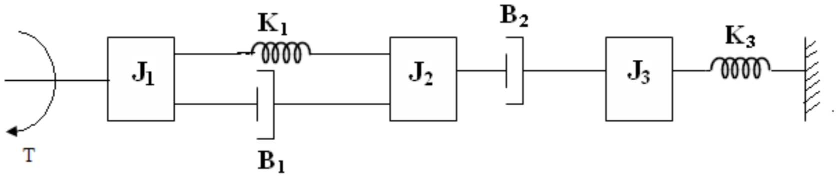
Substituting equation $Y_1(s)$ from equation (5) into equation (2) we get,

$Y_2(s)[\frac{M_2S^2+K_2}{K1}] + [M_1S^2 + Bs + (K_1+K_2)] - Y_2(s)K_2 = F(s)$

$Y_2(s)[\frac{M_2S^2+K_2)+[M_1S^2+Bs+(K_1+K_2)]-K_2^2}{K_2}] = F(s)$

$$\frac{Y_2(s)}{F(s)} = \frac{K_2}{(M_2S^2+K_2)+[M_1S^2+Bs+(K_1+K_2)]-K_2^2}$$

5.Write the differential equations governing the mechanical rotational system shown in fig. Draw the torque-voltage and torque-current electrical analogous circuits and verify by writing mesh and node equations.



Solution:

The given mechanical rotational system has three nodes. The differential equations governing the mechanical rotational system are given by torque balance equations at these nodes.

Let the angular displacements J_1, J_2 and J_3 be θ_1, θ_2 and θ_3 respectively. The corresponding angular velocities be ω_1, ω_2 and ω_3

Consider J_1.

By Newton's second law we get

$$J_1 \frac{d^2\theta_1}{dt^2} + B_1 \frac{d(\theta_1 - \theta_2)}{dt} + K_1(\theta_1 - \theta_2) = T$$

Consider J_2.

By Newton's second law we get

$$J_2 \frac{d^2\theta_2}{dt^2} + \frac{d(\theta_2 - \theta_3)}{dt} + K_1(\theta_2 - \theta_1) + B_1 \frac{d(\theta_2 - \theta_1)}{dt} = 0$$

Consider J_2.

By Newton's second law we get

$$J_3 \frac{d^2\theta_3}{dt^2} + B_2 \frac{d(\theta_3 - \theta_2)}{dt} + K_3\theta_3 = 0$$

On replacing the angular displacement by angular velocity in the differential equations we get $\left(\text{i.e} \frac{d^2\theta}{dt^2} = \frac{d\omega}{dt}; \frac{d\theta}{dt} = \omega \text{ and } \theta = \int \omega dt\right)$

$$J_1 \frac{d\omega_1}{dt} + B_1(\omega_1 - \omega_2) + K_1 \int (\omega_1 - \omega_2) dt = T$$

$$J_2 \frac{d\omega_2}{dt} + B_1(\omega_2 - \omega_1) + B_2(\omega_2 - \omega_3) + K_1 \int (\omega_2 - \omega_1) dt = 0$$

$$J_3 \frac{d\omega_3}{dt} + B_2(\omega_3 - \omega_2) + K_3 \int \omega_3 dt = 0$$

Torque voltage analogous circuit

The electrical analogous elements for the elements of mechanical rotational systems are given below

$\omega_1 \rightarrow i_1$	$J_1 \rightarrow L_1$	$B_1 \rightarrow R_1$	$K_1 \rightarrow 1/C_1$
$\omega_1 \rightarrow i_2$	$J_2 \rightarrow L_2$	$B_2 \rightarrow R_2$	$K_3 \rightarrow 1/C_3$
$\omega_3 \rightarrow i_3$	$J_3 \rightarrow L_3$		

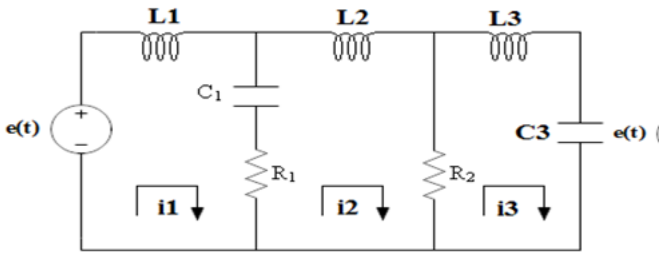
The Mesh basis equations using Kirchhoff's voltage law for the circuit is given by

$$L_1 \frac{di_1}{dt} + R_1(i_1 - i_2) + \frac{1}{C_1} \int (i_1 - i_2)\, dt = e(t)$$

$$L_2 \frac{di_2}{dt} + R_1(i_2 - i_1) + R_2(i_2 - i_3) + \frac{1}{C_1} \int (i_2 - i_1)\, dt = e(t)$$

$$L_3 \frac{di_3}{dt} + R_2(i_3 - i_2) + \frac{1}{C_3} \int i_3\, dt = 0$$

The electrical circuit is given by



Torque current analogous circuit

The electrical analogous elements for the elements of mechanical rotational systems are

$T \rightarrow i(t)$ $\omega_1 \rightarrow v_1$ $J_1 \rightarrow C_1$ $B_1 = 1/R_1$ $K_1 \rightarrow 1/L_1$

$\omega_2 \rightarrow v_2$ $J_2 \rightarrow C_2$ $B_2 = 1/R_2$ $K_3 \rightarrow 1/L_3$

$\omega_3 \rightarrow v_3$ $J_3 \rightarrow C_3$

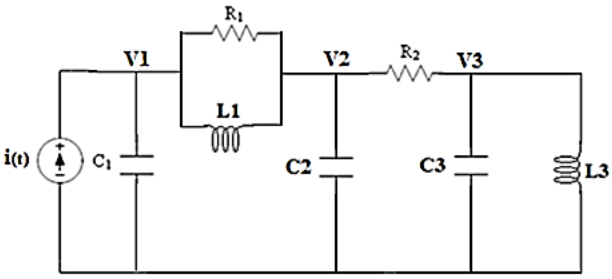
The node basis equations using Kirchhoff's current law for the circuit is

$$C_1\frac{dv_1}{dt}+\frac{1}{R_1}(v_1-v_2)+\frac{1}{L_1}\int(v_1-v_2)dt=i(t)$$

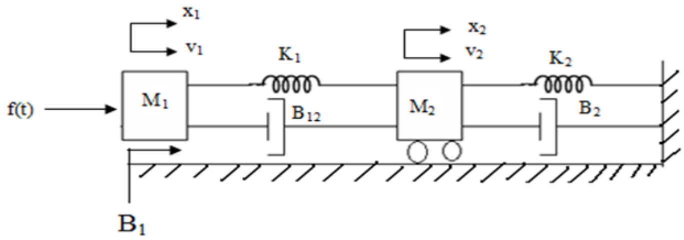
$$C_2\frac{dv_2}{dt}+\frac{1}{R_1}(v_2-v_1)+\frac{1}{R_2}(v_2-v_3)+\frac{1}{L_1}\int(v_2-v_1)dt=0$$

$$C_3\frac{dv_3}{dt}+\frac{1}{R_2}(v_3-v_2)+\frac{1}{L_3}\int v_3dt=0$$

The electrical circuit is given by



6.Write the differential equations governing the mechanical system shown in fig. Draw the force-voltage and force current electrical analogous circuits and verify by writing mesh and node equations.



Solution:

At M1:

$$M_1\frac{d^2x_1}{dt^2}+B_1\frac{dx_1}{dt}+B_{12}\frac{d}{dt}(x_1-x_2)+K_1(x_1-x_2)=0$$

At M2:

$$M_2\frac{d^2x_2}{dt^2}+B_2\frac{dx_2}{dt}+B_{12}\frac{d}{dt}(x_2-x_1)+K_2(x_2)+K_1(x_2-x_1)=0$$

Replacing the displacement by velocity in the differential equation we get,

$$\text{i.e } \frac{d^2x}{dt^2}=\frac{dv}{dt};\ \frac{dx}{dt}=v \text{ and } x=\int vdt$$

$$M_1\frac{d^2v_1}{dt^2}+B_1v_1+B_{12}(v_1-v_2)+\int K_1(v_1-v_2)\,dt=f(t)$$

$$M_2\frac{d^2v_2}{dt^2}+B_2v_2+B_{12}(v_2-v_1)+\int K_2(v_2-v_1)\,dt=0$$

Force voltage analogous circuit

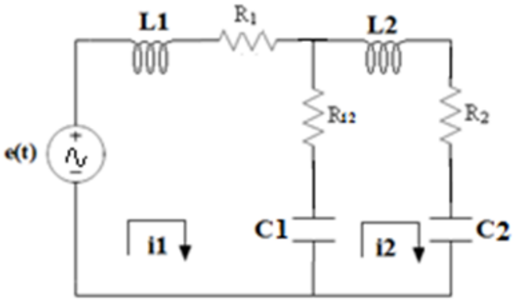
The electrical analogous elements for the elements of mechanical system is given by

$f(t) = e(t)$	$M_1 \rightarrow L_1$	$B_1 \rightarrow R_1$	$K_1 \rightarrow 1/C_1$
$v_1 = i_1$	$M_2 \rightarrow L_2$	$B_2 \rightarrow R_2$	$K_2 \rightarrow 1/C_2$
		$B_{12} \rightarrow R_{12}$	

The mesh basis equations using Kirchhoff's voltage law for the circuit shown is

$$L_1\frac{di_1}{dt}+R_1i_1+R_{12}(i_1-i_2)+\frac{1}{C_1}\int(i_1-i_2)\,dt=e(t)$$

$$L_2\frac{di_2}{dt}+R_2i_2+R_{12}(i_2-i_1)+\frac{1}{C_1}\int(i_2-i_1)\,dt=0$$



Force current analogous circuit

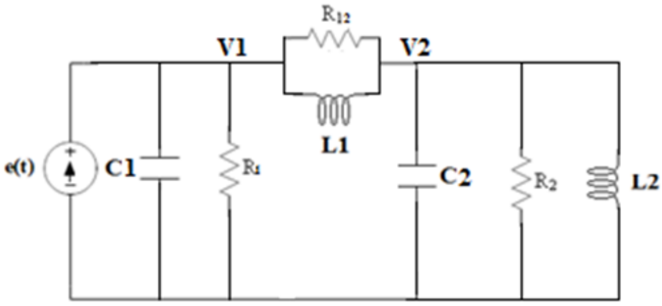
The electrical analogous elements for the elements of mechanical system is given by

$f(t) = i(t)$	$M_1 \rightarrow C_1$	$B_1 \rightarrow 1/R_1$	$K_1 \rightarrow 1/L_1$
$v_1 \rightarrow v_1$	$M_2 \rightarrow C_2$	$B_2 \rightarrow 1/R_2$	$K_2 \rightarrow 1/L_2$
$v_2 \rightarrow v_2$	$B_{12} \rightarrow 1/R_{12}$		

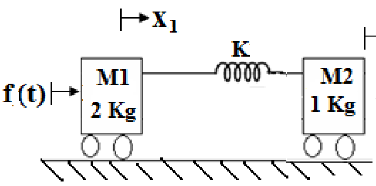
The node basis equations using Kirchhoff's current law for the circuit is

$$C_1\frac{dv_1}{dt}+\frac{1}{R_1}v_1+\frac{1}{R_{12}}(v_1-v_2)+\frac{1}{L_1}\int(v_1-v_2)\,dt=i(t)$$

$$C_2\frac{dv_2}{dt}+\frac{1}{R_2}v_2+\frac{1}{R_{12}}(v_2-v_1)+\frac{1}{L_2}\int v_2\,dt+\frac{1}{L_1}\int(v_2-v_1)\,dt=0$$



7.Derive the transfer function of the system show in the figure.



Applying Newton second law at M_1,

$$F(t)=M_1\frac{d^2x_1}{dt^2}+K(x_1-x_2)$$

Taking Laplace transform on both sides,

$$M_1S^2x_1(s)+K\left[x_1(s)-x_2(s)\right]=F(s)$$

$$x_1(s)\left[M_1S^2+K\right]-Kx_2(s)=F(s)\text{------}(1)$$

Applying Newton second law at M_2,

$$0=M_2\frac{d^2x_2}{dt^2}+K(x_2-x_1)$$

Taking Laplace transform on both sides,

$$M_2S^2x_2(s)+K\left[x_2(s)-x_1(s)\right]=0$$

$$M_2S^2x_2(s)+Kx_2(s)-Kx_1(s)=0$$

$$x_2(s)\left[M_2S^2+K\right]=Kx_1(s)$$

$$x_1(s)=\frac{x_2(s)\left[M_2S^2+K\right]}{K}$$

substitute value of $x_1(s)$ in (1)

$$x_2(s)\left[\frac{M_2S^2+K}{K}\right]\left[M_1S^2+K\right]-Kx_2(s)=F(s)$$

$$x_2(s)\left\{\left[\frac{(M_2S^2+K)(M_1S^2+K)}{K}\right]-K\right\}=F(s)$$

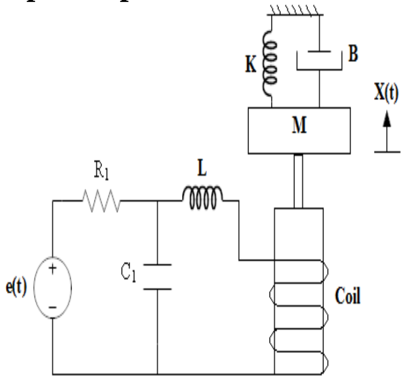
$$x_2(s)\left\{\frac{(M_2S^2+K)(M_1S^2+K)-K^2}{K}\right\}=F(s)$$

$$\frac{x_2(s)}{F(s)}=\frac{K}{(M_2S^2+K)(M_1S^2+K)-K^2}$$

Substituting the value of M1 =2kg and M2=1kg we get

$$\frac{X_2(s)}{F(s)}=\frac{K}{(S^2+K)(2S^2+K)-K^2}$$

8. In the system shown in the fig below, R, L, C are electric parameters while K, M, B are mechanical parameters. Find the transfer function $X(s)/E_1(s)$ for the system where $E_1(t)$ is input voltage while X(t) is the output displacement.



Apply Kirchhoff's voltage law at loop 1 in the above fig we get

$$Ri_1 + \frac{1}{C}\int (i_1 - i_2)\, dt = e$$

Taking laplace Transform of the above equation

$$RI_1(s) + \frac{1}{Cs}[I_1(s) - I_2(s)] = E(s) \text{ (or) } \left[R + \frac{1}{Cs}\right]I_1(s) - \frac{1}{Cs}I_2(s) = E(s) \quad ...(1)$$

Apply Kirchoff's Voltage law at loop 2 we get

$$L\frac{di_2}{dt} + \frac{1}{C}\int (i_2 - i_1)\, dt = -e_b = -K_b\frac{dx}{dt}$$

Taking laplace Transform of the above equation

$$sLI_2(s) + \frac{1}{Cs}[I_2(s) - I_1(s)] = -sK_bx(s)$$

$$\text{(or) } \frac{1}{Cs}[I_2(s) - I_1(s)] = -sK_bx(s) - sLI_2(s)$$

$$\text{(or) } \frac{1}{Cs}[I_1(s) - I_2(s)] = -sK_bx(s) - sLI_2(s) \quad ...(2)$$

Substituting (2) in (1)

$$RI_1(s) + sLI_2(s) + sK_bx(s) = E(s)$$

From equation (2)

$$\frac{1}{Cs}I_1(s) = sLI_2(s) + \frac{1}{C(s)}I_2(s) + sK_bx(s)$$

$$= \left(sL + \frac{1}{Cs}\right)I_2(s) + sK_bx(s)$$

$$I_1(s) = (s^2LC+1)I_2(s) + s^2K_bCx(s) \quad ...(3)$$

Substituting (3) in (1)

$$\left(R + \frac{1}{Cs}\right)[(s^2LC+1)I_2(s) + s^2K_bCx(s)] - \frac{1}{Cs}I_2(s) = E(s)$$

$$\text{(or) } (s^2RLC + sL + R)\, I_2(s) + (s^2K_bRC + sK_b)x(s) = E(s)$$

Apply Newtons Second law at M

$$F_c = K_ci_2 = M\frac{d^2x}{dt^2} + B\frac{dx}{dt} + 2Kx$$

Taking Laplace Transform

$$K_cI_2(s) = [Ms^2 + Bs + 2K]x(s) \text{ (or) } I_2(s) = \left[\frac{Ms^2 + Bs + 2k}{K_c}\right]x(s)$$

Substituting this value of $I_2(s)$ in eqn (3)

$$(s^2RLC + sL + R)\left(\frac{Ms^2 + Bs + 2k}{K_c}\right)x(s) + (s^2K_bRC + sK_b)x(s) = E(s)$$

$$\frac{X(s)}{E(s)} = \frac{K_c}{[(RLCs^4 + L(M + RCB)s^3 + (RM + LB + RC(2LK + K_bK_c))s^2 + (RB + 2LK + K_bK_c)s + 2RK]}$$

Servomechanism

A servo system mainly consists of three basic components - a controlled device, a output sensor, a feedback system. This is an automatic closed loop control system. Here, instead of controlling a device by applying the variable input signal, the device is controlled by a feedback signal generated by comparing output signal and reference input signal. When reference input signal or command signal is applied to the system, it is compared with output reference signal of the system produced by output sensor, and a third signal produced by a feedback system. This third signal acts as an input signal of controlled device.

This input signal to the device presents as long as there is a logical difference between reference input signal and the output signal of the system. After the device achieves its desired output, there will be no longer the logical difference between reference input signal and reference output signal of the system. Then, the third signal produced by comparing theses above said signals will not remain enough to operate the device further and to produce a further output of the system until the next reference input signal or command signal is applied to the system. Hence, the primary task of a servomechanism is to maintain the output of a system at the desired value in the presence of disturbances.

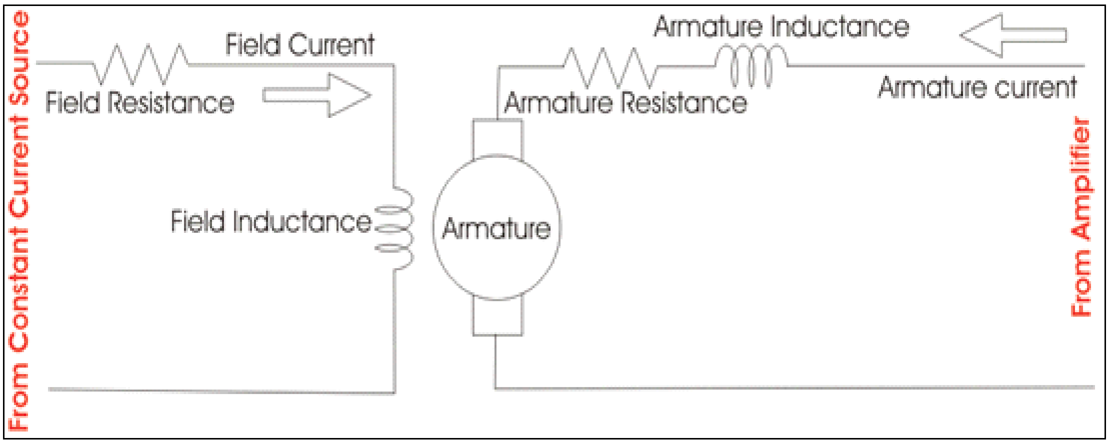
DC SERVO MOTOR

The motors which are utilized as DC servo motors generally have separate DC source for field winding and armature winding. The control can be achieved either by controlling the field current or armature current.

Armature Controlled DC Servo Motor

Theory:

The figure below shows the schematic diagram for an armature controlled DC servo motor. Here the armature is energized by amplified error signal and field is excited by a constant current source.



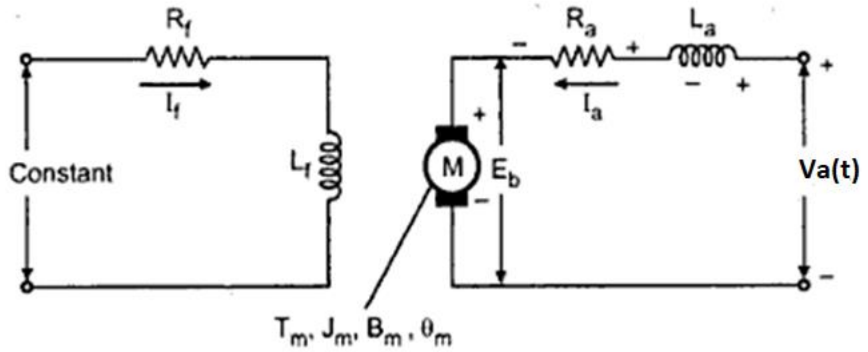
The field is operated at well beyond the knee point of magnetizing saturation curve. In this portion of the curve, for huge change in magnetizing current, there is very small change in mmf in the motor field. This makes the servo motor is less sensitive to change in field current. Actually for armature controlled DC servo motor, the motor should response to any change of field current.

Again, at saturation the field flux is maximum. The general torque equation of DC motor is, torque $T \propto \varphi I_a$. Now if φ is large enough, for every little change in armature current I_a there will be a prominent changer in motor torque. That means servo motor becomes much sensitive to the armature current.

As the armature of DC motor is less inductive and more resistive, time constant of armature winding is small enough. This causes quick change of armature current due to sudden change in armature voltage. That is why dynamic response of armature controlled DC servo motor is much faster than that of field controlled DC servo motor.

The direction of rotation of the motor can easily be changed by reversing the polarity of the error signal.

Transfer Function:



Let

R_a = Armature resistance, Ω

L_a = Armature Inductance, H

I_a = Armature current, A

V_a = armature voltage, V

E_b = back emf, V

K_t = Torque constant, N-m/A

T = Torque developed by motor, N-m

θ = Angular displacement of shaft, rad

J = Moment of inertia of motor and load, Kg-m^2

B = Frictional coefficient of motor and load, N-m/(rad/sec)

K_b = Back emf constant, V/(rad/sec)

The differential equation of armature circuit is

$$L_a \frac{di_a}{dt} + R_a i_a + e_b = V_a$$

Taking Laplace transform we get

$$L_a S I_a(s) + R_a I_a(s) + E_b(s) = V_a(s)$$

$$I_a(s)(L_a S + R_a) + E_b(s) = V_a(s)$$

$$I_a(s)(L_a S + R_a) = V_a(s) - E_b(s)$$

$$I_a(s) = \frac{V_a(s) - E_b(s)}{(L_a S + R_a)} \qquad [1]$$

Torque developed by motor is proportional to flux and current

$$T \alpha i_a \phi$$

$$T = K_T i_a$$

$$I_a(s) = \frac{T(s)}{K_T} \qquad [2]$$

According to Newton's second law the Rotational mechanical differential equation is given by

$$J \frac{d^2\theta}{dt^2} + B \frac{d\theta}{dt} = T$$

Taking Laplace transform

$$JS^2\theta(s) + BS\theta(s) = T(s) \qquad [3]$$

Also the back emf is proportional to the speed of shaft (Angular velocity)

$$e_b = K_b \frac{d\theta}{dt}$$

$$E_b(s) = K_b S\theta(s) \qquad [4]$$

Combining equation [1] and [3], we get

$$\frac{T(s)}{K_T} = \frac{V_a(s) - E_b(s)}{(L_a S + R_a)}$$

$$T(s) = \frac{K_T V_a(s) - K_T E_b(s)}{(L_a S + R_a)}$$

Substituting [3] we get

$$JS^2\theta(s) + BS\theta(s) = \frac{K_T V_a(s) - K_T E_b(s)}{(L_a S + R_a)}$$

$$\theta(s)(JS^2 + BS)(L_a S + R_a) = K_T V_a(s) - K_T E_b(s)$$

$$K_T V_a(s) = [\theta(s)(JS^2 + BS)(L_a S + R_a)] + K_T E_b(s)$$

Substituting [4] we get

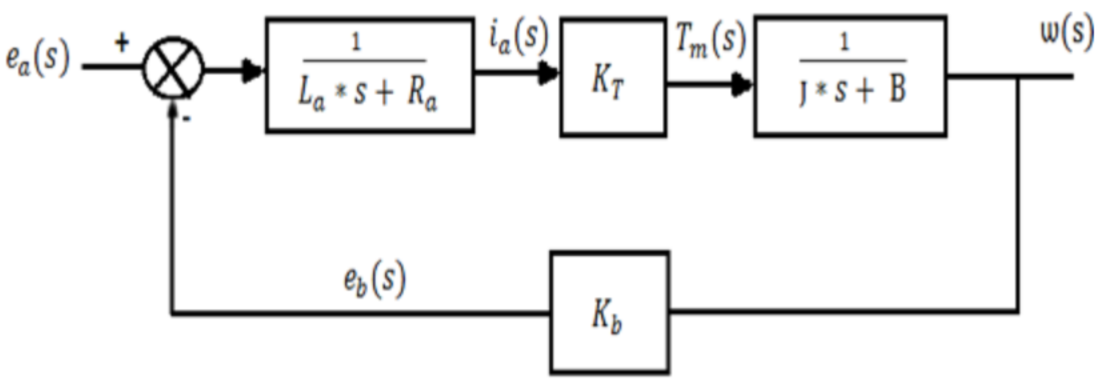
$$K_T V_a(s) = [\theta(s)(JS^2 + BS)(L_a S + R_a)] + K_T K_b S\theta(s)$$

$$K_T V_a(s) = \theta(s)[(JS^2 + BS)(L_a S + R_a) + K_T K_b S]$$

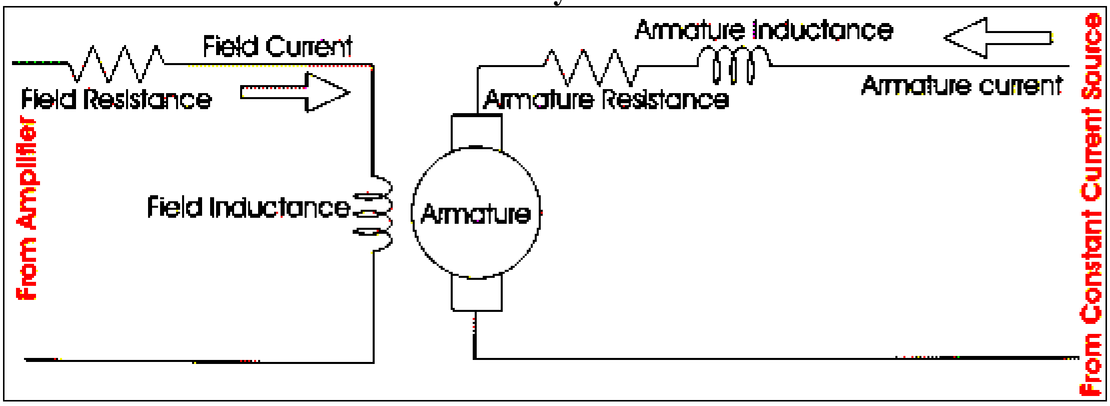
$$\frac{\theta(s)}{V_a(s)} = \frac{K_T}{[(JS^2 + BS)(L_a S + R_a) + K_T K_b S]}$$

$$\frac{\theta(s)}{V_a(s)} = \frac{K_T}{S^3 J L_a + S^2(BL_a + JR_a) + S(R_a B + K_T K_b)}$$

Block Diagram:



Field Controlled DC Servo Motor Theory



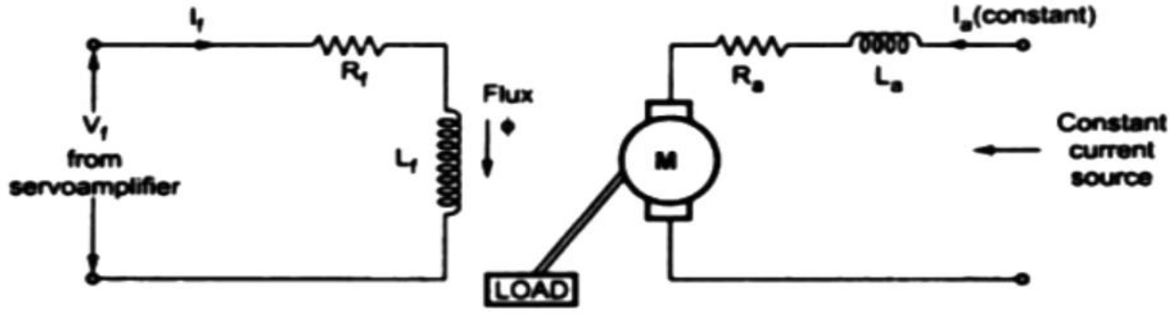
The figure illustrates the schematic diagram for a field controlled DC servo motor. In this arrangement the field of DC motor is excited be the amplified error signal and armature winding is energized by a constant current source . The field is controlled below the knee point of magnetizing saturation curve. At that portion of the curve the mmf linearly varies with excitation current. That means torque developed in the DC motor is directly proportional to the field current below the knee point of magnetizing saturation curve.

From general torque equation of DC motor it is found that, torque T $\propto \varphi I_a$. Where, φ is field flux and I_a is armature current. But in field controlled DC servo motor, the armature is excited by constant current source, hence I_a is constant here. Hence, T $\propto \varphi$

As field of this DC servo motor is excited by amplified error signal, the torque of the motor i.e. rotation of the motor can be controlled by amplified error signal. If the constant armature current is large enough then, every little change in field current causes corresponding change in torque on the motor shaft. The direction of rotation can be changed by changing polarity of the field. The direction of rotation can also be altered by using split field DC motor, where the field winding is divided into two parts, one half of the winding is wound in clockwise direction and other half in wound in anticlockwise direction. The amplified error signal is fed to the junction point of these two halves of the field as shown in the figure. The magnetic field of both halves of the field winding opposes each other. During operation of the motor, magnetic field strength of one half dominates other depending upon the value of amplified error signal fed between these halves. Due to this, the DC servo motor rotates in a particular direction according to the amplified error signal voltage.

The main disadvantage of field control DC servo motors, is that the dynamic response to the error is slower because of longer time constant of inductive field circuit. The field is an electromagnet so it is basically a highly inductive circuit hence due to sudden change in error signal voltage, the current through the field will reach to its steady state value after certain period depending upon the time constant of the field circuit. That is why field control DC servo motor arrangement is mainly used in small servo motor applications. The main advantage of using field control scheme is that, as the motor is controlled by field - the controlling power requirement is much lower than rated power of the motor.

Transfer Function:



Let

R_f = Field resistance, Ω,
L_f = Field inductance, H,
I_f = Field current, A,
V_f = Field voltage, V
T = Torque developed by motor, N-m,
K_{tf} = Torque constant, N-m/A
J = Moment of inertia of rotor and load, Kg-m^2/rad,
B = Frictional coefficient of rotor and load, N-m/(rad/sec)

We know

$T \alpha i_a i_f$

$T = K_{TF} i_f$

$T(s) = K_{TF} I_f(s)$ [1]

The differential equation of armature circuit is

$$L_f \frac{di_f}{dt} + R_f i_f = e_f$$

$$L_f S I_f(s) + R_f I_f(s) = E_f(s)$$

$$I_f(s)(L_f S + R_f) = E_f(s) \qquad [2]$$

According to Newton's second law the Rotational mechanical differential equation is given by

$$J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = T$$

Taking Laplace transform

$$JS^2\theta(s) + BS\theta(s) = T(s) \qquad [3]$$

Substituting [1] we get,

$$JS^2\theta(s) + BS\theta(s) = K_{TF} I_f(s)$$

$$I_f(s) = \frac{\theta(s)(JS^2 + BS)}{K_{TF}} \qquad [4]$$

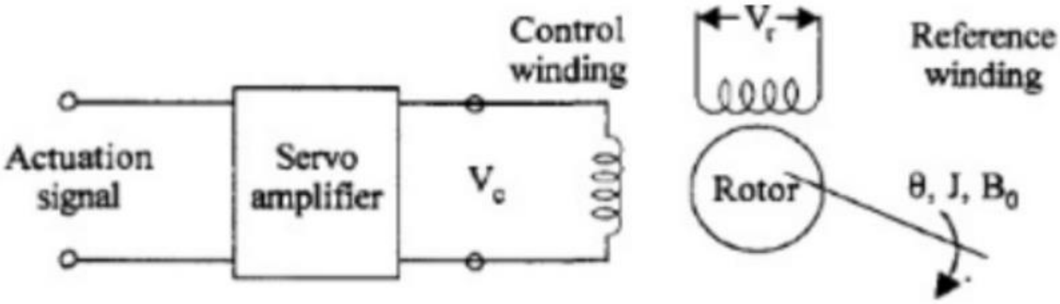
Substituting [4] in [2] we get,

$$\frac{\theta(s)(JS^2 + BS)}{K_{TF}}(L_f S + R_f) = E_f(s)$$

$$\frac{\theta(s)}{E_f(s)} = \frac{K_{TF}}{(JS^2 + BS)(L_f S + R_f)}$$

AC SERVOMOTOR

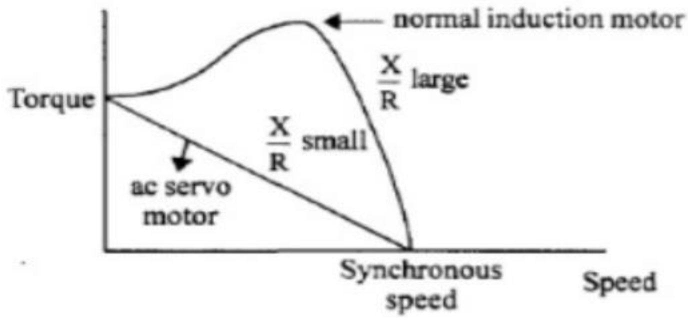
An AC servo motor is essentially a two phase induction motor with modified constructional features to suit servo applications.The schematic of a two phase or servo motor is shown



It has two windings displaced by 90°on the stator One winding, called as reference winding, is supplied with a constant sinusoidal voltage.The second winding, called control winding, is supplied with a variable control voltage which is displaced by -- 90° out of phase from the reference voltage.The major differences between the normal induction motor and an AC servo motor are

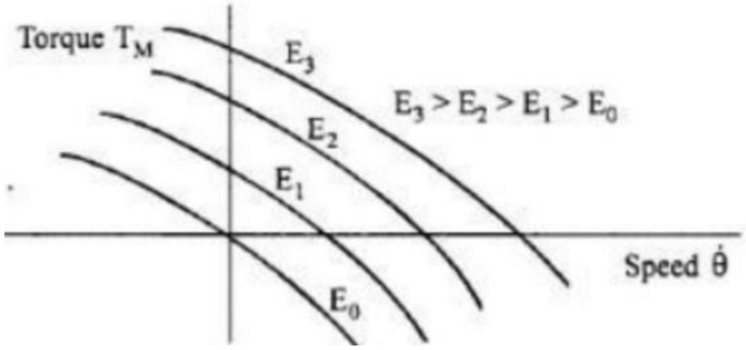
- The rotor winding of an ac servo motor has high resistance (R) compared to its inductive reactance (X) so that its X / *R* ratio is very low.
- For a normal induction motor, X / *R* ratio is high so that the maximum torque is obtained in normal operating region which is around 5% of slip.

The torque speed characteristics of a normal induction motor and an ac servo motor are shown in fig

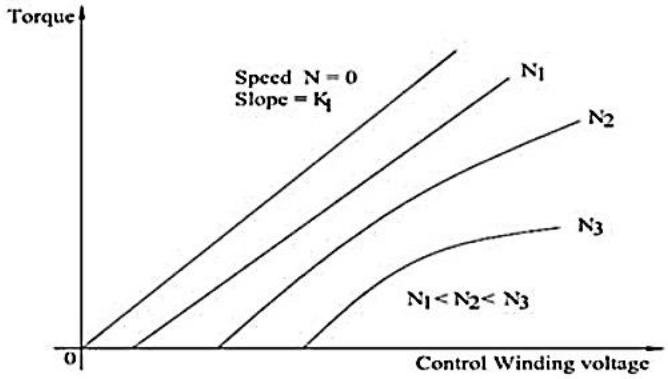


The Torque speed characteristic of a normal induction motor is highly nonlinear and has a positive slope for some portion of the curve. This is not desirable for control applications. as the positive slope makes the systems unstable. The torque speed characteristic of an ac servo motor is fairly linear and has negative slope throughout. The rotor construction is usually squirrel cage or drag cup type for an ac servo motor. The diameter is small compared to the length of the rotor which reduces inertia of the moving parts. Thus it has good accelerating characteristic and good dynamic response.

The supplies to the two windings of ac servo motor are not balanced as in the case of a normal induction motor. The control voltage varies both in magnitude and phase with respect to the constant reference vulture applied to the reference winding. The direction of rotation of the motor depends on the phase (± 90°) of the control voltage with respect to the reference voltage. For different rms values of control voltage the torque speed characteristics are shown in Fig.



The torque varies approximately linearly with respect to speed and also controls voltage. The torque speed characteristics can be linearized at the operating point and the transfer function of the motor can be obtained.



From the torque speed characteristics, we observe that even when Ec=0, the characteristics line runs through origin, which enables the stop of motor rapidly (decelerating torque). From torque-control voltage characteristics, we obtain that the high speed are nonlinear, so the AC servo motor is employed only for low speed.

With reference to the above characteristics, we assume that all lines are traight lines parallel to each other at rated input voltage ad are equally spaced for equal increments of input voltage.Under this assumption, the torque developed by the motor is,

$$T_m = K_1 e_c - K_2 \frac{d\theta}{dt} \qquad [1]$$

From the mechanical system we get,

$$T_m = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} \qquad [2]$$

At equilibrium the motor torque is equal to load torque

$$K_1 e_c - K_2 \frac{d\theta}{dt} = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt}$$

$$K_1 E_c(s) - K_2 S\theta(s) = JS^2\theta(s) + BS\theta(s)$$

$$K_1E_c(s) = \theta(s)(JS^2 + BS + K_2S)$$

$$\frac{\theta(s)}{E_c(s)} = \frac{K_1}{(JS^2 + BS + K_2S)}$$

$$\frac{\theta(s)}{E_c(s)} = \frac{K_1 / (B + K_2)}{S\left[\left(\frac{J}{B + K_2}\right)S + 1\right]}$$

Let $K_m = \frac{K_1}{B + K_2}$ be the motor gain constant and $\tau_m = \frac{J}{B + K_2}$ be the motor time constant, therefore

$$\frac{\theta(s)}{E_c(s)} = \frac{K_m}{S(\tau_m S + 1)}$$

SYNCHROS

The other names for synchros are Selsyn and autosyn. It is an electromagnetic transducer that produces an output voltage depending upon the angular displacement.it consists of two devices called Synchro Transmitter and Synchro Receiver. It is mostly used as an error detector in control system.

Synchro Transmitter:

It is similar to a Y connected 3-phase alternator. Stator winding are concentric coils displaced 120deg apart. Rotor is a salient pole type wound with concentric coils excited with single phase AC through slip rings. The Synchro transmitter acts as a transformer with single primary winding (Rotor) and there secondary winding displaced apart from each other.

The flux produced by the rotor is displaced along its axis and distributed sinusoidally in the air gaps depending upon its angular positions with rotor. Therefore the flux linked with the stator winding will induce an emf proportional to the cosine of the angle between the rotor and stator winding.

AC voltage applied across rotor $Vr(t) = A\sin\omega t$

Phase voltage induced in stator coils S_1, S_2 and S_3 are

$$Vs_1(t) = kA\sin\omega t\cos\theta$$

$$Vs_2(t) = kA\sin\omega t\cos(120 + \theta)$$

$$Vs_3(t) = kA\sin\omega t\cos(240 + \theta)$$

Corresponding line voltage are

$$V_{L1} = Vs_2 - Vs_1$$

$$V_{L1} = kA\sin\omega t[\cos(120 + \theta) - \cos\theta]$$

$$V_{L1} = kA\sin\omega t(2\sin(60 + \theta)\sin 60)$$

$$V_{L1} = kA\sin\omega t\sqrt{3}\sin(60 + \theta)$$

$$V_{L2} = Vs_3 - Vs_2$$

$$V_{L2} = kA\sin\omega t[\cos(240 + \theta) - \cos(120 + \theta)]$$

$$V_{L2} = kA\sin\omega t(\sin(180 + \theta)\sin 60)$$

$$V_{L2} = \sqrt{3}kA\sin\omega t\sin(180 + \theta)$$

$$V_{L3} = Vs_1 - Vs_3$$

$$V_{L3} = kA\sin\omega t[\cos\theta - \cos(240 + \theta)]$$

$$V_{L3} = -2kA\sin\omega t(\sin(120 + \theta)\sin 120)$$

$$V_{L3} = \sqrt{3}kA\sin\omega t\sin(300 + \theta)$$

When θ=0; $Vs_1(t) = kA\sin\omega t$ and $V_{L2} = 0$

The position at which V_{s1} is maximum and V_{L0} is zero is known as "electrical zero" or reference point of transmitter. The output of Synchro control transformer is the error signal which is proportional to the angular displacement between the two rotor of Synchro control transformer and Synchro transmitter.

Synchro control transformer:

The control transformer is similar in construction to a Synchro transmitter except the rotor is cylindrical in shape so that the air gap is uniform. Stator of both transmitter and transformer are identical and the output of the transmitter is given as input to the stator of Synchro transformer. A voltage will be induced in the rotor of control transformer by transformer action. This voltage is proportional to the cosine of the angle between the two rotors.

Therefore, $e(t) = k^{'}A\sin\omega t\cos\phi$

Where ϕ- angular displacement between two rotors

When ϕ=90; e(t)=0, that is error voltage is zero.

The position is known as electrical zero or reference.

Let the initial position of rotor be 90 deg out of phase as in figure

$e(t) = k^{'}A\sin\omega t\cos 90 = 0$

Let rotor transmitter is displaced by an angle θ and rotor of control transformer displaced by an angle α. Then the net displacement between the rotor is (90+θ-α).

$e(t) = k^{'}A\sin\omega t\cos(90+\theta-\alpha) = k^{'}A\sin\omega t\sin(\theta-\alpha)$

For small angular displacement

$e(t) = k^{'}A(\theta-\alpha)\sin\omega t$

Thus Synchro transmitter and control transformer acts as an error detector bygiving an error signal proportional to the angular difference between the transmitter and control transformer shaft position.

Input to the transmitter is a carrier signal error (θ-α) acts as modulating signal error signal e(t) is a modulating signal .

FEEDBACK AND FEEDFORWARD CONTROL THEORY

In feedback system, when a disturbance enters the system, the process deviates, the error is sensed from the feedback. The control action is based on the error signal. The main disadvantage is that only after the disturbance enters the process, the controlled variable is deviated, then only the corrective action is taken.

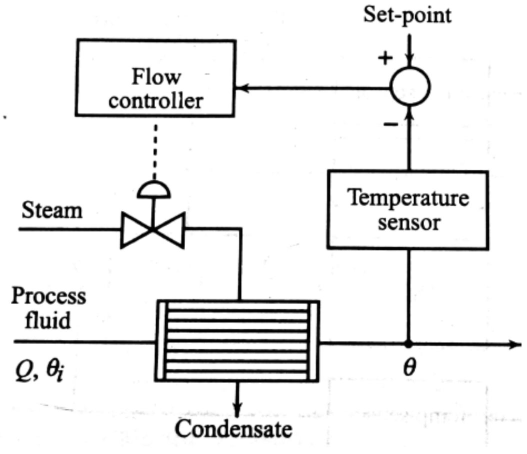


Fig: Feedback control

Whereas, in feed forward control system, the controller compensates before the disturbance affects the process. The efficiency of disturbance control depends on the ability to measure the disturbance. It estimates the effect of disturbance on the controlled variable, so that we can compensate for it.

For example, in a heat exchanger, the feedback control action depends on the sensed temperature. The input parameters to the plant are flow and temperature of the input fluid and the steam flow.

Any disturbance affecting the plant is sensed by the temperature sensor and then the control action is done by controlling the steam flow.

In feedforward control strategy the steam flow into the plant depends on the flow and temperature of the fluid. It is a kind of open loop control. The disturbance is anticipated prior to it affecting the plant. This control can minimize the transient error, with limited accuracy since it cannot cancel un-measurable disturbance.

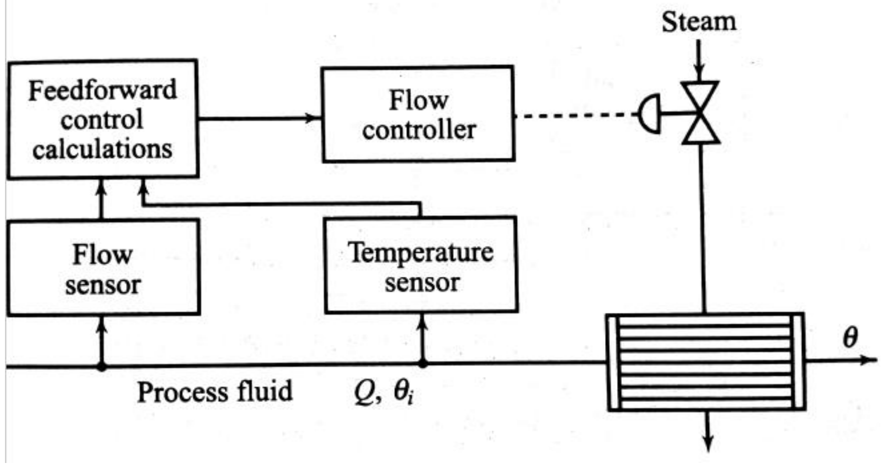


Fig: Feed forward control

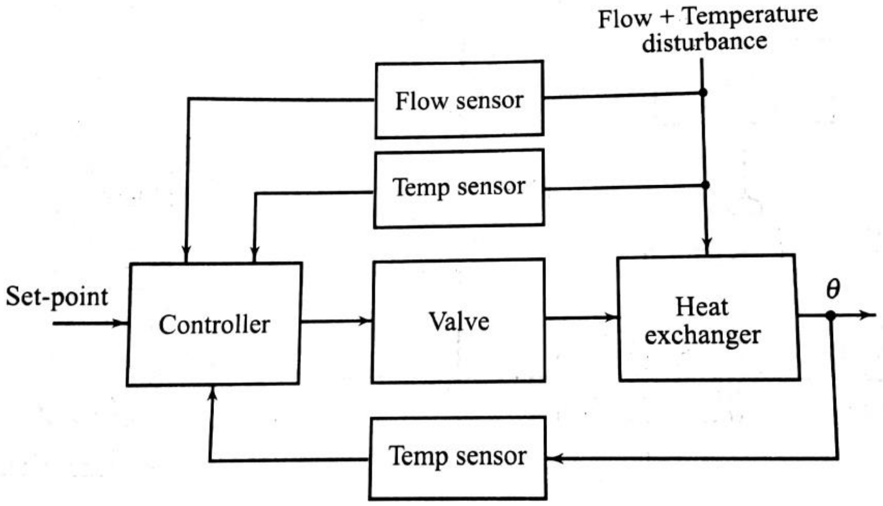


Fig: Feed forward control scheme

Another control scheme uses both Feed-forward and feedback control together, such that the system uses compensator and also provides the feedback control for unmeasurable disturbance.

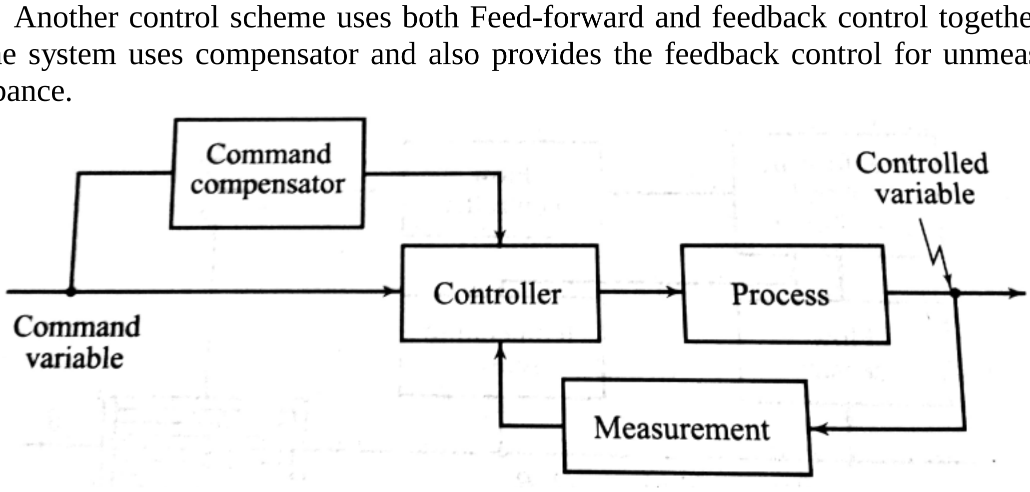


Fig: Combined Feed-forward and feedback control

MULTIVARIBLE CONTROL SCHEMES

Complex process and machines often have several variables (output) that we wish to control, and several manipulated input variables available to provide this control. Sometimes the control situation is simple; one input affects primarily one output and has only weak effect in the other outputs. In such situations, it is possible to ignore weak interactions (coupling) and design controllers under the assumption that one input affects only one output. Input-output paring to minimize the effects of interactions and application of SISO control schemes to obtain separate controllers for each input-output pair, results in an acceptable performance. This, in fact, amounts to considering the multivariable system as constituting of an appropriate number of separate SISO systems. Coupling effects are considered as disturbance to the separate control systems and may not cause significant degradation in their performance if the coupling is weak.

A multivariable system is said to have strong interaction (coupling) if one input affects more than one output appreciably. There are two approaches for the design of controllers for such system.

- Design a decoupling controller to cancel the interaction inherent in the system. Consider the resulting multivariable system as consisting of an appropriate number of SISO systems, and design a controller for each system.
- Design s single controller for the multivariable system, taking interacting into account.

UNIT II – TIME RESPONSE

Time response – Time domain specifications – Types of test input – I and II order system response – Error coefficients – Generalized error series – Steady state error – Root locus construction- Effects of P, PI, PID modes of feedback control –Time response analysis.

1. Time response:

Time response of a control system means, how output behaves with respect to time. So it can be defined as below.

Time response : *The response given by the system which is function of the time, to the applied excitation is called time response of a control system.*

In any practical system, output of the system takes some finite time to reach to its final value. This time varies from system to system and is dependent on different factors. Similarly final value achieved by the output also depends on the different factors like friction, mass or inertia of moving elements, some nonlinearities present etc.

Transient response :

The output variation during the time, it takes to achieve its final value is called as ***transient response****. The time required to achieve the final value is called* ***transient period.***

This can also be defined as that part of the time response which decays to zero after some time as system output reaches to its final value.

Steady state response :

It is that part of the time response which remains after complete transient response vanishes from the system output.

This also can be defined as **response of the system as time approaches infinity from the time at which transient response completely dies out.** The steady state response is generally the final value achieved by the system output. Its significance is that it tells us how far away the actual output is from its desired value.

2. Types of test input:

Standard Test Inputs

In practice, many signals are available which are the functions of time and can be used as reference inputs for the various control systems. These signals are step, ramp, sawtooth type, square wave, triangular etc. But while analysing the systems it is highly impossible to consider each one of it as an input and study the response. Hence from the analysis point of view, those signals which are most commonly used as reference inputs are defined as **Standard Test Inputs.**

i) Step input (Position function) :

It is the sudden application of the input at a specified time as shown in the Fig.

Mathematically it can be described as,

$$r(t) = A \quad \text{for } t \geq 0$$
$$= 0 \quad \text{for } t < 0$$

If A = 1, then it is called **unit step function** and denoted by u(t).

Laplace transform of such input is $\frac{A}{s}$.

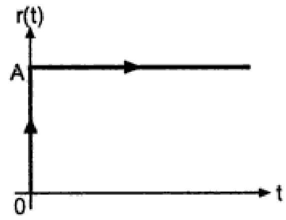


Fig. Step

ii) Ramp input (Velocity function) :

It is constant rate of change in input i.e. gradual application of input as shown in the Fig.

Magnitude of ramp input is nothing but its slope. Mathematically it is defined as,

$$r(t) = At \quad \text{for } t \geq 0$$
$$= 0 \quad \text{for } t < 0$$

If A = 1, it is called **unit ramp input**. It is denoted as r(t). Its Laplace transform is $\frac{A}{s^2}$.

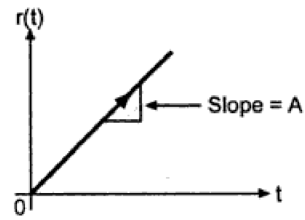


Fig. Ramp

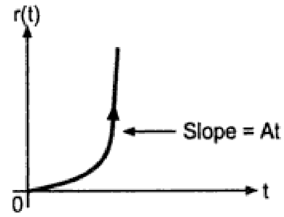


Fig. Parabolic

iii) Parabolic input (Acceleration function) :

This is the input which is one degree faster than a ramp type of input as shown in the Fig.

Mathematically this function is described as,

$$\therefore \quad r(t) = \frac{A}{2}t^2, \quad \text{for } t \geq 0$$
$$= 0, \quad \text{for } t < 0$$

where A is called magnitude of the parabolic input.

iv) Impulse Input :

It is the input applied instantaneously (for short duration of time) of very high amplitude as shown in the Fig.

It is the pulse whose magnitude is infinite while its width tends to zero i.e. $t \rightarrow 0$, applied momentarily.

Area of the impulse is nothing but its magnitude. If its area is unity it is called unit impulse input, denoted as $\delta(t)$.

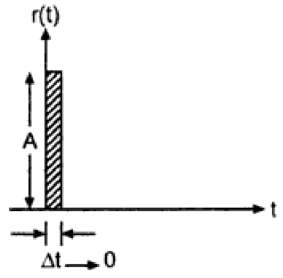


Fig. Impulse

Mathematically it can be expressed as,

$$\therefore \quad \boxed{\begin{aligned} r(t) &= A, \quad \text{for } t = 0 \\ &= 0, \quad \text{for } t \neq 0 \end{aligned}}$$

3. I and II order system response:

Analysis of First Order System

Order : Order of system is the highest power of 's' in the denominator of a *closed loop transfer function.*

Consider a simple system shown in the Fig. (a).

Find $v_o(t)$ i.e. response if it is excited by unit step input.

$$v_i(t) = 1, \quad t \geq 0$$
$$= 0, \quad t < 0$$
$$\therefore \quad V_i(s) = 1/s$$

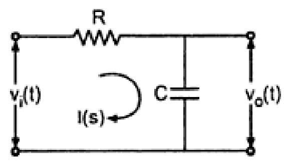


Fig. (a)

Now first calculate system T.F. The Laplace network is shown in the Fig. (b).

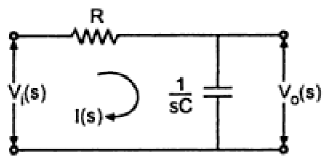


Fig. (b)

$$V_i(s) = I(s)\,R + \frac{1}{sC} I(s) \quad \text{... (1)}$$

$$V_o(s) = \frac{1}{sC} I(s)$$

$$\therefore \quad \boxed{\frac{V_o(s)}{V_i(s)} = \frac{1}{1+sRC} = \frac{1}{1+Ts}} \quad \text{where } T = RC$$

Unit Step Response of First Order System

Let input applied $v_i(t)$ is unit step voltage.

Substituting $V_i(s) = 1/s$ in the transfer function

$$V_o(s) = \frac{1}{s(1+sRC)} = \frac{A'}{s} + \frac{B'}{1+sRC'} \quad A' = 1 \text{ and } B' = -RC$$

$$\therefore \quad V_o(s) = \frac{1}{s} - \frac{RC}{1+sRC} = \frac{1}{s} - \frac{1}{s+(1/RC)}$$

Taking Laplace inverse,

$$v_o(t) = 1 - e^{-t/RC} \Rightarrow C_{ss} + c_t(t) \text{ form}$$

So $$\boxed{C_{ss} = 1 \text{ and } c_t(t) = e^{-t/RC}}$$

Now transient term is totally dependent on the values of R and C and its rate of exponential decay will get controlled by '$-1/RC$' which is pole of the system.

The response will be as shown in the Fig. (c).

t	$v_o(t)$
0	0
RC	0.632
2RC	0.860
3RC	0.950
4RC	0.982
∞	1

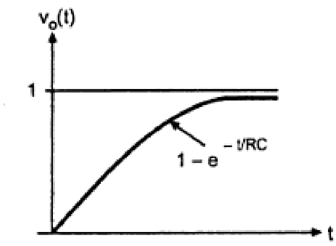


Fig. (c) Unit step response of first order system

The response is purely exponential.

Response of Second-Order System to the Unit-Step Input

Consider the second-order system shown in Figure . The closed-loop transfer function $C(s)/R(s)$ of the system is given by

$$\frac{C(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

where ξ = damping ratio (or damping factor)
and ω_n = undamped natural frequency.

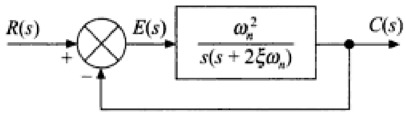


Figure Second-order system.

This form is called the standard form of the second-order system. The dynamic behaviour of the second-order system can then be described in terms of two parameters ξ and ω_n.

If $\xi = 0$, the poles are purely imaginary and lie on the $j\omega$-axis. The system is then called undamped. The transient response does not die out. It is purely oscillatory. If $0 < \xi < 1$, the closed-loop poles are complex conjugates and lie in the left half of the s-plane. The system is then called underdamped, and the transient response is oscillatory. If $\xi = 1$, the poles are real, negative and equal. The system is called critically damped. The response rises slowly and reaches the final value. If $\xi > 1$, the poles are real, negative and unequal. The system is called overdamped. The output rises towards its final value slowly. Critically-damped and overdamped systems do not exhibit any overshoot.

Response of an underdamped system $(0 < \xi < 1)$: In this case, $C(s)/R(s)$ can be written as

$$\frac{C(s)}{R(s)} = \frac{\omega_n^{\,2}}{s^2 + 2\xi\omega_n s + \omega_n^{\,2}} = \frac{\omega_n^{\,2}}{(s + \xi\omega_n + j\omega_d)(s + \xi\omega_n - j\omega_d)} \qquad (\ \ 10)$$

For a unit-step input, $R(s) = 1/s$. Therefore, Eq. (.10) becomes

$$C(s) = \frac{\omega_n^2}{s(s^2 + 2\xi\omega_n s + \omega_n^2)}$$

$$= \frac{1}{s} - \frac{s + 2\xi\omega_n}{(s^2 + 2\xi\omega_n s + \omega_n^2)} = \frac{1}{s} - \frac{s + 2\xi\omega_n}{[(s + \xi\omega_n)^2 + \omega_n^2 - \omega_n^2\xi^2]}$$

$$= \frac{1}{s} - \frac{s + \xi\omega_n}{(s + \xi\omega_n)^2 + \omega_d^2} - \frac{\xi\omega_n}{\omega_d} \cdot \frac{\omega_d}{(s + \xi\omega_n)^2 + \omega_d^2}$$

$$= \frac{1}{s} - \frac{s + \xi\omega_n}{(s + \xi\omega_n)^2 + \omega_d^2} - \frac{\xi}{\sqrt{1 - \xi^2}} \cdot \frac{\omega_d}{(s + \xi\omega_n)^2 + \omega_d^2} \qquad (\ \ 11)$$

Taking the inverse Laplace transform of Eq. (11),

$$c(t) = 1 - e^{-\xi\omega_n t}\cos\omega_d t - \frac{\xi e^{-\xi\omega_n t}}{\sqrt{1 - \xi^2}}\sin\omega_d t$$

$$= 1 - \frac{e^{-\xi\omega_n t}}{\sqrt{1 - \xi^2}}\left(\sqrt{1 - \xi^2}\cos\omega_d t + \xi\sin\omega_d t\right)$$

$$= 1 - \frac{e^{-\xi\omega_n t}}{\sqrt{1 - \xi^2}}(\sin\theta\cos\omega_d t + \cos\theta\sin\omega_d t)$$

$$= 1 - \frac{e^{-\xi\omega_n t}}{\sqrt{1 - \xi^2}}\sin(\omega_d t + \theta)$$

4. Time domain specifications:

The actual output behaviour according to the expression derived can be shown as in the Fig.

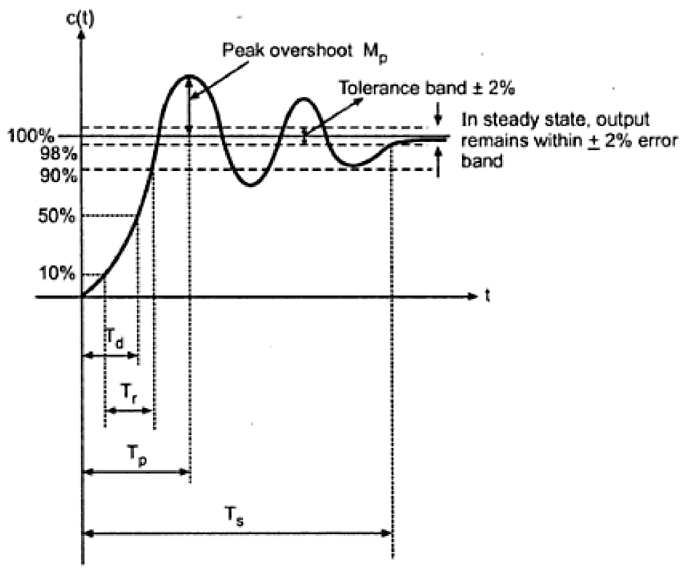


Fig. Transient response specifications

1) ***Delay Time T_d : It is the time required for the response to reach 50% of the final value in the first attempt.***

2) ***Rise Time T_r : It is the time required for the response to rise from 10% to 90% of the final value for overdamped systems and 0 to 100% of the final value for underdamped systems. The rise time is reciprocal of the slope of the response at the instant, the response is equal to 50% of the final value. It is given by,***

$$T_r = \frac{\pi - \theta}{\omega_d} \text{ sec where } \theta \text{ must be in radians.}$$

3) ***Peak Time T_p : It is the time required for the response to reach its peak value. It is also defined as the time at which response undergoes the first overshoot which is always peak overshoot.***

$$T_p = \frac{\pi}{\omega_d} = \frac{\pi}{\omega_n \sqrt{1-\xi^2}} \text{ sec}$$

4) ***Peak Overshoot M_p : It is the largest error between reference input and output during the transient period.***

It also can be defined as the amount by which output overshoots its reference steady state value during the first overshoot.

$$M_p = \left\{ c(t) \,|_{t = T_p} \right\} - 1 \quad 1 \text{ is for unit step input}$$

$$\% M_p = e^{-\pi\xi/\sqrt{1-\xi^2}} \times 100$$

5) ***Settling Time T_s : This is defined as the time required for the response to decrease and stay within specified percentage of its final value (within tolerance band).***

$$\text{Time constant of system} = \frac{1}{\xi \omega_n} = T$$

$$T_s = 4 \times \text{Time constant}$$

Practically the setting time is assumed to be 4 times, the time constant of the system.

$$T_s = \frac{4}{\xi \omega_n} \quad \text{..... for a tolerance band of } \pm 2\% \text{ of steady state}$$

Example:

A unity feedback system is characterized by an open-loop transfer function

$$G(s) = \frac{K}{s(s+10)}$$

Determine the gain K so that the system will have a damping ratio of 0.5. For this value of K determine the settling time, peak overshoot and time to peak overshoot for a unit-step input.

Solution: The closed-loop transfer function of the given unity feedback system is

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1+G(s)} = \frac{\frac{K}{s(s+10)}}{1+\frac{K}{s(s+10)}} = \frac{K}{s^2+10s+K}$$

Comparing it with the standard form of the transfer function of a second-order system, we have

$$\frac{C(s)}{R(s)} = \frac{K}{s^2 + 10s + K} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}$$

$$\omega_n^2 = K$$

or $$\omega_n = \sqrt{K}$$

$$2\xi\omega_n = 10$$

i.e. $$2 \times 0.5 \times \omega_n = 10$$

or $$\omega_n = 10$$

$\therefore$ $$K = \omega_n^2 = 10^2 = 100$$

So the gain $K = 100$ so that the system will have a damping ratio of 0.5.

The settling time for 5% criterion is

$$t_s = \frac{4}{\xi\omega_n} = \frac{4}{0.5 \times 10} = 0.8\text{s}$$

The settling time for 2% criterion is

$$t_s = \frac{3}{\xi\omega_n} = \frac{3}{0.5 \times 10} = 0.6\text{s}$$

The peak overshoot is

$$M_p = e^{-\pi\xi/\sqrt{1-\xi^2}} = e^{-3.14 \times 0.5/\sqrt{1-0.5^2}} = 0.163$$

The percentage peak overshoot is

$$\%M_p = M_p \times 100 = 0.163 \times 100 = 16.3\%$$

The peak time $t_p = \dfrac{\pi}{\omega_d} = \dfrac{\pi}{\omega_n\sqrt{1-\xi^2}} = \dfrac{3.14}{10 \times \sqrt{1-0.5^2}} = 0.363\text{s}$

That is the time to peak overshoot is $t_p = 0.363$s.

5. Error coefficients:

Error is defined as the deviation between the process response C(s) and the reference signal R(s). It is classified as follows:

(a) Steady state error:

Consider a simple closed loop system using negative feedback as shown in the Fig.

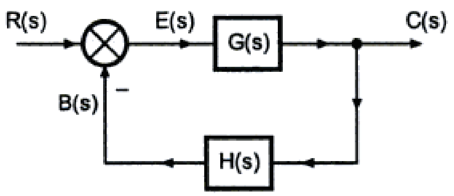


Fig.

where E(s) = Error signal, and B(s) = Feedback signal

Now, E(s) = R(s) – B(s)

But B(s) = C(s)H(s)

$$\therefore \quad E(s) = R(s) - C(s)H(s)$$

and
$$C(s) = E(s)G(s)$$

$$\therefore \quad E(s) = R(s) - E(s)\,G(s)H(s)$$

$$\therefore \quad E(s) + E(s)G(s)H(s) = R(s)$$

$$\therefore \quad E(s) = \frac{R(s)}{1+G(s)H(s)} \quad \text{for nonunity feedback}$$

$$E(s) = \frac{R(s)}{1+G(s)} \quad \text{for unity feedback}$$

This E(s) is the error in Laplace domain and is expression in `s'. We want to calculate the error value. In time domain, corresponding error will be e(t). Now steady state of the system is that state which remains as $t \to \infty$.

$$\therefore \quad \text{Steady state error, } e_{ss} = \lim_{t \to \infty} e(t)$$

Now we can relate this in Laplace domain by using **final value theorem** which states that,

$$\lim_{t \to \infty} F(t) = \lim_{s \to 0} sF(s) \qquad \text{where } F(s) = L\{ F(t) \}$$

Therefore,
$$e_{ss} = \lim_{t \to \infty} e(t) = \lim_{s \to 0} sE(s) \quad \text{where } E(s) \text{ is } L\{ e(t) \}.$$

Substituting E(s) from the expression derived, we can write

$$e_{ss} = \lim_{s \to 0} \frac{sR(s)}{1+G(s)H(s)}$$

(b) Generalized error series

It is also known as the dynamic error co-efficient.

Let $E(s) = \dfrac{R(s)}{1+G(s)H(s)}$

Let us assume that this is the product of two polynomials of 's'.

$$E(s) = F_1(s) \cdot F_2(s)$$

Where $$F_1(s) = \frac{1}{1+G(s)H(s)}, \quad F_2(s) = R(s)$$

Now if, $F(s) = F_1(s) \cdot F_2(s)$ then using convolution integral,

$$L^{-1}\{F(s)\} = F(t) = \int_0^t F_1(\tau)\; F_2(t-\tau)\; d\tau$$

Similarly $$e(t) = \int_0^t F_1(\tau)\; F_2(t-\tau)\; d\tau = \int_0^t F_1(\tau)\; R(t-\tau)\; d\tau$$

R (t − τ) can be expanded by using Taylor series form as,

$$R(t-\tau) = R(t) - \tau R'(t) + \frac{\tau^2}{2!}\; R''(t) - \frac{\tau^3}{3!} R'''(t) + \ldots..$$

Substituting $$e(t) = \int_0^t F_1(\tau) \left[R(t) - \tau R'(t) + \frac{\tau^2}{2!}\; R''(t) - \frac{\tau^3}{3!}\; R'''(t) + \ldots\ldots. \right] d\tau$$

$$= \int_0^t R(t) F_1(\tau)\, d\tau - \int_0^t \tau R'(t)\; F_1(\tau)\, d\tau + \ldots\ldots.$$

Now $$e_{ss} = \lim_{t\to\infty} e(t)$$

$$= \lim_{t\to\infty} \left[\int_0^t R(t)\; F_1(\tau)\, d\tau - \int_0^t \tau\; R'(t)\; F_1(\tau)\; d\tau + \ldots\ldots. \right]$$

$$= R(t) \int_0^\infty F_1(\tau)\; d\tau - R'(t) \int_0^\infty \tau F_1(\tau)\; d\tau + R''(t) \int_0^\infty \frac{\tau^2}{2!} F_1(\tau)\; d\tau \ldots\ldots..$$

Where $$K_0 = \int_0^\infty F_1(\tau)\; d\tau, \quad K_1 = -\int_0^\infty \tau\; F_1(\tau)\; d\tau, \quad K_2 = \int_0^\infty \tau^2\; F_1(\tau)\; d\tau \ldots..$$

Substituting these values we have,

$$e_{ss} = K_0 \; R(t) + K_1 \; R'(t) + \frac{K_2}{2!} \; R''(t) + \text{.........}$$

where K_0 , K_1 , K_2 .... are called **dynamic error coefficients.**

To calculate these coefficients use the following method :

According to definition of Laplace transform,

$$F(s) = \int_0^\infty F_1(\tau)\, e^{-s\tau} \, d\tau$$

Now

$$K_0 = \int_0^\infty F_1(\tau) \; d\tau$$

Multiplying by $e^{-s\tau}$ to both sides,

$$\therefore \qquad K_0 \, e^{-s\tau} = \int_0^\infty F_1(\tau) \; d\tau \; e^{-s\tau} = F_1(s)$$

Taking limit as $s \to 0$ of both sides,

$$\lim_{s \to 0} K_0 \;\; e^{-s\tau} = \lim_{s \to 0} \; F_1(s)$$

$$\therefore \qquad K_0 = \lim_{s \to 0} F_1(s) \qquad \text{where} \quad F_1(s) = \frac{1}{1 + G(s)H(s)}$$

Taking derivative of $K_0 \, e^{-s\tau}$ with respect to 's' we get,

$$-\tau K_0 \, e^{-s\tau} = \frac{d\,F_1(s)}{ds}$$

Substituting

$$K_0 = \int_0^\infty F_1(\tau)\, d\tau$$

$$-\tau \int_0^\infty F_1(\tau) \; d\tau \;\; e^{-s\tau} = \frac{d\,F_1(s)}{ds}$$

i.e.

$$K_1 \; e^{-s\tau} = \frac{d\,F_1(s)}{ds}$$

Taking limit as $s \to 0$ of both sides,

$$K_1 = \lim_{s \to 0} \frac{d\,F_1(s)}{ds}$$

In general,

$$K_n = \lim_{s \to 0} \frac{d^n \, F_1(s)}{ds}$$

*Along with the above said errors, the errors, such as Positional Error, Velocity Error and Acceleration Error are also used to analyse the performance the system.

- Positional Error $K_p = \lim_{s \to 0} G(s)H(s)$
- Velocity Error $K_v = \lim_{s \to 0} sG(s)H(s)$
- Acceleration Error $K_a = \lim_{s \to 0} s^2G(s)H(s)$

Relationship between K_p, K_v, K_a and e_{ss} based on type of the system:

Type of System	Error Coefficients			Error e_{ss} for		
	K_p	K_v	K_a	Step input	Ramp input	Parabolic input
0	K	0	0	$\frac{A}{1+K}$	∞	∞
1	∞	K	0	0	$\frac{A}{K}$	∞
2	∞	∞	K	0	0	$\frac{A}{K}$

Example:

A unity feedback system has $G(s) = \dfrac{40\,(s+2)}{s\,(s+1)\,(s+4)}$.

Determine (i) Type of the system, (ii) All error coefficients and (iii) Error for ramp input with magnitude 4.

Solution : To determine type of system arrange G(s)H(s) in time constant form.

$$G(s)H(s) = \frac{40(s+2)}{s(s+1)(s+4)} = \frac{40(2)(1+0.5s)}{s(1+s)(4)(1+0.25s)}$$

$$= \frac{20(1+0.5s)}{s(1+s)(1+0.25\,s)}$$

Comparing this with standard form,

$$G(s)H(s) = \frac{K(1+T_1\,s)(1+T_2\,s)\ldots\ldots}{s^j\,(1+T_a\,s)(1+T_b\,s)\ldots\ldots}$$

where j = Type of system

$\therefore$ j = 1 so given system is type 1 system.

Error coefficients :

1) $$K_p = \lim_{s \to 0} G(s)H(s) = \lim_{s \to 0} \frac{20(1+0.5s)}{s(1+s)(1+0.25s)}$$

$$= \infty$$

2) $$K_v = \lim_{s \to 0} sG(s)H(s) = \lim_{s \to 0} \frac{20(1+0.5s)}{(1+s)(1+0.25s)}$$

$$= 20$$

3) $$K_a = \lim_{s \to 0} s^2 G(s)H(s) = \lim_{s \to 0} \frac{s(1+0.5s) \cdot 20}{(1+s)(1+0.25s)}$$

$$= 0$$

Now steady state error for ramp input is given by,

$$e_{ss} = \frac{A}{K_v}$$

where A = Magnitude of ramp input

Here $A = 4$ and $K_v = 20$

$$\therefore \quad e_{ss} = \frac{4}{20} = 0.2$$

This is the final steady state error.

6. Root locus construction

Nature of the transient response is closely related to the location of the poles in the s-plane. It is advantageous to know how the closed loop poles move in the s-plane if some parameters of the system are varied. The knowledge of such movement of the closed loop poles with small changes in the parameters of the system greatly helps in the design of any closed loop system.

Such movement of the poles can be known by the **Root Locus method**, introduced by W. R. Evans in 1948. This is a graphical method, in which movement of poles in the s-plane is sketched when a particular parameter of system is varied from zero to infinity. Note that the parameter is usually the gain but any other parameter may be varied. But for root locus method, **gain** is assumed to be a parameter which is to be varied from zero to infinity.

Rules for Construction of Root Locus

Rule No. 1 : The root locus is always symmetrical about the real axis. The roots of the characteristic equation are either real or complex conjugates or combination of both. Therefore their locus must be symmetrical about the real axis of the s-plane.

Rule No. 2 : Let $G(s)H(s)$ = Open loop T.F. of the system

P = Number of open loop poles

Z = Number of open loop zeros

Then we can confirm basic information about the root locus as,

Case (i) P > Z Number of branches equal to number of open loop poles. N = P	Case (ii) Z > P Number of branches equal to the number of open loop zeros. N = Z
Branches will start from each of the location of open loop pole. Out of 'P' number of branches, 'Z' number of branches will terminate at the locations of open loop zeros. The remaining 'P – Z' branches will approach to infinity.	Branches will terminate at each of the finite location of open loop zero. But out of 'Z' number of branches, 'P' number of branches will start from each of the finite open loop pole locations while remaining Z – P number of branches will originate from infinity and will approach to finite zeros.
e.g. : If P = 4 and Z = 1 then number of root locus branches = 4, number P – Z = 3.	e.g. : If P = 1 and Z = 4 then number of separate branches = Z = 4, number of Z– P branches = 3.
4 branches will start from locations of open loop poles, out of this only one will terminate at the available finite open loop zero location. The remaining P – Z = 3 branches will approach to ∞.	3 branches will start from infinity while 1 branch will start from location of open loop pole and all 4 branches will terminate at available 4 finite locations of zeros.

Whatever may be the case, **branch direction always remains from open loop poles towards open loop zeros**. When P = Z, the number of branches N = P = Z. A separate branch will start from each of the open loop pole while will terminate at available each open loop zero. No branch will start or terminate at infinity when P = Z.

Rule No. 3 : A point on the real axis lies on the root locus if the sum of the number of open loop poles and the open loop zeros, on the real axis, to the right hand side of this point is odd.

Rule No. 4 : Generally number of poles are more than number of zeros and in such case 'P–Z' branches will approach to infinity. This rule gives us information about how these branches approach to infinity.

The branches which are approaching to infinity, do so along the straight lines called **Asymptotes** of the root locus. Asymptotes are the guidelines for the branches approaching to infinity. Angles of such asymptotes are given by ,

$$\theta = \frac{(2q+1)\,180^\circ}{P-Z} \qquad \text{where } q = 0, 1, 2 \ldots\ldots (P - Z - 1)$$

Asymptotes are always symmetrically located about real axis.

Rule No. 5 : Now only the angles of asymptotes are not sufficient but where the asymptotes are located in s-plane is equally important. Location of asymptotes in s – plane is given by this rule.

All the asymptotes intersect the real axis at a common point known as **centroid** denoted by σ. The co-ordinates of centroid can be calculated as,

$$\sigma = \frac{\sum \text{Real parts of poles of } G(s)H(s) - \sum \text{Real parts of zeros of } G(s)H(s)}{P-Z}$$

General Steps to Solve the Problem on Root Locus

Step 1 : Get the general information about number of open loop poles, zeros, number of branches etc. from G(s)H(s) .

Step 2 : Draw the pole-zero plot. Identify sections of real axis for the existence of the root locus. And predict minimum number of breakaway points by using general predictions.

Step 3 : Calculate angles of asymptotes.

Step 4 : Determine the centroid. Sketch a separate sketch for step 3 and step 4.

Step 5 : Calculate the breakaway and breakin points. If breakaway points are complex conjugates, then use angle condition to check them for their validity as breakaway points.

Step 6 : Calculate the intersection points of root locus with the imaginary axis.

Step 7 : Calculate the angles of departures or arrivals if applicable.

Step 8 : Combine steps 1 to 7 and draw the final sketch of the root locus.

Step 9 : Predict the stability and performance of the given system by using the root locus.

Example:

A certain unity negative feedback control system has the following open loop T.F. $GH(s) = \dfrac{K}{s(s+1)(s+3)}$. Draw the root locus for $0 \le K \le \infty$.

1. The three root loci start from poles at 0, –1 and –3 where the value of $K = 0$.
2. There is no zero here and so the three loci terminate at ∞ where $K = \infty$.
3. For the given open loop transfer function, $P = 3$ and $Z = 0$. Hence $N = 3$. There are three separate loci.
4. The asymptote of the root loci make $\theta = \dfrac{(2n+1)\pi}{(P-Z)}$ angles with the real axis. Hence the angles are $\pi, \dfrac{\pi}{3}$ and $\dfrac{5\pi}{3}$. The loci 1, 2 and 3 make these angles respectively.
5. The point of intersection of the asymptotes is given by,

$$x = \sum \text{poles of } GH(s) - \sum \text{zeros of } GH(s) = \frac{0-1-3-0}{3} = -1.33.$$

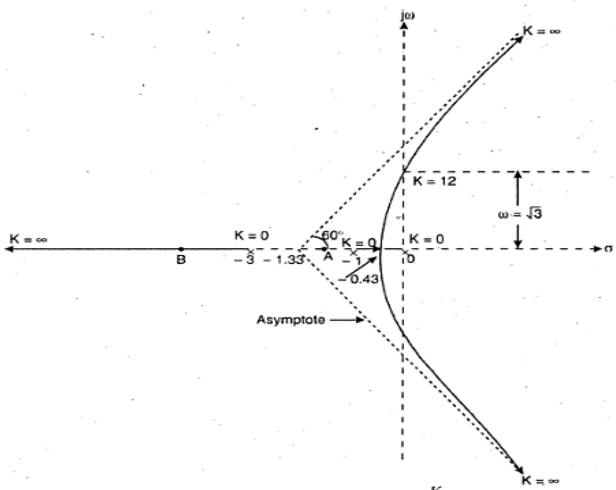


Fig. *Root Locus for* $G(s) = \dfrac{K}{s(s+1)(s+3)}$

The three poles are located as shown in Fig.

6. At point A there is no root locus, because two poles are lying to the right side of point A. For even number of poles and zeros to the right side of the point there cannot be any root locus on the real axis. On the other hand consider the point B. There are three poles on the right hand side of point B. This is an odd number. Hence there is root locus. Hence, on the real axis root loci exist between $s = 0$ and $s = -1$ and $s = -3$ and $s = -\infty$.

7. The characteristic equation is written as

$$F(s) = 1+G(s) = 0$$

$$s^3 + 4s^2 + 3s + K = 0$$

Differentiating the above equation with respect to s we get,

$$3s^2 + 8s + 3 + \frac{dK}{ds} = 0$$

Put $\frac{dK}{ds} = 0$ and solving for s we get,

$s_1 = -2.23$ and $s_2 = -0.43$.

The breakaway point at $s_1 = -2.23$ is ruled out since there is no root locus there. Hence $s_2 = -0.43$ is the breakaway point.

8. The critical value of K and the value of ω at the imaginary axis where the root locus crosses from LHP to RHP is obtained from the following Routh's array which is formed from the characteristic equation.

s^3	1	3
s^2	4	K
s^1	$\frac{12-K}{4}$	
s^0	K	

The critical value of $K = 12$. The auxiliary equation is obtained from the s^2 row as,

$$4s^2 + K = 0$$

Substituting $s = j\omega$ and $K = 12$, we get

$$-4\omega^2 + 12 = 0$$

or

$$\omega = \pm\sqrt{3}$$

9. The Complete root locus is shown in Fig

Sketch the root locus.

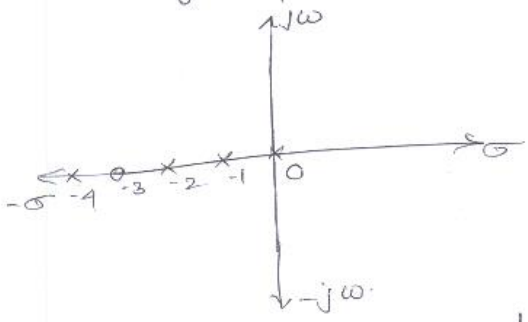
$$G(s) = \frac{K(s+3)}{s(s+1)(s+2)(s+4)}$$

1. Locate poles and zeros

$P_1 = 0$; $P_2 = -1$; $P_3 = -2$; $P_4 = -4$

$Z_1 = -3$

2. Locating the part of rootlocus



3. Angle of asymptotes and centroid.

$$\text{Angle of asymptotes} = \frac{\pm 180\,(2q+1)}{n-m}$$

$n = 4$; $q = 0, 1, 2, 3$

$m = 1$

$$\theta_1 = \frac{\pm 180\,(0+1)}{3} = \pm 60^\circ$$

$$\theta_2 = \frac{\pm 180\,(2+1)}{3} = \pm 180^\circ$$

$$\theta_3 = \frac{\pm 180\,(4+1)}{3} = \pm 300$$

$$\theta_4 = \frac{\pm 180\,(6+1)}{3} = \pm 420$$

$$\text{Centroid} = \frac{\text{Sum of poles} - \text{Sum of zeros}}{n-m}$$

$$= \frac{0-1-2-4+3}{3} = -1.33$$

4. Breakaway and Break in point.

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1+G(s).H(s)}$$

$$= \frac{\dfrac{K(s+3)}{s(s+1)(s+2)(s+4)}}{1+\dfrac{K(s+3)}{s(s+1)(s+2)(s+4)}}$$

Charac. Equation :

$$s(s+1)(s+2)(s+4) + K(s+3) = 0$$

$$s(s^2+3s+2)(s+4) + K(s+3) = 0$$

$$(s^2+4s)(s^2+3s+2) + K(s+3) = 0$$

$$s^4+3s^3+2s^2+4s^3+12s^2+8s+K(s+3) = 0$$

$$K = -\frac{s^4-7s^3-14s^2-8s}{s+3}$$

$$= -\frac{(s^4+7s^3+14s^2+8s)}{s+3}$$

$$\frac{dK}{ds} = -\frac{\{(s+3)(4s^3+21s^2+28s+8) - (s^4+7s^3+14s^2+8s)(1+0)}{(s+3)^2}$$

on simplifying

$$\frac{dK}{ds} = \frac{-3s^4-26s^3-77s^2-84s-24}{(s+3)^2}$$

$$\frac{dK}{ds} = 0$$

$$-3s^4-26s^3-77s^2-84s-24 = 0$$

$$3s^4+26s^3+77s^2+84s+24 = 0$$

$$s+0.286 \,\big|\, 3s^4 + 26s^3 + 77s^2 + 84s$$

$$3s^4 + 0.286s^3$$

$$25.714s^3 + 77s^2 + 84$$

$$25.714s^3 + 7.354s^2$$

$$69.646s^2 +$$

$$69.646s^2 +$$

6

6

(22a)

3rd trial $58.62S + 24 \Rightarrow S + 0.409$

$$\begin{array}{r|l} & 3S^3 + 24.77S^2 + 66.868S + 56.65 \\ S+0.409 & 3S^4 + 26S^3 + 77S^2 + 84S + 24 \\ & 3S^4 + 1.228S^3 \\ \hline & 24.77S^3 + 77S^2 + 84S + 24 \\ & 24.77S^3 + 10.132S^2 \\ \hline & 66.868S^2 + 84S + 24 \\ & 66.868S^2 + 27.349S \\ \hline & 56.65S + 24 \\ & 56.65S + 23.170 \\ \hline & 0.829 \end{array}$$

4th trial $S + 0.423$

$$\begin{array}{r|l} & 3S^3 + 24.729S^2 + 66.54S^2 + 55.85S \\ S+0.423 & 3S^4 + 26S^3 + 77S^2 + 84S + 24 \\ & 3S^4 + 1.271S^3 \\ \hline & 24.729S^3 + 77S^2 + 84S + 24 \\ & 24.729S^3 + 10.46S^2 \\ \hline & 66.54S^2 + 84S + 24 \\ & 66.54S^2 + 28.146S \\ \hline & 55.854S + 24 \\ & 55.854S + 23.626 \\ \hline & 0.173 \end{array}$$

5th trial

$S + 0.4297$

$$
\begin{array}{r|l}
 & 3S^3 + 24.711S^2 + 66.38S + 55.4768 \\
S + 0.4297 & 3S^4 + 26S^3 + 77S^2 + 84S + 24 \\
 & 3S^4 + 1.289S^3 \\
 & \quad 24.711S^3 + 77S^2 + 84S + 24 \\
 & \quad 24.711S^3 + 10.618S^2 \\
 & \qquad 66.38S^2 + 84S + 24 \\
 & \qquad 66.38S^2 + 28.524S \\
 & \qquad\quad 55.476S + 24 \\
 & \qquad\quad 55.476S + 23.838 \\
 & \qquad\qquad 0.162
\end{array}
$$

6th trial $S + 0.433$

$$
\begin{array}{r|l}
 & 3S^3 + 24.702S^2 + 66.304S + 55.29 \\
S + 0.433 & 3S^4 + 26S^3 + 77S^2 + 84S + 24 \\
 & 3S^4 + 1.297S^3 \\
 & \quad 24.702S^3 + 77S^2 \\
 & \quad 24.702S^3 + 10.696S^2 \\
 & \qquad 66.304S^2 + 84S \\
 & \qquad 66.304S^2 + 28.70S \\
 & \qquad\quad 55.29S + 24 \\
 & \qquad\quad 55.29S + 23.95 \\
 & \qquad\qquad + 0.05
\end{array}
$$

Factors

$$(S + 0.433)(3S^3 + 24.702S^2 + 66.304S + 55.28)$$

$$(S + 0.433)\ (S + 1.615)\ (S - (-3.309 + 0.66j))$$

$$(S - (-3.309 - 0.66j))$$

Roots are $s = -0.433$; $s = -1.615$ (5a)

$s = -3.309 \pm 0.677j$

Check for K.

$$K = -\frac{(s^4 + 7s^3 + 14s^2 + 8s)}{s+3}$$

$s = -0.433$

$K = 2.16$ (+ve)

$s = -1.615$

$K = 0.658$ (+ve)

For $s = -3.309 \pm 0.677j$; K is not real & +ve.

hence they cannot be real breakaway point.

Angle of departure :

No angle of deperature as there is no complex pole.

To find imaginary axis cross over.

$$1 + G(s).H(s) = 0$$

Charac. eqn $s^4 + 7s^3 + 14s^2 + 8s + Ks + 3K = 0$

Sub $s = j\omega$

$$(j\omega)^4 + 7(j\omega)^3 + 14(j\omega)^2 + 8(j\omega) + Kj\omega + 3K = 0$$

R.P = 0

$\omega^4 - 14\omega^2 + 3K = 0$

$$K = \frac{14\omega^2 - \omega^4}{3} \rightarrow (1)$$

I P

$-7\omega^3 + 8\omega + K\omega = 0$

$K = 7\omega^2 - 8 \rightarrow (2)$

Equate (1) & 2.

$$\frac{14\omega^2 - \omega^4}{3} = 7\omega^2 - 8$$

$$-\omega^4 - 7\omega^2 + 24 = 0$$

$(\because x = \omega^2)\ x^2 + 7x - 24 = 0$

$x = 2.52, -9.52$

$\omega = \pm\sqrt{2.52} = \pm 1.58$; $\omega = \pm j\,3.08$

7. Effects of P, PI, PID modes of feedback control

RESPONSE WITH P, PI, PD AND PID CONTROLLERS

Proportional Control

In proportional control, the actuating signal $E_a(s)$ is proportional to the error signal $E(s)$. Hence the name proportional control system. The block diagram of Figure shows the proportional control action.

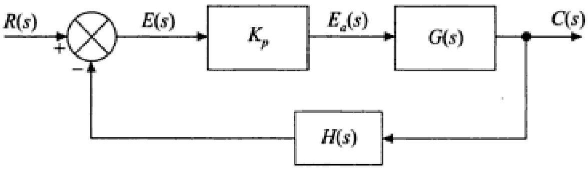


Figure Block diagram of proportional control system.

$$\frac{E_a(s)}{E(s)} = K_p$$

where K_p is known as proportional gain.

Derivative Control

In derivative control, the actuating signal consists of proportional error signal and derivative of the error signal, i.e.

$$e_a(t) = e(t) + T_d \frac{d}{dt} e(t)$$

Taking the Laplace transform on both sides of Eq. (4.27),

$$E_a(s) = E(s) + T_d sE(s)$$

i.e.

$$E_a(s) = (1 + sT_d)E(s)$$

Figure shows a block diagram of a second-order unity feedback control system using derivative control.

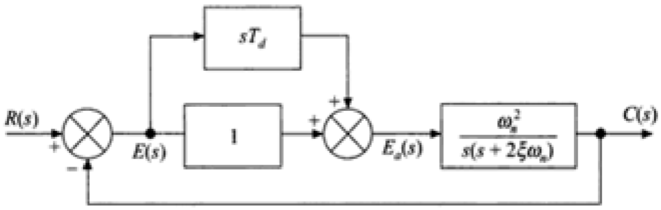


Figure Block diagram of a control system with derivative control.

The overall transfer function of the system of Figure is given by

$$\frac{C(s)}{R(s)} = \frac{(1+sT_d)\dfrac{\omega_n^2}{s(s+2\xi\omega_n)}}{1+(1+sT_d)\times\dfrac{\omega_n^2}{s(s+2\xi\omega_n)}}$$

$$= \frac{\omega_n^2(1+sT_d)}{s^2+2\xi\omega_n s+\omega_n^2+sT_d\omega_n^2}$$

$$= \frac{\omega_n^2(1+sT_d)}{s^2+(2\xi\omega_n+\omega_n^2 T_d)s+\omega_n^2}$$

Integral Control

For integral control action, the actuating signal consists of proportional error signal added with integral error signal, i.e.

$$e_a(t) = e(t) + K_i \int e(t)\, dt$$

where K_i is a constant.

Taking the Laplace transform on both sides of Eq. (4.34),

$$E_a(s) = E(s) + K_i \frac{E(s)}{s} = E(s)\left(1 + \frac{K_i}{s}\right)$$

Figure shows the block diagram of a system with integral control action.

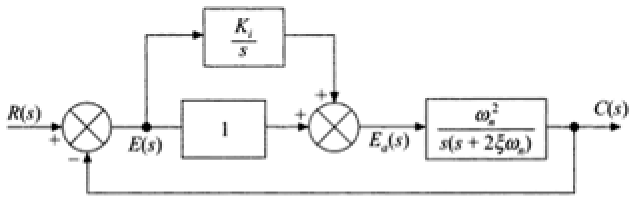


Figure Block diagram of a control system with integral control.

From the block diagram, the closed-loop transfer function is

$$\frac{C(s)}{R(s)} = \frac{\left(1 + \frac{K_i}{s}\right)\left(\frac{\omega_n^2}{s^2 + 2\xi\omega_n s}\right)}{1 + \left(1 + \frac{K_i}{s}\right)\left(\frac{\omega_n^2}{s^2 + 2\xi\omega_n s}\right)}$$

$$= \frac{(s + K_i)\,\omega_n^2}{s^3 + 2\xi\omega_n s^2 + \omega_n^2 s + K_i\omega_n^2}$$

Proportional-plus-Integral Plus Derivative Control (PID Control)

In PID control, the actuating signal consists of proportional error signal added with integral and derivative of error signal.

The actuating signal for the PID control is given by

$$e_a(t) = e(t) + T_d \frac{de(t)}{dt} + K_i \int e(t)\, dt$$

Taking the Laplace transform on both sides of Eq. (4.35),

$$E_a(s) = E(s) + T_d sE(s) + K_i \frac{E(s)}{s}$$

i.e.

$$E_a(s) = \left[1 + T_d s + \frac{K_i}{s}\right] E(s)$$

The block diagram of a second-order control system employing PID controller is shown in Figure .

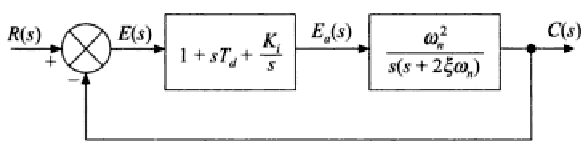


Figure Block diagram of a control system with PID control.

Proportional, integral and derivative actions and their various combinations are not the only control laws possible, but they are the most common. It has been estimated that 90% of the controllers are of the PI type. This percentage will probably decrease as digital control with its great flexibility becomes more widely used. But the PI and PID controllers will remain for some time as standard against which any new designs must compete.

Example:

The control system shown in Figure employs proportional plus error rate control. Determine the value of error rate constant K_e so that the damping ratio is 0.6

(a) Determine the value of settling time and maximum overshoot. Find the steady-state error if the input is a unit-ramp.

(b) What will be those values without error rate control?

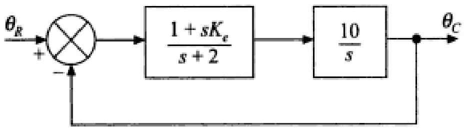


Figure Block diagram.

Solution: (a) *With error rate control*

$$G(s) = \frac{10(1+sK_e)}{s(s+2)}$$

Therefore, the closed-loop transfer function is

$$\frac{\theta_C(s)}{\theta_R(s)} = \frac{\dfrac{10(1+sK_e)}{s(s+2)}}{1+\dfrac{10(1+sK_e)}{s(s+2)}} = \frac{10+10sK_e}{s^2+s(2+10K_e)+10}$$

Comparing the characteristic equation $s^2+s(2+10K_e)+10=0$ with the standard form of the characteristic equation of a second-order system $s^2+2\xi\omega_n s+\omega_n^2=0$, we get

$$\omega_n^2 = 10, \quad \therefore \quad \omega_n = \sqrt{10} = 3.16 \text{ rad/s}$$

$$2\xi\omega_n = 2 + 10K_e$$

$$\therefore \quad K_e = \frac{2\xi\omega_n - 2}{10} = \frac{2\times0.6\times3.16-2}{10} = 0.18$$

The settling time

$$t_s = \frac{4}{\xi\omega_n} = \frac{4}{0.6\times3.16} = 2.11 \text{ s}$$

The peak overshoot

$$M_p = e^{-\pi\xi/\sqrt{1-\xi^2}} = e^{-\pi\times0.6/\sqrt{1-0.6^2}} = 0.0949$$

The peak % overshoot

$$M_p \times 100\% = 0.0949 \times 100\% = 9.49\%$$

Therefore, the steady-state error

$$e_{ss} = \frac{R}{K_v} = \frac{1}{K_v} = \frac{1}{\underset{s\to0}{\text{Lt}}\, sG(s)} = \frac{1}{\underset{s\to0}{\text{Lt}}\, s\dfrac{10(1+sK_e)}{s(s+2)}} = \frac{1}{5} = 0.2 \text{ rad}$$

8. Time response analysis:

Time response is defined as the response of the system with respect to time [C(t)].

Examples:

Example Obtain the response of a unity feedback system whose open-loop transfer function is

$$G(s) = \frac{3}{s(s+4)}$$

for a unit-step input.

Solution: The closed-loop unity feedback system is shown in Figure

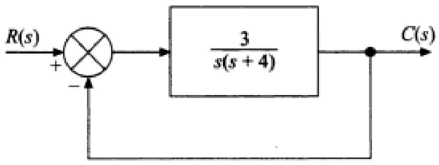


Figure Block diagram.

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1+G(s)} = \frac{\frac{3}{s(s+4)}}{1+\frac{3}{s(s+4)}} = \frac{3}{s^2+4s+3} = \frac{3}{(s+1)(s+3)}$$

For a unit-step input, $r(t) = 1$. Therefore,

$$R(s) = \frac{1}{s}$$

$$\therefore \qquad C(s) = \frac{3}{s(s+1)(s+3)} = \frac{1}{s} - \frac{\frac{3}{2}}{s+1} + \frac{\frac{1}{2}}{s+3}$$

Taking the inverse Laplace transform, the response is

$$c(t) = 1 - \frac{3}{2}e^{-t} + \frac{1}{2}e^{-3t}$$

Example A positional control system with velocity feedback is shown in Figure What is the response of the system for a unit-step input?

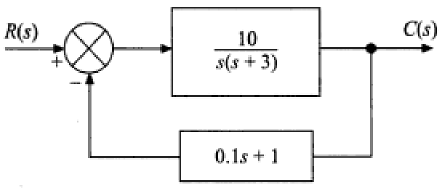


Figure Block diagram.

Solution: The closed-loop transfer function of the system is

$$\frac{C(s)}{R(s)} = \frac{\frac{10}{s(s+3)}}{1+\frac{10}{s(s+3)}\times(0.1s+1)} = \frac{10}{s^2+4s+10}$$

For a unit-step input, $r(t)=1$. Therefore,

$$R(s) = \frac{1}{s}$$

so

$$C(s) = \frac{1}{s}\times\frac{10}{s^2+4s+10} = \frac{A}{s}+\frac{Bs+C}{s^2+4s+10}$$

$$= \frac{1}{s}-\frac{s+4}{s^2+4s+10} = \frac{1}{s}-\frac{s+2}{(s+2)^2+(\sqrt{6})^2}-\frac{2}{\sqrt{6}}.\frac{\sqrt{6}}{(s+2)^2+(\sqrt{6})^2}$$

Taking the inverse Laplace transform, the response is

$$c(t) = 1-e^{-2t}\cos\sqrt{6}t-\frac{2}{\sqrt{6}}e^{-2t}\sin\sqrt{6}t$$

Example : *A certain control system is described by the differential equation.* $\frac{d^2y(t)}{dt^2}+7\frac{dy(t)}{dt}+12y(t)=12x(t)$. *Find its output response for unit step input.*

$y(t)$ = output, $x(t)$ = input

Solution : Taking Laplace of the equation neglecting initial conditions.

$$s^2Y(s)+7sY(s)+12Y(s) = 12X(s)$$

T.F. is

$$\frac{Y(s)}{X(s)} = \frac{12}{s^2+7s+12}$$

Comparing denominator with standard form

$\omega_n = \sqrt{12}$, $2\xi\omega_n = 7$ $\therefore \xi = 1.010363$

As $\xi > 1$, system is overdamped, hence the output will not contain any oscillations. Hence standard expression for c(t) cannot be used.

Now input is unit step, so $X(s) = 1/s$ Substituting in T.F.

$$Y(s) = \frac{12}{s(s^2+7s+12)}$$

Use partial fraction method

$$= \frac{12}{s(s+3)(s+4)} = \frac{A}{s}+\frac{B}{s+3}+\frac{C}{s+4}$$

where, $A = 1$, $B = -4$, $C = 3$

$$Y(s) = \frac{1}{s}-\frac{4}{s+3}+\frac{3}{s+4}$$

Taking Laplace inverse,

$$y(t) = 1-4e^{-3t}+3e^{-4t}$$

UNIT 3

1. Frequency response

The steady state response of a system to a purely sinusoidal input is defined as frequency response of a system. In such method frequency of the input signal is to be varied over a certain range and the resulting response of system is to be studied. Such response is called ***frequency response.***

Steady State Response to Sinusoidal Input : (Frequency Response)

Consider a linear time invariant system with its transfer function G(s) as shown.

Consider input r(t) to be purely sinusoidal.

$$r(t) = A\sin\omega t$$

$$R(s) = \frac{A\,\omega}{s^2+\omega^2}$$

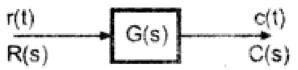


Fig.

While $$G(s) = \frac{N(s)}{(s+s_1)(s+s_2)\ldots(s+s_n)}$$

$\therefore$ Output $$C(s) = R(s)\cdot G(s) = \frac{A\,\omega}{(s^2+\omega^2)}\cdot\frac{N(s)}{(s+s_1)(s+s_2)\ldots(s+s_n)}$$

Assuming system to be stable, we can write,

$$C(s) = \frac{a}{s+j\omega}+\frac{\bar{a}}{s-j\omega}+\frac{b_1}{s+s_1}+\ldots+\frac{b_n}{s+s_n}$$

where a is constant while $\bar{a}$ is complex conjugate of a. Taking inverse Laplace,

$$\therefore \quad c(t) = ae^{-j\omega t}+\bar{a}\,e^{+j\omega t}+b_1e^{-s_1 t}+\ldots+b_n\,e^{-s_n t}$$

Steady state of the output is $\lim_{t\to\infty} c(t)$. Then all the terms from c(t) like $b_1e^{-s_1t}, \ldots b_ne^{-s_nt}$ will vanish.

$$\therefore \quad C_{ss}(t) = a\,e^{-j\omega t}+\bar{a}\,e^{+j\omega t}$$

Now a and $\bar{a}$ can be determined as follows.

$$a = G(s)\cdot\frac{A\,\omega}{s^2+\omega^2}\cdot(s+j\omega)\,\Big|_{s=-j\omega} = -\frac{A\,G(-j\omega)}{2j}$$

$$\bar{a} = G(s)\frac{A\,\omega}{s^2+\omega^2}\cdot(s-j\omega)\,\Big|_{s=+j\omega} = \frac{A\,G(+j\omega)}{2j}$$

Now as $G(j\omega)$ is a complex quantity having its own magnitude and phase angle ϕ. It can be written as,

$$G(j\omega) = |G(j\omega)|\,e^{j\phi}$$

where $$|G(j\omega)| = \sqrt{(\text{Real part})^2+(\text{Imj}\cdot\text{part})^2}$$

and $$\phi = \angle G(j\omega) = \tan^{-1}\left[\frac{\text{Imaginary part of } G(j\omega)}{\text{Real part of } G(j\omega)}\right]$$

Similarly $$G(-j\omega) = |G(-j\omega)|\,e^{-j\phi} = |G(j\omega)|\,e^{-j\phi}$$

$$\therefore \quad C_{ss}(t) = \frac{-A\,|G(-j\omega)|}{2j}\,e^{-j\phi}\cdot e^{-j\omega t}+\frac{A\,|G(j\omega)|}{2j}\,e^{j\phi}\cdot e^{j\omega t}$$

$$= A\,|G(j\omega)|\,\frac{e^{j(\omega t+\phi)}-e^{-j(\omega t+\phi)}}{2j}$$

Now $e^{j\theta} = \cos\theta + j\sin\theta \quad \therefore \cos\theta = \frac{e^{j\theta} + e^{-j\theta}}{2}$

$e^{-j\theta} = \cos\theta - j\sin\theta \quad \therefore \sin\theta = \frac{e^{j\theta} - e^{-j\theta}}{2j}$

$$\therefore \quad \boxed{C_{ss}(t) = A\,|G(j\omega)|\sin(\omega t + \phi)}$$

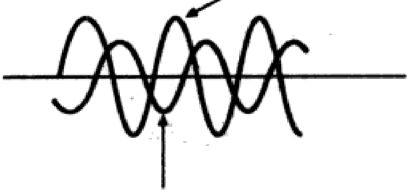


Fig.

Magnitude of output = Product of magnitude of input and $|G(j\omega)|$

While phase angle difference $\phi = \angle G(j\omega)$.

The sinusoidal transfer function $G(j\omega)$ is a complex quantity and can be represented as magnitude and phase angle with frequency ω as a variable parameter.

Such frequency domain transfer function can be obtained by substituting $j\omega$ for 's' in the transfer function G(s) of the system.

$$\boxed{G(j\omega) = G(s)|_{s=j\omega} = \text{Frequency domain transfer function}}$$

So to get frequency response means to sketch the variation in magnitude and phase angle of $G(j\omega)$, when ω is varied from 0 to ∞.

$$G(j\omega) = M\angle\phi$$

$$M = \text{Magnitude} \rightarrow f(\omega)$$

$$\phi = \text{Phase angle} \rightarrow f(\omega)$$

where ω = Input frequency

Frequency Domain Methods :

Variations in M and ϕ of $G(j\omega)$ as 'ω' the input frequency is varied from 0 to ∞ can be obtained by number of methods. The commonly used method to sketch such frequency response for given systems are

i) Bode Plot ii) Polar plot iii) Nyquist plot iv) M- ϕ plot

2. Bode plot

Introduction to Bode Plot

Basic of any frequency response is to plot magnitude M and angle ϕ against input frequency 'ω'. When 'ω' is varied from 0 to ∞ there is wide range of variations in M and ϕ and hence it becomes difficult to accommodate all such variations with linear scale. Hence H.W. Bode suggested the method in which logarithmic values of magnitude are to be plotted against logarithmic values of frequencies. Such plots are called Logarithmic plots which allows us to show wide range of variations in magnitude on a single paper.

Magnitude Plot

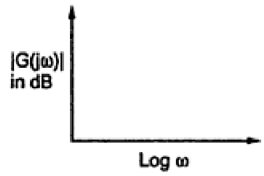
The magnitude can be expressed in its logarithmic values by finding out the value $20 \log_{10} |G(j\omega)|$, which has a unit as decibel denoted by dB.

For Bode Plot $\boxed{|G(j\omega)| = 20 \log_{10} |G(j\omega)| \text{ dB.}}$

Such decibels values are to be plotted against $\log_{10}(\omega)$.

So magnitude plot can be shown as in the Fig.

The Phase Angle Plot



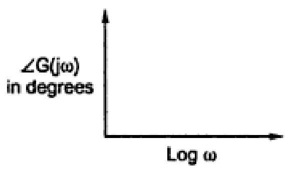


Fig. Magnitude plot **Phase angle plot**

In this, angle of $G(j\omega)$ is to be expressed in degrees which is to be plotted against Log ω.

The phase angle plot can be shown as in the Fig.

As for both plots X-axis is Log ω both may be drawn on same paper with common X-axis.

So for Bode plot. magnitude in dB and phase angle in degrees are the magnitudes and phase angles of $G(j\omega)H(j\omega)$, plotted against Log ω.

Steps to Sketch the Bode Plot

i) Express given G(s)H(s) into time constant form .

ii) Draw a line of 20 Log K dB.

iii) Draw a line of appropriate slope representing poles or zeros at the origin, passing through intersection point of $\omega = 1$ and 0 dB.

iv) Shift this intersection point on 20 Log K line and draw parallel line to the line drawn in step 3. This is addition of constant K and number of poles or zeros at the origin.

v) Change the slope of this line at various corner frequencies by appropriate value i.e. depending upon which factor is occurring at corner frequency. For a simple pole, slope must be changed by – 20 dB/decade, for a simple zero by + 20 dB/decade etc. **Do not draw these individual lines.** Change the slope of line obtained in step 5 by respective value and draw line with resultant slope. Continue this line till it intersects next corner frequency line. Change the slope and continue. Apply necessary correction for quadratic factor.

vi) Prepare the phase angle table and obtain the table of ω and resultant phase angle ϕ_R by actual calculation. Plot these points and draw the smooth curve obtaining the necessary phase angle plot.

Frequency Response Specifications

The basic objective of control system design is to meet the performance specifications. These specifications are the constraints or limitations put on the mathematical functions describing the system characteristics. Such frequency response specifications are described below.

Consider a general frequency response of a system.

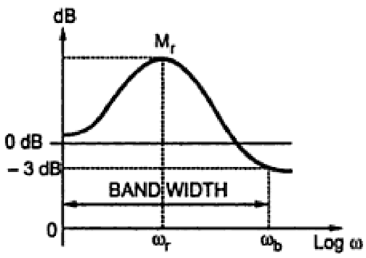


Fig.

Bandwidth : It is defined as the range of frequencies over which the system will respond satisfactorily. It can also be defined as range of frequencies in which the magnitude response is almost flat in nature.

Cutoff frequency : It is denoted by ω_b.

The frequency at which the magnitude of the closed loop response is 3 dB down from its zero frequency value is called cutoff frequency.

The range 0 to ω_b is nothing but bandwidth of the system whose frequency response is shown.

Bandwidth indicates the speed of the response. It indicates the ability to reproduce the input signal. It is inversely proportional to the rise time. Large bandwidth means small rise time means fast response.

Cutoff rate : The slope of the resultant magnitude curve near the cutoff frequency is called cutoff rate.

Resonant peak (M_r) : It is the maximum value of magnitude of the closed loop frequency response as shown. Larger the value of resonant peak more is the value of peak overshoot of system for step input. It is a measure of relative stability of the system.

Resonant frequency (ω_r) : The frequency at which resonant peak M_r occurs in closed loop frequency response is called resonant frequency. It is inversely proportional to the rise time.

These are the general specifications but the specification which are most important from the stability and relative stability analysis are discussed below.

Gain cross over frequency (ω_{gc}) : The frequency at which magnitude of $G(j\omega)H(j\omega)$ is unity i.e. 1 is called **gain cross over frequency.**

Generally magnitude of $G(j\omega)H(j\omega)$ is expressed in dB. And dB value of 1 is $20 \, \text{Log}_{10} \, 1 = 0$ dB.

It can be defined as the frequency at which magnitude of $G(j\omega)H(j\omega)$ is 0 dB is ω_{gc}.

Phase cross over frequency (ω_{pc}) : The frequency at which phase angle of $G(j\omega)H(j\omega)$ is $-180°$ is called **phase cross over frequency,** ω_{pc}.

$$\therefore \qquad \text{G.M.} = \frac{1}{|G(j\omega)H(j\omega)|_{\omega=\omega_{pc}}}$$

In decibels

$$\text{G.M.} = 20 \, \text{Log} \frac{1}{|G(j\omega)H(j\omega)|_{\omega=\omega_{pc}}}$$

$$\text{G.M.} = -20 \, \text{Log}_{10} |G(j\omega)H(j\omega)|_{\omega=\omega_{pc}}$$

More positive the G.M., more stable is the system.

Phase margin P.M. : Similar to the gain, it is possible to introduce phase lag in the system i.e. negative angles without affecting magnitude plot of $G(j\omega)H(j\omega)$.

The amount of additional phase lag which can be introduced in the system till system reaches on the verge of instability is called **phase margin P.M.**

The positive phase margin means such negative angle introduction in system is possible before system becomes unstable. Such system is stable system. While negative phase margin means present negative phase lag should be changed by adding positive angle hence phase margin is said to be negative and system is unstable.

Mathematically it can be defined as,

$$\text{P.M.} = [\angle G(j\omega)H(j\omega)|_{\text{at } \omega=\omega_{gc}}] - [(-180°)]$$

$$\therefore \qquad \text{P.M.} = 180° + \angle G(j\omega)H(j\omega)|_{\omega=\omega_{gc}}$$

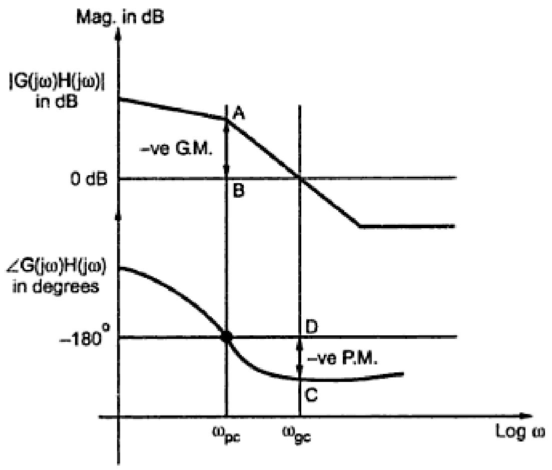


Fig. $\omega_{gc} > \omega_{pc}$ **G.M. and P.M. negative, unstable system**

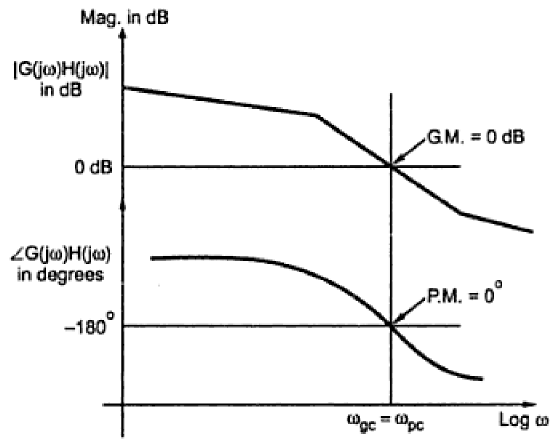


Fig. $\omega_{gc} = \omega_{pc}$ **G.M. and P.M. zero, marginally stable system**

Advantages of Bode Plots

1) It shows both low and high frequency characteristics of transfer function in single diagram.
2) The plots can be easily constructed using some valid approximations.
3) Relative stability of system can be studied by calculating G.M. and P.M. from the Bode Plot.
4) The various other frequency domain specifications like cutoff frequency, bandwidth etc. can be determined.
5) Data for constructing complicated polar and Nyquist plots can be easily obtained from Bode Plot.
6) Transfer function of system can be obtained from Bode plot.
7) It indicates how system should be compensated to get the desired response.
8) The value of system gain K can be designed for required specifications of G.M. and P.M. from Bode Plot.
9) Without the knowledge of the transfer function the Bode Plot of stable open loop system can be obtained experimentally.

Example : *A unity feedback control system has* $G(s) = \frac{80}{s(s+2)(s+20)}$. *Draw the Bode Plot. Determine G.M. P.M.* ω_{gc} *and* ω_{pc}. *Comment on the stability.*

Solution : Step 1 : Arrange G(s)H(s) in time constant form.

$$G(s)H(s) = \frac{80}{s(s+2)(s+20)} \quad , \; H(s) = 1$$

$$= \frac{80}{s(2)\left(1+\frac{s}{2}\right)(20)\left(1+\frac{s}{20}\right)} = \frac{2}{s\left(1+\frac{s}{2}\right)\left(1+\frac{s}{20}\right)}$$

Step 2 : Identify factors :

i) K = 2 ii) 1 pole at origin

iii) Simple pole $\frac{1}{\left(1+\frac{s}{2}\right)}$ with $T_1 = \frac{1}{2}$ $\therefore \omega_{c1} = \frac{1}{T_1} = 2$

iv) Simple pole $\frac{1}{\left(1+\frac{s}{20}\right)}$ with $T_2 = \frac{1}{20}$ $\therefore \omega_{c2} = \frac{1}{T_2} = 20$

Step 3 : Magnitude Plot Analysis

i) For K = 2, 20 Log K = 20 Log 2 = 6 dB

ii) For 1 pole at origin. Straight line of slope − 20 dB/decade passing through intersection point of $\omega = 1$ and 0 dB.

iii) Shift intersection point of $\omega = 1$ and 0 dB on 20 Log K line and draw parallel to − 20 dB /decade line drawn. This will continue as a resultant of K and $\frac{1}{s}$ till first corner frequency occurs i.e. $\omega_{c1} = 2$.

iv) At $\omega_{c1} = 2$, as there is simple pole it will contribute the rate of − 20 dB/ decade hence resultant slope after $\omega_{c1} = 2$ becomes − 20 − 20 = − 40 dB/decade. This is addition of K, $\frac{1}{s}$ and $\frac{1}{\left(1+\frac{s}{2}\right)}$. This will continue till it intersects next corner frequency line i.e. $\omega_{c2} = 20$.

v) At $\omega_{c2} = 20$, there is simple pole contributing −20 dB/decade and hence resultant slope after $\omega_{c2} = 20$ becomes − 40 − 20 = − 60 dB/decade.
This is resultant of overall G(s)H(s) i.e. G(jω)H(jω). The final slope is − 60 dB/decade, as there is no other factor present.

Step 4 : Phase Angle plot : Convert G(s)H(s) to G(jω)H(jω)

$$\therefore \quad G(j\omega)H(j\omega) = \frac{2}{j\omega\left(1+\frac{j\omega}{2}\right)\left(1+\frac{j\omega}{20}\right)}$$

$$\therefore \quad \angle G(j\omega)H(j\omega) = \frac{\angle 2+j\,0}{\angle j\omega \angle 1+\frac{j\omega}{2} \angle 1+\frac{j\omega}{20}}$$

$$\angle 2 + j0 = 0^\circ, \quad \frac{1}{\angle j\omega} \text{ i.e. 1 pole at origin is } -90^\circ \text{ constant}$$

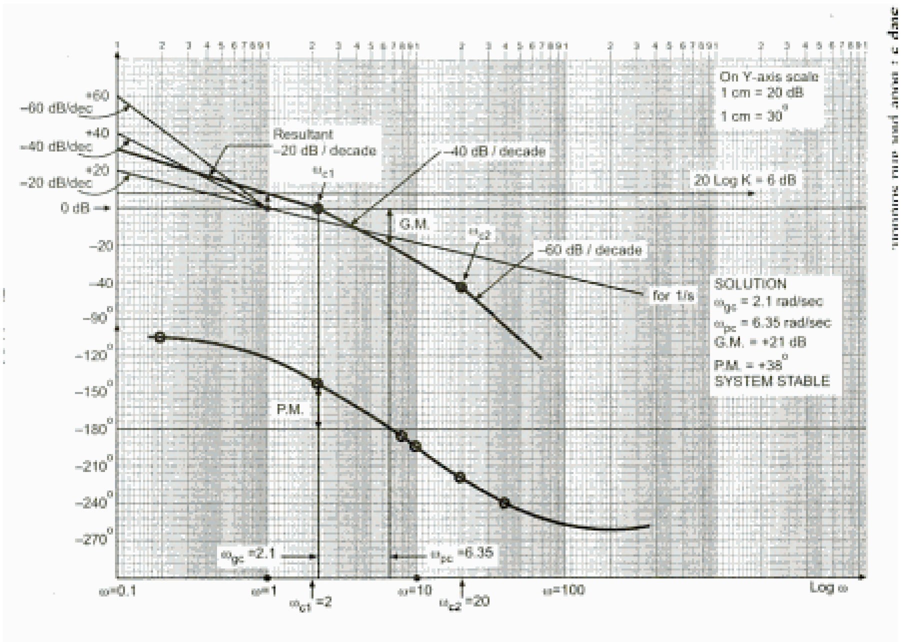
$$\angle \frac{1}{1+j\frac{\omega}{2}} = -\tan^{-1}\frac{\omega}{2} \text{ and } \angle \frac{1}{1+j\frac{\omega}{20}} = -\tan^{-1}\frac{\omega}{20}$$

∴ **Phase Angle Table :**

ω	$\frac{1}{j\omega}$	$-\tan^{-1}\frac{\omega}{2}$	$-\tan^{-1}\frac{\omega}{20}$	ϕ_R Resultant
0.2	−90°	− 5.7°	− 0.57°	− 96.27°
2	−90°	−4.5°	− 5.7°	− 140.7°
8	−90°	− 75.96°	− 21.8°	− 187.76°
10	−90°	− 78.69°	− 26.56°	− 195.29°
20	−90°	− 84.28°	− 45°	− 219.28°
40	−90°	− 87.13°	− 63.43°	− 240.58°
∞	−90°	− 90°	− 90°	− 270°

To draw straight lines of − 40 dB/decade and − 60 dB/decade from ω_{c1} = 2 and ω_{c2} = 20, draw faint lines of slopes − 20, − 40, − 60 dB/decade from intersection point of ω = 1 and 0 dB line and just draw parallel to them from respective points.

Step 5 : Bode plot and solution.



Example : *For a unity feedback system* $G(s) = \dfrac{800\,(s+2)}{s^2\,(s+10)\,(s+40)}$

Sketch the Bode plot , asymptotic in nature. Comment on stability.

Solution : Step 1 : Arrange G(s)H(s) in time constant form.

$$G(s)H(s) = \frac{800\times 2\times\left(\frac{s}{2}+1\right)}{s^2\times 10\left(1+\frac{s}{10}\right)\times 40\times\left(1+\frac{s}{40}\right)} = \frac{4\left(1+\frac{s}{2}\right)}{s^2\left(1+\frac{s}{10}\right)\left(1+\frac{s}{40}\right)}$$

Step 2 : Factors are

i) Constant K = 4,

ii) 2 poles at the origin , $1/s^2$

iii) Simple zero, $1+\frac{s}{2}$, $T_1 = 1/2$, $\omega_{c1} = \frac{1}{T_1} = 2$ rad/sec.

iv) Simple pole, $\dfrac{1}{1+\frac{s}{10}}$, $T_2 = 1/10$, $\omega_{c2} = \frac{1}{T_2} = 10$ rad/sec.

v) Simple pole, $\dfrac{1}{1+\frac{s}{40}}$, $T_3 = 1/40$, $\omega_{c3} = \frac{1}{T_3} = 40$ rad/sec.

Step 3 : Magnitude plot analysis

i) For K = 4, 20 Log K = 20 Log 4 = 12 dB.

ii) 2 poles at the origin i.e. $1/s^2$. It contributes a straight line of slope – 40 dB/decade passing through intersection point of ω = 1 and 0 dB. So starting slope becomes – 40 dB/decade.

iii) Shift intersection point of ω = 1 and 0 dB on 20 Log K line and draw parallel line to – 40 dB/decade. This represents addition of K and $1/s^2$. This resultant will continue till first corner frequency ω_{c1} = 2.

iv) At ω_{c1} = 2 , simple zero occurs which contributes + 20 dB/dec individually and hence resultant slope from '2' onwards becomes – 40 +20 = – 20 dB/dec. This continues till ω_{c1} = 10.

v) At ω_{c2} = 10, simple pole occurs which contributes – 20 dB/dec individually and hence resultant slope from 10 onwards becomes – 20 – 20 = – 40 dB/dec again. This continues till ω_{c3} = 40.

vi) At ω_{c3} = 40 , simple pole occurs which contributes – 20 dB/dec individually and hence resultant slope from 40 onwards becomes – 40 – 20 = – 60 dB/dec. This continues upto $\omega \to \infty$ as there is no other factor present in G(s)H(s).

Step 4 : Phase Angle Plot

$$G(j\omega)H(j\omega) = \frac{4\left(1+\frac{j\omega}{2}\right)}{(j\omega)^2\left(1+\frac{j\omega}{10}\right)\left(1+\frac{j\omega}{40}\right)}$$

$$\angle G(j\omega)H(j\omega) = \frac{\angle 4+j0 \quad \angle 1+\frac{j\omega}{2}}{\angle (j\omega)^2 \quad \angle 1+\frac{j\omega}{10} \quad \angle 1+\frac{j\omega}{40}}$$

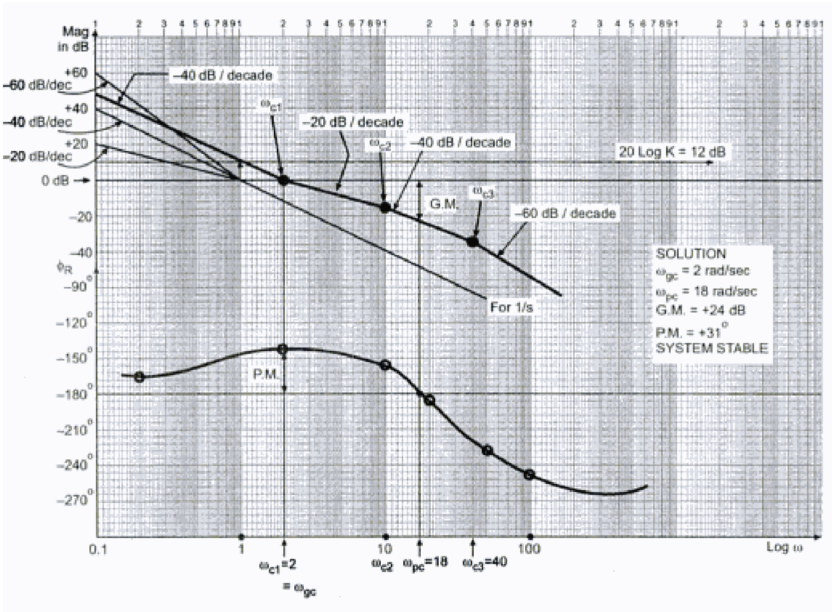
$$\angle 4+j0 = 0°, \quad \angle 1+\frac{j\omega}{2} = +\tan^{-1}\frac{\omega}{2}$$

$\angle \frac{1}{(j\omega)^2}$, 2 poles at origin = –180° constant

$$\angle \frac{1}{1+\frac{j\omega}{10}} = -\tan^{-1}\frac{\omega}{10} \text{ and } \angle \frac{1}{1+\frac{j\omega}{40}} = -\tan^{-1}\frac{\omega}{40}$$

Phase Angle Table

ω	$\frac{1}{(j\omega)^2}$	$+\tan^{-1}\frac{\omega}{2}$	$-\tan^{-1}\frac{\omega}{10}$	$-\tan^{-1}\frac{\omega}{40}$	ϕ_R
0.2	– 180°	+ 5.7°	– 1.14°	– 0.28°	– 175.72°
2	– 180°	+ 45°	– 11.3°	– 2.86°	– 149.16°
10	– 180°	+ 78.6°	– 45°	– 14.03°	– 160.43°
20	– 180°	+ 84.28°	– 63.43°	– 26.56°	– 185.71°
50	– 180°	+ 87.7°	– 78.6°	– 51.3°	– 222°
100	– 180°	+ 88.85°	– 84.28°	– 68.19°	– 243.54°
∞	– 180°	+ 90°	– 90°	– 90°	– 270°



3. Polar plot

Polar Plot

As seen earlier, to sketch the frequency response means to plot the variations in magnitude and phase angle versus the input frequency. The two plots constituting the frequency response are called **gain plot** or **magnitude plot** and the **phase plot**. The scientist Bode has suggested to use a logarithmic scale to sketch frequency response.

In polar plot, the magnitude of $G(j\omega)H(j\omega)$ is plotted against the phase angle of $G(j\omega)H(j\omega)$ for various values of ω. In frequency response we have,

$M = |G(j\omega)H(j\omega)| = \text{Magnitude}$

$\phi = \angle G(j\omega)H(j\omega) = \text{Phase}$

We can obtain the values of M and ϕ by varying the input frequency ω from 0 to ∞. The result can be tabulated as below.

ω	$M = \lvert G(j\omega)H(j\omega) \rvert$	$\phi = \angle G(j\omega)H(j\omega)$
0	M_0	ϕ_0
ω_1	M_1	ϕ_1
:	:	:
:	:	:
:	:	:
∞	M_∞	ϕ_∞

Now each value of M and ϕ corresponding to particular frequency ω decides a point as per the polar co-ordinate system. i.e. for $\omega = \omega_1$, $M = M_1$ and $\phi = \phi_1$. So it decides a point having polar co-ordinates as $M_1 \angle \phi_1$. This is the point which is tip of the phasor of magnitude M_1 plotted at an angle ϕ_1.

So without actually having an indication of frequency, for various values of frequencies from 0 to ∞ the magnitudes are plotted against phase angles.

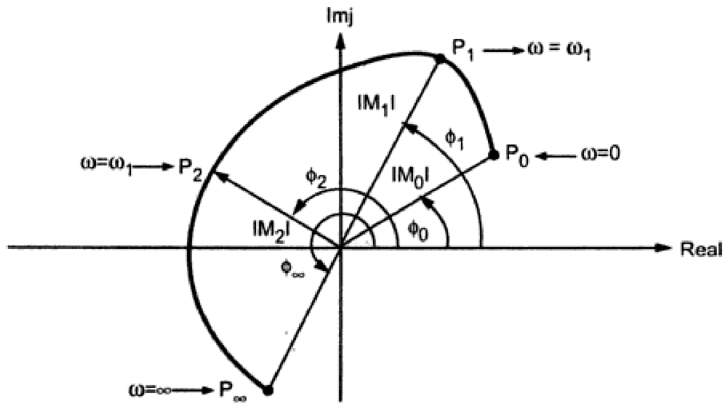


Fig. Polar plot

This is shown in the Fig.

So polar plot starts at point representing magnitude and phase angle for $\omega = 0$. While it terminates at a point representing magnitude and phase angle for $\omega = \infty$.

Determination of G.M. and P.M. from Polar Plot

According to definition of gain margin, it is margin in gain that can be introduced in the system till system reaches on the verge of instability

$$\text{G.M.} = \frac{1}{|G(j\omega)H(j\omega)|_{\omega=\omega_{pc}}}$$

In polar plot $|G(j\omega)H(j\omega)|_{\omega=\omega_{pc}}$ is nothing but $l(OQ)$ where Q is the intersection of polar plot with negative real axis. Q is the point corresponding to $\omega = \omega_{pc}$.

$$\therefore \quad \text{G.M.} = \frac{1}{l(OQ)}$$

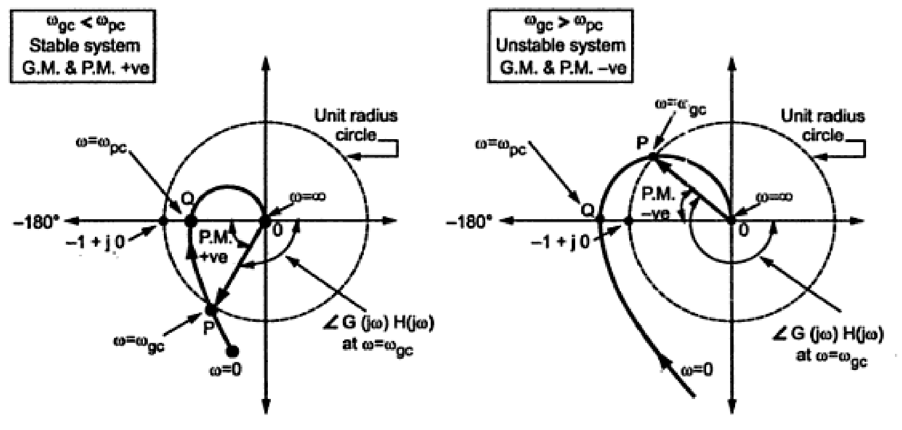
where Q is intersection of polar plot with negative real axis.

or $$\text{G.M.} = 20 \text{ Log}_{10} \frac{1}{|OQ|} \text{ dB.}$$ This gives G.M. in dB

According to definition of phase margin,

$$\text{P.M.} = 180° + \angle G(j\omega)H(j\omega)\,|_{\omega=\omega_{gc}}$$

Now point P is the point on polar plot corresponding to $\omega = \omega_{gc}$ obtained by drawing unit radius circle. So if ϕ is the angle of point P corresponding to $\omega = \omega_{gc}$ the P.M. can be calculated as shown in the Fig.



(a) **Fig.** (b)

Stability Determination From Polar Plot

stability depends on the comparison of magnitudes of ω_{gc} and ω_{pc}.

i) $\omega_{gc} < \omega_{pc}$, G.M. and P.M. are positive, system is stable .

ii) $\omega_{gc} > \omega_{pc}$ G.M. and P.M. are negative, system is unstable.

iii) $\omega_{gc} = \omega_{pc}$, G.M. = P.M. = 0. So system is marginally stable .

Example : *Consider a system with open loop transfer function as* $G(s)H(s) = \frac{10}{s}$. *Obtain its polar plot .*

Solution : Now to obtain its polar plot, obtain frequency domain transfer function by replacing s by jω.

$$G(j\omega)\,H(j\omega) = \frac{10}{j\omega} = \frac{10 + j0}{0 + j\omega}$$

$$\therefore \quad |G(j\omega)\,H(j\omega)| = M = \frac{10}{\omega}$$

$$\angle G(j\omega)H(j\omega) = \phi = \frac{\tan^{-1}\left(\frac{0}{10}\right)}{\tan^{-1}\left(\frac{\omega}{0}\right)} = \frac{0^\circ}{90^\circ} = -90^\circ$$

For various values of ω, M is changing but angle remains constant as –90°.

ω	M	φ
0	∞	– 90°
10	1	– 90°
100 : :	0.1	– 90°
∞	0	– 90°

So plot starts at ∞ at angle – 90° and terminates at origin along the axis of angle – 90° i.e. negative imaginary axis.

Hence we get the corresponding polar plot as shown in the Fig. which is negative imaginary axis.

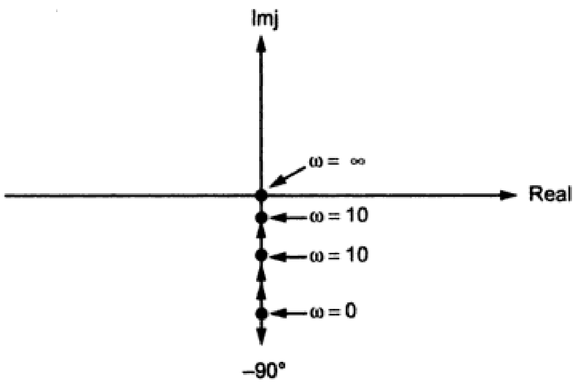


Fig.

Example Draw the polar plot for the following transfer function.

$$G(s)=\frac{10(s+2)}{s(s+1)(s+3)}$$

Solution

1. For the given transfer function, write the sinusodial transfer function by putting $s=j\omega$. Thus,

$$G(j\omega)=\frac{10(j\omega+2)}{j\omega(j\omega+1)(j\omega+3)}$$

2. Put the sinusoidal transfer function, in its magnitude and phase angle form. Thus,

$$G(j\omega)=\frac{10\sqrt{(\omega^2+4)}\,\underline{\left|\tan^{-1}\frac{\omega}{2}-90^\circ-\tan^{-1}\omega-\tan^{-1}\frac{\omega}{3}\right.}}{\omega\sqrt{(\omega^2+1)(\omega^2+9)}}$$

3. Give value of $\omega=0$ and $\omega=\infty$ and calculate the magnitude $|G(j\omega)|$ and phase ϕ.

   For $\omega=0$, $G(j\omega)=\infty\,\underline{|-90^\circ}$

   For $\omega=\infty$, $G(j\omega)=0\,\underline{|-180^\circ}$

4. Give various values of ω and each time calculate $|G(j\omega)|$ and ϕ. The values of ω is so chosen such that the phase angle range from -90° to -180° is more or less uniformly covered. Some 5 to 6 values of ω are chosen to get phase angle (say), around -105°, 120°, -135°, -150°, and -170°. The results are tabulated in Table .

Table

ω	0	0.8	1	1.5	3	5	∞
ϕ	-90°	-121.8°	-127°	-136°	-150°	-160°	-180°
$\lvert G(j\omega)\rvert$	∞	6.77	5	2.76	0.9	0.36	0

5. The values of Table are transferred to polar plot as explained below. For example consider the case where $\omega=1.5$ for which $\phi=-136^\circ$ and $|G(j\omega)|=2.76$. First draw a radial line OA with angle $\phi=-136^\circ$. (When polar graph sheets are supplied such lines are already drawn but in steps of 0°, 5°, 10°, 15° etc). On the line OA, after choosing any convenient scale measure OB = 2.76, the magnitude of $|G(j\omega)|$.
6. Similar to step 5, for each value of ω, one radial line is drawn with corresponding phase angle and the respective magnitude is marked on that radial line. Thus Table 6.1 is transferred into a polar plot. Also mark the value of ω by the side of each such points marked in the radial line. Join these points by a smooth curve. Put an arrow mark in the polar plot in the direction of increasing value of ω. Erase out the radial lines (if it is drawn in plain paper or draw thin radial lines so that it is less predominant than the polar plot). Fig. (a) shows the polar plot of example The polar plot drawn in polar graph sheet is shown in Fig. (b).

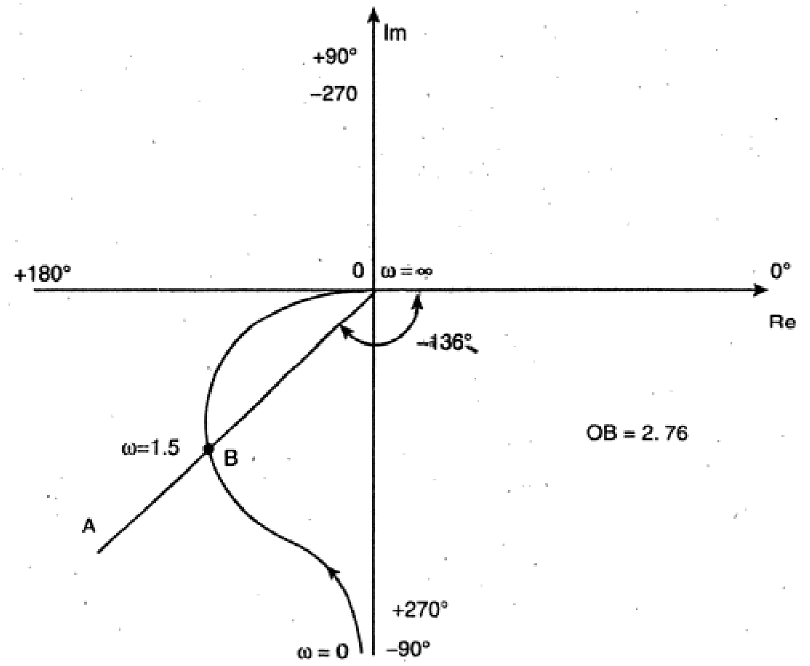


Fig. *(a)* *Locating the Magnitude and Phase in a Polar Graph*

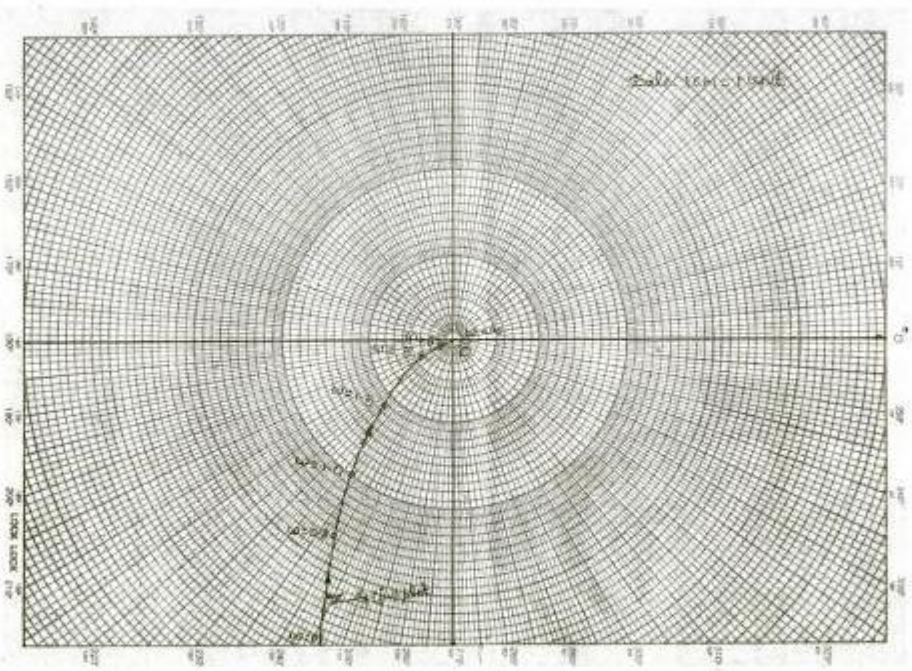


Fig. **(b)** *G(jω) Plot Drawn in a Polar Graph Sheet*

4. Determination of closed loop response from open loop response

For a unity feedback closed loop stable system, the closed loop frequency response can be obtained from the open loop frequency response. The closed loop transfer function of a unity feedback (H(s) = 1) system is given by,

$$M(s) = \frac{C(s)}{R(s)} = \frac{G(s)}{1+G(s)}$$

$$\therefore \quad M(j\omega) = \frac{C(j\omega)}{R(j\omega)} = \frac{G(j\omega)}{1+G(j\omega)}$$

The closed loop frequency response is the graph of magnitude of $C(j\omega)/R(j\omega)$ and phase angle of $C(j\omega)/R(j\omega)$ against frequency ω. The data required to obtain closed loop frequency response can be obtained from the polar plot plotted from open loop transfer function $G(j\omega)$. The Fig. shows the polar plot of $G(j\omega)$ ploted by varying ω from 0 to ∞.

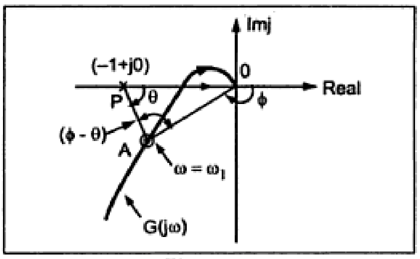


Fig.

The point A on the polar plot represent $|G(j\omega)|$ and $\angle G(j\omega)$ at $\omega = \omega_1$

$$\therefore \quad \vec{OA} = |G(j\omega)|$$

The point P is the critical point −1 + j0.

Now join point P to point A to get vector PA. The $\vec{PA}$ represents $1+G(j\omega)|_{\omega=\omega_1}$.

Hence the magnitude of $C(j\omega)/R(j\omega)$ i.e. $|M(j\omega)|$ at $\omega = \omega_1$ is the ratio of vectors $\vec{OA}$ and $\vec{PA}$.

$$\therefore \quad |M(j\omega)|_{\omega=\omega_1} = \left.\frac{C(j\omega)}{R(j\omega)}\right|_{\omega=\omega_1} = \frac{\vec{OA}}{\vec{PA}} = \left.\frac{G(j\omega)}{1+G(j\omega)}\right|_{\omega=\omega_1}$$

Similar phase angle of $C(j\omega) / R(j\omega)$ is the angle formed by the vector $\vec{OA}$ and $\vec{PA}$.

$$\therefore \quad \angle M(j\omega)|_{\omega=\omega_1} = \angle \left.\frac{C(j\omega)}{R(j\omega)}\right|_{\omega=\omega_1} = \frac{\angle \vec{OA}}{\angle \vec{PA}} = \frac{\phi}{\theta}$$

$$\therefore \quad \alpha = (\phi - \theta)$$

The procedure can be repeated for various values of ω to obtain magnitudes and phase angles of closed loop transfer function $C(j\omega) / R(j\omega)$. From this data, the closed loop frequency response can be obtained.

The method discussed above is complicated to obtain closed loop frequency response. Let us study how to obtain constant magnitude loci and constant phase angle loci for the closed loop transfer function. Such loci are called M and N circles These circles are very much convenient in determining the closed loop frequency response from the polar plot. It must be remembered that these circles are useful only for unity feedback systems.

M Circles [Constant Magnitude Loci]

The closed loop transfer function of a unity feedback system is,

$$M(s) = \frac{C(s)}{R(s)} = \frac{G(s)}{1+G(s)}$$

Now 's' is the complex variable hence $G(j\omega)$ is also a complex variable.

$$\therefore \quad G(j\omega) = X + jY$$

Now

$$M(j\omega) = \frac{G(j\omega)}{1+G(j\omega)} = \frac{X+jY}{1+X+jY}$$

Let M be the magnitude of $C(j\omega)/R(j\omega)$.

$$\therefore \quad M = \left|\frac{X+jY}{1+X+jY}\right| = \frac{\sqrt{X^2+Y^2}}{\sqrt{(1+X)^2+Y^2}}$$

Squaring both sides we get,

$$M^2 = \frac{X^2+Y^2}{(1+X)^2+Y^2}$$

$$\therefore \quad M^2[(1+X)^2+Y^2] = X^2+Y^2$$

$$\therefore \quad M^2[1+2X+X^2+Y^2]-X^2-Y^2 = 0$$

$$\therefore \quad X^2(M^2-1)+2XM^2+Y^2(M^2-1)+M^2 = 0 \qquad \text{... (1)}$$

Dividing by M^2-1,

$$X^2+\frac{2XM^2}{(M^2-1)}+Y^2+\frac{M^2}{(M^2-1)} = 0$$

$$\therefore \quad X^2-\frac{2XM^2}{(1-M^2)}+Y^2 = \frac{M^2}{1-M^2}$$ absorbing negative sign in denominator

To complete the square on left hand side, add $\left[\frac{M^2}{(1-M^2)}\right]^2$ on both sides.

$$\therefore \quad X^2-\frac{2XM^2}{(1-M^2)}+\left[\frac{M^2}{(1-M^2)}\right]^2+Y^2 = \frac{M^2}{(1-M^2)}+\left[\frac{M^2}{(1-M^2)}\right]^2$$

$$\therefore \quad \left[X-\frac{M^2}{(1-M^2)}\right]^2+Y^2 = \frac{M^2}{(1-M^2)}\left[1+\frac{M^2}{1-M^2}\right]$$

$$\therefore \quad \left[X-\frac{M^2}{1-M^2}\right]^2+Y^2 = \left[\frac{M}{(1-M^2)}\right]^2 \qquad \text{... (2)}$$

This equation is the equation of a circle with the center at $X=\frac{M^2}{1-M^2}$ and $Y = 0$ while radius = $\left|\frac{M}{1-M^2}\right|$.

For a particular value of M, we are getting a circle on which the value of M, the magnitude of closed loop transfer function is constant. And for various values of M, we are getting family of such circles. Hence these are called constant magnitude loci or M circles. Let us calculate center and radius for various values of M. The values are tabulated in the Table

M	Center $X=\frac{M^2}{1-M^2}$, $Y = 0$	Radius $R=\left\|\frac{M}{1-M^2}\right\|$
0.2	(0.041, 0)	0.208
0.5	(0.33, 0)	0.667
1	∞	∞
2	(– 1.33, 0)	0.667
5	(– 1.041, 0)	0.208

It can be observed from the Table that :

1. As M becomes larger and larger compared to 1, the radius becomes smaller and smaller and finally circles converge to the critical point $-1 + j0$.
2. For $M > 1$, the centers are to the left of point $-1 + j0$.
3. As M becomes smaller and smaller compared to 1, the radius becomes smaller and smaller and finally circles converge to the origin.
4. For $M < 1$, the centers are to the right of origin.
5. For $M = 1$, the locus is of the points which are equidistant from origin as well as from $-1 + j0$ point. Substituting $M = 1$ in equation (1) we get a straight line of $X = \frac{-1}{2}$ parallel to Y axis, passing through point $\left(-\frac{1}{2}, 0\right)$. Thus at $M = 1$, the circle degenerates into a straight line. All the M circles are symmetrical with respect to this straight line corresponding to $M = 1$.

The family of constant M circles is shown in the Fig.

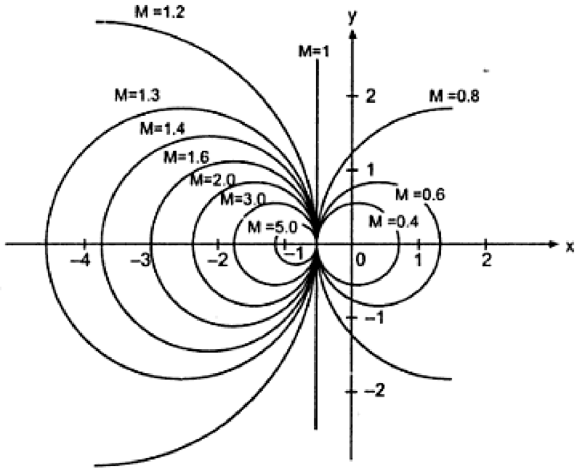


Fig. A family of constant M circles

N Circles [Constant Phase Loci]

Similar to the magnitude M of $C(j\omega) / R(j\omega)$, let us obtain the phase angle α interms of X and Y

$$\therefore \quad \angle \frac{C(j\omega)}{R(j\omega)} = \angle \frac{G(j\omega)}{1+G(j\omega)} = \angle \frac{X+jY}{(1+X)+jY}$$

$$\therefore \quad \alpha = \frac{\tan^{-1}\left(\frac{Y}{X}\right)}{\tan^{-1}\left(\frac{Y}{1+X}\right)}$$

$$\therefore \quad \alpha = \tan^{-1}\left(\frac{Y}{X}\right) - \tan^{-1}\left(\frac{Y}{1+X}\right)$$

Taking tan of both sides and defining $\tan\alpha = N$ we get,

$$\therefore \quad N = \tan\left[\tan^{-1}\left(\frac{Y}{X}\right) - \tan^{-1}\left(\frac{Y}{1+X}\right)\right]$$

Now $\quad \tan[A - B] = \frac{\tan A - \tan B}{1 + \tan A \tan B}$

$$\therefore \quad N = \frac{\tan\left[\tan^{-1}\left(\frac{Y}{X}\right)\right] - \tan\left[\tan^{-1}\left(\frac{Y}{1+X}\right)\right]}{1 + \tan\left[\tan^{-1}\left(\frac{Y}{X}\right)\right]\tan\left[\tan^{-1}\left(\frac{Y}{1+X}\right)\right]}$$

$$\therefore \quad N = \frac{\frac{Y}{X} - \frac{Y}{1+X}}{1 + \left(\frac{Y}{X}\right)\left(\frac{Y}{1+X}\right)} = \frac{Y}{X(1+X)+Y^2}$$

$$\therefore \quad X(1+X) + Y^2 = \frac{Y}{N}$$

$$\therefore \quad X^2 + X + Y^2 - \frac{Y}{N} = 0$$

Adding $\left(\frac{1}{4}\right) + \frac{1}{(2N)^2}$ to both sides for completing the square on left hand side we get,

$$X^2 + X + \frac{1}{4} + Y^2 - \frac{Y}{N} + \frac{1}{(2N)^2} = \frac{1}{4} + \frac{1}{(2N)^2}$$

$$\therefore \quad \left(X + \frac{1}{2}\right)^2 + \left(Y - \frac{1}{2N}\right)^2 = \frac{1}{4} + \frac{1}{(2N)^2} \quad \text{... (3)}$$

This is the equation of circle with centre at,

$X = -\frac{1}{2}$, $Y = \frac{1}{2N}$ with radius $\sqrt{\frac{1}{4} + \frac{1}{(2N)^2}}$

For different values of N we get the family of circles. On a particular circle, the value of N i.e. phase angle α remains constant hence these circles are called constant phase loci or N circles.

Let us calculate center and radius for various values of N. The result is tabulated in the Table

α	N = tan α	Centre $X = -\frac{1}{2}, Y = \frac{1}{2N}$	Radius $R = \sqrt{\frac{1}{4} + \frac{1}{(2N)^2}}$
−90°	∞	$\left(-\frac{1}{2}, 0\right)$	$\frac{1}{2} = 0.5$
−60°	− 1.732	$\left(-\frac{1}{2}, -0.288\right)$	0.577
−30°	− 0.5773	$\left(-\frac{1}{2}, -0.866\right)$	1
−0°	0	$\left(-\frac{1}{2}, \infty\right)$	∞
+30°	0.5773	$\left(-\frac{1}{2}, 0.866\right)$	1
+60°	1.732	$\left(-\frac{1}{2}, 0.288\right)$	0.577
+90°	∞	$\left(-\frac{1}{2}, 0\right)$	$\frac{1}{2} = 0.5$

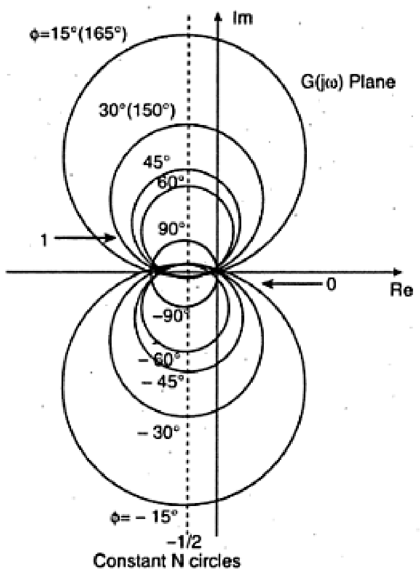


Fig. Constant N Circles

The constant M and N loci in the polar plane is used for both analysis and design of feedback systems. The design problems are conveniently solved in the gain-phase plane (decibel versus phase shift) also. Decibel versus phase shift plot known as Nichol's chart is derived from the constant M and constant N circles. For obtaining the closed loop magnitude and closed loop phase from open loop frequency response, the job is done twice, using M and N circles separately. However, the Nichol's chart incorporates both constant M circles and constant N circles and the closed loop frequency response is obtained at one attempt.

Nichols Chart:

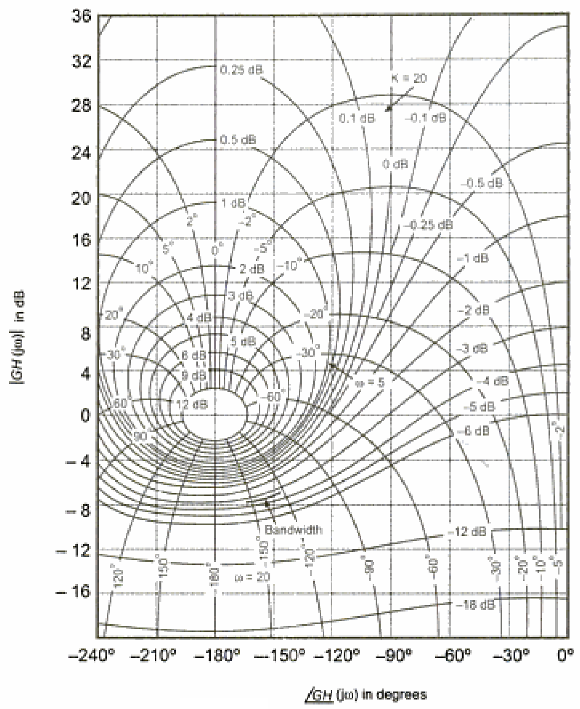
The Nichols chart is a very useful technique for determining stability and the closed-loop frequency response of a feedback system. Stability is determined from a plot of the open-loop gain versus phase characteristics. At the same time, the closed-loop frequency response of the system is determined by utilizing contours of constant closed-loop amplitude and phase shift which are overlaid on the gain-phase plot.

The Nichol's chart is useful for,

1. The complete closed loop frequency response can be obtained.
2. The value of resonant peak M_r of closed loop system with given $G(j\omega)$ can be obtained.
3. The frequency ω_r, corresponding to the M_r for the closed loop system can be obtained.
4. Once M_r and ω_r are known, the various other frequency and time domain specifications can be obtained.
5. The 3 dB bandwidth of the closed loop system can be obtained.
6. To design the value of K for the given M_r
7. To design the compensating networks which are useful to meet more than one specifications for the closed loop system.

Structure of Nichols chart:

It is combination of the M and N circles as given below:



Nichols chart

5. Correlation between frequency domain and time domain specifications

Co-relation between Time Domain and Frequency Domain for Second Order System

Consider a standard second order system with open loop, T.F.

$$G(s) = \frac{\omega_n^2}{s(s+2\xi\omega_n)}, \qquad H(s) = 1$$

T.F. $$G(j\omega) = \frac{\omega_n^2}{j\omega(j\omega+2\xi\omega_n)}, \qquad H(j\omega) = 1.$$

Now the closed loop transfer function in time domain is,

T.F. $$\frac{C(s)}{R(s)} = \frac{\omega_n^2}{s^2+2\xi\omega_n s+\omega_n^2}$$

Derivations of M_r and ω_r

We have seen in the time domain that second order underdamped system shows overshoot M_p at $t = T_p$. Similarly in frequency response, the second order system shows a peak. This is called resonant peak M_r and corresponding frequency is called resonant frequency ω_r.

Now to find resonant peak M_r, similar to M_p we must find input frequency ω which will maximise closed loop T.F. magnitude, which will be ω_r

$$\frac{C(j\omega)}{R(j\omega)} = \frac{\omega_n^2}{(j\omega)^2+2\xi\omega_n j\omega+\omega_n^2} = \frac{\omega_n^2}{-\omega^2+2\xi\omega_n j\omega+\omega_n^2}$$

Dividing by ω_n^2,

$$\frac{C(j\omega)}{R(j\omega)} = \frac{1}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]+2\xi j\frac{\omega}{\omega_n}}$$

Replacing $\frac{\omega}{\omega_n} = x$,

$$\frac{C(j\omega)}{R(j\omega)} = \frac{1}{[1-x^2]+2\xi j x}$$

Now Magnitude $$= \frac{1}{\sqrt{(1-x^2)^2+4\xi^2x^2}}$$

At `x' which will maximise magnitude, we can write ,

$$\frac{dM}{dx} = 0$$

$$\frac{dM}{dx} = \frac{d}{dx}\left[((1-x^2)^2+4\xi^2x^2)^{\frac{-1}{2}}\right]$$

$$= -\frac{1}{2}[(1-x^2)^2+4\xi^2x^2]^{\frac{-3}{2}}\frac{d}{dx}[(1-x^2)^2+4\xi^2x^2]$$

$$= -\frac{1}{2}\frac{1}{[(1-x^2)^2+4\xi^2x^2]^{\frac{3}{2}}}[-4x+4x^3+8\xi^2x] = 0$$

$\therefore\ 4x[x^2+2\xi^2-1] = 0$

$x = 0$ or $x^2+2\xi^2-1 = 0$ i.e. $x^2 = 1-2\xi^2$

$x = \sqrt{1-2\xi^2}$ as $x = 0$ has no pratical significance.

$\therefore\ \frac{\omega}{\omega_n} = \sqrt{1-2\xi^2}$ which maximises M.

UNIT IV STABILITY AND COMPENSATOR DESIGN

Characteristics equation – Routh Hurwitz criterion – Nyquist stability criterion-Performance criteria – Lag, lead and lag-lead networks – Lag/Lead compensator design using bode plots.

stability in a system implies that small changes in the system input, in initial conditions or in system parameters, do not result in large changes in system output. Stability is a very important characteristic of the transient performance of a system. Almost every working system is designed to be stable. Within the boundaries of parameter variations permitted by stability considerations, we can then seek to improve the system performance.

A linear time-invariant system is stable if the following two notions of system stability at satisfied:

(*i*) When the system is excited by a bounded input, the output is bounded.

(*ii*) In the absence of the input, the output tends towards zero (the equilibrium state of the system) irrespective of initial conditions. This stability concept is known as *asymptotic stability*.

Conditions for stability:

(*i*) If all the roots of the characteristic equation have negative real parts, the system is *stable*.

(*ii*) If any root of the characteristic equation has a positive real part or if there is a repeated root on the *jw*-axis, the system is *unstable*.

(*iii*) If the condition (*i*) is satisfied except for the presence of one or more nonrepeated roots on the *jw*-axis, the system is *limitedly stable*.

In further subdivision of the concept of stability, a linear system is characterized as:

(*i*) *Absolutely stable* with respect to a parameter of the system if it is stable for all values of this parameter.

(*ii*) *Conditionally stable* with respect to a parameter, if the system is stable for only certain bounded ranges of values of this parameter.

Relative Stability

In practical systems, it is not sufficient to know that the system is stable but a stable system must meet the specifications on *relative stability* which is a quantitative measure of how fast the transients die out in the system.

Relative stability may be measured by relative settling times of each root or pair of roots. It has been shown in the preceding chapter that the settling time of a pair of complex conjugate poles is inversely proportional to the real part (negative) of the roots. This result is equally valid for real roots.

Certain conclusions regarding the stability of a system can be drawn by merely inspecting the coefficients of its characteristic equation in polynomial form. In the following sections, we shall show that a necessary (but not sufficient) condition for stability of a linear system is that all the coefficients of its characteristic equation $q(s) = 0$, be real and have the same sign. Furthermore, none of the coefficients should be zero.

Consider the characteristic equation

$$q(s) + a_0 s^n + a_1 s^{n-1} + \dots + a_{n-1} s + a_n = 0;\ a_0 > 0$$

It is to be noted that there is no loss of generality in assuming $a_0 > 0$. In case $a_0 < 0$, it can be made positive by multiplying the characteristic equation by – 1 throughout.

1. Characteristics equation:

This represents a method of determining the location of poles of a characteristic equation with respect to the left half and right half of the s-plane without actually solving the equation.

The T.F. of any linear closed loop system can be represented as,

$$\frac{C(s)}{R(s)} = \frac{b_0 s^m + b_1 s^{m-1} + \dots + b_m}{a_0 s^n + a_1 s^{n-1} + \dots + a_n} = \frac{B(s)}{F(s)}$$

where `a' and `b' are constants.

To find closed loop poles we equate F(s) = 0. This equation is called **characteristic equation** of the system.

i.e. $$F(s) = a_0 s^n + a_1 s^{n-1} + a_2 s^{n-2} + \dots + a_n = 0$$

Thus the roots of the characteristic equation are the closed loop poles of the system which decide the stability of the system.

2. Routh Hurwitz criterion:

Routh's Criterion

The necessary and sufficient condition for system to be stable is "All the terms in the first column of Routh's array must have same sign. There should not be any sign change in the first column of Routh's array."

If there are any sign changes existing then,

a) System is unstable.

b) The number of sign changes equals the number of roots lying in the right half of the s-plane.

Example : $s^3 + 6s^2 + 11s + 6 = 0$

Solution : $a_0 = 1, \quad a_1 = 6, \quad a_2 = 11, \quad a_3 = 6, \quad n = 3$

s^3	1	11
s^2	6	6
s^1	$\frac{11 \times 6 - 6}{6} = 10$	0
s^0	6	

As there is no sign change in first column, **system is stable.**

Example : $s^3 + 4s^2 + s + 16 = 0$

Solution : $a_0 = 1, \quad a_1 = 4, \quad a_2 = 1, \quad a_3 = 16$

s^3	1	1
s^2	+ 4	16
s^1	$\frac{4-16}{4} = -3$	0
s^0	+ 16	

As there are two sign changes, **system is unstable.**

Number of roots located in the right half of s-plane = Number of sign changes = 2.

Advantages of Routh's Criterion

Advantages of Routh's array method are :

i) Stability of the system can be judged without actually solving the characteristic equation.

ii) No evaluation of determinants, which saves calculation time.

iii) For unstable system it gives number of roots of characteristic equation having positive real part.

iv) Relative stability of the system can be easily judged.

v) By using this criterion, critical value of system gain can be determined hence frequency of sustained oscillations can be determined.

vi) It helps in finding out range of values of K for system stability.

vii) It helps in finding out intersection points of root locus with imaginary axis.

Limitations of Routh's Criterion

i) It is valid only for real coefficients of the characteristic equation.

ii) It does not provide exact locations of the closed loop poles in left or right half of s-plane.

iii) It does not suggest methods of stabilising an unstable system.

iv) Applicable only to linear systems.

Special Cases

Occasionally, in applying the Routh stability criterion, certain difficulties arise causing the breakdown of the Routh's test. The difficulties encountered are generally of the following types.

Difficulty 1: *When the first term in any row of the Routh array is zero while rest of the row has at least one nonzero term.*

Because of this zero term, the terms in the next row become infinite and Routh's test breaks down. The following methods can be used to overcome this difficulty:

(*a*) Substitute a small positive number ε for the zero and proceed to evaluate the rest of the Routh array. Then examine the signs of the first column of Routh array by letteing $\varepsilon \to 0$.

(*b*) Modify the original characteristic equation by replacing* s by $1/z$. Apply the Routh's test on the modified equation in terms of z. The number of z-roots with positive real parts are the same as the number of s-roots with positive real parts. This method works in most but not all cases.

The following example illustrates these methods.

Example : Consider the characteristic equation

$$s^5 + s^4 + 2s^3 + 2s^2 + 3s + 5 = 0$$

Solution. The Routh array is

$$\begin{array}{c|ccc} s^5 & 1 & 2 & 3 \\ s^4 & 1 & 2 & 5 \\ s^3 & \varepsilon & -2 & \\ s^2 & \dfrac{2\varepsilon + 2}{\varepsilon} & 5 & \\ s^1 & \dfrac{-4\varepsilon - 4 - 5\,\varepsilon^2}{2\,\varepsilon + 2} \rightarrow -2 & & \\ s^0 & 5 & & \end{array}$$

From the Routh array, it is seen that first element in the third row is 0. This is replaced by ε, a small positive number. The first element in the 4th row is now $(2\varepsilon + 2)/\varepsilon$ which has a positive sign as $\varepsilon \rightarrow 0$. (In the Routh stability criterion, we are interested only in the signs of the terms in the first column and not in their magnitudes). The first term of the fifth row is $(-4\varepsilon - 4 - 5\varepsilon^2)/(2\varepsilon + 2)$, which has a limiting value of -2 as $\varepsilon \rightarrow 0$. Examining the terms in the first column of the Routh array, it is found that there are two changes in sign and hence the system is unstable having two poles in the right half s-plane.

Consider now the second method of overcoming the difficulty caused by a zero term in the first column of the Routh array.

Replacing s by $1/z$ in the characteristic equation and rearranging, we get

$$5z^5 + 3z^4 + 2z^3 + 2z^2 + z + 1 = 0$$

The Routh array for this equation is

$$\begin{array}{c|ccc} z^5 & 5 & 2 & 1 \\ z^4 & 3 & 2 & 1 \\ z^3 & -4/3 & -2/3 & \\ z^2 & 1/2 & 1 & \\ z^1 & 2 & & \\ z^0 & 1 & & \end{array}$$

There are two changes of sign in the first column of the Routh array, which tell us that there are two z-roots in the right half z-plane. Therefore the number of s-roots in the right half s-plane is also two.

Example : Consider a sixth-order system with the characteristic equation

$$s^6 + 2s^5 + 8s^4 + 12s^3 + 20s^2 + 16s + 16 = 0$$

The Routh array is

s^6	1	8	20	16
s^5	2	12	16	
s^5	1	6	8	
s^4	2	12	16	
s^4	1	6	8	
s^3	0	0		

Since the terms in the s^3-row are all zero, the Routh's test breaks down. Now the auxiliary polynomial is formed from the coefficients of the s^4-row, which is given by

$$A(s) = s^4 + 6s^2 + 8$$

The derivative of the polynomial with respect to s is

$$4s^3 + 12s + 0 = 4s^3 + 12s$$

The zeros in the s^3-row are now replaced by the coefficients 4 and 12. The Routh array then becomes

s^6	1	8	20	16
s^5	1	6	8	
s^4	1	6	8	
s^3	4	12		
s^3	1	3		
s^2	3	8		
s^1	1/3			
s^0	8			

We see that there is no change of sign in the first column of the new array.

By solving for the roots of auxiliary polynomial

$$s^4 + 6s^2 + 8 = 0$$

we find that the roots are

$$s = \pm j\sqrt{2} \text{ and } s = \pm j2$$

These two pairs of roots are also the roots of the original characteristic equation. Since there is no sign change in the new array formed with the help of the auxiliary polynomial, we conclude that no root of characteristic equation has positive real part. Therefore the system under consideration is limitedly stable.

Example : *For unity feedback system,*

$G(s) = \dfrac{K}{s(1+0.4s)(1+0.25s)}$ *, find range of values of K, marginal value of K and frequency of sustained oscillations.*

Solution : Characteristic equation, $1 + G(s)H(s) = 0$ and $H(s) = 1$

$$\therefore \quad 1+\frac{K}{s(1+0.4s)(1+0.25s)} = 0$$

$$s[1 + 0.65s + 0.1s^2] + K = 0$$

$$\therefore \quad 0.1s^3 + 0.65s^2 + s + K = 0$$

s^3	0.1	1	From s^0, $K > 0$
s^2	0.65	K	From s^1,
s^1	$\frac{0.65-0.1K}{0.65}$	0	$0.65 - 0.1K > 0$ $\therefore\ 0.65 > 0.1\ K$
s^0	K		$\therefore\ 6.5 > K$

$\therefore$ Range of values of K, $0 < K < 6.5$.

The marginal value of `K' is a value which makes any row other than s^0 as row of zeros.

$$\therefore \quad 0.65 - 0.1\,K_{mar} = 0$$

$$\therefore \quad \boxed{K_{mar} = 6.5}$$

To find frequency, find out roots of auxiliary equation at marginal value of `K'.

$$A(s) = 0.65s^2 + K = 0\ ;$$

$$\therefore \quad 0.65s^2 + 6.5 = 0 \qquad \because\ K_{mar} = 6.5$$

$$s^2 = -10$$

$$s = \pm\, \mathbf{j\ 3.162}$$

Comparing with $s = \pm\, j\omega$

ω = Frequency of oscillations

= **3.162 rad/sec.**

Example : *For system $s^4 + 22s^3 + 10s^2 + s + K = 0$, find K_{mar} and ω at K_{mar}.*

Solution :

s^4	1	10	K
s^3	22	1	0
s^2	9.95	K	0
s^1	$\frac{9.95-22K}{9.95}$	0	
s^0	K		

Marginal value of `K' which makes row of s^1 as row of zeros.

$$9.95 - 22\,K_{mar} = 0$$

$$\therefore \quad K_{mar} = \mathbf{0.4524}$$

Hence $\quad A(s) = 9.95s^2 + K = 0$

$$9.95s^2 + 0.4524 = 0$$

$$s^2 = -0.04546$$

$$s = \pm\, j\ 0.2132$$

Hence frequency of oscillations = **0.2132 rad/sec.**

Example : *For a system with characteristic equation*
$F(s) = s^6 + 3s^5 + 4s^4 + 6s^3 + 5s^2 + 3s + 2 = 0$, examine stability.

Solution :

s^6	1	4	5	2
s^5	3	6	3	0
s^4	2	4	2	0
s^3	0	0	0	0

Row of zeros

$$A(s) = 2s^4 + 4s^2 + 2 = 0 \quad \text{i.e.} \quad s^4 + 2s^2 + 1 = 0$$

$$\frac{dA(s)}{ds} = 4s^3 + 4s$$

s^6	1	4	5	2
s^5	3	6	3	0
s^4	2	4	2	0
s^3	4	4	0	0
s^2	2	2	0	0
s^1	0	0	0	0

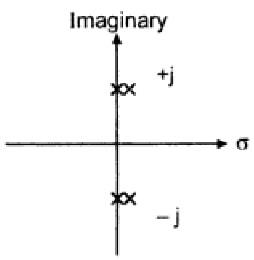
Row of zeros again

$$\therefore \quad A'(s) = 2s^2 + 2 = 0$$

$$\frac{dA'(s)}{ds} = 4s = 0$$

s^6	1	4	5	2
s^5	3	6	3	0
s^4	2	4	2	0
s^3	4	4	0	0
s^2	2	2	0	0
s^1	4	0	0	0
s^0	2	0	0	0

No sign change, hence no root is located in R.H.S. of s-plane. As row of zeros occur, system may be marginally stable or unstable. To examine that find the roots of first auxiliary equation.



$$A(s) = s^4 + 2s^2 + 1 = 0 \qquad s^2 = \frac{-2 \pm \sqrt{4-4}}{2} = -1$$

$$s^2 = -1, \qquad s^2 = -1, \qquad s_{1,2} = \pm j, \qquad s_{3,4} = \pm j$$

The roots of $A'(s) = 0$ are the roots of $A(s) = 0$. So do not solve second auxiliary equation. Predict the stability from the nature of roots of first auxiliary equation.

As there are repeated roots on imaginary axis, system is unstable.

3. Nyquist stability criterion:

Nyquist suggested to select a single valued function F(s) as 1 + G(s) H(s) where G(s) H(s) is open loop transfer function of the system.

$$F(s) = 1 + G(s)\,H(s)$$

Poles of 1 + G(s) H(s) = Poles of G(s) H(s) = open loop poles

These are known to us as G(s) H(s) is known to us

But Zeros of 1 + G(s) H(s) = Closed loop poles of the system.

For stability, all the zeros of 1 + G(s) H(s) must be in the left half of s-plane , none of the zeros should be in the right half of s-plane. Now the locations of zeros of 1 + G(s) H(s) are unknown to us.

In fact we are trying to study the stability by analyzing where these zeros of 1 + G(s) H(s) are located in s-plane.

Nyquist has suggested that rather than analyzing whether all the zeros are located in left half of s-plane, it is better to examine the presence of any one zero of 1 + G(s) H(S) in right half of s-plane making system unstable. Hence the active region from the stability point of view is right half of s-plane. So instead of choosing any arbitrary path $\tau(s)$ in s-plane, Nyquist has suggested to select a $\tau(s)$ path which will encircle the entire right half of s-plane. Such a path should start from $s = +j\infty$. It should be continued till $s = -j\infty$ along imaginary axis and should be completed with a semicircle of radius ∞, encircling entire right half of s-plane as shown in the Fig. This path is called Nyquist path and should not be changed except small modifications , while analyzing stability of any system.

Now as poles of G(s) H(s) are known which are the poles of 1 + G(s) H(s), we know the value of P i.e. poles of 1 + G(s) H(s) which are encircled by Nyquist path.

Now map all the points on the Nyquist path into F -plane with the help of mapping function 1 + G(s) H(s) to get $\tau'(s)$ locus.

This mapped locus obtained in F-plane by mapping all the points on Nyquist path is called Nyquist plot.

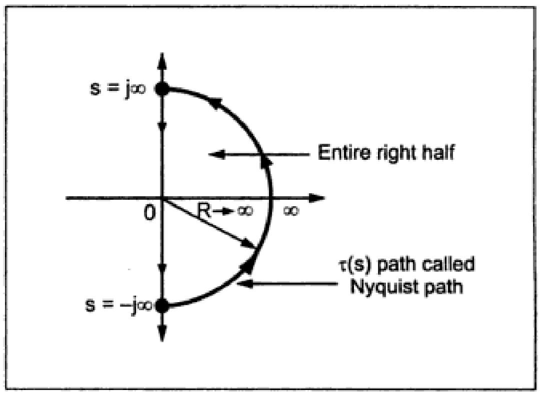


Fig.

As this locus is obtained, we can determine the number of encirclements of origin by Nyquist plot in F-plane, say N.

So N = encirclements of origin of F-plane by Nyquist plot. As per Mapping theorem theses encirclements must satisfy the equation.

$$N = Z - P$$

As N and P are known, we can get Z,

Z = Number of zeros of 1 + G(s) H(s) encircled by Nyquist path in s-plane.

But as Nyquist path encircles only right half of s-plane,

Z = Number of zeros of 1 + G(s) H(s) which are located in right half of s-plane.

For absolute stability, no zero of 1 + G(s) H(s) must be in right half of s-plane i.e. Z = 0 for stability.

So Nyquist stability criterion is obtained by substituting Z = 0 in N = Z – P

i.e $$N = -P$$

Nyquist stability criterion states that for absolute stability of the system, the number of encirclements of new origin of F-plane by Nyquist plot must be equal to number for poles of 1 + G(s) H(s) i.e. poles of G(s) H(S) which are in the right half of s-plane and in clockwise direction .

e.g. if $$G(s)\,H(s) = \frac{10}{s\,(s+1)}$$

Then P = No. of poles of G(s) H(s) which are located in right half of s-plane.

= 0 as there is no pole of G(s) H(s) in right half of s-plane

∴ For stability, $N = -P = 0$

i.e. the Nyquist plot obtained by mapping Nyquist path from s-plane to F-plane should not encircle origin of F -plane.

Note : Now for ease of mapping Nyquist path from s-plane to F -plane, instead of considering mapping function as 1+ G(s)H(s), it is considered as G(s)H(s) only.

But due to this, stability criterion remains the same i.e.

$$N = -P$$

where P = Number of poles of G(s)H(s) in right half of s-plane

But the change is,

N = Number of encirclements of a critical point –1 +j0 of F-plane by Nyquist plot instead of number of encirclements of an origin.

So in all the problems solved hereafter, N is the number of encirclements of a critical point –1+ j0 and not the encirclements of origin as mapping function used is G(s)H(s) and not the function 1 + G(s)H(s).

Generalized Nyquist Path and its Mapping

If the function has poles at origin or poles on the imaginary axis, Nyquist path cannot be selected along imaginary axis passing through origin. This is because mapping theorem states that at every point on Nyquist path, function must be analytic. But at its poles it can not be analytic. In such a case Nyquist path is modified in such a way to bypass these poles by selecting semicircles of radius tending to zero around them but still encircling entire right half of s-plane.

Depending upon the situation of poles of G(s)H(s), Nyquist path should be selected. The guidelines for selection of Nyquist path are given here.

Let F(s) has two poles on imaginary axis at $\pm j\omega_1$ while one pole at origin. Then Nyquist path should be selected as shown in the Fig.

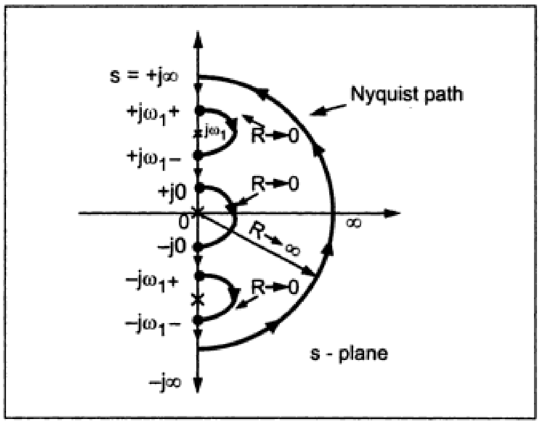


Fig.

The points by which path is modified are :

$+j\omega_1^+$ → A point just above $+j\omega_1$, very very close to $+j\omega_1$,.

$+j\omega_1^-$ → A point which is very very close to $+j\omega_1$, but just below it.

$-j\omega_1^+$ → A point which is very very close to $-j\omega_1$ but just above it.

$-j\omega_1^-$ → A point which is very very close to $-j\omega_1$ but just below it.

+j0 → A point which is very very close to origin but just above it on positive imaginary axis hence denoted as + j0

−j0 → A point which is very very close to origin but just below it on negative imaginary axis hence denoted as −j0.

The various sections of Nyquist path are,

Section	Start	End	Comment
I	$s = +j\infty$	$s = +j\omega_1^+$	Along the imaginary axis.
II	$s = +j\omega_1^+$	$s = +j\omega_1^-$	Along a semicircle of radius tending to zero
III	$s = +j\omega_1^-$	$s = +j0$	Along the imaginary axis.
IV	$s = +j0$	$s = -j0$	Along semicircle of radius tending to zero.
V	$s = -j0$	$s = -j\omega_1^+$	Along the imaginary axis.
VI	$s = -j\omega_1^+$	$s = -j\omega_1^-$	Along semicircle of radius tending to zero.
VII	$s = -j\omega_1^-$	$s = -j\infty$	Along the imaginary axis.
vIII	$s = -j\infty$	$s = +j\infty$	Along the semicircle of $R \to \infty$ encircling entire right half.

Now mapping of these sections in F-plane can be achieved by drawing the polar plots for various sections by shortcut method.

We have $F(s) = G(s)\,H(s)$

$\therefore$ In frequency domain $= G(j\omega)\,H(j\omega)$

Now for section I,

Starting point is $s = +j\infty$ i.e. $\omega = \infty$

Terminating point is $s = +j\omega_1^+$ i.e. $\omega = \omega_1^+$

Substitute to get magnitude and phase angle of $G(j\omega)\,H(j\omega)$ at $\omega = \infty$ and $\omega = \omega_1^+$. Get the rotation of plot and then rotate the starting point through angle of rotation to reach to terminating point. This rough curve gives us mapping of section I in F-plane.

Now for section II, the terminating point of section I becomes starting and using same procedure obtain the mapping of section II.

After mapping all sections, we will get a closed plot called Nyquist plot.

Steps to Solve Problems by Nyquist Criterion

Step 1 : Count how many number of poles of G(s)H(s) are in the right half of s-plane i.e. with positive real part. This is the value of P

Step 2 : Decide the stability criterion as $N = -P$ i.e. how many times Nyquist plot should encircle '$-1 + j0$' point for absolute stability.

Step 3 : Select Nyquist path as per the function G(s)H(s).

Step 4 : Analyse the sections as starting point and terminating point of plot. Last section analysis not required

Step 5 : Mathematically find out ω_{pc} and intersection of Nyquist plot with negative real axis by rationalizing $G(j\omega)\ H(j\omega)$.

Step 6 : With the knowledge of step 4 and 5, sketch the Nyquist plot.

Step 7 : Count the number of encirclements N of $-1 + j0$ by Nyquist plot. If this matches with the criterion decided in step 2 system is stable, otherwise unstable.

$$\text{G.M.} = \frac{1}{|OQ|} \quad \text{where}$$

Q = Intersection point of Nyquist plot with negative real axis obtained in step 5.

i.e.

$$\text{G.M.} = 20 \log_{10} \frac{1}{|OQ|} \text{ dB}$$

EXAMPLE:

For a certain control system

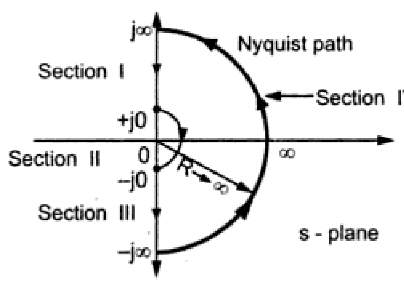
$$G(s)H(s) = \frac{K}{s(s+2)(s+10)}$$

Sketch the Nyquist plot and hence calculate the range of values of K for stability.

Sol. : ***Step 1 :*** $P = 0$

Step 2 : $N = -P = 0$, the critical point $-1 + j0$ should not get encircled by Nyquist plot.

Step 3 : Pole at origin hence Nyquist path is,



Step 4 : $G(j\omega)\,H(j\omega) = \dfrac{K}{j\omega(2+j\omega)(10+j\omega)}$

$$M = |G(j\omega)\,H(j\omega)| = \frac{K}{\omega \times \sqrt{4+\omega^2} \times \sqrt{100+\omega^2}}$$

$$\phi = \frac{\tan^{-1}\left(\frac{0}{K}\right)}{\tan^{-1}\left(\frac{\omega}{0}\right)\tan^{-1}\left(\frac{\omega}{2}\right)\tan^{-1}\left(\frac{\omega}{10}\right)}$$

$$= -90^\circ - \tan^{-1}\frac{\omega}{2} - \tan^{-1}\frac{\omega}{10}$$

Section I : $s = +j\infty$ to $s = +j0$ i.e. $\omega \to \infty$ to $\omega \to +0$

Starting point	$\omega \to \infty$	$0 \angle -270^\circ$	$-90-(-270) = +180^\circ$ Anticlockwise rotation
Terminating point	$\omega \to +0$	$0 \angle +90^\circ$	

Section II : $s = +j0$ to $s = -j0$ i.e. $\omega \to +0$ to $\omega \to -0$

Starting point	$\omega \to +0$	$\infty \angle -90^\circ$	$90-(-90) = +180^\circ$ Anticlockwise rotation
Terminating point	$\omega \to -0$	$\infty \angle +90^\circ$	

G(s) H(s). So just by inspection it is possible to write magnitudes and phase angles of $G(j\omega)\,H(j\omega)$ for extreme values of ω.

Section I : $s = +j\infty$ to $s = 0$ i.e. $\omega \to +\infty$ to $\omega = 0$.

Starting point	$\omega \to +\infty$	$0 \angle -270^\circ$	$0-(-270) = +270^\circ$ Anticlockwise rotation
Terminating point	$\omega \to 0$	$5 \angle 0^\circ$	

Plot will start from origin, tangential to -270° and in anticlockwise direction will rotate through 270° to meet a point $5 \angle 0^\circ$.

Section II is mirror image of section I ut real xis

Section III not required.

Step 5 : $$G(j\omega)\,H(j\omega) = \frac{40}{(4+j\omega)(2-\omega^2+2j\omega)}$$

Rationalising,

$$G(j\omega)\,H(j\omega) = \frac{40\,(4-j\,\omega)\;[(2-\omega^2)-2j\,\omega]}{(4+j\,\omega)\,(4-j\,\omega)\,[(2-\omega^2)+2\,j\,\omega]\;[(2-\omega^2)-2\,j\omega]}$$

$$= \frac{40\,[8-4\omega^2-8\,j\omega-2\,j\omega+j\omega^3-2\omega^2]}{(16+\omega^2)\;[(2-\omega^2)^2+4\omega^2]}$$

$$= \frac{40\,(8-6\omega^2)}{D}+j\,\frac{\omega\,(\omega^2-10)}{D}$$

Equating imaginary part to zero,

$$\omega(\omega^2-10) = 0$$

$$\therefore \quad \omega^2 = 10 \quad \text{and}$$

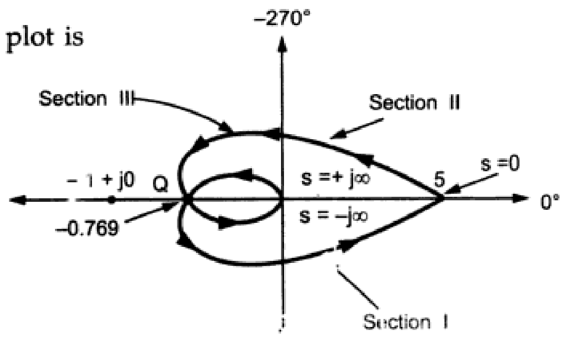
$$\omega_{pc} = \sqrt{10}$$

Substituting in real part,

$$\text{Point Q} = \frac{40\times(8-6\times 10)}{(16+10)\,[(2-10)^2+4\times 10]}$$

$$\therefore \quad Q = -0.769$$

Step 6 : Nyquist plot is



4. Performance criteria – Lag, lead and lag-lead networks

A compensator is a component in a control system that improves an undesirable frequency response in a feedback and control system. It is a fundamental building block in classical control theory.

Compensators influence disciplines as varied as robotics, satellite control, automobile diagnostics, and laser frequency stabilization. They are an important building block in analog control systems, and can also be used in digital control.

Given the control plant, desired specifications can be achieved using compensators. I, D, PI, PD, and PID, are optimizing controllers which are used to improve system parameters (such as reducing steady state error, reducing resonant peak, improving system response by reducing rise time). All these operations can be done by compensators as well.

Both lead compensators and lag compensators introduce a pole–zero pair into the open loop transfer function. The transfer function can be written in the Laplace domain as

$$\frac{Y}{X} = \frac{s+z}{s+p}$$

where X is the input to the compensator, Y is the output, s is the complex Laplace transform variable, z is the zero frequency and p is the pole frequency. The pole and zero are both typically negative, or left of the zero in the complex plane. In a lead compensator, $|z| < |p|$, while in a lag compensator $|z| > |p|$.

A lead-lag compensator consists of a lead compensator cascaded with a lag compensator. The overall transfer function can be written as

$$\frac{Y}{X} = \frac{(s+z_1)(s+z_2)}{(s+p_1)(s+p_2)}.$$

Typically $|p_1| > |z_1| > |z_2| > |p_2|$, where z_1 and p_1 are the zero and pole of the lead compensator and z_2 and p_2 are the zero and pole of the lag compensator. The lead compensator provides phase lead at high frequencies. This shifts the poles to the left, which enhances the responsiveness and stability of the system. The lag compensator provides phase lag at low frequencies which reduces the steady state error.

The precise locations of the poles and zeros depend on both the desired characteristics of the closed loop response and the characteristics of the system being controlled. However, the pole and zero of the lag compensator should be close together so as not to cause the poles to shift right, which could cause instability or slow convergence. Since their purpose is to affect the low frequency behaviour, they should be near the origin.

All the control systems are designed to achieve specific objectives. The certain requirements are defined for the control system. A good control system has less error, good accuracy, good speed of response, good relative stability, good damping which will not cause undue overshoots etc. For satisfactory performance of the system, gain is adjusted first. In practice, adjustment of gain alone can not provide satisfactory results. This is because when gain is increased, steady state behaviour of the system improves but results into poor transient response, in some cases may even instability. In such cases it is necessary to redesign the entire system. Thus the design of control systems is a challenging job. Practically the design specifications are provided interms of precise numerical values according to which the system is designed. The set of such specifications include peak overshoot, peak time, damping ratio, natural frequency of oscillations, error coefficients, gain margin, phase margin etc.

Types of Compensation

An external device, compensator can be introduced in a system anywhere as per the convenience and the requirement. Depending upon where the compensator is introduced in a system, the various types of compensation are,

1. Series compensation
2. Parallel compensation
3. Series-parallel compensation

1 Series Compensation

The compensator is a physical device whose transfer function is denoted as $G_c(s)$. If the compensator is placed in series with the forward path transfer function of the plant, the scheme is called **series compensation.** The arrangement is shown in the Fig. 1.

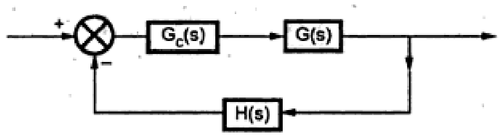


Fig. 1 Series compensation

This scheme is also called cascade compensation. The flow of signal in such a series scheme is from lower energy level towards higher energy level. This requires additional amplifiers to increase the gain and also to provide necessary isolation. The number of components required in series scheme is more than in parallel scheme.

2 Parallel Compensation

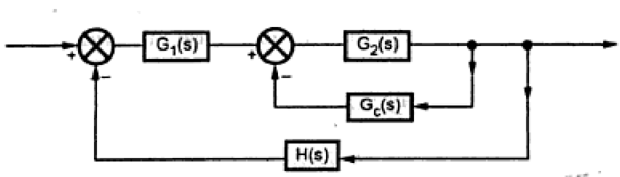


Fig. 2 Parallel compensation

In some cases, the feedback is taken from some internal element and compensator is introduced in such a feedback path to provide an additional internal feedback loop. Such compensation is called **feedback compensation** or **parallel compensation.** The arrangement is shown in the Fig. 2.

The energy transfer in such parallel scheme is from higher energy level towards lower energy level point. Hence in such scheme the additional amplifiers are not required. Thus the number of components required are less than required in the series scheme.

3 Series-Parallel Compensation

In some cases, it is necessary to provide both types of compensations, series as well as feedback. Such a scheme is called **series-parallel compensation.** The arrangement is shown in the Fig. 3.

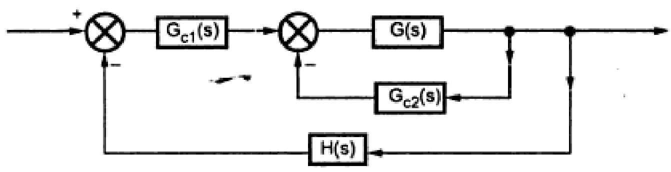


Fig. 3 Series-parallel compensation

The selection of the proper compensation scheme depends on the nature of the signals available in the system, the power levels at the various points, available components, the economic considerations, and the designer's experience.

Compensating Networks

The compensator is a physical device. It may be an electrical network, mechanical unit, pneumatic, hydraulic or combinations of various types of devices. In this chapter we are going to study the electrical networks which are used for series compensation.

The commonly used electrical compensating networks are,

1. Lead network or Lead compensator
2. Lag network or Lag compensator
3. Lag-lead network or Lag-lead compensator

When a sinusoidal input is applied to a network and it produces a sinusoidal steady state output having a phase lead with respect to input then the network is called **lead network**. If the steady state output has phase lag then the network is called **lag network**. In the lag-lead network both phase lag and lead occur but in the different frequency regions.

Lead Compensator

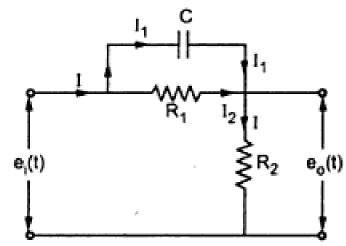


Fig. Lead network

Consider an electrical network which is a lead compensating network, as shown in the Fig.

Let us obtain the transfer function of such an electrical lead network. Assuming unloaded circuit and applying KCL for the output node we can write,

$$I_1 + I_2 = I$$

$$C\frac{d(e_i - e_o)}{dt} + \frac{1}{R_1}(e_i - e_o) = \frac{1}{R_2}e_o$$

Taking Laplace transform of the equation,

$$sC\,E_i(s) - sC\,E_o(s) + \frac{1}{R_1}E_i(s) - \frac{1}{R_1}E_o(s) = \frac{1}{R_2}E_o(s)$$

$$\therefore \quad E_i(s)\left[sC + \frac{1}{R_1}\right] = E_o(s)\left[sC + \frac{1}{R_1} + \frac{1}{R_2}\right]$$

$$\therefore \quad \frac{E_o(s)}{E_i(s)} = \frac{R_1R_2}{R_1 + R_2 + R_1R_2\,sC} \cdot \frac{1 + sCR_1}{R_1}$$

$$\therefore \quad \frac{E_o(s)}{E_i(s)} = \frac{\left(s + \frac{1}{R_1C}\right)}{s + \frac{(R_1 + R_2)}{R_1R_2C}} = \frac{\left(s + \frac{1}{R_1C}\right)}{\left[s + \frac{1}{\left(\frac{R_2}{R_1 + R_2}\right)R_1C}\right]}$$

This is generally expressed as,

$$\frac{E_o(s)}{E_i(s)} = \frac{s + \frac{1}{T}}{s + \frac{1}{\alpha T}}$$

where $T = R_1C$ and $\alpha = \frac{R_2}{R_1 + R_2} < 1$

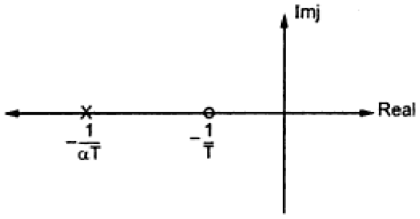


Fig.

The lead compensator has zero at $s = -\frac{1}{T}$ and a pole at $s = -\frac{1}{\alpha T}$.

As $0 < \alpha < 1$, the zero is always located to the right of the pole. The pole zero plot is shown in the Fig. The minimum value of α is generally taken as 0.05.

Effects of Lead Compensation

The various effects of a lead compensation are,

1. The lead compensator adds a dominant zero and a pole. This increases the damping of the closed loop system.
2. The increased damping means less overshoot, less rise time and less settling time. Thus there is improvement in the transient response.
3. It improves the phase margin of the closed loop system.

Lag-Lead Compensator

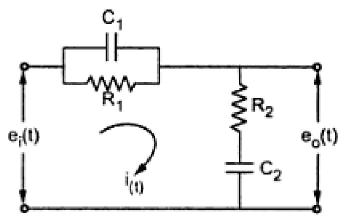


Fig. Lag-lead network

A combination of a lag and lead compensators is nothing but a lag-lead compensator. Consider an electrical network which is lag-lead network, as shown in the Fig.

Let us obtain the transfer function of the electrical lag-lead network.

Now sum of the current through R_1 and C_1 is nothing but current i(t).

$$\therefore \quad \frac{e_i - e_o}{R_1} + C_1 \frac{d\,(e_i - e_o)}{dt} = i(t)$$

Taking Laplace transform we get,

$$\frac{1}{R_1} E_i(s) - \frac{1}{R_1} E_o(s) + sC_1 E_i(s) - sC_1 E_o(s) = I(s) \quad \ldots(1)$$

The output equation is,

$$i(t) R_2 + \frac{1}{C_2} \int i(t)\, dt = e_o(t)$$

Taking Laplace transform,

$$I(s)\left[R_2 + \frac{1}{sC_2}\right] = E_o(s) \quad \ldots(2)$$

Substituting I (s) from (1) in (2) we get,

$$\left\{ E_i(s)\left[\frac{1}{R_1} + sC_1\right] - E_o(s)\left[\frac{1}{R_1} + sC_1\right]\right\}\left[R_2 + \frac{1}{sC_2}\right] = E_o(s)$$

$$\therefore \quad \frac{E_i(s)\,(1 + sR_1C_1) - E_o(s)(1 + sR_1C_1)}{R_1} \cdot \frac{(1 + sR_2C_2)}{sC_2} = E_o(s)$$

$$\therefore \quad E_i(s)\,\frac{(1 + sR_1C_1)\,(1 + sR_2C_2)}{sR_1C_2} = E_o(s)\left[1 + \frac{(1 + sR_1C_1)\,(1 + sR_2C_2)}{sR_1C_2}\right]$$

$$\therefore \quad \frac{E_o(s)}{E_i(s)} = \frac{(1+sR_1C_1)(1+sR_2C_2)}{sR_1C_2+(1+sR_1C_1)(1+sR_2C_2)}$$

$$\therefore \quad \frac{E_o(s)}{E_i(s)} = \frac{(1+sR_1C_1)(1+sR_2C_2)}{s^2 R_1R_2C_1C_2+s\,[R_1C_1+R_2C_2+R_1C_2]+1}$$

$$\therefore \quad \frac{E_o(s)}{E_i(s)} = \frac{R_1R_2C_1C_2\left(s+\frac{1}{R_1C_1}\right)\left(s+\frac{1}{R_2C_2}\right)}{R_1R_2C_1C_2\left[s^2+s\left(\frac{1}{R_1C_1}+\frac{1}{R_2C_2}+\frac{1}{R_2C_1}\right)+\frac{1}{R_1R_2C_1C_2}\right]}$$

$$\therefore \quad \frac{E_o(s)}{E_i(s)} = \frac{\left(s+\frac{1}{T_1}\right)\left(s+\frac{1}{T_2}\right)}{\left(s+\frac{\beta}{T_1}\right)\left(s+\frac{1}{\beta T_2}\right)} \qquad \ldots(3)$$

where $T_1 = R_1C_1, \quad T_2 = R_2C_2$

$$\frac{\beta}{T_1}+\frac{1}{\beta T_2} = \frac{1}{R_1C_1}+\frac{1}{R_2C_2}+\frac{1}{R_2C_1}$$

$$\alpha\,\beta\,T_1T_2 = R_1R_2C_1C_2$$

$$\alpha\,\beta = 1$$

It also can be expressed as,

$$\boxed{\frac{E_o(s)}{E_i(s)} = \frac{(1+T_1s)(1+T_2s)}{\left(1+\frac{T_1}{\beta}s\right)(1+T_2\beta s)}} \qquad \ldots(4)$$

where $\beta > 1$

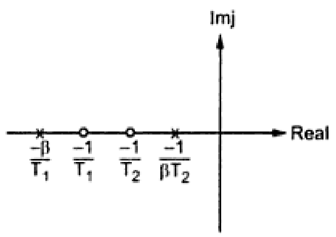


Fig.

The phase lead portion involving T_1, adds phase lead angle while the phase lag portion involving T_2 provide attenuation near and above the gain crossover frequency.

The pole are $s = -\frac{\beta}{T_1}, -\frac{1}{\beta T_2}$ while the zeros are at $s = -\frac{1}{T_1}, -\frac{1}{T_2}$. The pole-zero plot for the lag-lead compensator is shown in the Fig.

5. *Lag/Lead compensator design using bode plots:*

PROCEDURE FOR THE DESIGN OF LAG COMPENSATOR USING BODE PLOT

The following steps may be followed to design a lag compensator using bode plot and to be connected in series with transfer function of uncompensated system, G(s).

Step-1 : Choose the value of K in uncompensated system to meet the steady state error requirement.

Step-2 : Sketch the bode plot of uncompensated system. *[Refer Appendix-I for the procedure to sketch bode plot].*

Step-3 : Determine the phase margin of the uncompensated system from the bode plot. If the phase margin does not satisfy the requirement then lag compensation is required.

Step-4 : Choose a suitable value for the phase margin of the compensated system.

Let, γ_d = Desired phase margin as given in specifications.

and γ_n = Phase margin of compensated system.

Now, $\gamma_n = \gamma_d + \epsilon$

Where ϵ = Additional phase lag to compensate for shift in gain crossover frequency.

Choose an initial value of $\epsilon = 5°$.

Step-5 : Determine the new gain crossover frequency, ω_{gcn}. The new ω_{gcn} is the frequency corresponding to a phase margin of γ_n on the bode plot of uncompensated system.

Let, ϕ_{gcn} = Phase of G(jω) at new gain crossover frequency, ω_{gcn}

Now, $\gamma_n = 180° + \phi_{gcn}$ (or) $\phi_{gcn} = \gamma_n - 180°$

The new gain crossover frequency, ω_{gcn} is given by the frequency at which the phase of G(jω) is ϕ_{gcn}.

Step-6 : Determine the parameter, β of the compensator. The value of β is given by the magnitude of G(jω) at new gain crossover frequency, ω_{gcn}. Find the db gain (A_{gcn}) at new gain crossover frequency, ω_{gcn}

Now, $A_{gcn} = 20\log\beta$ (or) $\dfrac{A_{gcn}}{20} = \log\beta$, $\quad\therefore \beta = 10^{A_{gcn}/20}$

Step-7 : Determine the transfer function of lag compensator.

Place the zero of the compensator arbitrarily at 1/10th of the new gain crossover frequency, ω_{gcn}.

$$\therefore \text{Zero of the lag compensator, } z_c = \frac{1}{T} = \frac{\omega_{gcn}}{10}$$

$$\text{Now, } T = \frac{10}{\omega_{gcn}}.$$

Pole of the lag compensator, $p_c = 1/\beta T$

$$\left.\begin{matrix}\text{Transfer function}\\ \text{of lag compensator}\end{matrix}\right\} G_c(s) = \frac{s+\frac{1}{T}}{s+\frac{1}{\beta T}} = \beta\left(\frac{1+sT}{1+s\beta T}\right)$$

Step-8 : Determine the open loop transfer function of compensated system. The lag compensator is connected in series with the plant as shown in fig 1.7.

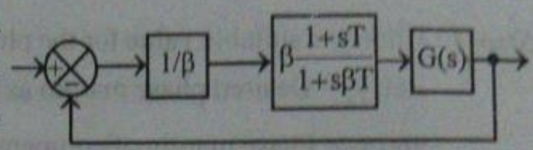


Fig 1.7 : Block diagram of lag compensated system

When the lag compensator is inserted in series with the plant, the open loop gain of the system is amplified by the factor $\beta(\because \beta>1)$. If the gain produced is not required then attenuator with gain $1/\beta$ can be introduced in series with the lag compensator to nullify the gain produced by lag compensator.

The open loop transfer function of the compensated system,

$$G_o(s) = \frac{1}{\beta}.G_c(s).G(s) = \frac{1}{\beta}.\beta\frac{(1+sT)}{(1+s\beta T)}.G(s) = \frac{(1+sT)}{(1+s\beta T)}\;.\;G(s)$$

Step-9 : Determine the actual phase margin of compensated system. Calculate the actual phase angle of the compensated system using the compensated transfer function at new gain crossover frequency, ω_{gcn}.

Let, ϕ_{gco} = Phase of $G_o(j\omega)$ at $\omega = \omega_{gcn}$

Actual phase margin of the compensated system, $\gamma_o = 180° + \phi_{gco}$

If the actual phase margin satisfies the given specification then the design is accepted. Otherwise repeat the procedure from step 4 to 10 by taking $\in$ as 5° more than previous design.

EXAMPLE

The open loop transfer function of certain unity feedback control system is given by $G(s) = K/s(s+4)(s+80)$. It is desired to have the phase margin to be atleast 33° and the velocity error constant $K_v = 30\ sec^{-1}$. Design a phase lag series compensator.

SOLUTION

Step-1 : Calculation of gain, K

Given that, $K_v = 30\ sec^{-1}$

By definition of velocity error constant, $K_v = \underset{s\to0}{Lt}\ s\,G(s)\,H(s)$

Since the system is unity feedback system, $H(s) = 1$.

$$\therefore K_v = \underset{s\to0}{Lt}\ sG(s) = \underset{s\to0}{Lt}\ s\frac{K}{s(s+4)(s+80)} = \frac{K}{4\times80}$$

i.e., $\frac{K}{4\times80} = 30, \quad \therefore K = 30\times80\times4 = 9600.$

Step-2 : Bode plot of uncompensated system

$$G(s) = \frac{9600}{s(s+4)(s+80)} = \frac{9600/4\times80}{s(1+\frac{s}{4})(1+\frac{s}{80})} = \frac{30}{s(1+0.25s)(1+0.0125s)}$$

$$\text{Let } s = j\omega, \therefore G(j\omega) = \frac{30}{j\omega(1+j0.25\omega)(1+j0.0125\omega)}$$

Magnitude plot

The corner frequencies are, $\omega_{c1} = 1/0.25 = 4$ rad/sec and $\omega_{c2} = 1/0.0125 = 80$ rad/sec. The various terms of $G(j\omega)$ are listed in table-1. Also the table shows the slope contributed by each term and the change in slope at the corner frequency.

TABLE-1

Term	Corner frequency rad/sec	Slope db/dec	Change in slope db/dec
$\frac{30}{j\omega}$	-	–20	-
$\frac{1}{1+j0.25\omega}$	$\omega_{c1} = \frac{1}{0.25} = 4$	–20	–20–20 = –40
$\frac{1}{1+j0.0125\omega}$	$\omega_{c2} = \frac{1}{0.0125} = 80$	–20	–40–20 = –60

Choose a low frequency ω_l such that $\omega_l < \omega_{c2}$ and choose a high frequency ω_h such that $\omega_h > \omega_{c2}$. Let $\omega_l = 1$ rad/sec and $\omega_h = 100$ rad/sec.

Let $A = |G(j\omega)|$ in db

At $\omega = \omega_l$, $A = 20\log\left|\frac{30}{j\omega}\right| = 20\log\frac{30}{1} = 29.5 \text{ db} \approx 30 \text{ db}$

At $\omega = \omega_{c1}$, $A = 20\log\left|\frac{30}{j\omega}\right| = 20\log\frac{30}{4} = 17.5 \text{ db} \approx 18 \text{ db}$

At $\omega = \omega_{c2}$, $A = \left[\text{slope from } \omega_{c1} \text{ to } \omega_{c2} \times \log\frac{\omega_{c2}}{\omega_{c1}}\right] + A_{(\text{at } \omega = \omega_{c1})}$

$$= -40\log\frac{80}{4} + 18 = -34 \text{ db}$$

At $\omega = \omega_h$, $A = \left[\text{slope from } \omega_{c2} \text{ to } \omega_h \times \log\frac{\omega_h}{\omega_{c2}}\right] + A_{(\text{at } \omega = \omega_{c2})}$

$$= -60 \times \log\frac{100}{80} + (-34) = -40 \text{ db}$$

Let the points a, b, c and d be the points corresponding to frequencies ω_l, ω_{c1}, ω_{c2} and ω_h respectively on the magnitude plot. In a semilog graph sheet choose appropriate scales and fix the points a, b, c and d. Join the points by straight lines and mark the slope on the respective region. The magnitude plot is shown in fig 1.2.1.

Phase Plot

The phase angle of $G(j\omega)$ as a function of ω is given by

$$\phi = \angle G(j\omega) = -90° - \tan^{-1}0.25\omega - \tan^{-1}0.0125\omega$$

The phase angle of $G(j\omega)$ are calculated for various values of ω and listed in table-2.

TABLE-2

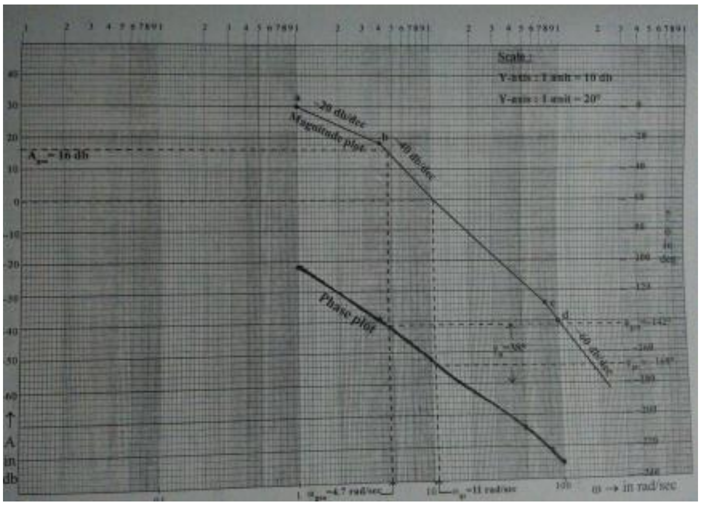
ω rad/sec	1	4	10	50	80	100
ϕ deg	−104	−138	$-165 \approx -164$	$-207 \approx -208$	−222	$-229 \approx -230$

On the same semilog sheet take another y-axis, choose appropriate scale and draw phase plot as shown in fig 1.2.1.

Step-3: Determination of phase margin of uncompensated system.

Let, ϕ_{gc} = Phase of $G(j\omega)$ at gain crossover frequency (ω_{gc}).

and γ = Phase margin of uncompensated system.



From the bode plot of uncompensated system we found that, $\phi_{gc} = -168°$.

Now, $\gamma = 180° + \phi_{gc} = 180° - 168° = 12°$

The system requires a phase margin of atleast 33°, but the available phase margin is 12° and so lag compensation should be employed to improve the phase margin.

Step-4 : Choose a suitable value for the phase margin of compensated system.

The desired phase margin, $\gamma_d = 33°$.

$\therefore$ Phase margin of compensated system, $\gamma_n = \gamma_d + \epsilon$

Let initial choice of $\epsilon = 5°$; $\therefore \gamma_n = \gamma_d + \epsilon = 33° + 5° = 38°$

Step 5 : Determine new gain crossover frequency.

Let ω_{gcn} = New gain crossover frequency and ϕ_{gcn} = Phase of $G(j\omega)$ at ω_{gcn}

Now, $\gamma_n = 180° + \phi_{gcn}$

$\therefore \phi_{gcn} = \gamma_n - 180° = 38° - 180° = -142°$

From the bode plot we found that, the frequency corresponding to a phase of −142° is 4.7 rad/sec.

$\therefore$ New gain crossover frequency, $\omega_{gcn} = 4.7$ rad/sec.

Step-6 : Determine the parameter, β

From the bode plot we found that, the db magnitude at ω_{gcn} as 16 db.

$\therefore |G(j\omega)|$ in db at $(\omega = \omega_{gcn}) = A_{gcn} = 16$ db

Also, $A_{gcn} = 20 \log \beta$; $\therefore \beta = 10^{A_{gcn}/20} = 10^{16/20} = 6.3$.

Step-7: Determine the transfer function of lag compensator.

The zero of the compensator is placed at a frequency one-tenth of ω_{gcn}.

$$\therefore \text{Zero of the lag compensator, } z_c = \frac{1}{T} = \frac{\omega_{gcn}}{10}$$

$$\text{Now, } T = \frac{10}{\omega_{gcn}} = \frac{10}{4.7} = 2.13$$

$$\text{Pole of the lag compensator, } p_c = \frac{1}{\beta T} = \frac{1}{6.3 \times 2.13} = \frac{1}{13.419}$$

$$\left.\begin{matrix}\text{Transfer function} \\ \text{of lag compensator}\end{matrix}\right\} G_c(s) = \frac{s + \frac{1}{T}}{s + \frac{1}{\beta T}} = \beta \frac{1 + sT}{1 + s\beta T} = 6.3 \frac{(1 + 2.13s)}{(1 + 13.419s)}$$

Step-8 : Determine the open loop transfer function of the compensated system.

The block diagram of the compensated system is shown in fig 1.2.2. The gain of the compensator is nullified by introducing an attenuator in series with the compensator, as shown in fig 1.2.2.

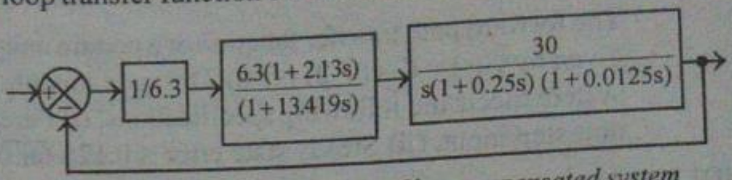


Fig 1.2.2 : Block diagram of lag compensated system

$$\left.\begin{matrix}\text{Open loop transfer function} \\ \text{of compensated system}\end{matrix}\right\} G_o(s) = \frac{1}{6.3} \times \frac{6.3\,(1 + 2.13s)}{(1 + 13.419s)} \times \frac{30}{s(1 + 0.25s)\,(1 + 0.0125s)}$$

$$= \frac{30\,(1 + 2.13s)}{s\,(1 + 13.419s)\,(1 + 0.25s)\,(1 + 0.0125s)}$$

Example : *Consider a type 1 unit feedback system with an OLTF* $G_f = \frac{K}{s(s+1)}$. *It is specified that* $K_v = 12\ sec^{-1}$ *and* $\phi_{PM} = 40^{\circ}$. *Design lead compensator to meet the specifications.*

Solution :

Step 1 :

Lead compensator $G_c(s) = K_c\ \alpha\ \frac{(1+Ts)}{(1+\alpha Ts)} = \frac{K(1+Ts)}{(1+\alpha\, Ts)}$

$$\therefore \qquad G_c(s)G(s) = \frac{(1+Ts)}{(1+\alpha Ts)} \times \frac{K}{s\,(s+1)} \quad \text{where } G(s) = \frac{1}{s\,(s+1)}$$

$$\text{Now} \qquad K_v = \lim_{s\to 0} sG_c(s)\, G(s) = \lim_{s\to 0} \frac{K}{s(s+1)} \frac{(1+Ts)}{(1+Ts)} = K$$

$$\therefore \qquad K = 12$$

$$\therefore \qquad G_1(s) = \frac{12}{s(s+1)}$$

Step 2 : Sketch the Bode plot of $G_1(s)$ i.e. uncompensated system as shown in the Fig.

Factors : K = 12 i.e. 20 Log K = 21.58 ≈ 22 dB

1. Pole at the origin i.e. – 20 dB/dec

1 simple pole with $\omega_{c1} = 1$ i.e. – 20 dB/dec for $\omega > 1$.

So resultant starting slope – 20 dB/dec and then – 40 dB/dec for $\omega > 1$.

Phase angle table : $G_1(j\omega) = \frac{12}{j\omega(1+j\omega)}$

ω	$\frac{1}{j\omega}$	$-\tan^{-1}\omega$	ϕ_R
0.1	– 90°	– 5.71°	– 95.71°
1	– 90°	– 45°	– 135°
2	– 90°	– 63.43°	– 153.43°
∞	– 90°	– 90°	– 180°

From the plot, ϕ_1 = P.M. = 15°, ω_{gc} = 3.5 rad/sec, G.M. = + ∞ dB

Step 3 : $\phi_s = 40°$ (given) i.e. given P.M.

$$\therefore \qquad \phi_m = \phi_s - \phi_1 + \varepsilon, \text{ Let } \varepsilon = 8°$$

$$= 40° - 15° + 8° = 33°$$

Step 4 : $\sin\phi_m = \frac{1-\alpha}{1+\alpha} = \sin 33° = 0.5446$

$$\therefore \qquad 1 - \alpha = 0.5446\,(1+\alpha)$$

$$\therefore \qquad \alpha = 0.2948$$

Choose α = **0.3**

Step 5 : $-\ 10 \text{ Log}\left(\frac{1}{\alpha}\right) = -\ 5.23$ dB

Find the frequency from the Fig. 13.36(a), which gain of uncompensated system is – 5.23 dB, which is ω_m.

Find the frequency from the Fig. 13.36(a), which gain of uncompensated system is – 5.23 dB, which is ω_m.

$$\therefore \qquad \omega_m = \mathbf{5.8\ rad/sec}$$

$$\text{But} \qquad \omega_m = \frac{1}{T\sqrt{\alpha}}$$

$$\therefore \qquad T = 0.3147 \quad \text{i.e} \quad \frac{1}{T} = 3.176$$

Step 6 : Two corner frequencies of lead compensator are,

$$\omega_{c1} = \frac{1}{T} = 3.176 \quad \omega_{c2} = \frac{1}{\alpha T} = \frac{1}{0.0944} = 10.6$$

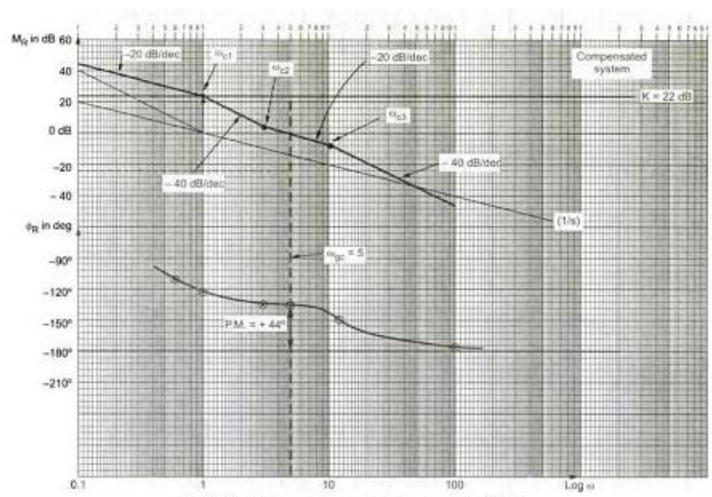
Step 7 : $$K = K_c\,\alpha$$

$$\therefore \qquad K_c = \frac{K}{\alpha} = \frac{12}{0.3} = 40$$

Step 8 : $$G_c(s) = \frac{40 \times 0.3 \times (1 + 0.3147\,s)}{(1 + 0.0944\,s)}$$

$$\therefore \qquad \boxed{G_c(s)G(s) = \frac{12(1 + 0.3147\,s)}{s(1 + 0.0944\,s)\,(1 + s)}}$$

Draw the Bode plot for new specifications.



Finally we can check the new Gain margin and phase margin values.

UNIT V STATE VARIABLE ANALYSIS

Concept of state variables – State models for linear and time invariant Systems – Solution of state and output equation in controllable canonical form – Concepts of controllability and observability – Effect of state feedback.

1. Concept of state variables:

The conventional approach used to study the behaviour of linear time invariant control systems, uses the time domain or frequency domain methods. In all these methods, the systems are modelled using transfer function approach, which is the ratio of Laplace transform of output to input, neglecting all the initial conditions. Thus this conventional analysis faces all the limitations associated with the transfer function approach.

Some of its limitations can be stated as :

1) Naturally, significant initial conditions in obtaining precise solution of any system, loose their importance in conventional approach.
2) The method is insufficient and troublesome to give complete time domain solution of higher order systems.
3) It is not very much convenient for the analysis of Multiple Input Multiple Output systems.
4) It gives analysis of system for some specific types of inputs like Step, Ramp etc.
5) It is only applicable to Linear Time Invariant Systems.
6) The classical methods like Root locus, Bode plot etc. are basically trial and error procedures which fail to give the optimal solution required.

Advantages of State Variable Analysis

The various advantages of state variable analysis are,

1) The method takes into account the effect of all initial conditions.
2) It can be applied to nonlinear as well as time varying systems.
3) It can be conveniently applied to Multiple Input Multiple Output systems.
4) The system can be designed for the optimal conditions precisely by using this modern method.
5) Any type of the input can be considered for designing the system.
6) As the method involves matrix algebra, can be conveniently adopted for the digital computers.
7) The state variables selected need not necessarily be the physical quantities of the system.
8) The vector matrix notation greatly simplifies the mathematical representation of the system.

Important Definitions

1) **State** : The state of a dynamic system is defined as a minimal set of variables such that the knowledge of these variables at $t = t_0$ together with the knowledge of the inputs for $t \geq t_0$, completely determines the behaviour of the system for
$t > t_0$.

2) **State Variables** : The variables involved in determining the state of a dynamic system X(t), are called the state variables. $X_1(t)$, $X_2(t)$ ......$X_n(t)$ are nothing but the state variables. These are normally the energy storing elements contained in the system.

3) **State Vector** : The `n' state variables necessary to describe the complete behaviour of the system can be considered as `n' components of a vector X(t) called the state vector at time `t'. The state vector X(t) is the vector sum of all the state variables.

4) **State Space** : The space whose co-ordinate axes are nothing but the `n' state variables with time as the implicit variable is called the state space.

5) **State Trajectory** : It is the locus of the tips of the state vectors, with time as the implicit variable.

State Model of Linear Systems

Consider Multiple Input Multiple Output, nth order system as shown in the Fig.

Number of inputs = m

Number of outputs = p

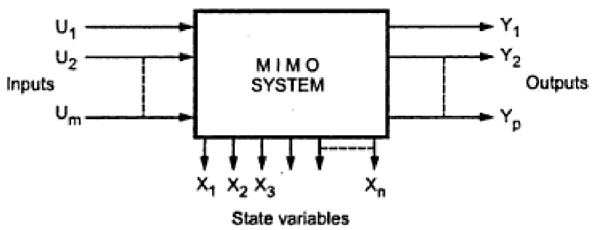


Fig.

$$U(t) = \begin{bmatrix} U_1(t) \\ U_2(t) \\ : \\ : \\ U_m(t) \end{bmatrix}, \quad X(t) = \begin{bmatrix} X_1(t) \\ X_2(t) \\ : \\ : \\ X_n(t) \end{bmatrix}, \quad Y(t) = \begin{bmatrix} Y_1(t) \\ Y_2(t) \\ : \\ : \\ Y_p(t) \end{bmatrix}$$

All are column vectors having orders $m \times 1$, $n \times 1$ and $p \times 1$ respectively.

For such a system, the state variable representation can be arranged in the form of 'n' first order differential equations.

$$\frac{dX_1(t)}{dt} = \dot{X}_1(t) = f_1(X_1, X_2, \ldots\ldots X_n, U_1, U_2 \ldots\ldots\ldots U_m)$$

$$\frac{dX_2(t)}{dt} = \dot{X}_2(t) = f_2(X_1, X_2, \ldots\ldots X_n, U_1, U_2 \ldots\ldots\ldots U_m)$$

$$:$$

$$:$$

$$\frac{dX_n(t)}{dt} = \dot{X}_n(t) = f_n(X_1, X_2, \ldots\ldots X_n, U_1, U_2 \ldots\ldots\ldots U_m)$$

Where $f = \begin{bmatrix} f_1 \\ f_2 \\ : \\ : \\ f_n \end{bmatrix}$ is the functional operator.

Integrating the above equation,

$$X_i(t) = X_i(t_0) + \int_{t_0}^{t} f_i(X_1, X_2 \ldots\ldots X_n\ U_1, U_2 \ldots\ldots U_m)\, dt$$

where $i = 1, 2, \ldots\ldots n$.

Thus 'n' state variables and hence state vector at any time 't' can be determined uniquely.

Any 'n' dimensional time invariant system has state equations in the functional form as,

$$\dot{X}(t) = f(X, U)$$

While outputs of such system are dependent on the state of system and instantaneous inputs.

$\therefore$ Functional output equation can be written as,

$$Y(t) = g(X, U) \quad \text{where 'g' is the functional operator.}$$

For time variant system, the same equations can be written as,

$$\dot{X}(t) = f(X, U, t) \ \ldots\ \text{State equation}$$

$$Y(t) = g(X, U, t) \ \ldots\ \text{Output equation}$$

State Model of Single Input Single Output System

Consider a single input single output system i.e. m = 1 and p = 1. But its order is 'n' hence n state variables are required to define state of the system. In such a case, the state model is

$$\dot{X}(t) = A\, x(t) + B\, U(t)$$

$$Y(t) = C\, x(t) + d\, U(t)$$

where $A = n \times n$ matrix, $B = n \times 1$ matrix

$C = 1 \times n$ matrix, d = constant

and $U(t)$ = single scalar input variable

In general remember the orders of the various matrices.

∴

A = Evolution matrix	⇒ **n × n**
B = Control matrix	⇒ **n × m**
C = Observation matrix	⇒ **p × n**
D = Transmission matrix	⇒ **p × m**

State Diagram Representation

It is the pictorial representation of the state model derived for the given system. It forms a close relationship amongst the state model, differential equations of the system and its solution. It is basically a block diagram type approach which is designed from the view of programming of a computer. The basic advantage of state diagram is when it is impossible to select the state variables as physical variables. When transfer function of system is given then state diagram may be obtained first. And then by assigning mathematical state variables therein, standard state model can be obtained.

State diagram of a linear time invariant continuous system is discussed here for the sake of simplicity. It is a proper interconnection of three basic units.

i) Scalars ii) Adders iii) Integrators

State Diagram of Standard State Model

Consider standard state model

$$\dot{X}(t) = A\, X(t) + B\, U(t) \text{ and}$$

$$Y(t) = C\, X(t) + D\, U(t)$$

So its state diagram will be as in the Fig. 2.12.

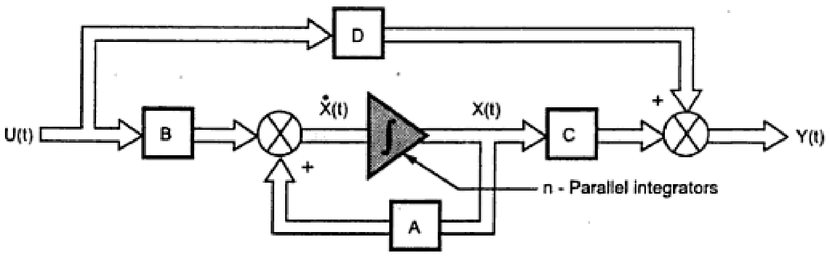


Fig. State diagram of MIMO system

The thick arrows indicate that there are multiple number of input, output and state variables. There must be n parallel integrators for n state variables. The output of each integrator is a seperate state variable. If such a state diagram for the system is obtained then the state model from the diagram can be easily obtained.

Example : *Construct the state model using phase variables if the system is described by the differential equation,*

$$\frac{d^2Y(t)}{dt^3} + 4\frac{d^2Y(t)}{dt^2} + 7\frac{dY(t)}{dt} + 2Y(t) = 5U(t)$$

Draw the state diagram.

Solution : Choose output Y(t) as the state variable $X_1(t)$ and successive derivatives of it give us remaining state variables. As order of the equation is 3, **only 3 state variables are allowed.**

$$X_1(t) = Y(t)$$

$\therefore$ $$X_2(t) = \dot{X}_1(t) = \dot{Y}(t) = \frac{dY(t)}{dt}$$

and $$X_3(t) = \dot{X}_2(t) = \ddot{Y}(t) = \frac{d^2Y(t)}{dt^2}$$

Thus $$\dot{X}_1(t) = X_2(t) \quad \ldots (1)$$

$$\dot{X}_2(t) = X_3(t) \quad \ldots (2)$$

To obtain $\dot{X}_3(t)$, substitute state variables obtained in the differential equation.

$$\frac{d^3Y(t)}{dt^3} = \dddot{Y}(t) = \frac{d}{dt}[\ddot{Y}(t)] = \frac{dX_3}{dt} = \dot{X}_3(t)$$

$$\therefore \dot{X}_3(t) + 4X_3(t) + 7X_2(t) + 2X_1(t) = 5U(t)$$

$\therefore$ $$\dot{X}_3(t) = -2X_1(t) - 7X_2(t) - 4X_3(t) + 5U(t) \quad \ldots (3)$$

The equations (1), (2) and (3) give us required state equation.

$\therefore$ $$\dot{X}(t) = A\,X(t) + B\,U(t)$$

where $$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -2 & -7 & -4 \end{bmatrix} \text{ and } B = \begin{bmatrix} 0 \\ 0 \\ 5 \end{bmatrix}$$

The output is, $$Y(t) = X_1(t)$$

$\therefore$ $$Y(t) = C\,X(t) + D\,U(t)$$

where $$C = [1\ 0\ 0],\ D = 0$$

This is the required state model using phase variables.

Example:

A system is represented by the state equation $\dot{X}$ =AX+BU; Y=CX where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & -1 & -10 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 10 \end{bmatrix} \text{ and } C = [100].$$

Determine the transfer function of the system.

Solution:

Transfer function = Y/U = C. B. $(SI-A)^{-1}$+D

In this, D matrix = 0

Hence, Transfer function = Y/U = C. B. $(SI-A)^{-1}$

Step 1: SI-A = S $\begin{bmatrix} S & 0 & 0 \\ 0 & S & 0 \\ 0 & 0 & S \end{bmatrix} - \begin{bmatrix} 0 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & -1 & -10 \end{bmatrix} = \begin{bmatrix} S & -1 & 0 \\ 0 & S+1 & -1 \\ 0 & 1 & S+10 \end{bmatrix}$

Step 2: det (SI-A) = S [(S+1)x (S+10) – (-1 x 1)]

$= S^3+11S^2+11S$

Step 3: Find adj (SI-A)= adj $\begin{bmatrix} S & -1 & 0 \\ 0 & S+1 & -1 \\ 0 & 1 & S+10 \end{bmatrix}$

$$\begin{bmatrix} + & - & + \\ - & + & - \\ + & - & + \end{bmatrix}$$

Cofactor values = $\begin{bmatrix} S^2+11S+11 & 0 & 0 \\ S+10 & S^2+10S & -S \\ 1 & S & S^2+S \end{bmatrix}$

adj (SI-A)= $[\text{Cofactor (SI-A)}]^T$

$$= \begin{bmatrix} S^2+11S+11 & S+10 & 1 \\ 0 & S^2+10S & S \\ 0 & -S & S^2+S \end{bmatrix}$$

Step 4: (SI - A)-1 = adj (SI-A) / det (SI-A)

$$= \begin{bmatrix} S^2+11S+11 & S+10 & 1 \\ 0 & S^2+10S & S \\ 0 & -S & S^2+S \end{bmatrix} 1/\ S^3+11S^2+11S$$

Step 5 : T.F = Y/U = C . $(SI-A)^{-1}$. B

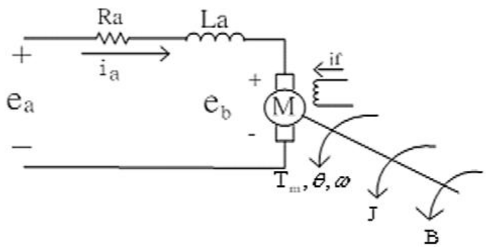
$$= [1\ 0\ 0] \begin{bmatrix} S^2+11S+11 & S+10 & 1 \\ 0 & S^2+10S & S \\ 0 & -S & S^2+S \end{bmatrix} 1/\ S^3+11S^2+11S \begin{bmatrix} 0 \\ 0 \\ 10 \end{bmatrix}$$

$$= [1\ 0\ 0] \begin{bmatrix} 10 \\ 10S \\ 10(S^2+S) \end{bmatrix} 1/\ S^3+11S^2+11S$$

$$= 10 / S^3+11S^2+11S$$

2. State models for linear and time invariant Systems

Example: State – Space representation of DC machine:



The equation for the electrical part is:

$$e_a(t) = R_a I_a + L\frac{di_a}{d_t} + e_b \qquad (1)$$

Where e_b is mainly due to the velocity of the armature, hence $e_b = K_1 \frac{d\theta}{dt}$ (2)

The equation for the mechanical part is:

$$J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = Torque \qquad (3)$$

Let the Torque is α I_a or Torque is = K_2 I_a (4)

The order of the mechanical part is two and the order of the electrical part is one. Hence we have to consider three state variables (X_1, X_2, X_3).

Let: $X_1 = \theta; X_2 = \dot{\theta}; X_3 = i_a$

Consider eqn. (1) and substitute eqn. (2) in (1):

$$e_a(t) - e_b = R_a I_a + L\frac{di_a}{d_t}$$

$$e_a(t) - K_1\frac{d\theta}{dt} = R_a I_a + L\frac{di_a}{d_t} \qquad (5)$$

Consider eqn. (3) and substitute eqn. (4) in (3):

$$J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} = K_2 \ I_a \qquad (6)$$

Substituting the state variables in eqn. (5) and (6):

$$e_a(t) - K_1 X_2 = R_a X_3 + L\dot{X}_3 \qquad (7)$$

$$J\dot{X}_2 + BX_2 = K_2 \ X_3 \qquad (8)$$

Simplifying eqn. (7) and (8):

$$\dot{X}_2 = \frac{K_2}{J} X_3 - \frac{B}{J} X_2$$

$$\dot{X}_3 = \frac{e_a(t)}{L} - \frac{K_1}{L} X_2 - \frac{R_a}{L} X_3$$

The state – eqn. is:

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{B}{J} & \frac{K_2}{J} \\ 0 & -\frac{K_1}{L} & -\frac{R_a}{L} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} e_a(t)$$

Example : *A feedback system is characterized by the closed loop transfer function,*

$$T(s) = \frac{s^2 + 3s + 3}{s^3 + 2s^2 + 3s + 1}$$

Draw a suitable signal flow graph and obtain the state model.

Solution : Divide N and D by s^3.

$$\therefore \quad T(s) = \frac{\frac{1}{s} + \frac{3}{s^2} + \frac{3}{s^3}}{1 + \frac{2}{s} + \frac{3}{s^2} + \frac{1}{s^3}} = \frac{\frac{1}{s} + \frac{3}{s^2} + \frac{3}{s^3}}{1 - \left[-\frac{2}{s} - \frac{3}{s^2} - \frac{1}{s^3}\right]}$$

$$\therefore \quad L_1 = -\frac{2}{s}, \quad L_2 = -\frac{3}{s^2}, \quad L_3 = -\frac{1}{s^3}$$

$$T_1 = \frac{1}{s}, \quad T_2 = \frac{3}{s^2}, \quad T_3 = \frac{3}{s^3}$$

And $\Delta_1 = \Delta_2 = \Delta_3 = 1$ with no combinations of non-touching loops.

There are many signal flow graphs which can be obtained to satisfy above transfer function.

Method 1 : The signal flow graph is as shown in the Fig.

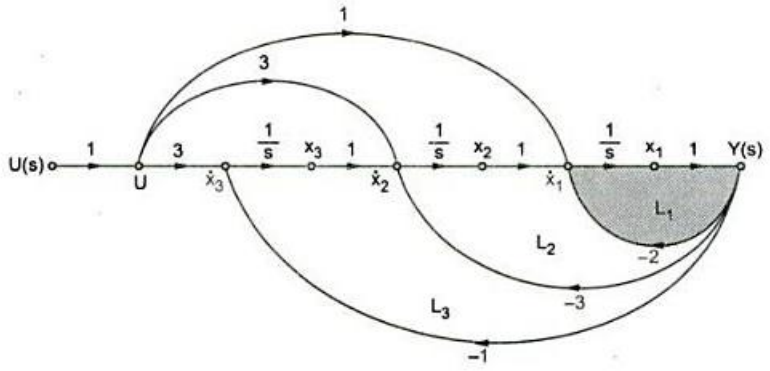


Fig.

From signal flow graph,

$$Y = X_1$$

$$\dot{X}_1 = X_2 + U - 2Y = -2X_1 + X_2 + U$$

$$\dot{X}_2 = X_3 + 3U - 3Y = -3X_1 + X_3 + 3U$$

$$\dot{X}_3 = 3U - Y = -X_1 + 3U$$

Hence the state model is,

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \end{bmatrix} = \begin{bmatrix} -2 & 1 & 0 \\ -3 & 0 & 1 \\ -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} + \begin{bmatrix} 1 \\ 3 \\ 3 \end{bmatrix} U(t)$$

i.e. $\dot{X} = A\,X(t) + B\,U(t)$

and $$Y(t) = [1 \;\; 0 \;\; 0] \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix}$$

i.e. $Y(t) = X(t)$ with $D = 0$

Derivation of Transfer Function from State Model

Consider a standard state model derived for linear time invariant system as,

$$\dot{X}(t) = A\,X(t) + B\,U(t) \qquad \text{... (1a)}$$

and $$Y(t) = C\,X(t) + DU(t) \qquad \text{... (1b)}$$

Taking Laplace transform of both sides,

$$[s\,X(s) - X(0)] = A\,X(s) + BU(s) \qquad \text{... (2a)}$$

and $$Y(s) = C\,X(s) + D\,U(s) \qquad \text{... 2(b)}$$

Note that as the system is time invariant, the coefficient of matrices A, B, C and D are constants. While the definition of transfer function is based on the assumption of zero initial conditions i.e. $X(0) = 0$.

$$\therefore \quad s\,X(s) = A\,X(s) + B\,U(s)$$

$$\therefore \quad s\,X(s) - A\,X(s) = B\,U(s)$$

Now s is an operator while A is matrix of order $n \times n$ hence to match the orders of two terms on left hand side, multiply 's' by identity matrix I of the order $n \times n$.

$$\therefore \quad sI\,X(s) - A\,X(s) = B\,U(s)$$

$$\therefore \quad [sI - A]\,X(s) = B\,U(s)$$

Premultiplying both sides by $[sI - A]^{-1}$,

$$[sI - A]^{-1}[sI - A]\,X(s) = [sI - A]^{-1}BU(s)$$

Now $$[sI - A]^{-1}[sI - A] = 1$$

$$\therefore \quad X(s) = [sI - A]^{-1}BU(s) \qquad \text{...(3)}$$

Substituting in the equation (2b),

$$Y(s) = C\,[sI - A]^{-1}B\,U(s) + D\,U(s)$$

$$\therefore \quad Y(s) = \{C\,[sI - A]^{-1}B + D\}\,U(s)$$

Example : *Determine the transfer matrix for MIMO system given by,*

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} 0 & 3 \\ -2 & -5 \end{bmatrix}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}\begin{bmatrix} U_1 \\ U_2 \end{bmatrix}, \quad \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} X_1 \\ X_2 \end{bmatrix}$$

Solution : From the given state model,

$$A = \begin{bmatrix} 0 & 3 \\ -2 & -5 \end{bmatrix}, \quad B = \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}, \quad C = \begin{bmatrix} 2 & 1 \\ 1 & 0 \end{bmatrix}, \quad D = [0]$$

$$\text{T.M.} = C\,[sI - A]^{-1} B + D$$

$$[sI - A] = \begin{bmatrix} s & -3 \\ 2 & s+5 \end{bmatrix}$$

$$\text{Adj}\,[sI - A] = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}^T = \begin{bmatrix} s+5 & -2 \\ 3 & s \end{bmatrix}^T = \begin{bmatrix} s+5 & 3 \\ -2 & s \end{bmatrix}$$

$$|sI - A| = s^2 + 5s + 6 = (s+2)(s+3)$$

$$\therefore \quad [sI - A]^{-1} = \frac{\text{Adj}\,[sI - A]}{|sI - A|} = \frac{\begin{bmatrix} s+5 & 3 \\ -2 & s \end{bmatrix}}{(s+2)(s+3)}$$

$$\therefore \quad \text{T.M.} = C[sI - A]^{-1} B = \frac{\begin{bmatrix} 2 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} s+5 & 3 \\ -2 & s \end{bmatrix}\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}}{(s+2)(s+3)}$$

$$= \frac{\begin{bmatrix} 2 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} s+8 & s+8 \\ s-2 & s-2 \end{bmatrix}}{(s+2)(s+3)} = \frac{\begin{bmatrix} 3s+14 & 3s+14 \\ s+8 & s+8 \end{bmatrix}}{(s+2)(s+3)}$$

$$= \begin{bmatrix} \frac{3s+14}{(s+2)(s+3)} & \frac{3s+14}{(s+2)(s+3)} \\ \frac{s+8}{(s+2)(s+3)} & \frac{s+8}{(s+2)(s+3)} \end{bmatrix}$$

i.e. $Y(s) = \text{T.M.}\ U(s)$

$$\begin{bmatrix} Y_1(s) \\ Y_2(s) \end{bmatrix} = \begin{bmatrix} \frac{3s+14}{(s+2)(s+3)} & \frac{3s+14}{(s+2)(s+3)} \\ \frac{s+8}{(s+2)(s+3)} & \frac{s+8}{(s+2)(s+3)} \end{bmatrix}\begin{bmatrix} U_1(s) \\ U_2(s) \end{bmatrix}$$

The above relation indicates that each output depends on both the inputs.

3. Solution of state and output equation in controllable canonical form

a. *Diagonalization:*

A diagonal system matrix A has the advantage that, each state equation is a function of only one state variable. Hence, each state equation can be solved independently. It is also known as decoupling.

Let the state equation is given as:

$$\dot{X} = AX + BU \qquad (1)$$

$$Y = CX + DU \qquad (2)$$

Let us transform the vector X into a new state vector Z using;

X= PZ (3)

Where P is a (n x m) non-singular matrix.

Substituting eqn. (3) in (1) and (2):

$$P\dot{Z} = APZ + BU \quad (4)$$

$$Y = CPZ + DU \quad (5)$$

Eqn. (4) can be written as;

$$\dot{Z} = \frac{APZ}{P} + \frac{BU}{P} = P^{-1}APZ + P^{-1}BU$$

Where $P^{-1}AP$ is a diagonal matrix and P is called the diagonalizing matrix.

Therefore the equations will be:

$\dot{Z} = \hat{A}Z + \hat{B}U$ and $Y = \hat{C}Z + \hat{D}U$

Where $\hat{A} = P^{-1}AP; \hat{B} = P^{-1}B; \hat{C} = CP$

b. Time – Domain solution of state Equation:

Let us consider the state equation:

$$\dot{X}(t) = AX(t) + BU(t)$$

Grouping the states together: $\dot{X}(t) - AX(t) = BU(t)$

Multiplying the above equation on both sides with $e^{-At,}$ we get;

$$e^{-At}[\dot{X}(t) - AX(t)] = e^{-At}BU(t)$$

$$e^{-At}\dot{X}(t) - Ae^{-At}X(t) = e^{-At}BU(t)$$

$$e^{-At}\frac{d}{dt}(X(t)) + \frac{d}{dt}(e^{-At})X(t) = e^{-At}BU(t)$$

$\frac{d}{dt}[e^{-At}X(t)] = e^{-At}BU(t)$ (Since, $\frac{d}{dt}[e^{-At}X(t)] = X(t)[-Ae^{-At}] - e^{-At}\dot{X}(t)$)

Integrating on both sides from 0 to t, we have:

$$e^{-At}X(t)\Big|_0^t = \int_0^t e^{-A\tau}BU(t)d\tau$$

$$e^{-At}X(t) - X(0) = \int_0^t e^{-A\tau}BU(t)d\tau$$

There fore $X(t)=\int_0^t e^{-A\tau}BU(t)d\tau \; e^{At} + X(0)e^{At}$

$$X(t)=\int_0^t e^{A(t-\tau)}BU(t)d\tau + X(0)e^{At}$$

Let $\phi(t) = e^{At}$

$$X(t)=\int_0^t \phi(t-\tau)BU(t)d\tau + \phi(t)X(0)$$

Where $\int_0^t \phi(t-\tau)BU(t)d\tau$ = zero state component and

$\phi(t)X(0)$ = zero input component

Example : *Find the state transition matrix for,*

$$A = \begin{bmatrix} 0 & -1 \\ +2 & -3 \end{bmatrix}$$

Solution : Use Laplace transform method,

$$[sI - A] = s\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} 0 & 1 \\ -2 & -3 \end{bmatrix} = \begin{bmatrix} s & +1 \\ -2 & s+3 \end{bmatrix}$$

$$\therefore \quad \text{Adj } [sI - A] = \begin{bmatrix} s+3 & 2 \\ -1 & s \end{bmatrix}^T = \begin{bmatrix} s+3 & -1 \\ 2 & s \end{bmatrix}$$

$$|sI - A| = \begin{bmatrix} s & +1 \\ -2 & s+3 \end{bmatrix} = s^2 + 3s + 2 = (s+1)(s+2)$$

$$\therefore \quad [sI - A]^{-1} = \frac{\text{Adj } [sI - A]}{|sI - A|} = \frac{\begin{bmatrix} s+3 & -1 \\ 2 & s \end{bmatrix}}{(s+1)(s+2)}$$

$$\therefore \quad \phi(s) = [sI - A]^{-1} = \begin{bmatrix} \frac{s+3}{(s+1)(s+2)} & \frac{-1}{(s+1)(s+2)} \\ \frac{2}{(s+1)(s+2)} & \frac{s}{(s+1)(s+2)} \end{bmatrix}$$

$$\therefore \quad e^{At} = L^{-1}[sI - A]^{-1} = L^{-1}\begin{bmatrix} \frac{s+3}{(s+1)(s+2)} & \frac{-1}{(s+1)(s+2)} \\ \frac{2}{(s+1)(s+2)} & \frac{s}{(s+1)(s+2)} \end{bmatrix}$$

Using partial fraction expansion for all the elements.

$$e^{At} = L^{-1}\begin{bmatrix} \frac{2}{s+1} - \frac{1}{s+2} & \frac{-1}{s+1} + \frac{1}{s+2} \\ \frac{2}{s+1} - \frac{2}{s+2} & \frac{-1}{s+1} + \frac{2}{s+2} \end{bmatrix}$$

$$\therefore \quad e^{At} = \begin{bmatrix} 2e^{-t} - e^{-2t} & -e^{-t} + e^{-2t} \\ 2e^{-t} - 2e^{-2t} & -e^{-t} + 2e^{-2t} \end{bmatrix} = \phi(t)$$

This is the required state transition matrix.

c. *Properties of state transition matrix*

Let us consider:

$$X(t)=e^{-At}X(0) = \phi(t)X(0)$$

Where $\phi(t)$ is identity matrix.

1. At t=0; $X(0)=\phi(0)X(0)$

From which we can write $\phi(0)=I$

2. $\phi(t)=e^{At}=(e^{-At})^{-1}=[\phi(-t)]^{-1}$

   ie. $\phi(t)=[\phi(-t)]^{-1}$

   Taking inverse on both sides; $\phi(t)^{-1}=[\phi(-t)]$

3. $\phi(t1+t2)=e^{A(t1+t2)}=e^{A(t1)}e^{A(t2)}+\phi(t1)\phi(t2)$
4. $[\phi(t)]^n=(e^{At})^n=e^{Atn}=\phi(nt)$

The various useful properties of the state transition matrix are,

$\phi(t) = e^{At}$ = State transition matrix

1. $\phi(0) = e^{A\times 0} = I$ = Identity matrix
2. $\phi(t) = e^{At} = (e^{-At})^{-1} = [\phi(-t)]^{-1}$

i.e. $\phi^{-1}(t) = \phi(-t)$

3. $\phi(t_1+t_2) = e^{A(t_1+t_2)} = e^{At_1}\cdot e^{At_2}$

   $= \phi(t_1)\,\phi(t_2) = \phi(t_2)\,\phi(t_1)$

4. $e^{A(t+s)} = e^{At}\,e^{As}$
5. $e^{(A+B)t} = e^{At}\,e^{Bt}$ only if AB = BA
6. $[\phi(t)]^n = [e^{At}]^n = e^{Ant} = \phi(nt)$
7. $\phi(t_2-t_1)\cdot\phi(t_1-t_0) = \phi(t_2-t_0)$

This property states that the process of transition of state can be divided into number of sequential transition. Thus t_0 to t_2 can be divided as t_0 to t_1 and t_1 to t_2, as stated in the property.

4. Concepts of controllability and observability

Let the state equation is given as:

$$\dot{X} = AX + BU \qquad (1)$$

$$Y = CX + DU \qquad (2)$$

The controllability and Observability can be tested with:

Kalman's Approach and Gilbert's Approach.

1. Kalman's Approach:

Controllability:

The above said linear system is said to be completely controllable if there exists an input vector u(t) which transfers the system from initial state $x(t_0)$ to the state $x(t_f)$ in a finite time.

Let us consider, $\dot{X} = AX + BU$ is an nth order system. It is completely controllable if and only if the rank of the composite matrix;

$Q_c = [B \;\; AB \;\; A^2B \;\; ... \;\; A^{n-1}B]$ is n.

Observability:

The above said linear system is completely observable if the knowledge of the outputs Y and inputs U over the time $t_0 < t < t_f$ is sufficient to determine every state.

The system is completely observable if and only if the rank of the composite matrix;

$$Q_o = \begin{bmatrix} C \\ CA \\ CA^2 \\ . \\ . \\ . \\ CA^{n-1} \end{bmatrix} \text{ is n.}$$

2. Gilbert's Approach:

Consider the transformed canonical or Jordan canonical form of the state model shown below which is obtained by using the transformation, X =MZ

= ΛZ + U

Y=Z + DU (Or)

= JZ + U

Y=Z + DU where =CM and M=modal matrix.

The necessary and sufficient condition for complete observability is that none of the columns of the matrix be zero. If any of the column is of has all zeros then the corresponding state variable is not observable.

X = AX + BU

Y = CX + DU

The model is transformed into the canonical form as follows,

Z = ΛZ + B˜U

Y = C˜Z + DU

Where Λ= MA¯¹M,   B˜ = M¯¹B and C˜ = CM

The system is completely state controllable if the matrix B does not have any row with all zeros.

Example:

A system is represented by the state and output equations given below. Find the poles of the system.

$$\dot{X} = \begin{bmatrix} -3 & -2 \\ -1 & -2 \end{bmatrix} X + \begin{bmatrix} 1 \\ 1 \end{bmatrix} u(t)$$

$$Y = \begin{bmatrix} 1 & 2 \end{bmatrix} X$$

Solution : $|SI - A| = 0$

$$\left| S\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} -3 & -2 \\ -1 & -2 \end{bmatrix} \right| = 0$$

$$\begin{vmatrix} s+3 & 2 \\ 1 & s+2 \end{vmatrix} = 0$$

= (s+3)(s+2)-(-2 x -1)=0

S^2+5S+4=0

Threfore the poles are S+4 =0 and S+1=0

The poles are -4 and -1.

Example : *Find the controllability of the system,*

$$\dot{X} = \begin{bmatrix} 1 & 1 \\ 2 & -1 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} U(t)$$

$$n = 2$$

Solution : $A = \begin{bmatrix} 1 & 1 \\ 2 & -1 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

$\therefore \quad AB = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$

$\therefore \quad Q_c = [B \;\; AB] = \begin{bmatrix} 0 & 1 \\ 1 & -1 \end{bmatrix}$

Now $\begin{vmatrix} 0 & 1 \\ 1 & -1 \end{vmatrix} = -1$ which is non-zero

$\therefore$ Rank of $Q_c = 2 = n$

Hence the given system is **completely controllable.**

Example : *Evaluate the controllability of the system*

with, $\dot{X} = AX + BU$

and $A = \begin{bmatrix} 1 & 1 \\ 0 & -1 \end{bmatrix} \quad B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$

Solution : $n = 2$

$\therefore \quad Q_c = [B \;\; AB]$

$AB = \begin{bmatrix} 1 & 1 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$

$\therefore \quad Q_c = \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix}$

Now $\begin{vmatrix} 1 & 1 \\ 0 & 0 \end{vmatrix}$ = Determinant of $2 \times 2 = 0$

Hence rank of $Q_c r = 1$ and

Rank of $Q_c \neq n$

$\therefore$ The system is **not state controllable.**

Example : *Consider the system with state equation.*

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -11 & -6 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} U(t)$$

Estimate the state controllability by
i) Kalman's test and ii) Gilbert's test

Solution : i) Kalman's test

$$Q_c = [B : AB : A^2B] \ldots n = 3$$

$$AB = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -11 & -6 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ -6 \end{bmatrix}$$

$$A^2 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -11 & -6 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -11 & -6 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ -6 & -11 & -6 \\ 36 & 60 & 25 \end{bmatrix}$$

$$\therefore \quad A^2B = \begin{bmatrix} 0 & 0 & 1 \\ -6 & -11 & -6 \\ 36 & 60 & 25 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ -6 \\ 25 \end{bmatrix}$$

$$\therefore \quad Q_c = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & -6 \\ 1 & -6 & 25 \end{bmatrix}$$

$$\begin{vmatrix} 0 & 0 & 1 \\ 0 & 1 & -6 \\ 1 & -6 & 25 \end{vmatrix} = 1, \quad \text{Thus } |Q_c| \text{ is non-singular.}$$

Hence the rank of Q_c is 3 which is 'n'.

Thus the system is **completely state controllable.**

ii) Gilbert's test

For this, it is necessary to express A in the canonical form. Find eigen values of A.

$$|\lambda I - A| = \begin{vmatrix} \lambda & -1 & 0 \\ 0 & \lambda & -1 \\ 6 & 11 & \lambda+6 \end{vmatrix} = 0$$

$$\therefore \quad \lambda^3 + 6\lambda^2 + 11\lambda + 6 = 0$$

$$\therefore \quad (\lambda + 1)(\lambda + 2)(\lambda + 3) = 0$$

$$\therefore \quad \lambda_1 = -1, \quad \lambda_2 = -2, \quad \lambda_3 = -3$$

As matrix A is in **phase variable form**, the **modal matrix M** is **Vander Monde Matrix**.

$$\therefore \quad M = \begin{bmatrix} 1 & 1 & 1 \\ \lambda_1 & \lambda_2 & \lambda_3 \\ \lambda_1^2 & \lambda_2^2 & \lambda_3^2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ -1 & -2 & -3 \\ 1 & 4 & 9 \end{bmatrix}$$

$$M^{-1} = \frac{\text{Adj}[M]}{|M|} = \frac{\begin{bmatrix} -6 & 6 & -2 \\ -5 & 8 & -3 \\ -1 & 2 & -1 \end{bmatrix}^T}{-2} = \frac{\begin{bmatrix} -6 & -5 & -1 \\ 6 & 8 & 2 \\ -2 & -3 & -1 \end{bmatrix}}{-2} = \begin{bmatrix} 3 & 2.5 & 0.5 \\ -3 & -4 & -1 \\ 1 & 1.5 & 0.5 \end{bmatrix}$$

$$\tilde{B} = M^{-1}B = \begin{bmatrix} 3 & 2.5 & 0.5 \\ -3 & -4 & -1 \\ 1 & 1.5 & 0.5 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0.5 \\ -1 \\ 0.5 \end{bmatrix}$$

As none of the elements of $\tilde{B}$ are zero, the system is **completely state controllable.**

Key Point: *As Gilbert's test requires to transform matrix A into canonical form, it is time consuming and hence Kalman's test is popularly used to test controllability.*

5. Effect of state feedback.

The closed loop poles of observed state feedback system consists of the poles due to pole placement design alone and poles due to observer design alone. Thus the pole placement design and observer design are independent of each other. The design of each can be done independently and it can be combined to get observed state feedback control system. For n as the order of the plant, the order of the observer is also n while the resulting characteristic equation of the total closed loop system is of order 2n.

To derive the transfer function of observer based controller, let us consider the system defined as

$$\dot{x} = Ax + Bu$$

$$y = Cx$$

Let the plant be completely observable and let the observed state feedback control is $u = -K\tilde{x}$.

$$\dot{\tilde{x}} = A\tilde{x} + Bu + K_e(y - C\tilde{x})$$

$$= A\tilde{x} + B(-K\tilde{x}) + K_e(y - C\tilde{x})$$

$$\therefore \dot{\tilde{x}} = (A - BK - K_eC)\tilde{x} + K_e y$$

Taking Laplace transform of above equation

$$s\tilde{x}(s) - \tilde{x}(0) = (A - BK - K_eC)\tilde{x}(s) + K_eY(s)$$

Example : *A system represented by following state model is controllable but not observable. Show that the non-observability is due to a pole-zero cancellation in C[sI – A]$^{-1}$.*

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -11 & -6 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u$$

$$Y = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix} x$$

Solution :

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -11 & -6 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u$$

$$Y = [1 \quad 1 \quad 0]x$$

Here,

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -11 & -6 \end{bmatrix}; \quad B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}; \quad C = [1 \quad 1 \quad 0]$$

$$[sI - A] = \begin{bmatrix} s & 0 & 0 \\ 0 & s & 0 \\ 0 & 0 & s \end{bmatrix} - \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -11 & -6 \end{bmatrix} = \begin{bmatrix} s & -1 & 0 \\ 0 & s & -1 \\ 6 & 11 & s+6 \end{bmatrix}$$

$$|sI - A| = s[(s+6)s+11]+1[6] = s^3+6s^2+11s+6$$

$$= (s+1)(s+2)(s+3)$$

$$[sI-A]^{-1} = \frac{\text{Adj of } [sI-A]}{|sI-A|}$$

$$= \frac{1}{(s+1)(s+2)(s+3)} \begin{bmatrix} s^2+6s+11 & -6 & -6s \\ +s+6 & s^2+6s & -11s-6 \\ 1 & s & s^2 \end{bmatrix}^T$$

$$= \frac{1}{(s+1)(s+2)(s+3)} \begin{bmatrix} s^2+6s+11 & s+6 & 1 \\ -6 & s(s+6) & s \\ -6s & -(11s+6) & s^2 \end{bmatrix}$$

$$\text{T.F.} = \frac{Y(s)}{U(s)} = C[sI-A]^{-1}B+D = C[sI-A]^{-1}B = (\because D=0)$$

$$= [1 \quad 1 \quad 0] \frac{1}{(s+1)(s+2)(s+3)} \begin{bmatrix} s^2+6s+11 & s+6 & 1 \\ -6 & s(s+6) & s \\ -6s & -(11s+6) & s^2 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$= \frac{1}{(s+1)(s+2)(s+3)} \left[s^2+6s+11-6 \quad (s+6)+s(s+6) \quad 1+s\right] \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$= \frac{1}{(s+1)(s+2)(s+3)} [s+1]$$

$$= \frac{s+1}{(s+1)(s+2)(s+3)}$$

$$\text{T.F.} = \frac{Y(s)}{U(s)} = \frac{s+1}{(s+1)(s+2)(s+3)}$$

Clearly it is seen that the factor (s+1) is cancelled from numerator and denominator.

$$\text{T.F.} = \frac{s+1}{s^3+6s^2+11s+6} = \frac{s+1}{[s(s+6)+11]s+6}$$

Let us draw the simulation of the transfer function.

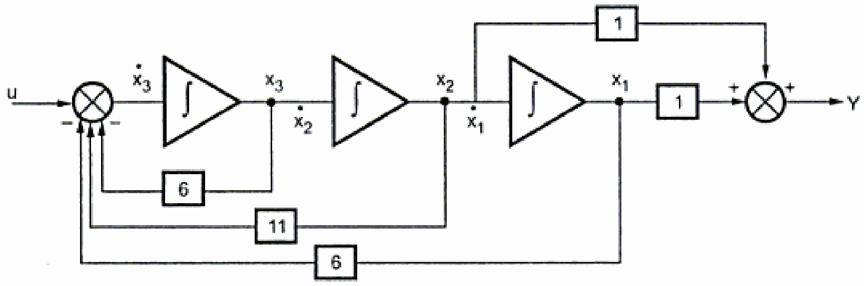


Fig.

There is no coupling between x_3 and y due to which state x_3 can not be observed from measurement of output y. Thus the system is not completely observable due to pole-zero cancellation as matrix C contains one of the terms as zero.

Assuming zero initial condition,

$$[sI-(A-BK-K_eC)]\,\tilde{x}(s) = K_e\,Y(s)$$

$$\therefore \qquad \tilde{x}(s) = (sI-A+BK+K_eC)^{-1}K_eY(s)$$

Substituting this value of $\tilde{x}(s)$ in equation for u,

$$U(s) = -K\,\tilde{x}(s)$$

$$\therefore \qquad U(s) = -K\,(sI-A+BK+K_eC)^{-1}\,K_e\,Y(s)$$

The transfer function is given by,

$$\frac{U(s)}{Y(s)} = -K(sI-A+K_eC+BK)^{-1}K_e$$

$$\therefore \qquad \frac{U(s)}{-Y(s)} = K(sI-A+K_eC+BK)^{-1}K_e$$

The block diagram representation of above system is shown in the Fig.

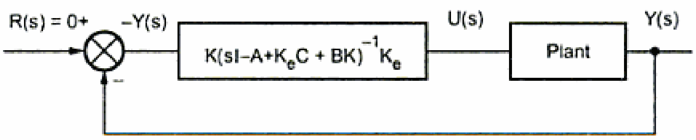


Fig.

Unit V - STATE VARIABLE ANALYSIS

1. Statespace modelling of Mechanical systems
2. Statespace modelling of Electrical systems
3. Statespace into transfer function
4. Transfer function into Statespace model
5. Controllability and Oservability

EXAMPLE

Construct the state model of mechanical system shown in fig 4.3.1.

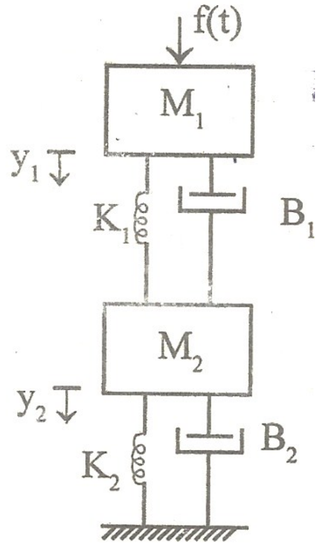
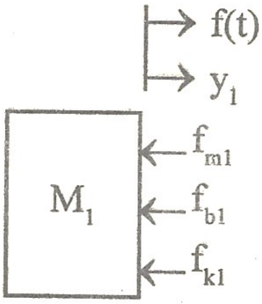


Fig 4.3.1.

SOLUTION

Free body diagram of M_1 is shown in fig 4.3.2.



$$f_{m1} = M_1 \frac{d^2 y_1}{dt^2} \quad ;$$

$$f_{b1} = B_1 \frac{d}{dt}(y_1 - y_2)$$

$$f_{k1} = K_1(y_1 - y_2)$$

Fig 4.3.2.

By Newton's second law, the force balance equation at node M_1 is,

$$f(t) = f_{m1} + f_{b1} + f_{k1}$$

$$f(t) = M_1 \frac{d^2 y_1}{dt^2} + B_1 \frac{d}{dt}(y_1 - y_2) + K_1(y_1 - y_2)$$

$$f(t) = M_1 \frac{d^2 y_1}{dt^2} + B_1 \frac{dy_1}{dt} - B_1 \frac{dy_2}{dt} + K_1 y_1 - K_1 y_2 \qquad .....(4.3.1)$$

Free body diagram of M_2 is shown in fig 4.3.3.

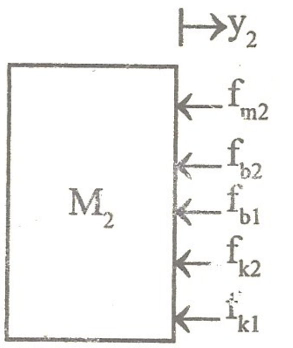


Fig 4.3.3.

$$f_{m2} = M_2 \frac{d^2 y_2}{dt^2} \quad ; \quad f_{b2} = B_2 \frac{dy_2}{dt}$$

$$f_{b1} = B_1 \frac{d}{dt}(y_2 - y_1) \quad ; \quad f_{k2} = K_2 y_2$$

$$f_{k1} = K_1(y_2 - y_1)$$

By Newton's second law, the force balance equation at node M_2 is,

$$f_{m2} + f_{b2} + f_{b1} + f_{k2} + f_{k1} = 0$$

$$\therefore M_2\frac{d^2y_2}{dt^2}+B_2\frac{dy_2}{dt}+B_1\frac{d}{dt}(y_2-y_1)+K_2y_2+K_1(y_2-y_1)=0$$

$$M_2\frac{d^2y_2}{dt^2}+B_2\frac{dy_2}{dt}+B_1\frac{dy_2}{dt}-B_1\frac{dy_1}{dt}+K_2y_2+K_1y_2-K_1y_1=0 \quad .....(4.3.2)$$

Let us choose four state variable x_1, x_2, x_3 and x_4. Also, let the input $f(t)=u$. The state variables are related to physical variables as follows

$$x_1=y_1\ ;\ x_2=y_2\ ;\ x_3=\frac{dy_1}{dt}\quad ;\quad x_4=\frac{dy_2}{dt}\ ;\ \dot{x}_3=\frac{d^2y_1}{dt^2}\quad ;\quad \dot{x}_4=\frac{d^2y_2}{dt^2}$$

On substituting $y_1=x_1$; $y_2=x_2$; $\frac{dy_1}{dt}=x_3$; $\frac{dy_2}{dt}=x_4$; $\frac{d^2y_1}{dt^2}=\dot{x}_3$ and $f(t)=u$ in equation (4.3.1) we get,

$$u=M_1\dot{x}_3+B_1x_3-B_1x_4+K_1x_1-K_1x_2$$

$$M_1\dot{x}_3=-B_1x_3+B_1x_4-K_1x_1+K_1x_2+u$$

$$\therefore \dot{x}_3=-\frac{K_1}{M_1}x_1+\frac{K_1}{M_1}x_2-\frac{B_1}{M_1}x_3+\frac{B_1}{M_1}x_4+\frac{1}{M_1}u \quad .....(4.3.3)$$

On substituting $y_1=x_1$; $y_2=x_2$; $\frac{dy_1}{dt}=x_3$; $\frac{dy_2}{dt}=x_4$ and $\frac{d^2y_2}{dt}=\dot{x}_4$ in equation (4.3.2) we get,

$$M_2\dot{x}_4+B_2x_4+B_1x_4-B_1x_3+K_1x_2+K_2x_2-K_1x_1=0$$

$$\therefore M_2\dot{x}_4=-B_2x_4-B_1x_4+B_1x_3-K_2x_2-K_1x_2+K_1x_1$$

$$=-(B_2+B_1)\,x_4+B_1x_3-(K_2+K_1)x_2+K_1x_1$$

$$\therefore \dot{x}_4=\frac{K_1}{M_2}x_1-\frac{(K_1+K_2)}{M_2}x_2+\frac{B_1}{M_2}x_3-\frac{(B_1+B_2)}{M_2}x_4 \quad .....(4.3.4)$$

The state variable $x_1=y_1$.

On differentiating $x_1=y_1$ with respect to t we get, $\frac{dx_1}{dt}=\frac{dy_1}{dt}$

$$\text{Let } \frac{dx_1}{dt}=\dot{x}_1 \text{ and } \frac{dy_1}{dt}=x_3\quad ;\ \therefore \dot{x}_1=x_3 \quad .....(4.3.5)$$

The state variable, $x_2=y_2$.

On differentiating $x_2=y_2$ with respect to t we get, $\frac{dx_2}{dt}=\frac{dy_2}{dt}$

Let $\frac{dx_2}{dt} = \dot{x}_2$ and $\frac{dy_2}{dt} = x_4$; $\therefore \dot{x}_2 = x_4$ .....(4.3.6)

The equations (4.3.3) to (4.3.6) are state equations of the mechanical system. Hence the state equations of the mechanical system are,

$$\dot{x}_1 = x_3$$

$$\dot{x}_2 = x_4$$

$$\dot{x}_3 = -\frac{K_1}{M_1}x_1 + \frac{K_1}{M_1}x_2 - \frac{B_1}{M_1}x_3 + \frac{B_1}{M_1}x_4 + \frac{1}{M_1}u.$$

$$\dot{x}_4 = \frac{K_1}{M_2}x_1 - \frac{(K_1+K_2)}{M_2}x_2 + \frac{B_1}{M_2}x_3 - \frac{(B_1+B_2)}{M_2}x_4$$

On arranging the state equations in the matrix form, we get,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{K_1}{M_1} & \frac{K_1}{M_1} & -\frac{B_1}{M_1} & \frac{B_1}{M_1} \\ \frac{K_1}{M_2} & -\frac{(K_1+K_2)}{M_2} & \frac{B_1}{M_2} & \frac{-(B_1+B_2)}{M_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{M_1} \\ 0 \end{bmatrix} [u]$$

.....(4.3.7)

Let the displacements y_1 and y_2 be the outputs of the system.

$\therefore y_1 = x_1$ and $y_2 = x_2$.

The output equation in matrix form is given by,

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$$

.....(4.3.8)

The state equation [equ (4.3.7)] and the output equation [equ (4.3.8)] together called state model of the system.

EXAMPLE

Obtain the state model of the mechanical system shown in fig 4.4.1 by choosing a minimum of three state variables.

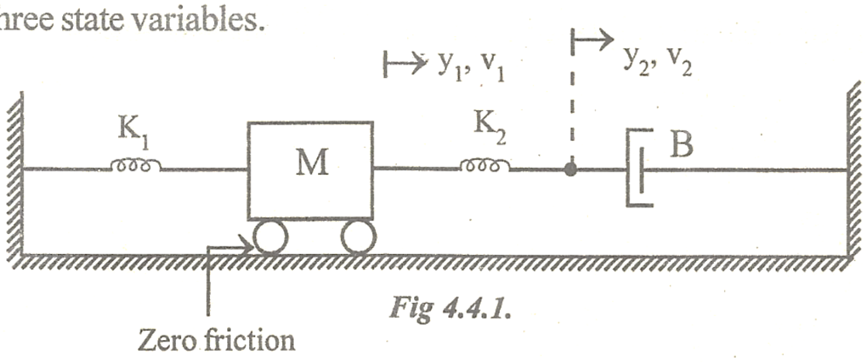


Fig 4.4.1.

SOLUTION

Let the three state variables be x_1, x_2 and x_3 and they are related to physical variables as shown below.

$$x_1 = y_1 \; ; \quad x_2 = y_2 \; ; \qquad x_3 = \frac{dy_1}{dt} = v_1 .$$

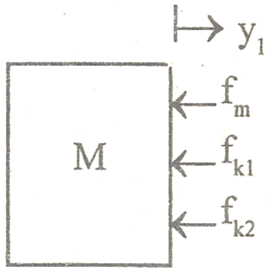


Fig 4.4.2.

Free body diagram of mass M is shown in fig 4.4.2.

$$f_m = M\frac{d^2y_1}{dt^2} \quad ; \quad f_{k1} = K_1 y_1 \quad ; \quad f_{k2} = K_2(y_1 - y_2)$$

By Newton's second law, the force balance equation at node M is,

$$f_m + f_{k1} + f_{k2} = 0$$

$$M\frac{d^2y_1}{dt^2} + K_1y_1 + K_2(y_1 - y_2) = 0$$

$$M\frac{d^2y_1}{dt^2} + K_1y_1 + K_2y_1 - K_2y_2 = 0 \qquad .....(4.4.1)$$

Put $\frac{d^2y_1}{dt^2} = \dot{x}_3$; $y_1 = x_1$, $y_2 = x_2$ in equ(4.4.1)

$$M\dot{x}_3 + K_1x_1 + K_2x_1 - K_2x_2 = 0$$

$$M\dot{x}_3 + (K_1 + K_2)\,x_1 - K_2x_3 = 0$$

$$\dot{x}_3 = -\frac{K_1 + K_2}{M}x_1 + \frac{K_2}{M}x_3 \qquad .....(4.4.2)$$

The freebody diagram of node 2 (meeting point of K_2 and B) is shown in fig (4.4.3).

$$f_b = B\frac{dy_2}{dt} \; ; \; f_{k2} = K_2(y_2 - y_1)$$

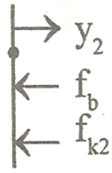


Fig 4.4.3.

Writing force balance equation at the meeting point of K_2 and B we get,

$$f_b + f_{k2} = 0$$

$$B\frac{dy_2}{dt} + K_2(y_2 - y_1) = 0$$

$$\therefore \frac{dy_2}{dt} = \frac{K_2}{B}y_1 - \frac{K_2}{B}y_2$$

Put $\frac{dy_2}{dt} = \dot{x}_2$, $y_1 = x_1$ and $y_2 = x_2$,

$$\therefore \dot{x}_2 = \frac{K_2}{B}x_1 - \frac{K_2}{B}x_2 \qquad .....(4.4.3)$$

The state variable, $x_1 = y_1$. On differentiating this expression with respect to t we get.

$$\frac{dx_1}{dt} = \frac{dy_1}{dt}$$

Let $\frac{dx_1}{dt} = \dot{x}_1$ and $\frac{dy_1}{dt} = x_3$; $\therefore \dot{x}_1 = x_3$ .....(4.4.4)

The state equations are given by equations (4.4.4), (4.4.3) and (4.4.2).

$$\dot{x}_1 = x_3$$

$$\dot{x}_2 = \frac{K_2}{B}x_1 - \frac{K_2}{B}x_2$$

$$\dot{x}_3 = -\frac{K_1 + K_2}{M}x_1 + \frac{K_2}{M}x_3$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

On arranging the state equations in the matrix form,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ \frac{K_2}{B} & -\frac{K_2}{B} & 0 \\ -\frac{K_1+K_2}{M} & 0 & \frac{K_2}{M} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \qquad .....(4.4.5)$$

If the desired outputs are y_1 and y_2, then $y_1 = x_1$ and $y_2 = x_2$

EXAMPLE

Obtain the state model of the electrical network shown in fig 4.1.1 by choosing minimal number of state variables.

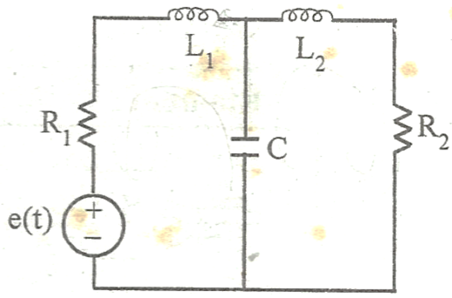


Fig 4.1.1.

SOLUTION

Let us choose the current through the inductances i_1, i_2 and voltage across the capacitor v_c as state variables. The assumed directions of currents and polarity of the voltage are shown in fig 4.1.2.

[*Note : The best choice of state variables in electrical network are currents and voltages in energy storage elements*].

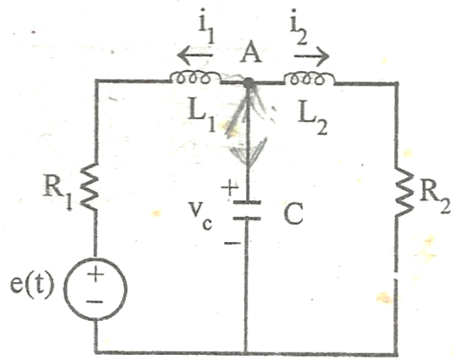


Fig 4.1.2.

Let the three state variables x_1, x_2 and x_3 be related to physical quantities as shown below.

$x_1 = i_1$ = Current through L_1

$x_2 = i_2$ = Current through L_2

$x_3 = v_c$ = Voltage across capacitor.

At node A, by Kirchoff's current law *(refer fig 4.1.3.)*,

$$i_1 + i_2 + C\frac{dv_c}{dt} = 0 \qquad .....(4.1.1)$$

On substituting the state variables for physical variables in equ (4.1.1) we get,

(i.e., $i_1 = x_1$, $i_2 = x_2$ and $\frac{dv_c}{dt} = \dot{x}_3$)

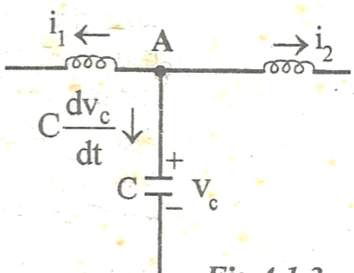


Fig 4.1.3.

$$x_1 + x_2 + C\dot{x}_3 = 0$$

$$C\dot{x}_3 = -x_1 - x_2$$

$$\dot{x}_3 = -\frac{1}{C}x_1 - \frac{1}{C}x_2 \qquad .....(4.1.2)$$

By Kirchoff's voltage law in the closed path shown in fig 4.1.4 we get,

$$e(t) + i_1R_1 + L_1\frac{di_1}{dt} = v_c \qquad .....(4.1.3)$$

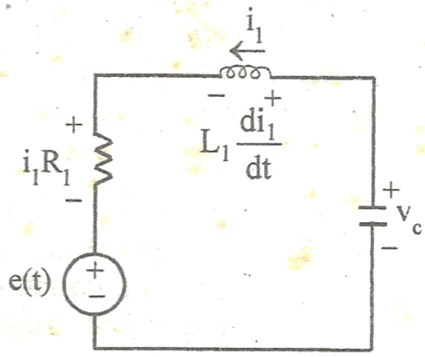


Fig 4.1.4.

On substituting the state variables for physical variables in equ (4.1.3) we get,

(i.e., $i_1 = x_1$, $\frac{di_1}{dt} = \dot{x}_1$ and $v_c = x_3$)

$$e(t) + x_1R_1 + L_1\dot{x}_1 = x_3$$

Also, let u(t) = e(t) = input to the system

$$\therefore u + x_1R_1 + L_1\dot{x}_1 = x_3$$

$$L_1\dot{x}_1 = x_3 - x_1R_1 - u$$

$$\dot{x}_1 = -\frac{R_1}{L_1}x_1 + \frac{1}{L_1}x_3 - \frac{1}{L_1}u \quad .....(4.1.4)$$

By Kirchoff's voltage law in the closed path shown in fig 4.1.5 we get,

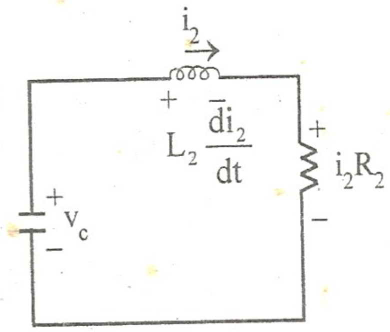


Fig 4.1.5.

$$v_c = L_2\frac{di_2}{dt} + i_2R_2 \quad .....(4.1.5)$$

On substituting the state variables for physical variables in equ (4.1.5) we get,

(i.e., $i_2 = x_2$, $\frac{di_2}{dt} = \dot{x}_2$ and $v_c = x_3$)

$$x_3 = L_2\dot{x}_2 + x_2R_2$$

$$\therefore L_2\dot{x}_2 = -x_2R_2 + x_3$$

$$\dot{x}_2 = -\frac{R_2}{L_2}x_2 + \frac{1}{L_2}x_3 \quad .....(4.1.6)$$

The equations (4.1.2), (4.1.4) and (4.1.6.) are the state equations of the system. Hence the state equations of the system are,

$$\dot{x}_1 = -\frac{R_1}{L_1}x_1 + \frac{1}{L_1}x_3 - \frac{1}{L_1}u$$

$$\dot{x}_2 = -\frac{R_2}{L_2}x_2 + \frac{1}{L_2}x_3$$

$$\dot{x}_3 = -\frac{1}{C}x_1 - \frac{1}{C}x_2$$

On arranging the state equations in the matrix form we get,

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix}-\frac{R_1}{L_1} & 0 & \frac{1}{L_1}\\ 0 & -\frac{R_2}{L_2} & \frac{1}{L_2}\\ -\frac{1}{C} & -\frac{1}{C} & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}-\frac{1}{L_1}\\ 0\\ 0\end{bmatrix}[u] \quad \text{State equation .....(4.1.7)}$$

Let us choose the voltage across the resistances as output variables and the output variables are denoted by y_1 and y_2.

$$\therefore y_1 = i_1 R_1 \qquad .....(4.1.8)$$

and $$y_2 = i_2 R_2 \qquad .....(4.1.9)$$

On substituting the state variables in equations (4.1.8) and (4.1.9) we get, (i.e., $i_1 = x_1$ and $i_2 = x_2$)

$$y_1 = x_1 R_1 \quad ; \quad y_2 = x_2 R_2$$

On arranging the above equations in the matrix form we get

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} R_1 & 0 \\ 0 & R_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad \text{output equation} \qquad .....(4.1.10)$$

The state equation [equ (4.1.7)] and output equation [equ (4.1.10)] together constitute the state model of the system.

EXAMPLE

Obtain the state model of the electrical network shown in fig 4.2.1. by choosing $v_1(t)$ and $v_2(t)$ as state variables.

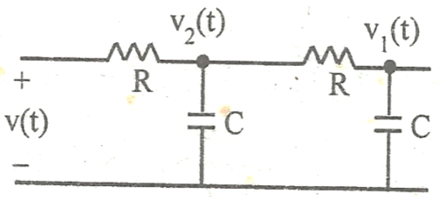


Fig 4.2.1.

SOLUTION

Connect a voltage source at the input as shown in fig 4.2.2.

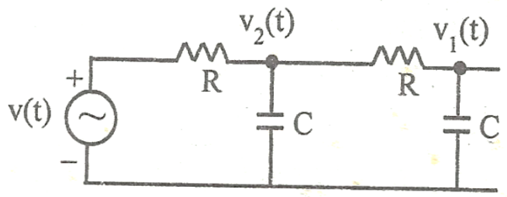


Fig 4.2.2.

Convert the voltage source to current source as shown in fig 4.2.3.

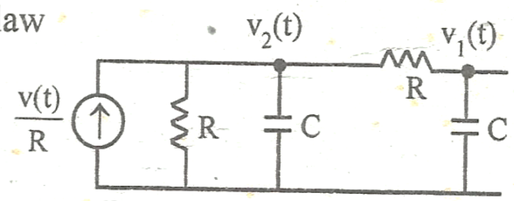


Fig 4.2.3.

At node 1, by Kirchoff's current law we can write *(refer fig 4.2.4)*

$$\frac{v_1 - v_2}{R} + C\frac{dv_1}{dt} = 0 \qquad .....(4.2.1)$$

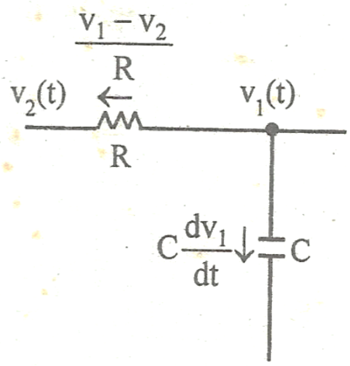


Fig 4.2.4

At node 2, by Kirchoff's current law, we can write *(Refer fig 4.2.5)*

$$\frac{v_2 - v_1}{R} + \frac{v_2}{R} + C\frac{dv_2}{dt} = \frac{v(t)}{R} \qquad .....(4.2.2)$$

Let the state variables be x_1 and x_2 and they are related to physical variable as shown below.

$$v_1 = x_1 \text{ and } v_2 = x_2$$

Also, Let $v(t) = u = \text{input}$.

On substituting the state variables in equations (4.2.1) and (4.2.2) we get,

$$\frac{x_1 - x_2}{R} + C\frac{dx_1}{dt} = 0 \quad .....(4.2.3)$$

$$\frac{x_2 - x_1}{R} + \frac{x_2}{R} + C\frac{dx_2}{dt} = \frac{u}{R} \quad .....(4.2.4)$$

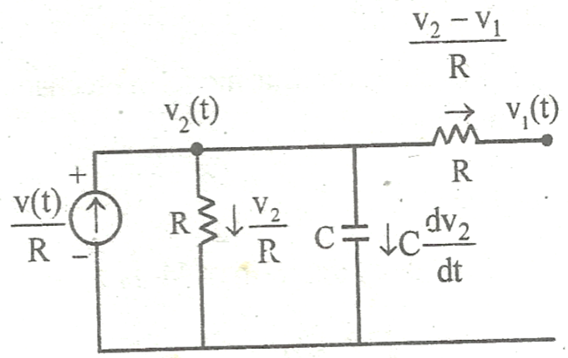


Fig 4.2.5

From equation (4.2.3) we get, $\frac{x_1}{R} - \frac{x_2}{R} + C\dot{x}_1 = 0$

$$\therefore C\dot{x}_1 = -\frac{x_1}{R} + \frac{x_2}{R}$$

$$\dot{x}_1 = -\frac{1}{RC}x_1 + \frac{1}{RC}x_2 \quad .....(4.2.5)$$

From equation (4.2.4) we get, $\frac{x_2}{R} - \frac{x_1}{R} + \frac{x_2}{R} + C\dot{x}_2 = \frac{u}{R}$

$$\therefore C\dot{x}_2 = \frac{x_1}{R} - \frac{x_2}{R} - \frac{x_2}{R} + \frac{u}{R}$$

$$\dot{x}_2 = \frac{1}{RC}x_1 - \frac{2}{RC}x_2 + \frac{1}{RC}u \quad .....(4.2.6)$$

The equation (4.2.5) and (4.2.6) are state equations of the system. Hence the state equations of the system are

$$\dot{x}_1 = -\frac{1}{RC}x_1 + \frac{1}{RC}x_2$$

$$\dot{x}_2 = \frac{1}{RC}x_1 - \frac{2}{RC}x_2 + \frac{1}{RC}u$$

On arranging the state equations in the matrix form,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} & \frac{1}{RC} \\ \frac{1}{RC} & \frac{-2}{RC} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{RC} \end{bmatrix} \begin{bmatrix} u \end{bmatrix} \quad .....(4.2.7)$$

The output, $y = v_1(t) = x_1$

$\therefore$ The output equation is $y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$ .....(4.2.8)

The state equation [equ (4.2.7)] and output equation [equ (4.2.8)] together constitute the state model of the system.

EXAMPLE

Construct a state model for a system characterized by the differential equation,

$$\frac{d^3y}{dt^3} + 6\frac{d^2y}{dt^2} + 11\frac{dy}{dt} + 6y + u = 0.$$

Give the block diagram representation of the state model.

SOLUTION

Let us choose y and their derivatives as state variables. The system is governed by third order differential equation and so the number of state variables are three.

The state variables x_1, x_2 and x_3 are related to phase variables as follows

$$x_1 = y$$

$$x_2 = \frac{dy}{dt} = \dot{x}_1$$

$$x_3 = \frac{d^2y}{dt^2} = \dot{x}_2$$

Put $y = x_1$, $\frac{dy}{dt} = x_2$ and $\frac{d^2y}{dt^2} = x_3$ and $\frac{d^3y}{dt^3} = \dot{x}_3$ in the given equation,

$$\therefore \dot{x}_3 + 6x_3 + 11x_2 + 6x_1 + u = 0$$

$$\text{or} \quad \dot{x}_3 = -6x_1 - 11x_2 - 6x_3 - u.$$

The state equations are

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = x_3$$

$$\dot{x}_3 = -6x_1 - 11x_2 - 6x_3 - u$$

On arranging the state equations in the matrix form we get,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -11 & -6 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix} [u]$$

Here, y = output

But, $y = x_1$

$$\therefore \text{The output equation is, } y = [1 \ \ 0 \ \ 0] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

The state equation and output equation, constitutes the state model of the system.

EXAMPLE 4.10

Obtain the state model of the system whose transfer function is given as,

$$\frac{Y(s)}{U(s)} = \frac{10}{s^3 + 4s^2 + 2s + 1}$$

SOLUTION

Given that, $$\frac{Y(s)}{U(s)} = \frac{10}{s^3 + 4s^2 + 2s + 1} \qquad .....(4.10.1)$$

On cross multiplying the equ (4.10.1) we get,

$$Y(s)\left[s^3 + 4s^2 + 2s + 1\right] = 10\,U(s)$$

$$s^3Y(s) + 4s^2Y(s) + 2s\,Y(s) + Y(s) = 10\,U(s) \qquad .....(4.10.2)$$

On taking inverse laplace transform of equ (4.10.2) we get,

$$\dddot{y} + 4\,\ddot{y} + 2\,\dot{y} + y = 10\,u. \qquad .....(4.10.3)$$

Let us define state variables as follows,

$$x_1 = y \quad ; \quad x_2 = \dot{y} \quad ; \quad x_3 = \ddot{y}$$

Put $\ddot{y} = \dot{x}_3$; $\ddot{y} = x_3$; $\dot{y} = x_2$ and $y = x_1$ in the equation (4.10.3)

$$\therefore \dot{x}_3 + 4x_3 + 2x_2 + x_1 = 10u$$

$$\text{or } \dot{x}_3 = -x_1 - 2x_2 - 4x_3 + 10u.$$

The state equations are

$$\dot{x}_1 = x_2 \quad ; \quad \dot{x}_2 = x_3 \quad ; \quad \dot{x}_3 = -x_1 - 2x_2 - 4x_3 + 10u.$$

The output equation is $y = x_1$

The state model in the matrix form is,

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -2 & -4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 10 \end{bmatrix} [u]$$

$$y = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

Statespace model into transfer function model

1. The state space representation of a system is given below:

$$\begin{pmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \end{pmatrix} = \begin{pmatrix} -2 & 1 & 0 \\ 0 & -3 & 1 \\ -3 & -4 & -5 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} u \ ; \ y = (0\ 1\ 0) \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}$$

Obtain the transfer function.

Solution

$$A = \begin{pmatrix} -2 & 1 & 0 \\ 0 & -3 & 1 \\ -3 & -4 & -5 \end{pmatrix} ; B = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \ ; \ C = (0\ 1\ 0)$$

Transfer function = $\frac{Y(s)}{U(s)} = C(SI - A)^{-1}B + D$

$$(SI - A) = \begin{pmatrix} s & 0 & 0 \\ 0 & s & 0 \\ 0 & 0 & s \end{pmatrix} - \begin{pmatrix} -2 & 1 & 0 \\ 0 & -3 & 1 \\ -3 & -4 & -5 \end{pmatrix} = \begin{pmatrix} s+2 & -1 & 0 \\ 0 & s+3 & -1 \\ 3 & 4 & s+5 \end{pmatrix}$$

$$(SI - A)^{-1} = \frac{Adj\ (sI - A)}{\det(sI - A)}$$

$$det(sI - A) = \begin{vmatrix} s+2 & -1 & 0 \\ 0 & s+3 & -1 \\ 3 & 4 & s+5 \end{vmatrix}$$

$$= (s+2)\{(s+3)(s+5) - (-4)\} - 1\{0(s+5) - (-3)\} + 0\{0 - 3(s+3)$$

$$= (s+2)(s^2 + 8s + 19) - 3)$$

$$= s^3 + 10s^2 + 35s + 41$$

$$Adj\ (sI - A) = (cofactor\ (sI - A))^T$$

$$= \begin{pmatrix} +\begin{vmatrix} (s+3) & -1 \\ 4 & (s+5) \end{vmatrix} & -\begin{vmatrix} 0 & -1 \\ 3 & (s+5) \end{vmatrix} & +\begin{vmatrix} 0 & (s+3 \\ 3 & 4 \end{vmatrix} \\ -\begin{vmatrix} -1 & 0 \\ 4 & (s+5 \end{vmatrix} & +\begin{vmatrix} (s+2) & 0 \\ 3 & (s+5) \end{vmatrix} & -\begin{vmatrix} (s+2) & -1 \\ 3 & 4 \end{vmatrix} \\ +\begin{vmatrix} -1 & 0 \\ (s+3) & -1 \end{vmatrix} & -\begin{vmatrix} (s+2) & 0 \\ 0 & -1 \end{vmatrix} & +\begin{vmatrix} (s+2) & -1 \\ 0 & (s+3) \end{vmatrix} \end{pmatrix}^T$$

$$= \begin{pmatrix} (s^2 + 8s + 19) & 3 & (3s+9) \\ (s+5) & (s^2 + 7s + 10) & -(4s+11) \\ 1 & (s+2) & (s^2 + 5s + 6) \end{pmatrix}^T$$

$$= \begin{pmatrix} (s^2 + 8s + 19) & (s+5) & 1 \\ 3 & (s^2 + 7s + 10) & (s+2) \\ (3s+9) & -(4s+11) & (s^2 + 5s + 6) \end{pmatrix}$$

$$(SI-A)^{-1} = \frac{Adj\,(sI-A)}{\det(sI-A)}$$

$$= \frac{1}{s^3+10s^2+35s+41}\begin{pmatrix} (s^2+8s+19) & (s+5) & 1 \\ 3 & (s^2+7s+10) & (s+2) \\ (3s+9) & -(4s+11) & (s^2+5s+6) \end{pmatrix}$$

$C(SI-A)^{-1}$

$$= (0 \quad 1 \quad 0)\ \frac{1}{s^3+10s^2+35s+41}\begin{pmatrix} (s^2+8s+19) & (s+5) & 1 \\ 3 & (s^2+7s+10) & (s+2) \\ (3s+9) & -(4s+11) & (s^2+5s+6) \end{pmatrix}$$

$$= \frac{1}{s^3+10s^2+35s+41}(3 \quad (s^2+7s+10) \quad (s+2))$$

$$C(SI-A)^{-1}B = \frac{1}{s^3+10s^2+35s+41}((s+5) \quad (s^2+7s+10) \quad -(4s+11))\begin{pmatrix}0\\0\\1\end{pmatrix}$$

$$\frac{Y(s)}{U(s)} = \frac{(s+2)}{s^3+10s^2+35s+41}$$

2. Determine the controllability and observability of the following system.

$$\begin{pmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{pmatrix} = \begin{pmatrix}\mathbf{0} & \mathbf{1} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{1}\\ \mathbf{0} & \mathbf{-2} & \mathbf{-3}\end{pmatrix}\begin{pmatrix}\boldsymbol{x_1}\\ \boldsymbol{x_2}\\ \boldsymbol{x_3}\end{pmatrix} + \begin{pmatrix}\mathbf{0}\\ \mathbf{0}\\ \mathbf{10}\end{pmatrix}\boldsymbol{u}; \quad \boldsymbol{y} = (\mathbf{1} \quad \mathbf{0} \quad \mathbf{0})\begin{pmatrix}x_1\\ x_2\\ x_3\end{pmatrix}$$

Solution

$$A = \begin{pmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & -2 & -3\end{pmatrix};\ B = \begin{pmatrix}0\\0\\10\end{pmatrix};\ C = (1\ 0\ 0)$$

Transfer function = $\frac{Y(s)}{U(s)} = C(SI-A)^{-1}B + D$

$$(SI-A) = \begin{pmatrix}s & 0 & 0\\ 0 & s & 0\\ 0 & 0 & s\end{pmatrix} - \begin{pmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & -2 & -3\end{pmatrix} = \begin{pmatrix}s & -1 & 0\\ 0 & s & -1\\ 0 & 2 & s+3\end{pmatrix}$$

$$(SI-A)^{-1} = \frac{Adj\,(sI-A)}{\det(sI-A)}$$

$$det(sI-A) = \begin{vmatrix}s & -1 & 0\\ 0 & s & -1\\ 0 & 2 & s+3\end{vmatrix}$$

$$= s\{s(s+3)-(-2)\} + 1\{0\} + 0\{0\}$$

$$= s(s^2+6s+4)$$

$$= s^3+6s^2+4s$$

$$Adj\ (sI - A) = (cofactor\ (sI - A))^T = \begin{pmatrix} +\begin{vmatrix} s & -1 \\ 2 & s+3 \end{vmatrix} & -\begin{vmatrix} 0 & -1 \\ 0 & (s+3) \end{vmatrix} & +\begin{vmatrix} 0 & s \\ 0 & 2 \end{vmatrix} \\ -\begin{vmatrix} -1 & 0 \\ 2 & (s+3) \end{vmatrix} & +\begin{vmatrix} s & 0 \\ 0 & (s+3) \end{vmatrix} & -\begin{vmatrix} s & -1 \\ 0 & 2 \end{vmatrix} \\ +\begin{vmatrix} -1 & 0 \\ s & -1 \end{vmatrix} & -\begin{vmatrix} s & 0 \\ 0 & -1 \end{vmatrix} & +\begin{vmatrix} s & -1 \\ 0 & s \end{vmatrix} \end{pmatrix}^T$$

$$= \begin{pmatrix} (s^2+3s+2) & 0 & 0 \\ (s+3) & (s^2+3s) & -2s \\ 1 & s & s^2 \end{pmatrix}^T$$

$$\begin{pmatrix} (s^2+3s+2) & (s+3) & 1 \\ 0 & (s^2+3s) & s \\ 0 & -2s & s^2 \end{pmatrix}$$

$$(SI - A)^{-1} = \frac{Adj\ (sI - A)}{\det(sI - A)} = \frac{1}{s^3 + 6s^2 + 4s}\begin{pmatrix} (s^2+3s+2) & (s+3) & 1 \\ 0 & (s^2+3s) & s \\ 0 & -2s & s^2 \end{pmatrix}$$

$$C(SI - A)^{-1} = (1 \quad 1 \quad 0)\ \frac{1}{s^3 + 6s^2 + 4s}\begin{pmatrix} (s^2+3s+2) & (s+3) & 1 \\ 0 & (s^2+3s) & s \\ 0 & -2s & s^2 \end{pmatrix}$$

$$= \frac{1}{s^3 + 6s^2 + 4s}((s^2+3s+2) \quad (s^2+4s+3) \quad (s+1))$$

$$C(SI - A)^{-1}B == \frac{1}{s^3 + 6s^2 + 4s}((s^2+3s+2) \quad (s^2+4s+3) \quad (s+1))\begin{pmatrix} 0 \\ 0 \\ 10 \end{pmatrix}$$

$$\frac{Y(s)}{U(s)} = \frac{10(s+1)}{s^3 + 6s^2 + 4s}$$

Controllability and Observability

Kalman's method of testing controllability and obsevability

Controllability

A system is said to be completely controllable if it is possible to transfer the system state from any initial state $X(t_o)$ at any other desired state X(t), in specified finite time by a control vector U(t)

$$Q_c = [B \quad AB \quad A^2B]$$

If rank and order of Q_c are equal then, the system is controllable

Observability

A system is said to be completely observable if every state X(t) can be completely identified by measurements of the output Y(t) over a finite time interval.

$$Q_0 = \ [C^T \quad A^TC^T \quad (A^T)^2C^T]$$

If rank and order of Q_c are equal then, the system is obsevable

Problems

1. Determine the controllability and observability of the following system.

$$\begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -2 & -3 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 10 \end{pmatrix} u \ ; \quad y = (1\ 0\ 0) \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}$$

Solution

$$A = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -2 & -3 \end{pmatrix} ; B = \begin{pmatrix} 0 \\ 0 \\ 10 \end{pmatrix} \ ; \quad C = (1\ 0\ 0)$$

Controllability

$$Q_c = (B \quad AB \quad A^2B)$$

$$B = \begin{pmatrix} 0 \\ 0 \\ 10 \end{pmatrix}$$

$$A.B = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -2 & -3 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 10 \end{pmatrix} = \begin{pmatrix} 0 \\ 10 \\ -30 \end{pmatrix}$$

$$A^2 = A.A = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -2 & -3 \end{pmatrix} \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -2 & -3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & -2 & -3 \\ 0 & 6 & 7 \end{pmatrix}$$

$$A^2B = \begin{pmatrix} 0 & 0 & 1 \\ 0 & -2 & -3 \\ 0 & 6 & 7 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 10 \end{pmatrix} = \begin{pmatrix} 10 \\ -30 \\ 70 \end{pmatrix}$$

$$Q_c = [B \quad AB \quad A^2B] = \begin{pmatrix} 0 & 0 & 10 \\ 0 & 10 & -30 \\ 10 & -30 & 70 \end{pmatrix}$$

$$|Q_c| = 10(-100) = -1000 \neq 0$$

$$Rank = Order = 3 \quad \therefore System\ is\ controllable$$

Obsevability

$$Q_0 = \begin{pmatrix} C \\ AC \\ A^2C \end{pmatrix} = (C^T \quad A^T C^T \quad (A^T)^2 C^T)$$

$$A^T = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & -2 \\ 0 & 1 & -3 \end{pmatrix} ; C^T = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

$$A^T C^T = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & -2 \\ 0 & 1 & -3 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

$$A^{T^2} = A^T A^T = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & -2 \\ 0 & 1 & -3 \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & -2 \\ 0 & 1 & -3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -2 & 6 \\ 1 & -3 & 7 \end{pmatrix}$$

$$A^{T^2} C^T = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -2 & 6 \\ 1 & -3 & 7 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

$$Q_0 = \;[C^T \quad A^T C^T \quad (A^T)^2 C^T] = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$|Q_0| = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{vmatrix} = 1(1) = 1 \neq 0$$

$Order = Rank = 3;\ \therefore\ system\ is\ observable$

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2. Determine the controllability and observability of the following system.

$$\begin{pmatrix} \boldsymbol{X_1} \\ \boldsymbol{X_2} \\ \boldsymbol{X_3} \end{pmatrix} = \begin{pmatrix} \mathbf{1} & \mathbf{2} & \mathbf{1} \\ \mathbf{0} & \mathbf{1} & \mathbf{0} \\ \mathbf{1} & \mathbf{-4} & \mathbf{3} \end{pmatrix} \begin{pmatrix} \boldsymbol{x_1} \\ \boldsymbol{x_2} \\ \boldsymbol{x_3} \end{pmatrix} + \begin{pmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{1} \end{pmatrix} \boldsymbol{u}\ ;\ \ \boldsymbol{y} = (\mathbf{1} \quad \mathbf{1} \quad \mathbf{0}) \begin{pmatrix} \boldsymbol{x_1} \\ \boldsymbol{x_2} \\ \boldsymbol{x_3} \end{pmatrix}$$

Controllability

$$Q_c = [B \quad AB \quad A^2 B]$$

$$B = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

$$A.B = \begin{pmatrix} 1 & 2 & 1 \\ 0 & 1 & 0 \\ 1 & -4 & 3 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 3 \end{pmatrix}$$

$$A^2 = A.A = \begin{pmatrix} 1 & 2 & 1 \\ 0 & 1 & 0 \\ 1 & -4 & 3 \end{pmatrix} \begin{pmatrix} 1 & 2 & 1 \\ 0 & 1 & 0 \\ 1 & -4 & 3 \end{pmatrix} = \begin{pmatrix} 2 & 0 & 4 \\ 0 & 1 & 0 \\ 4 & -14 & 10 \end{pmatrix}$$

$$A^2 B = \begin{pmatrix} 2 & 0 & 4 \\ 0 & 1 & 0 \\ 4 & -14 & 10 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 4 \\ 0 \\ 10 \end{pmatrix}$$

$$Q_c = [B \quad AB \quad A^2 B] = \begin{pmatrix} 0 & 1 & 4 \\ 0 & 0 & 0 \\ 1 & 3 & 10 \end{pmatrix}$$

$$|Q_c| = -1(0) + 4(0) = 0$$

$Rank\ \neq 3\ \ \therefore System\ is\ uncontrollable$

Obsevability

$$Q_0 = \begin{pmatrix} C \\ AC \\ A^2C \end{pmatrix} = (C^T \quad A^TC^T \quad (A^T)^2C^T)$$

$$A^T = \begin{pmatrix} 1 & 0 & 1 \\ 2 & 1 & -4 \\ 1 & 0 & 3 \end{pmatrix}; C^T = \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}$$

$$A^TC^T = \begin{pmatrix} 1 & 0 & 1 \\ 2 & 1 & -4 \\ 1 & 0 & 3 \end{pmatrix}\begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 \\ 3 \\ 1 \end{pmatrix}$$

$$A^{T^2} = A^TA^T = \begin{pmatrix} 1 & 0 & 1 \\ 2 & 1 & -4 \\ 1 & 0 & 3 \end{pmatrix}\begin{pmatrix} 1 & 0 & 1 \\ 2 & 1 & -4 \\ 1 & 0 & 3 \end{pmatrix} = \begin{pmatrix} 2 & 0 & 4 \\ 0 & 1 & -14 \\ 4 & 0 & 10 \end{pmatrix}$$

$$A^{T^2}C^T = \begin{pmatrix} 2 & 0 & 4 \\ 0 & 1 & -14 \\ 4 & 0 & 10 \end{pmatrix}\begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 2 \\ 1 \\ 4 \end{pmatrix}$$

$$Q_0 = [C^T \quad A^TC^T \quad (A^T)^2C^T] = \begin{pmatrix} 1 & 1 & 2 \\ 1 & 3 & 1 \\ 0 & 1 & 4 \end{pmatrix}$$

$$|Q_0| = \begin{vmatrix} 1 & 1 & 2 \\ 1 & 3 & 1 \\ 0 & 1 & 4 \end{vmatrix} = 1(12-1) - 1(4) + 2(1) = 9 \neq 0$$

$$Order = Rank = 3; \therefore system\ is\ observable$$

EXAMPLE 3

Write the state equations for the system shown in fig 5.6.1 in which x_1, x_2 and x_3 constitute the state vector. Determine whether the system is completely controllable and observable.

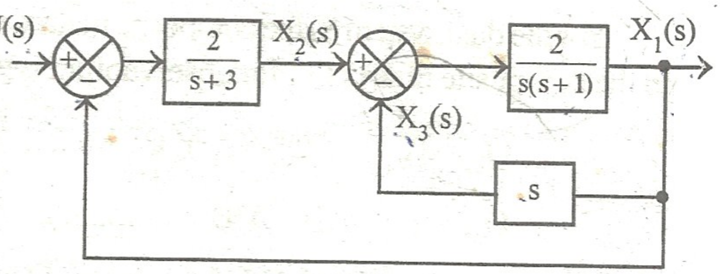


Fig 5.6.1

SOLUTION

To find state model

The state equations are obtained by writing equations for the output of each block and then taking inverse Laplace transform.

With reference to fig 5.6.2 we can write,

$$X_1(s) = [X_2(s) - X_3(s)]\left[\frac{2}{s(s+1)}\right]$$

$$s(s+1)\ X_1(s) = 2X_2(s) - 2X_3(s)$$

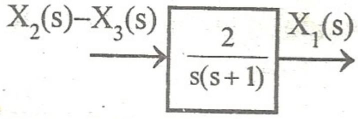


Fig 5.6.2

$$s^2 X_1(s) + s X_1(s) = 2X_2(s) - 2X_3(s)$$

On taking inverse laplace transform,

$$\ddot{x}_1 + \dot{x}_1 = 2x_2 - 2x_3 \qquad .....(5.6.1)$$

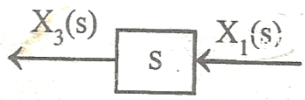


Fig 5.6.3

With reference to fig 5.6.3, we can write,

$$X_3(s) = sX_1(s)$$

On taking inverse laplace transform

$$x_3 = \dot{x}_1 \qquad .....(5.6.2)$$

With reference to fig 5.6.4 we can write

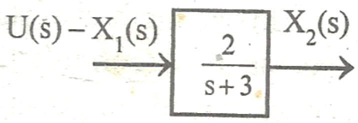


Fig 5.6.4

$$X_2(s) = [U(s) - X_1(s)]\left[\frac{2}{s+3}\right]$$

$$X_2(s)(s+3) = 2U(s) - 2X_1(s)$$

$$sX_2(s) + 3X_2(s) = 2U(s) - 2X_1(s)$$

On taking inverse Laplace transform

$$\dot{x}_2 + 3x_2 = 2u - 2x_1$$

$$\dot{x}_2 = -2x_1 - 3x_2 + 2u \qquad .....(5.6.3)$$

From equ(5.6.2) we get, $\dot{x}_1 = x_3$; $\therefore \ddot{x}_1 = \dot{x}_3$

Put $\dot{x}_1 = x_3$ and $\ddot{x}_1 = \dot{x}_3$ in equation (5.6.1)

$$\therefore \dot{x}_3 + x_3 = 2x_2 - 2x_3$$

$$\dot{x}_3 = 2x_2 - 2x_3 - x_3$$

$$\dot{x}_3 = 2x_2 - 3x_3 \qquad .....(5.6.4)$$

The state equation are given by equations (5.6.2), (5.6.3) and (5.6.4)

$$\dot{x}_1 = x_3$$

$$\dot{x}_2 = -2x_1 - 3x_2 + 2u$$

$$\dot{x}_3 = 2x_2 - 3x_3$$

The output equation is $y = x_1$

The state model in the matrix form is

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix}0 & 0 & 1\\ -2 & -3 & 0\\ 0 & 2 & -3\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0\\ 2\\ 0\end{bmatrix}u \quad ; \quad y = \begin{bmatrix}1 & 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix}$$

KALMAN'S TEST FOR CONTROLLABILITY

$$A^2 = A.A = \begin{bmatrix} 0 & 0 & 1 \\ -2 & -3 & 0 \\ 0 & 2 & -3 \end{bmatrix}\begin{bmatrix} 0 & 0 & 1 \\ -2 & -3 & 0 \\ 0 & 2 & -3 \end{bmatrix} = \begin{bmatrix} 0 & 2 & -3 \\ 6 & 9 & -2 \\ -4 & -12 & 9 \end{bmatrix}$$

$$A.B = \begin{bmatrix} 0 & 0 & 1 \\ -2 & -3 & 0 \\ 0 & 2 & -3 \end{bmatrix}\begin{bmatrix} 0 \\ 2 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ -6 \\ 4 \end{bmatrix}$$

$$A^2.B = \begin{bmatrix} 0 & 2 & -3 \\ 6 & 9 & -2 \\ -4 & -12 & 9 \end{bmatrix}\begin{bmatrix} 0 \\ 2 \\ 0 \end{bmatrix} = \begin{bmatrix} 4 \\ 18 \\ -24 \end{bmatrix}$$

The composite matrix for controllability, $Q_c = \begin{bmatrix} B & AB & A^2B \end{bmatrix}$

$$= \begin{bmatrix} 0 & 0 & 4 \\ 2 & -6 & 18 \\ 0 & 4 & -24 \end{bmatrix}$$

Determinant of $Q_c = \begin{vmatrix} 0 & 0 & 4 \\ 2 & -6 & 18 \\ 0 & 4 & -24 \end{vmatrix} = 4 \times 8 = 32$; Since $|Q_c| \neq 0$, the rank of $Q_c = 3$.

Hence the system is completely state controllable

KALMAN'S TEST FOR OBSERVABILITY

$$A^T = \begin{bmatrix} 0 & 0 & 1 \\ -2 & -3 & 0 \\ 0 & 2 & -3 \end{bmatrix}^T = \begin{bmatrix} 0 & -2 & 0 \\ 0 & -3 & 2 \\ 1 & 0 & -3 \end{bmatrix}$$

$$C^T = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^T = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$\left(A^T\right)^2 = \begin{bmatrix} 0 & -2 & 0 \\ 0 & -3 & 2 \\ 1 & 0 & -3 \end{bmatrix}\begin{bmatrix} 0 & -2 & 0 \\ 0 & -3 & 2 \\ 1 & 0 & -3 \end{bmatrix} = \begin{bmatrix} 0 & 6 & -4 \\ 2 & 9 & -12 \\ -3 & -2 & 9 \end{bmatrix}$$

$$A^TC^T = \begin{bmatrix} 0 & -2 & 0 \\ 0 & -3 & 2 \\ 1 & 0 & -3 \end{bmatrix}\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

$$\left(A^T\right)^2 C^T = \begin{bmatrix} 0 & 6 & -4 \\ 2 & 9 & -12 \\ -3 & -2 & 9 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 2 \\ -3 \end{bmatrix}$$

$$\left.\begin{matrix}\text{The composite matrix} \\ \text{for observability}\end{matrix}\right\} Q_o = \left[C^T \;\; A^T C^T \;\; \left(A^T\right)^2 C^T\right] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 2 \\ 0 & 1 & -3 \end{bmatrix}$$

$$\text{Determinant of } Q_o = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 0 & 2 \\ 0 & 1 & -3 \end{vmatrix} = 1 \times -2 = -2 \; ; \quad \text{Since } |Q_o| \neq 0, \quad \text{the rank of } Q_o = 3$$

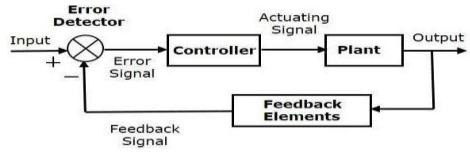
Hence the system is completely observable. (or all the state variables of the system are observable).

UNIT I – SYSTEMS AND REPRESENTATION

PART A

1) **Mention the basic elements of a control system. (Nov 2014) (May/June 2016)**

Error detector or comparator, controller, actuator or final control element, plant (system to be controlled) and feedback element (sensor or transmitters) are the basic elements of a control system.



2) **Define open loop and closed loop system. (Nov 2017)**

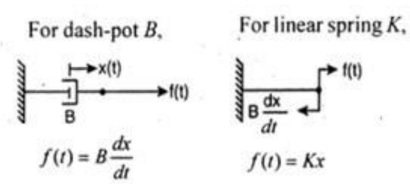
The control system in which the output quantity has no effect upon the input quantity is called open loop control system. The input has no feedback from the output.

The control system in which the output has an effect upon the input quantity so as to maintain the desired output values are called closed loop control system

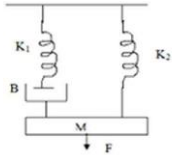
3) **Distinguish between open loop and closed loop system (Nov 2019)**

Sl. No	Open loop	Closed loop
1.	Any Change in output has no effect on the input.	Changes in output, affects the input which of possible by use of feedback.
2.	Feedback element is absent.	Feedback element is present.
3.	Simple and economical	Complex and costly
4.	They are generally stable	Great efforts are needed to design a stable system
5.	These are not reliable	These are reliable
6.	If calibration is good, they perform accurately	They are accurate because of feedback
7.	Highly affected by nonlinearities	Reduced effect of nonlinearities

4)	**What are the advantages and disadvantages of open loop control systems? (June2014)** Advantages 1. Open loop systems are simple in design and hence economical. 2. Very much convenient when output is difficult to measure. 3. The open loop systems are easier to construct. 4. Generally open loop systems are stable. Disadvantages 1. The open loop systems are not reliable. 2. The changes in the output due to external disturbances are not corrected automatically. 3. It cannot sense internal disturbances.
5)	**State any two advantages of feedback control system (or) State the advantages of closed loop system over open loop system (May/June 2015)** i) The controlled variable accurately follows the desired value. The feedback in the control loop allows accurate control of the output. ii) It greatly improves the speed of its response.
6)	**Why closed loop systems have a tendency to oscillate?** Controller takes corrective action based on the difference between input and feedback from the output. The output depends upon the controller action and so it has the tendency to oscillate.
7)	**Why negative feedback is preferred in control systems? (Nov 2016) (May 2017)** The negative feedback results in better stability in steady state and rejects any disturbance signals. Negative feedback leads to a tight control situation thereby the corrective action taken by the controller forces the controlled variable toward the set point.

8)	**List the characteristics of negative feedback in control system. (April/May2018)** • Accuracy in tracking steady state value. • Rejection of disturbance signals. • Low sensitivity to parameter variations. • Reduction in gain at the expense of better stability.
9)	**What is the mathematical model of a system?** Mathematical model is the mathematical representation of the physical model of a system through use of appropriate physical laws. For most physical systems they are characterized by differential equations. A mathematical model may either be time variant or time invariant.
10)	**Define the Transfer function of a system. (Nov2010, Nov 2013) (Nov2014) (May 2021)** The transfer function of a system is defined as the ratio between Laplace transform of the output and Laplace transform of the input when initial conditions are zero.
11)	**Write the force balance equation of ideal dashpot and ideal spring. (May 2015)** 
12)	**State the laws governing mechanical rotational elements.** Newton's law, which states that the applied torque will be equal to the sum of torque produced by all mechanical rotational elements (moment of inertia, viscous friction coefficient, torsional spring stiffness)
13)	**What are the basic elements used for modeling mechanical translational system. (Nov 2017)** Mass(M), spring(K) and dashpot (B) are three basic elements used for modeling mechanical translational system.

14) **Write the differential equations of the mechanical system shown in figure**



$$B\frac{d}{dt}(x_1 - x_2) + K_1 x_1 = 0$$

$$M\frac{d^2x_2}{dt^2} + B(x_2 - x_1) + K_2 x_2 = F(t)$$

15) **Define servo mechanism. (Nov 2018)**

The servomechanism is a feedback control system in which the output is mechanical position (or) time derivatives of position (e.g. velocity & acceleration).

16) **What do you mean by analogous system?**

If two systems are said to be analogous to each other if the following two conditions are satisfied.

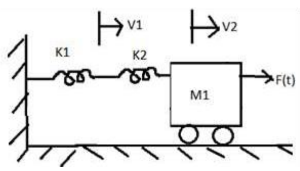
- The two systems are physically different
- Differential equation modelling of these two systems are same

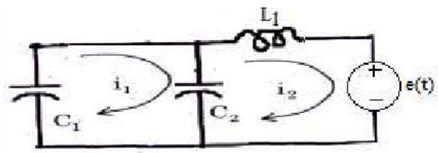
Electrical systems and mechanical systems are two physically different systems. There are two types of electrical analogies of translational mechanical systems. Those are force voltage analogy and force current analogy.

17) **Mention the equivalent electrical elements for the mass, damper, spring elements in mechanical system. / List the two types of electrical analogous for mechanical system.(May 2022)**

Mech.System Components	**Equivalent Electrical Elements**	
	Force – Voltage analogous	**Force – Current analogous**
Mass	Inductance (L)	Capacitance (C)
Damper	Resistance (R)	Reciprocal of resistance (1/R)
Spring	Reciprocal of capacitance (1/C)	Reciprocal of inductance (1/L)

18) **For the mechanical system shown in figure 1. Draw the corresponding Force-Voltage analogy circuit. (May 2019)**

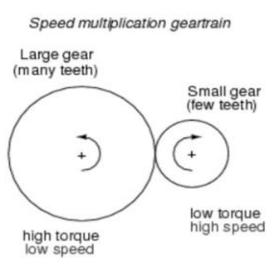


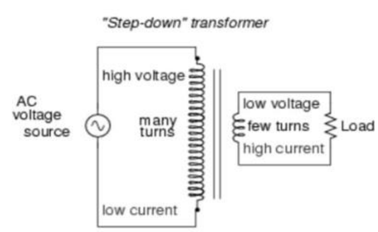


19) **Tabulate the parameters of the translational and rotational systems. (May 2019)**

S.No	Mechanical Translational system	Mechanical Rotational System
1.	Force (f)	Torque (T)
2.	Velocity (v)	Angular velocity (ω)
3.	Displacement (x)	Angular displacement(θ)
4.	Frictional Coefficient of Dashpot (B)	Rotational coefficient of dashpot (B)
5.	Mass (M)	Moment of Inertia (J)
6.	Stiffness of spring (K)	Stiffness of spring (K)

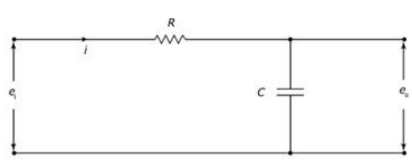
20) **What is electrical analogous of a gear?**

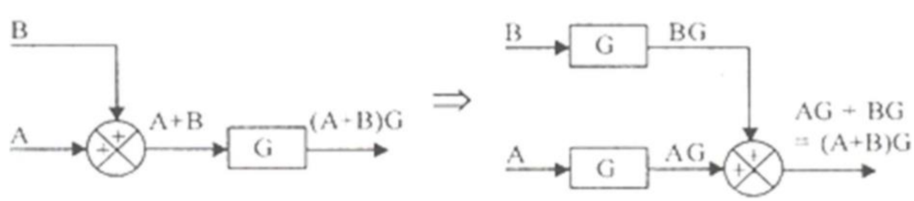




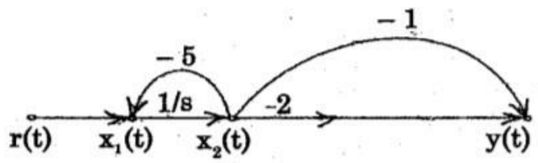
21) **Draw the electrical analog of thermometer. (Nov 2015)**

The thermometer is assumed to have a thermal capacitance C which stores heat and thermal resistance R which limits that flow.



22)	**What is block diagram? State its components. (May 2017)** A Block Diagram of a system is a pictorial representation of the functions performed by each component of the system and shows the flow of signals. The basic elements of block diagram are blocks, branch point and summing point.
23)	**What are the disadvantages of block diagram representation? (Nov 2018)** i) Not suitable for MIMO system ii) Not suitable for nonlinear system iii) Reduction of block diagram is becoming tedious for complex systems. iv) It is time consuming.
24)	**Write the expressions for Mason's gain formula. (May2018)** According to Mason's Gain formula, Overall gain, $T(s) = \frac{\sum_{k=1,2...} P_k \Delta_k}{\Delta}$ Where, T = Transfer function of the system, P_k= forward path gain of k^{th} forward path Δ = 1 - (sum of individual loop gain) + (sum of gain products of all possible Combinations of two non-touching loops) - (sum of gain products of all possible combination of three non-touching loops) +................... Δ_K = Δ of the K^{th} forward path.
25)	**What is the advantage of Signal flow graph method?** (i) It follows a generalized procedure (ii) It is easier to simplify even if the system has complex structures (iii) Signal flow graph has a systematic approach, whereas block diagram reduction depends on the complexity of the system.
26)	**Represent the rule for moving a summing point ahead of a block. (May 2022)** 

27) **Find the transfer function for the signal flow graph showing in figure below.(Nov 2019)**



Forward Paths Gain:

$$P_1 = -\frac{2}{s}$$

$$P_2 = -\frac{1}{s}$$

Individual loop Gain:

$$P_{11} = -\frac{5}{s}$$

Calculation of Δ and Δ_K :

$\Delta = 1 - P_{11} = 1 + (-5/s) = \frac{(s+5)}{s}$

$\Delta_1 = 1$, $\Delta_2 = 1$

Transfer Function:

$T = \sum P_k \Delta_k / \Delta = (P_1 \Delta_1 + P_2 \Delta_2) / \Delta$

$$T(s) = \frac{\left(-\frac{2}{s}\right)[1] + \left(-\frac{1}{s}\right)[1]}{\frac{(s+5)}{s}} = \frac{\left(-\frac{3}{s}\right)}{\frac{(s+5)}{s}} = \frac{-3}{s+5}$$

28) **What are the memory elements in mechanical translational and electrical system?(May 2021)**

Mechanical Translational System Components	**Equivalent Electrical Elements**	
	Force – Voltage analogous	**Force – Current analogous**
Mass	Inductance (L)	Capacitance (C)

	Spring	Reciprocal of capacitance (1/C)	Reciprocal of inductance (1/L)

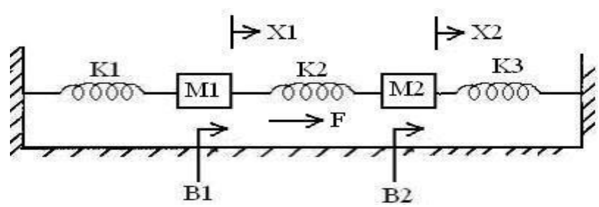
PART B

1) **(i)** Compare open loop and closed loop systems with examples**. (May 2016) (May 2017) (Nov 2018)**

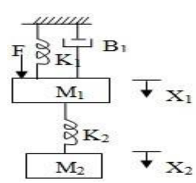
(ii) Derive the transfer function for an armature-controlled dc motor. **(Nov 2015) (Nov 2018) (May 2021)**

2) Define transfer function and derive the transfer function of field control DC servomotor. **(May 2019) (May 2022)**

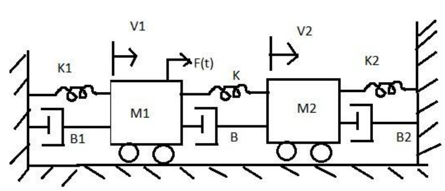
3) Write the differential equations governing the behaviour of the mechanical system shown in figure below. Obtain an analogous electric circuit based on force current analogy. **(April 2014)**



4) Write the differential equations governing the behaviour of the mechanical system shown in figure below. Draw the force voltage and force current electrical analogous circuits and verify by writing mesh and node equations**. (April 2011)**



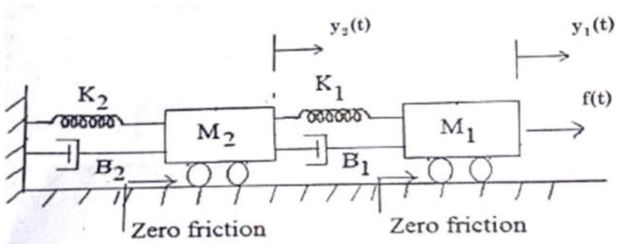
5) Write the differential equations governing the system and draw the force voltage and force current analogous circuit**. (May 2015)**



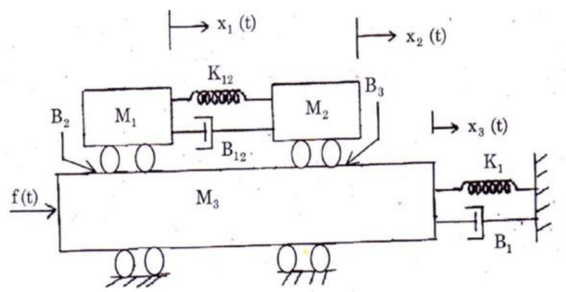
6) For the given system

(a) Draw the mechanical network diagram and hence write the differential equations describing the behavior of the system

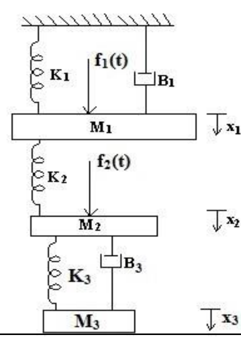
(b) Draw the force voltage and force current electrical analogous



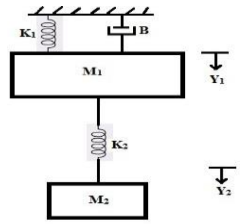
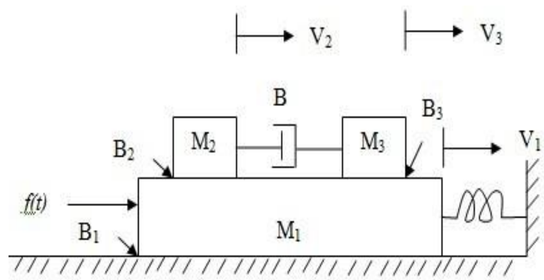
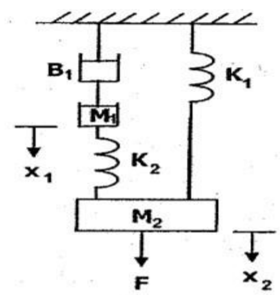
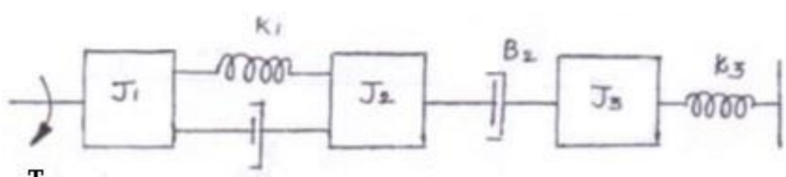
7) Write the differential equations governing the mechanical system shown in the figure. Draw the force –voltage and force current analogous circuits. **(Nov 2016)(Probable Part-C)**

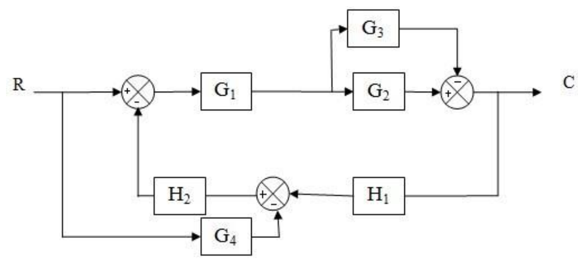
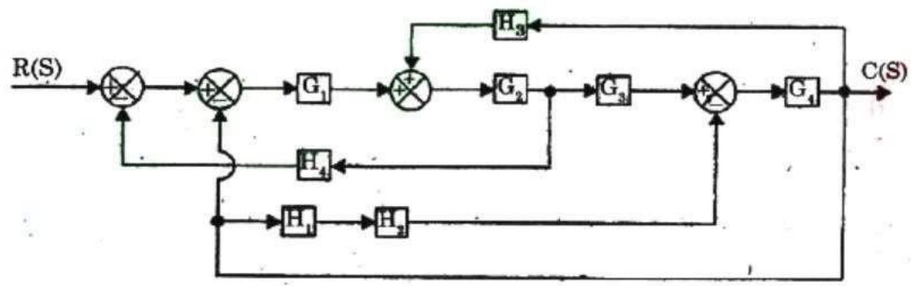
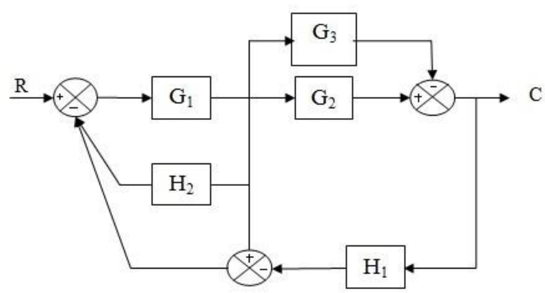
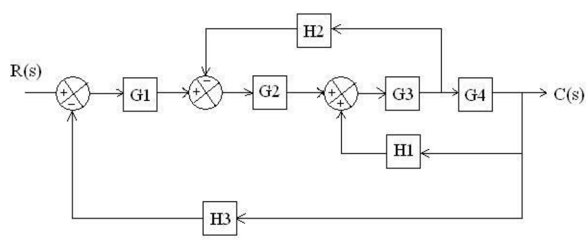


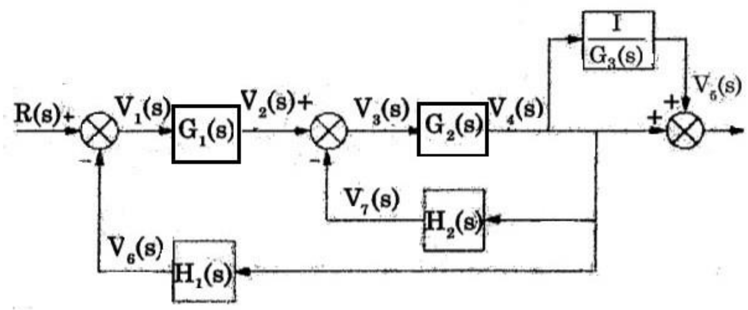
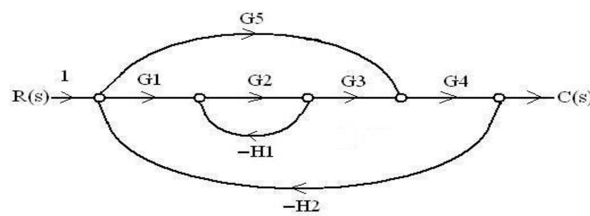
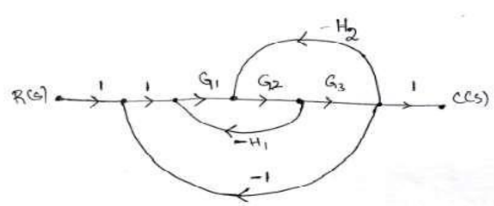
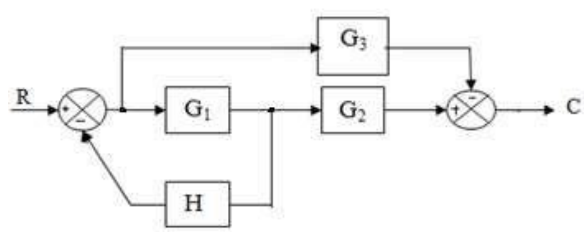
8) Write the differential equation governing the mechanical translational system shown in figure. Draw the electrical equivalent analogy circuit. **(May 2017) (May 2018)**

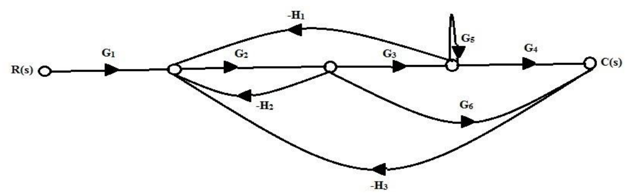


9) Find the transfer function $\frac{Y_2(s)}{f(s)}$. **(Nov 2017)**

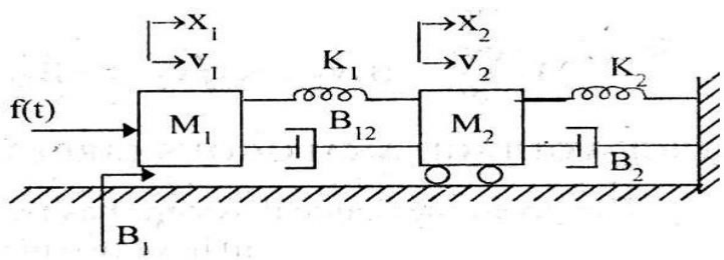
	
10)	Obtain the transfer function of the mechanical systems shown in the following figures. **(Nov 2018) (Probable Part-C)** 
11)	Find the transfer function $X_2(s)/F(s)$ for the figure shown below. **(Nov 2019)** 
12)	Write the differential equations governing the mechanical rotational system shown in the figure. Draw the both electrical analogous circuits**. (May 2016)** 
13)	Using block diagram reduction techniques find the closed loop transfer functions of the following system and verify it by using signal flow graph method. **(April 2011) (May 2019)**

	
14)	The block diagram of a closed loop system is shown in fig. using block diagram reduction technique; determine the closed loop transfer function. **(May 2018)** 
15)	Draw the signal flow graph and evaluate the closed loop transfer function of a system whose block diagram is given in the following figure. 
16)	Using block diagram reduction rules, convert the block diagram to a simple loop. **(Nov 2014)** 
17)	Reduce the block diagram shown in figure below. **(Nov 2019)**

	
18)	Consider the signal flow graph shown in figure. Obtain the closed loop transfer function C(s)/R(s) by the use of Mason's gain formula. **(April 2014)** 
19)	Obtain the transfer function using mason's gain formula for the given system. **(May 2015).** 
20)	For a non-unity negative feedback control system whose open loop transfer function is G(s) and feedback path transfer function is H(s), obtain the control ratio using mason's gain formula. **(Nov 2015)**
21)	Convert the given block diagram shown in the figure to signal flow graph and determine the closed loop transfer function C(S)/R(S **.(May 2016)** 
22)	Find the overall gain $\frac{C(s)}{R(s)}$ for the signal flow graph shown in Fig. **(Nov 2017)**



23) Write the differential equations governing the mechanical system shown in Fig.1. Draw the force-voltage and force-current electrical analogous circuits and verify by writing mesh and node equations. **(May 2022)**



24) Write the rules of block diagram reduction technique. **(May 2022)**

UNIT II – TIME RESPONSE

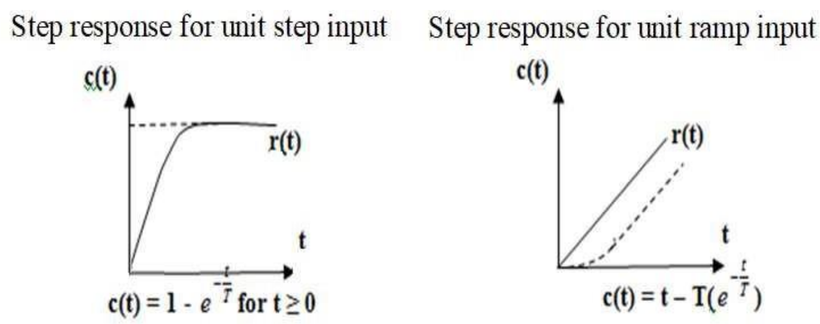
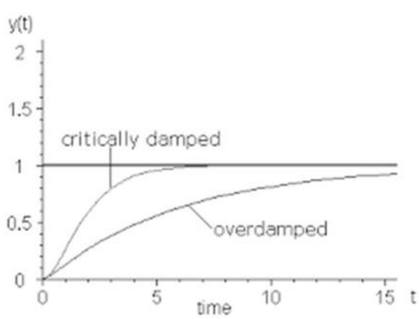
PART A

1) **Distinguish between steady state response and transient response**.

Steady state response	Transient response
The time response of the system when time tends to infinity	The time response of the system when the input changes from one state to another.
The response has settled value. It is represented by C_{ss}	The response may be exponential or oscillatory. It is represented by c(t).

2) **What are the standard test signals employed for time domain studies**? (or) **List the standard test signals used in analysis of control systems? (April 2011) (June2014) (Nov 2018)**

The standard test input signal are step input, ramp input, parabolic input and impulse input signals. By using above standard test signals of control systems, analysis and design of control systems are carried out, defining certain performance measures for the system.

3)	**What is the initial slope of a step response of a first order system?** The step response of first order is given by $c(t) = 1 - e^{-t/T}$, where T is time constant. The initial slope is given by, $(dc/dt)\|_{t=0} = (1/T)\, e^{-t/T}\|_{t=0} = 1/T$
4)	**Plot the time response of the first order system to a unit step and unit ramp input.** 
5)	**For the system described by $\frac{C(S)}{R(S)} = \frac{16}{S^2+8S+16}$ Find the nature of time response. (Nov 2015)** In the given transfer function C(s)/R(s); the value of $\omega_n^2 = 16$ and $2\zeta\omega_n = 8$ Hence the value of damping ratio $\zeta = \frac{8}{2.4} = 1$ Hence the given system is a critically damped system and the step response of the system will be like: 
6)	**What is the type and order of the system? (Nov2014) (May 2015) (Nov 2017)** Type – The number of poles of loop transfer function that lies at origin. The type of the system decides the steady state error. Order- The maximum power of "s" in denominator polynomial

7)	**Define type and order of the following system (May 2017** $G(s)H(s) = \dfrac{10}{s^3(s^2+2s+1)}$ Type = 3 and Order = 5
8)	**How a control system is classified depending on the value of damping? (May2018)** ❖ Under damped system ($0<\zeta<1$) ❖ Un damped system ($\zeta=0$) ❖ Critically damped system ($\zeta=1$) ❖ Over damped system ($\zeta>1$) where ζ is damping ratio
9)	**List the time domain specifications. (May 2016)** The performance of control system in time domain is evaluated by the following specifications, Delay time(t_d), Rise time (t_r), Peak time (t_p), Peak Overshoot(M_p), Settling Time(t_s).
10)	**Define delay time and peak time**. **Delay time:** It is the time taken for response to reach 50% of the final value, for the very first time. **Peak time:** It is the time taken for the response to reach the peak value for the very first time.(or) It is the time taken for the response to reach the peak overshoot, M_p.
11)	**Define: Settling time. (Nov 2018)** It is the time required for the step response curve of under damped second order system to reach and stay within a specified tolerance band. It is usually expressed as % of final value. The usual tolerable error is 2 % or 5 % of the final value.
12)	**Define maximum peak overshoot. (May 2017)** Maximum peak overshoot is defined as the ratio of maximum peak value measured from the maximum value to final value. $\%M_p = e^{\frac{-£}{\sqrt{1-£^2}}\times 100}$

13) **What is meant by reset time?**

In the integral mode of controller, the time during which the error signal is integrated is called the integral or reset time (T_i). In other words, in PI control, the time taken by the controller to 'reset' the set point to bring the output to the desired value.

$U(s) = K_c (1+ (1/T_i S)) E(s)$, where Ti is the integral (or) reset time.

14) **What is steady state error? (April 2011) (May 2018)**

The steady state error is the value of error signal e(t) when time (t) tends to infinity. It is a measure of system accuracy.

15) **Distinguish between generalized error constants over static error constant**.

Static error constants	Generalized error constants
1. Do not give the information regarding the variation of error with time.	1. Gives error signal as a function of time.
2. Static error constants can be used only for standard inputs.	2. Using generalized error constant the steady state error can be determined for any type of input.
3. Give the definite values for errors, either 0 or ∞ or a finite value.	3. Give the exact error values.

16) **Define velocity error constant.**

The velocity error constant

$$K_v = \lim_{s \to 0} sG(s)H(s)$$

The steady state error (e_{ss}) for type – 1 unit ramp input is given by. $\frac{1}{K_V}$

17) **What is the positional error coefficient?**

The positional error constant

$$K_p = \lim_{s \to 0} G(s)H(s)$$

The steady state error (e_{ss}) for type – 0 unit step input is given by $\frac{1}{1+K_p}$

18)	**Give the relation between the static and dynamic error co-efficient. (Nov 2016)** $C_0 = \frac{1}{K_p}$ for type-0 $C_1 = \frac{1}{1+K_v}$ for type-1 $C_2 = \frac{1}{1+K_a}$ for type-2 Where C_0, C_1, C_2 are dynamic error coefficient and K_p, K_v, K_a are static error coefficients.
19)	**For servomechanism with open loop transfer function given by $G(s) = \frac{1}{(s^2+2s+3)}$. Determine the position error constant and steady sate error for a unit step input. (May 2019)** $Positional\ error\ constant\ K_p = \lim_{s\to 0} G(s)H(s) = \lim_{s\to 0} \frac{1}{(s^2+2s+3)} = \frac{1}{3}$ $Steady\ state\ error\ for\ unit\ step\ e_{ss} = \frac{1}{1+K_p} = \frac{3}{4}$
20)	**Find the steady state error of the system $(s) = \frac{15}{s(s+8)}$ for unit ramp input. (Nov 2019)** $K_v = \lim_{s\to 0} sG(s)H(s) = \lim_{s\to 0} s\frac{15}{s(s+8)} = 1.875$ $e_{ss} = \frac{1}{K_v} = \frac{1}{1.875} = 0.533$
21)	**State the rule for finding out the root loci on the real axis.** A point on the real axis lies on the locus if the number of open loop poles plus zeros on the real axis to the right of this point is odd.
22)	**What are the applications of root locus method?** i) Root locus is used to study the dynamic response of a system ii) It visualizes the effects of varying various system parameters on root locations iii) It provides a measure of sensitivity of roots to the variation in the parameter being considered iv) It is applicable for single as well as multiple loop systems, and it helps to find the

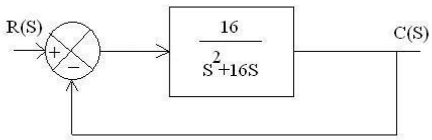
	closed loop response from the given open loop transfer function.
23)	**State the rule for finding the value of K at any point on the root locus diagram.** The value of gain K at any $s = s_a$ on the root locus is the ratio of product of all of the vector lengths drawn from poles of G(s)H(s) to s_a and product of all of the vector lengths drawn from zeroes of G(s)H(s) to s_a.
24)	**State: Magnitude criteria in root locus approach.** The root locus magnitude criteria at any points can be defined as, $\|G(s)H(s)\| = 1$. Using this formula we can calculate the value of K at any desired point.
25)	**What is root locus? (May 2012)** It is the locus of the closed loop poles obtained when the system gain 'K' is varied from $-\infty$ to $+\infty$. The stability of the system is determined using this technique. The range of value of K is found such that complete performance of the system will be satisfactory and the operation is stable.
26)	**What are asymptotes? How will you find the angle of asymptotes?** Asymptotes are straight lines which are parallel to root locus going to infinity and meet the root locus at infinity. Angles of asymptotes $= \frac{\pm 180^o(2q+1)}{n-m}; \; q = 0,1,2,3,....(n-m)$
27)	**State the rule for obtaining breakaway point in root locus. (May 2011)** The break away and break in points are found from an equation for K of the characteristic's equation, and differentiate the equation of K with respect to s. Then find the roots of equation $\frac{dK}{ds} = 0$ .The roots of $\frac{dK}{ds} = 0$ are breakaway or breaking points, provided for this value of root, the gain K should be positive real.
28)	**What is the condition for the system G(S) = K (S + a) / S (S + b) to have a circle in its root locus? (April 2005)** If root loci is circle for the transfer function is a circle, then two poles should be located adjacently i.e $b < a$, where b and a are the poles and zeroes of the open loop transfer function.

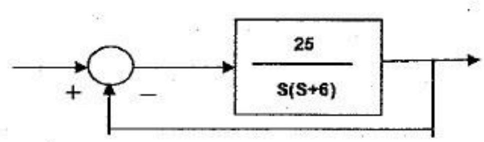
29)	**State the basic properties of root locus. (Nov 2016)** 1. The root locus is always symmetrical about the real axis. 2. If P>Z, Number of root locus branches equal to number of open loop poles. 3. If Z>P, Number of root locus branches equal to number of open loop zeroes.
30)	**Explain the function of a PID controller**. It combines all the three continuous controlling modes, gives the output which is proportional to the error signal, proportional to the rate of change of error signal and proportional to the integral of error signal. So, it has all the advantages of three individual modes. i.e. less rise time, less oscillations, zero offset and less settling time. $e_{ss} = 0$ can be achieved.
31)	**What is a derivative controller? What is its effect? (or) Why derivative controller is not used in control systems? (Nov 2015)** Derivative controller is a device that produces a control signal, which is proportional to the rate of change of input error signal. It is effective only during transient response and does not produce any corrective measures for constant errors $u(t) = k_d\, e(t)$
32)	**Write the transfer function of the PID controller. (Nov2014)** $U(s)/E(s) = K_p \left(1 + T_d s + \frac{1}{T_i s} \right)$ Where K_p – Positional Error Constant T_i – Integral Time Constant T_d – Derivative Time Constant
33)	**What is the effect of PD controller on the system performance? (June 2014)** The PD controller introduces a zero in the system and increases damping ratio. The addition of the zero may increase the peak overshoot and reduce the rise time. But the effect of increased damping ratio ultimately reduces the peak overshoot.
34)	**What is the effect on system performance when proportional controller is introduced in the system? (Nov 2015) (Nov 2017)** A proportional controller (P controller) is a control loop feedback mechanism commonly used in industrial control systems. A P controller

	continuously calculates an error value as the difference between a desired set point and a measured process variable. The controller attempts to minimize the error over time by adjustment of a control variable. The major effect on the system performance by the Proportional controller is the offset, a constant error (permanent deviation between the set point and a measured process variable)
35)	**State the effect of PI controller on the system performance. (May 2016)(May 2019) (or) What are the feautures of PI controller (Nov 2019)** 1. Order of the system is increased by one. 2. It introduces zero in the system(Roots in the numerator). 3. The increase in order makes the system less stable than the original one. 4. Reduces the steady state error.
36)	**Discuss the effect of adding a pole to the open loop transfer function of the system?** This will reduce the steady-state error and improves steady state performance. Closer the pole towards the origin the lesser will be the steady state error. But addition of pole increases the order of the system, making the system less stable.
37)	**Discuss the effect of adding a zero to the open loop transfer function of the system? (April 2011)** The addition of a zero to open loop transfer function of a system will improve the transient response, reduces the rise time. If the zero is introduced close to origin then the peak overshoot will be larger. If the zero is introduced far away then its effect is negligible.
38)	**What is dominant pole pair? What is its significance? (April 2015) (May 2018)** The dominant pole is a pair of complex conjugate pole, which decides transient response of the system. In higher order systems the dominant poles are very close to origin and all other poles of the system are widely separated and so they have less effect on transient response of the system.
39)	**What are the effects of adding open loop poles and zero on the nature of the root locus and on system. (Nov 2017)** By addition of poles, the root locus shifts towards imaginary axis and system

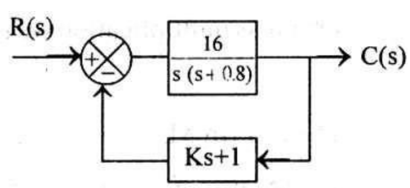
	stability decreases, while by addition of zeroes towards left half, the root locus moves away from imaginary axis and the system stability increases.
40)	**Derive the impulse response of first order system. (May 2021)** Consider the unit sample signal as an input to the first order system $$r(t) = \delta(t)$$ Apply Laplace transform on both the sides R(s)=1 Consider the first order transfer function $$\frac{C(s)}{R(s)} = \frac{1}{1+sT} \quad R(s)=1$$ $$C(s) = \frac{1}{1+sT}$$ Rearrange the above equation in one of the standard forms of Laplace transforms $$C(s) = \frac{1}{T\,(s+\frac{1}{T})}$$ Apply inverse Laplace transform on both sides $$c(t) = \frac{1}{T} e^{-t/T}\, u(t)$$
41)	**An open loop transfer function of unity feedback system is given as $(s) = \frac{10}{s+1}$** **What is the steady state error? (May 2021)** Type 0 system $$K_p = \lim_{s\to 0} G(s)\,H(s) = \lim_{s\to 0} \frac{10}{s+1} = 10$$ Steady state error $$e_{ss} = \frac{1}{1+K_p} = \frac{1}{1+10} = 0.09$$
42)	**The damping ratio of a system is 0.75 and the natural frequency of oscillation is 12 rad/sec. Determine the peak overshoot and the peak time. (May 2022)** ζ = 0.75 Peak Overshoot $M_p = e^{\frac{-£}{\sqrt{1-£^2}}} = e^{\frac{-0.75\times\pi}{\sqrt{1-0.75^2}}} = 0.028$

	$\%M_p = 2.8\%$ Damped frequency of oscillation $\omega_d = \omega_n \sqrt{1-\zeta^2} = 12\sqrt{1-0.75^2} = 7.94\ rad/sec$ Peak Time $t_d = \frac{\pi}{\omega_d} = \frac{\pi}{7.94} = 0.396 se$
PART-B	
1)	(i) (a) Derive the step response of a second order under damped system **(Nov 2017)** (b) Derive the step response of a second order undamped system **(April 2011) (Nov 2014) (Nov/Dec 2015) (Nov 2018) (Nov 2019) /** Derive the time response of undamped and critically damped second order sytem for unit step input**. (May 2017) (May 2018)** (ii) Explain PID Controller action with block diagram and obtain its transfer function model**. (Nov 2015) (April 2018)**
2)	The open loop T. F of a servo system with unity feedback system is G(s) $= \frac{10}{s(0.1s+1)}$ Evaluate the static error constants of the system. Obtain the steady state error of the system, when subjected to an input given by the polynomial r(t) = a_0 + $a_1t + \frac{a_2}{2}t^2$ Also find the generalized error constants and hence e_{ss} . **(April 2014) (April 2015)**
3)	A unity feedback control system has an open loop transfer function G(s) $= \frac{5}{s(s+1)}$ Find the rise time, peak overshoot, peak time, settling time, for a step input of 10 units. Also determine the peak overshoot**. (April 2011)**
4)	A unity feedback system is characterized by an open loop transfer function G(s) $= \frac{k}{s(s+2)(s+4)}$. Determine the gain k so that the system will have a damping ratio of 0.5. For this value of k, determine peak overshoot and peak time for a unit step input. **(April 2011) (April 2014**)
5)	Obtain the expression for dynamic error co-efficient of the following system is G(s) $= \frac{10}{s(s+1)}$ **(Nov2014)**

6)	Consider the closed loop system shown in Fig 2. Determine the range of k for which the system is stable. **(Nov 2014)** 
7)	The unity feedback system characterized by open loop transfer function G(s)=K/[s(s+10)].Determine the gain K such that the damping ratio will be 0.5 and find the time domain specifications for a unit step input**. (May 2015)**
8)	(i) The open loop transfer function of a unity feedback system is given by $G(s)=\frac{1}{S(1+S)}$. The input to the system is described by r(t)=4+6t.Find the generalized error coefficients and steady state error **(ii)** Explain the rules to construct root locus of a system. **(Nov/Dec 2015)**
9)	**(i)** The overall transfer function of the control system given by C(s)/R(s)=16/(s^2+1.6s+16). It is desired that the damping ratio is 0.8. Determine the derivative rate feedback constant K_t and compare the rise time, peak time, maximum overshoot and steady state error for unit ramp input function without and with derivative feedback control. **(Nov 2016)** **(ii)** Compare P, I and D controllers. **(Nov 2016)**
10)	Derive the time domain specifications of a second order system. **(April 2016) /** Derive the expression for rise time and peak time of a second order underdamped system due to unit step input. **(May 2019)**
11)	(i) For a unity feedback control system, the open loop transfer function is given by $$G(s) = \frac{10(s+2)}{s^2(s+1)}$$ (a) Find the position, velocity and acceleration error co-efficient. **(b)** Also find the steady state error when the input is $R(S) = \frac{3}{S} - \frac{2}{S^2} + \frac{1}{3S^3}$ **(May 2016) (May 2022)** (ii) With the neat diagram explain the working of PD controller in detail. **(May 2016)**
12)	(i) A unity feedback system has open loop transfer function G(s)=K/[s(s+2)].Find

	the rise time, peak time, percentage overshoot and settling time for step input of 12 units. **(May 2017)** (ii) For servomechanism with open loop transfer function shown below explain what type of input signal give rise to a steady state error and calculate their values. **(May 2017)** (1) G(s)=[20(s+2)]/[s(s+1)(s+3)] (2) G(s)=10/[s(s+2)(s+3)]
13)	Find the static error coefficients for a system whose transfer function is $G(s)H(s) = \frac{10}{s(1+s)(1+2s)}$. And also find the steady state error. **(Nov 2017)**
14)	**i)** Outline the time response of first order system when it is subjected to a unit step input. **(May 2018)** ii) Determine the response of the unity feedback system whose open loop transfer function is $G(s) = \frac{4}{s(s+5)}$. **(May 2018)**
15)	For the system shown in figure below, find the rise time, peak time, peak overshoot and settling time for 2% and 4% criteria for unit step input. **(Nov 2019)** 
16)	i) A unity feedback system has the forward transfer function $G(s) = \frac{K(2s+1)}{s(5s+1)(1+s)^2}$. when the input r(t)=1+6t, determine the minimum value of K so that the steady error is less than 0.1. **ii)** Derive the transfer function of PID controller. **(May 2018) (Nov 2019)**
17)	A unity feedback system is characterised by the open loop transfer function $G(s) = \frac{1}{s(0.5s+1)(0.2s+1)}$. **(May 2019)** i) Write the closed loop transfer function $\frac{C(s)}{R(s)}$ ii) Calculate steady state error due to unit step input.
18)	i) A closed loop control system is represented by the differential equation

	$\frac{d^2c}{dt^2} + 4\frac{dc}{dt} = 14e$ where e = r – c is the error signal. Determine the undamped natural frequency, damping ratio and percentage maximum overshoot for a unit step input. ii) A unity feedback system is characterized by the open loop transfer function $$G(s) = \frac{1}{s(0.5s+1)(0.2s+1)}$$ Determine the steady state errors for unit-step, unit-ramp and unit-acceleration input.**(May 2021)**
19)	Sketch the root locus of the system $= \frac{k}{s(s+2)(s+4)}$ and determine the value of K such that the damping ratio of the closed loop system is 0.5**(April 2015)**
20)	Sketch the root locus for. G(s)H(s) $= \frac{k(s+2)(s+3)}{(s+1)(s-1)}$ **(Nov 2013)**
21)	Draw the root locus plot for the system whose open loop transfer function $G(s) = \frac{k}{(s+2)(s+4)(s^2+6s+25)}$. Find the marginal value of k which causes sustained oscillations and the frequency of these oscillations. **(April 2014)**
22)	Draw the root locus of the following system**. (Nov 2014)** G(s)H(s) $= \frac{k}{s(s+1)(s+2)}$. **(Or)** A unity feedback system has an open loop transfer function $G(s) = \frac{K}{s(s+1)(s+2)}$. Make a rough sketch of the root locus of the system, explicitly identifying the centroid, the asymptodes, the departure angles from the complex poles of G(s) and the jω axis crossover point. By trial and error application of the angle criterion, locate a point on the locus that gives dominant closed loop poles with ζ=0.5. Evaluate the value of K at this point. **(May 2019) (Probable Part-C)**
23)	Draw the root locus of following the system **(Nov 2016) (Probable Part-C)** $$G(S) = \frac{K(s+1)}{s(s^2+5s+20)}$$

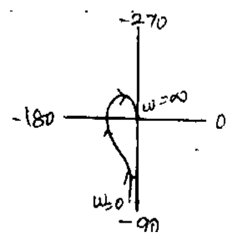
24)	Sketch the root locus of the system having $G(s) = \frac{k(s+3)}{s(s+1)(s+2)(s+4)}$ **(May 2013)** **(Nov 2018) (Probable Part-C)**
25)	A unity feedback control system has an open loop transfer function. Sketch the root locus. $G(S) = \frac{K}{s(s^2+4s+13)}$. **(May2018) (Probable Part C)**
26)	Construct the root locus of the open loop transfer function (**May 2021)** $G(s)H(s) = \frac{K}{s(s+2)(s^2+2s+5)}$
27)	An unity feedback servo mechanism whose $G(S) = \frac{K_v}{s(1+sT)}$ is designed to keep a radar antenna pointed at a flying aeroplane. If the aeroplane is flying with a velocity of 600 km/h, at a range of 2 km and the maximum tracking error is to within 0.1°, determine the required velocity error coefficient K_v. (**May 2021) (Probable Part-C)**
28)	The open loop transfer function of a unity feedback system is given by G(s) = K/s(sT+1), where K and T are positive constant. Identify the amplifier gain K for reducing peak overshoot of unit step response of the system from 0.75 to 0.25. **(May2022)**
29)	A position control system with velocity feedback is shown in Fig. (i.e. G(s) = 16/s(s+0.8) and H(s) = Ks+1). Find the response c(t) to the unit step input. Given that ξ = 0.5. Also calculate rise time, peak time, maximum overshoot and settling time. **(May2022)** 
30)	Explain the step by step procedure for constructing the root locus with example. Also, show the typical sketches of root locus plots. **(May2022)**
	UNIT III FREQUENCY RESPONSE **PART A**
1)	**What is meant by frequency response? (May 2017)** The magnitude and phase function of sinusoidal transfer function of a system are

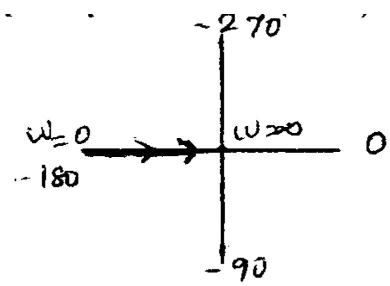
	real function of frequency ω and so they are called frequency response. The frequency response can be evaluated for open loop and closed loop system.
2)	**List any two advantages of frequency response analysis. (April 2005) (April 2011) (May 2018). Why frequency domain analysis is needed. (Nov 2018)** (a) The absolute and relative stability of the closed loop system can be estimated from the knowledge of the open loop frequency response.(b) The practical testing of system can be easily carried with available sinusoidal signal generators and precise measurement equipment. (c) The transfer function of the complicated functions can be determined experimentally by frequency response tests.(d) The design and parameter adjustments can be carried more easily.(e)The corrective measure for noise disturbance and parameter variation can be easily carried.(f)It can be extended to certain non - linear systems
3)	**What are frequency domain specifications? List it out. (Nov 2017)** The frequency domain specifications indicate the performance of the system in frequency domain; they are resonant peak, resonant frequency, Band width, Phase margin, Gain margin
4)	**Define resonant peak and resonant frequency (June 2014) (Nov 2014)** **Resonant peak:** The maximum value of the magnitude of closed loop transfer function is called resonant peak. A large resonant peak corresponds to a large overshoot in transient response. **Resonant frequency:** The frequency at which the resonant peak occurs is called resonant frequency. This is related to the frequency of oscillation in the step response and thus it is indicative of the speed of transient response. The resonant frequency, $\omega_r = \omega_n\sqrt{1-2\zeta^2}$
5)	**The damping ratio and natural frequency of oscillations of a second order system is 0.3 and 3 rad/sec respectively. Calculate resonant frequency and resonant peak. (May 2019) (May 2022)** Resonant frequency $\omega_r = \omega_n\sqrt{1-2\zeta^2} = 3\sqrt{1-2\times 0.3^2} = 2.71\ rad/sec$ Resonant Peak $M_r = \frac{1}{2\zeta\sqrt{1-\zeta^2}} == \frac{1}{2\times 0.3\sqrt{1-0.3^2}} = 0.57$

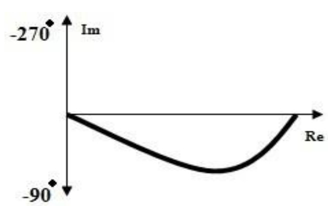
6)	**Define the term Gain Margin. (Nov 2014) (May 2021) (May 2022)** The gain margin is the factor by which the system gain can be increased to drive it to the verge of instability. It may be defined as the reciprocal of the gain at the phase cross over frequency (ω_{pc}). The phase cross over frequency is the frequency at which the phase is 180°. Gain margin $Kg = \frac{1}{\lvert G(j\omega_{pc})\rvert}$ The gain margin in db can be expressed as $Kg\,in\,db = 20\log Kg = 20\log \frac{1}{\lvert G(j\omega_{pc})\rvert}$
7)	**Define phase margin. (April 2004) (Nov 2014) (May 2015) (May 2018) (May 2021)** The phase margin is defined as the amount of additional phase lag at the gain crossover frequency (ω_{gc}) required to bring the system to the verge of instability. Phase margin $\gamma = \phi_{gc} + 180°$ Where $\phi_{gc} = \angle G(j\omega) H(j\omega)$ at $\omega = \omega_{gc}$
8)	**Define Gain Crossover Frequency. (April 2011) (May 2016)(Nov 2019)** The gain crossover frequency is the frequency at which the magnitude of open loop transfer function is unity. It is represented by ω_{gc}.
9)	**Define phase cross over frequency. (May 2016)** The phase cross over frequency is the frequency at which the phase of open loop transfer function is 180°. It is represented by ω_{pc}.
10)	**Obtain the corner frequencies of the system G(s)H(s) = (s+0.5)/(s+0.25) (s+4)** Corner frequency for the polynomial (1+sT) is 1/T Corner frequency for the polynomial (s+0.5) is 0.5 Corner frequency for the polynomial (s+0.25) is 0.25 Corner frequency for the polynomial (s+4) is 4
11)	**What is meant by the term 'corner frequency'? (May 2018)** Asymptotic straight lines can approximate the magnitude plot. The frequencies corresponding to the meeting point of asymptotes are called corner frequencies. The slope of the magnitude plot changes at every corner frequency.

12)	**What is bode plot? State the advantage of Bode plot.** The bode plot is a frequency response plot of the transfer function of a system. It consists of two plots, magnitude plot and phase plot. Magnitude plot: Plot between magnitude in db and $\log\omega$ for various values of ω. Phase plot: Plot between phase in degrees and $\log\omega$ for various values of ω. Usually both the plots are plotted on a common X-axis in which the frequencies are expressed in logarithmic scale. Advantages: (a) The approximate plot can be sketched quickly, (b) The frequency domain specifications can be easily determined; (c) The Bode plot can be used to analyze both open loop and closed loop system.
13)	**What is approximate bode plot.** In approximate bode plot, the magnitude plot of first and second order factors are approximated by two straight lines, which are asymptodes to exact plot. One straight line is at 0dB, for the frequency range of 0 to ω_c and other straight line is drawn with a slope of ±20n db/sec for the frequency range ω_c to ∞ .
14)	**If the bode plot crosses 180° line, either at very low frequencies or very high frequencies in the selected frequency range. What is the inference regarding the relationship between open loop gain and stability? (May 2019)** It is an indication that the closed loop response will be either absolutely stable or unstable, irrespective of the value of the open loop gain. So even if the phase line just grazes the 180° line without crossing it, it can be taken as phase crossover frequency ω_{pc} using which gain margin can determine.
15)	**What does a gain margin close to unity and phase margin close to zero indicate? (Nov 2016)** The gain margin close to unity and phase margin close to zero indicate that the system is relatively stable
16)	**Why is frequency domain compensation normally carried using the bode plots? (Nov 2016)** The frequency domain compensation may be carried out by using Nyquist plots, bode plots and Nicholas charts. Out of them normally bode plots are preferred,

<table>
<tr><td></td><td>because they are easier to draw and modify. Also, the gain adjustments can be carried out and also the error constants are always clearly in evidence in the bode plots.</td></tr>
<tr><td>17)</td><td>Show the shape of the polar plot for the transfer function K/s (1 +sT₁)(1 +sT₂) (Nov 2018)


</td></tr>
<tr><td>18)</td><td>Sketch the polar plot of $10/s^2$ (or) draw the approximate polar plot for type 0 second order system. (Dec 2015)


</td></tr>
<tr><td>19)</td><td>Sketch the polar plot for G(s)=1/1+sT (April 2015)
In the given transfer function, the type of the system is zero and the order is 1.
So, the model polar graph will be like:


</td></tr>
<tr><td>20)</td><td>What is a minimum phase transfer function?
A transfer function, which has all poles and zeros in the left half s–plane is known as minimum phase transfer function. The minimum phase systems are systems with minimum phase transfer functions.</td></tr>
</table>

21)	**What are all pass systems and non-minimum phase transfer function?** All pass systems: The magnitude is unity at all frequencies and the transfer function will have anti symmetric pole zero pattern (i.e. for every pole in the left half of s – plane, there is a zero in the mirror image position with respect to imaginary axis. Non-minimum phase transfer function: A transfer function, which has one or more zeros in the right half s – plane is known as non-minimum phase transfer function.
22)	**What are M and N circles.** The magnitude, M of closed loop transfer function with unity feedback will be in the form of circle in complex plan for each constant value of M. The families of these circles are called M circles. Let N=tanα, where α is the phase of closed loop transfer function with unity feedback. For each constant value of N, a circle can be drawn in the complex plan. The family of these circles are called N-circles.
23)	**How the closed loop frequency response is determined from the open loop frequency response using Nichols chart.** The G(jω) locus or the Nichols plot is sketched on the standard Nichols chart. The meeting point of M-contour with G(jω) locus gives the magnitude of closed loop system and the meeting point with N-circle gives the argument/phase of the closed loop system.
24)	**What is the phase shift contributed by single pole at origin in a transfer function.** The phase shift contributed by single pole at origin in a transfer function is -90°.
25)	**Find the type and order of the system $G(s) = \frac{10}{s^2(s+1)(s+2)}$ (May 2021)** Type : 2, Order: 4
PART B	
1)	Derive the expression for the frequency domain specifications. **(Nov 2018)**
2)	Explain how open loop response can be obtained from closed loop response. **(Nov 2018)**
3)	Sketch the polar plot of $G(s) = \frac{1}{[s(1+0.5s)(1+0.02s)]}$ and determine the phase cross

	over frequency. **(May 2022)**
4)	Given $G(s) = \frac{Ke^{-0.2s}}{[s(s+2)(s+8)]}$. Find K so that the system is stable with Gain margin equal to 6 db and (b) Phase margin equal to 45^0 using bode plots. **(Probable Part-C)**
5)	Sketch the Bode plot for the following transfer function and obtain gain and phase cross over frequencies. $G(s) = \frac{20}{[s(1+0.4s)(0.1s+1)]}$ **(April 2011)**
6)	The open loop transfer function of a unity feedback system is given by $G(s) = \frac{1}{[s^2(1+s)(1+2s)]}$ Sketch the polar plot and determine the phase margin and gain margin**. (April 2011) (April 2015)**
7)	Sketch the Bode plot showing the magnitude in db and phase angle in degrees as a function of log frequencies for the following transfer function $G(s) = \frac{75(1+0.2s)}{[s(s^2+16s+100)]}$ and obtain gain and phase cross over frequencies. **(April 2014) (April 2018) (May 2022)**
8)	**(i)** Discuss the correlation between the time and frequency response of second order system. **(April 2014) (Nov 2015) (Nov 2018)** (ii) Explain the use of nichol's chart to obtain closed loop frequency response from open loop frequency response of unity feedback system **(Nov/Dec 2015)**
9)	Using Bode plot of the following system $G(s) = \frac{10}{[s(.1s+1)(0.01s+1)]}$ and Hence obtain the gain crossover frequency**. (Nov 2014)**
10)	Using polar plot determine the gain cross over frequency, phase cross over frequency, gain margin, phase margin feedback system with open loop transfer function $G(s) = \frac{1}{[s\ (1+0.2s)(1+.002s)]}$ **. (Nov 2014)**
11)	Sketch the Bode plot for the following transfer function and obtain gain and phase cross over frequencies. $G(s) = \frac{10}{[s(1+0.4s)(0.1s+1)]}$ **(April 2015) (May 2016) (May 2017)**

12)	Sketch the Bode plot for the following transfer function and obtain gain and phase margin and closed loop system stability. $G(s) = \frac{4}{[s(1+0.5s)(0.08s+1)]}$ **(Nov 2015)**
13)	The open loop transfer function of the unity feedback system is given by $(S) = \frac{1}{S(S+1)^2}$ Sketch the polar plot and determine the gain and phase margin. **(May 2016)(May 2021)**
14)	Sketch the polar plot of $G(s) = \frac{1}{[s(1+s)(1+2s)]}$ and determine the phase margin and gain margin. (**Nov 2016) (May 2017)**
15)	Sketch the Bode plot for the following transfer function $G(s) = \frac{1}{[s(s^2+3s+5)]}$ and obtain gain and phase margin. (**Nov 2016)**
16)	Sketch the bode plot and hence find gain cross over frequency, phase cross over frequency, gain margin and phase margin for the function. (**Nov/Dec 2017)** $G(s) = \frac{10(s+3)}{s(s+2)(s^2+4s+100)}$.
17)	Sketch the polar plot for the following transfer function and find gain cross over frequency, phase cross over frequency, gain margin and phase margin for $G(s) = \frac{400}{s(s+2)(s+10)}$.(**Nov 2017)**
18)	Construct the polar plot and determine the gain and phase margin of a unity feedback control system whose open loop transfer function is, $G(s) = \frac{(1+0.2s)(1+0.025s)}{s^3(1+005s)(1+0.001s)}$ **(May 2018)**
19)	Sketch the Bode plot for the following transfer function and obtain gain and phase margin and closed loop system stability. $G(s) = \frac{100}{s(s+1)(s+2)}$ **(May 2019).**
20)	Sketch the polar plot for the following open loop transfer function and determine the gain margin and phase margin $G(s) = \frac{1}{(1+s)(1+2s)}$ **.(May 2019)**

21) Draw the bode plot for the transfer function $H(s) = \frac{100(s+1)}{(s+10)(s+100)}$ **(Nov 2019)**

22) Compare polar plots of type 0, type 1 and type 2 systems. **(Nov 2019)**

23) Sketch the Bode plot for the given transfer function. Determine Gain cross-over frequency phase cross-over frequency, gain margin and phase margin **(May 2021)**

$$G(s)H(s) = \frac{2000}{s(s+2)(s+100)}$$

UNIT IV – STABILITY AND COMPENSATION

PART A

1) **Define asymptotic stability. (April 2004) (Nov 2018)**

In the absence of the input, the output tends towards zero (the equilibrium state of the system) irrespective of initial conditions. This stability concept is known as asymptotic stability.

2) **State the necessary condition for the Routh's criterion for stability. (April 2015)/ What ate the necessary condition for stability. (Nov 2017) (May 2022)**

A necessary and sufficient condition for stability is that all of the elements in the first column of the Routh array be positive. If this condition is not met, the system is unstable and the number of sign changes in the elements of the first column of the Routh array corresponds to the number of roots of the characteristic equation in the right half of the s – plane.

3) **The characteristic equation of a feed back control system is $s^4 + 22 s^3 + 10s^2 + 32 s + K = 0$. Determine the range of K for which the system is stable.**

S^4	1	10	K	
S^3	22	32	0	
S^2	8.545		K	0
S^1	$\frac{(273.45 - 22K)}{8.545}$	0		
S^0	K	0		

For the system to be stable all the first column elements should be positive.

K> 0 and 273.45-22K > 0, 273.45> 22K, K< 12.43 When 0<K<12.43 the system is stable.

4) **What are the characteristics of an unstable system? (Nov 2004)**

The system will give unbounded output for a bounded input, the system has roots with positive real part, the system has repeated roots on jω axis.

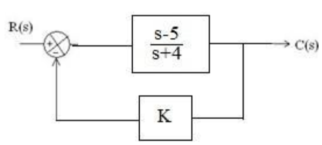
5) **Distinguish between relative stability and absolute stability.**

Relative stability	**Absolute stability**
Relative stability is a quantitative measure of how fast the transients die out in the system. It may be measured by relative settling times of each root or pair of roots.	A system is absolutely stable if it is stable for all values of system parameters.
It is defined based on the location of roots with respect to imaginary axis passing through a point other than the origin.	It is defined based on the location of roots with respect to imaginary axis passing through the origin.

6) **What is meant by characteristic equation? What is its significance? (May 2016) (May 2017)**

The denominator polynomial of closed loop transfer function equated to zero is the characteristic equation. It tells about the stability of the system.

7) **For what range of K the following system shown below is asymptotically stable. (May 2019)**



Characteristic equation is given by

1+G(s)H(s) = 0

$$1+\frac{K(s-5)}{s+4}=0$$

(K+1) s-5K+4=0

Using Routh Hurwitz criterion,

s^1	K+1	0
s^0	4-5K	

For marginal stability,

	K+1>0 4-5K>0 Hence range of K is -1<K<4/5
8)	**How are the locations of roots of characteristic equation related? (or) How are the roots of characteristic equation related to the stability of system (June 2014) (Nov 2015)** a) If all the roots of the characteristic equations have –ve real parts, the system is bounded Input bounded output stable. b) If any root of the characteristic equation has a +ve real part the system is unbounded and the impulse response is infinite and the system is unstable. c)If the characteristic equation has repeated roots on the j? axis the system is unstable. d)If the characteristic equation has non-repeated roots on the j? axis the system is limitedly Stable.
9)	**What are compensators? (Nov 2014)** In control systems design, under certain circumstances it is necessary to introduce some kind of corrective subsystems to force the chosen plant to meet the given specifications. These subsystems are known as compensators and their job is to compensate for the deficiency in the performance of the plant.
10)	**Why compensation is necessary in feedback control systems? (April 2011) (June 2014) (April 2015) (May 2019)** In feedback control systems compensation is required in the following situations. 1. When the system is absolutely unstable, then compensation is required to stabilize the system and also to meet the desired performance. 2. When the system is stable, then compensation is required to meet the desired performance.
11)	**What is lag compensator? Give an example?** A compensator having the characteristics of a lag network is called lag compensator. If a sinusoidal signal is applied then in steady state output there will be a phase lag with respect to input. E.g. R-C network.

12)	**What is lead compensator? Give an example?** A compensator having the characteristics of a lead network is called a lead compensator. It gives a phase lead with respect to input if applied with sinusoidal signal. A R- C network can realize it.
13)	**What is the basis for selection of particular compensator for a system? (Nov 2015)** When transient response needs is to improved, a lead compensator is chosen.When staedy state response is to be improved, while nearly preserving the transient response, a lag compensator is chosen.When both the transient and steady state response are to be improved, a lag lead compensator is chosen,
14)	**What is lag-lead compensator. (May 2016) (May 2017)** A compensator having the characteristics of lag-lead network is called lag-lead compensator. In lag-lead network when sinusoidal signal is applied, both phase lag and phase lead occur in the output, but in different frequency regions. Phase lag occurs in the low frequency region and phase lead occurs in the high frequency region (i.e) the phase angle varies from lag to lead as the frequency is increased from zero to infinity.
15)	**Give the need for lag/lag-lead compensation. (Nov 2017)** Phase lag network allows low frequencies and high frequencies are attenuated. It provides high steady state accuracy. Lag-lead compensator provides high steady state accuracy and speed of response.
16)	**State the property of a lead compensator. (Nov 2013)** The lead compensation increases the bandwidth and improves the speed of response. It also reduces the peak overshoot. If the pole introduced by the compensator is not cancelled by a zero in the system, then lead compensation increases the order of the system by one. When the given system is stable/unstable and requires improvement in transient state response then lead compensation is employed.

17) **Write the transfer function of a typical lag lead compensator. (April 2005) (June 2014)**

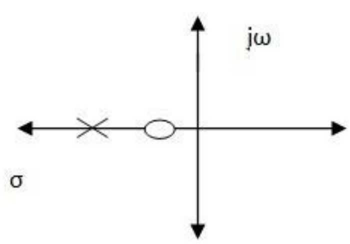
$$G(s) = \left(\frac{s+\frac{1}{\tau_1}}{s+\frac{1}{\beta\tau_1}}\right)\left(\frac{s+\frac{1}{\tau_2}}{s+\frac{1}{\alpha\tau_2}}\right)$$

The lag section has pole at s = $-1/\beta\,\tau_1$ and a zero at s = $-1/\tau_1$. The lead section has pole at s = $-1/\alpha\,\tau_1$ and a zero at s = $-1/\tau_2$

18) **Write the transfer function of a typical lead compensator and draw its pole-zero plot (April 2011)**

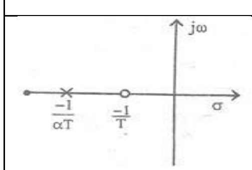
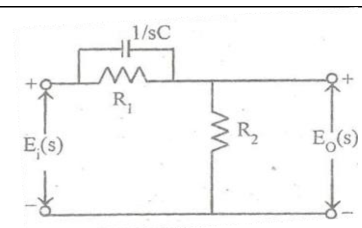
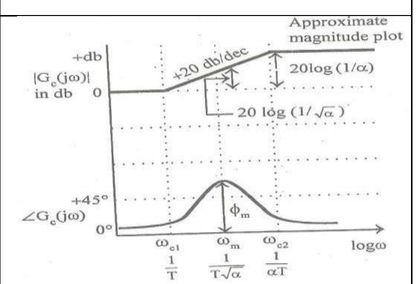
$$G(s) = \left(\frac{s+\frac{1}{\tau}}{s+\frac{1}{\alpha\tau}}\right)$$

Pole zero plot:

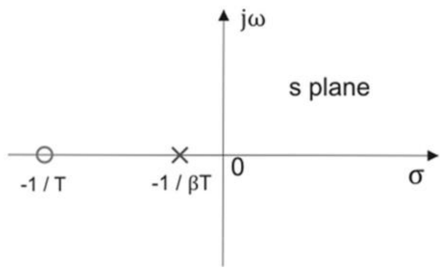


19) **Draw the circuit of lead compensator and draw its pole zero diagram. (May 2011) (Nov 2018)**

The lead compensator has a pole at $s = -\frac{1}{\alpha T}$ and a zero at $s = -\frac{1}{T}$.

Pole-zero diagram	**Electrical circuit**	**Bode plot**
		

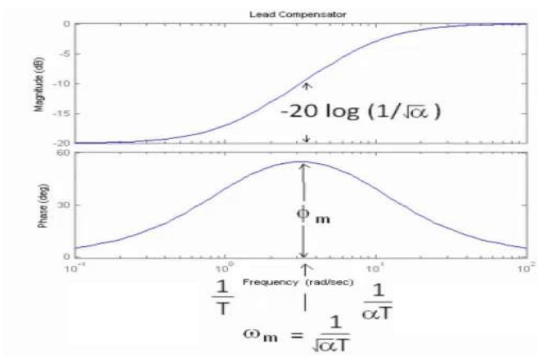
20)	**What are the effects and limitations of phase lag control? (Nov 2016)** (i) For a given forward path gain, K the magnitude of forward path transfer function is attenuated near the above the gain cross over frequency, thus improving the relative stability of the system. (ii) The gain cross over frequency is decreased and thus the bandwidth of the system is reduced. (iii) The rise time nad settling time of the system are usually longer, because the bandwidth is usually decreased. (iv) The system is more sensitive to the parameter variations because the sensitivity function is greater than unity for all frequencies approximately greater than bandwidth of the system.
21)	**State Nyquist stability criterion. (May 2012) (May 2013) (June 2014) (May 2016) (May 2017)(May 2021) (or) What is the condition for stability of a closed loop system according to Nyquist stability criterion. (Nov 2019).** If G(s)H(s) contour in the G(s)H(s) plane corresponding to Nyquist contour in s-plane encircles the point -1+j0 in the anti-clockwise direction as many times as the number of right halves of s-plane poles of G(s)H(s). Then the closed loop system is stable.
22)	**Write the transfer function of lag compensator and draw its pole-zero diagram (or) draw the electrical lag network and draw its pole-zero plot. (April 2015) (Nov 2015)** A system which has one zero and one dominating pole (the pole which is closer to origin that all other poles is known as dominating pole) is known as lag network. The basic requirement of the lag network is that all poles & zeros of the transfer function of the network must lie in (-) ve real axis interlacing each other with a pole located or on the nearest to the origin. $G(s) = \left(\frac{1+Ts}{1+\beta Ts}\right)$ The above network provides a high frequency gain of $1/\beta$



23) **What are the two notions of system stability to be satisfied for a linear time invariant system to be stable? (Nov 2016)**

The two notions of system stability to be satisfied for a linear time invariant system to be stable are (i)When the system is excited by a bounded input, the output is bounded.(ii) In the absence of the input, the output tends to zero irrespective of initial conditions.

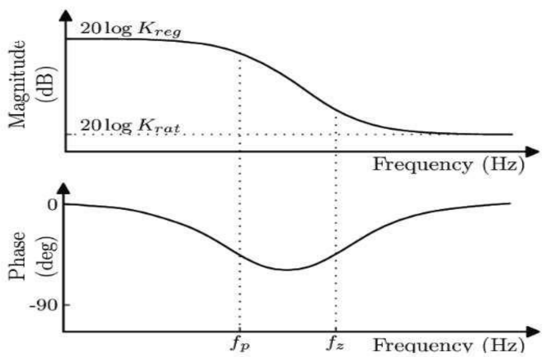
24) **Draw the frequency response of lead compensator. (Nov 2019)**



25) **Compare lag compensator with lead compensator. (May 2021)**

Lag compensator	Lead compensator
Lag compensator is a basically low pass filter	Lead compensator is a basically high pass filter
Lag compensator improves the steady state performance, reduce the bandwidth and increases the rise time	Lead compensator increases the bandwidth, improves the speed of response and reduces the peak overshoot
When the system is stable and does not satisfy the steady state performance	When the system is stable or unstable and requires to improvement in

	specifications then lag compensation is employed	transient state response then lead compensator is employed

26)	Draw the Bode plot of lag compensator. **(May 2022)** 
PART B	
1)	Construct the Routh array and determine the stability of the system represented by the characteristic equation $s^5+s^4+4s^3+24s^2+3s+63=0$. Comment on the location of the roots of characteristic equation **(April 2011)**
2)	The characteristic equation of a feedback control system is given by $s^4+20s^3+15s^2+25+K=0$. Determine the value of K which will cause sustained oscillations in the closed loop system. What are the corresponding oscillating frequencies? **(April 2011)**
3)	(i)The open loop transfer function of a unity feedback control system is given by $G(S)=\frac{K}{[(s+2)(s+4)(s^2+6s+25)]}$ By applying Routh criterion discuss the stability of the closed system as a function of K. Determine the values of K which will cause sustained oscillations in the closed loop system. What are the corresponding frequencies? **(April 2014) (Nov 2015)**
4)	Determine the stability of the given characteristic equation using Routh-Hurwitz criterion (a) $s^5+4s^4+8s^3+8s^2+7s+4=0$**(May 2016) (May 2019)** (b) $s^6+s^5+3s^4+3s^3+3s^2+2s+1=0$ **(April 2015)**
5)	Find the stability of the system with characteristic equation $2s^4+s^3+8s^2+s+1=0$

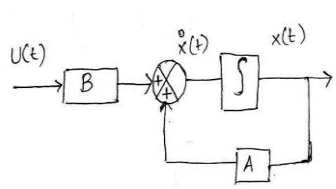
	using Routh Hurwitz Stability criteria, state its advantages and limitations. **(Nov 2019)**
6)	Determine the value of K for which the system describes by the following characteristics equation is stable $S^3+KS^2+(K+2)S+4=0$ **(Nov 2016)**
7)	Using Routh Hurwitz criterion, determine the stability of a system representing the characteristic equation $s^4+8s^3+18s^2+16s+5=0$. Comment on the location of roots of the characteristic equation. **(May 2017)**
8)	A unity feedback control system is characterized by the open loop transfer $G(s). = \frac{K(s+13)}{s(s+3)(s+7)}$. Using Routh criterion, calculate the range of values of K for the system to be stable. Also determine the value of K the system become marginally stable and calculate the frequency of oscillation if any.**(May 2021)**
9)	Explain in detail the design procedure of lag–lead compensator using Bode plot. **(May 2013) (April 2015)**
10)	(i) Explain in detail the design procedure of lag compensator using Bode plot. **(April 2014) (April 2015) (May 2016)(May 2017)** **(ii)** Derive the transfer function of lag-lead compensator. **(Nov 2015)**
11)	Explain the electric network realization of lead compensator and also its frequency response characteristics. **(April 2014)**
12)	The open loop transfer function of a unity feedback control system is $G_f(s) = \frac{k}{s(s+1)(s+2)}$ Design a suitable lag-lead compensator so as to meet the following specifications: static velocity error constant $K_v = 10\ sec^{-1}$, phase margin $= 50^\circ$ and gain margin $\geq$ 10db. **(May 2011)(Nov 2018)**
13)	A unity feedback control system has an open loop transfer function $G(s)= \frac{5}{[s(s+1)(0.5s+1)]}$ Design a suitable compensator such to maintain Phase margin of at least 40°**.(Nov 2014)**
14)	Explain in detail the realization of lag, lead and lag-lead electrical network. **(May 2017)**
15)	Explain in detail the design procedure of lead compensator using Bode plot. **(Nov**

	2015) (May 2022)
16)	Design a lead compensator for a unity feedback control system has an open loop transfer function G(s)= $\frac{k}{[s(s+1)]}$ for the specifications of K_V=10sec^{-1} and phase margin is 35°. **(Nov 2016) (Probable Part-C)**
17)	Consider the unity feedback whose open loop transfer function is $$G(s) = \frac{K}{S(0.1s+1)(0.2s+1)}$$ System to be compensated to meet the following specifications: Static velocity error constant = 30 /sec, Phase margin ≥50-degree, Bandwidth (ω_b) = 12 rad/sec. **(Nov 2018) (Probable Part-C)**
18)	Consider the unity feedback whose open loop transfer function is G(s)= $\frac{K}{[s(0.1s+1)(0.2s+1)]}$ system to be compensated to meet the following specifications Static velocity error constant = 30 sec, Phase margin ≥ 50°,Bandwidth ω_1=12 rad/ sec. **(Nov 2014) (Probable Part-C)**
19)	For the given system, $G(s) = \frac{K}{s(s+1)(s+2)}$, design a suitable lag-lead compensator to give velocity error constant =10sec^{-1}, phase margin=50°, gain margin≥10dB. Realize the basic compensators using electrical network and obtain the transfer function. **(Nov 2017) (Probable Part-C)**
20)	Design a lead compensator for unity feedback system whose open loop transfer function $G(s) = \frac{K}{S(s+1)(s+5)}$ to satisfy the following condition i) Velocity error constant Kv≥50 **ii)** Phase margin ≥20 degrees. **(May 2018) (Probable Part-C)**
21)	Design a lag compensator for the system $G(s) = \frac{K}{S(s+2)}$ to satisfy the following specifications: (i) Static velocity error constant Kv =10 sec^{-1}, (ii). Phase margin ϕ_m ≥60°. **(May 2019) (Probable Part-C)**
22)	Design a lag compensator for the system to have a phase margin of 65 degrees $$G(s) = \frac{1}{(S+1)(0.25s+1)}$$

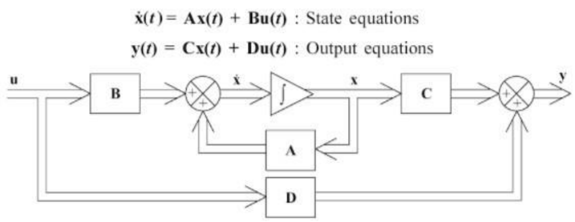
	H(s)=1, Maximum steady state error for unit step input =0.1. **(Nov 2019)**
23)	Sketch the Nyquist plot for the system whose open loop transfer function. $G(s)\,H(s) = \frac{K}{[s(s+2)(s+10)]}$ And find the range of K for stability of closed loop. **(May 2016) (Probable Part-C)**
24)	By use of Nyquist stability criterion determine whether the closed loop system having the following open loop transfer function is stable or not .If not how many closed loop poles lies in the right half s-plane $G(s)H(s)= \frac{(s+2)}{[(s+1)(s-1)]}$ **(Nov/Dec 2015) (Nov 2019)(Nov 2017)**
25)	Construct the Nyquist plot for a system whose open loop transfer function is given by $G(s) = \frac{K(1+s)^2}{s^3}$, find the range of K for stability. **(May 2018) (Probable Part-C)**
26)	Sketch the Nyquist plot for the system whose open loop transfer function. $G(s)\,H(s) = \frac{K(s+2)}{[s(s+3)(s+6)]}$. And find the range of K for stability of closed loop. Check your answer with Routh's criterion. **(Nov 2018)**
27)	Determine the stability of closed loop system by Nyquist stability criterion, whose open loop transfer function is given by, $G(s).H(s) = \frac{(s+4)}{(s+1)(s-1)}$. **(May 2021)**
28)	Construct the Routh array and determine the stability of the systemrepresented by the characteristics equation $s^5+s^4+2s^3+2s^2+3s+5 = 0$. Comment on the location of the roots of characteristics equation. **(May 2022)**
	UNIT V STATE VARIABLE ANALYSIS **PART A**
1)	**What are the advantages of state space analysis? (Nov 2011) (May 2013) (May 2018) (May 2019)(May 2021)** a) The state space analysis is applicable to any type of systems. They can be used for modelling and analysis of linear and nonlinear systems, time variant and time invariant systems and multi input multi output systems.

	b) The state space analysis can be performed with initial conditions. c) The variables used to represent the system can be any variables in the system. d) Using this analysis, the internal states of the system at any time instant can be predicted.
2)	**What is state space? (May 2016)** The set of all possible values which the state vector X(t) can have at time ‘t’ forms the state space of the system.
3)	**Define state and state variable. (Nov 2012) (May 2013) (Nov 2015)** State: the state is the condition of a system at any time instant. State variable: a set of variables which describe the state of the system at any time instant are called state variables.
4)	**What are phase variables?** The phase variables are defined as those particular state variables which are obtained from one of the system variable and its derivatives. Usually the variable used is the system output and the remaining state variable and then derivatives of the output.
5)	**Write the properties of state transition matrix. (May 2010) (May 2014)** The following are the properties of state transition matrix. 1. $\phi(0) = e^{A \times 0} = I \, (unit\, matrix)$ 2. $\phi(t) = e^{At} = \left(e^{-At}\right)^{-1} = \left[\phi(-t)\right]^{-1}$ 3. $\phi(t_1 + t_2) = e^{A(t_1+t_2)} = e^{At_1} e^{At_2} = \phi(t_1)\phi(t_2) = \phi(t_2)\phi(t_1)$
6)	**Define: State equation. (Nov2013)** The state variable model can be represented in the form of n first order differential equations as $\frac{dX_1}{dt} = \dot{X}_1(t) = A_{11}X_1(t) + A_{12}X_2(t) +, \ldots\ldots + A_{1n}X_n(t) + B_1u(t)$ $\frac{dX_2}{dt} = \dot{X}_2(t) = A_{21}X_1(t) + A_{22}X_2(t) +, \ldots\ldots + A_{2n}X_n(t) + B_2u(t)$: : $\frac{dX_n}{dt} = \dot{X}_n(t) = A_{n1}X_1(t) + A_{n2}X_2(t) +, \ldots\ldots + A_{nn}X_n(t) + B_nu(t)$ These equations are called state equations

7)	**What is state diagram? What are the basic elements used to construct the state diagram.** The pictorial representation of the state model of a system is called state diagram. The state diagram of the system can be either in block diagram or in a signal flow graph form. The basic elements used to construct the state diagram are scalar, adder and integrator.
8)	**What are the advantages of state space modelling using physical variables?** (a) The state variable can be utilized for the purpose of feedback (b) The implementation of design with state variable feedback becomes straight forward (c) The solution of state equation gives time variation of variables which have direct relevance to the physical system.
9)	**What is the advantage and disadvantage in canonical form of state model.** The advantage of canonical form is that the state equation are independent of each other. The disadvantage is that the canonical variables are not physical variables and so they are not available for measurement and control.
10)	**Write the solution for homogenous state equations.** The solution of homogenous state equation is $X(t) = e^{At} X_0$ where X(t) = State vector at time time, t e^{At} = State transition matrix X_0 = Initial condition vector at t=0
11)	**What is resolvant matrix.** The laplace transform of state transition matrix is called resolvant matrix. Resolvant matrix $\phi(s) = £[\phi(t)] = £[e^{At}]$ Also $\phi(s) = [SI-A]^{-1}$
12)	**How the model matrix is determined? (May 2012)** The model matrix M can be formed from eigenvectors. Let $m_1, m_2, m_3, \ldots m_n$ be the eigen vectors of a n^{th} order system. Now the modal matrix M is obtained by arranging all the eigen vectors column wise as shown below. Modal matrix = M = $[\ m_1\ m_2\ \ m_3\ \ , \ldots\ m_n]$

13)	**Give the concept of controllability. (Nov 2013) (Nov 2015) (May 2017)** A system is said to be completely state controllable if it is possible to transfer the system state from any initial state $X(t_0)$ at any other desired state X(t), in specified finite time by a control vector U(t). Controllability test is necessary to find the usefulness of a state variable. If the state variables are controllable then by controlling the state variables the desired outputs of the system are achieved.
14)	**When a system is said to be completely observable? (May 2016)** A system is said to be completely observable if every state X(t) can be completely identified by measurements of the output Y(t) over a finite time interval.
15)	**State the concept of observability? (May 2018) (Nov 2018) (May 2022)** The observability test is necessary to find weather the state variables are measurable are not. If the state variables are measurable then the state of the system can be determined by practical measurements of the state variables.
16)	**What is the necessary condition for complete Observability of a system? (Nov 2019)** For a nth order system described by state model $X = AX + BU$ $Y = CX + DU$ We can form a composite matrix Q_0 where $$Q_0 = [C^T \;\; A^T C^T \;\; (A^T)^2 C^T \;\; (A^T)^3 C^T \ldots\ldots (A^T)^{n-1} C^T \;]$$ If the system is completely observable if the rank of composite matrix Q_0 is n.
17)	**State the limitations of state variable feedback. (Nov 2016)** The limitations of state variable feedback are more states are to be known. These states can either measured or estimated. This technique is insensitive to system parameter changes and external disturbances.
18)	**For a first order differential equation described by *X* =Ax(t)+bu(t). Draw the block diagram form of the state diagram. (Nov 2016).** 

19) **Draw the block diagram representation of state model. (May 2017)**



20) **State the mechanism in control engineering which implies an ability to measure the stable by taking measurement at output. (May 2019)**

Observability and Controllability are the two methods to check the output response characteristics and observability in control engineering implies an ability to measure the stable by taking measurement at output.

21) **Find the controllability matrix for the system**

$$\begin{bmatrix} x_{1r} \\ x_{2r} \end{bmatrix} = \begin{bmatrix} -2 & -3 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} x_{1r} \\ x_{2r} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} u$$

$$y = [0 \ 1] \begin{bmatrix} x_{1r} \\ x_{2r} \end{bmatrix}$$

$$Q_c = [B \quad AB] = \begin{bmatrix} 1 & -2 \\ 0 & 1 \end{bmatrix} = 1 \neq 0$$

The rank of Q_c is 2

The system is completely controllable.

22) **Write the state model of a linear time invariant system.(May 2021)**

The state model of a linear time invariant system is given by

$X = AX + BU$

$Y = CX + DU$

X- Differential state vector

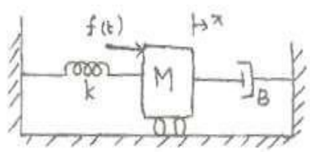
Y – Output vector ,U – Input vector, A – State matrix, B – Input matrix, C – Output matrix, D – Transition matrix

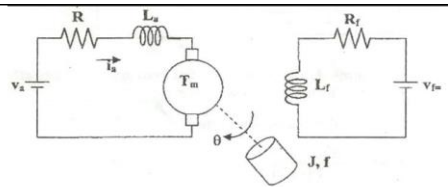
23) **List the merits and demerits of phase variables. (May 2022)**

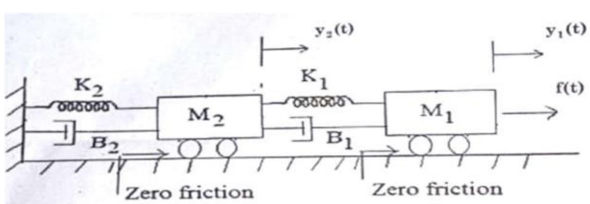
Merits:

Using phase variables, the system state model can be written directly by inspection from differential equation governing the system.

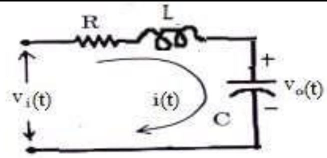
The phase variables provide a link between the transfer function design approach

	and time domain design approach. **Demerits:** The disadvantages in choosing phase variables is that the phase variables are not physical variables of the system and therefore are not available for measurement and control process
	PART – B
1)	The state space representation of a system is given below. Obtain the transfer function. **(May 2011)** $\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix}-2 & 1 & 0\\ 0 & -3 & 1\\ -3 & -4 & -5\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 1\end{bmatrix}u \quad y = \begin{bmatrix}0 & 1 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix}$
2)	**(i)** Find the state variable equation for a mechanical system (spring-mass-damper system) shown below. (**Nov 2011)**  (ii) A LTI system is characterized by the state equation $\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}1 & 0\\ 1 & 1\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}0\\ 1\end{bmatrix}u$ where u is a unit step function. Compute the solution of these equations assuming initial conditions $x_0 = \begin{bmatrix}1\\ 0\end{bmatrix}$
3)	Obtain the time response of the system described by $\dot{x}(t) = \begin{bmatrix}0 & 1\\ -1 & -2\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix} + \begin{bmatrix}1\\ -1\end{bmatrix}U(t)$ With the initial conditions $\begin{bmatrix}x_1(0)\\ x_2(0)\end{bmatrix} = \begin{bmatrix}0\\ 1\end{bmatrix}$; $y(t) = \begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}x_1(t)\\ x_2(t)\end{bmatrix}$.**(Nov 2016)**
4)	Obtain the state space representation of armature-controlled D.C. motor with load shown below

	 Choose the armature current i_a, the angular displacement of shaft θ, and the speed $\frac{d\theta}{dt}$ as state variables and θ as output variable. **(May 2012) /** Determine and show the state model of armature-controlled DC motor with neat sketch. **(May 2022)**
5)	**(i)** The state model matrices of a system are given below. Evaluate the observability of the system using Gilbert's test. **(May 2012)** $A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -2 & -3 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} and\ C = \begin{bmatrix} 3 & 4 & 1 \end{bmatrix}.$ (ii) Find the controllability of the system described by the following equation. $\dot{X} = \begin{bmatrix} -1 & -1 \\ 2 & -1 \end{bmatrix} \begin{bmatrix} X_1 \\ X_1 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} U(t)$
6)	A system is represented by the state equation X=AX+BU; Y=CX where $A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & -1 & -10 \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ 10 \end{bmatrix} and\ C = [\ 100\ ].$ Determine the transfer function of the system. **(May 2013)**
7)	A system is characterized by the transfer function $\frac{Y(s)}{U(s)} = \frac{3}{s^3 + 5s^2 + 11s + 6}$. Identify the first state as the output. Determine whether or not the system is completely controllable and observable. **(May 2013)**
8)	For the given state variable representation of a second order system given below find the state response for a unit step input and by using the discrete time approximation. $\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -2 & -3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 2 \end{bmatrix} [u]\ \begin{bmatrix} x_1(0) \\ x_2(0) \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ **(Nov 2013)**
9)	Consider the system with the state equation. Check the controllability of the

	system. **(Nov 2013)** $\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ -6 & -11 & -6\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 1\end{bmatrix}u$
10)	(i) Obtain the state model of the system described by the following transfer function. $\frac{y(s)}{u(s)} = \frac{5}{s^2 + 6s + 7}$. (ii) Obtain the state transition matrix for the state model whose system matrix A is given by $A = \begin{bmatrix}1 & 1\\ 0 & 0\end{bmatrix}$ **(May 2014)**
11)	**(i)** Check the controllability of the following state space system. **(May 2014)** $x_1 = x_2 + u_2\,;\ x_2 = x_3\,; x_3 = -2x_2 - 3x_3 + u_1 + u_2$ (ii) Obtain the transfer function model for the following state space system. $A=\begin{bmatrix}0 & 1\\ -6 & -5\end{bmatrix}$ $B=\begin{bmatrix}1\\ 0\end{bmatrix}$ $C=\begin{bmatrix}1 & 0\end{bmatrix}$ $D=\begin{bmatrix}0\end{bmatrix}$
12)	Consider the system with the state equation. Check the controllability and observability of the system. **(Nov 2015) (May 2016)** $A=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ -6 & -11 & -6\end{bmatrix}, B=\begin{bmatrix}1\\ 0\\ 1\end{bmatrix} C^T=\begin{bmatrix}10\\ 5\\ 1\end{bmatrix}$
13)	**(i)** Obtain the state model of the system **(Nov 2015)**  **(ii)** State and prove the properties of state transition matrix (**Nov 2015)**
14)	(i) The state model of the system is defined by $\dot{x}(t)$=Ax(t)+bu(t), y(t)=CX(t) where

	$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -6 & -11 & -6 \end{bmatrix}$, $B = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$, C = [1 0 0]. Obtain the diagonal canonical form of the state model by the suitable transformation matrix. **(May 2016)** (ii) Explain about the effect of state feedback**. (May 2016)**
15)	Determine whether the system described by the following state model is completely controllable and observable **(Nov 2016)** $\dot{x}(t) = \begin{bmatrix} 0 & 0 & 1 \\ -2 & -3 & 0 \\ 0 & 2 & -3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 2 \\ 0 \end{bmatrix} u(t)$; $Y(t) = [1\ 0\ 0] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$
16)	Check the controllability and observability of the system whose state space representation is given as **(May 2017)** $\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 1 & -2 & 0 \\ 2 & 1 & -3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 10 \\ 1 \\ 0 \end{bmatrix} u \quad y = [1\ \ 0\ \ 0] \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$
17)	**(i)** What are state variables. Explain the state formulation with its equation. **(May 2017)** **(ii)** Given that **(May/June 2017)** $A_1 = \begin{bmatrix} \sigma & 0 \\ 0 & \sigma \end{bmatrix}$ $A_2 = \begin{bmatrix} 0 & \omega \\ -\omega & 0 \end{bmatrix}$ $A_3 = \begin{bmatrix} \sigma & \omega \\ -\omega & \sigma \end{bmatrix}$ Compute state transition matrix.
18)	Explain the concepts of controllability and observability. **(Nov 2017)**
19)	Determine the canonical state model of the system whose transfer function is $T(s) = \frac{2(s+5)}{(s+2)(s+3)(s+4)}$ **(May 2018)**
20)	Consider a linear system described by the following transfer function, $\frac{F(s)}{U(s)} = \frac{10}{s(s+1)(s+2)}$ Design a feedback controller with a state feedback so that the closed loop poles are placed at -2. -1±j1. **(May 2018)**
21)	Consider the following RLC series circuit shown in figure below and obtain its state model. **(May 2019)**

	
22)	Consider the following plant of the state space representation $A = \begin{bmatrix} 0 & 1 \\ -2 & -3 \end{bmatrix}\ B = \begin{bmatrix} -2 \\ 2 \end{bmatrix}\ C = \begin{bmatrix} -2 & 0 \end{bmatrix}$ Examine the controllability and observability of a state-space formed by the system**. (May 2019)**
23)	Derive the state variable formulation of parallel RLC circuit with current source input. **(Nov 2019)**
24)	i) Obtain the state model for the system described by the transfer function $T(s) = \frac{Y(s)}{U(s)} = \frac{1}{s^3 + 6s^2 + 10s + 5}$ **(May 2021)** **ii)** Obtain state transition matrix for the state model whose A matrix is given by $A = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$ **(May 2021)**
25)	Determine the state controllability and observability of the system $x\ (t)$=Ax(t)+bu(t), y(t)=CX(t) **(May 2021)** A= $\begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & -1 \end{bmatrix}$, B= $\begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$, C = [1 0 1].
26)	The state model of a system is given by the given state equation. Verify that the system is controllable and observable. **(May 2022)** $\dot{X} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -5 & -1 \end{bmatrix} X + \begin{bmatrix} 0 \\ 5 \\ -24 \end{bmatrix} u$ $\mathbf{y} = [\mathbf{1} \quad \mathbf{0} \quad \mathbf{0}]\, \boldsymbol{x} + [\mathbf{0}]\, \boldsymbol{u}$

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE3501- POWER SYSTEM ANALYSIS

SEMESTER V

REGULATIONS 2021

NOTES

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QUESTION BANK

EE3501 – SYLLABUS

UNIT I POWER SYSTEM

Need for system planning and operational studies — Power scenario in India — Power system components — Representation — Single line diagram — per unit quantities — p.u. impedance diagram — p.u. reactance diagram — Network graph, Bus incidence matrix, Primitive parameters, Bus admittance matrix from primitive parameters — Representation of offnominal transformer — Formation of bus admittance matrix of large power network.

UNIT II POWER FLOW ANALYSIS

Bus classification — Formulation of Power Flow problem in polar coordinates — Power flow solution using Gauss Seidel method — Handling of Voltage controlled buses — Power Flow Solution by Newton Raphson method.

UNIT III SYMMETRICAL FAULT ANALYSIS

Assumptions in short circuit analysis — Symmetrical short circuit analysis using Thevenin?s theorem — Bus Impedance matrix building algorithm (without mutual coupling) — Symmetrical fault analysis through bus impedance matrix — Post fault bus voltages — Fault level — Current limiting reactors.

UNIT IV UNSYMMETRICAL FAULT ANALYSIS

Symmetrical components — Sequence impedances — Sequence networks — Analysis of unsymmetrical faults at generator terminals: LG, LL and LLG — unsymmetrical fault occurring at any point in a power system — computation of post fault currents in symmetrical component and phasor domains.

UNIT V STABILITY ANALYSIS

Classification of power system stability — Rotor angle stability — Swing equation — Swing curve — Power-Angle equation — Equal area criterion — Critical clearing angle and time — Classical step-by-step solution of the swing equation — modified Euler method.

COURSE OUTCOMES:

Upon the successful completion of the course, students should have the:

CO1: Ability to model the power system under steady state operating condition. CO2: Ability to carry out power flow analysis using.

CO3: Ability to infer the significance of short circuit studies in designing circuit breakers.

CO4: Ability to analyze the state of the power system for various unsymmetrical faults.

CO5: Ability to analyze the stability of power system using different methods.

TEXT BOOKS:

1. John J. Grainger, William D. Stevenson, Jr, ‘Power System Analysis’, Mc Graw Hill Education (India) Private Limited, New Delhi, 2017.

2. Kothari D.P. and Nagrath I.J., ‘Power System Engineering’, Tata McGraw-Hill Education, 3rd edition 2019.

3. Hadi Saadat, ‘Power System Analysis’, Tata McGraw Hill Education Pvt. Ltd., New Delhi, 21st reprint, 2010.

REFERENCES

1. Pai M A, ‘Computer Techniques in Power System Analysis’, Tata Mc Graw-Hill Publishing Company Ltd., New Delhi, Second Edition, 2007.

2. J. Duncan Glover, Mulukutla S.Sarma, Thomas J. Overbye, ‘Power System Analysis & Design’, Cengage Learning, Fifth Edition, 2012.

3. P. Venkatesh, B. V. Manikandan, A. Srinivasan, S. Charles Raja, “Electrical Power Systems: Analysis, Security and Deregulation” Prentice Hall India (PHI), second edition - 2017

4. Gupta B.R., ‘Power System - Analysis and Design’, S. Chand Publishing, Reissue edition 2005.

5. Kundur P., ‘Power System Stability and Control’, Tata McGraw Hill Education Pvt. Ltd., New Delhi, 2013

Subject Title : Power system analysis **Subject Code** : EE3501

UNIT I - INTRODUCTION

Need for system planning and operational studies – basic components of a power system.- Introduction to restructuring - Single line diagram – per phase and per unit analysis – Generator - transformer – transmission line and load representation for different power system studies.- Primitive network - construction of Y-bus using inspection and singular transformation methods – z-bus.

PART – A

1. **Mention the requirements of planning the operation of power system**

   To monitor the voltage at various buses, real and reactive power flow between buses.
   To design the circuit breakers.
   To plan future expansion of the existing system
   To analyze the system under different fault conditions
   To study the ability of the system for small and large disturbances (Stability studies)

2. **What is the need for base values?**

   The components or various sections of power system may operate at different voltage and power levels. It will be convenient for analysis of power system if the voltage power, current and impedance ratings of components of power system are expressed with reference to a common value called base value. Hence for analysis purpose a base value is chosen for voltage, power, current and impedance. Then all the voltage, power, current and impedance ratings of the components are expressed as a percent or per unit of the base value.

3. **Define per unit value of an electrical quantity and write the equations for base impedance for a three phase power system.** ,

   The per unit value of any quantity is defined as the ratio of the actual value of the quantity to the base value expressed as a decimal. The base value is an arbitrary chosen value of the quantity.

   The per unit value of base impedance for a three phase power system is as,

$$Z_b = \frac{kV_b x1000}{\sqrt{3}I_b}$$

4. **Write the equation for per unit impedance if change of base occurs.**

   The equation for converting per unit impedance form one base to another can be given as follows.

$$Z_{p.u.\,new} = Z_{pu,old}\ x\frac{kV_{b,old}^{2}}{kV_{b,new}^{2}}\ x\ \frac{MVA_{b,new}}{MVA_{b,old}}$$

5. **What are the advantages of per unit computation?**

   The advantages of per unit method over percent method is that the product of two Quantities expressed in per unit are expressed in per unit itself, but the product of two quantities

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expressed in percent must be divided by100 to obtain the result in percent.

6. **A Y connected generator rated at 300 MVA, 33 KV has a reactance of 1.24 p.u. Find the Ohmic value of the reactance.**

$$\text{Per unit Value} = \frac{\text{Actual value}}{\text{Base value}}$$

Actual Value = Pu value * base value

= 1.24 * (33^2/300)

= 4.5012 Ω

7. **State the advantages of per unit analysis.**

The advantages of per unit representation are

1. Per unit data representation yields valuable relative magnitude information.
2. Circuit analysis of system containing transformers of various transformation ratio is greatly simplified.
3. Circuit parameters tend to fall in relatively narrow numerical ranges making erroneous data east to spot.

8. **How are the loads represented in the reactance and impedance diagram? (NOV/DEC 2016)**

The loads are represented in reactance diagram with an internal emf in series with reactance and resistance.

The same load is represented in impedance diagram as internal emf in series with reactance without resistance.

9. **What is single line diagram**

Single line diagram is diagrammatic representation of power system in which the components are represented by their symbols and the interconnections between them are shown by a single straight line (even though the system is 3- phase system). The ratings and the impedances of the components are also marked on the single line diagram.

10. **Define per unit value.**

The per unit value of any quantity is defined as the ratio of the actual value of the quantity to the base value expressed as a decimal. The base value is an arbitrary chosen value of the quantity.

$$\text{Per unit Value} = \frac{\text{Actual value}}{\text{Base value}}$$

11. **Define Power System, Power System Analysis and Per Phase Analysis.**

Power system

The conveyance of electrical power from a power station to consumer premises is known as electrical power system.

Power System Analysis

The evaluation of power system is called as power system analysis.

Per Phase Analysis.

A balanced three phase system is always analyses on per phase basis by considering one of the three phase lines and neutral.

.

12. **What are the components of power system?**
The various components of power system includes
Generators,
Power Transformers,
Transmission lines,
Substation Transformers,
Distribution Transformers and
Loads.

13. **What are the main divisions of power system?**
If a sudden change or sequence of changes occurs in one or more of the system parameters or one or more of its operating quantities, the system is said to have undergone a disturbance from its steady state operating condition.
The two types of disturbances in a power system are,
Large disturbance
Small disturbance

14. **What is a small disturbance? Give example.**
If the power system is operating in a steady state condition and it undergoes Change, which can be properly analyzed by linearized versions of its dynamic and algebraic equations, a small disturbance is said to have occurred.
Example of small disturbance is a change in the gain of the automatic voltage regulator in the excitation system of a large generating unit.

15. **What is a large disturbance? Give some examples.**
A large disturbance is one for which the nonlinear equations describing the dynamics of the power system cannot be validly linearized for the purpose of analysis.
Examples of large disturbances are transmission system faults, sudden load changes, loss of generating units and line switching.

16. **What are the assumptions for transient stability?**
The assumptions to be followed for the transient stability are as follows.
Generators are represented by the constant internal voltage behind transient reactance.
The turbine mechanical power outputs are assumed to be constant and the governor corrective action is ignored.
All resistance is neglected.
Damping is neglected.

17. **When is a power system said to be transiently stable?**
Transient stability is defined as the ability of the power system to remain in synchronism under large disturbance conditions, such as fault and switching operations. The maximum power transfer limit is less than that of the steady state condition.
If the machines of the system are found to remain essentially in synchronism within the first second following a system fault or other large disturbance, the system is considered to be transiently stable.

18. **What is the objective of short circuit study?**
The objective of the short circuit analysis is to precisely determine the currents and voltages at the

.

different locations of the power system corresponding to the different types of faults, such as three phase to ground fault, line to ground fault, line to line fault, double line to ground fault and open conductor fault. The data is used to select fuses, protective relays and circuit breakers to rescue the system from the abnormal condition. The symmetrical components and sequence networks are used in the analysis of unsymmetrical faults.

19. **What is a bus?**

The meeting point of various components in a power system is called a bus. The bus is a conductor made of copper or aluminum having an eligible resistance. The buses are considered as points of constant voltage in a power system.

Types of bus includes

Slack bus,

Generator Bus,

Load Bus,

20. **State the need for per unit value. (or) What is the need of per unit**

The needs of per unit value are stated as follows.

The per unit impedance referred to either side of a single phase transformer is the same.

The chance of confusion between line and phase quantities in a three phase balanced system is greatly reduced.

21. **What are the advantages of per-unit computations?**
    1. Manufacturers usually specify the impedance of a device or machine in per unit on the base of the name plate rating.
    2. The p.u values of widely different rating machines lie within a narrow range, even though the ohmic value has a very large range.
    3. The p.u. impedance of circuit element connected by transformers expressed on a proper base will be same if it is referred to either side of a transformer.

    The p.u. impedance of a 3-phase transformer isindependent of the type of winding connection (Y or Δ).

22. **A generator rated at 30 MVA, 11 kV has a reactance of 20%. Calculate its p.u. Reactance's for a base of 50 MVA and 10kV.**

Solution.

New p.u. reactance if generator = $X_{pu,old} \times \frac{kV_{b,old}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,old}}$

Here, $X_{pu,old}$=20%=0.2 p.u.; $kV_{b,old}$= 11kV,$MVA_{b,old}$=30MVA, $kV_{b,new}$=10kV; $MVA_{b,new}$=50MVA

New p.u. reactance of generator=$0.2 \times \left(\frac{11}{10}\right)^2 \times \frac{50}{30}$ = 0.403 p.u

23. **What is impedance and reactance diagram?**

The impedance diagram is the equivalent circuit of power system in which the various components of power system are represented by the approximate or simplified equivalent circuits.

.

The impedance diagram is used for load flow studies. The reactance diagram is the simplified equivalent circuit of power system in which the various components are represented by their reactance. The reactance diagram can be obtained for impedance diagram fall the resistive components are neglected. The reactance diagram is used for fault calculations.

24. What are the approximations made in impedance diagram?

The following approximations are made in impedance diagram.

The neutral reactance's are neglected.

Shunt branches in the equivalent circuits of transformer are neglected

The resistances are neglected.

All static loads and induction motors are neglected.

The capacitances of the transmission lines are neglected.

25. **Whatis busadmittancematrix?**

The matrix consisting of the self and mutual admittances of the network of a power system is called bus admittance matrix. It is given by the admittance matrix in the node basis matrix equation of a power system and it is denoted as Y_{bus}.

The bus admittance matrix is symmetrical. Inverse of bus impedance matrix is the bus admittance matrix.

26. What is bus impedance matrix?

The matrix consisting of driving point impedances and impedances of the network of a power system is called bus impedance matrix. It is given by the inverse of bus admittance matrix and it is denoted as Z_{bus}.

The bus impedance matrix is symmetrical matrix.

27. How the Z_{bus} is modified when a branch of impedance Z_b is added from a new bus-p to the reference bus?

When a branch of impedance Z_b is added from a new bus-p to the reference bus, the order of the bus impedance matrix increases by one.

Let the original bus impedance matrix have an order of n and so the new bus impedance matrix has an order of (n+1).The first nx n sub matrix of new bus impedance matrix is the original bus impedance matrix. The elements of $(n+1)^{th}$ column and row are all zeros except the diagonal. The (n+1) diagonal element is the added branch impedance Z_b.

28. What are symmetrical components?

An unbalanced system of N related vectors can be resolved in to N systems of balanced vectors. The N–sets of balanced vectors are called symmetrical components. Each set consists of N–vectors which are equal in length and having equal phase angles between adjacent vectors.

29. What are sequence impedance and sequence networks?

The sequence impedances are impedances offered by the devices or components for the like sequence component of the current. The single phase equivalent circuit of a power system consisting of impedances to the current of any one sequence only is called sequence network.

30. List out the major stages in a single line diagram of a power system.

The different stages of power in power system are

.

Primary transmission
Secondary transmission
Primary distribution
Secondary distribution

31. **Give the formula to calculate base current, I_b and base impedance of a three- phase system.**

The equation for base current I_b is,

$$I_b = \frac{KVA_b}{\sqrt{3}\ KV_b}$$

The equation for base impedance is,

$$Z_b = \frac{kV_b x 1000}{\sqrt{3} I_b}$$

Where

I_b=Line value of base current.

kVA_b=3-phasebaseKVA

kV_b =line to line base kV

Z_b=Base impedance per phase.

32. **What is the advantage of per unit method over percent method?**

Theadvantageofperunitmethodoverpercentmethodisthattheproductoftwo
Quantities expressed in per unit are expressed in per unit itself, but the product of two quantities expressed in percent must be divided by100 to obtain theresult inpercent.

33. **What is the need for base values?**

Thecomponentsofvarioussectionsofpowersystemmayoperateatdifferent
Voltage and power levels. It will be convenient for analysis of power system if the voltage, power, current and impedance ratings of power system components are expressed with reference to a common value called base value. Then all the voltages, power, current and impedance ratings of the components are expressed as a percent or per unit of the base value.

34. **Why the three phase kVA is directly used for per unit calculation in three phase systems?**

The per unit value of a 3-phase kVA on the 3-phase kVA base is identical to the per unit value of kVA per phase on the kVA per phase base.

$$\frac{3\ phase\ KVA}{3\ phase\ base\ KVA} = \frac{KVA\ per\ phase}{base\ KVA\ per\ phase},$$

Thereforein3phasesystems,thelinevalueofvoltageand3phasekVAare directly used for per unit calculations.

35. **Give the equation for transforming base kV on LV side to HV side of a transformer and vice versa.**

$$\text{Base kV on HVside} = \text{Base kV on LV side x } \frac{\textbf{HV rating}}{\textbf{LV rating}}$$

.

Base kV on LVside = Base kV on HV side x $\frac{\text{LV rating}}{\text{HV rating}}$

36. **List the methods of improving the transient stability limit of a power system.**

The methods of improving the transient stability limit of a power system are listed as follows.
(1)Increase of system voltage, use of AVR.
(2)Use of high speed excitation systems.
(3)Reduction in system transfer reactance.
(4)Use of high speed reclosing breakers.

37. Give the equation for load impedance and load admittance per phase of a balanced star connected load.

Load impedance per phase, Z = $\frac{|V_L|}{P - jQ}$ Load admittance per phase, = $\frac{P - jQ}{|V_L|^2}$

Where,
P = Three phase active power of star connected load in watts.
Q = Three phase reactive power of star connected load in VARs.
V_L= Line voltage of load.

38. **What are the methods available for forming bus impedance matrix?**

Form the bus impedance matrix and then take its inverse to get bus
1. Impedance Matrix.
2. Directly from the bus impedance matrix from the reactance diagram. This Method utilizes the techniques of modifications of existing bus impedance Matrix due to addition of new bus.

39. Name the diagonal and off diagonal elements of Bus Impedance Matrix.

Bus Admittance Matrix.

The diagonal elements of bus admittance matrix are called self-admittances of the Buses and off diagonal elements are called mutual admittances of the buses.

Bus Impedance Matrix.

The diagonal elements of bus impedance matrix are called driving point impedances of the buses and off diagonal elements of bus impedance matrix are called transfer Impedances of the buses.

40. Mention the advantages of bus admittance matrix, Y_{bus}.

The advantages if bus admittance matrix is listed as follows.
i) Data preparation is simple.
ii) Formation and modification is easy.
iii) Since the bus admittance matrix is sparse matrix(i.e., most of its elements are zero), the computer memory requirements are less.

41. What are the considerations used to select base values?

Selection of Base MVA.

First a base value is chosen for the network.
The same MVA will be used in all parts of the system.

.

It may be the largest MVA of a section, or total MVA of the system or any value like 10,100,1000 MVA etc.

Selection of Base KVA.

The rated voltage of the largest section may be taken as base Selection of Base MVA.

The base voltages of remaining sections assigned, depends on the turns ratio of the transformer.

42. Prove the per unit impedance of the transformer referred to the primary side is equal to the per unit impedance referred to secondary side.

Let the impedance of the transformer referred to primary side be Z_P and that on secondary side be Z_S then,

$Z_P = Z_S\,(V_P / V_S)^2$

Where, V_P and V_S are the primary and secondary voltage of the transformer.

Z_P p.u = ($I_P\ Z_P / V_P$)

= $Z_S\,(V_P / V_S)^2\,(I_P / V_P)$

(i) $= Z_S\ I_P\ V_P / V_S^2$

i) $= Z_S\,(I_S V_S / V_S^2)$

ii) $= Z_S I_S / V_S = Z_S$ p.u

Therefore Z_P p.u = Z_S p.u

43. A generator rated at 30MVA, 11KV has a reactance of 20%.Calculate its per unit reactance for a base of 50 MVA and 10KV.

$MVA_{new} = 50$; $KV_{new} = 10$; $MVA_{old} = 30$; $KV_{old} = 11$

$X_{p.u} = 20\% = 20/100 = 0.2$ p.u

$$X_{p.u,new} = X_{p.u,old} \times \left[\frac{Base\ KV_{old}}{Base\ KV_{new}}\right]^2 \times \left[\frac{Base\ MVA_{new}}{Base\ MVA_{old}}\right]$$

$$X_{p.u,new} = j0.2 \times \left[\frac{11}{10}\right]^2 \times \left[\frac{50}{30}\right] = j0.4033\ \ p.u$$

44. What is the new p.u impedance if the new base MVA is twice the old base MVA?

$$MVA_{new} = 2\ MVA_{old}$$

$$Z_{p.u,new} = Z_{p.u,old} \times \left[\frac{Base\ KV_{old}}{Base\ KV_{new}}\right]^2 \times \left[\frac{Base\ MVA_{new}}{Base\ MVA_{old}}\right]$$

$$Z_{p.u,new} = Z_{p.u,old} \times \left[\frac{Base\ KV_{old}}{Base\ KV_{new}}\right]^2 \times \left[\frac{2\ Base\ MVA_{old}}{Base\ MVA_{old}}\right]$$

45. Write the equation for base impedance and per unit impedance if change of base occurs.

Base Impedance

The equation for base impedance is given as follows

$$Base\ Impedance = \frac{(Base\ KV)^2}{Base\ MVA}$$

Per unit impedance if change of base occurs.

The equation for per unit impedance if change of base occurs.

$$Z_{p.u,new} = Z_{p.u,old} \times \left[\frac{Base\ KV_{old}}{Base\ KV_{new}}\right]^2 \times \left[\frac{Base\ MVA_{new}}{Base\ MVA_{old}}\right]$$

46. Why bus admittance matrix is preferred in load flow?

Bus admittance matrix is preferred in load flow problem because,

It is easy to formulate.

No need of taking inverse.

Computation time is less.

Matrix is symmetric, so calculation of upper or lower triangular matrix is enough.

Each bus is connected to only a few nearby buses.so many diagonal elements are zero.

47. **Distinguish between impedance and reactance diagram**

The resistive and reactive loads can be represented by any one of the following representation.

Constant power representation.

Load power, S = P + JQ.

Constant current representation.

Load current. , I = $\frac{\sqrt{P^2 + Q^2}}{|V|} \angle\delta - \theta$

Constant impedance representation.

Load current, Z = $\frac{|V|^2}{P - jQ}$

48. Give the methods available for forming bus impedance matrix.

The three main methods available in forming bus impedance matrix are as follows.

Form the bus admittance matrix and take the inverse to get bus impedance matrix.

Using bus building algorithm.

Using L-U factorization of Y-bus matrix.

49. List out the application of Y-Bus.

The application of Y-bus matrix is as follows.

Y-bus is used in solving load flow problems.

It has gained applications owing to the simplicity in data preparation.

It can be easily formed and modified for changes in the network.

It reduces computer memory and time requirements because of sparse matrix.

50. What are the various methods to form Y-Bus matrix by singular transformation?

Various methods to form Y-Bus matrix by singular transformation are

Formation of network.

Formation of Graph.

Formation of oriented Graph.

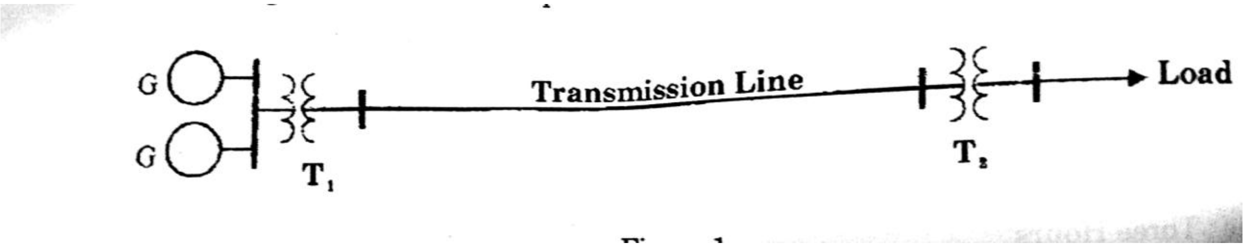
Formation of Loop.

Formation of Tree.

Formation of Link or chord.

PART B

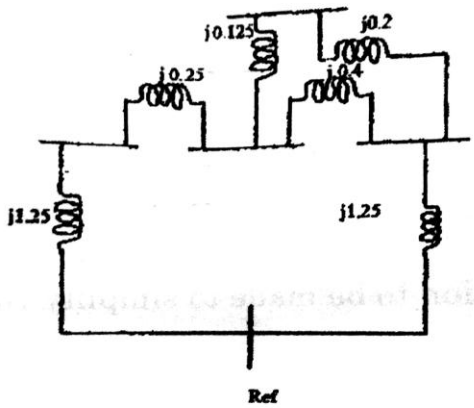
1. **In the single line diagramshown in fig. 1 each three phase generator G is rated at 200 MVA, 13.8 Kv and has a reactance of 0.85 pu and are generating 1.15 pu. Transformer T1 is rated at 500 MVA, 13.5 KV/220 KVA and has a reactance of 8%. The transmission line has a reactance of 7.8 ohm. T=Transformer T2 has a rating of 4010 MVA, 22 KV/33 KV and a reactance of 11%. The load is 250 MVA at a power factor of 0.85 lag. Convert all quantities to a common base of 500MVA and 220 KV on the line and draw the circuit diagram with values expressed in pu.** **(APR/MAY 2018)**



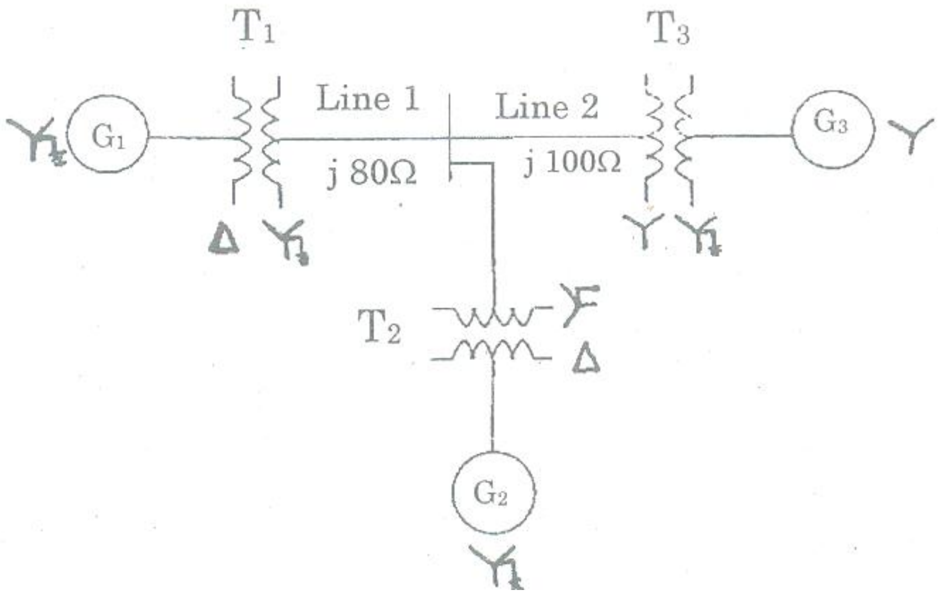
2. **A 200 MVA, 13.8 KV generator has a reactance of 0.85pu. and is generating 1.15 pu voltage. Determine the actual value of the line voltage, phase voltage and reactance.**

(APR/MAY 2018)

3. **Determine Z-bus for system whose reactance diagram is shown in given fig. where the impedance is given in p.u, preserve all the nodes. (APR/MAY 2018)**



4. **Draw the reactance diagram for the power system shown infig. Neglect resistance and use a base value of 50 MVA and 13.8 KV on generator G1. (Nov/Dec 2015, 2017)**
   Generator, G_1=20 MVA, 13.8 kV, X"= 20%
   Generator, G_2=30 MVA, 18.0 kV, X"= 20%
   Generator, G_3=30 MVA, 20.0 kV, X"= 20%
   Transformer, T_1 = 25 MVA, 220/13.8 kV, X=10%
   Transformer, T_2 = 3 single phase unit rated 10 MVA, 127/18 kV, X=10%
   Transformer, T_3 = 35 MVA, 220/22 kV, X=10%



Determine the new values of per unit reactance of G1, T1, transmission line Transmission line 2, G2, T2, G3 and T3.

Solution.

Choose

$KV_{b,new}$

$MVA_{b,new}$

Generator 1,2 & 3:

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^{2}}{kV_{b,new}^{2}} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

=

Transformer, T_1(Py):

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^{2}}{kV_{b,new}^{2}} \times \frac{MVA_{b,new}}{MVA_{b,given}} = j0.2 \text{ p.u}$$

Transmission Line:

Transformer secondary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{H.T \text{ side rating of } T_1}{L.T \text{ side rating of } T_1} \right)$$

$$Z_{p.u} = \left(\frac{Z_{actual}}{kV_b^{2}} \right) \times MVA_b$$

Transformer, T_2(Sy):

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^{2}}{kV_{b,new}^{2}} \times \frac{MVA_{b,new}}{MVA_{b,given}} = j0.2 \text{ p.u}$$

Transformer, T_3(Sy):

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^{2}}{kV_{b,new}^{2}} \times \frac{MVA_{b,new}}{MVA_{b,given}} = j0.2 \text{ p.u}$$

Load, M : Transformer secondary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_2}{H.T\ side\ rating\ of\ T_2} \right)$$

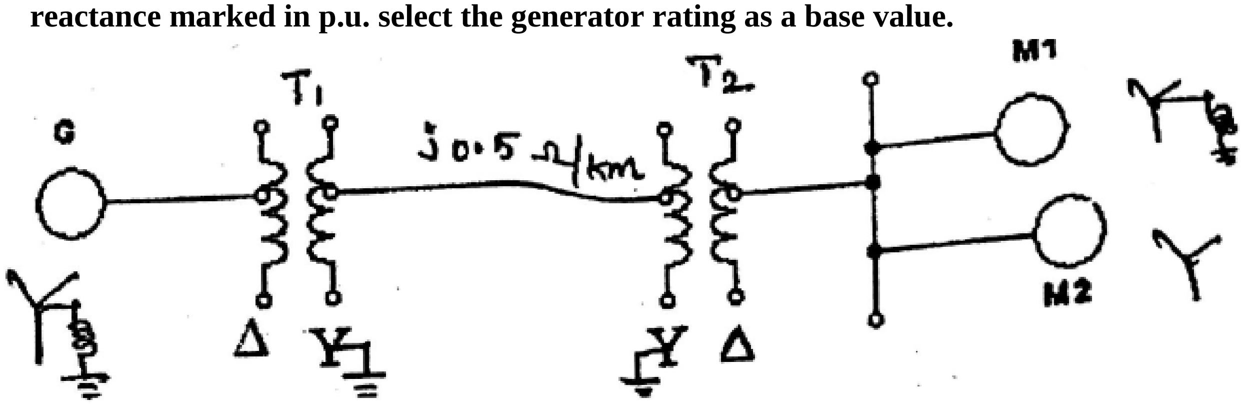
$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{{kV_{b,given}}^2}{{kV_{b,new}}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

5. **Describe Z bus building algorithm in details by using a three bus system. (NOV/DEC 2017)**

6. **300 MVA, 20 kv, 3 Φ generator has sub transient reactance of 20%. The generator supplies 2 synchronous motors through a 64 KM transmission line having transformer at both ends as shown. In this , T1 is a 3 Φ transformer 350MVA, 20/230 KV, 10% reactance & T2 is made of 3 single phase transformer of rating 100 MVA, 127/13.2 KV, 10% reactance.**

   (MAY/JUNE 2017)

   Series reactance of the transmission line is 0.5Ω/KM. The rating of 2 motors are M1 = 200 MVA, 13.2 KV, & M2 = 100 MVA, 13.2 KV, 20%. Draw the reactance diagram with all the reactance marked in p.u. select the generator rating as a base value.



Solution:

Choose $MVA_{b,new}$

Choose $kV_{b,new}$

Generator:

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

Transformer T_1 referred to Primary side:

Transformer T_1 Primary side change occurs, so calculate $KV_{b,new}$ as

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

Transformer T_1 referred to Primary side:

$KV_{b,new} = 11$ kV

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

j 0.5Ω/KM line :

Transformer T_3 Secondary side change occurs, so calculate $KV_{b,new}$ as

$KV_{b,new} = KV_{b,old} * \left(\frac{H.T\ side\ rating\ of\ T_3}{L.T\ side\ rating\ of\ T_3} \right)$

$Z_{p.u\ new} = \frac{Z_{actual}}{Z_{base}} = \left(\frac{Z_{actual}}{kV_b^2} \right) \times MVA_b$

Transformer T_5 referred to Primary side:

$KV_{b,} = 66$ kV

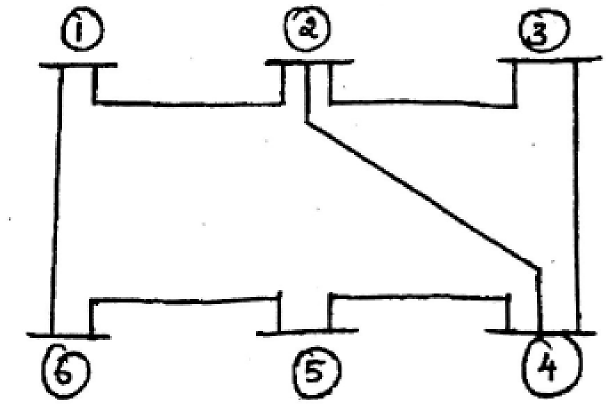
$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

Motor : $KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_5}{H.T\ side\ rating\ of\ T_5} \right)$

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}} = j\ 0.225$ p.u

7. **Form bus admittance matrix for the data given below using singular transformation method. Take node 6 as reference node. (MAY/JUNE 2017)**

ELEMENTS	BUS CODE	X (p.u)
1	1-2	0.04
2	1-6	0.06
3	2-4	0.03
4	2-3	0.02
5	3-4	0.08
6	4-5	0.06
7	5-6	0.05



Solution:

Solution:

The Y_{bus} Matrix of the network is

The elements of new bus matrix after eliminating

$Y_{jknew=}Y_{jk} - \left(\frac{Y_{jn}.Y_{nk}}{Y_{nn}} \right)$, where, n=4, j=1,2,3 , k=1,2,3.

The bus admittance matrix is symmetrical. $\therefore Y_{kjnew} = Y_{jknew}$

$$Y_{11new} = Y_{11} - \frac{Y_{14}.Y_{41}}{Y_{44}} = -j1.3 - \frac{(j0.4).(j0.4)}{-j0.9} = -j1.12$$

$$Y_{12new} = Y_{12} - \frac{Y_{14}.Y_{42}}{Y_{44}} = j0.5 - \frac{(j0.4).(0)}{-j0.9} = j0.5$$

$$Y_{13new} = Y_{13} - \frac{Y_{14}.Y_{43}}{Y_{44}} = j0.4 - \frac{(j0.4).(j0.5)}{-j0.9} = j0.622$$

$$Y_{21new} = Y_{12new} = j0.5$$

$$Y_{22new} = Y_{22} - \frac{Y_{24}.Y_{42}}{Y_{44}} = -j1.1 - \frac{(0).(0)}{-j0.9} = -j1.1$$

$$Y_{23new} = Y_{23} - \frac{Y_{24}.Y_{43}}{Y_{44}} = 0.6 - \frac{(0).(0.5)}{-0.9} = j0.6$$

$$Y_{31new} = Y_{13new} = j0.622$$

$$Y_{32new} = Y_{23new} = j0.6$$

$$Y_{33new} = Y_{33} - \frac{Y_{34}.Y_{43}}{Y_{44}} = -j1.5 - \frac{(j0.5).(j0.5)}{-j0.9} = -j1.222$$

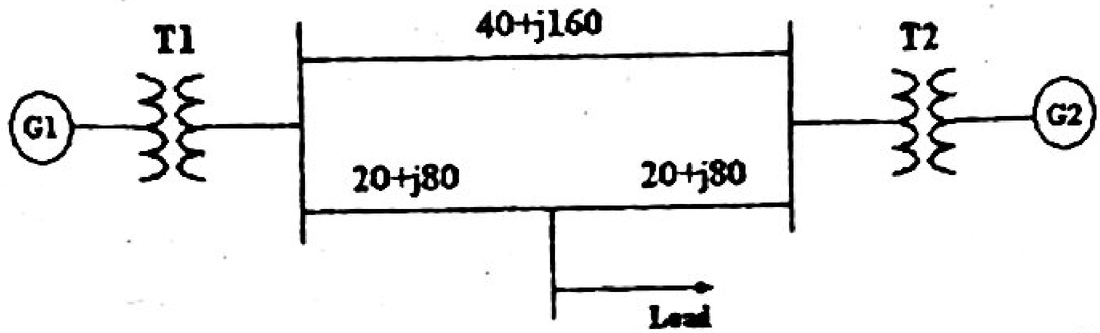
The reduced bus admittance matrix after eliminating n+1th row is in order 5*5

8. Prepare a per phase schematic of the system shown and show all the impedance in per unit on a 100 MVA, 132 KV, base in the transmission line circuit. The necessary data are given as follows:

G1 : 50 MVA, 12.2 KV, X = 0.15 pu

G2 : 20 MVA, 13.8 KV, X = 0.15 ohms

T1 : 80 MVA, 12.2/161 KV, X = 0.1 pu
T2 : 40 MVA, 13.8/161 KV, X" = 16.0 pu
Load : 50 MVA, 0.8 pf lag operating at 154 KV
Determine the pu impedance of the load.



Solution.

Choose

$KV_{b,new}$

$MVA_{b,new}$

Generator:

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

=

Transformer, T_1(Py):

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}} = j0.2 \text{ p.u}$$

Transmission Line:

Transformer secondary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{H.T \text{ side rating of } T_1}{L.T \text{ side rating of } T_1} \right)$$

$$Z_{p.u} = \left(\frac{Z_{actual}}{kV_b^2} \right) \times MVA_b$$

Transformer, T_2(Sy):

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}} = j0.2 \text{ p.u}$$

Load, M : Transformer secondary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{L.T \text{ side rating of } T_2}{H.T \text{ side rating of } T_2} \right)$$

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

9. The parameters of a 4-bus system are as under:

Line starting bus	Line ending bus	Line Impedance	Line charging admittance
1	2	0.2+j0.8	j0.02
2	3	0.3+j0.9	J0.03
2	4	0.25+j1.0	J0.04
3	4	0.2+j0.8	J0.02
1	3	0.1+j0.4	J0.01

Draw the network and find bus admittance matrix.

Solution:

The Y_{bus} Matrix of the network is

$Y_{jknew=}Y_{jk} - \left(\frac{Y_{jn}.Y_{nk}}{Y_{nn}}\right)$, where, n=4, j=1,2,3 , k=1,2,3.

The bus admittance matrix is symmetrical. $\therefore Y_{kjnew} = Y_{jknew}$

$$Y_{11new} = Y_{11} - \frac{Y_{14}.Y_{41}}{Y_{44}} = -j1.3 - \frac{(j0.4).(j0.4)}{-j0.9} = -j1.12$$

$$Y_{12new} = Y_{12} - \frac{Y_{14}.Y_{42}}{Y_{44}} = j0.5 - \frac{(j0.4).(0)}{-j0.9} = j0.5$$

$$Y_{13new} = Y_{13} - \frac{Y_{14}.Y_{43}}{Y_{44}} = j0.4 - \frac{(j0.4).(j0.5)}{-j0.9} = j0.622$$

$$Y_{21new} = Y_{12new} = j0.5$$

$$Y_{22new} = Y_{22} - \frac{Y_{24}.Y_{42}}{Y_{44}} = -j1.1 - \frac{(0).(0)}{-j0.9} = -j1.1$$

$$Y_{23new} = Y_{23} - \frac{Y_{24}.Y_{43}}{Y_{44}} = 0.6 - \frac{(0).(0.5)}{-0.9} = j0.6$$

$$Y_{31new} = Y_{13new} = j0.622$$

$$Y_{32new} = Y_{23new} = j0.6$$

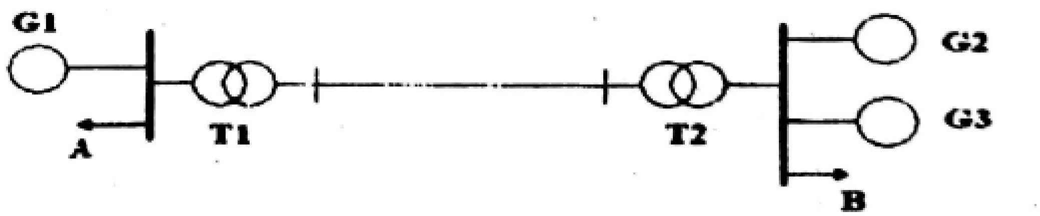
$$Y_{33new} = Y_{33} - \frac{Y_{34}.Y_{43}}{Y_{44}} = -j1.5 - \frac{(j0.5).(j0.5)}{-j0.9} = -j1.222$$

The reduced bus admittance matrix after eliminating 4th row is shown below

10. The data for the system whose single line diagram shown

G1 : 30 MVA, 10.5 KV, X" = 1.6 ohms
G2 : 15 MVA, 6.6 KV, X" = 1.2 ohms
G3 : 25 MVA, 6.6 KV, X" = 0.56 ohms
T1 : 15 MVA, 33/11 KV, X" = 15.62 ohms/phase on H.T side
T2 : 15 MVA, 33/6.2 KV, X" = 16.0 ohms/phase on H.T side
Transmission line : X = 20.5 ohms/phase
Loads : A : 40 MW, 11 KV, 0.9 pf lagging
B : 40 MW, 6.6 KV, 0.85 pf lagging

Choose the base power as 30 MVA and approximate base voltages for different parts. Draw the reactance diagram, indicate pu reactance on the diagram.



<u>Solution.</u>

Choose Base values

$KV_{b,new}$, $MVA_{b,new}$

For Generator, transformer and load:

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

=

Transmission Line:

Transformer secondary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{H.T\ side\ rating\ of\ T_1}{L.T\ side\ rating\ of\ T_1}\right)$$

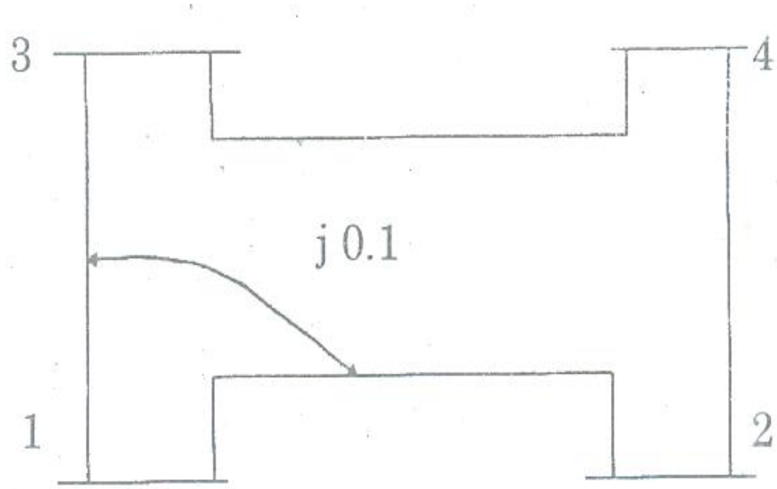
$$Z_{p.u} = \left(\frac{Z_{actual}}{kV_b^2}\right) \times MVA_b$$

Load, M : Transformer secondary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_2}{H.T\ side\ rating\ of\ T_2}\right)$$

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

9. Form Y_{bus} of the test system shown in fig using singular transformation method. The impedance data is given in Table Take (1) as reference node.



Table

Element No	**self**		**Mutual**	
	Bus code	**Impedance**	**Bus code**	**Impedance**
1	**1-2**	**0.5**	**1-2**	**0.1**
2	**1-3**	**0.6**		
3	**3-4**	**0.4**		
4	**2-4**	**0.3**		

Solution:

Let us first eliminate 4th bus. $\therefore Y_{nn} = Y_{44} = -j18.0$ **(2)**

The elements of new bus admittance after eliminating 4th row and 4th column is given by,

$Y_{jknew} = Y_{jk} = \dfrac{Y_{jn}.Y_{nk}}{Y_{nn}}$, Where, n=4, j=1,2,3 , k=1,2,3. **(6)**

$$Y_{11new} = Y_{11} - \frac{Y_{14}.Y_{41}}{Y_{44}} = -j9.8 - \frac{(j5.0).(j5.0)}{-j18.0} = -j8.411$$

$$Y_{12new} = Y_{12} - \frac{Y_{14}.Y_{42}}{Y_{44}} = 0 - \frac{(j5.0).(j5.0)}{-j18.0} = j1.388$$

$$Y_{13new} = Y_{13} - \frac{Y_{14}.Y_{43}}{Y_{44}} = j4.0 - \frac{(j5.0).(j8.0)}{-j18.0} = j6.222$$

$$Y_{21new} = Y_{12new} = j1.3888$$

$$Y_{22new} = Y_{22} - \frac{Y_{24} - Y_{42}}{Y_{44}} = -j8.3 - \frac{(j5.0).(j5.0)}{-j18.0} = -j6.911$$

$$Y_{23new} = Y_{23} - \frac{Y_{24}.Y_{43}}{Y_{44}} = j2.5 - \frac{(j5.0).(j8.0)}{-j18.0} = j4.722$$

$$Y_{31new} = Y_{13new} = j6.222$$

$$Y_{32new} = Y_{23new} = j4.722$$

$$Y_{33new} = Y_{33} - \frac{Y_{34}.Y_{43}}{Y_{44}} = -j14 - \frac{(j8.0).(j8.0)}{-j18.0} = -j10.444$$

The reduced bus admittance matrix after eliminating 4th node is given by,

$$Y_{bus} = \begin{bmatrix} -j8.411 & j1.388 & j6.222 \\ j1.388 & -j6.911 & j4.722 \\ j6.222 & j4.722 & -j10.444 \end{bmatrix}$$

Elimination of node 3: $Y_{nn} = Y_{33} = -j10.444$

The other elements of reduced bus admittance matrix can be formed from the equation

$Y_{jknew} = Y_{jk} - \dfrac{Y_{jn}.Y_{nk}}{Y_{nn}}$, Where, n=3, j=1,2, k=1,2

$$Y_{11new} = Y_{11} - \frac{Y_{13}.Y_{31}}{Y_{33}} = -j8.411 - \frac{(j6.222).(j6.222)}{-j10.444} = -j4.7043$$

$$Y_{12new} = Y_{12} - \frac{Y_{13}.Y_{32}}{Y_{33}} = j1.388 - \frac{(j6.222).(j4.722)}{-j10.444} = j4.2011$$

$$Y_{21new} = Y_{12new} = j4.2011$$

$$Y_{22new} = Y_{22} - \frac{Y_{23}.Y_{32}}{Y_{33}} = -j6.911 - \frac{(j4.722).(j4.722)}{-j10.444} = -j4.7761$$

The reduced bus admittance matrix after eliminating node 3 and 4 is

$$\boxed{Y_{bus} = \begin{bmatrix} -j4.7043 & j4.2011 \\ j4.2011 & -j4.7761 \end{bmatrix}}$$

10. **Draw the structure of an electrical power system and describe the components of the system with typical values.**

Single line diagram

Single line diagram is a simplified representation of power system components along with their interconnections with each other. Each component is represented by its symbol.

Limitations

The only limitation of single line diagram is that it cannot represent the conditions during unbalanced operation of a power system. Under the unbalanced operation of a power system, all three phases are to be shown for currents and voltages and single line diagram proves to be insufficient.

Power system Components - Generator, Transformer, Transmission lines & Distribution

Generator –Generates electrical energy

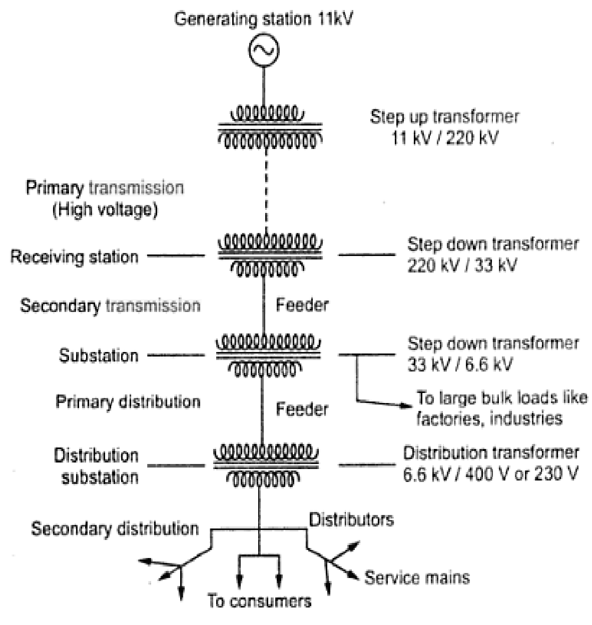
Transformer – transfer power from one circuit to another without change in frequency.

Transmission line - Power transfer from one location to other location

Purpose of control equipment's - Protection from lightning and prevent damage

Tolerance level - +5 to 10%. Difference in voltages caused due to variation in loads

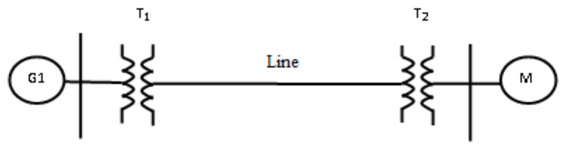
Primary transmission - First stage of transmission, 110kV,132 kV or 220 kV or400 kV or 765 kV, high voltage transmission, 3Ø , 3 wire system.



Secondary transmission - 3Ø , 3 wire system,33kV high voltage line 66kv to factory supply
Primary distribution - 3Ø , 3 wire system,11kv or 6.6 kV, 3Ø , 3 wire system
Secondary distribution - 400V, 3phase, 230V, 1phase, 3 phase 4 wire
Components of secondary distribution - Substation, feeders, service mains
Interconnection diagram - Feeders, service mains, distributors
Feeder - Conductors that take power from receiving station to substation
Distributor - Conductor that transfer power to consumers by tapping
Service mains - Connects distributor and consumer premises

i. 3 phase 3 wire circuits - Instantaneous sum of three line current is zero
ii. 3 phase circuit advantages - Economical , carry three times more power than single phase
iii. 3 phase 4 wire circuits - 4^{th} wire is Neutral wire and acts as return conductor

11. The three phase power and line to line voltage rating of the electric power system is shown in figure



Generator, G= 60MVA, 20 kV, X”= 9 %
Transformer, T_1 = 50 MVA, 20/200 kV, X=10 %
Transformer, T_2 = 50 MVA, 200/20 kV, X=10 %
Motor, M = 43.2 MVA, 18 kV, X”= 8 %
Line, 200kV, Z = 120 + j200 Ω
Draw an impedance diagram showing all impedance in p.u on a 100 MVA base. Choose 20 kV as base voltage for generator.

Solution.

$KV_{b,new}$ = 20
$MVA_{b,new}$ = 100

Generator: $KV_{b,given}$ = 20, $MVA_{b,given}$ = 60 MVA, $Z_{pu,given}$ = 9% = 0.09

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$= 0.09 \times \frac{20^2}{20^2} \times \frac{100}{60} = j0.15 \text{ p.u}$$

Transformer, T_1(Py): $KV_{b,new}$ = 20, $Z_{pu,given}$ = 10% = 0.1

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}} = j0.2 \text{ p.u}$$

Transmission Line: 200kV, Z = 120 + j200 Ω,
Transformer secondary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{H.T\ side\ rating\ of\ T_1}{L.T\ side\ rating\ of\ T_1} \right)$$

$$= 20 * \left(\frac{200}{20} \right) = 200 \text{ kV}$$

$Z_{p.u} = \left(\frac{Z_{actual}}{kV_b^2}\right) \times MVA_b = \left(\frac{120 + j200}{200^2}\right) \times 100 = 0.3 + j\,0.5$ p.u

Transformer, T_2(Sy): $KV_{b,new} = 200$, $Z_{pu,given} = 10\% = 0.1$

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}} = j0.2 \text{ p.u}$$

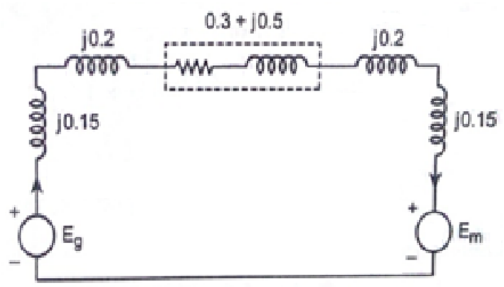
Motor, M : Transformer secondary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{L.T \text{ side rating of } T_2}{H.T \text{ side rating of } T_2}\right)$$

$= 20 * \left(\frac{20}{200}\right) = 20$ kV

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}} = j\,0.15 \text{ p.u}$$

Impedance diagram



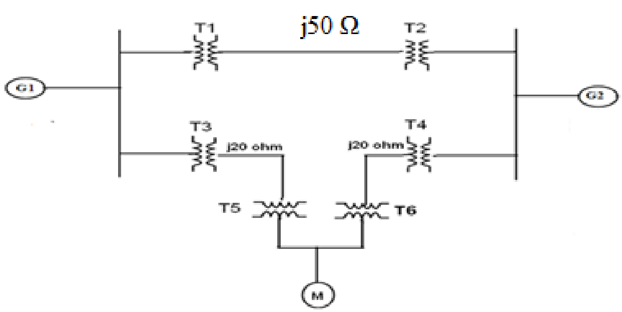
12. Draw the reactance diagram for the power system shown in fig. The ratings of generator, motor and transformers are given below. Assume 50MVA as base in the j50Ω line

Generator G1:50MVA, 11kV, X"=14%

Generator G2:50MVA, 11 kV, X"=16%

Transformer, T_1, T_2, T_3, T_4 : 30MVA, 66/11 kV, X=12%

Synchronous motor: 20MVA, 11 kV, X"=15%



Solution:

$MVA_{b,new}$ = 30 in transmission line (j 40Ω)

$kV_{b,new}$ = 66 kV (voltage in the j 40Ω)

j 50Ω line :

$Z_{p.u\ new} = \frac{Z_{actual}}{Z_{base}} = \left(\frac{Z_{actual}}{kV_b^2}\right) \times MVA_b$

$= \frac{j50}{66^2} \times 30 = j0.344$ p.u

Transformer T_1 referred to Primary side:

Transformer T_1 Primary side change occurs, so calculate $KV_{b,new}$ as

$KV_{b,new} = 66 * \left(\frac{11}{66}\right) = 11$ kV

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.12 \times \frac{11^2}{11^2} \times \frac{30}{30} = j\ 0.12$ p.u

Generator, G_1 : $KV_{b,new} = 11$ kV

$KV_{b,new} = j0.14 \times \frac{11^2}{11^2} \times \frac{30}{50} = j\ 0.084$ p.u

Transformer T_1 referred to Primary side:

$KV_{b,new} = 11$ kV

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.12 \times \frac{11^2}{11^2} \times \frac{30}{30} = j\ 0.12$ p.u

j 50Ω line :

Transformer T_3 Secondary side change occurs, so calculate $KV_{b,new}$ as

$KV_{b,new} = KV_{b,old} * \left(\frac{H.T\ side\ rating\ of\ T_3}{L.T\ side\ rating\ of\ T_3}\right)$

$KV_{b,new} = 11 * \left(\frac{66}{11}\right) = 66$ kV

$Z_{p.u\ new} = \frac{Z_{actual}}{Z_{base}} = \left(\frac{Z_{actual}}{kV_b^2}\right) \times MVA_{b,\ new}$

$Z_{p.u.\ new} = \frac{j20}{66^2} \times 30 = j\ 0.138$ p.u

Transformer T_5 referred to Primary side:

$KV_{b,} = 66$ kV

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$= j0.1 \times \frac{66^2}{66^2} \times \frac{30}{15} = j\ 0.2$ p.u

Motor : $KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_5}{H.T\ side\ rating\ of\ T_5}\right)$

$= 66 * \left(\frac{11}{66}\right) = 11$ kV

$Z_{p.u.\,new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}} = j\,0.225$ p.u

Transformer T_6 referred to Secondary side:

$KV_{b,new} = 11$ kV

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$Z_{p.u.\,new} = j0.1 \times \frac{11^2}{11^2} \times \frac{30}{15} = j\,0.2$ p.u

j 20Ω line :

Transformer T_6 Primary side change occurs, so calculate $KV_{b,new}$ as

$KV_{b,new} = 11 * \left(\frac{66}{11}\right) = 66$ kV

$$Z_{p.u\,new} = \frac{Z_{actual}}{Z_{base}} = \left(\frac{Z_{actual}}{kV_b^2}\right) \times MVA_{b,\,new}$$

$$= \frac{j20}{66^2} \times 30 = j\,0.138 \text{ p.u}$$

Transformer T_4 : $Z_{p.u.\,new} = j\,0.12$ p.u (Because transformer T_4 is identical with transformer)

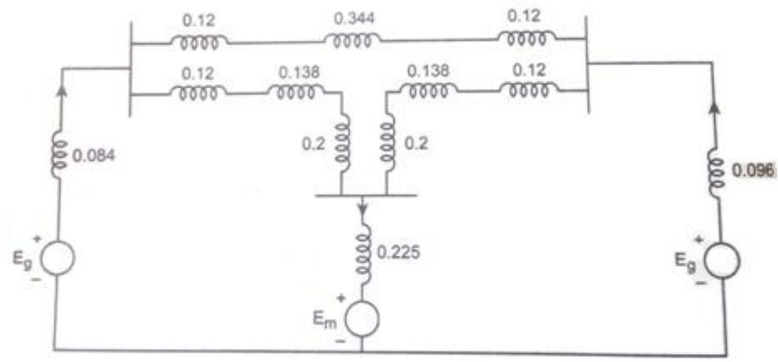
Transformer T_2 : $Z_{p.u.\,new} = j\,0.12$ p.u (Because transformer T_2 is identical with transformer)

Generator, G_1 : Transformer T_2 Secondary side change occurs, so calculate$KV_{b,new}$ as

$= 66 * \left(\frac{11}{66}\right) = 11$ kV

$Z_{p.u.\,new} = j0.16 \times \frac{11^2}{11^2} \times \frac{30}{50} = j\,0.096$ p.u

Reactance diagram



13. The single line diagram of an unloaded power system is shown in fig. The generator and transformers are rated as follows.

Generator, G1=20MVA, 13.8 kV, X"=20 %

Generator, G2=30 MVA, 18 kV, X"=20 %

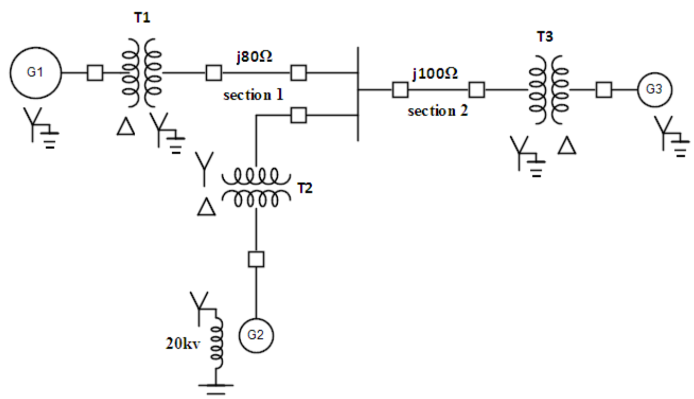
Generator, G3=30 MVA, 20 kV, X"=20 %

Transformer, T1 = 25 MVA, 220/13.8 kV, X=10 %

Transformer, T2 = 3 single phase units each rated at 10 MVA, 127/18 kV, X=10 %

Transformer, T3 = 35 MVA, 220/22 kV, X=10 %

Draw the reactance diagram using a base of 50 MVA and 13.8 kV on the generator G1.



Solution :

$MVA_{b,new} = 50$

$kV_{b,new} = 13.8$ kV

Generator, G_1 : $Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$= j0.2 \times \frac{13.8^2}{13.8^2} \times \frac{50}{20} = j\ 0.5$ p.u

Transformer T_1 referred to Primary side:

$kV_{b,new} = 13.8$ kV

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$= j0.1 \times \frac{13.8^2}{13.8^2} \times \frac{50}{25} = j\ 0.2$ p.u

Transmission line j 80Ω :

Transformer T_1 Secondary side change occurs, so calculate $KV_{b,new}$ as

$KV_{b,new} = KV_{b,old} * \left(\frac{H.T\ side\ rating\ of\ T_1}{L.T\ side\ rating\ of\ T_1} \right)$

$KV_{b,new} = 13.8 * \left(\frac{220}{13.8} \right) = 220$ kV

$Z_{actual} = j\ 80\Omega$

$Z_{p.u\ new} = \frac{Z_{actual}}{Z_{base}} = \left(\frac{Z_{actual}}{kV_b^2} \right) \times MVA_{b,new}$

$= \frac{j80}{220^2} \times 50 = j\ 0.0826$ p.u

Transmission line j 100Ω :

$KV_{b,new} = 220$ kV

$Z_{actual} = j\ 100\Omega$

$Z_{p.u} = \frac{j100}{220^2} \times 50 = j\ 0.1033$ p.u

Transformer T_2 referred to Primary side: 3 single phase units are used.

Voltage rating: 3 x 127/18 kV = 220/18 kV

Note: Star side , $V_L = \sqrt{3}\ V_p$;**Delta side ,** $V_L = V_p$; Power = 3 $V_L I_L$

$MVA_{b,given} = 3 \times 10 = 30\ MVA$

$KV_{b,new} = 220$ kV

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$= j0.1 \times \frac{220^2}{220^2} \times \frac{50}{30} = j\ 0.1667 \text{ p.u}$$

Generator, G_2 :

Transformer T_2 Primary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_2}{H.T\ side\ rating\ of\ T_2}\right)$$

$$KV_{b,new} = 20 * \left(\frac{18}{220}\right) = 18 \text{ kV}$$

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$= j0.2 \times \frac{18^2}{18^2} \times \frac{50}{30} = j\ 0.333 \text{ p.u}$$

Transformer T_3 referred to Secondary side:

$KV_{b,new} = KV_{b,given} = 220$ kV

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$Z_{p.u.\ new} = j0.1 \times \frac{220^2}{220^2} \times \frac{50}{35} = j\ 0.1429 \text{ p.u}$$

Generator, G_3 :

Transformer T_3 Primary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_3}{H.T\ side\ rating\ of\ T_3}\right)$$

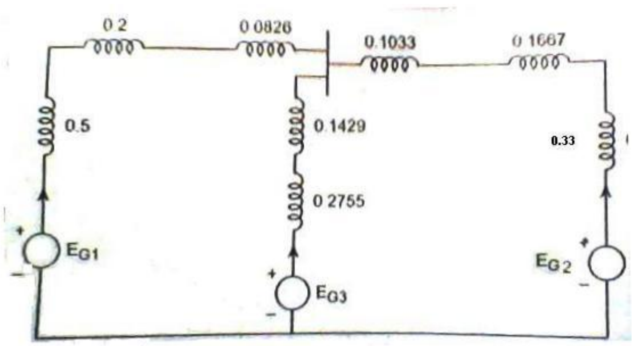
$$KV_{b,new} = 220 * \left(\frac{22}{220}\right) = 22 \text{ kV}$$

$KV_{b,given} = 20$ kV

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$Z_{p.u.\ new} = j0.2 \times \frac{20^2}{22^2} \times \frac{50}{30} = j\ 0.2755 \text{ p.u}$$

Reactance diagram



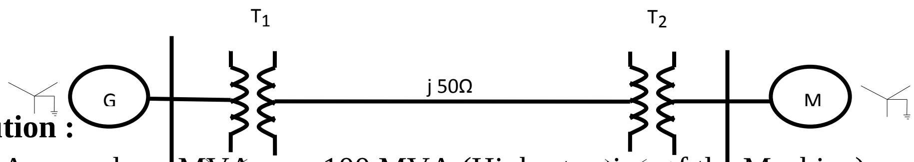
14. Draw the reactance diagram for the power system shown in fig. Neglect resistance and use a base of 100 MVA, 220 kV in 50Ω line. The ratings of the generator, motor and transformer are given below.

Generator: 40MVA, 25 kV, X"=20 %

Synchronous motor: 50 MVA, 11 kV, X"=30 %

Y- Y Transformer: 40MVA, 33/220 kV, X=15 %

Y -Δ Transformer: 30 MVA, 11/220 kV (Δ/Y), X=15 %



Solution :

Assume base MVA_{new} = 100 MVA (Highest rating of the Machine)

Base kV_{new} = 11 KV

Generator, G₁ : $KV_{b,given}$ = 11 kV, $MVA_{b,given}$ = 100 MVA

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{{kV_{b,given}}^2}{{kV_{b,new}}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$= j0.2 \times \frac{11^2}{11^2} \times \frac{100}{100} = j\,0.2 \text{ p.u}$$

Transformer Primary : $KV_{b,given}$ = 11 kV, $MVA_{b,given}$ = 50 MVA

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{{kV_{b,given}}^2}{{kV_{b,new}}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$Z_{p.u.\,new} = j0.1 \times \frac{11^2}{11^2} \times \frac{100}{50} = j\,0.2 \text{ p.u}$$

Transmission line : $KV_{b,\,new}$ = KV_b of secondary side of transformer.

$$= KV_{b,old} * \left(\frac{H.T\ side\ rating\ of\ Transformer}{L.T\ side\ rating\ of\ Transformer}\right)$$

$$= 11 \times \frac{220}{11} = 220 \text{ kV}$$

$$Z_{p.u} = \left(\frac{Z_{actual}}{{kV_b}^2}\right) \times MVA_b$$

$$= \frac{j120}{220^2} \times 100$$

$$Z_{p.u} = j\,0.248 \text{ p.u}$$

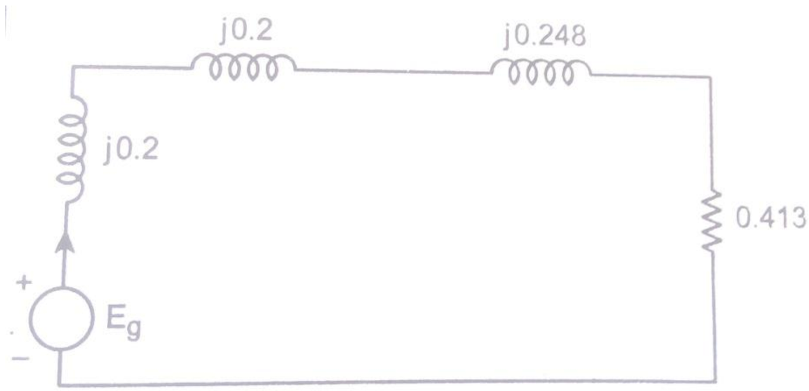
Resistive load :

$KV_{b,\,new}$ = 220 kV

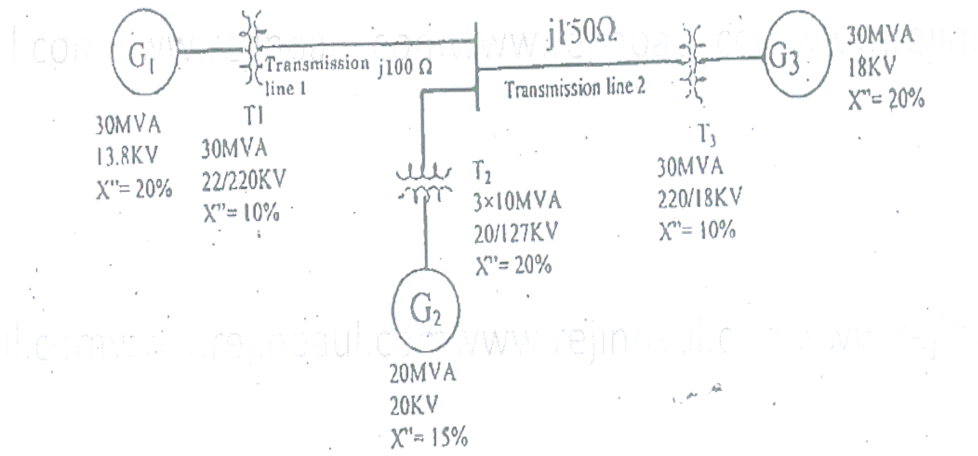
$$R_{p.u} = \left(\frac{R_{actual}}{{kV_b}^2}\right) \times MVA_b$$

$$R_{p.u} = \frac{200}{220^2} \times 100 = 0.413 \text{ p.u}$$

Impedance diagram



15. **The single line diagram of a power system is shown in fig. . Determine the new per unit values and draw the reactance diagram. Assume 25 MVA and 20 KV as new base on Genretor G_1**



Solution:

Base $MVA_{b,new}$ = 100 MVA

Base $kV_{b,new}$ = 220 kV

Transmission line j 50Ω:

Z_{actual} = j50

$Z_{p.u\ new} = \frac{Z_{actual}}{Z_{base}} = \frac{Z_{actual}}{(kV_{b,new}^2)} \times MVA_{b,new}$

$Z_{p.u\ new} = \frac{j50}{220^2} \times 100 = j0.1033$ p.u

Transformer T_1:

$KV_{b,old} = 220$ kV

$KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_1}{H.T\ side\ rating\ of\ T_1}\right)$

$KV_{b,new} = 220 * \left(\frac{33}{220}\right) = 33$ kV

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$$Z_{p.u\ new} = j0.15 \times \frac{33^2}{33^2} \times \frac{100}{40} = j\,0.375\ p.u$$

Generator, G_1 : $Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$$Z_{p.u\ new} = j0.2 \times \frac{33^2}{33^2} \times \frac{100}{40} = j\,0.287\ p.u$$

Transformer T_2:

$KV_{b,old}$ = 220 kV(H.T side voltage)

$$KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_2}{H.T\ side\ rating\ of\ T_2}\right)$$

$$= 220 * \left(\frac{11}{220}\right) = 11\ kV$$

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

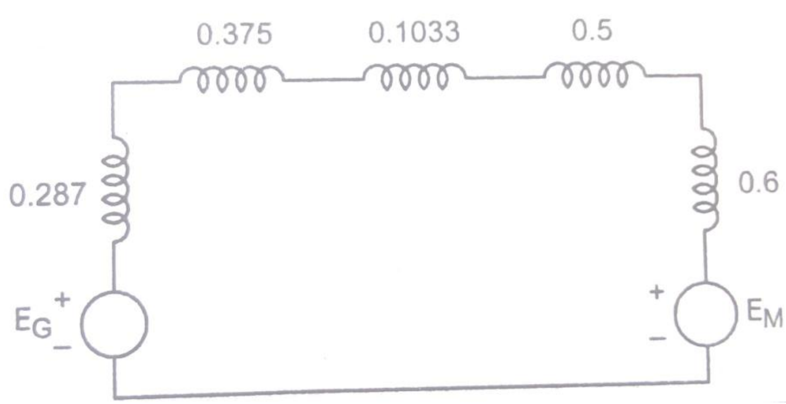
$$Z_{p.u\ new} = j0.15 \times \frac{11^2}{11^2} \times \frac{100}{30} = j\,0.5\ p.u$$

Synchronous Motor :

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$Z_{p.u.\ new} = j0.3 \times \frac{11^2}{11^2} \times \frac{100}{50} = j\,0.6\ p.u$$

Reactance diagram.



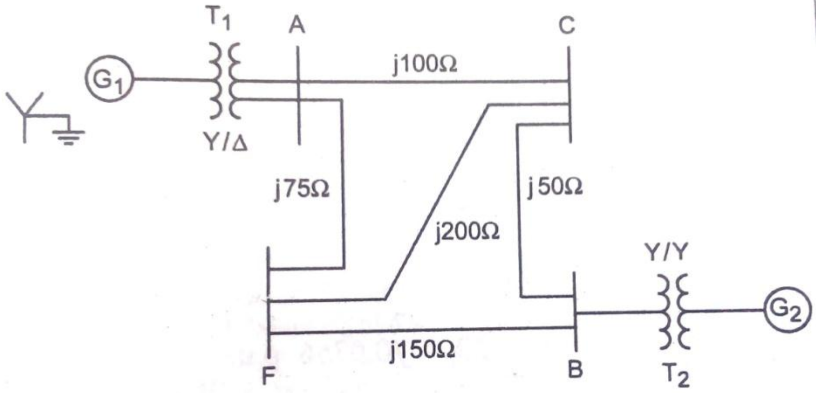
16. Draw the reactance diagram for the system is shown in fig. and mark all reactance in p.u on 20 MVA and 6.6 kV basis .

Generator, G1=10MVA, 65.6 kV, X"=10 %

Generator, G2=20 MVA, 11.5 kV, X"=10 %

Transformer, T1 = 10 MVA, 3∅, 6.6/115 kV, X=15 %

Transformer, T2 = 3 single phase units each rated at 10 MVA, 7.5/75 kV, X=10 %



Solution:

$MVA_{b,new}$ = 20

$kV_{b,new}$ = 6.6 kV

Therefore first consider G_1 which has 6.6kV as base.

Generator, G_1 : $kV_{b,new}$ = 6.6 kV

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$Z_{p.u.\,new} = j0.1 \times \frac{6.6^2}{6.6^2} \times \frac{20}{10} = j\,0.2 \text{ p.u}$$

Transformer T_1 referred to Primary side:

$kV_{b,new}$ = 6.6 kV

$$Z_{p.u.\,new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$Z_{p.u.\,new} = j0.15 \times \frac{6.6^2}{6.6^2} \times \frac{20}{10} = j\,0.3 \text{ p.u}$$

Transmission line j 100Ω :

Transformer T_1 Secondary side change occurs, so calculate $KV_{b,new}$ as

$$KV_{b,new} = KV_{b,old} * \left(\frac{H.T \text{ side rating of } T_1}{L.T \text{ side rating of } T_1}\right)$$

$$KV_{b,new} = 6.6 * \left(\frac{115}{6.6}\right) = 115 \text{ kV}$$

Z_{actual} = j 100Ω

$$Z_{p.u\,new} = \frac{Z_{actual}}{Z_{base}} = \left(\frac{Z_{actual}}{kV_b^2}\right) \times MVA_{b,new}$$

$$Z_{p.u} = \frac{j100}{115^2} \times 20 = j\,0.1512 \text{ p.u}$$

Transmission line j 75Ω :

$KV_{b,new}$ = 115 kV

Z_{actual} = j 75Ω

$$Z_{p.u} = \frac{j75}{115^2} \times 20 = j\,0.1134 \text{ p.u}$$

Transmission line j 50Ω :

$KV_{b,new} = 115$ kV

$Z_{actual} = j\ 50\Omega$

$Z_{p.u} = \frac{j50}{115^2} \times 20 = j\ 0.0756$ p.u

Transmission line j 200Ω :

$KV_{b,new} = 115$ kV

$Z_{actual} = j\ 200\Omega$

$Z_{p.u} = \frac{j200}{115^2} \times 20 = j\ 0.0302$ p.u

Transmission line j 150Ω :

$KV_{b,new} = 115$ kV

$Z_{actual} = j\ 150\Omega$

$Z_{p.u} = \frac{j150}{115^2} \times 20 = j\ 0.2268$ p.u

Transformer T_2 referred to Primary 3 single phase transformer units.

Note: **Star side** , $V_L = \sqrt{3}\ V_p$;**Delta side ,** $V_L = V_p$; Power = 3 $V_L I_L$

$MVA_{b,given} = 3 \times 10 = 30\ MVA$

$KV_{b,new} = 115$ kV, $KV_{b,given} = 75 \times \sqrt{3} = 130$ kV

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.1 \times \frac{130^2}{115^2} \times \frac{20}{30} = j\ 0.085$ p.u

Generator, G_2 :

Transformer T_2 Secondary side change occurs, so calculate $KV_{b,new}$ as

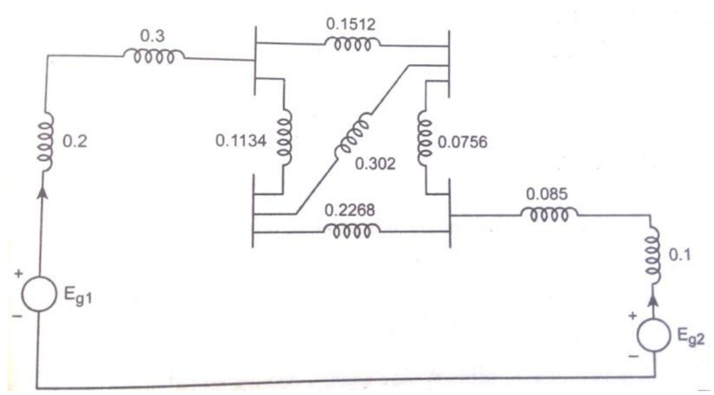
$KV_{b,new} = KV_{b,old} * \left(\frac{H.T\ side\ rating\ of\ T_2}{L.T\ side\ rating\ of\ T_2} \right)$

$KV_{b,new} = 115 * \left(\frac{13}{130} \right) = 11.5$ kV

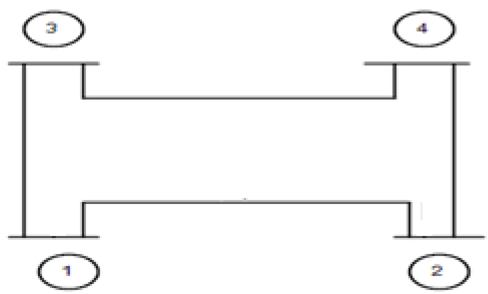
$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.1 \times \frac{11.5^2}{11.5^2} \times \frac{20}{20} = j\ 0.1$ p.u

Reactance diagram.



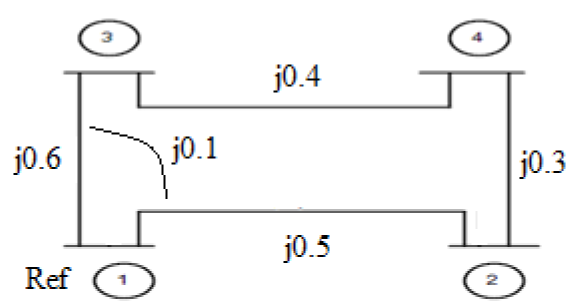
17. **Form Y-bus for the network shown in fig. The impedance data is given in table. Select node (1) as reference node.**



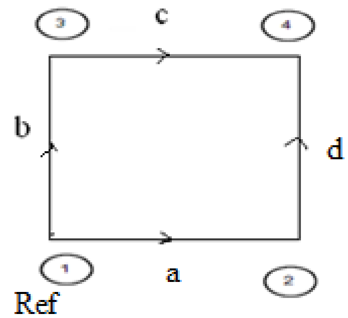
Element No.	Self		Mutual	
	Bus code	Impedance	Bus code	Impedance
1	1-2	0.6	1-2	0.1
2	1-3	0.5		
3	3-4	0.5		
4	2-4	0.2		

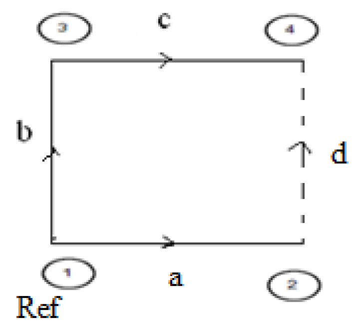
Solution:

Oriented graph.



Take (1) as reference. Draw Tree





Incidence matrix $[A] = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & -1 \end{bmatrix}$

$[A]^T = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 1 & -1 \\ 1 & 0 & -1 \end{bmatrix}$

Primitive impedance matrix $[Z_{Primitive}] = \begin{bmatrix} j0.5 & j0.1 & 0 & 0 \\ j0.1 & j0.6 & 0 & 0 \\ 0 & 0 & j0.4 & 0 \\ 0 & 0 & 0 & j0.3 \end{bmatrix}$

Primitive admitance matrix $[Y_{Primitive}] = [Z_{Primitive}]^{-1}$

Consider the matrix $\begin{bmatrix} j0.5 & j0.1 \\ j0.1 & j0.6 \end{bmatrix}^{-1} = \frac{1}{-0.29}\begin{bmatrix} j0.6 & -j0.1 \\ -j0.1 & j0.5 \end{bmatrix}$

$= \begin{bmatrix} -j2.0689 & j0.3448 \\ j0.3448 & -j1.724 \end{bmatrix}$

$[Y_{Primitive}] = \begin{bmatrix} -j2.0689 & j0.3448 & 0 & 0 \\ j0.3448 & -j1.724 & 0 & 0 \\ 0 & 0 & -j2.5 & 0 \\ 0 & 0 & 0 & -j3.333 \end{bmatrix}$

Bus admittance matrix $[Y_{bus}] = [A][Y_{Primitive}][A]^T$

$[Y_{Primitive}][A]^T = \begin{bmatrix} -j2.0689 & j0.3448 & 0 & 0 \\ j0.3448 & -j1.724 & 0 & 0 \\ 0 & 0 & -j2.5 & 0 \\ 0 & 0 & 0 & -j3.333 \end{bmatrix}\begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 1 & -1 \\ 1 & 0 & -1 \end{bmatrix}$

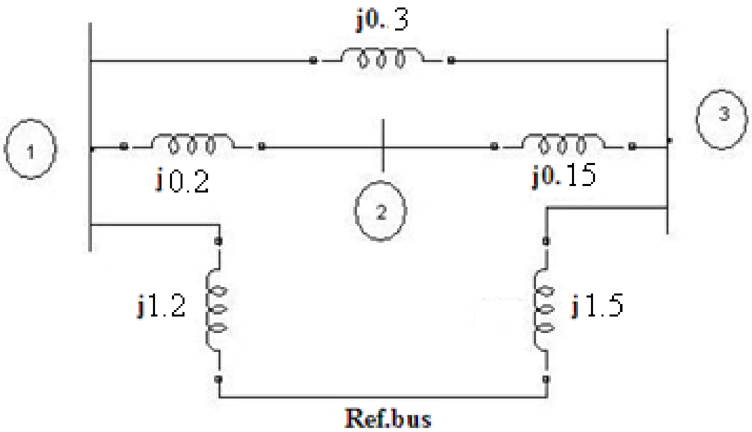
$= \begin{bmatrix} -j2.0689 & j0.3448 & 0 \\ -j0.3448 & j1.724 & 0 \\ 0 & -j2.5 & j2.5 \\ -j3.333 & 0 & j3.333 \end{bmatrix}$

Bus admittance matrix

$$[Y_{bus}] = [A][Y_{Primitive}][A]^T = \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & -1 \end{bmatrix} \begin{bmatrix} -j2.0689 & j0.3448 & 0 \\ -j0.3448 & j1.724 & 0 \\ 0 & -j2.5 & j2.5 \\ -j3.333 & 0 & j3.333 \end{bmatrix}$$

$$\text{Bus admittance matrix } [Y_{bus}] = \begin{bmatrix} -j5.4019 & j03448 & j3.333 \\ j0.3448 & -j4.224 & j2.5 \\ j3.333 & j2.5 & -j5.8333 \end{bmatrix}$$

18. Determine Z_{bus} for the system whose reactance diagram is shown in fig. where the impedance are given in p.u. preserve all the three nodes.

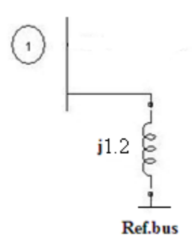


Solution

Step 1:

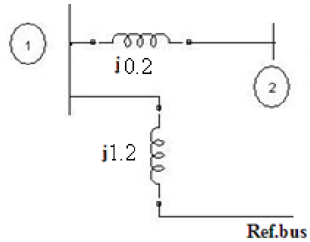
Consider the branch with impedance j 1.2 p.u connected between bus-1 and reference bus.

- The system having a single bus and so the order of bus impedance matrix is one.
  $Z_{bus} = [j\ 1.2]$



Step 2:

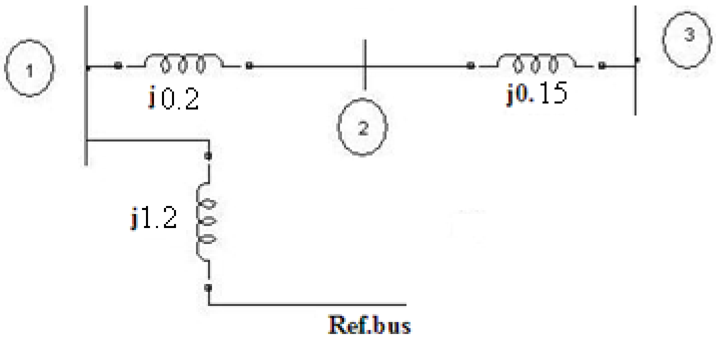
- Connect bus 2 to bus 1 through am impedance j 0.2.
- This is case 2 modification and so the order of matrix is increased by one.
- In this new bus impedance matrix the elements of 1st row and column is copied as element of 2nd row and 2nd column. The diagonal matrix is given by $Z_{11} + Z_b$ where $Z_b = j\ 0.2$



$$Z_{bus} = \begin{bmatrix} j\,1.2 & j\,1.2 \\ j\,1.2 & j\,1.2 + j\,0.2 \end{bmatrix} = \begin{bmatrix} j\,1.2 & j\,1.2 \\ j\,1.2 & j\,1.4 \end{bmatrix}$$

Step 3:

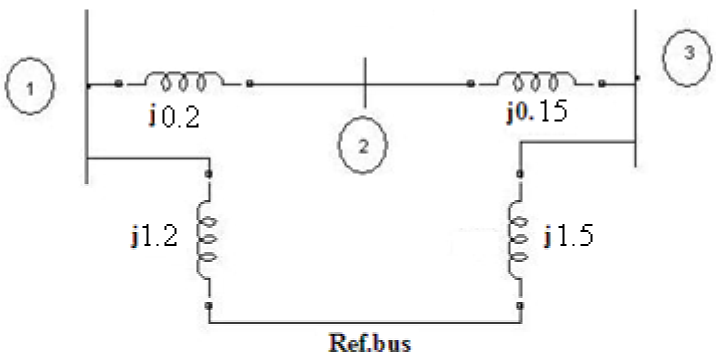
- Connect bus 3 to bus 2 through am impedance j 0.15.
- This is case 2 modification and so the order of bus impedance matrix is increased by one.
- In this new bus impedance matrix the elements of 2nd row and column is copied as element of 3rd row and column. The diagonal matrix is given by $Z_{22} + Z_b$ where Z_b = j 0.15



$$Z_{bus} = \begin{bmatrix} j\,1.2 & j\,1.2 & j\,1.2 \\ j\,1.2 & j\,1.4 & j\,1.4 \\ j\,1.2 & j\,1.4 & j\,1.4 + j\,0.15 \end{bmatrix} = \begin{bmatrix} j\,1.2 & j\,1.2 & j\,1.2 \\ j\,1.2 & j\,1.4 & j\,1.4 \\ j\,1.2 & j\,1.4 & j\,1.55 \end{bmatrix}$$

Step 4 :

- Connect impedance j1.5 from bus 3 to reference bus.
- This is case 3 modification. In this case new bus impedance matrix is framed as that of the last row and column are eliminated by node elimination techniques.
- In new bus impedance matrix the elements of 3rd row and column are copied for the 4th row and column.
- The diagonal matrix is given by $Z_{33} + Z_b$ where Z_b = j 1.5



$$Z_{bus} = \begin{bmatrix} j\,1.2 & j\,1.2 & j\,1.2 & j\,1.2 \\ j\,1.2 & j\,1.4 & j\,1.4 & j\,1.4 \\ j\,1.2 & j\,1.4 & j\,1.55 & j\,1.55 \\ j\,1.2 & j\,1.4 & j\,1.55 & j\,1.55 + j\,1.5 \end{bmatrix}$$

$$Z_{bus} = \begin{bmatrix} j\,1.2 & j\,1.2 & j\,1.2 & j\,1.2 \\ j\,1.2 & j\,1.4 & j\,1.4 & j\,1.4 \\ j\,1.2 & j\,1.4 & j\,1.55 & j\,1.55 \\ j\,1.2 & j\,1.4 & j\,1.55 & j\,3.05 \end{bmatrix}$$

Actual new bus impedance matrix is obtained by eliminating the 3rd row and 3rd column. The element Z_{jk} of the new bus impedance matrix is given by,

$$Z_{jk,\,act} = Z_{jk} - \frac{Z_{j(n+1)}\,Z_{(n+1)k}}{Z_{(n+1)(n+1)}}$$ where n=3 ; j=1,2,3 and k=1,2,3

$$Z_{11,\,act} = Z_{11} - \frac{Z_{14}\,Z_{41}}{Z_{44}} = j1.2 - \frac{j1.2 \times j1.2}{j\,3.05} = j0.728$$

$$Z_{12,\,act} = Z_{12} - \frac{Z_{14}\,Z_{42}}{Z_{44}} = j1.2 - \frac{j1.2 \times j1.4}{j\,3.05} = j0.649$$

$$Z_{13,\,act} = Z_{13} - \frac{Z_{14}\,Z_{43}}{Z_{44}} = j1.2 - \frac{j1.2 \times j1.55}{j\,3.05} = j0.590$$

$Z_{21,\,act} = Z_{12,\,act} = j0.649$

$$Z_{22,\,act} = Z_{22} - \frac{Z_{24}\,Z_{42}}{Z_{44}} = j1.4 - \frac{j1.4 \times j1.4}{j\,3.05} = j0.757$$

$$Z_{23,\,act} = Z_{23} - \frac{Z_{24}\,Z_{43}}{Z_{44}} = j1.4 - \frac{j1.4 \times j1.55}{j\,3.05} = j0.689$$

$Z_{31,\,act} = Z_{13,\,act} = j0.590$

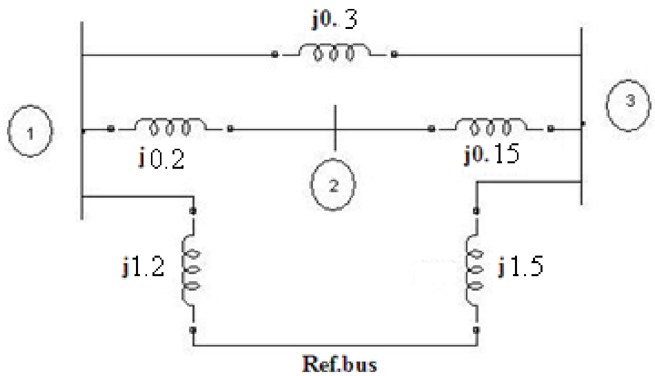
$Z_{32,\,act} = Z_{23,\,act} = j0.689$

$$Z_{33,\,act} = Z_{33} - \frac{Z_{34}\,Z_{43}}{Z_{44}} = j1.55 - \frac{j1.55 \times j1.55}{j\,3.05} = j0.762$$

$$Z_{bus} = \begin{bmatrix} j\,0.728 & j\,0.649 & j\,0.590 \\ j\,0.649 & j\,0.757 & j\,0.689 \\ j\,0.590 & j\,0.689 & j\,0.762 \end{bmatrix}$$

Step 5 : Connect impedance j0.3 between bus 1 and bus 3.

- In new bus impedance matrix, the elements of 4th row and column are obtained by subtracting the elements of 1st row and column.



- The element of Z_{44} is given by $Z_{44} = Z_b + Z_{11} + Z_{33} - 2Z_{13}$

WhereZ_b = j0.3

Therefore Z_{44} = j0.3 + j0.728 + j0.762 – 2(j0.59) = j0.61

$$Z_{bus} = \begin{bmatrix} j\,0.728 & j\,0.649 & j\,0.59 & j\,0.728 - j\,0.590 \\ j\,0.649 & j\,0.757 & j\,0.689 & j\,0.649 - j\,0.689 \\ j\,0.590 & j\,0.689 & j\,0.762 & j\,0.59 - j\,0.762 \\ j\,0.728 - j\,0.590 & j\,0.649 - j\,0.689 & j\,0.59 - j\,0.762 & j\,0.61 \end{bmatrix}$$

$$Z_{bus} = \begin{bmatrix} j\,0.728 & j\,0.649 & j\,0.59 & j\,0.138 \\ j\,0.649 & j\,0.757 & j\,0.689 & -0.04 \\ j\,0.590 & j\,0.689 & j\,0.762 & -j\,0.172 \\ j\,0.138 & -0.04 & -j\,0.172 & j\,0.61 \end{bmatrix}$$

Since this modification does not add a new, the 4th row and column has to be eliminated using node elimination technique, to determine the actual new bus impedance matrix. The element Z_{jk} of actual new bus impedance matrix is given by.

$$Z_{jk,\,act} = Z_{jk} - \frac{Z_{j(n+1)}\,Z_{(n+1)k}}{Z_{(n+1)(n+1)}} \qquad \text{where n=3 ; j=1,2,3 and k=1,2,3}$$

$$Z_{11,\,act} = Z_{11} - \frac{Z_{14}\,Z_{41}}{Z_{44}} = j0.728 - \frac{j\,0.138\ x\ j\,0.138}{j\,0.61} = j0.697$$

$$Z_{12,\,act} = Z_{12} - \frac{Z_{14}\,Z_{42}}{Z_{44}} = j\,0.649 - \frac{j\,0.138\ x\ (-j\,0.04)}{j\,0.61} = j0.658$$

$$Z_{13,\,act} = Z_{13} - \frac{Z_{14}\,Z_{43}}{Z_{44}} = j\,0.59 - \frac{j\,0.138\ x\ (-j0.172)}{j\,0.61} = j0.629$$

$Z_{21,\,act} = Z_{12,\,act}$ = j0.658

$$Z_{22,\,act} = Z_{22} - \frac{Z_{24}\,Z_{42}}{Z_{44}} = j0.757 - \frac{(-j\,0.04)x(-j\,0.04)}{j\,0.61} = j0.754$$

$$Z_{23,\,act} = Z_{23} - \frac{Z_{24}\,Z_{43}}{Z_{44}} = j0.689 - \frac{(-j\,0.04)x(-j\,0.172)}{j\,0.61} = j0.678$$

$Z_{31,\,act} = Z_{13,\,act}$ = j0.629

$Z_{32,\,act} = Z_{23,\,act}$ = j0.678

$$Z_{33,\,act} = Z_{33} - \frac{Z_{34}\,Z_{43}}{Z_{44}} = j0.762 - \frac{(-j\,0.172)x(-j\,0.172)}{j\,0.61} = j0.714$$

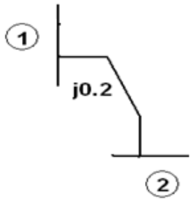
$$Z_{bus} = \begin{bmatrix} j\,0.697 & j\,0.658 & j\,0.629 \\ j\,0.658 & j\,0.754 & j\,0.678 \\ j\,0.629 & j\,0.678 & j\,0.714 \end{bmatrix}$$

19. For the system shown in fig form the bus impedance matrix using building algorithm. Consider node 2 as reference node.

Solution :

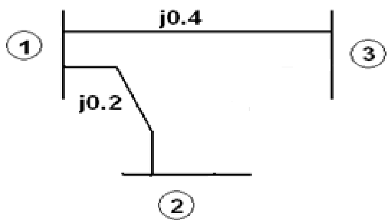
Step 1: Add an element between reference and node (1).

$Z_{bus} = [j\,0.2]$



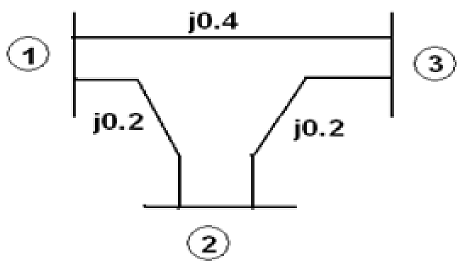
Step 2 : Add element between existing node (1) and the new node (3).

$$Z_{bus} = \begin{bmatrix} j\,0.2 & j\,0.2 \\ j\,0.2 & j\,0.6 \end{bmatrix}$$



Step 3 : Add element between existing node (3) and the reference node.

$$Z_{bus} = \begin{bmatrix} j\,0.2 & j\,0.2 & j\,0.2 \\ j\,0.2 & j\,0.6 & j\,0.6 \\ j\,0.2 & j\,0.6 & j\,0.8 \end{bmatrix}$$



Using Kron's reduction technique

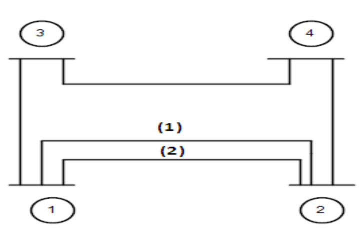
$$Z_{11} = Z_{11} - \frac{Z_{13}\,Z_{31}}{Z_{33}} = j0.2 - \frac{j\,0.2 \times j\,0.2}{j\,0.8} = j0.15$$

$$Z_{12} = Z_{21} = Z_{12} - \frac{Z_{13}\,Z_{32}}{Z_{33}} = j0.2 - \frac{j\,0.2 \times j\,0.6}{j\,0.8} = j0.05$$

$$Z_{22} = Z_{22} - \frac{Z_{23}\,Z_{32}}{Z_{33}} = j0.6 - \frac{j\,0.6 \times j\,0.6}{j\,0.8} = j0.15$$

$$Z_{bus} = \begin{bmatrix} j\,0.15 & j\,0.05 \\ j\,0.05 & j\,0.15 \end{bmatrix}$$

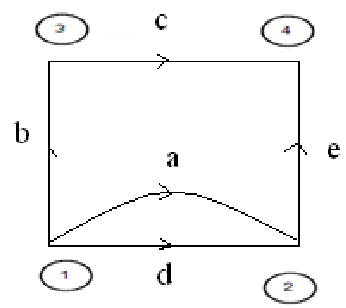
20. Form Y-bus by singular transformation for the network shown in fig. The impedance data is given in table. Take (1) as reference node.



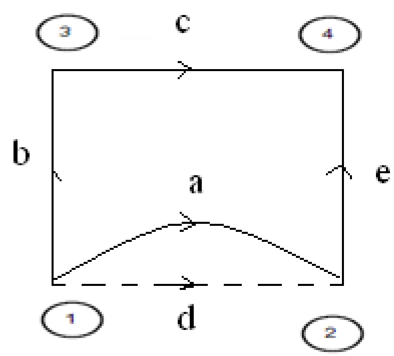
Element No.	Self	
	Bus code	**Impedance**
1	**1-2 (1)**	**0.6**
2	**1-3**	**0.5**
3	**3-4**	**0.5**
4	**1-2 (2)**	**0.4**
5	**2-4**	**0.2**

Solution:

Oriented graph.



Take (1) as reference. Draw Tree



Incidence matrix $[A] = \begin{bmatrix} -1 & 0 & 0 & -1 & 1 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & -1 \end{bmatrix}$

$[A]^T = \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 0 \\ 1 & 0 & -1 \end{bmatrix}$

Primitive impedance matrix $[Z_{Primitive}] = \begin{bmatrix} j0.6 & 0 & 0 & 0 & 0 \\ 0 & j0.5 & 0 & 0 & 0 \\ 0 & 0 & j0.5 & 0 & 0 \\ 0 & 0 & 0 & j0.4 & 0 \\ 0 & 0 & 0 & 0 & j0.2 \end{bmatrix}$

Primitive admitance matrix $[Y_{Primitive}] = [Z_{Primitive}]^{-1}$

$$= \begin{bmatrix} -j1.667 & 0 & 0 & 0 & 0 \\ 0 & -j2.0 & 0 & 0 & 0 \\ 0 & 0 & -j2 & 0 & 0 \\ 0 & 0 & 0 & -j2.5 & 0 \\ 0 & 0 & 0 & 0 & -j5 \end{bmatrix}$$

Bus admittance matrix $[Y_{bus}] = [A][Y_{Primitive}][A]^T$

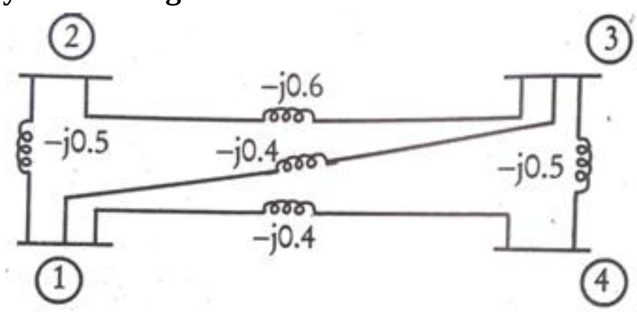
$$[Y_{Primitive}][A]^T = \begin{bmatrix} j1.667 & 0 & 0 \\ 0 & j2 & 0 \\ 0 & -j2 & j2 \\ j2.5 & 0 & 0 \\ -j5 & 0 & j5 \end{bmatrix}$$

Bus admittance matrix $[Y_{bus}] = [A][Y_{Primitive}][A]^T = \begin{bmatrix} -j1.667 - j2.5\ j5 & 0 & j5 \\ 0 & -j2 - j2 & j2 \\ j5 & j2 & -j2 - j5 \end{bmatrix}$

Bus admittance matrix $[Y_{bus}] = \begin{bmatrix} -j9.167 & 0 & j5 \\ 0 & -j4 & j2 \\ j5 & j2 & -j7 \end{bmatrix}$

PART-C

21. For the network shown in fig. form the bus admittance matrix. Determine the reduced admittance matrix by eliminating node 4. The values are marked in p.u.



Solution:

The Y_{bus} Matrix of the network is

$$Y_{bus} = \begin{bmatrix} -(j0.5+j0.4+j0.4) & j0.5 & j0.4 & j0.4 \\ j0.5 & -(j0.5+j0.6) & j0.6 & 0 \\ j0.4 & j0.6 & -(j0.6+j0.5+j0.4) & j0.5 \\ j0.4 & 0 & j0.5 & -(j0.5+j0.4) \end{bmatrix}$$

$$Y_{bus} = \begin{bmatrix} -j1.3 & j0.5 & j0.4 & j0.4 \\ j0.5 & -j1.1 & j0.6 & 0 \\ j0.4 & j0.6 & -j1.5 & j0.5 \\ j0.4 & 0 & j0.5 & -j0.9 \end{bmatrix}$$

The elements of new bus matrix after eliminating 4th row and 4th column is given by

$Y_{jknew=}Y_{jk} - \left(\frac{Y_{jn}.Y_{nk}}{Y_{nn}}\right)$, where, n=4, j=1,2,3 , k=1,2,3.

The bus admittance matrix is symmetrical. $\therefore Y_{kjnew} = Y_{jknew}$

$$Y_{11new} = Y_{11} - \frac{Y_{14}.Y_{41}}{Y_{44}} = -j1.3 - \frac{(j0.4).(j0.4)}{-j0.9} = -j1.12$$

$$Y_{12new} = Y_{12} - \frac{Y_{14}.Y_{42}}{Y_{44}} = j0.5 - \frac{(j0.4).(0)}{-j0.9} = j0.5$$

$$Y_{13new} = Y_{13} - \frac{Y_{14}.Y_{43}}{Y_{44}} = j0.4 - \frac{(j0.4).(j0.5)}{-j0.9} = j0.622$$

$$Y_{21new} = Y_{12new} = j0.5$$

$$Y_{22new} = Y_{22} - \frac{Y_{24}.Y_{42}}{Y_{44}} = -j1.1 - \frac{(0).(0)}{-j0.9} = -j1.1$$

$$Y_{23new} = Y_{23} - \frac{Y_{24}.Y_{43}}{Y_{44}} = 0.6 - \frac{(0).(0.5)}{-0.9} = j0.6$$

$$Y_{31new} = Y_{13new} = j0.622$$

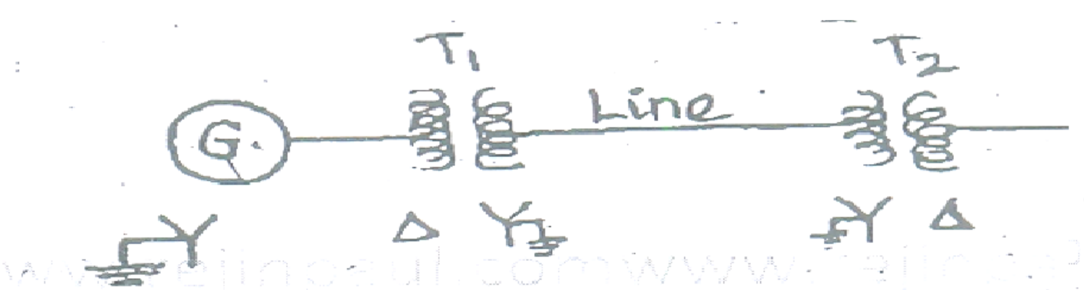
$$Y_{32new} = Y_{23new} = j0.6$$

$$Y_{33new} = Y_{33} - \frac{Y_{34}.Y_{43}}{Y_{44}} = -j1.5 - \frac{(j0.5).(j0.5)}{-j0.9} = -j1.222$$

The reduced bus admittance matrix after eliminating 4th row is shown below

$$Y_{bus} = \begin{bmatrix} -j1.12 & j0.5 & j0.622 \\ j0.5 & -j1.1 & j0.6 \\ j0.622 & j0.6 & -j1.222 \end{bmatrix}$$

22. A 90 MVA 11 KV 3 phase generator has a reactance of 25%. The generator supplies two motors through transformer and transmission line as shoen in fig. The transformer T1 is a 3-phase transformer 100 MVA 10/132 KV, 6% reactance. The transformer T2 is composed of 3 single phase units each rated 300 MVA: 66/10 KV with 5% reactance. The connection of T1 & T2 are shown. The motors are rated at 50 MVA and 400 MVA both 10 KV and 20% reactance. Taking the generator rating as base, Draw reactance diagram and indicate the reactance in per unit. The reactance of line is 100 ohms.



Solution:

$MVA_{b,new}$ = 90

$kV_{b,new}$ = 11 kV (Generator,G_1)

Generator, G_1 : $Z_{p.u.\ new} = Z_{pu,given}\ x\ \frac{kV_{b,given}^2}{kV_{b,new}^2}\ x\ \frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.2\ x\ \frac{6.6^2}{6.6^2}\ x\frac{30}{25} = j\ 0.24$ p.u

Transformer T_1 referred to Primary side:

$kV_{b,new} = 6.6$ kV

$Z_{p.u.\ new} = Z_{pu,given}\ x\ \frac{kV_{b,given}^2}{kV_{b,new}^2}\ x\ \frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.1\ x\ \frac{6.9^2}{6.6^2}\ x\frac{30}{30} = j\ 0.109$ p.u

Transmission line j 120Ω :

$KV_{b,new} = KV_{b,old} * \left(\frac{H.T\ side\ rating\ of\ T_1}{L.T\ side\ rating\ of\ T_1}\right)$

$KV_{b,new} = 6.6 * \left(\frac{115}{6.9}\right) = 110$ kV

$Z_{actual} = j\ 120\Omega$

$Z_{p.u\ new} = \frac{Z_{actual}}{Z_{base}} = \left(\frac{Z_{actual}}{kV_b^2}\right)\ x\ MVA_{b,\ new}$

$Z_{p.u.\ new} = \frac{j120}{110^2}\ x\ 30 = j\ 0.298$ p.u

Transmission line j 90Ω :

$KV_{b,new} = 110$ kV

$Z_{actual} = j\ 90\Omega$

$Z_{p.u} = \frac{j90}{110^2}\ x\ 30 = j\ 0.223$ p.u

Transformer T_3 referred to Primary side: 3 single phase units are used.

Voltage rating: $\frac{\sqrt{3}\ x\ 69}{\sqrt{3}\ x\ 6.9} = 119.5/11.95$ kV

$MVA_{b,given} = 3x10 = 30\ MVA$

$KV_{b,new} = 119.5$ kV

$Z_{p.u.\ new} = Z_{pu,given}\ x\ \frac{kV_{b,given}^2}{kV_{b,new}^2}\ x\ \frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.1\ x\ \frac{119.5^2}{119.5^2}\ x\frac{30}{30} = j\ 0.1$ p.u

Generator, G_3 :

$KV_{b,new} = 119.5 * \left(\frac{11.95}{119.5}\right) = 11.95$ kV

$Z_{p.u.\ new} = Z_{pu,given}\ x\ \frac{kV_{b,given}^2}{kV_{b,new}^2}\ x\ \frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.15\ x\ \frac{13.2^2}{11.95^2}\ x\frac{30}{30} = j\ 0.183$ p.u

Transformer T_2 referred to Secondary side:

$KV_{b,new} = 110\ kV$

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$Z_{p.u.\ new} = j0.1 \times \frac{115^2}{110^2} \times \frac{30}{15} = j\ 0.218\ p.u$$

Generator, G_2 :

Transformer T_3 Primary side change occurs, so calculate $KV_{b,new}$ as

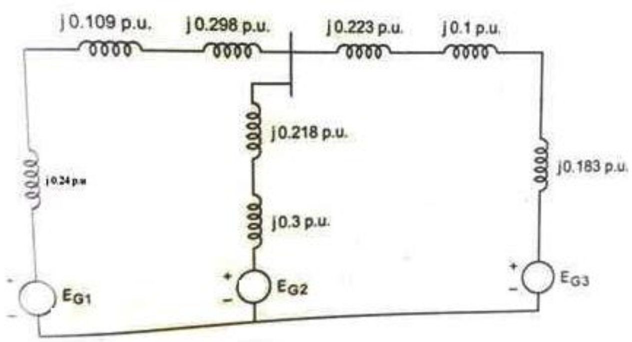
$$KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_2}{H.T\ side\ rating\ of\ T_2}\right)$$

$$KV_{b,new} = 110 * \left(\frac{6.9}{115}\right) = 6.6\ kV$$

$$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$$

$$Z_{p.u.\ new} = j0.15 \times \frac{6.6^2}{6.6^2} \times \frac{30}{15} = j\ 0.3\ p.u$$

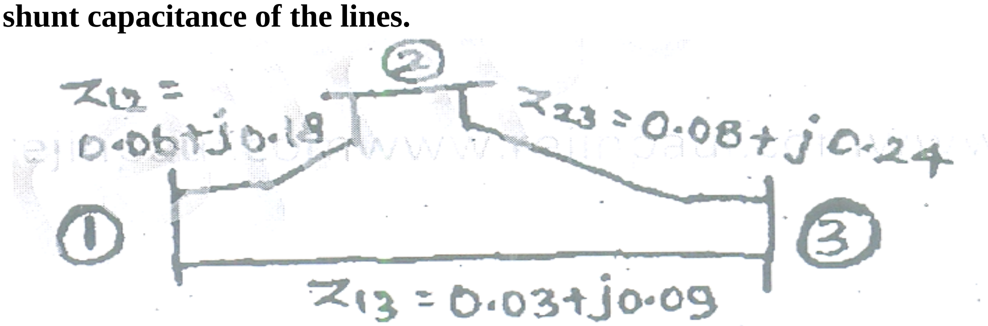
Impedance diagram.



23. Determine Ybus for the 3-bus system shown in fig. the line series impedance as follows

Line (bus to bus)	Impedance (pu)
1-2	**0.06+j0.18**
1-3	**0.03+j0.09**
2-3	**0.08+j0.24**

Neglect the shunt capacitance of the lines.

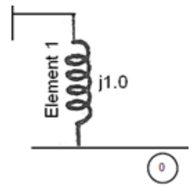


Solution:

Solution :

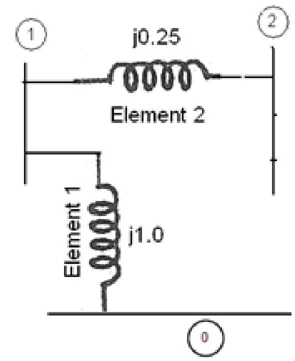
Step 1: Add an element between reference and node (1).

$Y_{bus} = [j\ 1.0]$



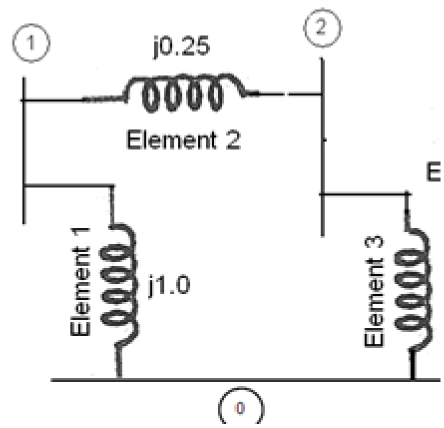
Step 2 : Add element between existing node (1) and the new node (2).

$$Y_{bus} = \begin{bmatrix} j\,1.0 & j\,1.0 \\ j\,1.0 & j\,1.0 + j\,0.25 \end{bmatrix} = Z_{bus} = \begin{bmatrix} j\,1.0 & j\,1.0 \\ j\,1.0 & j\,1.25 \end{bmatrix}$$



Step 3 : Add element between existing node (3) and the reference node.

$$Y_{bus} = \begin{bmatrix} j\,1.0 & j\,1.0 & j\,1.0 \\ j\,1.0 & j\,1.25 & j\,1.25 \\ j\,1.0 & j\,1.25 & j\,1.25 + j\,1.25 \end{bmatrix} = \begin{bmatrix} j\,1.0 & j\,1.0 & j\,1.0 \\ j\,1.0 & j\,1.25 & j\,1.25 \\ j\,1.0 & j\,1.25 & j\,2.5 \end{bmatrix}$$



Fictitious node can be eliminated by

$$Z_{ij}^{new} = Z_{ij}^{old} - \frac{Z_{i(n+1)}\, Z_{(n+1)j}}{Z_{(n+1)(n+1)}}$$

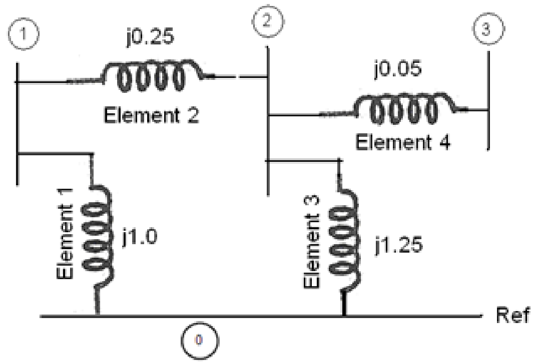
$$Z_{11}^{new} = Z_{11}^{old} - \frac{Z_{13}\, Z_{31}}{Z_{33}} = j1.0 - \frac{j\,1.0 \ x \ j\,1.0}{j\,2.5} = j0.6$$

$$Z_{12}^{new} = Z_{21}^{old} = Z_{12}^{new} - \frac{Z_{13}\, Z_{32}}{Z_{33}} = j1.0 - \frac{j\,1.0 \ x \ j\,1.25}{j\,2.5} = j0.5$$

$$Z_{22}^{new} = Z_{22}^{old} - \frac{Z_{23}\, Z_{32}}{Z_{33}} = j1.25 - \frac{j\,1.25 \ x \ j\,1.25}{j\,2.5} = j0.625$$

$$Y_{bus} = \begin{bmatrix} j\,0.6 & j\,0.6 \\ j\,0.6 & j\,0.625 \end{bmatrix}$$

Step 4 : Add element between existing node (2) and the new node (3).



$$Y_{bus} = \begin{bmatrix} j\,0.6 & j\,0.6 & j\,0.6 \\ j\,0.6 & j\,0.625 & j\,0.625 \\ j\,0.6 & j\,0.625 & j\,0.625 + j\,0.05 \end{bmatrix}$$

$$Y_{bus} = \begin{bmatrix} j\,0.6 & j\,0.6 & j\,0.6 \\ j\,0.6 & j\,0.625 & j\,0.625 \\ j\,0.6 & j\,0.625 & j\,0.675 \end{bmatrix}$$

24. Obtain the per unit impedance diagram of the power system of fig. shown below

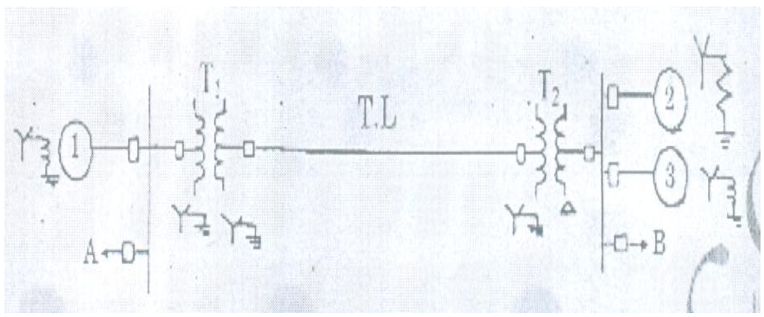


Fig one line diagram representation of a simple power system

Generator, G_1=1:30 MVA, 10.5 kV, X"=1.6 ohms

Generator, G_2=2:15 MVA, 6.6 kV, X"=1.2 ohms

Generator, G_3=3:25 MVA, 6.6 kV, X"=0.56 ohms

Transformer, T_1 = 15 MVA, 33/11 kV, X=15.2 ohms/phase on hgh tension side

Transformer, T_1 = 15 MVA, 33/6.2 kV, X=16 ohms/phase on hgh tension side

Transmission line: 20.5 ohms/phase

Load A: 15 MW, 11 KV, 0.9 lagging power factor

Load B: 40 MW, 6.6 KV, 0.85 lagging power factor

Solution:

$MVA_{b,new}$ = 50

$kV_{b,new}$ = 11 kV

Generator, G_1 : $Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.25 \times \frac{11^2}{11^2} \times \frac{50}{20} = j\,0.625$ p.u

Transformer T_1 referred to Primary side:

$kV_{b,new}$ = 11 kV

$Z_{p.u.\ new} = Z_{pu,given}$ x $\frac{kV_{b,given}^2}{kV_{b,new}^2}$ x $\frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.15 \times \frac{13.8^2}{11^2} \times \frac{50}{25} = j\ 0.472$ p.u

Transmission line j 80Ω :

Transformer T_1 Secondary side change occurs, so calculate $KV_{b,new}$ as

$KV_{b,new} = KV_{b,old} * \left(\frac{H.T\ side\ rating\ of\ T_1}{L.T\ side\ rating\ of\ T_1}\right)$

$KV_{b,new} = 11 * \left(\frac{220}{13.8}\right) = 175.36$ kV

$Z_{actual} = j\ 80\Omega$

$Z_{p.u\ new} = \frac{Z_{actual}}{Z_{base}} = \left(\frac{Z_{actual}}{kV_b^2}\right) \times MVA_{b,\ new}$

$Z_{p.u} = \frac{j80}{175.36^2} \times 50 = j\ 0.163$ p.u

Transmission line j 100Ω :

$KV_{b,new} = 175.36$ kV

$Z_{actual} = j\ 100\Omega$

$Z_{p.u} = \frac{j100}{175.36^2} \times 50 = j\ 0.163$ p.u

Transformer T_2 referred to line side: 3 single phase units are used.

Voltage rating: 3 x 127/18 kV = 220/18 kV

Note: Star side , $V_L = \sqrt{3}\ V_p$;**Delta side ,** $V_L = V_p$; Power = 3 $V_L I_L$

$MVA_{b,given} = 3 \times 10 = 30\ MVA$

$Z_{p.u.\ new} = Z_{pu,given}$ x $\frac{kV_{b,given}^2}{kV_{b,new}^2}$ x $\frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.15 \times \frac{220^2}{175.36^2} \times \frac{50}{30} = j\ 0.393$ p.u

Generator, G_2 :

Transformer T_2 Primary side change occurs, so calculate $KV_{b,new}$ as

$KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_3}{H.T\ side\ rating\ of\ T_3}\right)$

$KV_{b,new} = 175.36 * \left(\frac{18}{220}\right) = 14.348$ kV

$Z_{p.u.\ new} = Z_{pu,given}$ x $\frac{kV_{b,given}^2}{kV_{b,new}^2}$ x $\frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.25 \times \frac{18^2}{14.348^2} \times \frac{50}{30} = j\ 0.656$ p.u

Transformer T_3 referred to line side:

$KV_{b,new} = 175.36$ kV

$Z_{p.u.\ new} = Z_{pu,given}$ x $\frac{kV_{b,given}^2}{kV_{b,new}^2}$ x $\frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.15 \times \frac{220^2}{175.36^2} \times \frac{50}{35} = j\ 0.337$ p.u

Generator, G_3 :

Transformer T_3 Primary side change occurs, so calculate $KV_{b,new}$ as

$KV_{b,new} = KV_{b,old} * \left(\frac{L.T\ side\ rating\ of\ T_3}{H.T\ side\ rating\ of\ T_3} \right)$

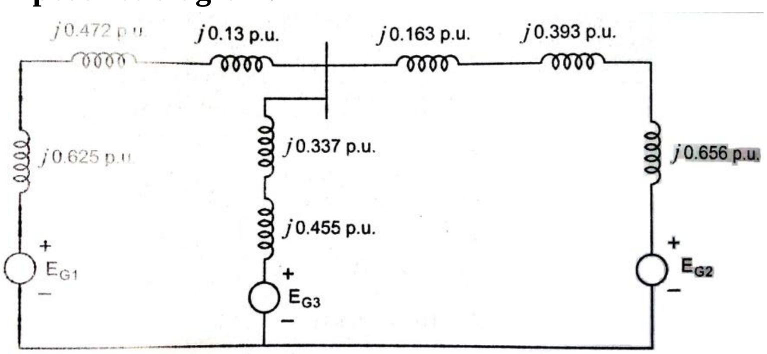
$KV_{b,new} = 175.36 * \left(\frac{22}{220} \right) = 17.536$ kV

$KV_{b,given} = 20$ kV

$Z_{p.u.\ new} = Z_{pu,given} \times \frac{kV_{b,given}^2}{kV_{b,new}^2} \times \frac{MVA_{b,new}}{MVA_{b,given}}$

$Z_{p.u.\ new} = j0.21 \times \frac{20^2}{17.536^2} \times \frac{50}{30} = j\ 0.455$ p.u

Impedance diagram.



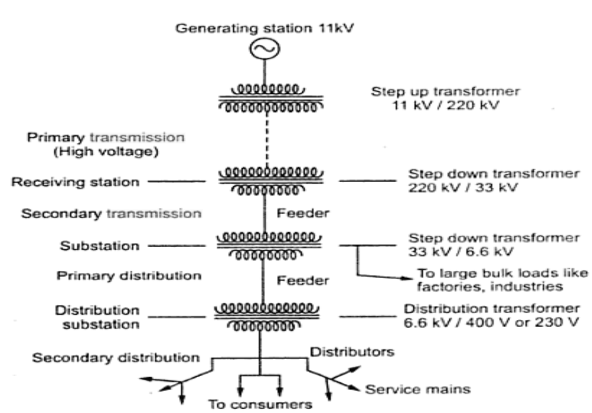
25. Explain the structure of modern power system with a neat sketch.

i. 3 phase 3 wire circuits - Instantaneous sum of three line current is zero
   a. 3 phase circuit advantages - Economical , carry three times more power than single phase

ii. 3 phase 4 wire circuits - 4th wire is Neutral wire and acts as return conductor

Single line diagram

Single line diagram is a simplified representation of power system components along with their interconnections with each other. Each component is represented by its symbol.



Power system Components - Generator, Transformer, Transmission lines & Distribution
Tolerance level - +5 to 10%. Difference in voltages caused due to variation in loads
Primary transmission - First stage of transmission, 110kV,132 kV or 220 kV or400 kV or 765 kV, high voltage transmission, 3Ø , 3 wire system.
Secondary transmission - 3Ø , 3 wire system,33kV high voltage line 66kv to factory supply
Primary distribution - 3Ø , 3 wire system,11kv or 6.6 kV, 3Ø , 3 wire system
Secondary distribution - 400V, 3phase, 230V, 1phase, 3 phase 4 wire
Components of secondary distribution - Substation, feeders, service mains
Interconnection diagram - Feeders, service mains, distributors
Feeder - Conductors that take power from receiving station to substation
Distributor - Conductor that transfer power to consumers by tapping
Service mains - Connects distributor and consumer premises

Unit : II - POWER FLOW ANALYSIS

Importance of power flow analysis in planning and operation of power systems. Statement of power flow problem - classification of buses into P-Q buses, P-V (voltage-controlled) buses and slack bus. Development of Power flow model in complex variables form and polar variables form. Iterative solution using Gauss-Seidel method including Q-limit check for voltage-controlled buses – algorithm and flow chart. Iterative solution using Newton-Raphson (N-R) method (polar form) including Q-limit check and bus switching for voltage-controlled buses - Jacobian matrix elements – algorithm and flow chart. Development of Fast Decoupled Power Flow (FDPF) model and iterative solution – algorithm and flowchart; Comparison of the three methods.

PART – A

1. **Write the need for slack bus in load flow analysis. (APR/MAY 18, NOV/DEC 16)**

   The slack bus is needed to account for transmission line losses. In a power system the total power generated will be equal to sum of power consumed by loads and losses. In a power system only the generated power and load power are specified for buses. The slack bus is assumed to generate the power required for losses. Since the losses are unknown the real and reactive power are not specified for slack bus. They are estimated through the solution of load flow equations.

2. **Discuss the effect of acceleration factor in load flow study. (APR/MAY 18)**

   In load flow solution by iterative methods, the number of iterations can be reduced if the correction voltage at each bus is multiplied by some constant. The multiplication of the constant will increase the amount of correction to bring the voltage closer to the value it is approaching. The multipliers that accomplish this improved convergence are called acceleration factors. An acceleration factor of 1.6 is normally used in load flow problems. Studies may be made to determine the best choice for a particular system

3. **What is need for load flow analysis?**

   (MAY/JUNE 2016 & NOV/DEC 2015 & 2017)

   Power flow analysis or load flow analysis is one of the basic tools used in power systems studies. It is concerned with the steady state analysis of the system when it is working under a normal balanced operating condition. Load flow or power flow analysis is the determination of the voltage, current, real power and reactive power at points in electrical network

4. **Mention the various types of buses in power system with specified quantities for each bus. (MAY/JUNE 2016, NOV/DEC 2017)**

   The following table shows the quantities specified and to be obtained for various types of buses.

Bus type	Quantities specified	Quantities to be obtained
Load bus	P,Q	$\lvert V \rvert$, δ
Generator bus	P, $\lvert V \rvert$	Q, δ
Slack bus	$\lvert V \rvert$, δ	P,Q

5. **Compare the Newton Raphson and Gauss Seidal methods of load flow solutions.**

   (MAY/JUNE 2017)

Gauss Seidal method	Newton Raphson method
Variable is expressed in rectangular	Variables are expressed in polar

coordinates.	coordinates.
Computation time per iteration is less	Computation time per iteration is more.
It has linear convergence characteristics.	It has quadratic convergence characteristics.
The number of iterations required for convergence increases with size of the system.	The numbers of iterations are independent of the size of the system.
The choice of slack bus is critical.	The choice of slack bus is arbitrary.

6. Write are the quantities that are associated with each bus in a system. (MAY/JUNE 2017)

Each bus in a power system is associated with four quantities and they are

i. real power
ii. reactive power
iii. magnitude of voltage,
iv. phase angle of voltage.

7. What is jacobian matrix? (NOV/DEC 2016)

The matrix formed from the first derivatives of load flow equation is called jacobian matrix and it is denoted by J.

The elements of jacobian matrix will change in every iteration. The elements of the jacobian matrix are obtain matrix are obtained by partially differentiating the load flow equation with respect to a unknown variable and then evaluating the first derivative as using the solution of previous iteration

8. When is generator buses treated as load bus? (NOV/DEC 2015)

If the reactive power constraints of a generator bus violates the specified limits then the generator is treated as load bus.

If $Q_i > Q_{i(max)}$, substitute $Q_i = Q_{i(max)}$

If $Q_i^{cal} < Q_{i(min)}$, substitute $Q_i = Q_{i(min)}$

9.Write the most important mode of operation of power system and mention the major problems encountered with it.

Symmetrical steady state is the most important mode of operation of power system. Three major problems are encountered in this mode of operation. They are,

1) Load flow problem
2) Optimal load scheduling problem
3) Systems control problem

10. What is power flow study or load flow study ?

The study of various methods of solution to power system network is referred to as load flow study. The solution provides the voltages at various buses, power flowing in various lines and line-losses.

The load flow study of a power system is essential to decide the best operation of existing system and for planning the future expansion of the system. It is also essential for designing a new power system.

11.Why the load flow studies are important for planning the existing system as well as its future expansion?

The load flow studies are very important for planning, economic scheduling, control and operation of existing systems as well as planning its future expansion depends upon knowing the effect of interconnections, new loads, new generating stations, or new transmission lines, etc. before they installed.

12.Draw sample power system network.

Power system network consist of following parts namely as

a. Generator,
b. Transmission lines,
c. Transformer,
d. load

13.Why power flow analysis is made?

Power flow analysis is performed to calculate the magnitude and phase angle of voltages at the buses and also the active power and reactive volt-amperes flow for the given terminal or bus conditions. The variables associated with each bus or node are,

a. Magnitude of voltage |V|
b. Phase angle of voltage δ
c. Active power, P
d. Reactive voltamperes, Q

14.What are the works involved in a load flow study? (Or) How a load flow study is performed?

The following work has to be performed for a load flow study.

(i) Representation of the system by single line diagrams.
(ii) Determining the impedance diagram using the information in single line diagram.
(iii) Formulation of network equations.
(iv) Solution of network equations.

15.What are the information that are obtained from a load flow study?

The information obtained from a load flow study are magnitude and phase angles of bus voltages, real and reactive power flowing in each line and line losses. The load flow solution also gives the initial conditions of the system when the transient behavior of the system is to be studied.

16.Write about ideal load flow problem.

The network configuration and all the bus power injections.

$P_i = P_G - P_D$

Where

P_i = bus power injection.
P_G = Bus generation
P_D = Bus demand.

To determine the complex voltages at all the buses.

The state vector X is defined as $X = [V_1, V_2 \ldots, V_N, \delta_1, \delta_2 \ldots \delta_N]^T$

Once the voltages at all the buses are known, then we can compute slack bus power, power flows in the transmission lines and power loss in the transmission lines.

17. What is meant by flat voltage start?

In iterative methods of load flow solution, the initial voltages of all buses exept slack bus are assumed as 1+j0 pu. This is referred as flat voltage profile.

V = $|V_{spec}|$ ∠0° for slack bus

V = $|V_{spec}|$ ∠0° for generator bus

V = 1 ∠0° for load bus

18.Write an equation in loop frame of reference for power flow analysis.

$[V_{LOOP}] = [Z_{LOOP}] [I_{LOOP}]$

Where $[Z_{LOOP}]$ = Bus impedance matrix.

$[V_{LOOP}]$ = Voltage matrix

$[I_{LOOP}]$ = Current matrix.

19. Why do we go for iterative methods to solve load flow problems?

The load (or power) flow equations are nonlinear equations and so explicit solution is not possible. The solution of nonlinear equations can be obtained only by iterative numerical techniques. As the number of iteration increases in a load flow problem or power flow problem the solution obtained will be more accurate.

20. What are the operating constraints imposed in the load flow studies & What are the iterative methods used for solution of load flow study ?

The operating constraints imposed in load flow studies are reactive power limits for generator buses and allowable change in magnitude of voltage for load buses.

- *Iterative methods used for load flow study.*
    1. Guass seidal method
    2. Newton Raphson method
    3. Fast decouple method.

21.-Write about practical load flow problem.

The network configuration, complex power demands for all buses, real power generation schedules and voltage magnitudes of all the P-V buses and voltage magnitude of the slack bus.

To determine:

Bus admittance matrix.

Bus voltage phase angles of all buses except the slack bus and bus voltage magnitudes of all the P-Q buses.

The state vector X is defined as X= $[V_1, V_2 \ldots, V_N, \delta_1, \delta_2 \ldots \delta_N]$

22. What is a bus?

The meeting point of various components in a power system is called a bus. The bus is a conductor made of copper or aluminum having negligible resistance .At some of the buses power is being injected into the network, whereas at other buses it is being tapped by the system loads.

23. What are the different types of buses in a power system?

The buses of a power system can be classified into three types based on the quantities being specified for the buses, which are as follows:

a. Load bus or PQ bus (P and Q are specified)

b. Generator bus or voltage controlled bus or PV bus (P and V are specified)

c. Slack bus or swing bus or reference bus (|V| and δ are specified)

24. Define Voltage controlled bus.

A bus is called voltage controlled bus if the magnitude of voltage |V| and real power (P) are specified for it. In a voltage controlled bus the magnitude of the voltage is not allowed to change. The other names for voltage controlled bus are generator bus and PV bus. In this bus the phase angle of the voltages and the reactive power are to be determined. The limits on the reactive power are also specified.

25. What is swing bus?

A bus is called swing bus when the magnitude and phase for bus voltage are specified for it. The swing bus is the reference bus for load flow solution and it is required for accounting line losses. Usually one of the generator bus selected as the swing bus.

Swing bus is also called as Slack bus.

26. What will be the reactive power and bus voltage when the generator bus is treated as load bus?

When the generator bus is treated as load bus the reactive power of the bus is equated to the limit it has violated, and the previous iteration value of bus voltage is used for calculating current iteration value.

If $Q_i > Q_{i(max)}$, then $Q_i = Q_{i(max)}$

If $Q_i < Q_{i(min)}$, then $Q_i = Q_{i(min)}$

Reactive power of the bus has violates the specified limits, then the P-V bus will act as load bus.

27. What is jacobian matrix? How the elements of jacobian matrix are computed?

The matrix formed from the first derivatives of load flow equation is called jacobian matrix and it is denoted by J.

The elements of jacobian matrix will change in every iteration. The elements of the jacobian matrix are obtain matrix are obtained by partially differentiating the load flow equation with respect to a unknown variable and then evaluating the first derivative as using the solution of previous iteration .

29. What is the use of acceleration factor in load flow algorithm.

The acceleration factor is a real quantity and it modifies the magnitude of voltage alone. Since in voltage controlled bus (generator bus), the magnitude of bus voltage is not allowed to change, the acceleration factor is not used for voltage controlled bus. (i.e acceleration factor is used only for load bus)

30. Give the power flow equation in polar form

$P_i = |V_i|^2 \, |Y_{ii}| \, cos\, \theta_{ii} \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \, cos\,(\theta_{ij} + \delta_j - \delta_i)$

$Q_i = - |V_i|^2 \, |Y_{ii}| \, sin\, \theta_{ii} \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \, cos\,(\theta_{ij} + \delta_j - \delta_i)$

The above equations are called as polar form of the power flow equations.

31.Define primitive network.

Primitive network is a set of unconnected elements which provides information regarding the characteristics of individual elements only. The performance equations of primitive network are given below.

V + E = ZI (In Impedance form)

I + J = YV (In Admittance form)

where V and I are the element voltage and current vectors respectively.

J and E are source vectors.

Z and Y are the primitive Impedance and Admittance matrices respectively.

32.What are the iterative methods mainly used for solution of load flow study?

The Gauss seidal method and Newton Raphson method are the two iterative methods which are mainly used in load flow study. Because Fast decoupled method requires more number of iteration when compared to other two iteration methods and the FDLF is suitable only for large size bus systems.

33.Why it is necessary to use acceleration factor in Gauss Seidal method of load flow studies?

In Gauss Seidal method, the number of iteration required for convergence can be reduced if the voltage computed at each iteration is multiplied by a factor greater than unity called acceleration factor to bring the voltage closer to the value to which it is converging. The range of 1.3 to 1.7 is found to be satisfactory for the typical systems.

$$V_i^{new} = V_i^{old} + \propto [V_i^{new} - V_i^{old}]$$

Where V_i^{old} = Voltage value obtained in previous iteration

V_i^{new} = New value of Voltage value obtained in current iteration

$\propto$ = Acceleration factor

34. Write the load flow equation of Gauss-Seidel method.

$$V_i^{new} = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^{*old}} - \sum_{j=1}^{i=1} Y_{ij} V_j^{new} - \sum_{j=i+1}^{N} Y_{ij} V_j^{old}\right]$$

Above equation is used to determine the new voltage in load flow analysis in Gauss-Seidel method.

35.Why bus admittance matrix is used in Gauss Seidal instead of bus impedance matrix?

Using bus admittance matrix is amenable to digital computer analysis, because it could be formed and modified for network changes in subsequent cases. Bus admittance matrix is used in Gauss seidal method because of the following reasons.

- It requires less computation time
- Less memory allocation

36.What are the advantages of Gauss seidal method?

The advantages of Gauss seidal method are as follows

i. Calculations are simple and so the programming task is less.
ii. The memory requirement is less.
iii. Useful for small systems

37.What are the disadvantages of Gauss seidal method?

The disadvantages of Gauss seidal method are listed as follows

i. Requires large no. of iterations to reach converge
ii. Not suitable for large systems.
iii. Convergence time increases with size of the system

38.Give the Q limit condition for Gauss seidal load flow method.

If $Q_{i(min)} < Q_{Gi} < Q_{i(max)}$, then $Q_{i(spec)} = Q_i^{cal}$

If $Q_{i(min)} < Q_{Gi}$, then $Q_{i(spec)} = Q_{i(min)} - Q_{Li}$

If $Q_{i(max)} < Q_{Gi}$, then $Q_{i(spec)} = Q_{i(max)} - Q_{Li}$

If Q limit is violated, then treat this bus as P-Q bus till convergence is obtained.

39.What are the advantages of Newton-Raphson method?

The advantages of Newton-Raphson method are,

i. This load flow method is faster, more reliable and he results are accurate.
ii. Requires less number of iterations for convergence.
iii. The number of iterations are independent of the size of the system.
iv. Suitable for large size systems.

40.What are the disadvantages of Newton-Raphson method?

The disadvantages of Newton-Raphson method are,

i. Programming is more complex.
ii. The memory requirement is more.
iii. Computational time per iteration is higher due to larger number of calculations per iteration.

41.How the disadvantages of N-R method are overcome?

The disadvantage of large memory requirement can be overcome by decoupling the weak coupling between P-δ and Q-V. (i.e., using decoupled load flow algorithm). The disadvantage of large computational time per iteration can be reduced by simplifying the decoupled load flow equations. The simplifications are made based on the practical operating conditions of a power system.

42. Give the Q limit condition for Newton Raphson load flow method.

for PV bus, Check for Q limit violation

If $Q_{i(min)} < Q_i^{cal} < Q_{i(max)}$, the bus acts as PV bus

If $Q_i^{cal} > Q_{i(max)}$, then $Q_{i(spec)} = Q_{i(max)}$

If $Q_i^{cal} < Q_{i(min)}$, then $Q_{i(spec)} = Q_{i(min)}$, the PV bus will act as PQ bus.

43.Write the load –flow equations for Newton-Raphson method.

$$P_i = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| cos(\theta_{ij} + \delta_j - \delta_i)$$

$$Q_i = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| sin(\theta_{ij} + \delta_j - \delta_i)$$

Above equation is used to determine the power flow in load flow analysis in Newton-Raphson method.

44.How approximation is performed in Newton-Raphson method?

In Newton-Raphson method, the set of nonlinear simultaneous (load flow) equations are approximated to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to first order approximation. The approximation procedure involved is based upon the initial estimate of unknown and simply it is called as successive approximation method.

45.How the convergence of N-R method is speeded up?

The convergence can be speeded up in N-R method by using Fast Decoupled Load Flow (FDLF) algorithm. In FDLF method the weak coupling between P-δ and Q-V are decoupled and then the equations are further simplified equations are further simplified using the knowledge of practical operating conditions of a power system.

46.List out the advantages of Fast Decoupled method.

The advantages of Fast Decoupled method are,

i. This load flow method is faster, more reliable and the results are accurate.
ii. Programming is simple
iii. The memory requirement is less compared to NR method.

iv. Computational time per iteration is less.

47.What are the disadvantages of Fast Decoupled method?

The main disadvantages of Fast Decoupled method are listed as follows,

i. Require more number of iterations.
ii. Suitable only for large bus systems but the number of iteration does not depend upon the size of the system.

48.In contingency analysis, which load flow is preferred? And give reasons for it.

In contingency analysis, fast decoupled method is suitable for performing load flow analysis due to following reasons.

i. Programming is simple.
ii. Computational time per iteration is less.

49. Give the Q limit condition for Fast decoupled load flow method.

for PV bus, Check for Q limit violation

If $Q_{i(min)} < Q_i < Q_{i(max)}$, calculate P_i^{cal}

If $Q_i^{cal} < Q_{i(min)}$, then $Q_{i(spec)} = Q_{i(min)}$

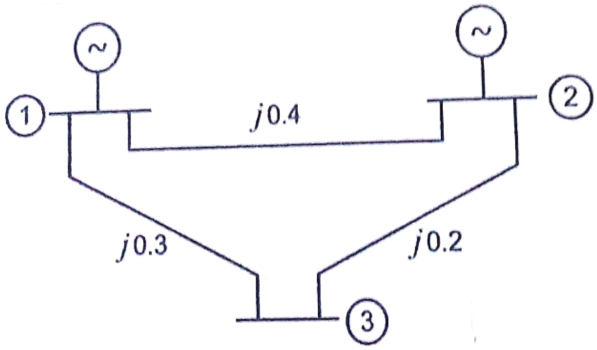
If $Q_i^{cal} > Q_{i(max)}$, then $Q_{i(spec)} = Q_{i(max)}$, the PV bus will act as PQ bus.

50.Compare all the different methods of load flow study.

S.No	G.S	N.R	FDLF
1	Require large number of iterations to reach convergence.	Require less number of iterations to reach convergence.	Require more number of iterations than N.R method
2	Computation time per iteration is less	Computation time per iteration is more	Computation time per iteration is less
3	It has linear convergence	It has quadratic convergence	No convergency
4	The number of iterations required for convergence increases	The number of iterations are independent of the	The number of iterations are does not dependent of the
5	Less memory requirements.	More memory requirements.	Less memory requirements than N.R. method.

PART – B

1. **For the system shown in Fig., determine the voltages at the end of the first iteration by Gauss – seidel method and also find the slack bus power, line flows, transmission line loss. Assume base MVA as 100. (APRIL/MAY 2018)**



Solution:

Bus No.	Voltage	Generator		Load		Q_{min} MVAR	Q_{max} MVAR
		P	Q		Q		
1.	1.05∠0° p.u.	-	-		-	-	-
2.	1.02 p.u.	0.3 p.u.	-		-	-10	100
3.	-	-	-		0.2 p.u.	-	-

Step – 1: From Y-bus.

$$Y_{bus} = \begin{bmatrix} \frac{1}{Y_{11}} & \frac{-1}{Y_{12}} & \frac{-1}{Y_{13}} \\ \frac{-1}{Y_{21}} & \frac{1}{Y_{22}} & \frac{-1}{Y_{23}} \\ \frac{-1}{Y_{31}} & \frac{-1}{Y_{32}} & \frac{1}{Y_{33}} \end{bmatrix} = \begin{bmatrix} \frac{1}{j0.4} + \frac{1}{j0.3} & \frac{-1}{j0.4} & \frac{-1}{j0.3} \\ \frac{-1}{j0.4} & \frac{1}{j0.4} + \frac{1}{j0.2} & \frac{-1}{j0.2} \\ \frac{-1}{j0.3} & \frac{-1}{j0.2} & \frac{1}{j0.3} + \frac{1}{j0.2} \end{bmatrix}$$

$$Y_{bus} = \begin{bmatrix} -j5.8333 & j2.5 & j3.3333 \\ j2.5 & -j7.5 & j5 \\ j3.3333 & j5 & -j8.3333 \end{bmatrix}$$

Step – 2: Initialize bus voltages.

$V_1^{old} = 1.05\angle 0°$ p.u. [Bus 1 is a slack bus i.e., V and δ is specified]

$V_2^{old} = 1.02\angle 0°$ p.u. [Bus 2 is a PV bus i.e., P and V is specified]

$V_3^{old} = 1.0$ p.u. [Bus 3 is a load bus i.e., P and Q is specified]

Note

For Slack bus, the specified voltage will not change in any iteration.

For generation bus, calculate V_i^{new} using the formula and write

$$V_i^{new} = V_{specified}\angle\delta_{calculated\ value}$$

Step 3 : Calculate Q value for all generator buses.

Q_i^{cal} = - Im {V_i^{old}*$[\sum_{j=1}^{i-1} Yij\ Vjnew + \sum_{j=i}^{N} Yij\ Vjold]$}

Q_2^{cal} = - Im {V_2^{old}*[$Y_{21}V_1^{new}$ +$Y_{22}V_2^{old}$ + $Y_{23}V_3^{old}$]}

Q_2^{cal} = - Im {1.02∠0° *[j2.5X1.05∠0° +(-j7.5X1.02∠0°) + j5 X 1∠0°]}

Q_2^{cal} = - Im {1.02∠0° *j2.625-j7.65+j5]}

Q_2^{cal} = 0.025 p.u.

Now $Q_{2(min)} \le Q_2^{cal} \le Q_{2(max)}$

i.e., Q_2^{cal} is within the specified limit.

Step – 4: Calculate V_i^{new} .

V_i^{new} = 1.05∠0° p.u.

$$V_i^{new} = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^{old*}} - \sum_{j=1}^{i-1} Y_{ij}\, V_j^{new} - \sum_{J=i+1}^{N} Y_{ij}\, V_j^{old}\right]$$

$$V_2^{new} = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{V_2^{old*}} - Y_{21}V_1^{new} - Y_{23}\, V_3^{old}\right]$$

P_2 = 0.3 p.u. (Given); Q2= 0.025 p.u.

$$V_2^{new} = \frac{1}{-j7.5}\left[\frac{0.3 - j0.025}{1.02\angle 0°} - j2.5\ X\ 1.05\angle 0° - j5\ X\ 1\angle 0°\right]$$

= 1.0199+j0.0392

V_2^{new} = 1.0207∠2.2°

$V_2^{new} = V_{2(spec)}\angle\delta_2^{cal}$ = 1.02∠2.2° = 1.0192 + j0.0392

$P_3 = P_{G3} - P_{L3}$ = 0- 0.4 = -0.4 p.u.

$Q_3 = Q_{G3} - Q_{L3}$ = 0 – 0.2 = -0.2 p.u.

$$V_3^{new} = \frac{1}{Y_{33}}\left[\frac{P_3 - jQ_3}{V_3^{old*}} - Y_{31}V_1^{new} - Y_{32}\, V_2^{new}\right]$$

$$V_3^{new} = \frac{1}{-j8.3333}\left[\frac{-0.4 + j0.2}{1.0\angle 0°} - j3.3333\ X\ 1.05\angle 0° - j5\ X\ 1.02\angle 2.2°\right]$$

$$= \frac{1}{-j8.3333}[-0.4 + j0.2 - j3.4999 - j5.096 + 0.196]$$

= 1.0075 – j0.0244 = 1.0078 ∠-1.39°

V_3^{new} = 1.0075 – j0.0244 = 1.0078 ∠ -1.39°

Step 5: Slack bus power

$S_1 = P_1 - jQ_1 = V_1^* \sum_{j=1}^{N} Y_{ij}V_j$

$S_1 = V_1^*\ [Y_{11}V_1 + Y_{12}V_2 + Y_{13}V_3]$

= 1.05[−j5.8333 X 1.05 ∠0° + j2.5 X (1.0192 + j0.0392) + J3.3333 (1.0075 − j0.0244)]

= -0.0175 – j0.2295 p.u.

P_1= -0.0175 p.u. = -1.75 MW

Q_1= 0.2295 p.u. = 22.95 MVAR

Step 6: Line flow

$S_{ij} = P_{ij} + jQ_{ij} = V_i\ [\ V_i^* - V_j^*]Y_{ij\ series}^* + |Vi|^2 Y_{Pi}^*$

Line flow from bus 1 to 2.

$S_{12} = P_{12} + jQ_{12} = V_1[V_1^* - V_2^*]\ Y_{12\ series}^*$

= 1.05[(1.05∠-0°) – 1.0192+j0.0392] j2.5

= -0.1029 + j0.0808 p.u.

$S_{21} = P_{21}+jQ_{21} = V_2[V_2^* - V_1^*]\ Y_{21\ Series}^*$

= 1.0192 + j0.0392 [1.0192-j0.0392-1.05] j2.5

$= 0.1029 - j0.0746$ p.u

$S_{23} = P_{23}+jQ_{23}$

$S_{23} = V_2 [V_2^* - V_3^*] Y_{23}^*{}_{series}$

$= 1.0192 + j0.0392 [1.0192 - j0.0392 – 1.0075 – j0.0244] j5$

$= 0.3218 + j0.072$ p.u

$S_{32} = P_{32} + jQ_{32}$

$S_{32} = V_3 [V_3^* - V_2^*] Y_{32}^*{}_{series}$

$= 1.0075 – j0.0244 [1.0075 + j0.0244 – 1.0192 + j0.0392] j5$

$S_{32} = -0.3218 – j0.0512$ p.u

$S_{13} = P_{13} + jQ_{13}$

$S_{13} = V_1 [V_1^* - V_3^*] Y_{13}^*{}_{series} = 1.05[1.05\angle-0° - 1.0075 – j0.0244] j3.3333$

$S_{13} = 0.085 + j0.148$ p.u.

$S_{31}= P_{31} + jQ_{31}$

$S_{31} = V_3 [V_3^* - V_1^*] Y_{31}^*{}_{series}$

$= 1.0075 – j0.0244 \times [1.0075 + j0.0244 – 1.05] \times j3.3333$

$S_{31}= -0.085 – j0.1407$ p.u

Transmission Loss

$S_{ij\ Loss} = S_{ij} + S_{ji}$

For line 1-2,

$S_{12} = P_{12\ Loss} + jQ_{12\ Loss} = S_{12} + S_{21}$

$S_{12\ Loss} = - 0.1029 + j0.0808 + 0.1029 – j0.0746 = 0+j0.0061$

$P_{12\ Loss} = 0$, $Q_{12\ Loss} = 0.0061$ p.u. =0.61 MVAR

For line 2-3,

$S_{23\ Loss} = P_{23\ Loss} + jQ_{23\ Loss} = S_{23} + S_{32}$

$=0.3218 + j0.072 +(- 0.3218 – j0.0512)$

$=0 + j0.021$

$P_{23\ Loss} = 0$, $Q_{23\ Loss} = 0.021$ p.u. = 2.1 MVAR

For line 1-3,

$S_{13\ Loss} = P_{13\ Loss} + jQ_{13\ Loss} = S_{13} + S_{31}$

$= 0.085 + j0.148 + [- 0.085 –j0.1407]$

$= 0+j0.00726$

$P_{13\ Loss} = 0$,

$Q_{13\ Loss} = 0.00726$ p.u. =0.726 MVAR

2. **Perform two iteration of Newton Raphson load flow method and determine the power flow solution for the given system. Take base MVA as base 100. (APRIL/MAY 2018)**

Solution:

Line Data:

Line	Bus	R(p.u.)	X(p.u.)	Half line charging

	From	To			admittance ($\frac{Y_P}{2}$ (p.u.))
1	1	2	0.0839	0.5183	0.0636

Bus Data:

Bus	P_L	Q_L
1	90	20
2	30	10

Step – 1: $Y_{bus} = \begin{bmatrix} 0.3044 - j1.816 & -0.3044 + j1.88 \\ -0.3044 + j1.88 & 0.3044 - j1.816 \end{bmatrix}$

$Y_{bus} = \begin{bmatrix} 1.842\angle -1.405 & 1.904\angle 1.7314 \\ 1.904\angle 1.7314 & 1.842\angle -1.405 \end{bmatrix}$ {Note: Use in rad mode}

Step – 2: Assume the initial value i.e., δ=0, V=1.0

$[X] = \begin{bmatrix} \delta_2 \\ V_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1.0 \end{bmatrix}$

Step – 3: Calculate P_2^{cal}, Q_2^{cal}, ΔP_2 and ΔQ_2.

$P_2^{cal} = |V_2|\{|V_1||Y_2|\cos(\theta_{12} + \delta_2 - \delta_1) + |V_2||Y_{22}|\cos(\theta_{22} + \delta_2 - \delta_2)\}$

= 1.0[1.05 X 1.904 cos(1.7314) + 1.842 cos(-1.405)]

= 1.05 X 1.904(-0. 15991) + 1.842(0.16503)

= -0.015 p.u.

$P_{2(spec)} = P_{G2} - P_L$

$= 0 - \frac{30}{100} = -0.3$ p.u.

$P_{2(spec)} = -0.3$ p.u.

$\Delta P_2 = P_{2(spec)} - P_2^{cal}$

= -0.3 – (-0.015)= - 0.285

$Q_2^{cal} = -V_2\{|V_1||Y_{21}|\sin(\theta_{12} + \delta_1 - \delta_2) + |V_2||Y_{22}|\sin(\theta_{22} + \delta_2 - \delta_2)\}$

= - 1.0[1.05 X 1.904 sin(1.7314)+ 1.0 X 1.842 sin(-1.405)]

= - 0.157 p.u.

$\Delta Q_2 = Q_{2(spec)} - Q_2^{cal} = -0.1 - (-0.157)$

= 0.057

Step – 4: Form Jacobian matrix

$$\begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \frac{\partial P_2}{\partial V_2} \\ \frac{\partial Q_2}{\partial \delta_2} & \frac{\partial Q_2}{\partial V_2} \end{bmatrix} \begin{bmatrix} \Delta\delta_2 \\ \Delta V_2 \end{bmatrix} = \begin{bmatrix} \Delta P_2 \\ \Delta Q_2 \end{bmatrix}$$

$\frac{\partial P_2}{\partial \delta_2} = |V_2||V_1||Y_{12}|\sin(\theta_{12} + \delta_1 - \delta_2) + |V_2|^2|Y_{22}| X 0$

= 1.0 X 1.05 X1.904 sin(1.7314)

= 1.973

Step – 5: Compute Δx,

$$\begin{bmatrix} \Delta\delta 2 \\ \Delta V2 \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \frac{\partial P_2}{\partial V_2} \\ \frac{\partial Q2}{\partial \delta_2} & \frac{\partial Q_2}{\partial V_2} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \Delta P_2 \\ \Delta Q_2 \end{bmatrix}$$

$$= \begin{bmatrix} 1.973 & 0.289 \\ -0.3196 & 1.66 \end{bmatrix} \times \begin{bmatrix} -0.285 \\ 0.057 \end{bmatrix}$$

$$= \begin{bmatrix} 0.493 & -0.086 \\ 0.0949 & 0.586 \end{bmatrix} \begin{bmatrix} -0.285 \\ 0.057 \end{bmatrix}$$

$$\begin{bmatrix} \Delta\delta 2 \\ \Delta V2 \end{bmatrix} = \begin{bmatrix} -0.145 \\ 0.0064 \end{bmatrix}$$

$$X = X° + \Delta X = \begin{bmatrix} 0 \\ 1.0 \end{bmatrix} + \begin{bmatrix} -0.145 \\ 0.0064 \end{bmatrix} = \begin{bmatrix} -0.145 \\ 0.0064 \end{bmatrix}$$

Iteration – 2: Compute mismatch vectors.

P_2^{cal} = 1.0064 [1.05 X 1.904 cos(1.7314 + 0+(-0.145)) + 1.0064 X 1.842 X cos(-1.405)]

= -0.297

$\Delta P_2 = P_{2(spec)} - P_2^{cal}$ = -0.3 – (-0.297) = - 0.003

ΔP_2 = - 0.003

Q_2^{cal} = - {1.0064 [1.05 X 1.904 X sin (1.7314+ 0-(-0.145)) + 1.0064 X 1.842 X sin(-1.405)]}

= -0.078

$\Delta Q_2 = Q_{2(spec)} - Q_2^{cal}$ = -0.1 – (-0.078) = -0.021

ΔQ_2 = -0.021

Compute Jacobian matrix

$\frac{\partial P_2}{\partial \delta_2}$ = 1.0064 X 1.05 X 1.904 sin(1.7314 + 0.145)

= 1.919

$\frac{\partial P_2}{\partial V_2}$ = 1.05 X 1.904 cos(1.7314+0.145)+2 X 1.0064 X 1.842 X cos(-1.405)

= 0.011

$\frac{\partial Q_2}{\partial \delta_2}$ = 1.0064 X 1.05 X 1.904 cos(1.7314+0.145)

$\frac{\partial Q_2}{\partial \delta_2}$ = -0.605

$\frac{\partial Q_2}{\partial V_2}$ = -1.05 X 1.904 sin(1.7314 + 0.145) – 2 X 1.0064 X 1.842 X sin(-1.405)

$\frac{\partial Q_2}{\partial V_2}$ = 1.75

$$\begin{bmatrix} \Delta\delta 2 \\ \Delta V2 \end{bmatrix} = \begin{bmatrix} 1.919 & 0.011 \\ -0.605 & 1.75 \end{bmatrix}^{-1} . \begin{bmatrix} \Delta P_2 \\ \Delta Q_2 \end{bmatrix}$$

$$= \begin{bmatrix} 0.52 & -0.0033 \\ 0.179 & 0.57 \end{bmatrix} \begin{bmatrix} -0.003 \\ -0.021 \end{bmatrix}$$

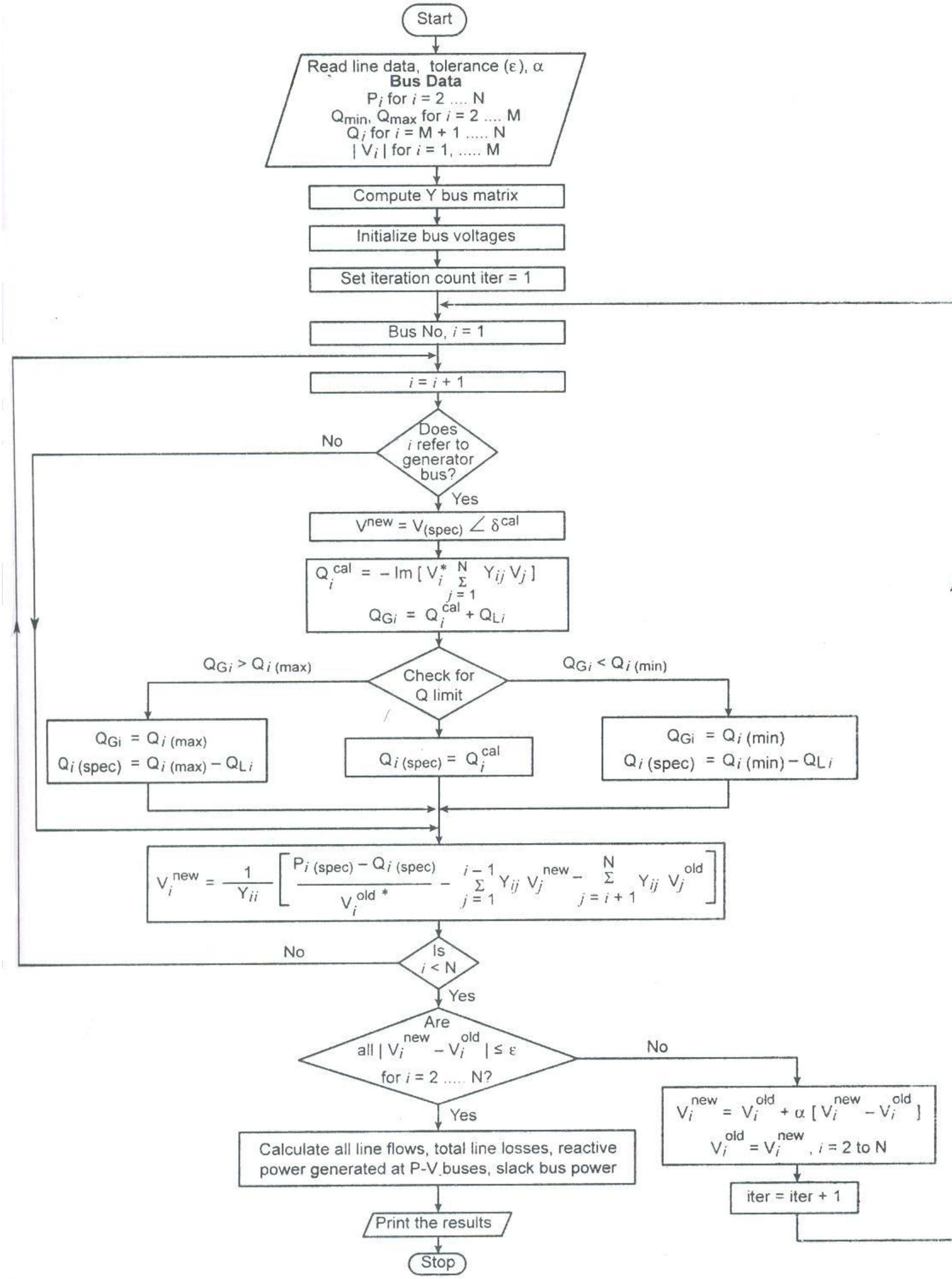
$$\begin{bmatrix} \Delta\delta 2 \\ \Delta V2 \end{bmatrix} = \begin{bmatrix} -0.0015 \\ -0.0125 \end{bmatrix}$$

$$\begin{bmatrix} \delta_2 \\ V_2 \end{bmatrix} = \begin{bmatrix} \delta_2^{old} \\ V_2^{old} \end{bmatrix} + \begin{bmatrix} \Delta\delta_2 \\ \Delta V_2 \end{bmatrix}$$

$$= \begin{bmatrix} -0.145 \\ 1.0064 \end{bmatrix} + \begin{bmatrix} -0.0015 \\ -0.0125 \end{bmatrix} = \begin{bmatrix} -0.1465 \text{ rad} \\ 0.994 \text{ p.u.} \end{bmatrix} = \begin{bmatrix} -8.39° \\ 0.994 \text{ p.u.} \end{bmatrix}$$

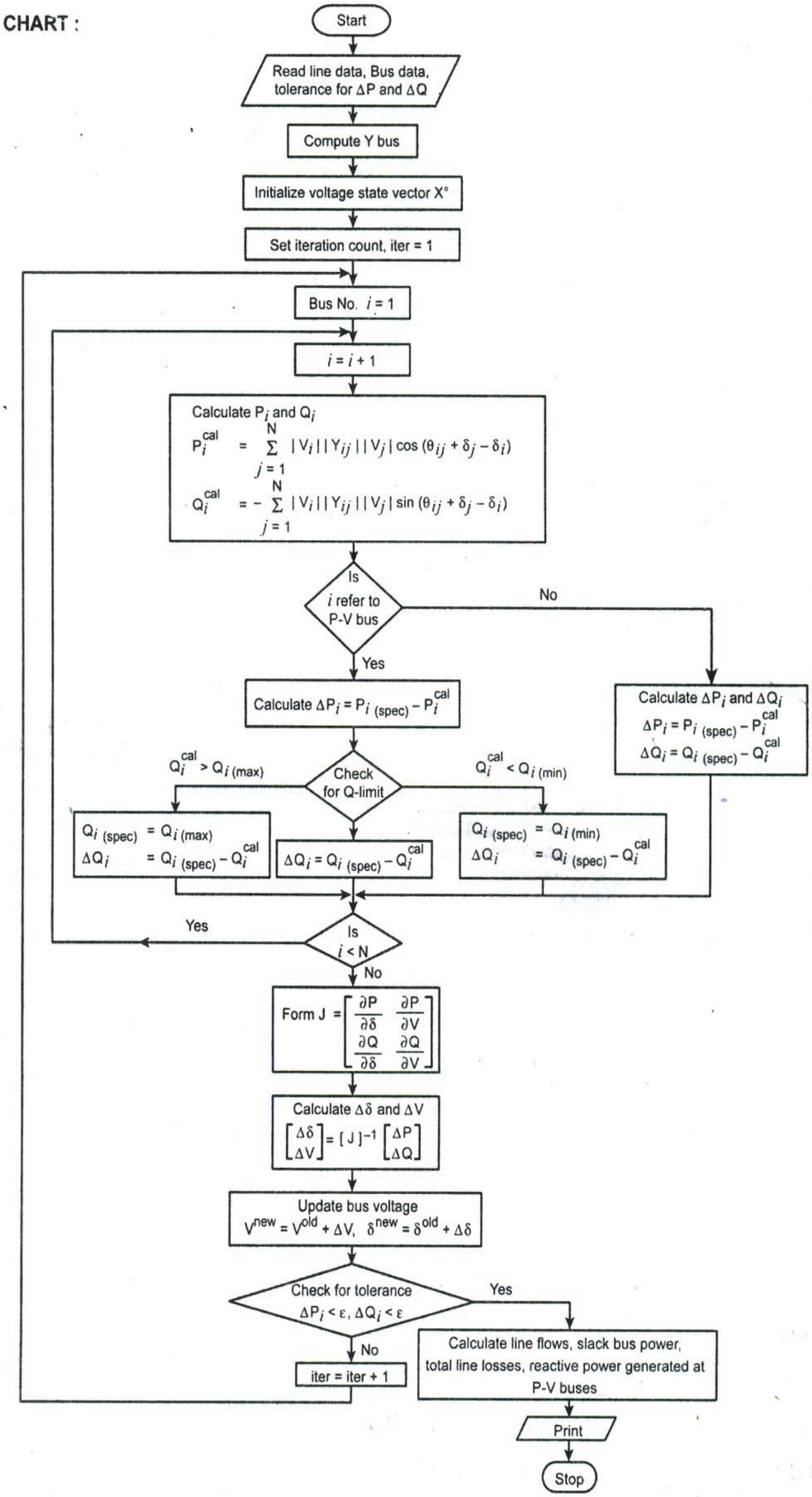
$V_2 = 0.994\angle -8.39°$

3. With a neat flowchart, explain the computational procedure for load flow solution using Gauss-seidal load flow solution. (NOV/DEC2015, 2017)



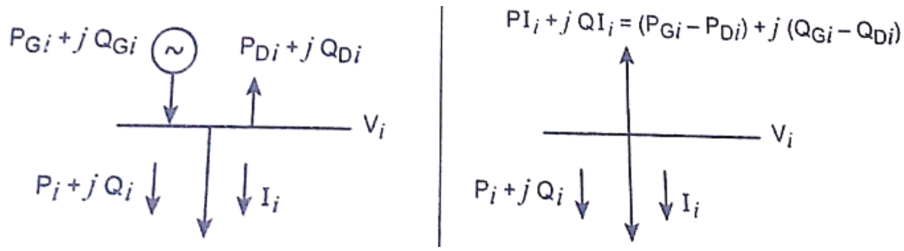
4. Draw a flowchart and explain the algorithm of Newton Raphson iterative method when the system containall types of buses. (NOV/DEC 2015)

FLOW CHART :



5. Write a neat flowchart, explain the computational procedure for load flow solution using Newton Raphson iterative method whenthe system contains all types of buses.

The most widely used method for solving simultaneous non linear algebraic equation is the Newton Raphson method.



from the fig the complex power balance at bus i is given by

$PI_i + jQI_i = P_i + jQ_i$ ……………………………………………………..…(1)

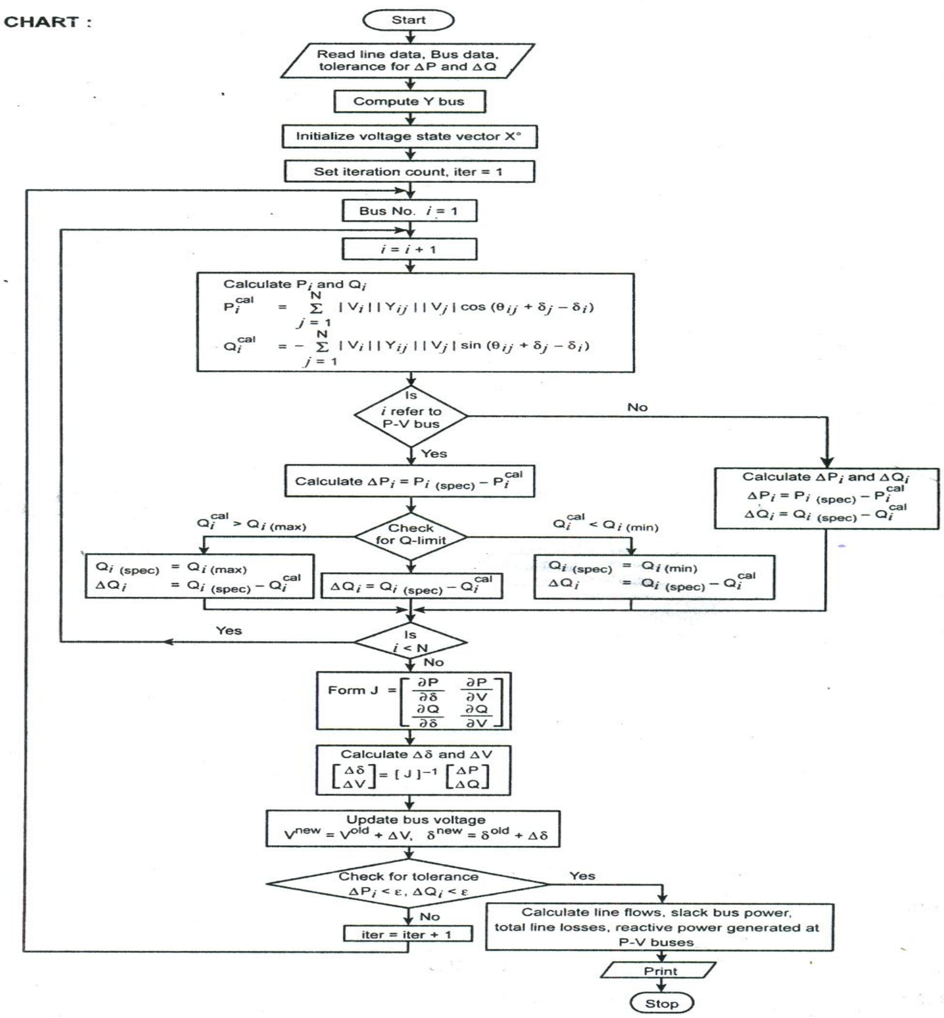
Complex power injection at the i^{th} bus $PI_i + jQI_i$

$= (P_{Gi} - P_{Di}) + (jQ_{Gi} - jQ_{Di})$

Since the bus generation and demand are specified, the complex the complex power injection is a specified quantity and is given by,

(MAY/JUNE 17 & NOV/DE 16)

FLOW CHART :



$PI_{i(spec)} + jQI_{i(spec)} = [P_{Gi(spec)} - P_{Di(spec)}] + j[Q_{Gi(spec)} - Q_{Di(spec)}]$ ………………(a)

The current entering bus i is given by,

$I_i = \sum_{j=1}^{N} Y_{ij} V_j$

In polar form

$I_i = \sum_{j=1}^{N}|Y_{ij}||V_i|\angle(\theta_{ij} + \delta_j)$ ……………………………………………………(b)

$[Y_{ij} = |Y_{ij}|\angle\theta_{ij} ; V_j = |V_i|\angle\delta_i]$

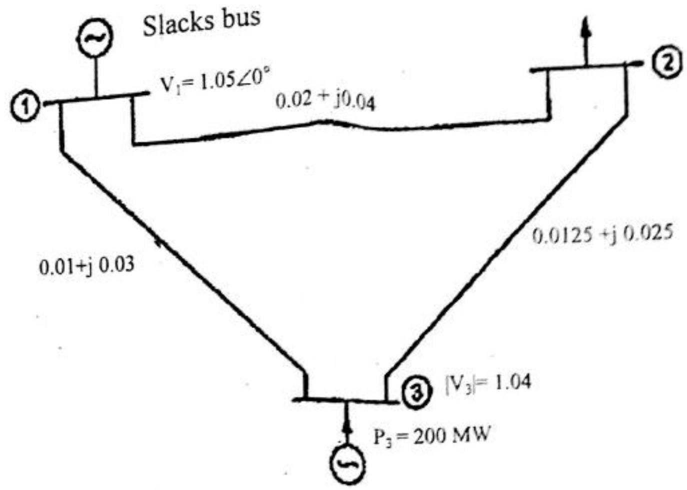
Equating the real and imaginary parts

$P_i = \sum_{j=1}^{N}|V_i||Y_{ij}||V_j|cos(\theta_{ij} + \delta_j - \delta_i)$………………………(c)

$Q_i = \sum_{j=1}^{N}|V_i||Y_{ij}||V_j|sin(\theta_{ij} + \delta_j - \delta_i)$ ……………………………………………(d)

6. Single line diagram of simple power system, with generators at buses 1 and 3 is shown. The magnitude of voltage at bus 1 is 1.05 pu. Voltage magnitude at bus 3 is fixed at 1.04 pu with active power generation of 200MW. A load consisting of 400 MW and 250 MVAR is taken from bus 2. Line impedance are marked in pu on a 100 MVA base and the line charging susecptances are neglected.

Determine the voltage at buses 2 and 3 using G-S method at the end of first iteration. Also calculate slack bus power. (MAY/JUNE 2017)



Solution:

Step1: Formulate Ybus.

When the switch is open, there is no connection of capacitor at bus 2.

Take the bus as load bus.

Step2: Initialize bus voltages

$V_2^{old} = 1.05\angle0°$

$V_3^{old} = 1.04\angle0°$

Step3: Calculate V_2^{new}.

$V_2^{new} = 1.018\angle-8.915°$

Step 4: Calculate V_2^{new} using acceleration factor

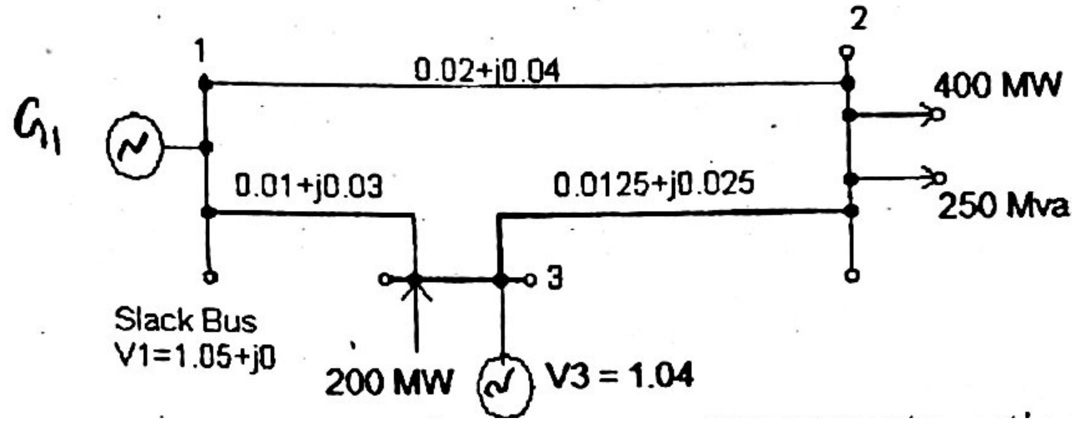
Step 5: Slack bus power

$S_1 = P_1 - jQ_1$

Real power generation $P_{G1} = P_1 + P_{L1}$

3. The figure shows the one line diagram of a simple 3 bus power system with generators at

buses 1 and 3 line impedances are marked in pu on a 100 MVA base. Determine the bus voltage at the end of second iteration using G-S method. (NOV/DEC 2016)



Solution:

Formulate Ybus.

When the switch is open, there is no connection of capacitor at bus 2.

Take the bus as load bus.

Initialize bus voltages

Calculate V_2^{new}.

$$V_2^{new} = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{V_2^{old*}} - Y_{21}V_1^{new}\right]$$

Calculate V_2^{new} using acceleration factor

$$V_2^{new}{}_{acc} = V_2^{old} + \alpha[V_2^{new} - V_2^{old}]$$

Slack bus power

$$S_1 = P_1 - jQ_1$$

Line flow

$S_{ij} = P_{ij} + jQ_{ij} = V_i\,[\,V_i^* - V_j^*]Y_{ij}^*{}_{series} + |Vi|^2 Y_{Pi}^*$

Line flow from bus 1 to 2.

$S_{12} = P_{12} + jQ_{12} = V_1[V_1^* - V_2^*]\,Y_{12}^*{}_{series}$

7. **The system data for a load flow solution are given in tables. Determine the voltages at the end of first iteration using G-S method. Take α = 1.6 (MAY/JUNE 2016)**

LINE ADMITTANCE

Bus code	**Admittance**
1-2	**2-j8.0**
1-3	**1-j4.0**
2-3	**0.666-j2.664**
2-4	**1-j4.0**
3-4	**2-j8.0**

Schedule of active and reactive powers

Bus code	**P in pu**	**Q in pu**	**V in pu**	**Remarks**
1	**-**	**-**	**1.06**	**SLACK**
2	**0.5**	**0.2**	**1+J0.0**	**PQ**
3	**0.4**	**0.3**	**1+J0.0**	**PQ**
4	**0.3**	**0.1**	**1+J0.0**	**PQ**

Solution:

Step1: Formulate Ybus.

When the switch is open, there is no connection of capacitor at bus 2.

Take the bus as load bus.

Step2: Initialize bus voltages

Step3: Calculate V_2^{new}.

$$V_2^{new} = \frac{1}{Y_{22}}\left[\frac{P_2\text{-}jQ_2}{V_2^{old*}} - Y_{21}\, V_1^{new}\right]$$

Step 4: Slack bus power

$S_1=P_1\text{-}jQ_1$

8. Draw and explain the step by step procedure of load flow solution for Gauss-seidal method with PV buses are present. (MAY/JUNE 2016)

Step 1 : form Y-Bus

Step 2 : Assume $V_k = V_{k(spec)}\angle 0^0$ at all generator buses.

Step 3 : Assume $V_k = 1\angle 0^0 = 1+j0$ at all load buses.

Step 4 : set iteration count = 1 (iter = 1)

Step 5 : let bus number i = 1

Step 6 : If 'i' refers to generator bus go to step no. 7, otherwise go to step 8.

Step 7(a) : If 'i' refers to slack bus go to step no. 9, otherwise go to step 7(b).

Step 7(b) :compute Q_i using

$$Q_i^{\ cal} = -\ \mathrm{Im}\left[\sum_{j=1}^{N} V_i^* Y_{ij} V_j\right]$$

$Q_{Gi} = Q_i^{\ cal} + Q_{Li}$

Check for Q limit violation

If $Q_{i(min)} < Q_{Gi} < Q_{i(max)}$, then $Q_{i(spec)} = Q_i^{\ cal}$

If $Q_{i(min)} < Q_{Gi}$, then $Q_{i(spec)} = Q_{i(min)} - Q_{Li}$

If $Q_{i(max)} < Q_{Gi}$, then $Q_{i(spec)} = Q_{i(max)} - Q_{Li}$

If Qlimit is violated, then treat this bus as P-Q bus till convergence is obtained.

Step 8 : Compute V_i using eqn.

$$V_i^{new} = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^{old*}} - \sum_{i=1}^{j-1} Y_{ij} V_j^{new} - \sum_{i=j+1}^{N} Y_{ij} V_j^{old}\right]$$

Step 9 : If i is less than number of buses, increment I by 1 and go to step 6.

Step 10 : Compare two successive iteration values for V_i

If $V_i^{new} - V_i^{old} <$ tolerance, go to step 12.

Step 11 : Update the new voltage as

$$V^{new} = V^{old} + \propto (V^{new} - V^{old})$$

$$V^{new} = V^{old}$$

Iter = iter +1; go to step 5.

Step 12: Compute relevant quantities.

Slack bus power, $S_1 = V^*I = V_i^* \sum_{j=i}^{N} Y_{ij} V_j$

line flow losses, $S_{ij} = P_{ij} + jQ_{ij}$

Real power loss, $P_{loss} = P_{ij} + P_{ji}$

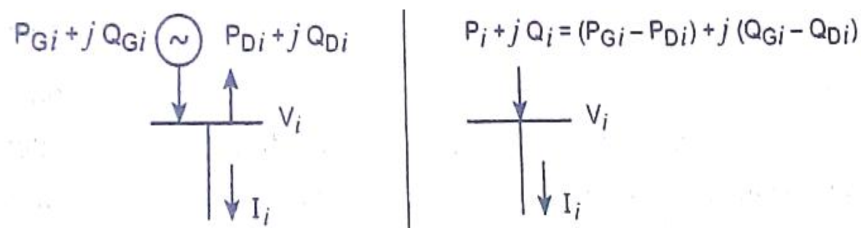
Reactive power loss, $Q_{loss} = Q_{ij} + Q_{ji}$

Step 13 : Stop the execution.

9. Derive the development of load flow model in complex variable form and polar variable form.

Solution

The power flow or load flow model in complex form is obtained by writing one complex power matching equation at each bus for the figure shown below.



Net power injected into the bus i.

$S_i = S_{Gi} - S_{Di}$

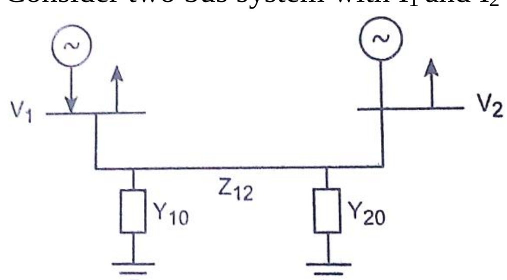
$= P_{Gi} + jQ_{Gi} - (P_{Di} + jQ_{Di})$

$= P_i + jQ_i$

We know,

$P_i + jQ_i = V_i I_i^*$

Consider two bus system with I_1 and I_2 as net current entering into bus 1 and 2.



$$[I] = [Y][V]$$

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

$$Y_{11} = y_{10} + y_{12}$$

$$Y_{22} = y_{20} + y_{21}$$

$$Y_{12} = Y_{21} = - y_{21}$$

In general, Yij = $|Y_{ij}| \angle \theta_{ij}$

$I_1 = Y_{11} V_1 + Y_{12} V_2$

$I_2 = Y_{21} V_1 + Y_{22} V_2$

In general , the net current entering into i^{th} bus

$I_i = Y_{i1}V_1 + Y_{i2}V_2 + \ldots\ldots\ldots\ldots + Y_{iN}V_N = \sum_{j=1}^{N} Y_{ij}V_j$

Substituting the value of I_i in power flow eqn we get.

$S_i = P_i + jQ_i = V_i I_i^*$

$S_i = P_i - jQ_i = V_i I_i^*$

$P_i - jQ_i = V_i^* \sum_{j=1}^{N} Y_{ij}V_j$ where i = 1,2,3…………..N

There are N complex variable equations for which the N unknown complex variables $V_1, V_2 \ldots\ldots V_N$ can be determined.

Substituting Y_{ij} from the above eqn, we get.

$P_i - jQ_i = V_i^* \sum_{j=1}^{N} |Y_{ij}| \angle\theta_{ij} \, V_j$

Where $V_i = |V_i|\angle\delta_i$, $V_i^* = |V_i|\angle -\delta_i$,

$V_j = |V_j|\angle\delta_j$

Therefore net power equations can be written as

$P_i - jQ_i = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \angle(\theta_{ij} + \delta_j - \delta_i)$

Equating real and reactive parts,

$P_i = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \cos(\theta_{ij} + \delta_j - \delta_i)$

$Q_i = - \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \sin(\theta_{ij} + \delta_j - \delta_i)$

We can write the above equation as

$P_i = |V_i|^2 |Y_{ii}| \cos\theta_{ii} \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \cos(\theta_{ij} + \delta_j - \delta_i)$

$Q_i = - |V_i|^2 |Y_{ii}| \sin\theta_{ii} \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \cos(\theta_{ij} + \delta_j - \delta_i)$

The above equations are called as polar form of the power flow equations.

10. **Derive the load flow equation using Gauss seidal method.**

Bus 1 is generator bus take it as reference bus or slack bus. Here the voltages are specified.

In load buses, assume initial value of voltage as $1\angle 0^0$ and find the new value of voltages.

The calculation starts from bus 2 onwards. In the generator bus first check generator limit and find the voltages.

Injected bus power is given by,

$S_i = P_i - jQ_i = V_i^* I_i$

$= V_i^* \sum_{j=1}^{N} Y_{ij} V_j$

$P_i - jQ_i = V_i^* Y_{ii} V_i + V_i^* \sum_{j=1 \neq i}^{N} Y_{ij} V_j$

$V_i = \frac{1}{Y_{ii}} [\frac{P_i - jQ_i}{V_i^*} - \sum_{j=1 \neq i}^{N} Y_{ij} V_j]$

i = 1,2,3………..N except slack bus.

Let $V_1^{old}, V_2^{old} \ldots\ldots V_N^{old}$ be initial voltage. On substituting initial values in above eqn we get $V_1^{new}, V_2^{new} \ldots\ldots V_N^{new}$. After calculating each voltages replace the old values by new values.

Therefore $V_i^{new} = \frac{1}{Y_{ii}} [\frac{P_i - jQ_i}{V_i^{*old}} - \sum_{j=1}^{i=1} Y_{ij} V_j^{new} - \sum_{j=i+1}^{N} Y_{ij} V_j^{old}]$ ……………(a)

For load bus,

The above equation is applicable to find $|V|$ and δ values.

For slack bus,

The voltage is specified and so it will not change in each iteration.

For PV bus or generator bus,

(i) Q value is not specified for PV bus. So $V_i^{new} = |V_i|_{spec}\angle\delta^{cal}$

(ii) Compute reactive power generation using the V_i^{new} as.

$Q_i^{cal} = - \mathrm{Im}\{V_i^{*old} [\sum_{j=1}^{i=1} Y_{ij} V_j^{new} - \sum_{j=i+1}^{N} Y_{ij} V_j^{old}]\}$

$Q_{Gi} = Q_i^{cal} + Q_{Di}$

If $Q_{Gi(min)} \leq Q_{Gi} \leq Q_{Gi(max)}$, set $Q_i = Q_{Gi} - Q_{Di}$ then compute V_i^{new}

If $Q_{Gi} < Q_{Gi(min)}$, set $Q_{Gi} = Q_{Gi(min)}$, then compute V_i^{new} using eqn (a)

If $Q_{Gi} > Q_{Gi(max)}$, set $Q_{Gi} = Q_{Gi(max)}$, then compute V_i^{new} using eqn (a)

Acceleration factor ($\propto$)

$V_i^{new} = V_i^{old} + \propto [V_i^{new} - V_i^{old}]$

Where V_i^{old} = Voltage value obtained in previous iteration

V_i^{new} = New value of Voltage value obtained in current iteration

$\propto$ = Acceleration factor

Computation of transmission loss.

$S_{ij(loss)} = S_{ij} = S_{ji}$

$= P_{ij} + jQ_{ij} + P_{ji} + jQ_{ji}$

Real power loss = $P_{ij} + P_{ji}$
Reactive power loss = $Q_{ij} + Q_{ji}$

11. What is the need for load flow analysis (or) importance of power flow analysis.

Load flow analysis is performed on a symmetrical steady state operating conditions of a power system under normal mode of operation. The solution of load flow gives bus voltages and line/transformer power flows for a given load condition. This information is essential for long term planning and operational planning.

long term planning.

Load flow analysis helps in investigating the effectiveness of alternative plans and choosing the best plan for system expansion to meet the projected operating state.

Operational planning.

It helps in choosing the best unit commitment plan and generation schedules to run the system efficiently for the next day's load condition without violating the bus voltages and line flow operating limits.

Steps for load flow study.

The following work has to be performed for a load flow study.

(i) Representation of the system by single line diagrams.

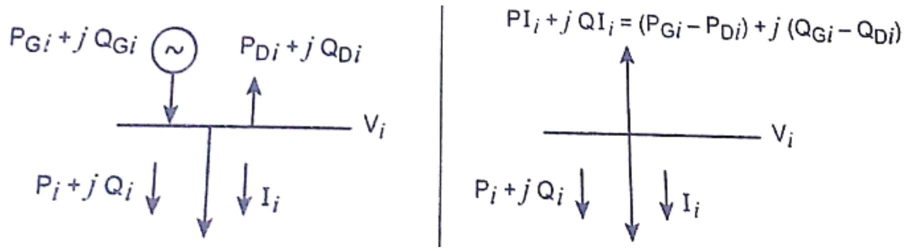
(ii) Determining the impedance diagram using the information in single line diagram.

(iii) Formulation of network equations.

(iv) Solution of network equations.

12. Derive the load flow equation using Newton Raphson method.

The most widely used method for solving simultaneous non linear algebraic equation is the Newton Raphson method.



from the fig the complex power balance at bus i is given by

$PI_i + jQI_i = P_i + jQ_i$ ……………………………………………………..…(1)

Complex power injection at the i^{th} bus $PI_i + jQI_i$

$= (P_{Gi} - P_{Di}) + (jQ_{Gi} - jQ_{Di})$

Since the bus generation and demand are specified, the complex the complex power injection is a specified quantity and is given by,

$PI_{i(spec)} + jQI_{i(spec)} = [P_{Gi(spec)} - P_{Di(spec)}] + j[Q_{Gi(spec)} - Q_{Di(spec)}]$ ………………(a)

The current entering bus i is given by,

$I_i = \sum_{j=1}^{N} Y_{ij}V_j$

In polar form

$I_i = \sum_{j=1}^{N} |Y_{ij}||V_i|\angle(\theta_{ij} + \delta_j)$ ……………………………………………….(b)

$[Y_{ij} = |Y_{ij}|\angle\theta_{ij}\ ;\ V_j = |V_i|\angle\delta_i]$

Complex power at bus i

$P_i - jQ_i = V_i^* \ I_i = V_i^* \sum_{j=1}^{N} Y_{ij}V_j$

Substituting from eqn (b), we get

$P_i - jQ_i = |V_i|\angle{-\delta_i} \sum_{j=1}^{N} |Y_{ij}||V_j|\angle(\theta_{ij} + \delta_j)$

$= \sum_{j=1}^{N} |V_i||Y_{ij}||V_j|\angle(\theta_{ij} + \delta_j - \delta_i)$

Equating the real and imaginary parts

$P_i = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| cos(\theta_{ij} + \delta_j - \delta_i)$………………………(c)

$Q_i = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| sin(\theta_{ij} + \delta_j - \delta_i)$ ……………………………………….(d)

The above eqn constitute a set of nonlinear algebraic equations in terms of the independent variables.

Substitute eqn (a),(c),(d) in (1) we get power balance eqns.

$P_i (\delta, V) - PI_{i(spec)} = 0$

$Q_i (\delta, V) - QI_{i(spec)} = 0$

13. Write the Procedure for load flow solution by Newton Raphson method.

Step 1 : form Y-Bus

Step 2 : Assume flat start voltage solution

$\delta_i^0 = 0$, for i = 1…..N

$|V_i^0| = 1.0$,

$|V_i| = |V_i|_{spec}$

Step 3 : for load buses, calculate P_i^{cal} and Q_i^{cal}

Step 4 : for PV bus, Check for Q limit violation

If $Q_{i(min)} < Q_i^{cal} < Q_{i(max)}$, the bus acts as PV bus

If $Q_i^{cal} > Q_{i(max)}$, then $Q_{i(spec)} = Q_{i(max)}$

If $Q_i^{cal} < Q_{i(min)}$, then $Q_{i(spec)} = Q_{i(min)}$, the PV bus will act as PQ bus.

Step 5 : Compute mismatch vector using.

$\Delta P_i = P_{i(spec)} - P_i^{cal}$

$\Delta Q_i = Q_{i(spec)} - Q_i^{cal}$

Step 6 : Compute $\Delta P_{i(max)} = \max |\Delta P_i|$ i = 1,2……….N except slack

$\Delta Q_{i(max)} = \max |\Delta Q_i|$ i = M+1……….N

Step 7 : compute jacobian matrix using $J = \begin{bmatrix} \frac{\partial P_i}{\partial \delta} & \frac{\partial P_i}{\partial |V|} \\ \frac{\partial Q_i}{\partial \delta} & \frac{\partial Q_i}{\partial |V|} \end{bmatrix}$

Step 8 : Obtain state correction vector $\begin{bmatrix}\Delta V\\ \Delta\delta\end{bmatrix}$ = $[J]^{-1}$ $\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}$

$V^{new} = V^{old} + \Delta V$

$\delta^{new} = \delta^{old} + \Delta\delta$

Step 9 : Update state vector using .

$V^{new} = V^{old} + \Delta V$

$\delta^{new} = \delta^{old} + \Delta\delta$

Step 10 : This procedure is continued until

$|\Delta P_i| < \varepsilon$ and $|\Delta Q_i| < \varepsilon$, otherwise go to step 3.

14. Explain the significance of load flow analysis or power flow analysis.

The information of load flow is essential for analyzing the effective alternative plans for the system expansion to meet increase load demand.

The load flow studies are very much important for planning, economic scheduling, control and operations of existing systems as well as planning its future expansions depends upon knowing the effect of interconnections, new loads , new generating stations, or new transmission lines, etc., before they are installed.

With help of load flow studies we can determine the best size as well as the most favourable locations for the power system capacitors both for the improvement for the power factor and raising the bus voltages of the electrical network. It helps us to determine the capacity of the proposed generating stations, substations or new lines.

The information obtained from a load flow study are magnitude and phase angles of bus voltages, real and reactive power flowing in each line and line losses. The load flow solution also gives the initial conditions of the system when the transient behavior of the system is to be studied.

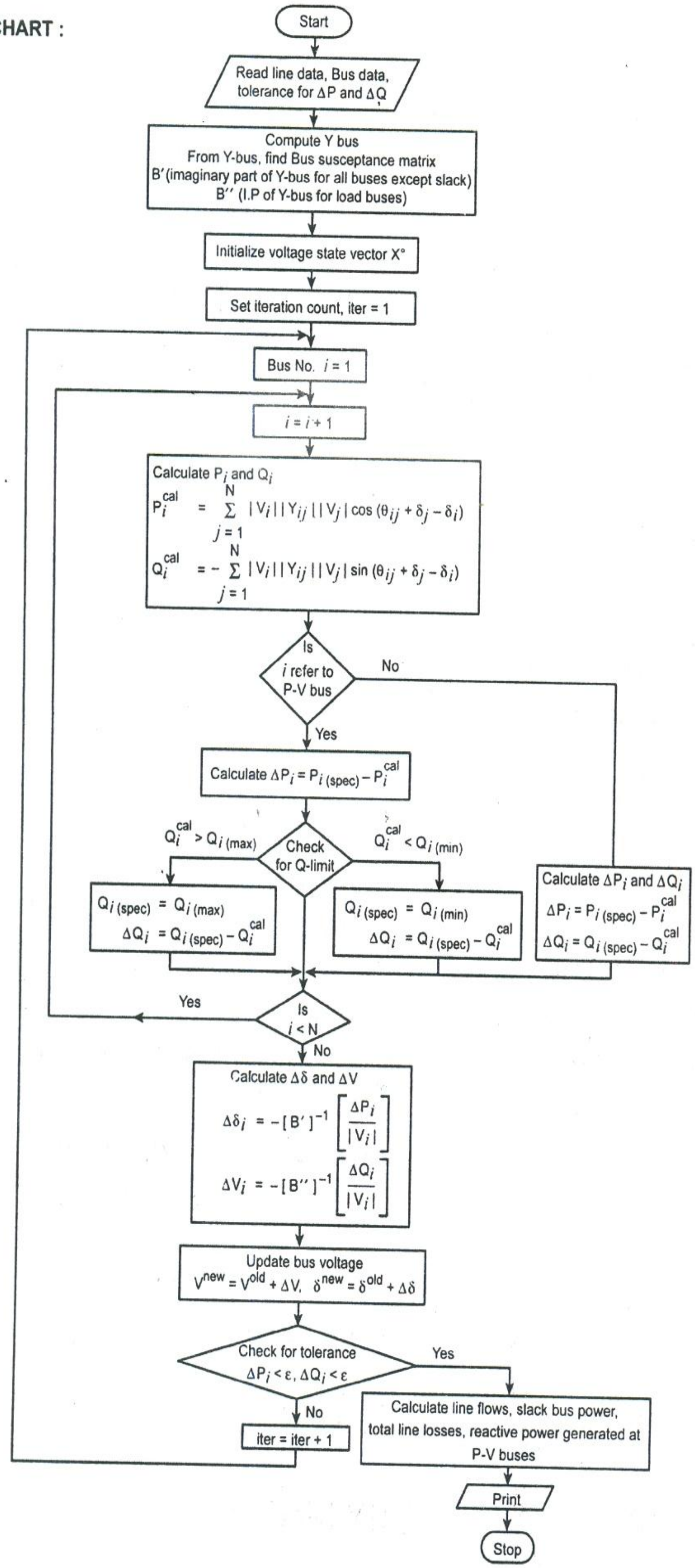
The mathematical formulation of the load flow problem results in a system of nonlinear equations. These equations can be written in terms of either the bus admittance matrix or bus impedance matrix. Using bus admittance matrix is amenable to digital computer analysis, because it could be formed and modified for network changes in subsequent cases, and requires less computation time and memory.

The load flow analysis can be carried out for small and medium size power systems. It suits for radial distribution systems with high R/X ratio. The load flow analysis helps to identify the overloaded or under loaded lines and transformers as well as the overvoltage or under voltage buses in the power system network.

It is used to study the optimum location of capacity and their size to improve the unacceptable voltage profile.

15. Draw the flowchart for Fast Decoupled method.

FLOW CHART :


Start
Read line data, Bus data, tolerance for ΔP and ΔQ
Compute Y bus
From Y-bus, find Bus susceptance matrix
B′ (imaginary part of Y-bus for all buses except slack)
B′′ (I.P of Y-bus for load buses)
Initialize voltage state vector X°
Set iteration count, iter = 1
Bus No. i = 1
i = i + 1
Calculate P_i and Q_i
$P_i^{cal} = \sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \cos(\theta_{ij} + \delta_j - \delta_i)$
$Q_i^{cal} = -\sum_{j=1}^{N} |V_i||Y_{ij}||V_j| \sin(\theta_{ij} + \delta_j - \delta_i)$
Is i refer to P-V bus
No
Yes
Calculate $\Delta P_i = P_{i\,(spec)} - P_i^{cal}$
$Q_i^{cal} > Q_{i\,(max)}$
Check for Q-limit
$Q_i^{cal} < Q_{i\,(min)}$
$Q_{i\,(spec)} = Q_{i\,(max)}$
$\Delta Q_i = Q_{i\,(spec)} - Q_i^{cal}$
$Q_{i\,(spec)} = Q_{i\,(min)}$
$\Delta Q_i = Q_{i\,(spec)} - Q_i^{cal}$
Calculate ΔP_i and ΔQ_i
$\Delta P_i = P_{i\,(spec)} - P_i^{cal}$
$\Delta Q_i = Q_{i\,(spec)} - Q_i^{cal}$
Yes
Is i < N
No
Calculate Δδ and ΔV
$\Delta\delta_i = -[B']^{-1} \left[\frac{\Delta P_i}{|V_i|}\right]$
$\Delta V_i = -[B'']^{-1} \left[\frac{\Delta Q_i}{|V_i|}\right]$
Update bus voltage
$V^{new} = V^{old} + \Delta V, \quad \delta^{new} = \delta^{old} + \Delta\delta$
Check for tolerance
$\Delta P_i < \varepsilon, \Delta Q_i < \varepsilon$
Yes
No
iter = iter + 1
Calculate line flows, slack bus power, total line losses, reactive power generated at P-V buses
Print
Stop

16. Explain the classification of buses.

The meeting point of various components in a power system is called a bus. At some of the buses power is being injected into the network, whereas at other buses it is being tapped by the system loads.

The buses of a power system can be classified into three types based on the quantities being specified for the buses, which are as follows:

a. Load bus or PQ bus (P and Q are specified)
b. Generator bus or voltage controlled bus or PV bus (P and V are specified)
c. Slack bus or swing bus or reference bus (|V| and δ are specified)

Each bus in a power system is associated with four quantities and they are

Real power (P), Reactive power (Q), magnitude of voltage (V), phase angle of voltage(δ).

Bus type	Quantities specified	Quantities to be obtained
Load bus	P,Q	$\lvert V \rvert$, δ
Generator bus	P, $\lvert V \rvert$	Q, δ
Slack bus	$\lvert V \rvert$, δ	P,Q

Voltage controlled bus. (Generator bus)

A bus is called voltage controlled bus if the magnitude of voltage $\lvert V \rvert$ and real power (P) are specified for it. In a voltage controlled bus the magnitude of the voltage is not allowed to change. The other names for voltage controlled bus are generator bus and PV bus. In this bus the phase angle of the voltages and the reactive power are to be determined. The limits on the reactive power are also specified.

PQ-bus (load bus)

A bus is called PQ-bus when real and reactive components of power are specified for the bus. In this bus the magnitude and phase angle of voltage are unknown. In PQ bus the voltage is allowed to vary within permissible limits.

Swing bus (Slack bus)

A bus is called swing bus when the magnitude and phase for bus voltage are specified for it. The swing bus is the reference bus for load flow solution and it is required for accounting line losses. Usually one of the generator bus selected as the swing bus.

Need for Slack bus (or) Swing bus.

The slack bus is needed to account for transmission line losses. In a power system the total power generated will be equal to sum of power consumed by loads and losses. In a power system only the generated power and load power are specified for buses. The slack bus is assumed to generate the power required for losses. Since the losses are unknown the real and reactive power are not specified for slack bus. They are estimated through the solution of load flow equations.

When the generator bus is treated as load bus the reactive power of the bus is equated to the limit it has violated, and the previous iteration value of bus voltage is used for calculating current iteration value.

If $Q_i > Q_{i(max)}$, then $Q_i = Q_{i(max)}$

If $Q_i < Q_{i(min)}$, then $Q_i = Q_{i(min)}$

Reactive power of the bus has violates the specified limits, then the P-V bus will act as load bus.

If the reactive power constraints of a generator bus violates the specified limits then the generator is treated as load bus.

If $Q_i > Q_{i(max)}$, substitute $Q_i = Q_{i(max)}$

If $Q_i^{cal} < Q_{i(min)}$, substitute $Q_i = Q_{i(min)}$

17. Write the step-by-step algorithm to solve the load flow problem using Fast decoupled method.

Step 1 : form Y-Bus and then compute bus susceptance matrices B' and B''

Step 2 : Assume flat start for starting voltage solution

$\delta_i^0 = 0$, for i = 1…..N (for all bus except slack bus)

$|V_i^0|=1.0$, for i = M+1……….N (for all PQ buses)

$|V_i| = |V_i|_{spec}$ for all PV bus and slack bus.

Step 3 : for load buses, calculate P_i^{cal} and Q_i^{cal}

$$P_i^{cal} = \sum_{j=1}^{N}|V_i||Y_{ij}||V_j|cos(\theta_{ij} + \delta_j - \delta_i)$$

$$Q_i^{cal} = \sum_{j=1}^{N}|V_i||Y_{ij}||V_j|sin(\theta_{ij} + \delta_j - \delta_i)$$

Step 4 : for PV bus, Check for Q limit violation

If $Q_{i(min)} < Q_i < Q_{i(max)}$, calculate P_i^{cal}

If $Q_i^{cal} < Q_{i(min)}$, then $Q_{i(spec)} = Q_{i(min)}$

If $Q_i^{cal} > Q_{i(max)}$, then $Q_{i(spec)} = Q_{i(max)}$, the PV bus will act as PQ bus.

Step 5 : Compute mismatch vector using.

$$\Delta P_i = P_{i(spec)} - P_i^{cal}$$

$$\Delta Q_i = Q_{i(spec)} - Q_i^{cal}$$

Step 6 : Compute $\Delta P_{i(max)} = \max|\Delta P_i|$ i = 1,2……….N ; ≠except slack

$\Delta Q_{i(max)} = \max|\Delta Q_i|$ i = M+1……….N

Step 7 : compute jacobian matrix using $J = \begin{bmatrix} \frac{\partial P_i}{\partial \delta} & \frac{\partial P_i}{\partial |V|} \\ \frac{\partial Q_i}{\partial \delta} & \frac{\partial Q_i}{\partial |V|} \end{bmatrix}$

Step 8 : Calculate $\Delta\delta$ *and* ΔV using

$$[\Delta\delta_i] = -[B']^{-1}.\left[\frac{\Delta P_i}{|V_i|}\right]$$

$$[\Delta V_i] = -[B'']^{-1}.\left[\frac{\Delta Q_i}{|V_i|}\right]$$

Step 9 : Update state vector using .

$$V^{new} = V^{old} + \Delta V$$

$$\delta^{new} = \delta^{old} + \Delta\delta$$

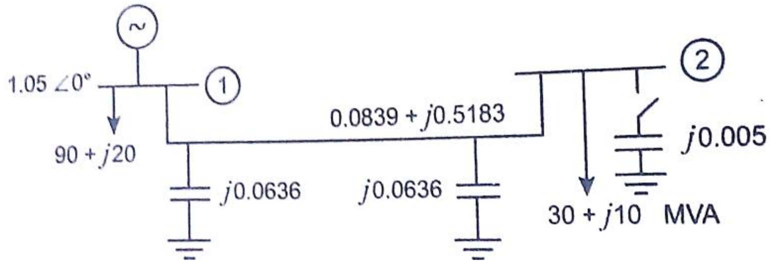
Step 10 : This procedure is continued until

$|\Delta P_i| < \varepsilon$ and $|\Delta Q_i| < \varepsilon$,

Otherwise go to step 3.

18. Perform power flow of one iteration for the system as shown in fig. using Gauss - seidel method. Determine slack bus power, line flows and line losses. Take base MVA as 100

(α=1).



Solution:

Step1: Formulate Ybus.

When the switch is open, there is no connection of capacitor at bus 2.

Take the bus as load bus.

$Y_{bus}=\begin{bmatrix} 0.3044 - j1.816 & -0.3044 + j1.88 \\ -0.3044 + j1.88 & 0.3044 - j1.816 \end{bmatrix}$

Step2: Initialize bus voltages

$V_1^{old} = 1.05\angle 0°$

$V_2^{old} = 1.0\angle 0°$

Step3: Calculate V_2^{new}.

P_2 = -30 MW = $\frac{-30}{100}$p.u. = -0.3 p.u.

Q_2 = -10 MVAR = $\frac{-10}{100}$p.u. = -0.1 p.u.

$V_2^{new} = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{V_2^{old*}} - Y_{21} V_1^{new}\right]$

$=\frac{1}{0.3044 - j1.816}[\frac{-0.3+j0.1}{1.0\angle -0°} - (-0.344 + j1.88)1.05]$

$=1.0054 - j0.1577$

$=1.018\angle -8.915°$

$V_2^{new} = 1.018\angle -8.915°$

Step 4: Calculate V_2^{new} using acceleration factor

$V_{2\,acc}^{new} = V_2^{old} + \alpha[V_2^{new} - V_2^{old}]$

$=1.0+1.1[1.0054-j0.1577-1]$

$=1.0059-j0.173$

$V_{2\,acc}^{new} = 1.0207\angle -9.78°$

Step 5: Slack bus power

$S_1 = P_1 - jQ_1$

$=1.05\angle -0°[(0.3044-j1.816)1.05+(-0.3044+j1.88)(1.0207\angle -9.78°)]$

$=0.3566+j0.0388$ p.u

$=35.56+j3.88$ MVA

P_1=35.56 MW, Q_1=-3.88 MVAR

Real power generation $P_{G1}=P_1+P_{L1}$

=35.56+90=125.56 MW

P_{G1}=125.56 MW

Reactive power generation $Q_{G1}=Q_1+Q_{L1}$

=-3.88+20=16.12 MVAR

Q_{G1}=16.12 MVAR

Step - 6: Line flows

Bus		
From	To	$S_{ij}=P_{ij}+jQ_{ij}=V_i[V_i^*-V_j^*]Y_{ij}^*{}_{series}+\|V_i\|^2Y^*_{Pi}$
1	2	$S_{12}=V_1[V_1^*-V_2^*]Y_{12}^*{}_{series}+\|V_1\|^*Y^*_{10}$ =1.05[1.05∠-0°(1.0059+j0.173)]*(0.3044+j1.88)+1.05^2*(-j0.0636) = 0.3556 - j0.0383 p.u P_{12}= 0.3556 p.u=35.56 MW Q_{12}= - 0.0383 p.u= -3.83 MVAR
2	1	$S_{21}=V_2[V^*_2 - V_1^*]Y_{12}^*{}_{series}+\|V_2\|^2Y_{20}^*$ = (1.0059 – j0.173)[1.0059+j0.173-1.05]x (0.3044+j1.88)+1.0207^{2}x(-j0.0636) =-0.3459-j0.038 p.u. P_{21}=-0.3459 p.u. = -34.59 MW Q_{21}= - 0.038 p.u. = -3.8 MVAR

Step – 7: Transmission line loss ($S_{ij\ Loss} = S_{ij} + S_{ji}$)

P_{12}Loss = P_{12} + P_{21} =35.56 -34.59 =0.97 MW

Q_{12}Loss = Q_{12} + Q_{21} = - 3.83 + (-3.8) = -7.63 MVAR

P_{12}Loss =0.97 MW

Q_{12}Loss = -7.63 MVAR

19. Perform two iteration of Newton Raphson load flow method and determine the power flow solution for the given system. Take base MVA as base 100, Bus 2 is a voltage controlled bus having the rating P_G = 60MW, V_2=1.02p.u. -10 < Q_2 < 100 MVAR. Carry out two iterations and determine bus voltage magnitudes.

Solution:

$$Y_{bus} = \begin{bmatrix} 1.842\angle-80.49° & 1.904\angle 99.2° \\ 1.904\angle 99.2° & 1.842\angle-80.49° \end{bmatrix}$$

X° = [δ_2] = 0 rad

Compute θ_{12} in radians:

$$Y_{bus} = \begin{bmatrix} 1.842\angle-1.405 & 1.904\angle 1.7314 \\ 1.904\angle 1.7314 & 1.842\angle-1.405 \end{bmatrix}$$

Check for Q- Limit:

$Q_2^{cal} = - |V_2|\{|V_1||Y_{21}|\sin(\theta_{12} + \delta_1 - \delta_2) + |V_2||Y_{22}|\sin(\theta_{22})\}$

= -1.02 {1.05 X 1.904 sin(1.7314) + 1.02 X 1.842 sin(-1.405)}

Q_2^{cal} = -0.1239 p.u.

$Q_{2(min)} < Q_2^{cal} < Q_{2(max)}$

So the bus acts as generator bus.

Compute ΔP_2 :

$P_2^{cal} = |V_2|\{|V_1||Y_{21}|\cos(\theta_{12} + \delta_1 - \delta_2) + |V_2||Y_{22}|\cos(\theta_{22} + \delta_2 - \delta_2)\}$

= 1.02[1.05 X 1.904 cos(1.7314) + 1.02 X 1.842 cos(-1.405)]

$= 1.02(-0.3197 + 0.3100)$

$P_2^{cal} = -0.009$ p.u.

$\Delta P_2 = P_{2(spec)} - P_2^{cal}$

$= 0.6 - (-0.009) = 0.609$ p.u.

Form Jacobian matrix

$J = \left[\frac{\partial P_2}{\partial \delta_2}\right] = |V_2|\{|V_1||Y_{21}| + \sin(\theta_{12} + \delta_1 - \delta_2)\}$

$= 1.02 \text{ X } 1.05 \text{ X } 1.904 \sin(0\text{-}0\text{+}1.7314) = 2.013$

Compute $\Delta\delta_2$:

$\Delta\delta_2 = [J]^{-1} [\Delta P_2]$

$= \frac{1}{2.013} \text{ X } 0.609 = 0.303$ rad

$\delta_2^{new} = \delta_2^{old} + \Delta\delta_2 = 0+0.303 = 0.303$ rad

$|V_2^{new}| = 1.02$

Iteration 2:

$P_2^{cal} = 1.02[1.05 \text{ X } 1.904 \cos(1.7314+0-0.303) + 1.02 \text{ X } 1.842 \cos(-1.405)]$

$= 0.606$

$\Delta P_2 = P_{2(spec)} - P_2^{cal}$

$= 0.6 - 0.606 = -0.006$

$Q_2^{cal} = -1.02 \{1.05 \text{ X } 1.904 \sin(1.7314+0-0.303) + 1.02 \text{ X } 1.842 \sin(-1.405)\}$

$= -0.128$

$Q_{2(min)} < Q_2^{cal} < Q_{2(max)}$

$\therefore$ This bus acts as generator bus.

Jacobian matrix

$J = \left[\frac{\partial P_2}{\partial \delta_2}\right] = |V_2|\{|V_1||Y_{21}| + \sin(\theta_{12} + \delta_1 - \delta_2)\}$

$= 1.02 \text{ X } [1.05 \text{ X } 1.904 \sin(1.7314+0-0.303) = 2.0185$

Compute $\Delta\delta_2$:

$\Delta\delta_2 = [J]^{-1} [\Delta P_2]$

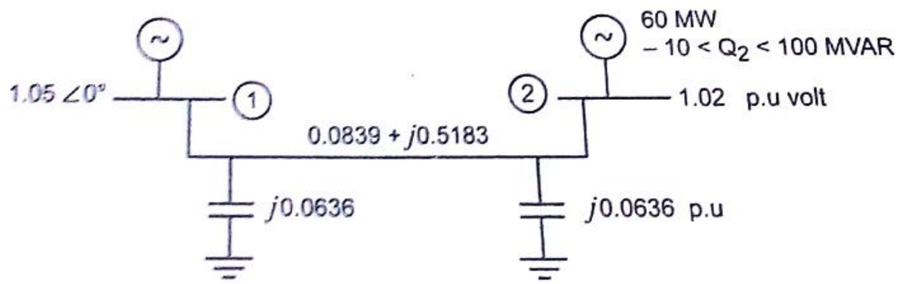
$= \frac{1}{2.0185} \text{ X } -0.006 = -0.003$

$\delta_2^{new} = \delta_2^{old} + \Delta\delta_2 = 0.303+(-0.003)$

$\delta_2 = 0.3$ rad $= 17.19°$

$|V_2| = 1.02$ p.u.

20. Perform two iterations of decoupled load flow method and determine the power flow solution for the system as shown in Fig. Take base MVA as 100.



Solution:

Step -1 : Form Y_{bus} matrix

$$Y_{bus} = \begin{bmatrix} 0.3043 - j1.817 & -0.3044 + j1.88 \\ -0.3044 + j1.88 & 0.3043 - j1.817 \end{bmatrix}$$

$$Y_{bus} = \begin{bmatrix} 1.842\angle -1.405 & 1.904\angle 1.7314 \\ 1.904\angle 1.7314 & 1.842\angle -1.405 \end{bmatrix}$$ {Note: Use in rad mode}

Step – 2:Initialize bus voltages

$V_1^{old} = 1.05\angle 0$ p.u. (slack bus)

$V_2^{old} = 1.02\angle 0$ p.u. (P-V bus)

Step – 3: Check for Q-limit violation.

$Q_2^{cal} = -\{|V_2||V_1||Y_{21}|\sin(\theta_{21} + \delta_1 - \delta_2) + |V_2|^2|Y_{22}|\sin(\theta_{22} + \delta_2 - \delta_2)\}$

$= -1.02[1.05 \text{ X } 1.904 \sin(1.7314) + 1.02^2 \text{ X } 1.842 \sin(-1.405)]$

$Q_2^{cal} = -0.1228$ p.u.

$Q_{2(min)} = 10 \text{ MVAR} = \frac{10}{100}$p.u. =0.1 p.u.

$Q_2 < Q_{2(min)};\ \therefore Q_2 = Q_{2(min)} = 0.1$ p.u.

and the bus 2 will acts as load bus, $V_2 = 1\angle 0$ p.u.

Step – 4: Compute ΔP and ΔQ.

$P_2^{cal} = |V_2|\{|V_1||Y_{21}|\cos(\theta_{21} + \delta_1 - \delta_2) + |V_2|^2|Y_{22}|\cos(\theta_{22} + \delta_2 - \delta_2)\}$

$= 1.0[1.05 \text{ X } 1.904 \cos(1.7314) + 1.0^2 \text{ X } 1.842 \cos(-1.405)]$

$= -0.0157$ p.u.

$P_{2(spec)} = P_{G2} - P_{L2} = \frac{60}{100} = 0.6$ p.u.

$\Delta P_2 = P_{2(spec)} - P_2^{cal} = 0.6 - (-0.0157) = -0.6157$

$\Delta Q_2 = Q_{2(spec)} - Q_2^{cal} = 0.1 - (-0.1) = 0.2$

Step – 5: Bus susceptance matrix

$[B'] = 2\ [1.817]$

$[B']^{-1} = \frac{1}{-1.817} = -0.5504$

$[B''] = 2\ [1.817],\ [B'']^{-1} = -0.5504$

NOTE:

B′ matrix is the imaginary part of Y_{bus} for the buses except slack bus.

B″ matrix is the imaginary part of Y_{bus} for the load buses.

Step – 6: Calculate Δδ and ΔV.

$$[\Delta\delta_2] = -[B']^{-1}\left[\frac{\Delta P_2}{|V_2|}\right] = -(-0.5504)\left[\frac{0.6157}{1.0}\right] = 0.34$$

$$[\Delta V_2] = -[B'']^{-1}\left[\frac{\Delta Q_2}{|V_2|}\right] = -(-0.5504)\left[\frac{0.2}{1.0}\right] = 0.1226 \text{ p.u.}$$

$\delta_2^1 = \delta_2^0 + \Delta\delta_2 = 0+0.34 = 0.34$ rad

$V_2^1 = V_2^0 + \Delta V_2 = 1.0 + 0.1226 = 1.1226$ p.u.

$V_2^1 = 1.1226\angle 0.34$

Iteration – 2: Check for Q-limit

$Q_2^{cal} = -[1.1226 \text{ X } 1.05 \text{ X } 1.904 \sin(1.7314 - 0.34) + 1.1226^2 \text{ X } 1.842 \sin(-1.405)]$

$= -(-0.0812) = 0.0812$

$0.0812 < 0.1$, $Q_2^{cal} < Q_{2(min)}$

$\therefore Q_2 = Q_{2(min)} = 0.1$ p.u. MVAR

Bus 2 again act as load bus. $V_2^{old} = 1.1226\angle 0.34$

$P_2^{cal} = 1.1226 \text{ X } 1.05 \text{ X } 1.904 \cos(1.7314 - 0.34) + 1.1226^2 \text{ X } 1.842 \cos(-1.405)$

$= 0.7836$ p.u.

$P_{2(spec)} = P_{G2} - P_{L2} = \frac{60}{100} = 0.6$ p.u.

$\Delta P_2 = P_{2(spec)} - P_2^{cal} = 0.6 - (0.7836) = -0.1836$

$\Delta Q_2 = Q_{2(spec)} - Q_2^{cal} = 0.1 - 0.0812 = 0.0188$

Step – 5: Bus susceptance matrix

$[B''] = [B'] = [1.817]$

$[B']^{-1} = [B'']^{-1} = -0.5504$

Step – 6: Calculate $\Delta\delta$ and ΔV.

$[\Delta\delta_2] = -[B']^{-1}\left[\frac{\Delta P_2}{|V_2|}\right] = -(-0.5504)\left[\frac{-0.1836}{1.1226}\right] = -0.09$

$[\Delta V_2] = -[B'']^{-1}\left[\frac{\Delta Q_2}{|V_2|}\right] = -(-0.5504)\left[\frac{0.0188}{1.1226}\right] = 0.0092$

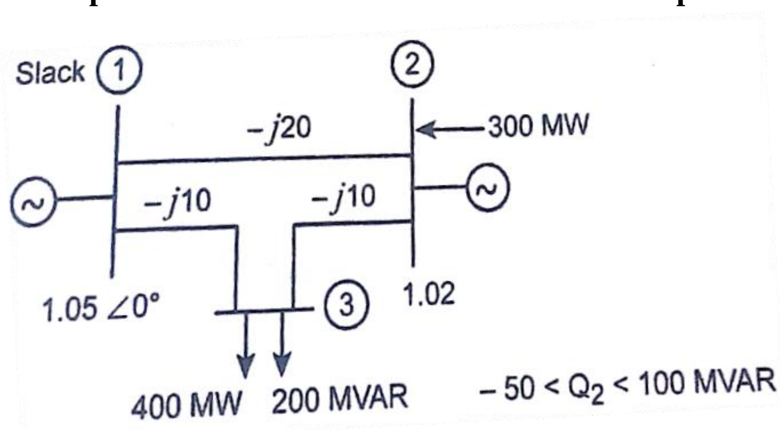
$\delta_2^2 = \delta_2^1 + \Delta\delta_2 = 0.34+(-0.09) = 0.25 \text{ rad} = 14°$

$V_2^2 = V_2^1 + \Delta V_2 = 1.1226 + 0.0092 = 1.1318$

$V_2^1 = 1.1318\angle 14°$

PART-C

21. Obtain the power flow solution(one iteration) for the system shown in Fig. The line admittances are in per unit on a 100MVA base. Use fast decoupled load flow method.



Solution:

Step -1 : Form Y_{bus} matrix

$$Y_{bus} = \begin{bmatrix} Y_{12} + Y_{13} & -Y_{12} & -Y_{13} \\ -Y_{12} & Y_{12} + Y_{23} & -Y_{23} \\ -Y_{13} & -Y_{23} & Y_{13} + Y_{23} \end{bmatrix}$$

$$Y_{bus} = \begin{bmatrix} -j20+(-j10) & j20 & j10 \\ j20 & -j20+j10 & j10 \\ j10 & j10 & -j10+(-j10) \end{bmatrix}$$

$$Y_{bus} = \begin{bmatrix} 30\angle-1.57 & 20\angle1.57 & 10\angle1.57 \\ 20\angle1.57 & 30\angle-1.57 & 10\angle1.57 \\ 10\angle1.57 & 10\angle1.57 & 20\angle-1.57 \end{bmatrix}$$ {Note: Use in rad mode}

Step – 2: Initialize bus voltages

$V_1^{old} = 1.05\angle0$ p.u. (slack bus)

`$V_2^{old} = 1.02\angle0$ p.u. (P-V bus)

$V_3^{old} = 1.0\angle0$ p.u. (P-Q bus)

Step – 3: Check for Q-limit violation for Q bus.

$Q_2^{cal} = -\{|V_2||V_1||Y_{21}|\sin(\theta_{21}+\delta_1-\delta_2) + |V_2|^2|Y_{22}|\sin(\theta_{22}) + |V_2||V_3||Y_{23}|\sin(\theta_{23}+\delta_3-\delta_2)\}$

$= -1.02[1.05 \text{ X } 20 \sin(1.57\text{-}0\text{+}0) + 1.02^2 \text{ X } 30 \sin(-1.57) + 1.02 \text{ X } 1.0 \text{ X } 10 \text{ X } \sin(1.57\text{-}0\text{+}0)]$

$Q_2^{cal} = -0.408$ p.u.

$\frac{-50}{100} < -0.408 < \frac{100}{100}$

$Q_{2(min)} < Q_2 < Q_{2(max)}$, $\therefore$ Bus 2 acts as P-V bus.

Step – 4: Compute ΔP and ΔQ.

$P_2^{cal} = |V_2|\{|V_1||Y_{21}|\cos(\theta_{21}+\delta_1-\delta_2) + |V_2|^2|Y_{22}|\cos(\theta_{22}) + |V_2||V_3||Y_{23}|\cos(\theta_{23}+\delta_3-\delta_2)\}$

$= 1.02 \text{ X } 1.05 \text{ X } 20 \cos(1.57\text{-}0\text{+}0) + 1.02^2 \text{ X } 30 \cos(-1.57) + 1.02 \text{ X } 1.0 \text{ X } 10 \text{ X } \cos(1.57 - 0 + 0)]$

$P_2^{cal} = 0.05$

$P_3^{cal} = \{|V_3||V_1||Y_{31}|\cos(\theta_{31}+\delta_1-\delta_3) + |V_3||V_2||Y_{32}|\cos(\theta_{32}-\delta_3+\delta_2) + |V_3||V_3||Y_{33}|\cos(\theta_{33})\}$

$= 1.0 \text{ X } 1.05 \text{ X } 10 \cos(1.57\text{-}0\text{+}0) + 1.0 \text{ X } 1.02 \text{ X } 10 \cos(1.57 - 0 + 0) + 1.0^2 \text{ X } 20 \text{ X } \cos(-1.57)]$

$P_3^{cal} = 0.0324$

$Q_3^{cal} = -\{|V_3||V_1||Y_{31}|\sin(\theta_{31}+\delta_1-\delta_3) + |V_3||V_2||Y_{32}|\sin(\theta_{32}-\delta_3+\delta_2) + |V_3||V_3||Y_{33}|\sin(\theta_{33})\}$

$= -1.0 \text{ X } 1.05 \text{ X } 10 \sin(1.57\text{-}0\text{+}0) + 1.0 \text{ X} 1.02 \text{X} 10 \sin(1.57 - 0 + 0) + 1.0^2 \text{ X} 20 \text{X} \cos(1.57 - 0 + 0)]$

$Q_3^{cal} = -0.7$

$\Delta P_2 = P_{2(spec)} - P_2^{cal} = 3 - 0.05 = 2.95$

$\Delta P_3 = P_{3(spec)} - P_3^{cal} = -4 - 0.0324 = -4.0324$

$\Delta Q_3 = Q_{3(spec)} - Q_3^{cal} = -2 - (-0.7) = -1.3$

Step – 5: Bus susceptance matrix

$[B'] = \begin{bmatrix} -30 & 10 \\ 10 & -20 \end{bmatrix}$
3

$[B']^{-1} = \frac{1}{500}\begin{bmatrix} -20 & -10 \\ -10 & -30 \end{bmatrix}$
3

$[B']^{-1} = \begin{bmatrix} -0.04 & -0.02 \\ -0.02 & -0.06 \end{bmatrix}$

$[B''] = 3\,[-20]$

$[B'']^{-1} = \frac{1}{-20} = -0.05$

$[B'']^{-1} = -0.05$

Note

B′ matrix is the imaginary part of Y_{bus} matrix for the buses except slack bus.

B″ matrix is the imaginary part of Y_{bus} matrix for the P - V buses only.

Step – 6: Calculate Δδ and ΔV.

$$\begin{bmatrix}\Delta\delta_2\\ \Delta\delta_3\end{bmatrix} = -[B']^{-1}\begin{bmatrix}\frac{\Delta P_2}{|V_2|}\\ \frac{\Delta P_3}{|V_3|}\end{bmatrix} = -\begin{bmatrix}-0.04 & -0.02\\ -0.02 & -0.06\end{bmatrix}\begin{bmatrix}\frac{2.95}{1.02}\\ \frac{-4.0324}{1.0}\end{bmatrix} = \begin{bmatrix}-0.04 & -0.02\\ -0.02 & -0.06\end{bmatrix}\begin{bmatrix}2.892\\ -4.0324\end{bmatrix}$$

$$\begin{bmatrix}\Delta\delta_2\\ \Delta\delta_3\end{bmatrix}=\begin{bmatrix}0.035\\ -0.184\end{bmatrix}$$

$\delta_2^{1} = \delta_2^{0} + \Delta\delta_2 = 0+0.035 = 0.035$ rad

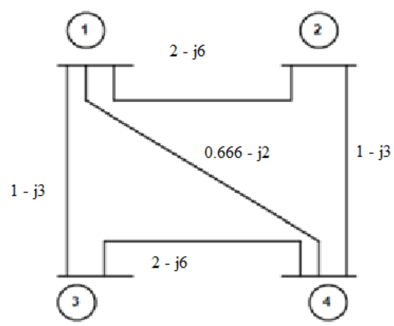
$\delta_3^{1} = \delta_3^{0} + \Delta\delta_3 = 0+(-0.184) = -0.184$ rad

$[\Delta V_3] = -[B'']^{-1}\left[\frac{\Delta Q_3}{|V_3|}\right] = -(-0.05)\left[\frac{-1.3}{1.0}\right] = -0.065$ p.u.

$V_3^{1} = V_3^{0} + \Delta V_3 = 1.0 + (-0.065) = 0.935$ p.u.

$V_3^{1} = 0.935$ p.u.

22. For the system shown in fig., generators are connected to all the four buses, while loads are at buses 2 and 3. The specifications of the buses are given in table.1 and the values of real and reactive powers are listed in table. Bus 2 be a PV bus with V_2 =1.04 p.u and bus 3 and 4 are PQ bus. Assuming a flat voltage start, find bus voltages and bus angles the end of first Gauss-Seidal iteration. And consider the reactive power limit as 0.2 ≤Q2≤1.



Bus code	P	Q	V	Remarks
1	-	-	$1.04\angle 0^{o}$	Slack bus
2	0.5	-	1.04 p.u	PV bus
3	-1.0	0.5	-	PQ bus
4	0.3	-0.1	-	PQ bus

Solution

Step – 1: Formulate Y-bus matrix. The given values of admittance are.

$$Y_{bus} = \begin{bmatrix} 3-j9 & -2+j6 & -1+j3 & 0 \\ -2+j6 & 3.666-j11 & -0.666+j2 & -1+j3 \\ -1+j3 & -0.666+j2 & 3.666-j11 & -2+j6 \\ 0 & -1+j3 & -2+j6 & 3-j9 \end{bmatrix}$$

Step – 2: Initialize bus voltages.

$V_1^{old} = 1.04\angle 0°$ p.u. (Slack bus)

$V_2^{old} = 1.04$ p.u. (PV bus)

$V_3^{old} = 1.0$ p.u. $\angle 0°$ p.u. (PQ)

$V_4^{old} = 1.0$ p.u. $\angle 0°$ p.u. (PQ)

Step – 3: Calculate Q2 for the PV bus.

$Q_2^{cal} = -I_m\{V_2^{old} \times [Y_{21} V_1^{new} + Y_{22} V_2^{old} + Y_{23} V_3^{old} + Y_{24} V_4^{old}]\}$

$= -I_m\{1.04 \times [(-2 + j6)1.04 + (3.666 - j11) \times (-0.0666 + j2) \times 1.0 + (-1 + j3) \times 1.0]\}$

$= -I_m\{0.069 - j0.208\} = 0.208$ p.u

$Q_2^{cal} = 0.208$ p.u

$0.2 < Q_2^{cal} < 1$, within limits.

Bus 2 acts as PV bus.

$P_2 = 0.5$ p.u, $Q_2 = 0.208$ p.u

Calculate V_2

$$V_2^{new} = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{V_2^{old*}} - Y_{21}V_1^{new} - Y_{23}V_3^{old}\right]$$

$$= \frac{1}{3.666 - j11}\left[\frac{0.5 - j0.208}{1.04} - (-2 + j6)\times 1.04 - (-0.666 + j2)\,1.0 - (-1 + j3)\times 1.0\right]$$

$= 1.051 + j0.0339 = 1.0518\angle 1.846° = 1.0518\angle 0.032$ rad.

$\delta_2 = 0.032$ rad

$V_2^{new} = 1.04\angle 0.032$ rad $= 1.0395 + j0.0333$

$$V_3^{new} = \frac{1}{Y_{33}}\left[\frac{P_3 - jQ_3}{V_3^{old*}} - Y_{31}V_1^{new} - Y_{33}V_2^{new} - Y_{34}V_4^{old}\right]$$

$$= \frac{1}{3.666 - j11}\left[\frac{-1.0 - j0.5}{1.0} - (-1 + j3)\times 1.04 - (-0.666 + j2)\times(1.0395 - j0.0333) - (-2 + j6)\times 1.0\right]$$

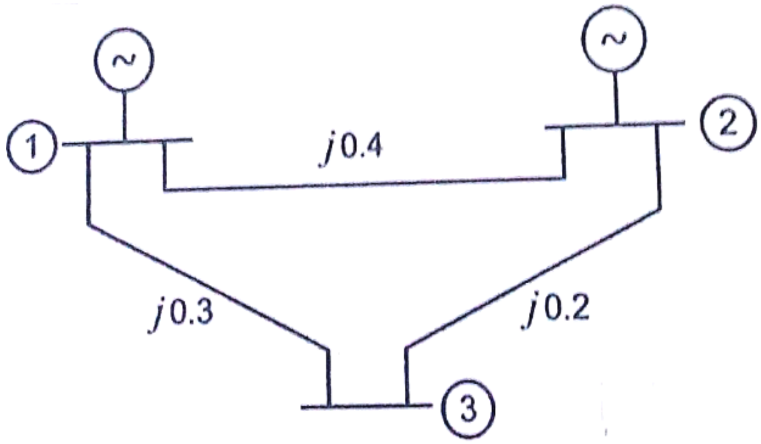
$V_3^{new} = 1.0317 - j0.0894$ p.u

$$V_4^{new} = \frac{1}{Y_{44}}\left[\frac{P_4 - jQ_4}{V_4^{old*}} - Y_{41}V_1^{new} - Y_{42}V_2^{new} - Y_{43}V_3^{new}\right]$$

$$= \frac{1}{3 - j9}\left[\frac{0.3 + j015}{1.0} - 0\times 1.04 - (-1 + j3)\times 1.0395 + j0.0333) - (-2 + j6)\times(1.0317 - j0.0894)\right]$$

V_4^{new} **= 1.0343 – j0.015 p.u**

23. for the system shown in fig., determine the voltages at the end of the first iteration by Gauss-Seidal method and also find the slack bus power, line flows, transmission loss. Assume base MVA as 100. Resolve the previous problem, the reactive power constraint on generator bus – 2 be changed to $10 \leq Q_2 \leq 100$. Determine slack bus power. [Q_2 in MVAR].



Solution:

Step 1: $Y_{bus} = \begin{bmatrix} -j5.8333 & j2.5 & j3.333 \\ j2.5 & -j7.5 & j5 \\ j3.333 & j5 & -j8.333 \end{bmatrix}$

Step 2: Initialize bus voltage

$$V_1^{old} = 1.05\angle 0^\circ \ p.u$$

$$V_2^{old} = 1.02\angle 0^\circ \ p.u$$

$$V_3^{old} = 1.0\angle 0^\circ \ p.u$$

Step 3: Calculate Q Value for generator bus

$$Q_2^{cal} = -\text{Im}\left[1.02\angle 0^\circ \left[j2.5*1.05\angle 0^\circ + \left(-j.5*1.02\angle 0^\circ\right) + j5*1\angle 0^\circ \right]\right]$$

$$Q_2^{cal} = 0.025 \text{ p.u}$$

$Q_2^{cal} < Q_{2(\min)}$ [Q_2 exceeds the limit $\therefore$ Bus 2 will act as load bus, i.e. $V_2^{old} = 1.0\angle 0^\circ$]

Substituting $Q_2 = Q_{2(\min)} = 10 MVAR$

$$= \frac{10}{100} = 0.1 p.u$$

$$V_2^{old} = 1.0\angle 0^\circ$$

Step 4: Calculate V_i^{new}

$$V_2^{new} = \frac{1}{Y_{22}}\left[\frac{P_2 - jQ_2}{V_2^{old*}} - Y_{21}V_1^{new} - Y_{23}V_3^{old}\right]$$

$$= \frac{1}{-j.5}\left[\frac{0.3 - j0.1}{1\angle 0^\circ} - j2.5\times 1.05\angle 0^\circ - j5\times 1\angle 0^\circ\right]$$

$$= 1.03 + j0.04 = 1.0308\angle 2.22^\circ$$

$$V_3^{new} = \frac{1}{Y_{33}}\left[\frac{P_3 - jQ_3}{V_3^{old*}} - Y_{31}V_1^{new} - Y_{32}V_2^{new}\right]$$

$$= \frac{1}{-j8.3333}\left[\frac{-0.4 + j0.2}{1.0\angle -0^\circ} - j3.3333\times 1.05\angle 0^\circ - j5\times 1.0308\angle 2.22^\circ\right]$$

$$= 1.014 - j0.024 = 1.014\angle -1.36^\circ$$

$$V_1^{new} = 1.05\angle 0^\circ$$
$$V_2^{new} = 1.0308\angle 2.22^\circ$$
$$V_3^{new} = 1.014\angle -1.36^\circ$$

Slack b

$$Y_{12}V_2 + Y_{13}V_3 \big]$$

$$= 1.05\angle 0^\circ \left[-j5.8333 \times 1.05\angle 0^\circ + j2.5 \times \left(1.0308\angle 2.22^\circ\right) + j3.3333\left(1.014\angle -1.36^\circ\right)\right]$$
$$= -0.0206 - j0.1794\, p.u$$

$$P_1 = -0.0206\, p.u = -2.06 MW$$
$$Q_1 = 0.1794\, p.u = 17.94 MVAR$$

24. Bus 2 is a P-V bus having the rating P_G = 60MW, V_2=1.02 p.u. 10 < Q_2 < 100 MVAR, carry out one iteration. Perform load flow using Newton Raphson method to determine bus voltages. Take base MVA as 100

Line data:

Line	**bus**		**R (p.u)**	**X (p.u)**	**Half line charging admittance ($\frac{Y_p}{2}$ (p.u))**
	From	**To**			
1	**1**	**2**	**0.839**	**0.5183**	**0.0636**

Bus data:

Bus	**P_L**	**Q_L**
1	**90**	**20**
2	**30**	**10**

Solution:

Step 1: Form Y_{bus}

$$Y_{bus} = \begin{bmatrix} 1.842\angle -1.405 & 1.904\angle 1.7314 \\ 1.904\angle 1.7314 & 1.842\angle -1.405 \end{bmatrix}$$ θ_{12} in rad.

Step 2: Check for Q limit violation.

$$Q_2^{cal} = -\left\{|V_2||V_1||Y_{21}|\sin\left(\theta_{12} - \delta_2 + \delta_1\right) + |V_2|^2 |Y_{22}|\sin\theta_{22}\right\}$$
$$= -\left\{1.02 \times 1.05 \times 1.904 \times \sin\left(1.7314\right) + 1.02^2 \times 1.842 \times \sin\left(-1.405\right)\right\}$$

` $Q_2^{cal} = -0.1239$

$Q_2^{cal} < Q_{2(\min)}$

$$Q_2 = Q_{2(\min)} = \frac{10}{100} = 0.1 p.u MVAR$$

Now bus will act as load bus.

$$V_2 = 1.0\angle 0\, p.u$$

Step 3: Compute ΔP_2 and ΔQ_2

$$P_2^{cal} = |V_2||V_1||Y_{21}|\cos(\theta_{12} - \delta_2 + \delta_1) + |V_2|^2|Y_{22}|\cos\theta_{22}$$
$$= 1.0 \times 1.05 \times 1.904 \times \cos(1.7314) + 1.0^2 \times 1.842 \times \cos(-1.405)$$
$$P_2^{cal} = -0.0157$$
$$\Delta P_2 = P_{2(spec)} - P_2^{cal} = \frac{60}{100} - (-0.0157) = 0.6157$$
$$\boxed{\Delta Q_2 = Q_{2(spec)} - Q_2^{cal} = 0.1 - (-0.1239) = 0.2239}$$

Step 4: Form Jacobian matrix.

$$\frac{\partial P_2}{\partial \delta_2} = |V_2||V_1||Y_{12}|\sin(\theta_{12} + \delta_2 - \delta_1)$$
$$= 1.0 \times 1.05 \times 1.904 \times \sin(1.7314 - 0 + 0)$$
$$\frac{\partial P_2}{\partial \delta_2} = 1.973$$
$$\frac{\partial P_2}{\partial V_2} = |V_1||Y_{12}|\cos(\theta_{12} - \delta_2 + \delta_1) + 2|V_2||Y_{22}|\cos\theta_{22}$$
$$= 1.05 \times 1.904 \times \cos(1.7314) + 2 \times 1.0 \times 1.842 \times \cos(-1.405)$$
$$\frac{\partial P_2}{\partial V_2} = 0.288$$
$$\frac{\partial Q_2}{\partial \delta_2} = |V_2||V_1||Y_{12}|cos(\theta_{12} + \delta_2 - \delta_1)$$
$$\frac{\partial Q_2}{\partial \delta_2} = -0.3197$$
$$\frac{\partial Q_2}{\partial V_2} = |V_1||Y_{12}|\sin(\theta_{12} - \delta_2 + \delta_1) + 2|V_2||Y_{22}|\sin\theta_{22}$$
$$= -1.05 \times 1.904 \sin(1.314) - 2 \times 1.0 \times 1.842 \times \sin(-1.405)$$
$$\boxed{\frac{\partial Q_2}{\partial V_2} = 1.66}$$

Step 5: Calculate $\Delta\delta$ and ΔV

$$\begin{bmatrix} \Delta\delta_2 \\ \Delta V_2 \end{bmatrix} = \begin{bmatrix} 1.973 & -0.3197 \\ 0.288 & 1.66 \end{bmatrix}^{-1} \begin{bmatrix} \Delta P_2 \\ \Delta Q_2 \end{bmatrix}$$
$$= \frac{1}{3.367} \begin{bmatrix} 1.66 & 0,288 \\ -0.3197 & 1.973 \end{bmatrix} \begin{bmatrix} 0.615 \\ 0.2239 \end{bmatrix}$$
$$\boxed{\begin{bmatrix} \Delta\delta_2 \\ \Delta V_2 \end{bmatrix} = \begin{bmatrix} 0.3227 rad \\ 0.073 p.u \end{bmatrix}}$$
$$\delta_2^1 = \delta_2^0 + \Delta\delta_2 = 0 + 0.3227 = 0.3227 rad = 18.49^\circ$$
$$V_2^1 = V_2^0 + \Delta V_2 = 1.0 + 0.073 = 1.073$$
$$\boxed{V_2^{new} = 1.073\angle 18.49^\circ}$$

UNIT III - FAULT ANALYSIS – BALANCED FAULTS

Importance of short circuit analysis - assumptions in fault analysis - analysis using Thevenin's theorem - Z-bus building algorithm - fault analysis using Z-bus – computations of short circuit capacity, post fault voltage and currents.

PART – A

1. **What is the significance of sub transient reactance and transient reactance in short circuit Studies? (APR/MAY 2017)**

   The sub transient reactance is the ratio of induced emf on no-load and the sub transient symmetrical rms current, (i.e, it is the reactance of a synchronous machine under transient condition)

   The faults or short circuits are associated with sudden change in currents. Most of the components of the power system have inductive property which opposes any sudden change in currents and so the faults (short circuit) are associated with transients.

2. **For a fault at a given location, rank the various faults in the order of severity. (APR/MAY 2017)**

   In a power system relatively the most severe fault is the three phase fault and less severe fault is the open conductor fault.

   The various faults in the order of decreasing severity is given below.

   a. 3-phase fault.
   b. Double line to ground fault.
   c. Line to line fault.
   d. Single line to ground fault.
   e. Open conductor fault.

3. **What is the need of short circuit study? (NOV/DEC 2016)**

   The short circuit studies are essential in order to design or develop the protective schemes for various parts of the system. The protective scheme consists of current & voltage sensing devices, protective relays and circuit breakers. The selection (or proper choice) of these device mainly depends on various currents that may flow in the fault conditions.

4. **How the shunt and series faults are classified? (NOV/DEC 2016)**

   Shunt faults

   a. Shunt faults are symmetrical in nature.
   b. Shunts faults are caused due to short circuits in conductors.
   c. The shunt fault is also called as short circuit faults.

   Series faults

   a. Series faults are unsymmetrical in nature.
   b. Series faults are caused due to open conductors.

5. **State and explain symmetrical fault. (MAY/JUNE 2016)**

   The currents and voltages at various parts of the system can be estimated by different methods. The fault on the power system which gives rise to symmetrical fault currents (i.e. equal fault current in the lines with 120^0 displacement) is called as symmetrical faults. The symmetrical fault occurs when all the three conductors of phase are brought together simultaneously in short circuit condition.

6. **What is bolted fault or solid fault? (MAY/JUNE 2016)**

A fault represents a structural network change be equivalent with that caused by the additional of impedance at the place of fault. If the fault impedance is zero, then the fault is referred as bolted fault or solid fault.

7. **Why do faults occur in a power system? (NOV/DEC 2015)**

In a power system the fault may occur due to the following reasons.
Insulation failure of equipment's., Flashover of lines initiated by a lightning stroke, Switching surges, Sudden releasing of heavy loads at same instant of time, Due to accidental faulty operation of power system operators.

8. **What is direct axis reactance? (NOV/DEC 2015)**

It is the apparent reactance of the armature winding just at the instant of the short circuit occurs at the terminals of the unloaded synchronous generator and it causes heavy currents to flow during the first few cycles.

9. **What is meant by a fault?**

A fault in a circuit is any failure which interferes with the normal flow of current. The faults are associated with abnormal change in current, voltage and frequency of the power system. The faults may cause damage to the equipment's if it is allowed to persist for a long time. Hence every part of a system has been protected by means of relays and circuit breakers to sense the faults and to isolate the faulty part from the healthy part in the event of fault.

10. **Give the general reason for which fault occurs in a power system.**

In a power system the fault may occur due to the following reasons.

a. Insulation failure of equipment's.
b. Flashover of lines initiated by a lightning stroke.
c. Switching surges.
d. Sudden releasing of heavy loads at same instant of time.
e. Due to accidental faulty operation of power system operators.

11. **Why does symmetrical fault occur in a power system?**

The short circuit fault occurs in a power system due to the following reasons.

a. Insulation failure of equipment's,
b. Flashover of lines initiated by a lightning stroke
c. Through accidental faulty operation.
d. Birds shorting out lines.
e. Aircraft colliding with lines.
f. Trees falling over lines.

12. **How are the faults classified?**

Generally the faults are classified as follows.

1. **Shunt faults**
   d. Shunt faults are symmetrical in nature.
   e. Shunts faults are caused due to short circuits in conductors.
   f. The shunt fault is also called as short circuit faults.
2. **Series faults**
   c. Series faults are unsymmetrical in nature.
   d. Series faults are caused due to open conductors.

13. **List the types of Short circuit faults.**

Shorts circuit faults can be classified as follows:

Symmetrical fault or balanced fault

- Three phase fault

Unsymmetrical fault or unbalanced fault

- Line to ground (L-G) fault
- Line to Line (L-L) fault
- Double line to ground (L-L-G) fault.

14. List out the various faults in the order of severity.

In a power system relatively the most severe fault is the three phase fault and less severe fault is the open conductor fault.

The various faults in the order of decreasing severity is given below.

f. 3-phase fault.
g. Double line to ground fault.
h. Line to line fault.
i. Single line to ground fault.
j. Open conductor fault.

15. List out the differences in representing the power system for load flow and short circuit studies.

S.No	Load flow studies	Fault analysis
1	Both resistances and reactances are considered.	Resistances are neglected.
2	Bus admittance matrix is used.	Bus impedance matrix is used.
3	The exact voltages and currents are to be determined.	The voltages can be safely assumed as 1 p.u. and the prefault current can be neglected.

16. What is the need for short circuit studies or fault analysis?

a. The short circuit studies are essential in order to design or develop the protective schemes for various parts of the system.
b. The protective scheme consists of current & voltage sensing devices, protective relays and circuit breakers.
c. The selection (or proper choice) of these device mainly depends on various currents that may flow in the fault conditions.

17. What are the objectives of short circuit analysis?

a. To check the MVA ratings of the existing circuit breakers, when new generation are added into the system.
b. To select the rating for fuses, circuit breakers and switch gear in addition to the set up of protective relays.
c. To determine the magnitudes of currents flowing throughout the power system at various time intervals after a fault occurs.

18. State the applications of short circuit analysis.

a. For proper relay setting and coordination.
b. To obtain the rating of protective switch gears.

c. To select the circuit breakers.
d. To perform whenever system expansion is planned.

19. What are the ways to reduce short circuit current?

Following are the two important ways to reduce the short circuit current:

a. By providing neutral reactance.
b. By introducing a large value of shunt reactance between the buses.

20. What are the various period involved in fault calculation?

The fault condition of a power system can be divided into

a. Sub transient period,
b. Transient period,
c. Steady state periods.

The currents in the various parts of the system and in the fault locations are different in these periods. The estimation of these currents for various types of faults at various locations in the system is commonly referred to as fault calculations.

21. How are symmetrical faults analyzed?

The symmetrical faults are analyzed using per unit reactance diagram of the power system. Once the reactance diagram is formed, then the fault is simulated by short circuit or by connecting the fault impedance at the fault point. The currents and voltages at various parts of the system can be estimated by different methods. The fault on the power system which gives rise to symmetrical fault currents (i.e. equal fault current in the lines with 120^0 displacement) is called as symmetrical faults. The symmetrical fault occurs when all the three conductors of phase are brought together simultaneously in short circuit condition.

22. What are the points to be noticed while undergoing symmetrical fault analysis?

The points to be noticed while undergoing symmetrical faults are given as follows.

a. The symmetrical faults rarely occur in practice as majority of the faults are of unsymmetrical nature.
b. The symmetrical fault is the most severe and imposes more heavy duty on the circuit breaker.

23. Why the computation of prefault currents neglected in fault calculation?

The changes in the short circuit currents are limited only by the series impedance elements. Post fault currents are almost purely reactive whereas the pre fault load currents are almost purely real. The total post fault current is therefore obtained as the vectorial sum of two currents having a phase difference of almost 90^0. The magnitude of total current is approximately equal to the magnitude of the largest component. So we can neglect the prefault current.

24. What are the different methods by which faulted network can be solved?

The different methods by which faulted network can be solved are listed as follows.

1) By use of transient and subtransient internal voltages.
2) Using Thevenin's theorem
3) By forming bus impedance matrix.

25. What are symmetrical components?

An unbalanced system of N related vectors can be resolved into N systems of balanced vectors called symmetrical components. The various symmetrical components are as follows.

a. Positive sequence components
b. Negative sequence components
c. Zero sequence components

This type of fault is defined as the simultaneous short circuit across all the three phases. It occurs infrequently, but it is the most severe type of fault encountered. Because the network is balanced, it is solved by per phase basis using Thevenin's theorem or bus impedance matrix or KVL, KCL laws.

26. What are the needs of sequence network in power system?

a. Sequence network in power system is very much useful for computing unsymmetrical for computing unsymmetrical faults at different points of the power system network.
b. Positive sequence network is necessary for load flow studies.
c. Negative and zero sequence networks are used in stability studies involving unsymmetrical faults**.**

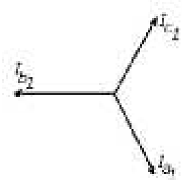
27. What are the assumptions made in short circuit studies of a large power system network?

a. The phase to neutral emfs of all generators remain constant, balanced and unaffected by the faults.
b. Each generator is represented by an emf behind either the sub transient or transient reactance depending upon whether the short circuit current is to be found immediately after the short circuit or after about 3 – 4 cycles.
c. Load currents may often be neglected in comparison with fault currents.
d. All network impedances are purely reactive. Thus the series resistances of lines and transformers are neglected in comparison with their resistances.

28. Write few words about Positive sequence components.

Positive sequence components consist of three phasors equal in magnitude, displaced from each other by 120^{o} in phase, and having the same sequence as the original phasors.

It is denoted as a_1,b_1 and c_1.

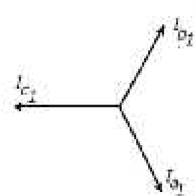


Positive sequence components

29. Write about negative sequence components.

Negative sequence components consist of three phasors equal in magnitude, displaced from each other by 120^{o} in phase, and having the phase sequence opposite to that of the original phasors. V_{a2}, V_{b2} and V_{c2} are the negative sequence components of V_a, V_b and v_c.

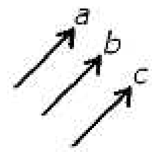
If a_2, b_2 and c_2 are the three phasors and if a_2 is followed by c_2 followed by b_2 they are said to have negative sequence.



Negative sequence components

30. Write about zero sequence components.

Zero sequence components consist of three phasors equal in magnitude and with Zero phase displacement from each other. V_{ao}, V_{bo} and V_{co} are the zero sequence components of V_a, V_b and V_c.



Zero sequence components

31. What are the advantages of symmetrical components?

The advantages of symmetrical components are given as follows:

a. The unbalance system of n related vectors can be resolved into n system of balanced vectors.

b. The positive sequence components consists of three vectors equal in magnitude, displace from each other by 120^o in phase, and having the same phase sequence as the original vectors.

c. Unsymmetrical fault analysis can be done by using symmetrical components.

32. In what way does the negative sequence network differ from the positive sequence network?

The negative sequence network is very much similar like that of positive sequence network but they differ in following aspects.

a. Normally there is no negative sequence e.m.f source.

b. Negative sequence impedance of rotating machine is generally different from their positive sequence impedances.

c. The phase displacement of transformer banks for negative sequence is of opposite sign to that of positive sequence.

33. How does the zero sequence networks differ from positive sequence and negative sequence network?

Zero sequence network differ greatly from positive sequence and negative sequence network in the following aspects.

a. Zero sequence reactance of transmission lines is higher than that for positive sequence.

b. Equivalent circuit for transformers is different.

c. The neutral grounding should be considered in zero sequence network.

34. Why delta connected load will not have any zero sequence components?

The current in the neutral is three times the zero sequence line current. A delta connected load provides no path to neutral and hence the line currents flowing to a delta connected load contain zero components. Hence the delta connected load will not have any zero sequence components.

35. Write down the expression of power in terms of symmetrical components.

The expression or equation power in terms of symmetrical components is given by

$$P=3V_0I_0^* +3V_1I_1^* +3V_2I_2^*$$

Where V_0 and I_0 are zero sequence voltage and current.

V_1 and I_1 are positive sequence voltage and current.

V_2 and I_2 are negative sequence voltage and current.

36. What is symmetrical components of three phase system?

Symmetrical components of three phase system is given as:

For voltage

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$

For current.

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

37. Write the relative frequency of occurrence of various types of faults.

Types of fault	Relative frequency of occurrence of faults
Three phase fault	5%
Double line to ground fault	10%
Line to Line fault	15%
Line to ground fault	70%

38. Name the reactance used in the analysis of symmetrical faults on the synchronous machines as its equivalent reactance.

The reactance used in the analysis of symmetrical faults on the synchronous machines as its equivalent reactance are given below. They are.

a. Subtransient reactance.
b. Transient reactance.
c. Synchronous reactance.

39. Define synchronous reactance?

The synchronous reactance is the ratio of induced emf and the steady state rms current (i.e. it is the reactance of a synchronous machine under steady state condition). It is the sum of leakage reactance and the reactance representing armature reaction.

It is given by,

$X_s = X_l + X_a$

Where,

X_s = Synchronous reactance

X_l = Leakage reactance

X_a = Armature reaction reactance.

40. What is the reason for transients during short circuits?

The faults or short circuits are associated with sudden change in currents. Most of the components of the power system have inductive property which opposes any sudden change in currents and so the faults (short circuit) are associated with transients. The transient reactance is used to estimate the transient state fault current. Most of the circuit breakers open their contacts only during this period. Therefore for a circuit breaker used for fault clearing (or protection), the interrupting short circuit current rating should be less than the transient fault current.

41. Define sub transient reactance and give its significance.

The sub transient reactance is the ratio of induced emf on no-load and the sub transient symmetrical rms current, (i.e, it is the reactance of a synchronous machine under transient condition)

Sub transient reactance = $\frac{\text{Induced } emf \text{ on no-load}}{\text{Sub transient symmetrical } rms \text{ current}}$

The sub-transient reactance can be used to estimate the initial value of fault current immediately on the occurrence of the fault. The maximum momentary short circuit current rating of the circuit breaker used for protection or fault clearing should be less than this initial fault current.

42. List the advantages of symmetrical components.

a. This method is simple.

b. This method leads to accurate prediction of system behavior.

c. Unsymmetrical faults on the transmission system are studied by the method of symmetrical components.

d. They suitable to determine the currents and voltages in all parts of the power system after the occurrence of fault**.**

43. How transients occur during short circuits?

A sudden change or sudden disturbance in the voltage and current rating of a system then the system is said to be in transient. The faults or short circuits are associated with sudden change in currents. Most of the components of the power system have inductive property which opposes any sudden change in currents, so the faults are associated with transients. The main reasons for transients are insulation failure, switching surges, improper earthing, flashover,etc.

44. What is the purpose of analyzing unsymmetrical fault?

Analysis of unsymmetrical fault is very important for the following reasons. They are given as follows

a. Relay setting,

b. Single phase switching

c. System stability studies

45. Write down the equation to find the fault current in bus-k and change in voltages in other buses due to a 3-phase fault in bus-k using impedance matrix.

The fault current in bus-k, $I_f = \frac{V_{pf}}{Z_{kk}}$

Where, V_{pf} = prefault voltage in bus-k, (normally 1 p.u)

The change in bus-q voltage due to a 3 phase fault in bus-k, $\Delta V_q = -I_f Z_{qk}$; for q=1,2,3…n

46. Define direct axis subtransient reactance and transient reactance.

It is the apparent reactance of the armature winding just at the instant of the short circuit occurs at the terminals of the unloaded synchronous generator and it causes heavy currents to flow during the first few cycles.

The effective reactance after the damper winding currents have died out is called transient reactance of the machine. It determines the fault current after several cycles.

47. Define direct axis synchronous reactance and state which fault is the severe fault when compared to all.

Direct axis synchronous reactance is the apparent reactance of the armature winding and it comes into action only after the transient period is over and steady state condition is reached.

Three phase short circuit occurs rarely but it is the most severe type of fault involving largest fault currents.

48. What are sequence impedances and sequence networks?

The sequence impedances are the impedances offered by the devices or Components for the like sequence component of the current.

The single phase equivalent circuit of a power system consists of impedances and current at any one sequence only is called sequence network.

49. Define transient reactance and DC off set current

Transient reactance

The synchronous reactance is the ratio of induced emf on no load and the transient symmetrical rms current.

DC off set current.

The unidirectional transient component of short circuit current is called DC off set current.

50. Define short circuit capacity of power system (or) fault level.

Short circuit capacity or short circuit MVA of fault level at a bus is defined as the product of the magnitudes of the perfect bus voltage and the post fault current.

Uses of short circuit capacity

a. It is used for determining the dimension of a bus bar
b. It is used for determining the interrupting capacity of a circuit breaker.
c. It helps to find out the magnitude of fault current.

PART – B

1. **A 3 phase 5 MVA 6.6 KV alternator with a reactance of 8% is connected toa afeeder series impedance (0.12 + j0.48)ohm/phase/km through a step up transformer. The transformer is rated at 3 MVA, 6.6 KV/33 KV and has a reactance of 5%. Determine the fault current supplied by the generator operating under no load with a voltage of 6.9 KV, when a 3 phase symmetrical fault occurs at a point 15KM along the feeder. (APR/MAY 2017)**

$\therefore$ Actual value of fault current, I_f= p.u. value of $I_f \times I_b = 9.3179\angle -84.9° \times 67.4773$

$I_f = 45.2\angle -97.6°$ amps.

Result:

Fault current = $7.9\angle -17.6°$ p.u. or $465.2\angle -87.6°$ A.

2. **Draw the detailed flowchart, which explains how a symmetrical fault can be analyzed using Z - bus. (APR/MAY 2017)**

Step 1 : Start.

Step 2 : Read line impedance, generator impedance and fault impedance.

Step 3 : Form the Z_{bus} matrix using step by step assembly using 4 types of modifications.

Step 4 : Set all bus voltages as $1\angle 0°$ p.u.

Step 5 : Connect Z_f in series with faulted bus.

Step 6 : Calculate fault current for i^{th} bus.

$$I_i(F) = \frac{V_{i(o)}}{Z_{ii}+Z_f}$$

Step 7 : Calculate the generator current $I_G = Z_{eq}\, I_{Gi}$

Step 8 : Calculate change in voltage ΔV_i and $V_i(F)$

$$V_i(F) = V_{i(o)} + \Delta V_i$$

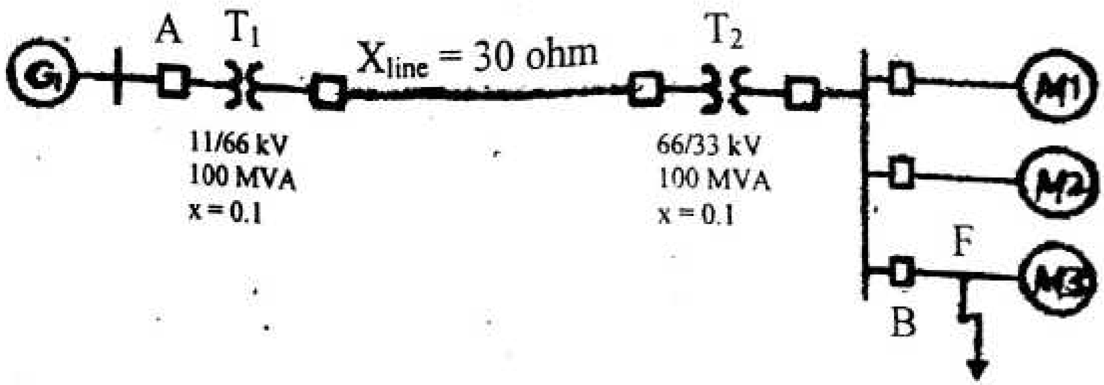
Step 9 : Calculate $V_j(F) = V_{j(o)} = -\sum_{\substack{j=1 \\ \neq i}}^{n} Z_{ij} I_i(F)$

Step 10 : Calculate $I_{ij}(F) = \frac{V_i(F)-V_j(F)}{Z_{ij}}$

Step 11 : Print the result.

Step 12 : Stop.

3. **A 100 MVA, 11 KV generator with X"=0.20p.u is connected through a transformer and line to a bus bar that supplies three identical motor as shown in fig and each motor has X"=0.20 p.u and X"=0.25p.u on a baase of 20 MVA, 33 KV, the bus voltage at the motors is 33KV when three phase balanced fault occurs at the point F. calculate (i) sub transient current in the fault (ii) sub transient current in the circuit breaker (iii) Momentary current in the circuit breaker (iv) the current to be interrupted by C.B.B in 5 cycles. (APR/MAY 2017)**

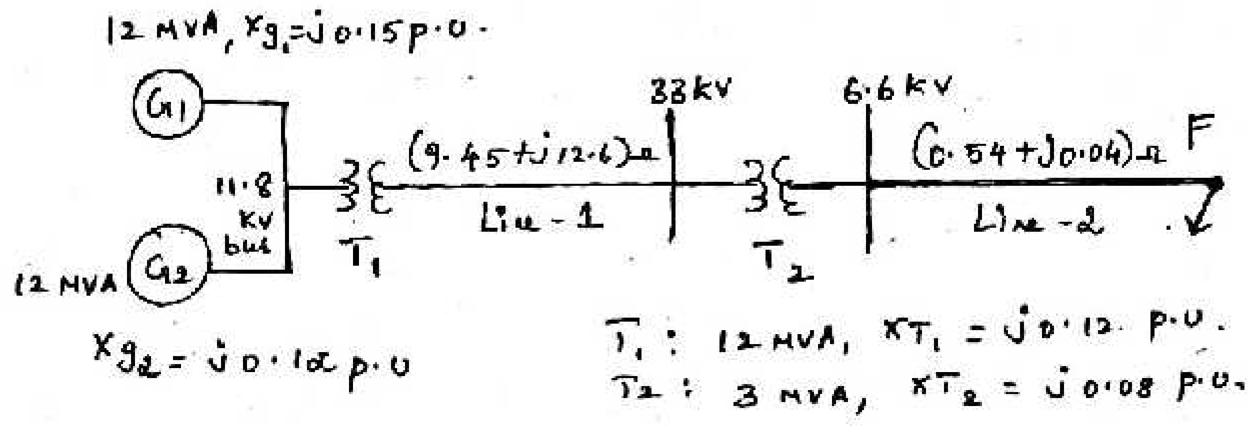


Actual value of current in the fault during subtransient state $I_f" = 10.1\angle -80° \times 156.16$

$I_f" = 50.56\angle -90° = 16.752\angle -20°$ kA

$I_f" = 50.56\angle -90°$ kA

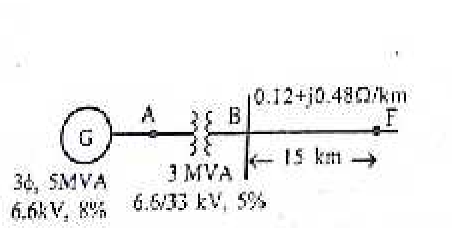
4. **For the radial network shown in fig. 3 phase fault occurs at point F. determine the fault current and the line voltage at 11.8 KV bus under fault condition. (NOV/DEC 2016)**



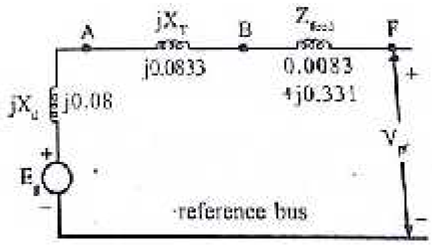
$I_f" = 12.0\angle -90°$

$I_f" = 12.0\angle -90°$ kA

5. **A 3-phase, 5 MVA, 6.6 kV alternator with a reactance of 8% is connected to a feeder of series impedance of 0.12+j0.48 ohms/phase per km. The transformer is rated at 3 MVA, 6.6kV/3.3 kV and has a reactance of 5%. Determine the fault current supplied by the generator operating under no-load with a voltage of 6.9kV, when a 3-phase symmetrical fault occurs at a point 15km along the feeder. 1.For the two bus system as shown in fig. Determine the fault current at the fault point and in other element and post fault voltage, for a bolted fault at bus 4.The subtransient reactance of the generators and positive sequence reactance of other elements are given. (NOV/DEC 2016)**



Single line diagram



Prefault reactance diagram

Let us choose generator rating as base values.

$\therefore MVA_b = 5$ MVA and $kV_b = 6.6$ kV

To find generator reactance:

$\therefore$ p.u. reactance of the generator, $X_d = 8\% = 0.08$ p.u.

$X_d = 8\% = 0.08$ p.u.

To find transformer reactance:

$$X_{pu,new} = X_{pu,old} \times \left(\frac{kV_{b,old}}{kV_{b,new}}\right)^2 \times \frac{MVA_{b,new}}{MVA_{b,old}}$$

Here $X_{pu,old} = 5\% = 0.05$ p.u.

$\therefore$p.u. reactance of transformer, $X_T = 0.05 \times \frac{66}{6.6} \times \frac{5}{3} = 0.0833$ p.u.

$X_T = 0.0833$ p.u.

To find feeder reactance:

$$Z_{feed} = (0.12+j0.48)\times 15 = 1.8+j7.2\Omega/\text{phase}$$

$\therefore$ p.u. value of the impedance of the feeder, $Z_{feed} = \frac{\text{Actual impedance}}{\text{Base impedance}} = \frac{1.8+j7.2}{217.8}$

$Z_{feed} = 0.0083+j0.0331$ p.u.

To find fault current:

$Z_{th} = 0.1966\angle 87.6°$ p.u.

The fault in the feeder can be represented by a short circuit as shown. Now the current If through the short circuit is the fault current.

$\therefore$p.u. value of fault current, $I_f = \frac{V_{th}}{Z_{th}} = \frac{1.0455\angle 0°}{0.1966\angle 87.6°} = 5.3179\angle -87.6°$ p.u.

$I_f = 5.3233\angle -90°$ p.u.

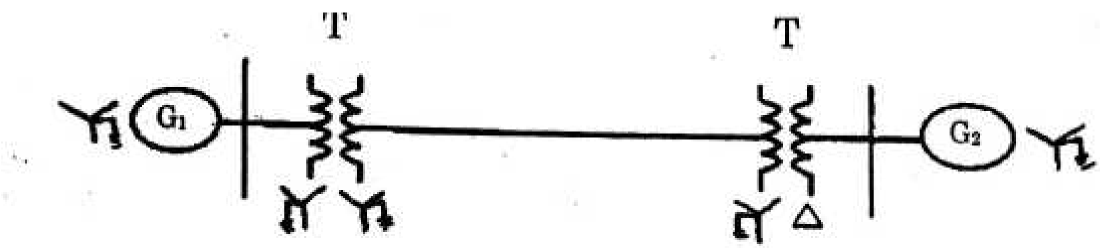
It is important to note that the error in neglecting the resistive component is negligible.

Base current, $I_b = \frac{kVA_b}{\sqrt{3}kV_b} = \frac{MVA_b \times 1000}{\sqrt{3}kV_b} = \frac{5\times 1000}{\sqrt{3}\times 33} = 87.4773$ A.

Result:

Fault current = $5.3179\angle -87.6°$ p.u. or $465.2\angle -87.6°$ A.

6. **Generator G1 and G2 are identical and rated 11KV, 20MVA and have a transient reactance of 0.25p.u at own MVA base. The transformers T1 and T2 are also identical and are rated 11/66 KV, 5 MVA and have a reactance of 0.06p.u to their own MVA base. A 50KM long transmission line is connected betweek the two generators. Calculate three phase fault current, when fault current occurs at middle of the line as shown in fig. (MAY/JUNE 2016)**

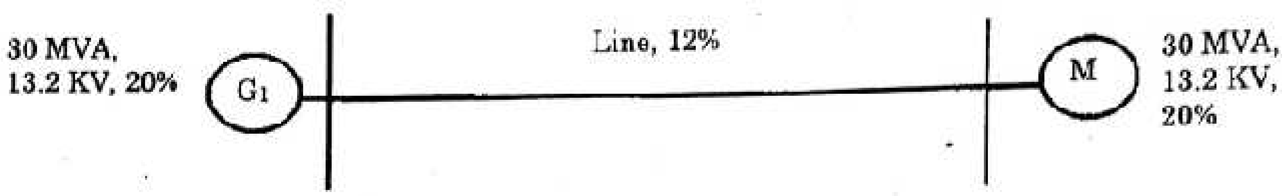


Assuming bolted fault or solid fault, $Z_f = 0$. Prefault voltage $E_{Th} = 1\angle 0^0$

Fault current $I_f = \frac{E_{Th}}{Z_f + Z_{Th}} = \frac{E_{Th}}{Z_f + Z_{Th}} = \frac{1\angle 0^0}{0 + j0.144} = 9.68\angle -90^0$ p.u

Fault current $I_f = 9.68\angle -90^0$ p.u

7. A synchronous generator and motor are rated for 30000kVA, 13.2kV and both have subtransient reactance of 20%. The line connecting them has a reactance of 10% on the base of machine ratings. The motor is drawing 20000kW at 0.8pf leading. The terminal voltage of the motor is 12.8kV. When a symmetrical three phase fault occurs at motor terminals, find the subtransient current in generator, motor and at the fault point. (MAY/JUNE 2016)



The base values are, MVA_b =30 MVA, kV_b = 13.2 kV

Base current, $I_b = \frac{kVA_b}{\sqrt{3} kV_b} = \frac{30 \times 1000}{\sqrt{3} \times 13.2}$ = 1312.16 A

I_b = 1312.16 A

Prefault condition:

The voltages and currents in the various elements of the system just before the fault are shown in fig. in this circuit V_{tm} and I_L are known values and using these values the subtransient internal voltages E_g” and E_m” can be calculated by Kirchoff’s voltage Law(KVL) as shown below.

Fig. Prefault current and voltages.

By applying KVL in the circuit of fig, we get,

$E_g'' = j0.2\, I_L + j0.1\, I_L + V_{tm}$

$= j0.3\, I_L + V_{tm}$

$\therefore E_m'' = V_{tm} - j0.2\, I_L = 0.9697\angle 0° - (0.2\angle 90° \times 0.8594\angle 36.9°)$

$= 0.9697\angle 0° - (0.1719\angle 12.9°) = 0.9697 - (-0.1032 + j0.1375)$

$= 1.0729 - j0.1375 = 1.0817\angle -7.3°$ p.u.

$E_m'' = 1.0817\angle -7.3°$ p.u.

$I_g'' = 2.802\angle -75.8°$ p.u.

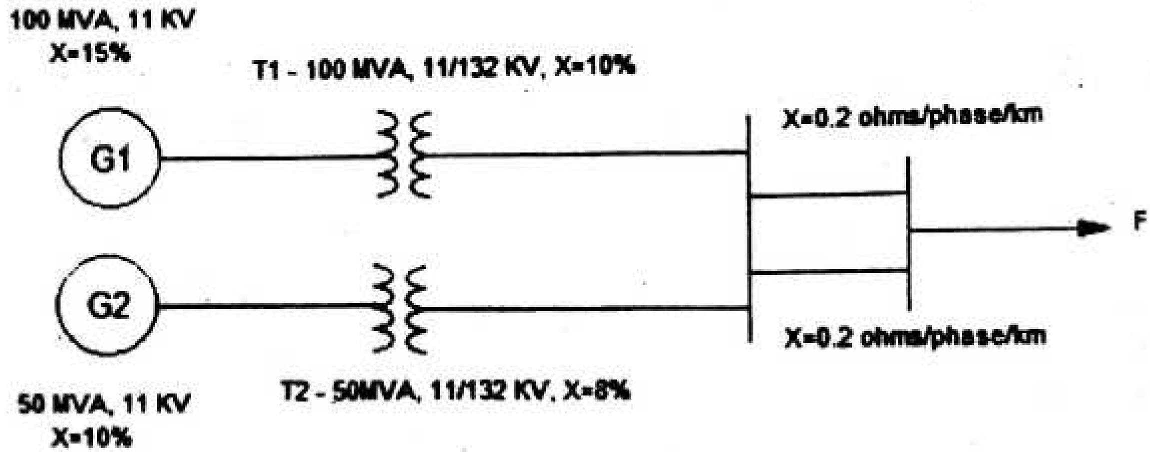
$I_m'' = 5.4085\angle -97.3°$ p.u.

Actual value of current in the fault during subtransient state $I_f'' = 8.081\angle -90° \times 1312.16$

$I_f'' = 10603.56\angle -90° = 10.60356\angle -90°$ kA

$I_f'' = 10.60356\angle -90° \text{ kA}$

8. A generating station feeding a 132 KV system is shown in fig. determine the total fault current, fault level and fault current supplied by each alternator for a 3 phase fault at the receiving end bus. The line is 200KM long. (NOV/DEC 2015)



Assuming bolted fault or solid fault, $Z_f = 0$. Prefault voltage $E_{Th} = 1\angle 0^0$

Fault current $I_f = \frac{E_{Th}}{Z_f+Z_{Th}} = \frac{E_{Th}}{Z_f+Z_{Th}} = \frac{1\angle 0^0}{0+j0.144} = 6.94\angle -90^0$ p.u

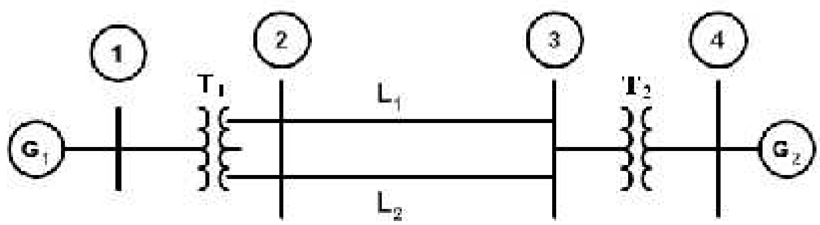
Fault current $I_f = 6.94\angle -90^0$ p.u

9. A symmetrical fault occurs on bus 4 of system shown in fig. Determine the fault current, post fault voltages and line currents. (NOV/DEC 2015)

G_1, G_2 : 100 MVA, 20 KV, X^+=15%.

Transformer: X_{leak}=9%

L_1, L_2: X^+=10%.



$$= \begin{bmatrix} j0.1075 & j0.172 & j0.068 & j0.0424 \\ j0.172 & j0.13 & j0.108 & j0.068 \\ j0.068 & j0.108 & j0.13 & j0.082 \\ j0.0424 & j0.13 & j0.082 & j0.075 \end{bmatrix}$$

Step 1: fault current

$$I_f = \frac{V^0}{Z_{qq}+Z_f} = \frac{1\angle 0^0}{j0.1075} = 9.3\angle -90^0 \text{ p.u}$$

$I_f = 9.3\angle -90^0$ p.u

Actual current in KA = p.u value x base current.

$= 9.3\angle -90^0 \times \frac{MVA}{\sqrt{3} \times KV}$

$= 9.3\angle -90^0 \times \frac{100}{\sqrt{3} \times 20} = 26.85$ KA

Actual current in KA = 26.85 KA

Step 2 : Post fault line currents.

$$I_{ij}^f = \frac{V_i^f - V_j^f}{Z_{ij\,series}} \; ; \; I_{12}^f = \frac{V_1^f - V_2^f}{Z_{12}} = \frac{0.6056 - 0.3686}{j\,0.09}$$

$|I_{12}^f|$ = 2.634 p.u

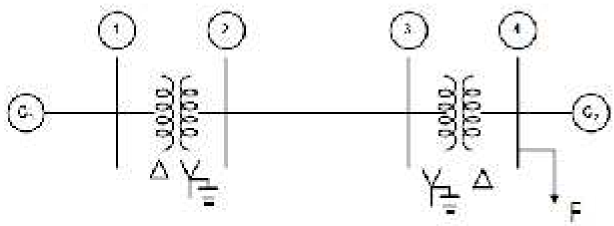
$$I_{23}^f = \frac{V_2^f - V_3^f}{Z_{23}} = \frac{0.3686 - 0.2374}{j\,0.05}$$

$|I_{23}^f|$ = 2.63 p.u.

$$I_{34}^f = \frac{V_3^f - V_4^f}{Z_{34}} = \frac{0.2374 - 0}{j\,0.09}$$

$|I_{34}^f|$ = 2.637 p.u.

10. For the two bus system shown in fig. determine the fault current, bus voltages, line currents during the fault when a 3 phase fault impedance Z_f = j0.15. p.u occurs on Bus 4.



Therefore $Z_{Th} = \frac{j0.15 \times j0.85}{j0.15 + j0.85}$ = j 0.1275

Z_{Th} = j 0.1275

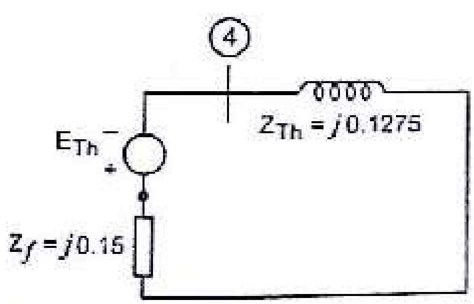
Thevenin's equivalent circuit.

Prefault voltage $E_{Th} = 1\angle 0^0$

Fault current $I_f = \frac{E_{Th}}{Z_{Th} + Z_f} = \frac{1\angle 0^0}{j01.1275 + j0.15}$

$= -j3.604 = 3.604\angle -90^0$ p.u

Fault current $I_f = 3.604\angle -90^0$ p.u



$I_{G1} = 0.5406\angle -90^0$ p.u

$I_{G2} = 3.0634\angle -90^0$ p.u

Line flows (post fault):

$I_{12} = \frac{V_1 - V_2}{Z_{12}} = \frac{0.9189 - 0.8108}{j0.2}$ = -j0.5406 p.u

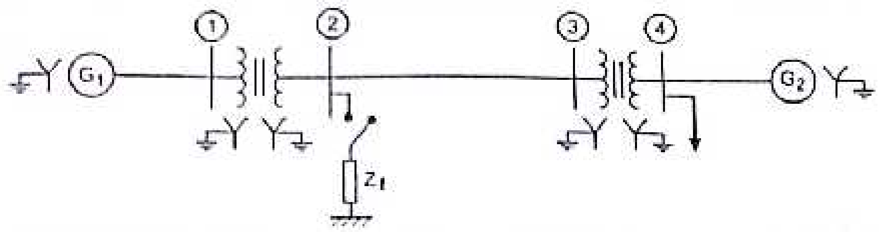
$I_{23} = \frac{V_2 - V_3}{Z_{23}} = \frac{0.8108 - 0.6486}{j0.3}$ = -j0.5406 p.u

$I_{34} = \frac{V_3 - V_4}{Z_{34}} = \frac{0.6486 - 0.5406}{j0.2}$ = -j0.54 p.u

I_{12} = - j0.5406 p.u
I_{23} = - j0.5406 p.u
I_{34} = - j0.54 p.u

11. For the two bus system shown in fig. determine the fault current at the fault point and in other elements for a fault at bus 2 with Z_f =0. The subtransient reactance of the generators and positive sequence reactance of other elements are given.

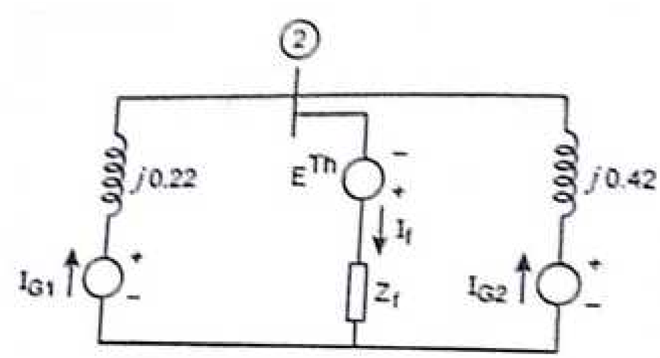
Generator X=10%, Transmission line X=20%, Transformer X=12 %.



p.u

Fault current $I_f = 6.94\angle -90^0$ p.u

Step 1: Current contribution from generators.



In general, $I_G = I_{Total} \times \frac{Z_{parallel}}{Z_{Total}}$

$I_{G1} = I_f \times \frac{j0.42}{j0.22 + j0.42}$ = -j4.55 p.u = $4.55 \angle -90^0$ p.u

$I_{G1} = 4.55 \angle -90^0$ p.u

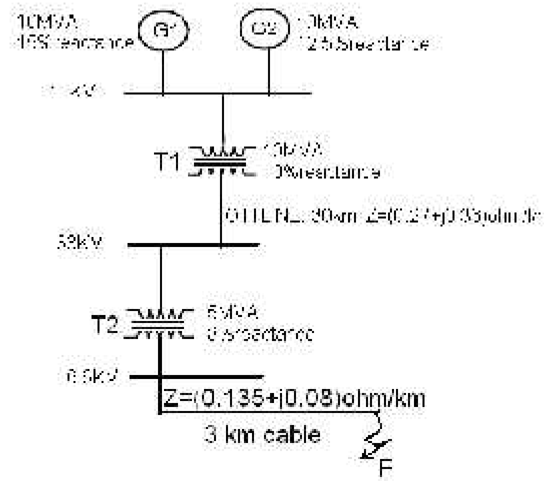
$I_{G2} = I_f \times \frac{j0.42}{j0.42 + j0.22}$ = -j2.39 p.u = $2.39\angle -90^0$ p.u

$I_{G2} = 2.39\angle -90^0$ p.u
E_{Th} = 7.843 p.u

SCC = $\frac{1}{X_{Th}}$ p.u.MVA = $\frac{1}{0.144}$ = 6.94 p.u. MVA

SCC = 6.94 p.u. MVA

12. For the radial network shown in the figure, three phase fault occurs at F. Determine the fault current and the line voltage at 11KV bus under fault conditions.



Base MVA = 10 MVA

Base KV = 11KV

Voltage at 11 KV bus : Z_{AF} = j0.1 + 0.0744 +j0.0992 + j0.16 + 0.093 + j0.55

= 0.1674 + j0.4142

= 0.447 $\angle 67.99^0$ p.u

Voltage at 11 KV bus = $Z_{AF\ p.u}$ x $I_{f\ p.u}$

= 0.447 $\angle 67.99^0$ x 1.959 $\angle -70.85^0$

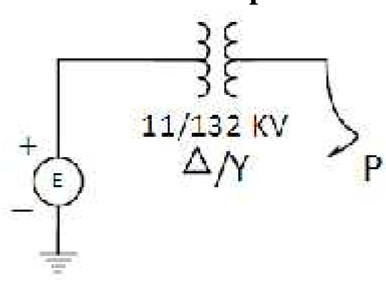
= 0.874 – j0.0436 = 0.875 p.u

= 0.875 x Base voltage

= 0.875 x11 = 9.615 KV

Voltage at 11 KV bus = 9.615 KV

13. A 60 MVA, Y connected 11 kv synchronous generator is connected to a 60 MVA, 11/132 KV Δ/Y transformer. The subtransient reactance X_d" of the generator is 0.12 p.u on a 60 MVA base, while the transformer reactance is 0.1 p.u. on the same base. The generator is unloaded when a symmetrical fault is suddenly place at point P as shown in fig. Find the subtransient fault current in p.u amperes and actual amperes on both sides of the transformer. Phase to neutral voltage of the generator at no load is 1.0 p.u.



Secondary side of transformer:

Base KV_{new} = KV_{old} x $\frac{H.V\ side\ rating}{L.V\ side\ rating}$

= 11 x $\frac{132}{11}$ = 132 KV

Base KV_{new} = 132 KV

Base current = $\frac{Base\ MVA}{\sqrt{3}\ x\ KV_b} = \frac{60}{\sqrt{3}\ x\ 132}$ = 0.262 KA

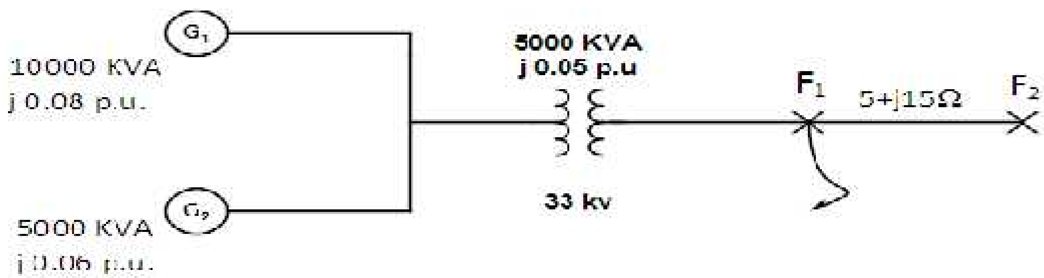
Base current = 0.262 KA

Actual current = $I_{F\ p.u}$ x Base current

= 4.54 x 0.262 = 1.189 KA

Actual current = 1.189 KA

14. A 3 phase transmission line operating at 33kv and having resistance and reactance of 5 ohms and 15 ohms respectively is connected to the generating station bus-bar through a 5000 KVA step up transformer which has a reactance of 0.05 p.u. Connected to the bus-bars are two alternators, are 10,000 KVA having 0.08 p.u. reactance and another 5000 KVA having 0.06 p.u. reactance. Calculate the KVA at a short circuit fault between phases occurring at the high voltage terminals of the transformers.



a. Total impedance upto the fault F_1, $Z_{1\ p.u}$ = - j0.148 p.u

Short circuit KVA fed into the fault at F_1 = $|KVA_{1\ S.C}| = \frac{|KVA_b|}{|Z_{1\ p.u}|}$

$= \frac{10,000}{0.148}$ = 67567.56 KVA

= 67.568 MVA

Short circuit KVA fed into the fault at F_1 = 67.568 MVA

b. Total impedance upto the fault F_2, $Z_{2\ p.u}$ = 0.0459 +j0.2857 p.u

$|Z_{2\ p.u}|$ = 0.289 p.u

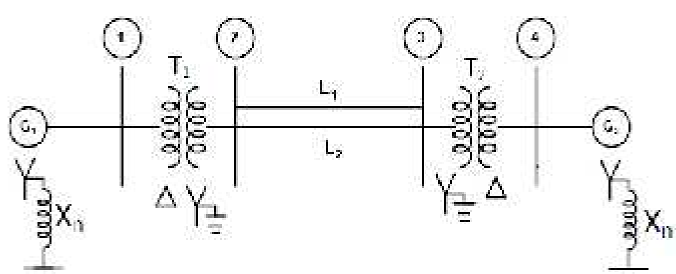
Short circuit KVA fed into the fault at F_2 = $|KVA_{2\ S.C}| = \frac{|KVA_b|}{|Z_{2\ p.u}|}$

$= \frac{10,000}{0.289}$ = 34602 KVA

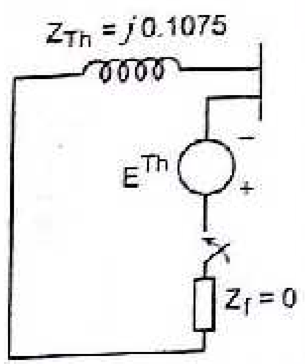
= 34.602 MVA

Short circuit KVA fed into the fault at F_2 = 34.602 MVA

15. A symmetrical fault occurs on bus 4 of system shown in fig. compute the fault current, post fault voltage, line flow.



Generator: G_1, G_2: 100 MVA, 20 KV, X^+ =15%.
Transformer: T_1, T_2: X_{leak} = 9%.
Transmission line L_1, L_2: X^+ =10%.
Thevenin's equivalent circuit.



I_{12} = - j2.632 p.u

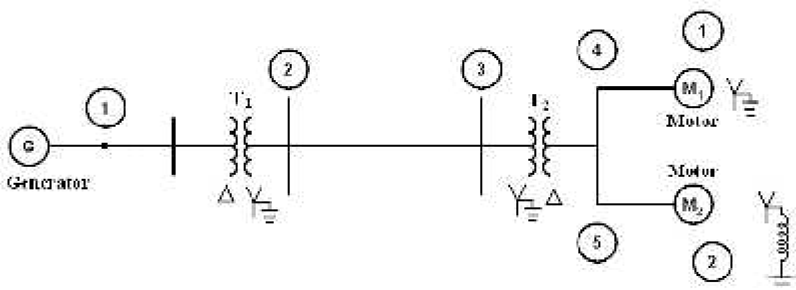
$I_{23} = \frac{V_2 - V_3}{Z_{23}} = \frac{0.2683-0.2367}{j0.05}$ = -j2.632 p.u

I_{23} = - j2.632 p.u

$I_{34} = \frac{V_3 - V_4}{Z_{34}} = \frac{0.2367-0}{j0.09}$ = -j2.6 p.u

I_{34} = - j2.6 p.u

16. A 25 MVA, 11 KV, 3φ generator has a subtransient reactance of 20 %. The generator supplies two motors over a transmission line with transformers at both ends as shown in fig. The motors have rated input of 15 and 7.5 MVA, both 10 KV and 20% subtransient reactance. The 3φ transformers are both rated 50 MVA, 10.8/121 KV with delta-star connection with leakage reactance of 10% each. The series reactance of the line is 80 Ω. Draw the impedance diagram of the system with reactances marked in p.u. when symmetrical fault occurs at bus 2 and calculate fault current.



$I_f = 5.28 \angle -90^0$ p.u

Base current $I_{base} = \frac{MVA_b}{\sqrt{3} \times KV_b} = \frac{25 \times 10^6}{\sqrt{3} \times 123.24 \times 10^3}$

[KV_b for secondary of transformer 1 or transmission line]

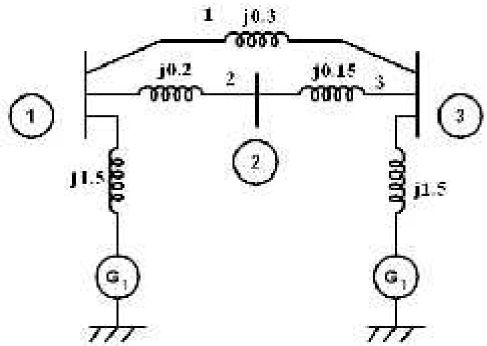
= 117.119 Amp.

Base current I_{base} = 117.119 Amp.

Actual fault current = I_f x I_{base} = 5.28 x 117.119 = 618.388 Amp.

Actual fault current = 618.388 Amp.

17. The generator at buses 1 and 3 of the network have impedances j1.5 p.u. If a 3 phase short circuit fault occurs at bus 3, when there is no load (all bus voltages are equal to $1.0\angle 0^o$ p.u), find initial symmetrical current in fault in the line 1-3, and post fault voltages when a fault at bus 2 using bus building algorithm.



Line flows.

$$I_{13} = \frac{V_1 - V_3}{Z_{13\ series}} = \frac{0.1103 - 0.0969}{j0.3} = -j\ 0.0447 \text{ p.u}$$

$I_{13} =$ - j 0.0447 p.u

Fault is at bus 3, so, $Z_{Th} = Z_{33} =$ j0.7879 p.u

$E_{Th} = 1\angle 0^0$; $Z_f = 0$

$$I_f = \frac{E_{Th}}{Z_{Th} + Z_f} = \frac{1\angle 0^0}{j0.7879 + 0} = -j1.2692 = 1.2692 \angle -90^0 \text{ p.u}$$

$I_f = 1.2692 \angle -90^0$ p.u

$V_1 = 1\angle 0^0 - I_1 Z_{1f} = 1\angle 0^0 - (-j1.2692) x\ j0.7111 = 0.09747\ p.u$

$V_2 = 1\angle 0^0 - I_2 Z_{2f} = 1\angle 0^0 - (-j1.2692) x\ j0.7551 = j0.4163\ p.u$

$V_1 = 0.09747\ p.u$

$V_2 = j0.4163\ p.u$

$V_3 = 1\angle 0^0 - I_3 Z_{3f} = 1\angle 0^0 - (-j1.2692) x\ j0.7879 = 0\ p.u.$

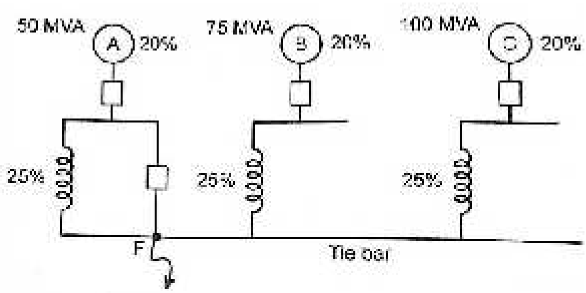
$V_3 = 0\ p.u.$

Line flows.

$$I_{13} = \frac{V_1 - V_3}{Z_{13}} = \frac{0.09747 - 0}{j0.3} = -j\ 0.3249 \text{ p.u}$$

$I_{13} =$ - j 0.3249 p.u

18. Three 11 KV generators, A,B and C each of 20% leakage reactance and MVA ratings 50,75 and 100 respectively are interconnected electrically as shown in fig. by a tie bar through current limiting reactor, each of 25% reactance based upon the bus-bar of generator A at a line voltage of 11 KV. The feeder has a resistance of 0.08 Ω/ph and an inductive reactance of 0.16 Ω/ph. Estimate the maximum MVA that can be fed into a symmetrical short circuit at the end of the feeder.



Current limiting reactor at A :

$Z_{p.u.\ new} = Z_{pu,given}$ x $[\frac{kV_{b,given}}{kV_{b,new}}]^2$ x $[\frac{MVA_{b,new}}{MVA_{b,given}}]$

= j 0.25 x $(11/11)^2$ x(100/50)

Z_{new} = j 0.5 p.u

Current limiting reactor at B :

$Z_{p.u.\ new} = Z_{pu,given}$ x $[\frac{kV_{b,given}}{kV_{b,new}}]^2$ x $[\frac{MVA_{b,new}}{MVA_{b,given}}]$

= j 0.25 x $(11/11)^2$ x(100/75)

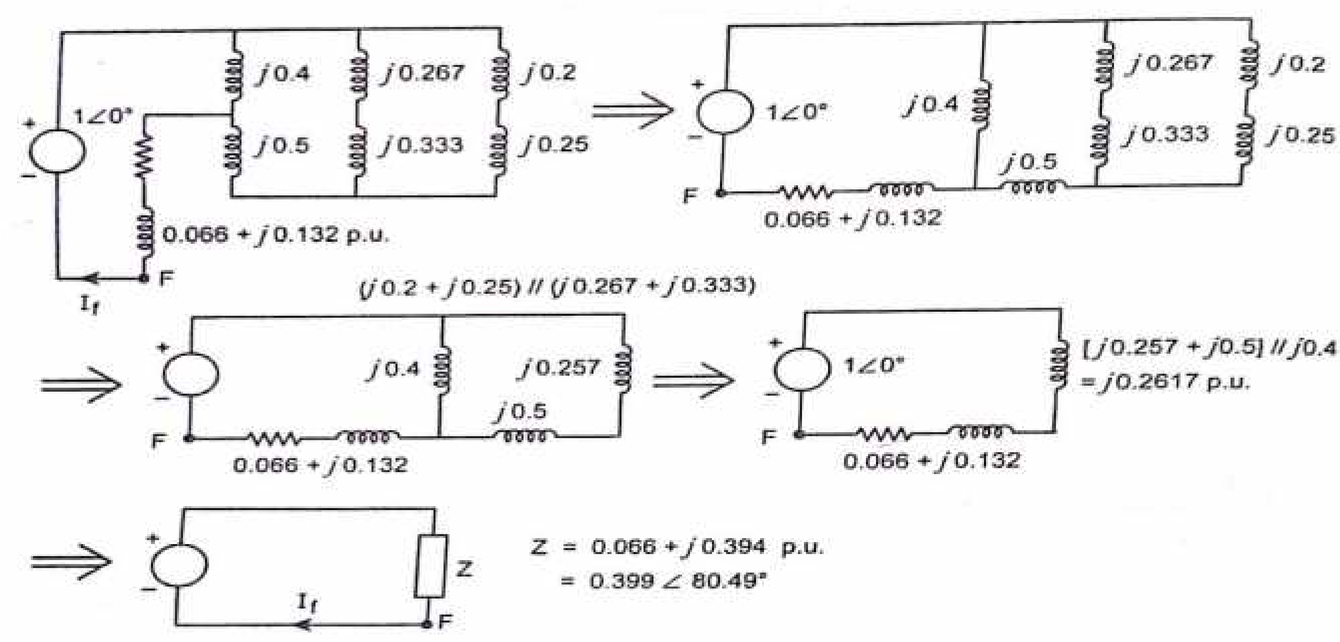
Z_{new} = j 0.33 p.u

Current limiting reactor at A :

$Z_{p.u.\ new} = Z_{pu,given}$ x $[\frac{kV_{b,given}}{kV_{b,new}}]^2$ x $[\frac{MVA_{b,new}}{MVA_{b,given}}]$

= j 0.25 x $(11/11)^2$ x(100/100)

Z_{new} = j 0.25 p.u



Short circuit MVA = $\frac{1}{Z_{Th}}$ p.u MVA

= $\frac{1}{0.399}$ = 2.506 p.u MVA

= 2.506 x100 = 250.6 MVA

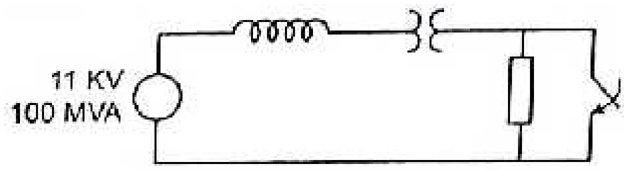
Short circuit MVA = 250.6 MVA

19. A 100 MVA, 11KV, 50 Hz, star connected three phase synchronous generator connected to a 11/220 KV, 100 MVA, Δ - Y connected transformer. The reactances are in per unit on the same base.

Reactance of generator: Xd = 0.9 p.u. X'_d = 0.2 p.u; X''_d = 0.1 p.u

Reactance of transformer is 0.2 p.u

A three phase load of 100 MVA, 0.8 p.f. lagging is connected to the transformer secondary side as shown in figure. The line to line voltage at the load terminals is 220 KV. A 3 phase short circuit occurs at the load terminals. Find the generator transient current including the load current.



Generator transient current = $I_f + I_L$

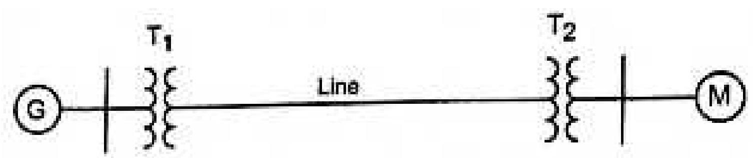
= - j2.5 + 0.8 – j0.6

= 0.8 – j3.1 p.u

= 3.2 $\angle -75.53^0$ p.u

Generator transient current = 3.2 $\angle -75.53^0$ p.u

20. A synchronous generator and synchronous motor each rated 30 MVA, 11 KV having 20% subtransient reactance are connected through transformers and line as shown in fig. the transformers are rated 30 MVA, 11/66 KV and 66/11 KV with leakage reactance of 10% each. The line has a reactance of 10% on a base of 30 MVA, 66 KV. The motor is drawing 20MW at 0.8 p.f leading and a terminal voltage of 10.6 KV when a symmetrical three phase fault occurs at the motor terminals. Find subtransient current in generator and motor.



Generator: Voltage behind sub transient reactance

$$E_g'' = V^o + j I^o X_{dg}'' = 0.9636\angle 0^\circ + j0.865\angle 36.87^o \times 0.5$$

= 0.704+j0.346 p.u

E_g'' = 0.704+j0.346 p.u

Under faulted condition $I_g'' = \dfrac{E_g''}{Z\ upto\ fault\ point\ from\ Generator}$

$$= \frac{0.704 + j0.346}{j0.5} = 0.642 - j1.408\ p.u$$

$I_g'' = 0.642 - j1.408\ p.u$

Motor: Voltage behind sub transient reactance:

$$E_m'' = V^o - jI^o \times X_{dm}'' = 0.9636\angle 0 - j0.865\angle 36.87^0 \times 0.2$$

$$=1.0674 - j0.1384\ p.u$$

Under faulted conditions, $I_m^{"} = \dfrac{E_m^{"}}{Zupto\ fault\ point\ from\ motor}$

$$= \frac{1.0674 - j0.1384}{j0.2} = -0.692 - j5.337\ p.u$$

$I_m^{"} = -0.692 - j5.337\ p.u$

Fault current $I_f = I_g^{"} + I_m^{"} = -j6.745\ p.u$

Base current (Gen/motor) $= \dfrac{MVA_b}{\sqrt{3} \times KV_b} = \dfrac{30}{\sqrt{3} \times 11} = 1.5746\ KA$

$$I_g^{"} = (0.692 - j1.408) \times 1.5746 = 1.086 - j2.217\ KA$$

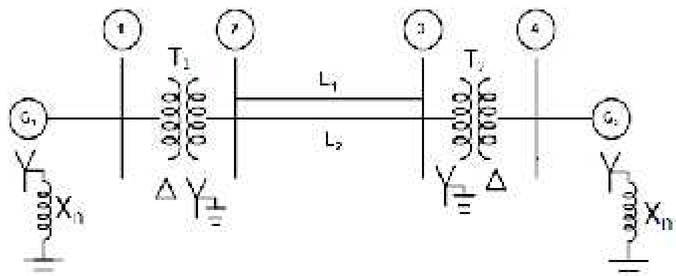
$$I_m^{"} = -0.692 - j5.337 \times 0.5746 = -1.089 - j8.404\ KA$$

$$I_f = -j6.745 \times 1.5337 = -j10.62\ KA$$

$I_f = -j10.62\ KA$

PART-C

21. A symmetrical fault occurs on bus 4 of system shown in fig. When Zf = j0.14 p.u., determine fault current and current supplied by the generators.



Fault current I_f = 4.04 ∠-90° p.u

Actual fault current = p.u value x base current.

$$= 4.04 \times \frac{MVA}{\sqrt{3}\ KV} = \frac{4.04 \times 100}{\sqrt{3} \times 20} = 11.66\ KA$$

Actual fault current = 11.66 KA

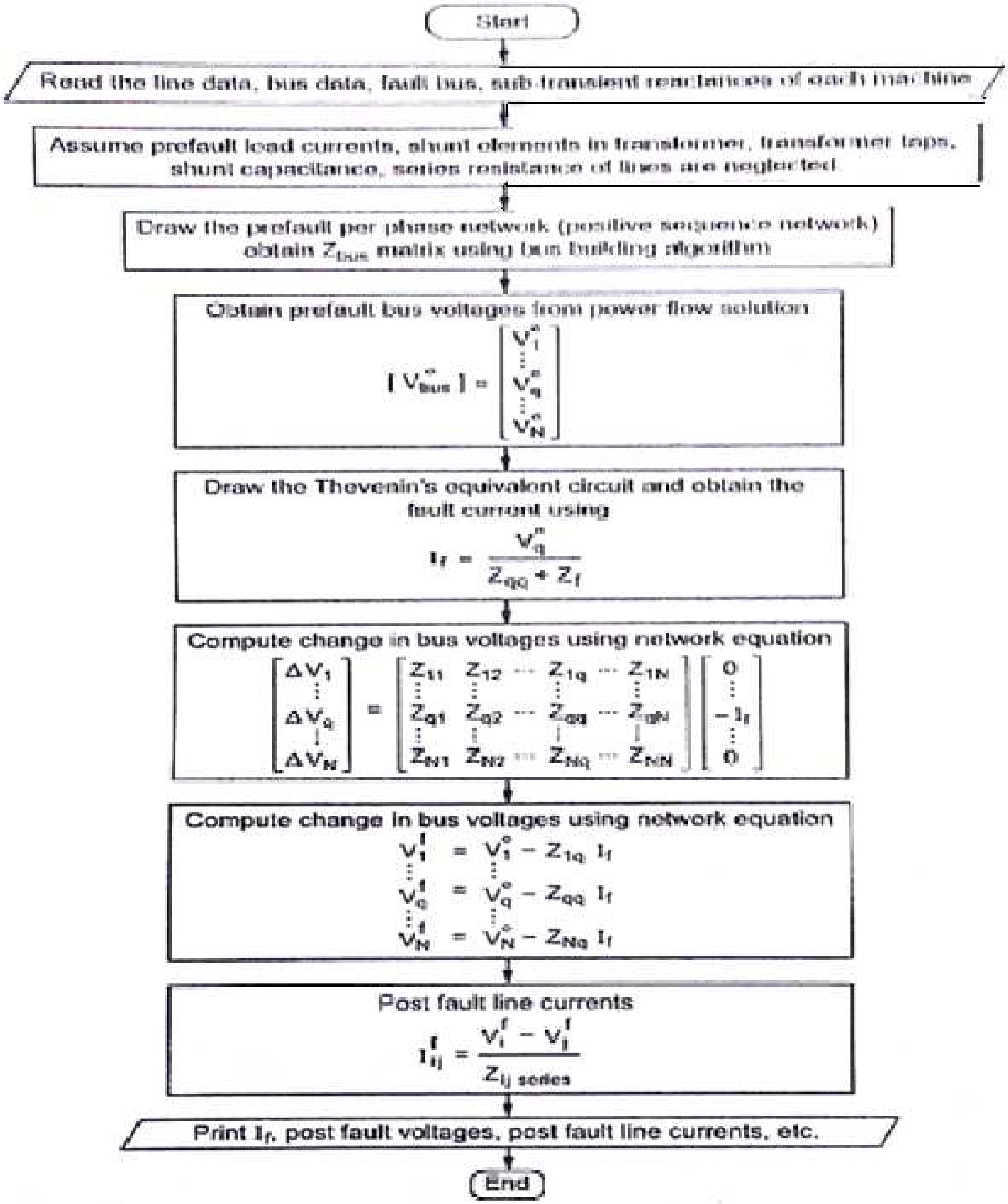
Current contribution from the Generators.

$$I_{G1} = I_f \times \frac{j0.15}{j0.15 + j0.38} = 1.1434 \angle -90^0\ p.u$$

$$I_{G2} = I_f \times \frac{j0.38}{j0.15 + j0.38} = 2.8966 \angle -90^0\ p.u$$

$I_{G1} = 1.1434 \angle -90^0$ p.u $I_{G2} = 2.8966 \angle -90^0$ p.u

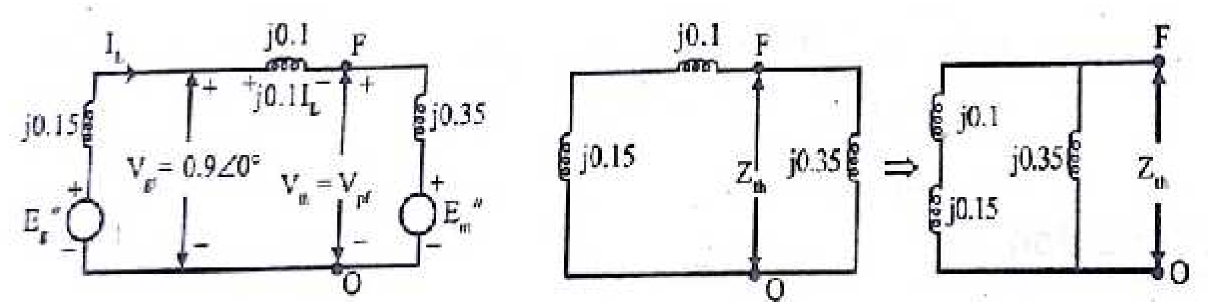
22. Draw the flowchart for symmetrical fault analysis using Z_{bus}



23. A generator is connected through a transformer to a synchronous motor. The subtransient reactances of generator and motor are 0.15 and 0.35 respectively. The leakage reactance of the transformer is 0.1 p.u. All the reactances are calculated on a common base. A three phase fault occurs at the terminals of the motor when the terminal voltage of the generator is 0.9 p.u. The output current of generator is 1 p.u. and 0.8 pf leading. Find the subtransient current in p.u. in the fault, generator and motor, Use the terminal voltage of the generator as reference vector.

Using Thevenin's theorem,

To find fault current:



In fig. using KVL we get,

$V_{tg} = j0.1I_L + V_{th}$

Thevenin's voltage, $V_{th} = V_{tg} – j0.1I_L$

$= 0.9\angle 0° - (0.1\angle 90° \times 1\angle 36.9°)$

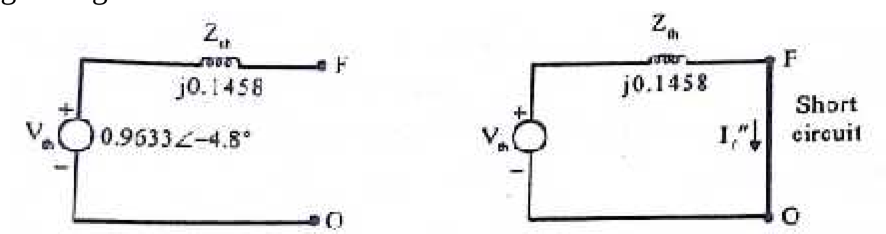
$= 0.9\angle 0° - (0.1\angle 126°) = 0.9 – (-0.06 + j0.08)$

$= 0.96 – j0.08 = 0.9633 \angle -4.8°$ p.u.

Thevenin's equivalent impedance, $Z_{th} = \frac{(j0.15+j0.1)j0.35}{(j0.15+j0.1)+j0.35} = j0.1458$ p.u.

$Z_{th} =$ j0.1458 p.u.

The Thevenin's equivalent of the circuit with respect to fault point is shown. Now short circuiting the terminals of the Thevenin's equivalent circuit as shown is equivalent to the fault condition. The current flowing through the short is the fault current.



Prefault thevenin's equivalent at fault point *Thevenin's equivalent under fault condition*

Current in the fault, If" $= \frac{V_{th}}{Z_{th}} = \frac{0.9633\angle -4.8°}{0.1458\angle 90°} = 6.606\angle -94.8°$ p.u.

If " = $6.606\angle -94.8°$ p.u.

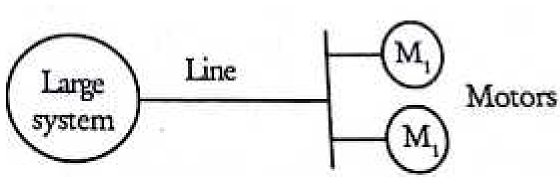
24. Two synchronous motors are connected to the bus of a large system through a transmission line as shown, The ratings of the various components are,

Motor each: 1 MVA, 440 V, 0.1 p.u. transient reactance

Line: 0.0 ohm reactance

Large system: Short circuit MVA at its bus at 440 V is 8.

When the motors are operated at 400V, calculate the short circuit current fed into a three phase fault at motor bus.



$I_f = 21.6969\angle -90°$ p.u.

Base current, $I_b = \frac{kVA_b}{\sqrt{3}kV_b} = \frac{1 \times 1000}{\sqrt{3} \times 0.44}$ = 1312.16 A = 1.3122 kA.

$\therefore$ Actual value of fault current, I_f = p.u. value of $I_f \times I_b = 21.6969\angle{-90°} \times 1.3122$

$I_f = 28.4707\angle{-90°}$ kA.

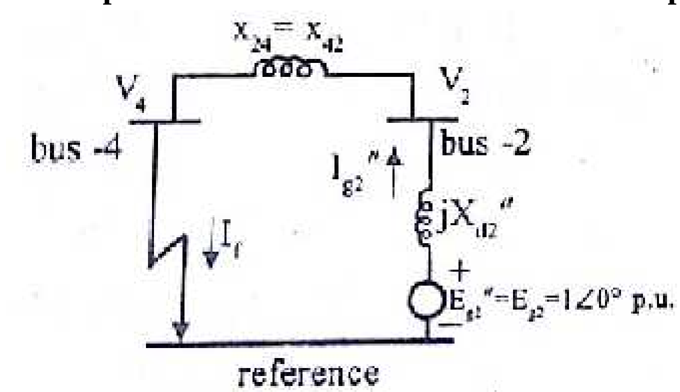
Result:

Fault current = $21.6969\angle{-90°}$ p.u. or $28.4707\angle{-90°}$ kA.

25. The bus impedance matrix of four bus system with values in p.u. is given by,

$$Z_{bus} = j\begin{bmatrix} 0.15 & 0.08 & 0.04 & 0.07 \\ 0.08 & 0.15 & 0.06 & 0.09 \\ 0.04 & 0.06 & 0.13 & 0.05 \\ 0.07 & 0.09 & 0.05 & 0.12 \end{bmatrix}$$

In this system generators are connected to buses 1 and 2 and their subtransient reactances were included when finding Zbus. If prefault current is neglected, find subtransient current in p.u. in the fault on a bus 4. Assume prefault voltage as 1 p.u. If the subtransient reactance of generator in bus 2 is 0.2 p.u. find the subtransient fault current supplied by generator.



With reference to fig.

The subtransient fault current delivered by the generator at bus -2, $I_{g2}'' = \frac{E_{g2}'' - V_2}{jX_{d2}''}$

$$I_{g2}'' = \frac{1\angle 0° - 0.25\angle 0°}{j0.2} = \frac{1 - 0.25}{0.2\angle 90°} = 3.75\angle{-90°} \text{ p.u.}$$

$I_{g2}'' = 3.75\angle{-90°}$ p.u.

Note: $I_f = I''_{g1} + I''_{g2}$

Result:

The subtransient fault current in the bus -4 = $I_f'' = 8.333\angle{-90°}$ p.u.

The voltage at bus – 2 when there is a 3 phase fault in bus – 4 = $V_2 = 0.75\angle 0°$ p.u.

The subtransient fault current delivered by the generator – 2 when there is a 3 – phase fault in bus – 4 } $I_{g2}'' = 3.75\angle{-90°}$ p.u.

IV - FAULT ANALYSIS – UNBALANCED FAULTS

Introduction to symmetrical components – sequence impedances – sequence circuits of synchronous machine, transformer and transmission lines - sequence networks analysis of single line to ground, line to line and double line to ground faults using Thevenin's theorem and Z-bus matrix.

PART – A

<u>Introduction to symmetrical components</u>

1. What is meant by unsymmetrical fault?

When the system is unsymmetrically faulted or loaded, neither the phase currents nor the phase voltages will possess three phase symmetry i.e the system remains unbalanced with unequal displacement. If the insulation of the system fails at a point or if a conducting object comes in contact with a bare conductor, an unsymmetrical fault is said to occur. If unsymmetrical fault occurs, the balanced currents will flow in the system. Symmetrical components are used for analyzing the unsymmetrical faults.

2. List out the different types of unsymmetrical faults.

The types of unsymmetrical faults are listed as follows.

- Line to Line fault (L-L)
- Line to Ground fault (L-G)
- Double line to Ground fault (L-L-G)
- Open conductor fault.

3. What is the purpose of analyzing unsymmetrical fault?

Analysis of unsymmetrical fault is very important for the following reasons. They are given as follows

- Relay setting,
- Single phase switching
- System stability studies

4. For a fault at a given location, rank the various faults in the order of severity.

In a power system, the most severe fault is three phase fault and less severe fault is open conductor fault. The various faults in the order of decreasing severity are,

- Three phase fault
- Double line to ground fault
- Line to line fault
- Single line to ground fault
- Open conductor fault

5. Give the steps followed in short circuit analysis of unbalanced low order systems?

The different steps to be followed in analyzing short circuit of an unbalanced low order system are as follows:

- Draw the positive, negative and zero sequence networks with their appropriate description.
- Choice of type of fault (L-G, L-L, or L-L-G) and location of fault and mathematical description for the particular type of fault.
- Using Thevenin's theorem or bus impedance matrix, determine the solution of the network equation. Fault current, post currents, post fault voltages are found at the point of fault, all the bus voltages, and the line flows.

6. What are the different symbols used in unsymmetrical fault calculation?

The following symbols are used in unsymmetrical fault calculation.

- Superscript f represents post fault or fault values.
- Super script +, - and 0 represents positive, negative and zero sequence voltages, current and impedance.
- A number subscript following this positive (+), negative (-) and zero (0) represents the bus code.

- Phase values of voltages and currents are indicated collectively by subscript p and individually by the subscript a, b and c.

Sequence Impedances – Sequence Networks

7. What is sequence network? (M/J'11). What are sequence impedances?

An unbalanced system of n related phasors can be resolved into n systems of balanced phasors called symmetrical components. Symmetrical components are positive, negative and zero sequence components. Hence these sequence component creates the network called as **Sequence network.**

Sequence impedances are the impedances offered by the power system components or elements to +ve, -ve and zero sequence current

8. What are the features of zero sequence current? (M/J'13)

It consists of three phasors equal in magnitude and with zero phase displacement from each other.

Zero sequence phasors a, b, c can be written as

$I_a^0 = I_b^0 = I_c^0$

Where I_a^0, I_b^0, I_c^0 are the sequence components of I^a, I^b *and* I^c

9. Define negative sequence impedance. (M/J'13, N/D'11)

The impedance offered to the flow of negative sequence currents is known as the negative sequence impedance and it is denoted by Z^-. The negative sequence impedance is occurred in all the fault condition and it is important to find the fault current.The positive sequence impedance and negative sequence impedance are same for transformers and power lines. But it in case of rotating machines the positive and negative sequence impedances are different.

10. Write the symmetrical component currents of phase 'a' in terms of three phase currents. (M/J'14)

$The\ symmentrical\ componets\ of\ currents\ are,$

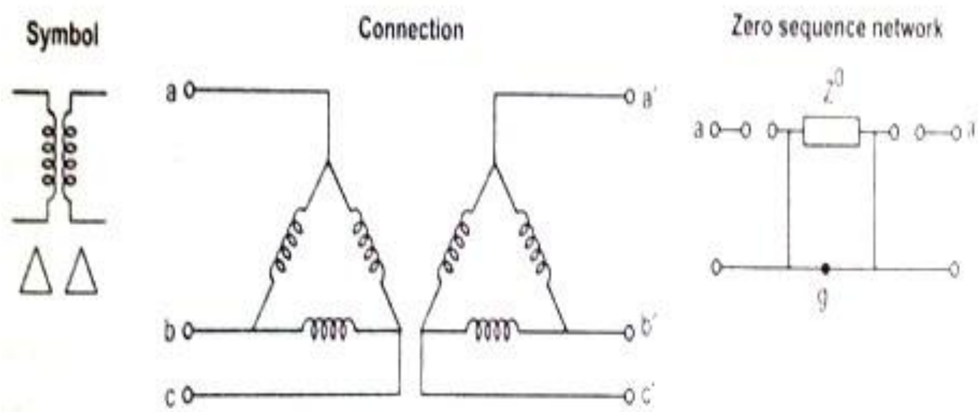
$$\begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$I_a^0 = \frac{1}{3}\left[I_a + I_b + I_c\right]$$

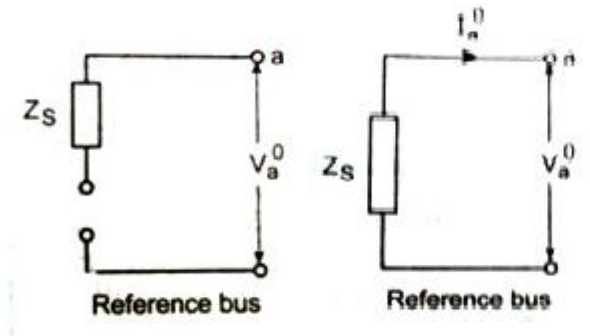
$$I_a^+ = \frac{1}{3}\left[I_a + aI_b + a^2 I_c\right]$$

$$I_a^- = \frac{1}{3}\left[I_a + a^2 I_b + aI_c\right]$$

11. Draw the sequence network for Δ – Δ connected transformer. (N/D'12)



12. Draw zero sequence impedance of generator. (M/D'12)



13. Write down the equation for symmetrical component of current vector of a three phase system.

$$I_a = I_a^0 + I_a^+ + I_a^-$$

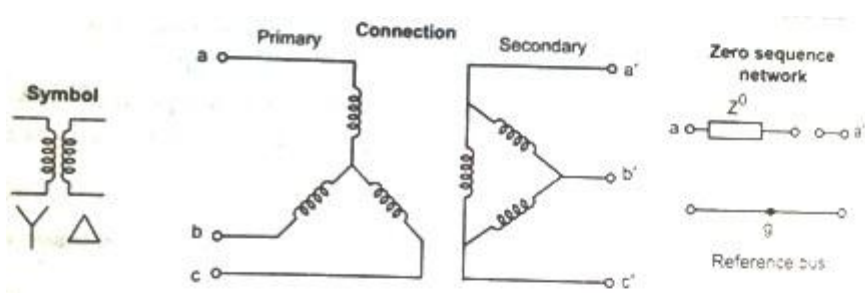
$$I_b = I_b^0 + I_b^+ + I_b^-$$

$$I_c = I_c^0 + I_c^+ + I_c^-$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}$$

$$where\ a = 1\angle 120^\circ\ and\ a^2 = 1\angle 240^\circ$$

<u>14. Draw the sequence network for Y – Δ connected transformer. (M/J'10)</u>



<u>15. Write the symmetrical components of a 3 Phase system. (M/J'11)</u>

In a 3 phase system, three unbalanced vectors can be resolved into three balance system of vectors.

- Positive sequence components
- Negative sequence components

- Zero sequence components.

16. What are positive sequence components?

The positive sequence components of a three phase unbalanced vectors consists of three components of equal magnitude, displaced each other by 120° in phase, and having the phase sequence same as the original vectors.

Three phases are written as

$$I_a^+ = I_a^+ \angle 0°$$
$$I_b^+ = I_a^+ \angle 240° = a^2 I_a^+$$
$$I_c^+ = I_a^+ \angle 120° = a I_a^+$$
$$where\ I_a^+, I_b^+, I_c^+ \ are\ the\ Positive\ sequence\ component\ of\ I_a, I_b and I_c$$

17. What are negative sequence components and zero sequence components?

The negative sequence components of a three phase unbalanced vectors consists of three components of equal magnitude, displaced each other by 120^{O} in phase, and having the phase sequence opposite to that of the original vectors.

The zero sequence components of a three phase unbalanced vectors consists of three vectors of equal magnitude and with zero phase displacement from each other.

18. Write down the equations to convert symmetrical quantities into phase quantities.

$$Let\ I_a, I_b, I_c\ be\ the\ unbalanced\ phase\ currents.$$
$$Let\ I_a^0, I_a^+, I_a^-\ be\ the\ symmetrical\ components\ of\ phase.$$
$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}$$
$$where\ a = 1\angle 120°\ and\ a^2 = 1\angle 240°$$

19.What is positive, negative and zero sequence impedance?

- Impedance offered to the flow of positive sequence current is known as positive sequence impedance and it is denoted by Z^+
- Impedance offered to the flow of negative sequence current is known as negative sequence impedance and it is denoted by Z^-
- Impedance offered to the flow of zero sequence current is known as Zero sequence impedance and it is denoted by Z^0

20. What are the causes of unsymmetrical faults?

The various causes for unsymmetrical faults are listed as follows.

- Lightning
- Wind damage
- Tree falling across lines
- Vehicles colliding with towers or poles, birds.
- Shorting lines
- Breaking due to excessive ice loading or snow loading, salt spray.

21. What is meant by fault calculations?

The fault condition of a power system can be divided into transient, sub-transient and steady state periods. The currents in the various parts of the system and in the fault locations are different in these periods. The estimation of these currents for various types of faults at various locations in the system can be commonly referred to as fault calculations.

22. Name the fault involving ground.

The fault which involve ground are given as follows.

- Line to ground fault
- Double line to ground fault
- 3phase to ground fault

Representation of single line to ground fault

23. What are the observation made from the analysis of various fault ? (N/D'13)

- Finding out the value of Fault current under different fault conditions
- Zero sequence is not presence in LL fault conditions
- Positive and negative sequence component of currents are opposite and equal to each other in LL fault condition
- Positive and negative sequence component of voltage are equal in LLG fault condition

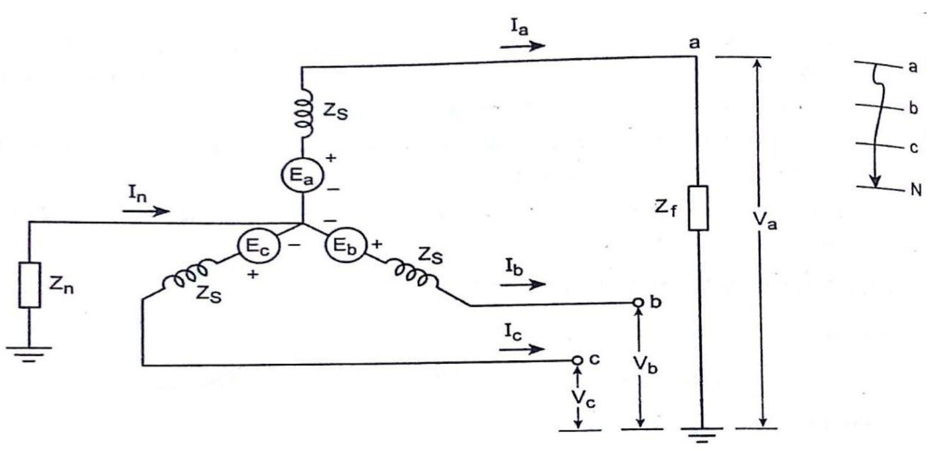
24. Write the boundary condition for the single line to ground fault. (N/D'13)

The boundary condition for the single line to ground fault are

- If the generator is solidly grounded, $Z_n = 0$ and for bolted fault or solid fault, $Z_f = 0$.
- If the neutral of the generator is ungrounded, the zero sequence network is open circuited.

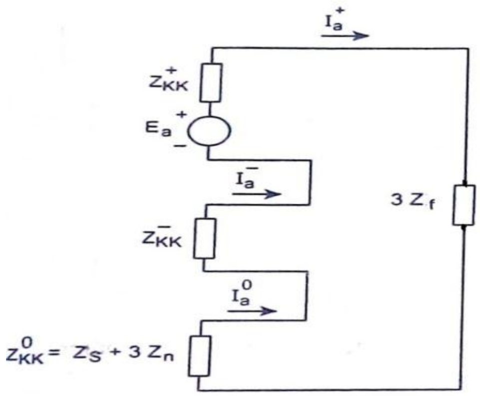
$\therefore I_a^+ = I_a^- = I_a^0 \; and \; I_f = 0$

25. Draw the diagram for L-G fault at phases.

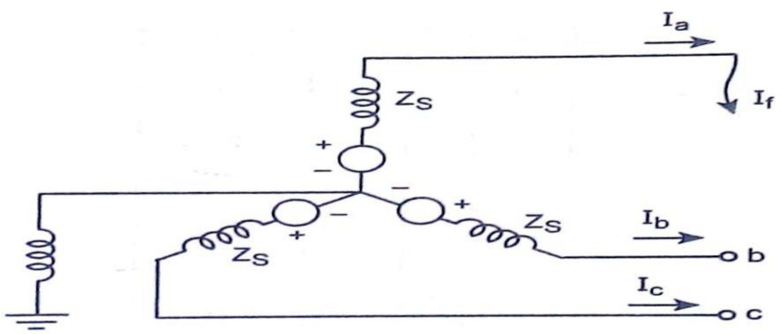


Single line to ground fault at phase 'a'

26. Draw the equivalent sequence network diagram for LG fault.

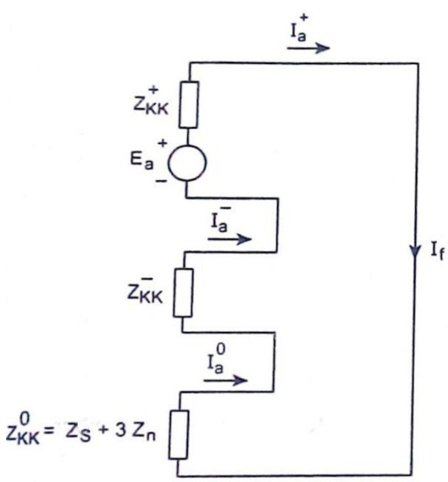


27. Draw the figure showing direct short circuit or bolted line to ground fault.



Direct short circuit LG fault at phase 'a'

28. Draw the equivalent sequence network diagram for direct short circuit or bolted L-G fault.



29. Name the fault in which all the sequence components are to be presents and give the reason for occurrence.

Single line to ground fault is the fault in which all the sequence components are present.

The reason for occurrence of fault are given as follows

- Lightning
- Conductors making contact with grounded structures like towers or poles, etc.

30. Write down the expression for fault current in LG fault.

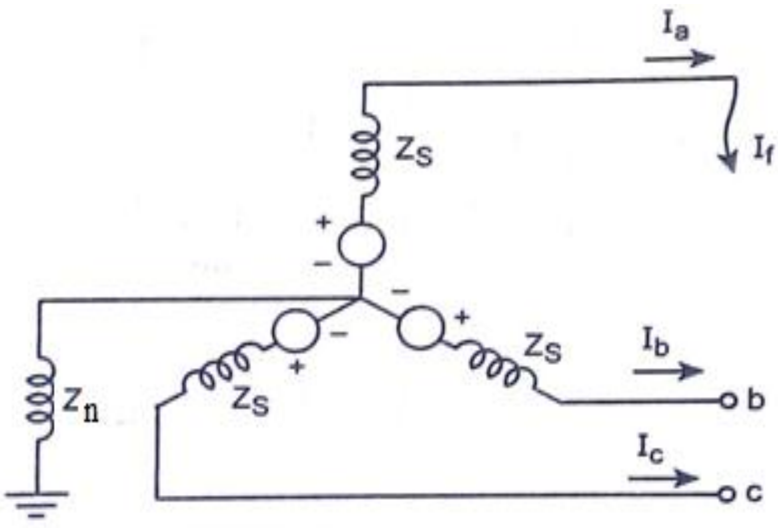
The expression for fault current in LG fault is given as follows

$$I_f = \frac{3E_a}{Z_{kk}^0 + Z_{kk}^+ + Z_{kk}^- + 3Z_f}$$

$$\begin{aligned} \textit{Where } Z_{kk}^0 &= \textit{Zero sequence impedance} \\ Z_{kk}^+ &= \textit{Positive sequence impedance} \\ Z_{kk}^- &= \textit{Negative sequence impedance} \\ E_a &= \textit{prefault voltage} \\ Z_f &= \textit{Fault impedance} \end{aligned}$$

31. In which type of fault at phase ‘a’, there is no current flows through ‘b’ and ‘c’ phases.

Line to ground fault is the only fault in which there is no flow of current between the phases



From the above figure b and c phases are open. Therefore no current flows through b and c phases.

32. Write the general equation to determine post fault voltages.

$$Post\ fault\ positive\ sequence\ bus\ voltages:$$

$$V_f^+ = V_0^+ + Z_{ik}^+ I_f = V_0^+ - Z_{ik}^+ I_f^+$$

$$Post\ fault\ negative\ sequence\ bus\ voltages:$$

$$V_f^- = -Z_{ik}^- I_f^-$$

$$Post\ fault\ positive\ sequence\ bus\ voltages:$$

$$V_f^0 = -Z_{ik}^0 I_f^0$$

33. Write the general equation to determine sequence line currents.

$$Positive\ sequence\ current\ I_{ij}^+ = \frac{V_{fi}^+ - V_{fj}^+}{Z_{ij}^+}$$

$$Negative\ sequence\ current\ I_{ij}^- = \frac{V_{fi}^- - V_{fj}^-}{Z_{ij}^-}$$

$$Zero\ sequence\ current\ I_{ij}^0 = \frac{V_{fi}^0 - V_{fj}^0}{Z_{ij}^0}$$

Representation of line to line fault

34. Name the faults which do not have zero sequence current flowing (N/D'11) and zero sequence components.

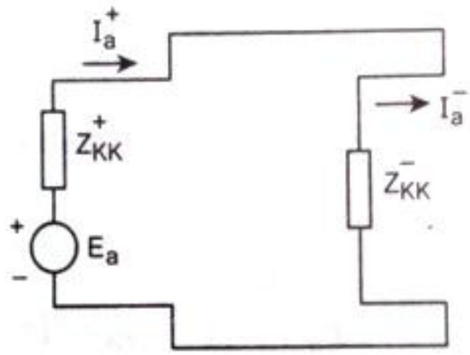
Double line fault (LL fault) because voltage through zero sequence network is zero and there are no zero sequence sources and $I_a^0 = 0$, current is not being injected into that network due to the fault. Hence LL fault does not involve zero sequence network.

The faults which does not have zero sequence components are given as follows. They are:

- Three phase fault

- Line – Line fault

35. Draw the equivalent sequence network for L-L bolted fault in power system. (M/J'10)



36. Which type of fault has + and – sequence current are same and opposite in direction?

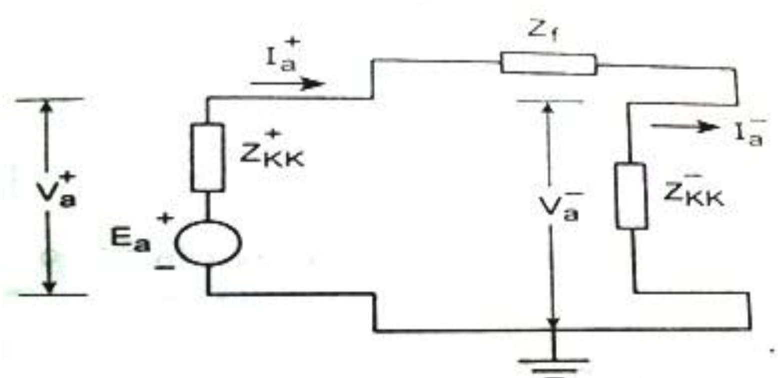
Line to Line fault.

$$I_a^+ = \frac{1}{3}\left[aI_b - a^2 I_b\right]$$

$$I_a^- = \frac{1}{3}\left[a^2 I_b - aI_b\right]$$

$$\therefore I_a^+ = -I_a^-$$

37. Draw the sequence network connection to LL fault. (M/J'13)



38. Write down the expression for fault current in L-L fault.

$$I_f = I_b = \frac{-j\sqrt{3}E_a}{Z_{kk}^{+} + Z_{kk}^{-} + Z_f}$$

Where

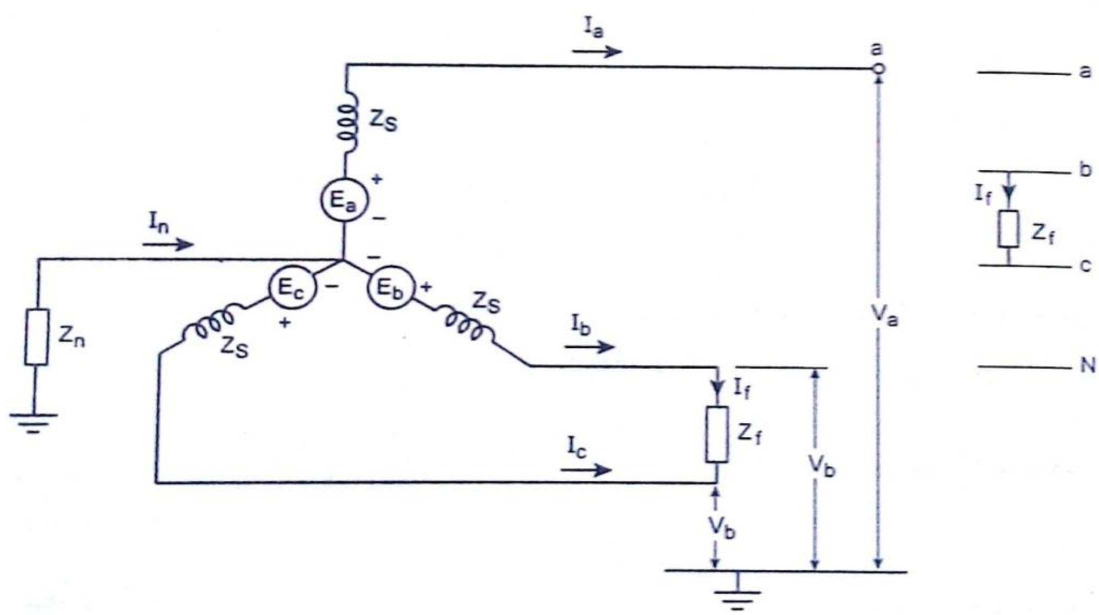
$Z_{kk}^{+} = Positive\ sequence\ impedance$

$Z_{kk}^{-} = Negative\ sequence\ impedance$

$E_a = prefault\ voltage$

$Z_f = Fault\ impedance$

39. Draw the figure showing L-L fault between two phases.



Line to line fault between phases b and c

40. Name the fault in which + and – sequence voltage are equal.

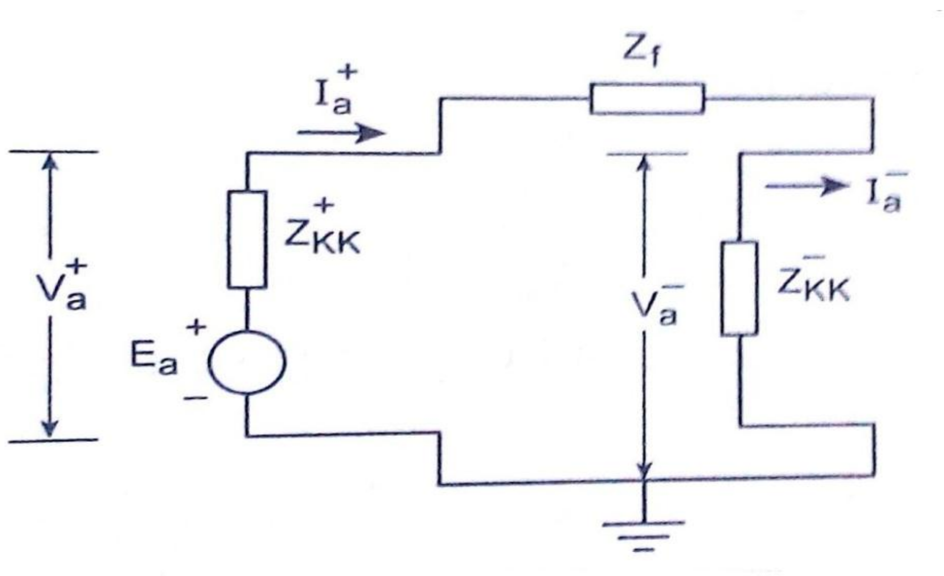
Double line to ground fault

$$V_a^{+} = \frac{1}{3}[V_a - V_b]$$

$$V_a^{-} = \frac{1}{3}[V_a - V_b]$$

$$\therefore V_a^{+} = V_a^{-}$$

41. Draw the equivalent sequence network for L-L fault.



Representation of line to line to ground fault

42. Write the equation to determine fault current for L-L-G fault with fault impedance between phase 'b' and 'c'.

$$Fault\ current\ I_f = 3I_a^0 = -3\left[\frac{E_a - Z_{KK}^+ I_a^+}{Z_{KK}^0 + 3Z_f}\right]$$

$Where\ \ I_a^+ = Positive\ sequence\ current$

$E_a = prefault\ voltage$

$Z_{KK}^0 = Zero\ sequence\ impedance$

$Z_{KK}^+ = Positive\ sequence\ impedance$

$Z_f = Fault\ impedance$

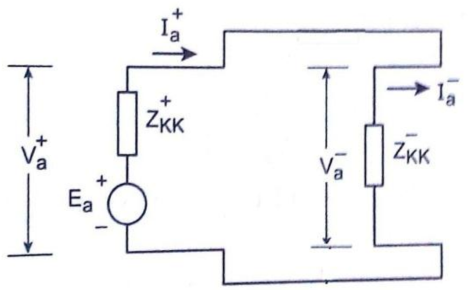
43. What type of fault occurs when fault impedance is infinite for LLG fault?

Line to line fault occurs, because

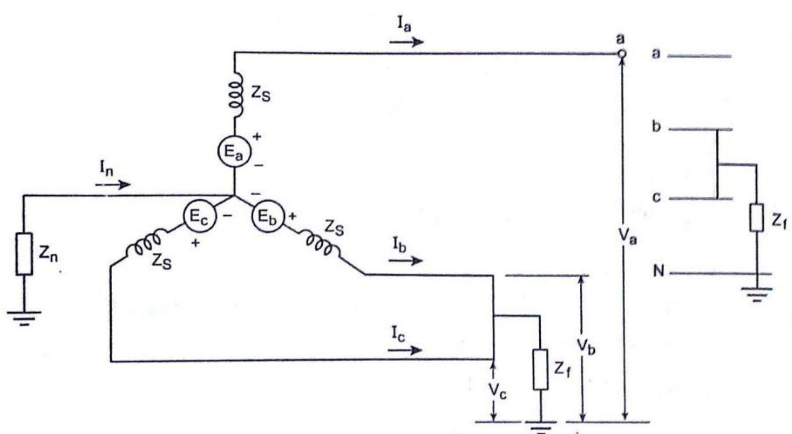
$Z_f = \infty$

$I_a^0 = 0$

Hence the sequence network becomes



44. Draw the diagram for L-L-G fault between phases.



Double line to ground fault between phases b and c

45. Give the expression for fault current in L-L-G fault.

$$I_f = \frac{-3}{Z_{KK}^0 + 3Z_f}\left[\frac{E_a \times Z_{KK}^- \left(Z_{KK}^0 + 3Z_f\right)}{Z_{KK}^- \times Z_{KK}^0 + 3Z_f Z_{KK}^+ + Z_{KK}^+ Z_{KK}^- + Z_{KK}^- Z_{KK}^0 + 3Z_f Z_{KK}^-}\right]$$

Where

$Z_{kk}^+ =$ *Positive sequence impedance*

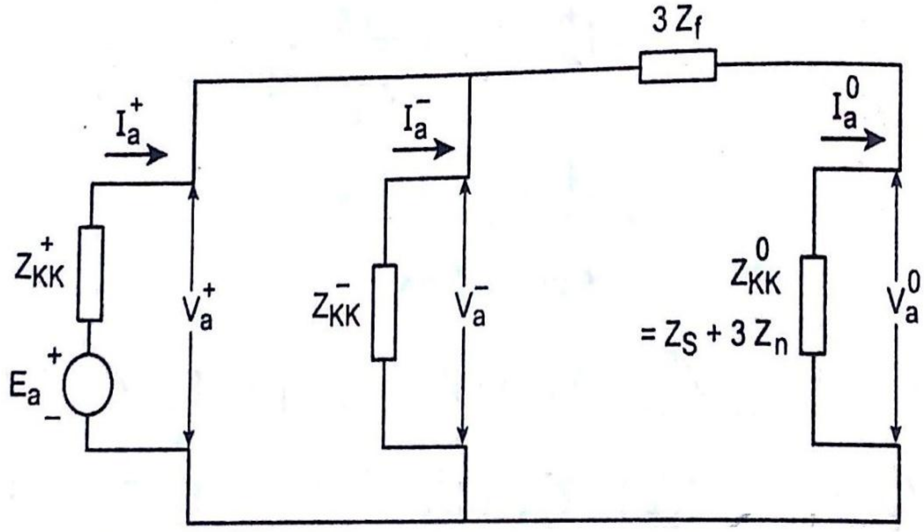
$Z_{kk}^- =$ *Negative sequence impedance*

$Z_{kk}^0 =$ *Zero sequence impedance*

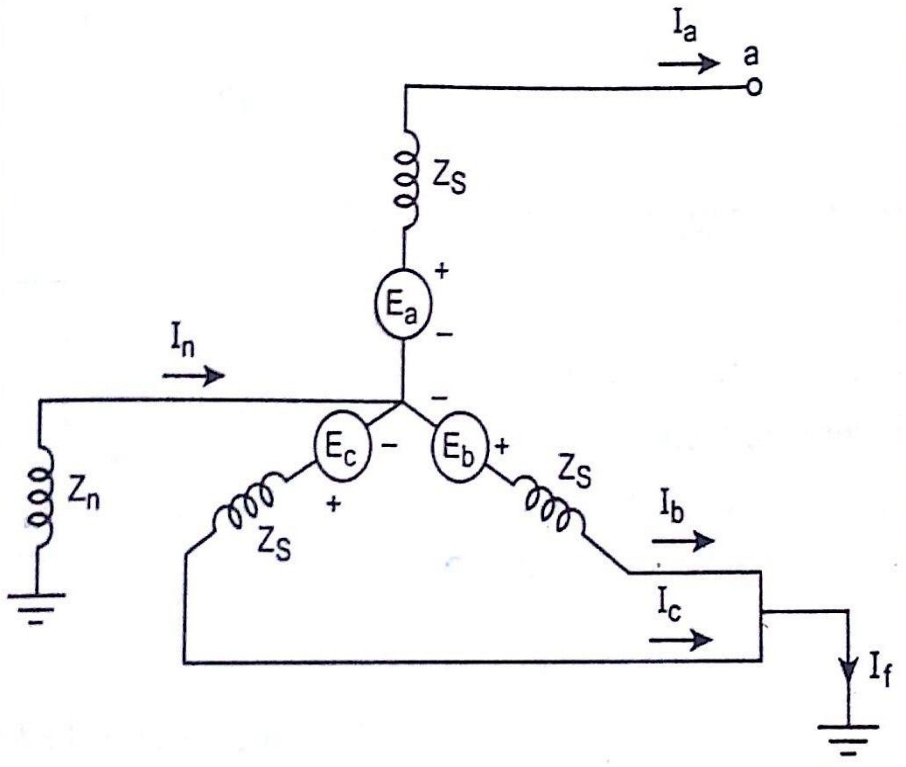
$E_a =$ *prefault voltage*

$Z_f =$ *Fault impedance*

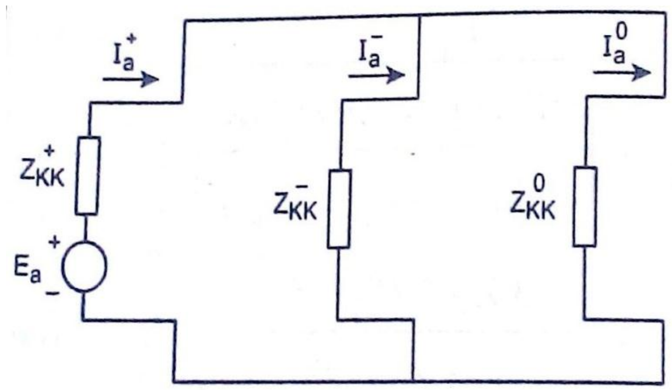
46. Draw the equivalent sequence network diagram for L-L-G fault.



47. Draw the figure showing direct short circuit or bolted L-L-G fault.



48. Draw the equivalent sequence network diagram for bolted L-L-G fault.



49. Find the fault if prefault voltage at the fault point is 0.97 p.u.

Solution:

j0.2 and j0.15 are in series

Its becomes, j0.2 + j0.15 = j0.35

j0.35 is in parallel with j0.15.

$$Z_{Th} = \frac{j0.35 \times j0.15}{j0.5 + j0.15} = j0.105\, p.u.$$

$$Fault\, current\, I_f = \frac{V_{Th}}{Z_{Th}} = \frac{0.97}{j0.105} = -j9.238\, p.u.$$

50. What is the need for short circuit study?

Whenever a fault occurs in an electrical power system, relatively high currents flow, producing large amounts of destructive energy in the forms of heat and magnetic forces. A short circuit study ensures that protective device ratings within a power system are adequate for maximum currents that flow during a fault.

A short circuit study is performed to:

1. Make certain protective devices have adequate interrupting current capability;
2. Ensure power system components can withstand mechanical and thermal stresses that occur during a fault; and
3. Calculate current data for protective device coordination studies.

51. Express short circuit KVA in terms of base of KVA and per unit reactance.

$$Short\ circuit\ capacity = \frac{1}{X_{Th}}\ p.u.MVA$$
$$= \frac{1}{X_{Th}} \times MVA_b \quad MVA$$
$$= \frac{1}{X_{Th}} \times KVA_b \quad KVA$$

where X_{Th} = Thevenin equivalent reactance.

KVA_b = Base KVA.

52. Define transient reactance.

It is the ratio of induced emf on no-load and the transient symmetrical rms current.

It is given by,

$$Transient\ reactance,\ X_d^{'} = \frac{|E_g|}{|I'|} = X_l + \frac{1}{\frac{1}{X_a} + \frac{1}{X_f}}$$

where X_l = Leakage reactance

X_f = Field winding reactance

X_a = Armature reaction reactance

53. What is meant by sub transient reactance?

The sub transient reactance is the ratio of included emf on no load and the sub transient symmetrical rms current. It is given by

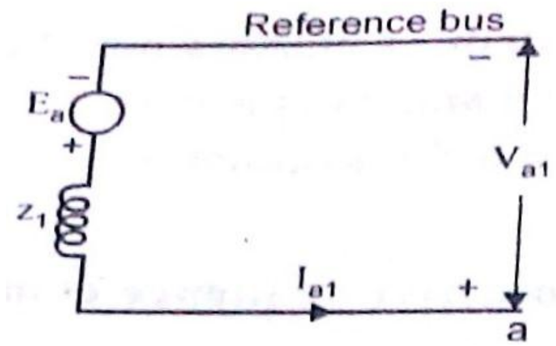
$$X_d^{"} = \frac{|E_g|}{|I"|} = X_l + \frac{1}{\frac{1}{X_a} + \frac{1}{X_f} + \frac{1}{X_{dw}}}$$

54. What is the significance of sub transient reactance and transient reactance in short circuit studies?

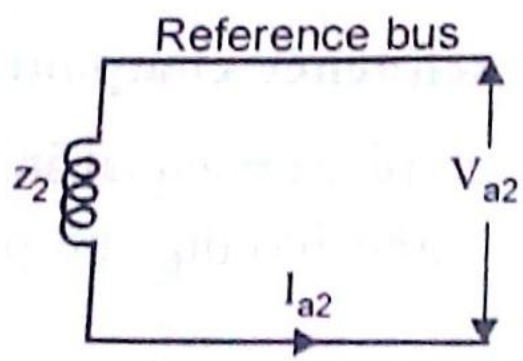
The sub transient reactance can be used to estimate the initial value of fault current immediately on the occurrence of fault. The maximum momentary short circuit of the current rating of the circuit breaker used for protection of fault clearing should be less than its initial fault current.

The transient reactance is used to estimate the transient state fault current. Most of the circuit breakers open their contacts only during this period. Therefore for a circuit breaker used for fault clearing, its interrupting short circuit current rating should be less than the transient fault current.

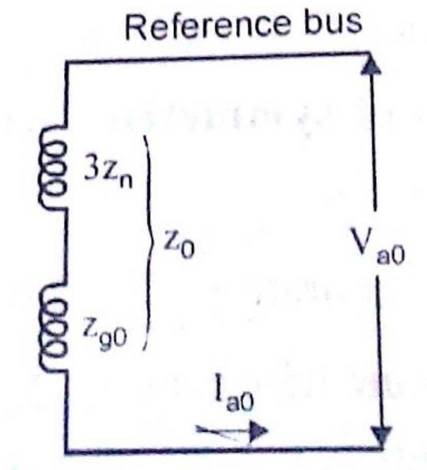
55. Draw the positive sequence network of an unloaded synchronous generator with its neutral grounded through reactor.



56. Draw the negative sequence network of an unloaded synchronous generator with its neutral grounded through reactor.



57. Draw the zero sequence network of an unloaded synchronous generator with its neutral grounded through reactor.



58. Why delta connected load will not have any zero sequence components?

Delta connected load will not have zero sequence components because the current in the neutral is three times the zero sequence line current. A delta connected load provides no path to neutral and hence line currents flowing to a delta connected load cannot contain zero sequence components.

59. Write about the lightning effect on electrical installations.

Lightning damages electrical and electronic systems in particular: transformers, electricity meters and electrical appliances on both residential and industrial premises.
The cost of repairing the damage caused by lightning is very high. But it is very hard to assess the consequences of the following:

- Disturbances caused to computers and telecommunication networks;
- Faults generated in the running of programmable logic controller programs and control systems.

Moreover, the cost of operating losses may be far higher than the value of the equipment destroyed.

60. Write about the electric strokes impact on a building.

Lightning strokes can affect the electrical (and/or electronic) systems of a building in two ways:

- By direct impact of the lightening stroke on the building
- By indirect impact of the lightning stroke on the building

a. A lightning stroke can fall on an overhead electric power line supplying a building. The over current and overvoltage can spread several kilometers from the point of impact.

b. A lightning stroke can fall near an electric power line. It is the electromagnetic radiation of the lightning current that produces a high current and an overvoltage on the electric power supply network.

   In the latter two cases, the hazardous currents and voltages are transmitted by the power supply network.

c. A lightning strike can fall near a building. The earth potential around the point of impact rises dangerously.

61. How does the open conductor fault occurs?

When one or two of a three phase circuit is open due to accidents, storms, etc.., then unbalance is created and the asymmetrical currents flow. Such types of faults that come in series with the lines are referred as the open conductor faults. The open conductor faults can be analyzed by using the sequence networks drawn for the system under consideration as seen from the point of fault, F. These networks are then suitably connected to simulate the given type of fault.

62. How is the analysis of unsymmetrical faults done on power systems?

The analysis of unsymmetrical fault in power systems is done in a similar way as that followed thus far for the case of a fault at the terminals of a generator. Here, instead of the sequence impedances of the generator, each and every element is to be replaced by their corresponding sequence impedances and the fault is analyzed by suitably connecting them together to arrive at the Thevenin's equivalent impedance if that given sequence.

PART - B

1. Explain about the concept of symmetrical component. (N/D'14) (16)

One of the most powerful tools for dealing with unbalanced polyphase circuits is the method of symmetrical components. An unbalanced system of n related phasors can be resolved into n systems of balanced phasors called symmetrical components. Symmetrical components are positive, negative and zero sequence components.

Balanced System **(2)**

The load impedance is the same in all 3Φ and the voltage and currents are characterized by complete three phase symmetry. It is given by

$$I_a + I_b + I_c = I_n = 0$$

Unbalance fault

In an unsymmetrical fault or loaded system, neither the phase currents nor the phase voltages possess three-phase symmetry.

The algebraic sum of the phase current is equal to the neutral current flowing in the system. It is given by,

$$I_a + I_b + I_c = I_n$$

Where

I_a, I_b, I_c *are phase current*

I_n *is the neutral current.*

Phase Sequence **(3)**

In three phase system, the phase sequence is defined as the order in which they pass through a positive maximum.

Consider the unbalanced current I_a, I_b, I_c shown in figure. These current are resolved into three symmetrical components. They are positive, negative and zero sequence.

Positive Sequence Components

It consists of three components of equal magnitude, displaced each other by 120^o in phase, and having the phase sequence abc as shown in figure.

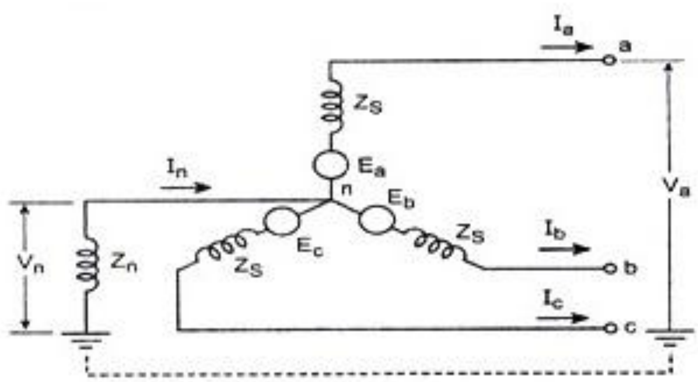
Let I_a^+ be the reference phasor.

Positive sequence phasors a,b,c can be written in terms of I_a^+ as,

$$I_a^+ = I_a^+ \angle 0°$$
$$I_b^+ = I_a^+ \angle 240° = a^2 I_a^+$$
$$I_c^+ = I_a^+ \angle 120° = a I_a^+$$
$$where\ I_a^+, I_b^+, I_c^+ \ are\ the\ Positive\ sequence\ component\ of\ I_a, I_b\ and\ I_c$$

<u>Negative Sequence components</u> **(3)**

It consists of three components of equal magnitude, displaced by 120^o in phase, and having the phase sequence abc as shown in figure.



Unbalanced generator equivalent circuit

Let I_a^- be the reference phasor.

Negative sequence phasors a,b,c can be written in terms of I_a^- as,

$$I_a^- = I_a^- \angle 0°$$
$$I_b^- = I_a^- \angle 120° = a I_a^+$$
$$I_c^- = I_a^- \angle 240° = a^2 I_a^+$$
$$where\ I_a^-, I_b^-, I_c^- \ are\ the\ negative\ sequence\ component\ of\ I_a, I_b and\ I_c$$

<u>Zero Sequence Components</u> **(2)**

It consists of three phasors equal in magnitude and with zero displacement from each other as shown in figure.

Zero sequence phasors a,b,c can be written as

$$I_a^0 = I_b^0 = I_c^0$$

$$\text{where } I_a^0, I_b^0, I_c^0 \text{ are the zero sequence components of } I_a, I_b \text{ and } I_c$$

<u>Symmetrical component transformation</u> **(6)**

The three phase unbalanced currents $I_a, I_b and\ I_c$ can be represented in terms of sequence currents as

$$I_a = I_a^0 + I_a^+ + I_a^-$$
$$I_b = I_b^0 + I_b^+ + I_b^-$$
$$I_c = I_c^0 + I_c^+ + I_c^-$$

According to the definition of symmetrical components, we can rewrite above equation in terms of phase a components.

$$I_a = I_a^0 + I_a^+ + I_a^-$$
$$I_b = I_b^0 + a^2 I_b^+ + a I_b^-$$
$$I_c = I_c^0 + a I_c^+ + a^2 I_c^-$$

Write the above equation in matrix form,

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}$$

$$\text{where } a = 1\angle 120° \text{ and } a^2 = 1\angle 240°$$

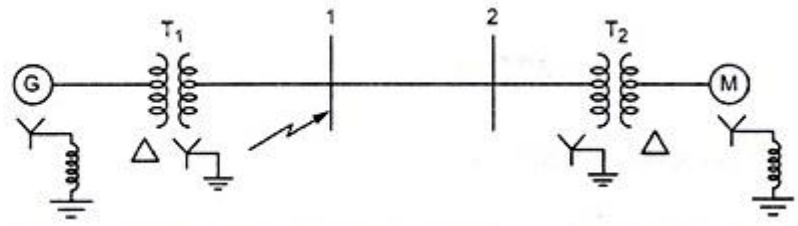
In simple form,

$$[I_p] = [T][I_s]$$

$$\text{where } I_p = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$I_s = \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix} \quad T = \text{Symmetrical component transformation matrix}$$

2. **A single line to ground fault occurs on the bus 1 of the power system of fig. shown below.**



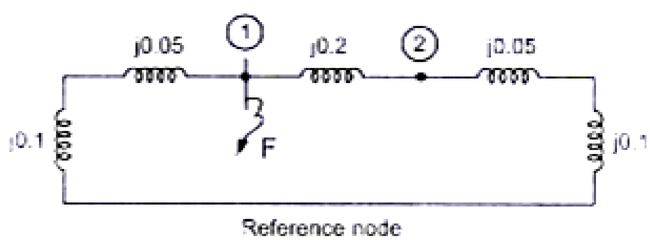
Find:

i. **Current in the fault**
ii. **SC current in phase a of generator**
iii. **Voltage of the healthy phases of the bus 1 using Z_{bus} method.**

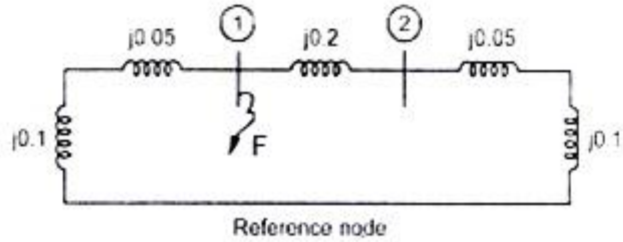
Given values: Rating of each machine 1200 KVA, 600 V with X_1=X_2=10 % and X_0= 5%. Each three phase transformer is rated 1200 KVA, 600 V / 3300 V (Δ/Y) with leakage reactance of 5%. The reactance of transmission line are X_1=X_2=20 % and X_0 = 40 % on the base of 1220 KVA, 3300 V. The reactance of neutral grounding reactance are 5% on the KVA and voltage base of the machines. (N/D'14) (16)

Solution :

Positive sequence (1)



Negative sequence (1)



$$Formulate\ Z_{bus}:$$

$$Z_{bus}^{new} = \begin{bmatrix} j0.15 & j0.15 \\ j0.15 & j0.35 \end{bmatrix}$$

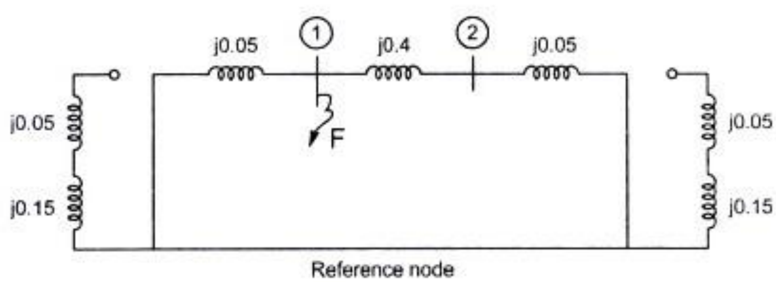
Adding an element between existing node

$$Z_{bus}^{new} = \begin{bmatrix} j0.15 & j0.15 & j0.15 \\ j0.15 & j0.35 & j0.35 \\ j0.15 & j0.35 & j0.5 \end{bmatrix}$$ **(4)**

$$Apply\ Kron\ reduction, Z_{bus}^{+} = Z_{bus}^{-} = \begin{bmatrix} j0.105 & j0.045 \\ j0.045 & j0.105 \end{bmatrix}$$

$$Z_{11}^{+} = Z_{11}^{-} = j0.105$$

Zero sequence **(2)**



$$Z_{bus} = [j0.05]$$

Adding an element $j0.4$ *between nodes* (1) *and* (2)

$$Z_{bus} = \begin{bmatrix} j0.05 & j0.05 \\ j0.05 & j0.45 \end{bmatrix}$$

Adding an element $j0.05$ *between nodes* (2) *and ref node,*

$$Z_{bus} = \begin{bmatrix} j0.05 & j0.05 & j0.05 \\ j0.05 & j0.45 & j0.45 \\ j0.05 & j0.45 & j0.5 \end{bmatrix}$$ **(2)**

Apply Kron reduction,

$$Z_{bus}^0 = \begin{bmatrix} j0.045 & j0.005 \\ j0.005 & j0.045 \end{bmatrix}$$

$$Z_{11}^0 = j0.045$$

Current in the fault $I_f = 3I_a^+$

$$I_a^+ = \frac{1\angle 0°}{Z_{11}^+ + Z_{11}^- + Z_{11}^0 + 3Z_f}$$

$$= \frac{1\angle 0°}{j0.105 + j0.105 + j0.045 + 0} = -j3.92\ p.u.$$

Current in the fault $I_f = 3 \times (-j3.92) = -j11.7\ p.u.$

Current in the fault $I_f = 3I_a^+$
$I_a^+ = -j3.92\ p.u.$
Current in the fault $I_f - j11.7\ p.u.$

ii) short circuit current on transmission lines

Positive sequence post fault bus voltages,

$$V_f^+ = V_f^+ - Z_{11}^+ I_f^+$$

$$= 1.0 - j0.105 \times (-j3.92) = 0.5884$$ **(3)**

$$V_{f2}^+ = V_0^+ - Z_{12}^+ I_f^+$$

$$= 1.0 - j0.045 \times (-j3.92) = 0.8236$$

Negative sequence post fault bus voltages

$$V_f^- = -Z_{11}^- I_f^-$$

$$= -j0.105 \times (-j3.92) = -0.4116$$

$$V_{f2}^- = -Z_{12}^0 I_f^0$$

$$= -j0.045 \times (-j3.92) = -0.1764$$

Zero sequence post fault bus voltages

$$V_f^0 = -Z_{11}^0 I_f^0$$
$$= -j0.045 \times (-j3.92) = -0.1764$$
$$V_{f2}^0 = -Z_{12}^0 I_f^0$$
$$= -j0.005 \times (-j3.92) = -0.0196$$

$$\text{Positive sequence current } I_{12}^+ = \frac{V_{f1}^+ - V_{f2}^+}{Z_{12(line)}^+}$$
$$= \frac{0.5884 - 0.8236}{j0.2} = j1.176\ p.u$$

$$I_{12}^- = \frac{V_{f1}^- - V_{f2}^-}{Z_{12(line)}^-} = \frac{-0.4116 - (-0.1764)}{j0.2} = j1.176\ p.u$$
$$I_{12}^0 = \frac{V_{f1}^0 - V_{f2}^0}{Z_{12(line)}^0} = \frac{-0.1764 - (-0.0196)}{j0.4} = j0.392\ p.u$$

$$\text{Positive sequence current } I_{12}^+ = j1.176\ p.u$$

$$I_{12}^- = j1.176\ p.u$$
$$I_{12}^0 = j0.392\ p.u$$

iii) Voltage of healthy phase of bus 1:

$$V_a = 0$$
$$V_b = a^2 V_1^+ + a V_1^- + V_1^0$$
$$= 1\angle 240° \times 0.5884 + 1\angle 120° \times (-0.4116) + (-0.1764)$$
$$= -0.2646 - j0.866$$
$$= 0.9056\angle -107°$$
$$V_c = a V_1^+ + a^2 V_1^- + V_1^0$$
$$= 1\angle 120° \times 0.5884 + 1\angle 240° \times (-0.4116) + (-0.1764)$$
$$= 0.9056\angle 107°$$

(3)

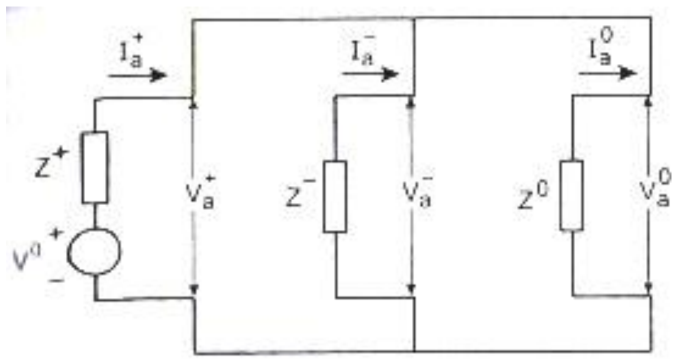
Voltage of healthy phase of bus 1:

$$V_a = 0$$
$$V_b = 0.9056\angle -107°$$
$$V_c = 0.9056\angle 107°$$

3. **A 25 MVA, 13.2 KV alternator with solidly grounded neutral has a sub transient reactance of 0.25 p.u. The negative and zero sequence reactance are 0.35 and 0.01 p.u respectively. If a double line to ground fault occurs at the terminal of the alternator, determine the fault current and line to line voltage at the fault.**

(M/J'14) (16)

Solution : Sequence network is **(2)**



Prefault voltage = $E_a = V_0 = 1\angle 240°$

$$\text{Positive sequence current } I_a^+ = \frac{V^0}{Z^+ + \left(\frac{Z^- \times Z^0}{Z^- + Z^0}\right)}$$ **(4)**

$$= \frac{1\angle 0°}{j0.25 + \left(\frac{j0.35 \times j0.1}{j0.35 + j0.1}\right)} = -j3.0508\ p.u$$

$$I_a^- = -I_a^+ \times \frac{Z^0}{Z^- + Z^0}$$

$$= -(-j3.0508) \times \frac{j0.1}{j0.35 + j0.1} = j0.678\ p.u$$

$$I_a^0 = -I_a^+ \times \frac{Z^-}{Z^- + Z^0}$$

$$= -(-j3.0508) \times \frac{j0.35}{j0.35 + j0.1} = j2.373\ p.u$$

$$Fault\ current = 3I_a^0 = 3 \times j2.373 = j7.119\ p.u$$ **(3)**

$$Base\ current = \frac{MVA}{\sqrt{3} \times KV_b} = \frac{25 \times 10^3}{\sqrt{3} \times 132} = 1093.466\ Amp$$

$$I_f\ in\ Amp = j7.119 \times 1093.466 = j7.784\ Amp$$

$$\boxed{\begin{aligned} &Fault\ current = j7.119\ p.u \\ &Base\ current = 1093.466\ Amp \\ &I_f\ in\ Amp = j7.784\ Amp \end{aligned}}$$

Symmetrical component of voltages:

$$V_a^0 = -Z^0 I_a^0$$

$$= -j0.1 \times j2.373 = 0.2373\ p.u$$

$$V_a^+ = E_a - Z^+ I_a^+$$

$$= 1\angle 0° - j0.25 \times -j3.0508 = 0.2373\ p.u$$

$$V_a^- = -Z^- I_a^- = -j0.35 \times j0.678$$

$$= 0.2373\ p.u$$

$$\therefore V_a^+ = V_a^-$$

(4)

$$\boxed{\begin{aligned} &Symmetrical\ component\ of\ voltages: \\ &V_a^0 = 0.2373\ p.u \\ &V_a^+ = 0.2373\ p.u \\ &V_a^- = 0.2373\ p.u \end{aligned}}$$

Phase voltages:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix}$$ **(3)**

$$V_a = 0.2373 + 0.2373 + 0.2373 = 0.7119$$

$$V_b = 0.2373 + (-0.5 - j0.866)0.2373 + (-0.5 + j0.866)0.2373 + 0$$

$$V_c = 0$$

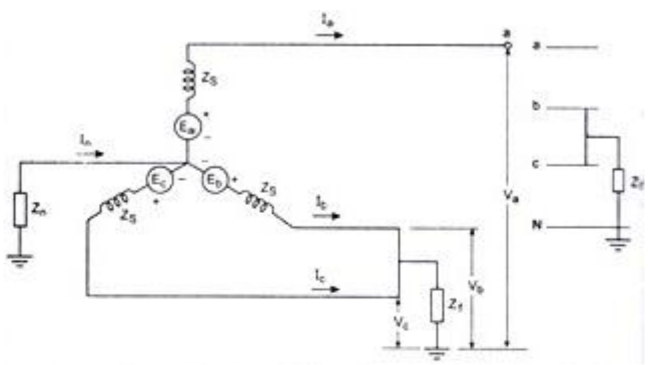
$$\therefore V_b = V_c = 0$$

$$Line-line\,voltage$$
$$V_{ab}=V_a-V_b=0.7119-0=0.7119\,p.u$$
$$V_{bc}=V_b-V_c=0.7119-0=0.7119\,p.u$$
$$V_{bc}=V_b-V_c=0-0=0\,p.u$$

$$\boxed{\begin{array}{l} Line-line\,voltage \\ V_{ab}=0.7119\,p.u \\ V_{bc}=0.7119\,p.u \\ V_{bc}=0\,p.u \end{array}}$$

4. Obtain the expression for fault current for a line to line fault taken place through an impedance Z_b in a power system. (M/J'14, N/D'13) (16)

Solution:- (2)



$$I_b=-I_c$$
$$I_a=0\,(unloaded\ generator)$$
$$V_b-V_c=Z_fI_b\Rightarrow V_c=V_b-Z_fI_b$$
$$Substitute\ for\ I_b=-I_c, I_a=0, the\,symmetrical\,components\,of\ current\,are:$$

$$\begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}=\frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$\begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}=\frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix}$$ **(3)**

$$Substitute\,the\,value\,of\ I_b, we\,get$$
$$(a^2-a)\left[V_a^+-V_a^-\right]=(a^2-a)I_a^+Z_f$$
$$V_a^+-V_a^-$$

$$I_a^0 = \frac{1}{3}[0 + I_b - I_b] = 0$$

$$I_a^+ = \frac{1}{3}\left[aI_b - a^2 I_b\right]$$

$$I_a^- = \frac{1}{3}\left[a^2 I_b - aI_b\right]$$

$$\therefore I_a^+ = -I_a^- \ and \ I_a^0 = 0$$

From sequence network of the generator, the symmetrical voltage are give by

$$\begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} \begin{bmatrix} Z_{kk}^0 & 0 & 0 \\ 0 & Z_{kk}^+ & 0 \\ 0 & 0 & Z_{kk}^- \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}$$

$$V_a^0 = -Z_{kk}^0 I_a^0 = -Z_{kk}^0 \times 0 = 0$$

$$V_a^+ = E_a - Z_{kk}^+ I_a^+$$

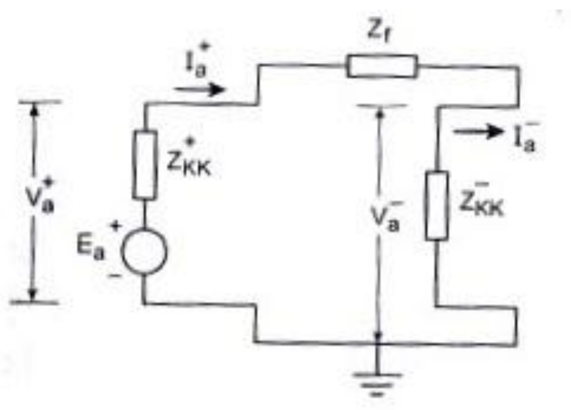
$$V_a^- = -Z_{kk}^- I_a^- = Z_{kk}^- I_a^+$$

The Phase current are given by

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 0 \\ I_a^+ \\ -I_a^- \end{bmatrix}$$ **(4)**

$$I_a = 0, I_b = a^2 I_a^+ - aI_a^- = I_a^+(a^2 - a)$$

$$I_c = aI_a^+ - a^2 I_a^+ = I_a^+(a - a^2) = -I_b$$



Sequence network for LL fault with Z_f **(3)**

The Phase voltage are

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 0 \\ V_a^+ \\ V_a^- \end{bmatrix}$$

$$V_a^0 = 0$$

$$V_a = V_a^+ + V_a^-$$

$$V_b = a^2 V_a^+ + aV_a^-$$

$$V_c = aV_a^+ + a^2 V_a^-$$

From the condition $V_b - V_c = Z_f I_b$

Substituting V_b *and* V_c, *we get*

$$(a^2 - a)\left[V_a^+ - V_a^-\right] = Z_f I_b$$

Substitute the value of I_b, *we get*

$$(a^2 - a)\left[V_a^+ - V_a^-\right] = (a^2 - a) I_a^+ Z_f$$

$$V_a^+ - V_a^-$$

Substitue V_a^+, V_a^-, *we get,*

$$E_a = \left[Z_K^+ + Z_K^- + Z_f\right] I_a^+$$

$$I_a^+ = \frac{E_a}{Z_K^+ + Z_K^- + Z_f}$$

$$I_a^- = -I_a^+$$

(4)

$$I_a^0 = 0$$

Current phase domine

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix} = \begin{bmatrix} 0 + I_a^+ - I_a^+ \\ 0 + (a^2 - a) I_a^+ \\ 0 + (a + a^2) I_a^+ \end{bmatrix} \begin{bmatrix} 0 \\ (a^2 - a) I_a^+ \\ -(a + a^2) I_a^- \end{bmatrix}$$

The fault current is $I_b = -I_c = (a^2 - a) I_a^+$

$$= (-0.5 - j0.866 + 0.5 - j0.866) I_a^+ = -j1.732 I_a^+$$

$$= -j\sqrt{3} I_a^+$$

Substituting I_a^+ *we get,*

$$I_f = I_b = \frac{-j\sqrt{3} E_a}{Z_{KK}^+ + Z_{KK}^- + Z_f}$$

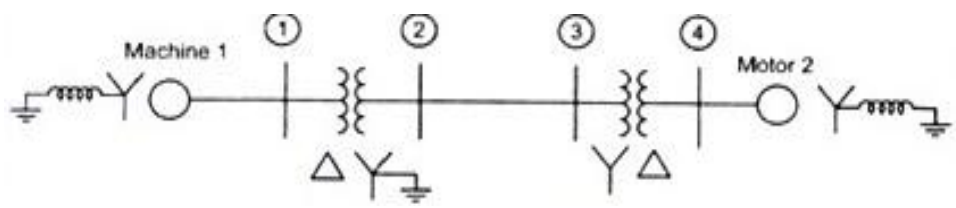
5. Two synchronous machines are connected through three phase transformers to the transmission line shown in fig. The rating and reactance of the machines and transformers are:

Machine 1 and 2: 100 MVA, 20 KV; $X''_d = X_1 = X_2 = 20\%$; $X_0 = 4\%$, $X_n = 5\%$

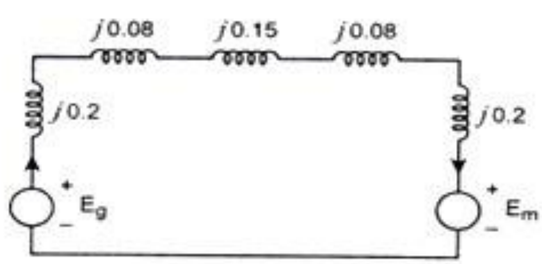
Transformer T1 and T2 : 100MVA, 20Δ/345 Y KV ; X=8%

On a chosen base of 100 MVA, 345 KV in transmission line circuit, line reactance are $X_1 = X_2 = 15\%$ and $X_0 = 50\%$.

Draw each of three sequences networks and find the zero sequence bus impedance matrices by means of Z_{bus} building algorithm. (16)



Solution: Positive sequence network: **(8)**



$$= (1)\begin{bmatrix} \overset{(1)}{j0.19} \end{bmatrix}$$

$$= \begin{matrix}(1)\\(2)\end{matrix}\begin{bmatrix} \overset{(1)}{j0.19} & \overset{(2)}{0} \\ 0 & j0.08 \end{bmatrix}$$

$$= \begin{matrix}(1)\\(2)\\(3)\end{matrix}\begin{bmatrix} \overset{(1)}{j0.19} & \overset{(2)}{0} & \overset{(3)}{0} \\ 0 & j0.08 & j0.8 \\ 0 & j0.08 & j0.8 \end{bmatrix}$$

$$= \begin{matrix} (1) \\ (2) \\ (3) \\ (a) \end{matrix} \begin{bmatrix} \overset{(1)}{j0.9} & \overset{(2)}{0} & \overset{(3)}{0} & \overset{(a)}{0} \\ 0 & j0.08 & j0.08 & j0.08 \\ 0 & j0.08 & j0.58 & j0.08 \\ 0 & j0.08 & j0.58 & j0.66 \end{bmatrix}$$

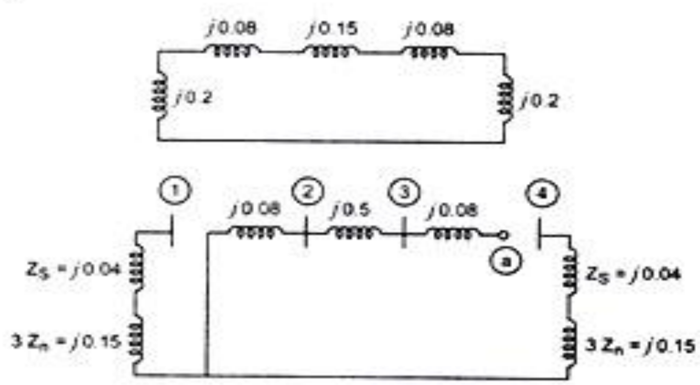
Node a is eliminating using Kron reduction techniques, we get **(8)**

$$= \begin{bmatrix} j0.19 & 0 & 0 \\ 0 & j0.08 & j0.08 \\ 0 & j0.08 & j0.58 \end{bmatrix}$$

Add branch j0.19 from bus (4) to the ref. we get,

$$Z_{bus}^{0} = \begin{matrix} (1) \\ (2) \\ (3) \\ (4) \end{matrix} \begin{bmatrix} \overset{(1)}{j0.19} & \overset{(2)}{0} & \overset{(3)}{0} & \overset{(4)}{0} \\ 0 & j0.08 & j0.08 & 0 \\ 0 & j0.08 & j0.58 & 0 \\ 0 & 0 & 0 & j0.19 \end{bmatrix}$$

Negative sequence network :

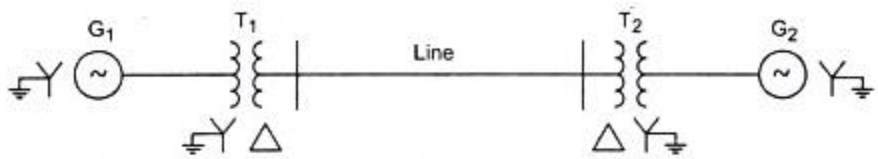


The Zeros in Z_{bus}^{0} shows that the zero sequence current injected into bus (1) or bus (4) Cannot cause voltage at the other buses because of the open circuits introduced by the Δ-Y transformers.

6. A single line diagram of power system is shown in figure, determine the fault current and fault MVA for a line to line fault occurs between phases b and c at bus 4 as shown in fig.

G1:G2 : 100 MVA, 20KV, X^{+}=X^{-}15 %

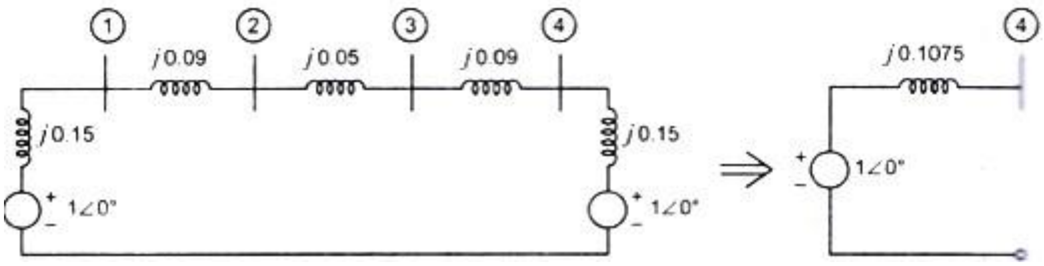
T!,T2 : 100 MVA, 20/345 KV, X_{leak}=9 %: Line : X^{+}=X^{-}5 % (M/J'13)(16)



Solution:

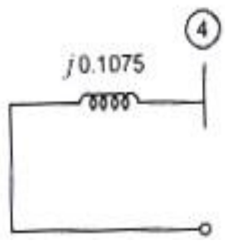
Positive Sequence Thevenin equivalent: **(6)**

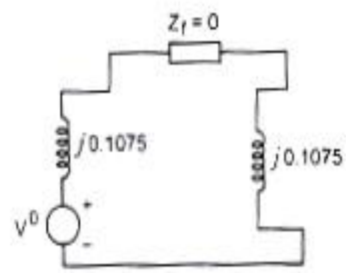
Positive sequence Thevenin equivalent :



Negative sequence thevenin equivalent:

Negative sequence Thevenin equivalent : ***Sequence network :***





Current in phase domine :

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 0 \\ -j13.426 \\ j13.426 \end{bmatrix}$$

$$I_a = 0$$

$$I_b = 1 \times 0 + a^2(-j13.426) + a(j13.426) = -23.254\,KA$$

$$I_c = -I_b = 23.254\,KA$$

$$I_n = I_a + I_b + I_c = 0$$

$$Fault\ MVA = \sqrt{3} \times I_f(KA) \times KV = \sqrt{3} \times 23.254 \times 20$$

$$= 805.542$$

$$prefault\ voltage = E_a = V^0 = 1\angle 0^\circ$$

$$I_a^+ = -I_a^- = \frac{1\angle 0^\circ}{j0.1075 + j0.1075} = -j4.651\,p.u$$

(8)
$$|I_a^+| = |I_a^-| = 4.651 \times \frac{100}{\sqrt{3}\times 20} = 13.426\,KA$$
$$I_a^+ = -j13.426,\ I_a^- = j13.426\,KA$$

Current in phase domine:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 0 \\ -j13.426 \\ j13.426 \end{bmatrix}$$

$$I_a = 0$$
$$I_b = 1\times 0 + a^2(-j13.426) + a(j13.426) = -23.254\,KA$$
$$I_c = -I_b = 23.254\,KA$$
$$I_n = I_a + I_b + I_c = 0$$
$$Fault\ MVA = \sqrt{3}\times I_f(KA)\times KV = \sqrt{3}\times 23.254\times 20$$
$$= 805.542$$

$$\boxed{\begin{aligned} &I_a = 0 \\ &I_b = -23.254\,KA \\ &I_c = -I_b = 23.254\,KA \\ &I_n = 0 \\ &Fault\ MVA = 805.542 \end{aligned}}$$ **(2)**

7. Discuss in detail about the sequence impedance and network of synchronous machine, transmission lines transformers and loads (M/J'13) (16)

Synchronous Generator

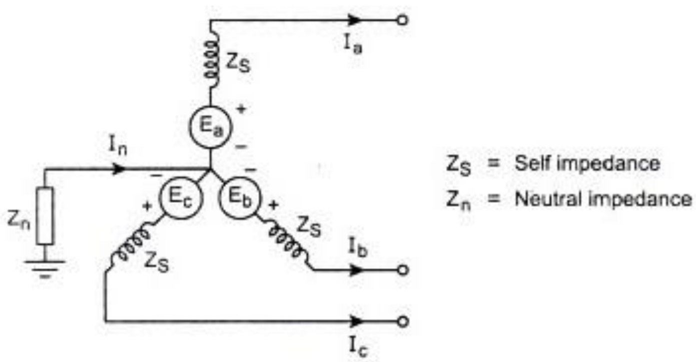
Consider the three phase synchronous generator with netural grounded through an impedance Z_n is as shown in figure

Let V_a, V_b,V_c be the phase voltages (line to neutral). **(4)**

Let I_a, I_b,I_c be the phase currents.

Line to neutral voltages are written as

$$V_a = E_a - Z_s I_a - Z_n I_n$$
$$V_b = E_b - Z_s I_b - Z_n I_n$$
$$V_c = E_c - Z_s I_c - Z_n I_n$$



3ϕsynchronous generator with neutral grounded through impedance

$$\text{Substituting } I_n = I_a + I_b + I_c \text{ in (1), we get}$$

$$V_a = E_a - Z_s I_a - Z_n I_a - Z_n I_b - Z_n I_c$$

$$V_b = E_b - Z_s I_b - Z_n I_a - Z_n I_b - Z_n I_c$$

$$V_c = E_c - Z_s I_c - Z_n I_a - Z_n I_b - Z_n I_c$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} Z_s + Z_n & Z_n & Z_n \\ Z_n & Z_s + Z_n & Z_n \\ Z_n & Z_n & Z_s + Z_n \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$[V_P] = [E_P] - \left[Z^{abc}\right][I_P]$$

$$\left[V^{abc}\right] = \left[E^{abc}\right] - \left[Z^{abc}\right]\left[I^{abc}\right]$$

$$\text{where the sequence impedance} \left[Z^{012}\right] = [T]^{-1}\left[Z^{abc}\right][T]$$

$$\left[Z^{012}\right] = \begin{bmatrix} Z_s + 3Z_n & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_s \end{bmatrix} = \begin{bmatrix} Z^0 & 0 & 0 \\ 0 & Z^+ & 0 \\ 0 & 0 & Z^- \end{bmatrix}$$

$$\text{Since the generator emf is balance, threr is only positive-sequence voltage } E_a$$

$$\therefore \left[Z^{012}\right] = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z^0 & 0 & 0 \\ 0 & Z^+ & 0 \\ 0 & 0 & Z^- \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}$$

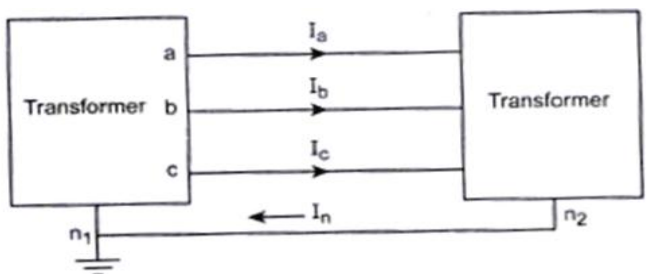
From equation (6), we can write

$$\therefore V_a^0 = -Z^0 I_a^+$$

$$V_a^+ = E_a - Z^+ I_a^+$$

$$V_a^- = -Z^- I_a^-$$

Sequence Impedance of Transmission Line **(4)**



A 3Φ balanced transposed line shown in Figure. Impedance per phase is independent of the phase sequence of balance set of currents. Because the voltages and currents encounter the same geometry of the line. Thus the positive, negative impedance are equal.

For symmetrical line,

$$\begin{bmatrix} \Delta V_{an1} \\ \Delta V_{bn1} \\ \Delta V_{cn1} \end{bmatrix} = \begin{bmatrix} Z_1 & Z_2 & Z_2 \\ Z_2 & Z_1 & Z_2 \\ Z_2 & Z_2 & Z_1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

WKT,

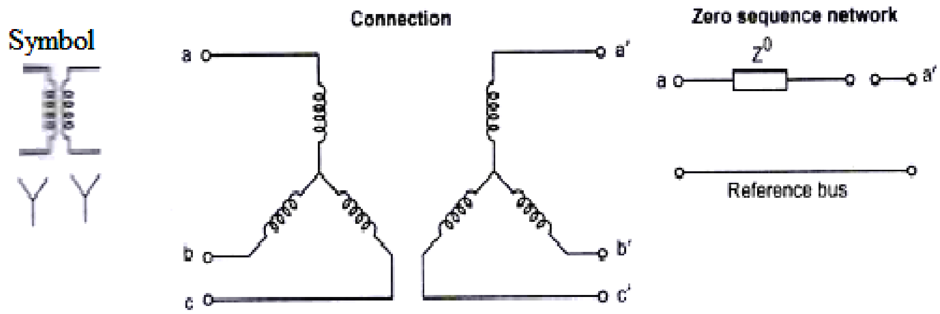
$$[Z_s] = [T]^{-1}[Z_P][T]$$

$$\begin{bmatrix} Z^0 \\ Z^+ \\ Z^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 3Z_1 + 6Z_2 & 0 & 0 \\ 0 & 3Z_1 + 3Z_2 & 0 \\ 0 & 0 & Z_1 + 3Z_2 \end{bmatrix}$$

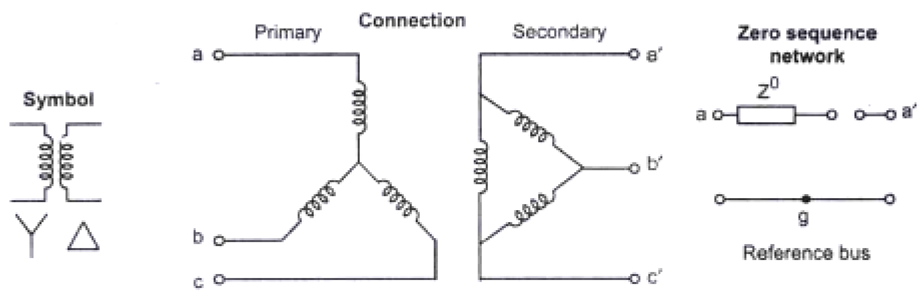
$$= \begin{bmatrix} Z_1 + 2Z_2 & 0 & 0 \\ 0 & Z_1 + Z_2 & 0 \\ 0 & 0 & Z_1 + Z_2 \end{bmatrix}$$

Transformers:-

Y-Y connected **(2)**

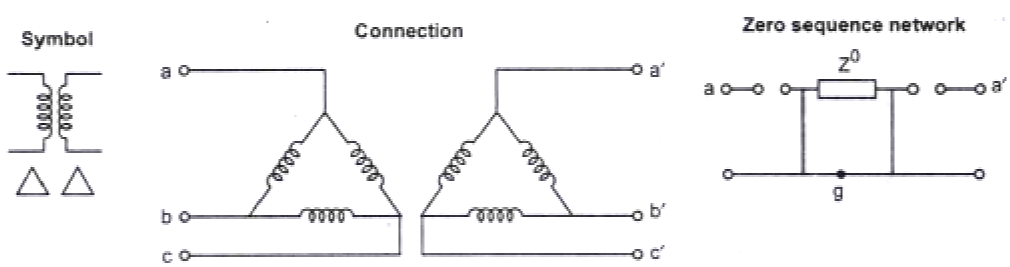


Y-Δ connected **(2)**



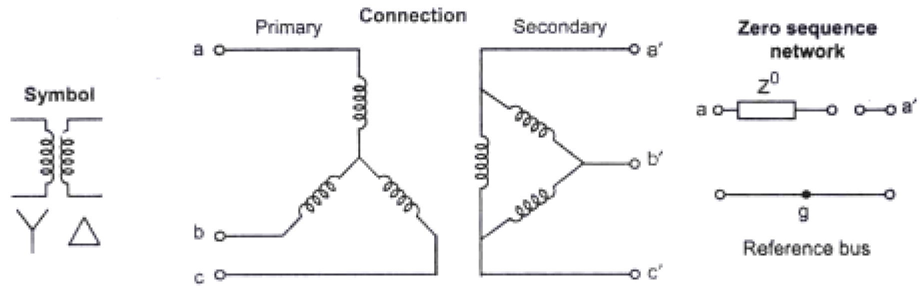
Transformer Y-Δ connected with isolated neutral

Δ-Δ connected **(2)**



Transformer Δ-Δ connected

$Y - \Delta\, connected\, , neutral\; solidly\; grounded$ **(2)**

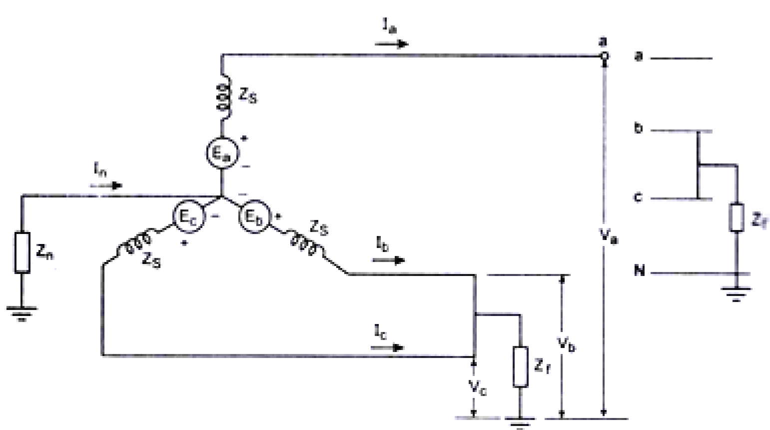


Transformer Y-Δ connected with isolated neutral

8.Draw the sequence network connection for a double line to ground fault at any point in a power system and from thaat obtain an expression for the fault current. (N/D'12) (16)

A three phase generator with a fault on phases b and c through an impedance Z_f to ground.

(3)



$$I_a = 0$$
$$I_b + I_c = I_f$$
$$V_b = V_c = Z_f I_f = Z_f (I_b + I_c)$$

(3)

The symmetrical components of voltage are :

$$\begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Substitute $V_b = V_c$ in equation (2), we get

$$\begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_b \end{bmatrix}$$

$$V_a^0 = \frac{1}{3}(V_a + 2V_b)$$

$$V_a^+ = \frac{1}{3}(V_a - V_b)$$

$$V_a^- = \frac{1}{3}(V_a - V_b)$$

(3)

$$V_a^+ = V_a^-$$

The Phase current are given by

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}\begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}$$

$$I_a = I_a^0 + I_a^+ + I_a^-$$

$$I_b = I_a^0 + a^2 I_a^+ + a I_a^-$$

$$I_c = I_a^0 + a I_a^+ + a^2 I_a^-$$

$$I_f = I_b + I_c = I_a^0 + a^2 I_a^+ + a I_a^- + I_a^0 + a I_a^+ + a^2 I_a^-$$

$$= 2I_a^0 + I_a^+(a^2 + a) + I_a^-(a + a^2)$$

$$(I_a^+ + I_a^-) = -I_a^0$$

substituting (5) *in* (6), *we get*

$$I_b + I_c = 3I_a^0$$

From the condition, $V_b = 3Z_f I_a^0$

The Phase voltage are

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}\begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix}$$

(3)

$$V_a = V_a^0 + V_a^+ + V_a^-$$

$$V_b = V_a^0 + a^2 V_a^+ + a V_a^+ \qquad \left[\because V_a^+ = V_a^-\right]$$

$$V_b = V_a^0 + V_a^+ \qquad \left[\therefore V_b = 3Z_f I_a^0\right]$$

The symmetrical components voltage is given by

$$V_a^0 = -Z_{KK}^0 I_a^0$$
$$V_a^+ = E_a - Z_{KK}^+ I_a^+ \qquad \textbf{(4)}$$
$$V_a^- = -Z_{KK}^- I_a^-$$

$$Then\ I_a^0 = \frac{-[E_a - Z_{KK}^+ I_a^+]}{Z_{KK}^0 + 3Z_f}$$

$$I_a^- = \frac{-[E_a - Z_{KK}^+ I_a^+]}{Z_{KK}^-}$$

$$-I_a^0 = I_a^+ + I_a^-$$
$$I_a^+ = -I_a^- - I_a^0$$

on by solving we get

$$I_a^+ = \frac{E_a}{Z_{KK}^+ + \dfrac{Z_{KK}^-(Z_{KK}^0 + 3Z_f)}{Z_{KK}^0 + 3Z_f + Z_{KK}^-}}$$

$$\boxed{I_f = \frac{3}{Z_{KK}^0 + 3Z_f}\left[E_a - \frac{Z_{KK}^+ E_a}{Z_{KK}^+ + \dfrac{Z_{KK}^-(Z_{KK}^0 + 3Z_f)}{Z_{KK}^0 + Z_{KK}^+ + 3Z_f}}\right]}$$

9. i) Derive an expression for the total power in a three phase system in terms of sequence components of voltage and currents (3)

Ans :

$$Apparent\ power\ S_{(3\phi)} = [V_P]^T [I_P]^*$$

By using symmetrical component transformation,

$$= [TV_S]^T [TI_S]^*$$

$$S_{(3\phi)} = V_S^T T^T T^* I_S^*$$

$$T^T T^* = TT^* = 3 \qquad \left[T^T = T\right]$$

$$\therefore S_{(3\phi)} = 3\left[V_S^T I_S^*\right]$$

$$= 3V_a^0 I_a^{0*} + 3V_a^+ I_a^{+*} + 3V_a^- I_a^{-*}$$

The Total unbalanced power can be obtained from the sum of the symmetrical components powers.

$$\boxed{S_{(3\phi)} = 3V_a^0 I_a^{0*} + 3V_a^+ I_a^{+*} + 3V_a^- I_a^{-*}}$$

ii) Discuss in detail about the sequence impedance of transmission lines (3)

A 3Φ balanced transposed line shown in Figure. Impedance per phase is independent of the phase sequence of balance set of currents. Because, the voltages and currents encounter the same geometry of the line. Thus the positive, negative impedance are equal.

For symmetrical line,

$$\begin{bmatrix} \Delta V_{an1} \\ \Delta V_{bn1} \\ \Delta V_{cn1} \end{bmatrix} = \begin{bmatrix} Z_1 & Z_2 & Z_2 \\ Z_2 & Z_1 & Z_2 \\ Z_2 & Z_2 & Z_1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

we know that,

$$[Z_s] = [T]^{-1}[Z_P][T]$$

$$\begin{bmatrix} Z^0 \\ Z^+ \\ Z^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 3Z_1 + 6Z_2 & 0 & 0 \\ 0 & 3Z_1 + 3Z_2 & 0 \\ 0 & 0 & Z_1 + 3Z_2 \end{bmatrix}$$

$$= \begin{bmatrix} Z_1 + 2Z_2 & 0 & 0 \\ 0 & Z_1 + Z_2 & 0 \\ 0 & 0 & Z_1 + Z_2 \end{bmatrix}$$

iii) The bus impedance matrix of four bus system with values in p.u. is given by,

$$\mathbf{Z_{bus} = j}\begin{bmatrix} 0.15 & 0.08 & 0.04 & 0.07 \\ 0.08 & 0.15 & 0.06 & 0.09 \\ 0.04 & 0.06 & 0.13 & 0.05 \\ 0.07 & 0.09 & 0.05 & 0.12 \end{bmatrix}$$

In this system generators are connected to buses 1 and 2 and their subtransient reactances were included when finding Zbus. If prefault current is neglected, find subtransient current in p.u. in the fault on a bus 4. Assume prefault voltage as 1 p.u. If the subtransient reactance of generator in bus 2 is 0.2 p.u. find the subtransient fault current supplied by generator. (10)

<u>Solution</u>:

Let I_f'' be the subtransient current in the fault on bus 4.

Now, $I_f'' = \frac{V_{pf}}{Z_{44}}$

Where V_{pf} = prefault voltage at bus 4 = $1\angle 0°$ p.u.

$$\therefore I_f'' = \frac{1\angle 0°}{j0.12} = -j8.333 = 8.333\angle -90° \text{ p.u.}$$

$I_f'' = 8.333\angle -90°$ p.u.

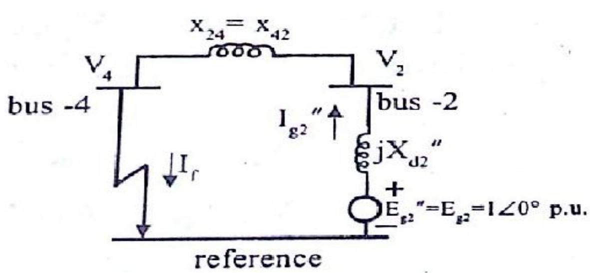
The voltage at bus 2 when there is a 3 phase fault in bus 4 is given by,

$$V_2 = V_{pf} - I_f'' Z_{pf}$$

$$\therefore V_2 = 1\angle 0° - 8.333\angle -90° \times j0.09 = 1 - 8.333\angle -90° \times 0.09\angle 90°$$

$$V_2 = 1 - 0.74997 = 0.25003 \approx 0.25\angle 0° \text{ p.u.}$$

Since there is no current in the system prior to the fault all the buses will be at same potential prior to fault. Also there won't be any potential drop in the synchronous reactance of the generator, because it does not deliver any current prior to fault. Hence the induced emef of the generator in bus – 2 is also 1 p.u. . The generator in bus – 2 can be represented as shown fig.



With reference to fig.

The subtransient fault current delivered by the generator at bus -2, $I_{g2}'' = \frac{E_{g2}'' - V_2}{jX_{d2}''}$

$$I_{g2}'' = \frac{1\angle 0° - 0.25\angle 0°}{j0.2} = \frac{1 - 0.25}{0.2\angle 90°} = 3.75\angle -90° \text{ p.u.}$$

$I_{g2}'' = 3.75\angle -90°$ p.u.

Note: $I_f = I''_{g1} + I''_{g2}$

Result:

The subtransient fault current in the bus -4 = $I_f'' = 8.333\angle -90°$ p.u.

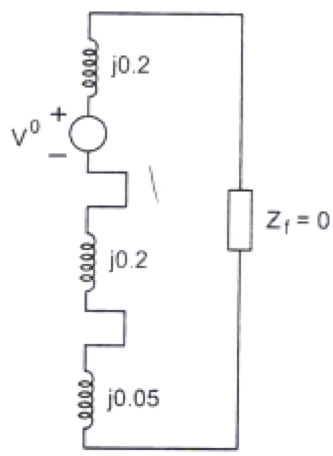
The voltage at bus – 2 when there is a 3 phase fault in bus – 4 = $V_2 = 0.75\angle 0°$ p.u.

$\left.\begin{array}{l}\text{The subtransient fault current delivered by the generator} - 2\\ \text{when there is a } 3 - \text{phase fault in bus} - 4\end{array}\right\} I_{g2}'' = 3.75\angle -90°$ p.u.

10. A 30 MVA . 11 KV generator has $Z_1=Z_2=j0.2$ p.u, $Z_0=j0.05$ p.u. A line to ground fault occurs on the generator terminals. Find the fault current and line to line voltage during limit conditions. Assume that the generator neutral is solidly grounded and that the generator is operating at no load and at rated voltage at the occurrence of fault.

(N/D'11) (16)

Solution : - **(4)**



$$Z^+ = j0.2\ p.u$$
$$Z^- = j0.2\ p.u$$
$$Z^0 = j0.05\ p.u$$
$$prefault\ voltage, V^0 = 1\angle 0°$$

Symmetrical components of fault current

$$I_a^+ = I_a^- = I_a^0 = \frac{V^0}{Z^+ + Z^- + Z^0}$$
$$= \frac{1\angle 0°}{j0.2 + j0.2 + j0.05}$$
$$= -j2.222\ p.u$$

$$Fault\ current\ in\ p.u = 3I_a^+$$
$$= 3 \times -j2.222$$
$$= -j6.666\ p.u$$

$$Base\ current = \frac{MVA_b \times 10^3}{\sqrt{3} \times KV_b} = \frac{30 \times 10^3}{\sqrt{3} \times 11}$$ **(4)**
$$= 1574.6\ Amp$$

$$Fault\ current\ in\ Amp = -j6.666 \times 1574.6$$
$$= 10496.3\ Amp$$

Symmetrical components of fault current
$I_a^+ = -j2.222\ p.u$
$Fault\ current\ in\ p.u = -j6.666\ p.u$
$Base\ current = 1574.6\ Amp$
$Fault\ current\ in\ Amp = 10496.3\ Amp$

(4)

Line to line voltage during the fault :

$$V_a^0 = -Z^0 I_a^+$$
$$= -j0.05 \times -j2.222 = -0.1111$$
$$V_a^+ = V^0 - Z^+ I_a^+$$
$$= 1\angle 0° - j0.2 \times -j2.222$$
$$= 0.5555$$
$$V_a^- = -Z^- I_a^+$$
$$= -j0.2 \times -j2.222$$
$$= -0.4444$$

Line to line voltage during the fault :
$V_a^0 = -0.1111$
$V_a^+ = 0.5555$
$V_a^- = -0.4444$

Subtransient phase voltages

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix}$$

$$V_a = V_a^0 + V_a^+ + V_a^-$$

$$= -0.111 + 0.5555 - 0.4444 = 0$$

$$V_b = V_a^0 + a^2 V_a^+ + aV_a^-$$ **(4)**

$$= -0.1111 + 1\angle -240° \times 0.5555 + 1\angle -120° \times -0.4444$$

$$= -0.29 - j0.0267$$

$$V_c = V_a^0 + aV_a^+ + a^2 V_a^-$$

$$= -0.29 + j0.267$$

Subtransient phase voltages
$V_a = 0$
$V_b = -0.29 - j0.0267$
$V_c = -0.29 + j0.267$

Line to line Voltage

$$V_{ab} = V_a - V_b = 0 - [-0.29 - j0.267]$$

$$= 0.29 + j0.267 \ p.u$$

$$V_{bc} = V_b - V_c = -0.29 - j0.267 - [-0.29 + j0.267]$$

$$= -j0.534 \ p.u$$

$$V_{ac} = V_a - V_c = 0 - [-0.29 + j0.267]$$

$$= 0.29 - j0.267$$

Line to line Voltage
$V_{ab} = 0.29 + j0.267 \ p.u$
$V_{bc} = -j0.534 \ p.u$
$V_{ac} = 0.29 - j0.267$

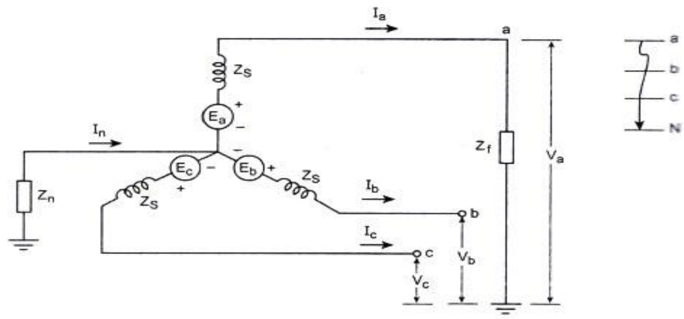
11. A 50 MVA, 11KV, 3ph alternator was subjected to different types of faults. The fault current are 3-ph fault 1870 A, line to line fault 2590 A, single line to ground fault 4130 A. The alternator neutral is solidly grounded. Find the p.u values of three sequence reactance of the alternator. (M/J'12) (16)

Solution :- **(10)**

$$MVA_b = 50$$
$$KV_b = 11$$
$$I_f(3\phi\, fault) = 1870A$$
$$I_f(L-L\ fault) = 2590A$$
$$I_f(L-G\ fault) = 4130A$$
$$Z^0, Z^+, Z^- = ?$$
$$Base\,current = \frac{MVA_b \times 10^3}{\sqrt{3} \times KV_b}$$
$$= \frac{50 \times 10^3}{\sqrt{3} \times 11} = 2624.3A$$
$$Base\,current = 2624.3A$$
$$I_{f\ p.u(3\phi)} = \frac{V^0}{Z^+}$$
$$= \frac{1870}{2624.3} = -j0.713$$
$$\Rightarrow Z^+ = \frac{1\angle 0°}{-j0.713} = j1.4\ p.u$$
$$I_{f\ p.u}(L.L) = \frac{-j\sqrt{3}V^0}{Z^+ + Z^-} = \frac{2590}{2624.3} = -j0.99$$
$$Z^+ + Z^- = \frac{-j\sqrt{3} \times 1\angle 0°}{-j0.99} = j1.75\ p.u$$
$$Z^- = j1.75 - Z^+$$
$$= j1.75 - j1.4 = j0.35$$
$$I_{fp.u}(LG) = \frac{3V^0}{Z^+ + Z^- + Z^0}$$
(6)
$$= \frac{4130}{2624.3} = -j1.57$$
$$Z^+ + Z^- + Z^0 = \frac{3 \times 1\angle 0°}{-j1.57} = j1.91$$
$$Z^0 = j1.91 - j1.4 - j0.35$$
$$= j0.16\ p.u$$

12. Derive the equation for the L-G fault under symmetrical analysis. The single line to ground fault is the most common type of fault, is caused by lightning or by conductors making contact with grounded structures. **(16)**

Suppose a line to ground fault is occurs on phase a connected to ground through impedance Z_f. **(6)**



$$V_a = Z_f I_a$$
$$I_b = I_c = 0$$
$$I_f = I_a$$

Symmetrical componets ofcurrents are

$$\begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Substitute for $I_b = I_c = 0$, *symmetrical components of currents are*

$$\begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix}$$

From eq(3), *we get*

$$I_a^0 = \frac{I_a}{3}$$

$$I_a^+ = \frac{I_a}{3} \qquad \textbf{(5)}$$

$$I_a^- = \frac{I_a}{3} = \frac{I_f}{3}$$

$$I_a^+ = I_a^- = I_a^0 = \frac{I_a}{3}$$

From sequence network of generator, symmetrical voltages are given by

$$\begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_{KK}^0 & 0 & 0 \\ 0 & Z_{KK}^+ & 0 \\ 0 & 0 & Z_{KK}^- \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}$$

$$V_a^0 = -Z_{KK}^0 I_a^0 = -Z_{KK}^0 I_a^+$$

$$V_a^+ = E_a - Z_{KK}^+ I_a^+$$

$$V_a^- = -Z_{KK}^- I_a^- = -Z_{KK}^- I_a^+$$

The phase voltage are given by

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix}$$

From eq.(6) we get,

$$V_a = V_a^0 + V_a^+ + V_a^-$$

From the condition $V_a = Z_f I_a$

$$\therefore V_a^0 + V_a^+ + V_a^- = Z_f I_a$$

Substituting the symmetrical components, we get

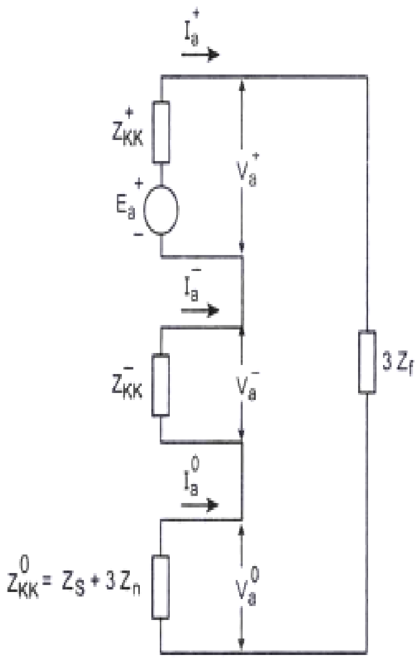
$$I_a^+ = \frac{E_a}{Z_{KK}^0 + Z_{KK}^+ + Z_{KK}^- + 3Z_f}$$

(5)

The fault current is

$$I_f = I_a = 3I_a^+ = \frac{3E_a}{Z_{KK}^0 + Z_{KK}^+ + Z_{KK}^- + 3Z_f}$$

$$\boxed{\text{The fault current}, I_f = I_a = 3I_a^+ = \frac{3E_a}{Z_{KK}^0 + Z_{KK}^+ + Z_{KK}^- + 3Z_f}}$$



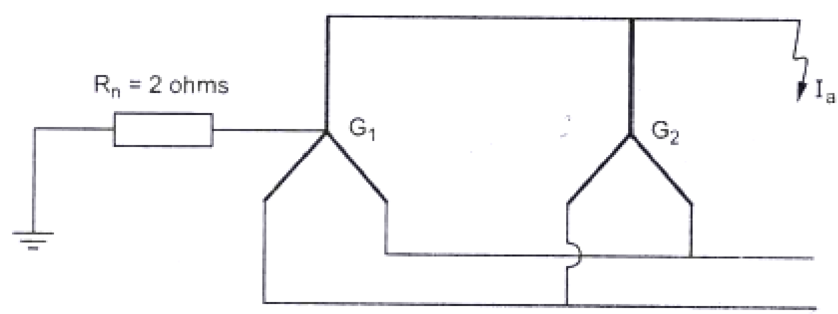
13. Two 11 KV, 20 MVA, three phase star connected generators operate in parallel as shown in figure. The positive, negative and zero sequence reactance's of each being . respectively, j0.18, j0.15,j0.10 p.u. The star point of one of the generators is isolated and that of other is earthed through a 2 ohms resistor. A single line to ground fault occurs at the terminals of one of the generators.

Estimate ,

i) The fault current,

ii) Current in grounding resistor and

iii) The voltage across grounding resistor, **(M/J'11) (16)**



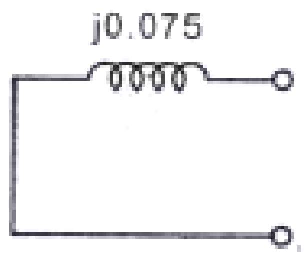
Solution :-

Positive sequence network : (Generator G1 & G2 are in parallel) **(5)**

$$Z^{+} = \frac{j0.18 \times j0.18}{j0.18 + j0.18} = j0.09$$

Negative Sequence network :

$$Z^{-} = \frac{j0.15 \times j0.15}{j0.15 + j0.15} = j0.075$$



Zero Sequence network,

$$Z^{0} = Z_s + 3Z_n$$

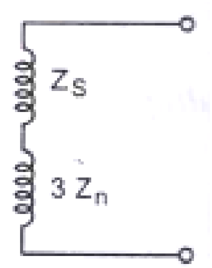
$$Z_{n\,p.u} = \frac{2 \times MVA_b}{KV_b^2}$$

$$= 2 \times \frac{20}{11^2} = 0.33\, p.u$$

$$Z^{0} = Z_s + 3Z_n$$

$$= j0.1 + 3 \times j0.33$$

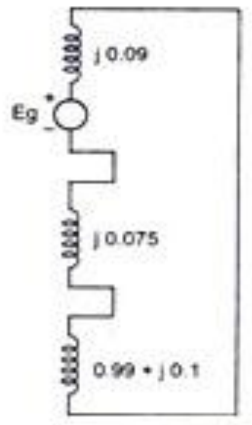
$$= 0.99 + j0.1$$



Sequence network for L-G fault: **(5)**

$$I_a^+ = I_a^- = I_a^0$$
$$= \frac{E_a}{Z^+ + Z^- + Z^0}$$
$$= \frac{1\angle 0^\circ}{j0.09 + j0.075 + 0.99 + j0.1}$$
$$= \frac{1}{0.99 + j0.265}$$

Sequence network for L-G fault



$i)\ Fault\ current\ I_f\ in\ p.u. = 3I_a^+$ **(6)**

$$= 3\times\frac{1}{0.99 + j0.265}$$
$$= 2.827 - j0.756\ p.u$$

$$\boxed{Fault\ current\ I_f\ in\ p.u. = 2.827 - j0.756\ p.u}$$

$ii) Current\ in\ the\ grounding\ resistor\ I_r :$

$I_f = 2.827 - j0.756\ p.u.$

$|I_f| = 2.926\ p.u$

$$Base\ current = \frac{MVA_b}{\sqrt{3}\times KV_b} = \frac{20\times 10^3}{\sqrt{3}\times 11} = 10497\ A$$

$|I_r|\ in\ Amp = 2.926\times 10497 = 3.07\ KA$

$$\boxed{Base\ current = 3.07\ KA}$$

$iii) Voltage\ across\ the\ grounding\ resistor :$

$$= |I_r|\ in\ Amp \times 2\Omega$$
$$= 3.07\times 2 = 6.14\ KV$$

$$\boxed{Voltage\ across\ the\ grounding\ resistor = 6.14\,KV}$$

14 .i) Explain how an unbalanced set of three phase can be represented by system of balance voltages. (7)

Let V_a, V_b, V_c *be the phase voltages and* V_a^0, V_a^+, V_a^- *be the positive, negative sequence voltages of phase 'a'.*

$$V_a = V_a^0 + V_a^+ + V_a^-$$
$$V_b = V_a^0 + V_a^+ + V_a^-$$
$$V_b = V_a^0 + V_a^+ + V_a^-$$

Substituting the symmetrical components with respect to phase a.

$$V_a = V_a^0 + V_a^+ + V_a^-$$
$$V_b = V_a^0 + a^2V_a^+ + aV_a^-$$
$$V_b = V_a^0 + aV_a^+ + a^2V_a^-$$

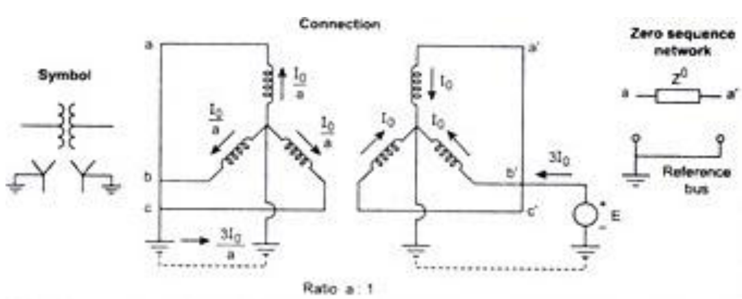
In matrix form,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix}$$

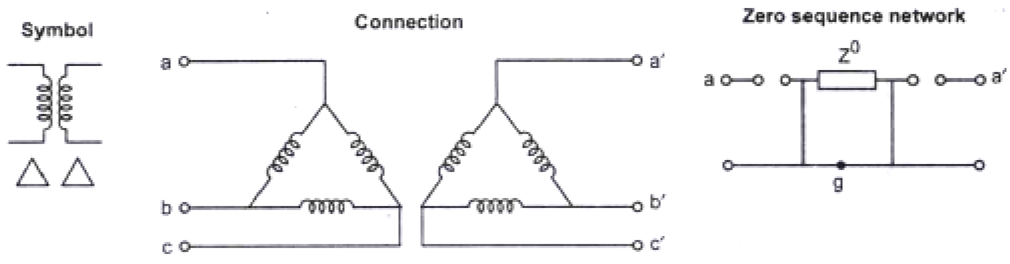
$$[V_P] = [T][V_s]$$
$$(or)$$
$$\left[V^{abc}\right] = [T]\left[V^{012}\right]$$

ii) Draw the Zero sequence network for (3)

1. Y grounded-Y grounded transformer

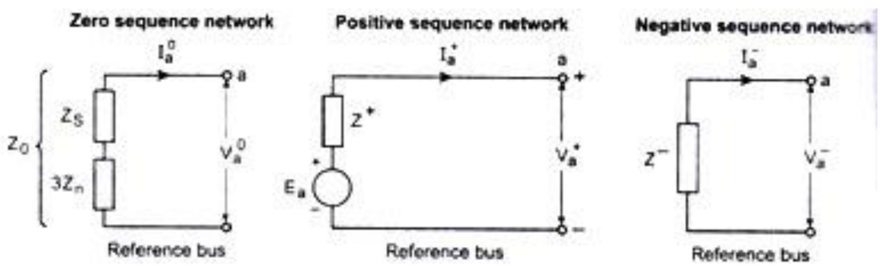


2. Δ-Δ connected transformer (5)



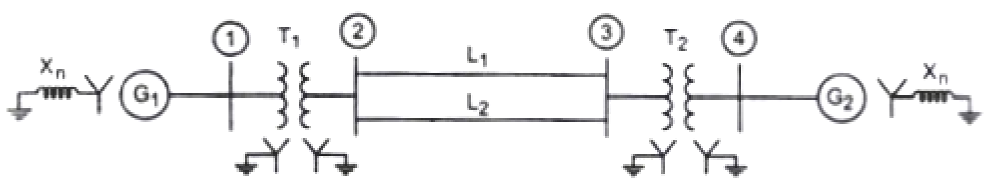
Transformer Δ-Δ connected

3. **Generator sequence diagram** (5)



Zero, positive and negative sequence network

15. Determine the fault current and MVA at faulted bus for a line to ground (solid) fault at bus 4 as shown in fig.



G1,G2: 100MVA, 11KV, $X^+= X^-=15\%$, $X^0=5\%$, $X^n=6\%$

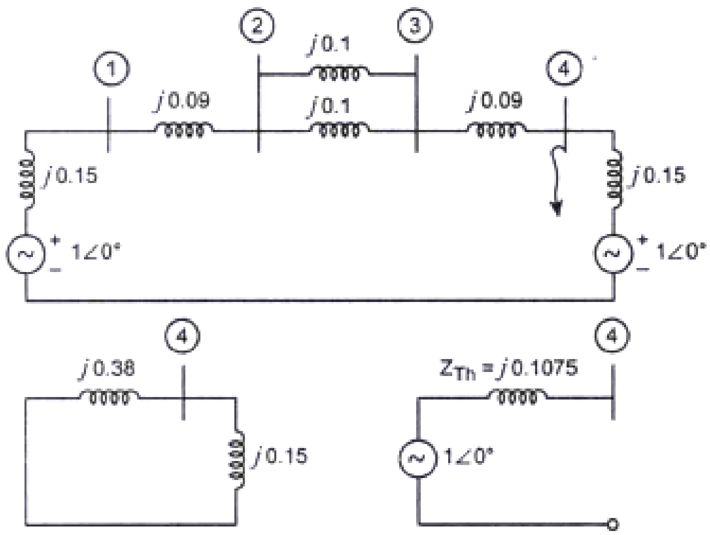
T1,T2: 100 MVA, 11 KV/220KV, $X_{leak}= 9\%$

L1,L2: $X^+= X^-=10\%$, $X^0=10\%$, on a base of 100 MVA.

Consider a fault at phase 'a' (16)

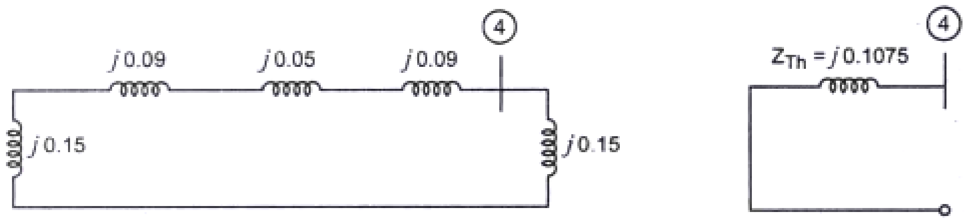
Solution :-

Step 1: Positive sequence Thevenin equivalent viewed from bus 4: (2)

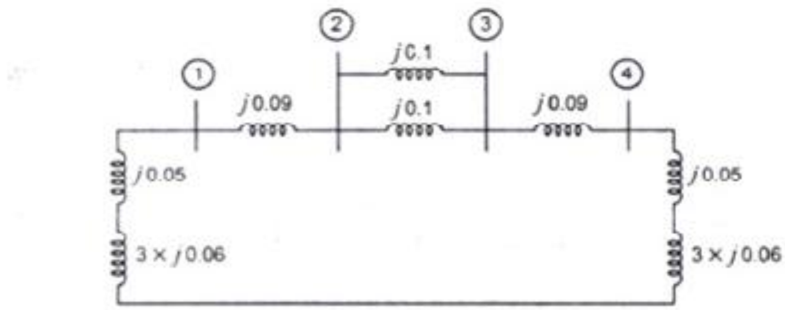


Determination of Thevenin's equivalent impedance *Thevenin's circuit*

Step 2: Negative sequence Thevenin equivalent viewed from bus 4: **(2)**



Step 3: Zero sequence Thevenin equivalent viewed from bus 4: **(8)**

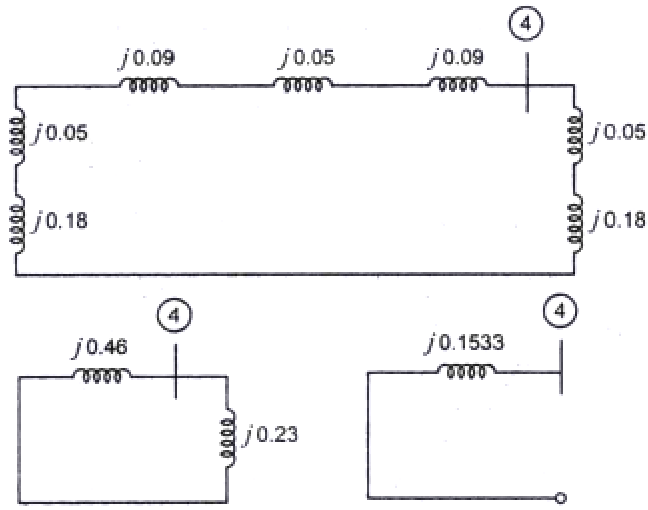


$$For\ transmission\ line\ Z_{p.u}^{new} = \frac{Actual\ value}{Base\ value} = \frac{j0.121}{Base\ KV^2} \times Base\ MVA$$

$$= \frac{j0.121}{11^2} \times 100 = j0.1$$

$j0.1$ *and* $j0.1$ *are in parallel.*

$$\frac{j0.1 \times j0.1}{j0.1 + j0.1} = j0.05$$



Step 4: Draw sequence network. **(4)**

$$prefault\ voltage\ E_a = V^0 = 1\angle 0°$$

$$I_a^+ = I_a^- = I_a^0$$

$$= \frac{V^0}{Z_{44}^+ + Z_{44}^- + Z_{44}^0 + Z_f}$$

$$= \frac{1\angle 0°}{j0.1075 + j0.1075 + j0.1533}$$

$$= -j2.7152$$

$$I_f = 3 \times I_a^+ = 3 \times -j2.7152$$

$$= -j8.1455\ p.u$$

$$Actual\ \ fault\ current\ (KA) = I_{f\ p.u} \times Base\ current$$

$$= 8.1455 \times \frac{100}{\sqrt{3} \times 11} = 42.75\ KA$$

$$Fault\ MVA = \sqrt{3} \times KV \times KA$$

$$= \sqrt{3} \times 11 \times 42.75 = 814.55$$

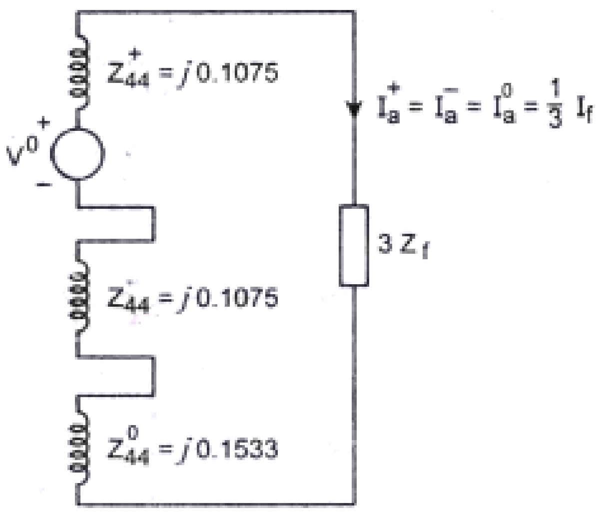
$$\boxed{Fault\ MVA = 814.55}$$

Current in phase domain :

$$I_a = I_f = 42.75\ KA$$

$$I_a = I_c = 0$$

$$I_n = I_a + I_b + I_c = 42.75\ KA$$

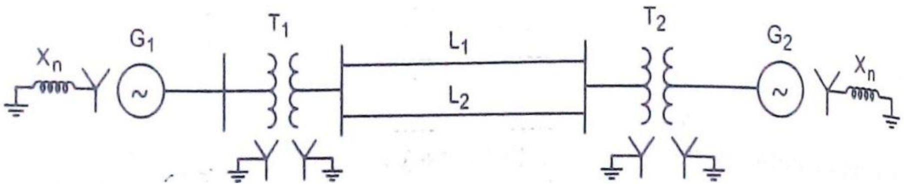


16 (i). What are the different steps involved in unsymmetrical fault analysis. (6)

The unsymmetrical fault analysis can be done by using the following steps.

- Assemble the Thevenin's equivalent positive, negative and zero sequence networks separately using the sequence impedance of various power system. Components like generators, motors, transformers and transmission lines.
- Compute the positive, negative and zero sequence impedance matrices Z^+, Z^- and Z^0 using bus building algorithm or short circuit fault impedance matrix $Z_{s,bus}$
- Select the type (L-L, L-G, L-L-G), location (bus number) and mathematical description of the fault.
- Determine the fault current at the bus using the sequence networks for a L-G, L-L and L-L-G fault.
- Determine the prefault sequence voltages and post fault sequence voltages.
- Compute the positive, negative and zero sequence line currents.

16 (ii).Determine the fault current when LLG fault occurs between phases b and c. Fault impedance is j0.15 p.u. (10)



G_1, G_2: 100 MVA, 11 KV, $X^+ = X^- = 15\%$, $X^o = 5\%$, $X_n = 6\%$

T_1, T_2: 100 MVA, 11/220 KV, $X_{leak} = 9\%$

L_1, L_2: $X^+ = X^- = 10\%$, $X^o = 10\%$ on a base of 100 MVA.

Solution:

Positive sequence impedance $Z_{44}^+ = j0.1075$ p.u. **(5)**

Negative sequence impedance $Z_{44}^- = j0.1075$ p.u.

Zero sequence impedance $Z_{44}^0 = j0.1533$ p.u.

Fault impedance $Z_f = j0.15$ p.u.

Prefault voltage = $E_a = V^0 = 1\angle 0°$

Symmetrical components of currents are:

$$I_a^+ = \frac{V^0}{Z^+ + \frac{Z^-(Z^0+3Z_f)}{Z^- + Z^0 + 3Z_f}}$$

$$= \frac{1\angle 0°}{j0.1075 + \frac{j0.1075\ (0.1533+3\ X\ j0.15)}{j0.1533\ +3\ X\ j0.15+j0.1075}} = -j5.0317 \text{ p.u.}$$

$I_a^+ = -j5.0317$ p.u.

$$I_a^- = -\ I_a^+\left[\frac{3Z_f+Z_{44}^0}{Z_{44}^- + 3Z_f + Z_{44}^0}\right] = -\ (-j5.0317)\left[\frac{3\ X\ j0.15\ + j0.1553}{j0.1075\ +3\ X\ j0.15 + j0.1533}\right]$$ **(5)**

$I_a^- = j4.2707$ p.u.

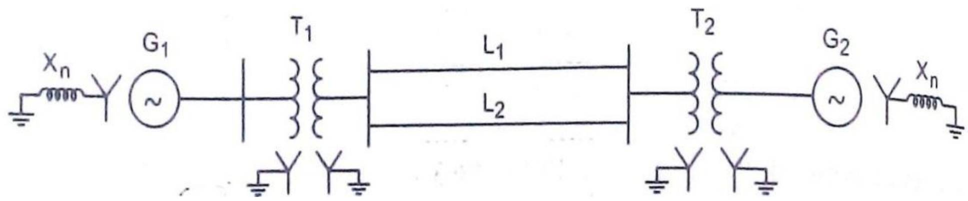
$$I_a^0 = -\ I_a^+\left[\frac{Z_{44}^-}{Z_{44}^- + 3Z_f + Z_{44}^0}\right] = -\ (-j5.0317)\left[\frac{j0.1075}{j0.1075\ +3\ X\ j0.15 + j0.1533}\right]$$

$I_a^- = j0.761$ p.u.

Fault current $I_f = 3\ I_a^0 = 3 \times j0.761 = j2.2829$ p.u.

Fault current $I_f = j2.2829$ p.u.

17. Determine the fault current in p.u., current in phase domain form for a double line to ground fault occurs between phases 'b' and 'c'. (16)



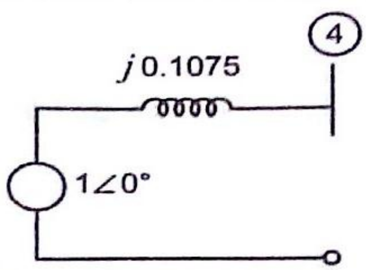
G_1, G_2: 100 MVA, 11 KV, $X^+ = X^- = 15\%$, $X^o = 5\%$, $X_n = 6\%$

T_1, T_2: 100 MVA, 11/220 KV, $X_{leak} = 9\%$

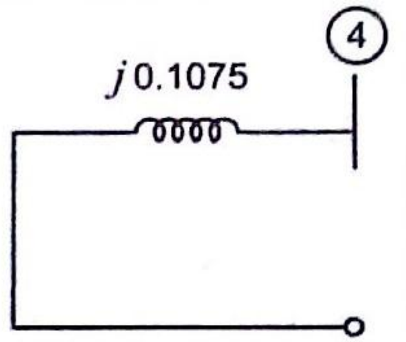
L_1, L_2: $X^+ = X^- = 10\%$, $X^o = 10\%$ on a base of 100 MVA.

Solution:

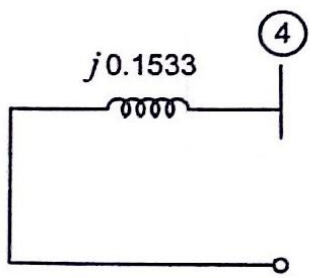
Step 1: Positive sequence Thevenin equivalent (2)



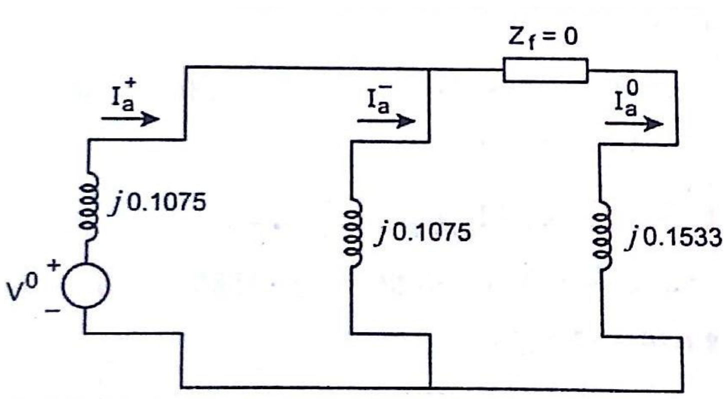
Step 2: Negative sequence Thevenin equivalent (2)



Step 3: Zero sequence Thevenin equivalent **(2)**



Step 4: Sequence Network. ` **(2)**



(4)

$$I_a^+ = \frac{V^0}{Z^+ + \frac{Z^-(Z^0+3Z_f)}{Z^- + Z^0 + 3Z_f}}$$

$$Zf = 0;\ I_a^+ = \frac{V^0}{Z^+ + \frac{Z^- Z^0}{Z^- + Z^0}} = \frac{1\angle 0^\circ}{j0.1075 + \frac{j0.1075\ X\ j0.1588}{j0.1075 + j0.1588}}$$

$$I_a^+ = \frac{1\angle 0^\circ}{j0.1707} = -j5.856 \text{ p.u.}$$

$I_a^+ = -j5.856$ p.u.

$$I_a^- = -\left[\frac{I_a^+ X\ Z^0}{Z^- + Z^0}\right] = -\left[\frac{-j\,5.8586\ X\ j0.1533}{j0.1075 + j0.1533}\right] = j3.4437 \text{ p.u.}$$

$I_a^- = j3.4437$ p.u.

$$I_a^0 = -\left[\frac{I_a^+ X\ Z^-}{Z^- + Z^0}\right] = -\left[\frac{-j\,5.8586\ X\ j0.1075}{j0.1075 + j0.1533}\right] = j2.4149 \text{ p.u.}$$

$I_a^0 = j2.4149$ p.u.

Current in the phase domain: **(4)**

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}$$

$I_a = I_a^+ + I_a^- + I_a^0$

$= -\ j5.8586 + j3.4437 + j2.4149 = 0$

$I_b = I_a^0 + a^2\ I_a^+ + a\ I_a^-$

$= j2.4149 + (-0.5 – j0.866)\ X\ –j5.8586 + (-0.5 + j0.866)\ X\ j3.4437$

$= -8.056 + j3.6223$ p.u.

$I_c = I_a^0 + a\ I_a^+ + a^2\ I_a^-$

$= j2.4149 + (-0.5 + j0.866)\ X\ j5.8586 + (-0.5 – j0.866)\ X\ 3.4437$

$= 8.056 + j3.6223$ p.u.

$I_n = I_a + I_b + I_c$

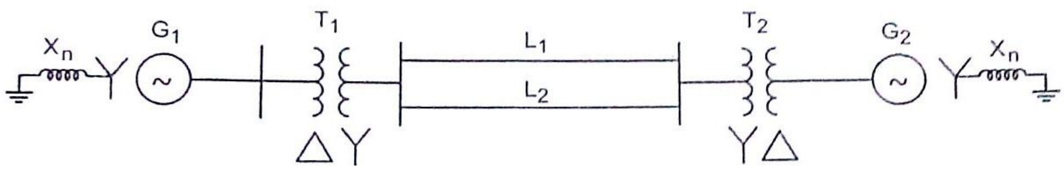
$= 0 – 8.056 + j3.6223 + 8.056 + j0.3.6223$

$= j7.2446$ p.u.

Fault current $I_f = 3 \text{ X } I_a^0 = 3 \text{ X } j2.4149 = j7.2447$ p.u.

Fault current $I_f = j7.2447$ p.u.

18. Determine the fault current in p.u., current in phase domain form for a double line to ground fault occurs between phases 'b' and 'c'. (16)



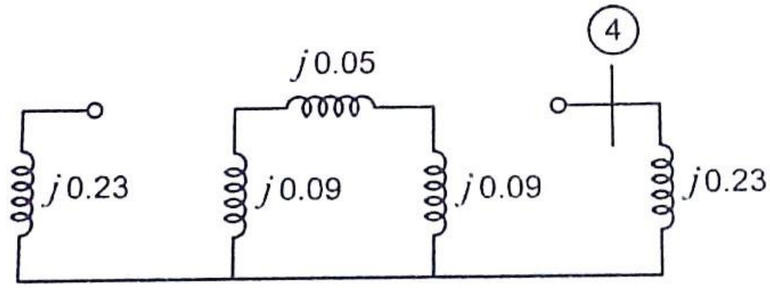
G_1, G_2: 100 MVA, 11 KV, $X^+ = X^- = 15\%$, $X^o = 5\%$, $X_n = 6\%$

T_1, T_2: 100 MVA, 11/220 KV, $X_{leak} = 9\%$

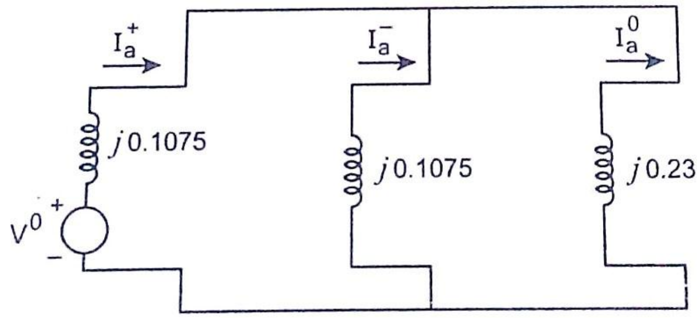
L_1, L_2: $X^+ = X^- = 10\%$, $X^o = 10\%$ on a base of 100 MVA.

Solution:

$Z^+ = j0.1075$, $Z^- = j0.1075$, $Z^0 = j0.23$ **(4)**



Sequence network. (6)



Prefault voltage = $E_a = V^0 = 1\angle 0°$

$$I_a^+ = \frac{V^0}{Z^+ + \frac{Z^- Z^0}{Z^- + Z^0}} = \frac{1\angle 0°}{j0.1075 + \frac{j0.1075 \times j0.23}{j0.1075 + j0.23}} = \text{j5.5322 p.u.}$$

$$I_a^- = -\left[\frac{-j5.5322 \times j0.23}{j0.1075 + j0.23}\right] = \text{j3.77 p.u.}$$

$$I_a^- = -\left[\frac{-j5.5322 \times j0.1075}{j0.1075 + j0.23}\right] = \text{j1.7621 p.u.}$$

Fault current $I_f = 3I_a^0$ = 3 X j1.7621 = j5.2863 p.u.

Fault current I_f = j5.2863 p.u.

Current in phase domain: **(6)**

$$I_a = I_a^+ + I_a^- + I_a^0 = 0$$

$$I_b = I_a^0 + a^2 I_a^+ + a I_a$$

$$= j1.7621 + (-0.5 - j0.866)(-j5.5322) + (-0.5 + j0.866) \times j3.77$$

$$= -8.0557 + j2.6431 \text{ p.u.}$$

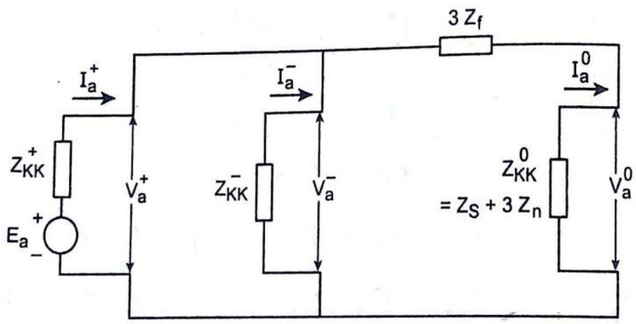
$$I_c = I_a^0 + a I_a^+ + a^2 I_a^- = 8.0557 + j2.6431 \text{ p.u.}$$

I_n = 5.286 p.u.

19. Derive expression for bolted LLG fault **(16)**

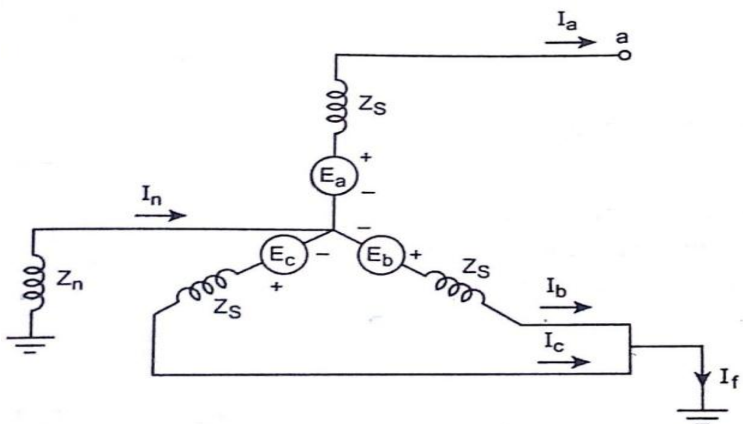
Double Sequence Network: **(4)**

The positive, negative and zero sequence networks are connected in parallel as shown in figure.



Direct short circuit or Bolted LLG Fault: **(8)**

Figure shows the direct short circuit or bolted double line to ground fault.

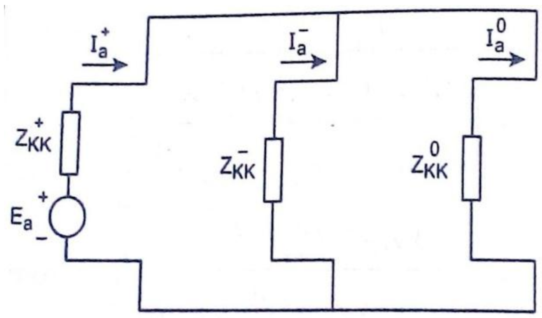


Fault impedance, $Z_f = 0$

The conditions of the fault at bus K are,

$$I_a = 0, V_b = 0, V_c = 0$$
$$I_f = I_b + I_c$$

The sequence network for short circuit LLG fault is as shown.



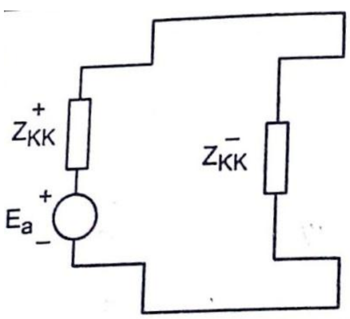
$$I_a^+ = \frac{E_a}{Z_{KK}^+ + \left[\frac{Z_{KK}^- \text{ X } Z_{KK}^0}{Z_{KK}^- + Z_{KK}^0}\right]}$$

$$I_a^- = - I_a^+ \text{ X } \frac{Z_{KK}^0}{Z_{KK}^- + Z_{KK}^0}$$

$$I_a^0 = - I_a^+ \text{ X } \frac{Z_{KK}^-}{Z_{KK}^- + Z_{KK}^0}$$

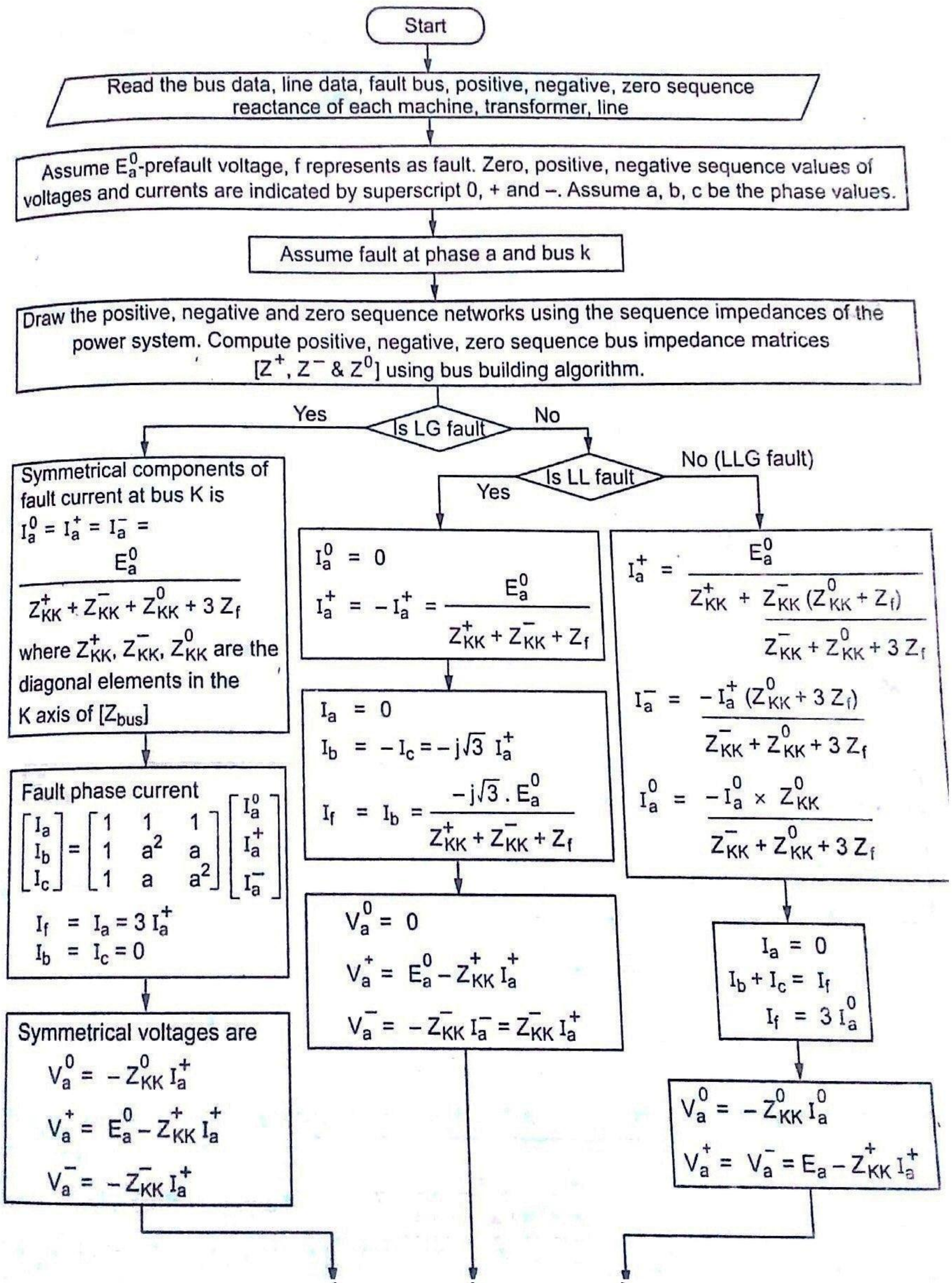
Double line to Ground fault when $Z_f = \alpha$ **(4)**

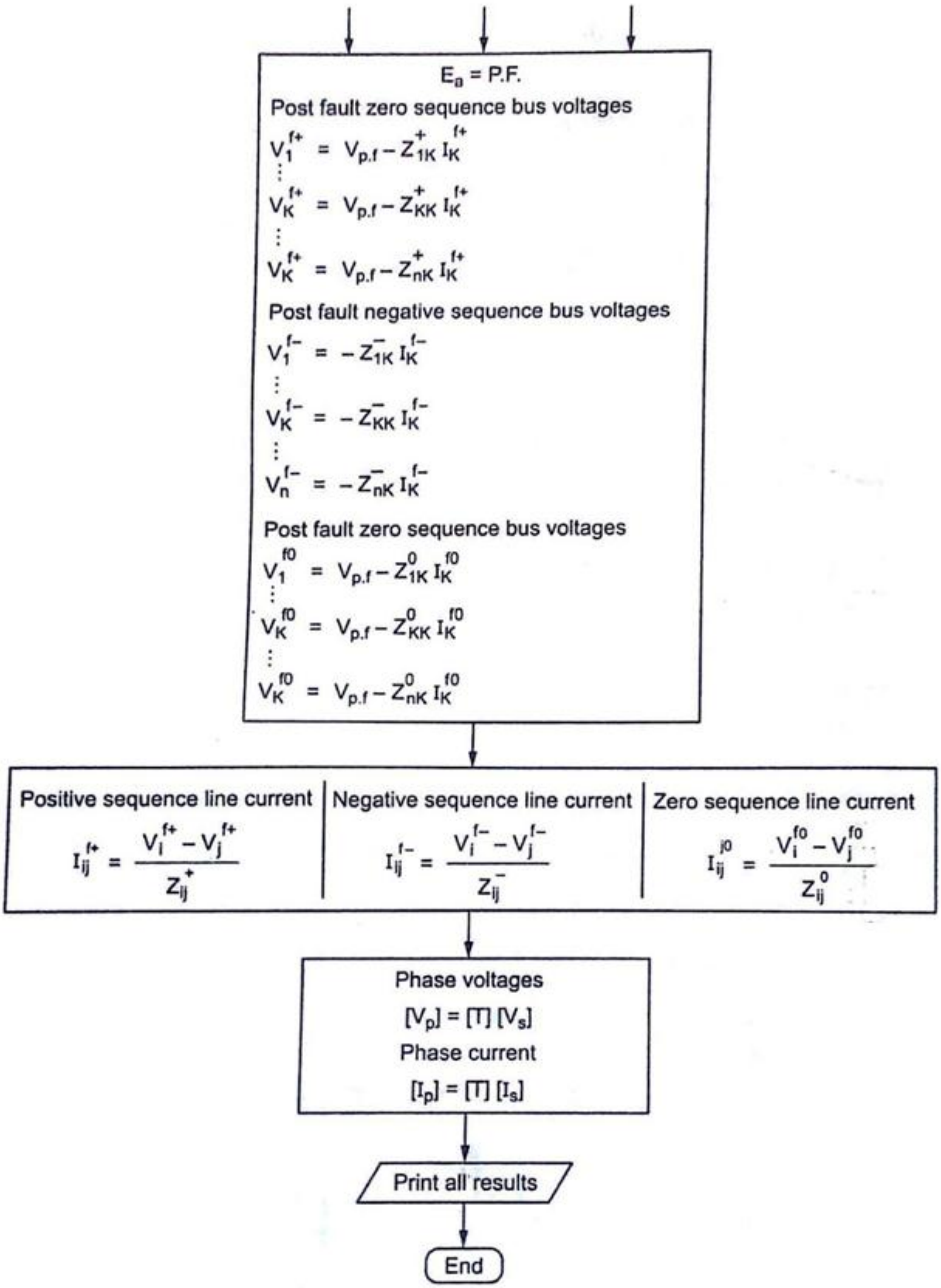
When $Z_f = \alpha$



Zero sequence circuit becomes an open circuit. Therefore no zero sequence circuit can flow. The Sequence network is similar to that of bolted line to line fault.

20. Discuss unsymmetrical fault with a neat flowchart. **(16)**


Start
Read the bus data, line data, fault bus, positive, negative, zero sequence reactance of each machine, transformer, line
Assume E_a^0-prefault voltage, f represents as fault. Zero, positive, negative sequence values of voltages and currents are indicated by superscript 0, + and –. Assume a, b, c be the phase values.
Assume fault at phase a and bus k
Draw the positive, negative and zero sequence networks using the sequence impedances of the power system. Compute positive, negative, zero sequence bus impedance matrices $[Z^+, Z^- \& Z^0]$ using bus building algorithm.
Is LG fault
Yes
No
Symmetrical components of fault current at bus K is $I_a^0 = I_a^+ = I_a^- = \dfrac{E_a^0}{Z_{KK}^+ + Z_{KK}^- + Z_{KK}^0 + 3Z_f}$ where $Z_{KK}^+, Z_{KK}^-, Z_{KK}^0$ are the diagonal elements in the K axis of $[Z_{bus}]$
Fault phase current $\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_a^0 \\ I_a^+ \\ I_a^- \end{bmatrix}$
$I_f = I_a = 3I_a^+$
$I_b = I_c = 0$
Symmetrical voltages are
$V_a^0 = -Z_{KK}^0 I_a^+$
$V_a^+ = E_a^0 - Z_{KK}^+ I_a^+$
$V_a^- = -Z_{KK}^- I_a^+$
Is LL fault
Yes
No (LLG fault)
$I_a^0 = 0$
$I_a^+ = -I_a^+ = \dfrac{E_a^0}{Z_{KK}^+ + Z_{KK}^- + Z_f}$
$I_a = 0$
$I_b = -I_c = -j\sqrt{3}\, I_a^+$
$I_f = I_b = \dfrac{-j\sqrt{3}\,.\,E_a^0}{Z_{KK}^+ + Z_{KK}^- + Z_f}$
$V_a^0 = 0$
$V_a^+ = E_a^0 - Z_{KK}^+ I_a^+$
$V_a^- = -Z_{KK}^- I_a^- = Z_{KK}^- I_a^+$
$I_a^+ = \dfrac{E_a^0}{Z_{KK}^+ + \dfrac{Z_{KK}^- (Z_{KK}^0 + Z_f)}{Z_{KK}^- + Z_{KK}^0 + 3Z_f}}$
$I_a^- = \dfrac{-I_a^+ (Z_{KK}^0 + 3Z_f)}{Z_{KK}^- + Z_{KK}^0 + 3Z_f}$
$I_a^0 = \dfrac{-I_a^0 \times Z_{KK}^0}{Z_{KK}^- + Z_{KK}^0 + 3Z_f}$
$I_a = 0$
$I_b + I_c = I_f$
$I_f = 3I_a^0$
$V_a^0 = -Z_{KK}^0 I_a^0$
$V_a^+ = V_a^- = E_a - Z_{KK}^+ I_a^+$


E_a = P.F.
Post fault zero sequence bus voltages
$V_1^{f+} = V_{p.f} - Z_{1K}^{+} I_K^{f+}$
$V_K^{f+} = V_{p.f} - Z_{KK}^{+} I_K^{f+}$
$V_K^{f+} = V_{p.f} - Z_{nK}^{+} I_K^{f+}$
Post fault negative sequence bus voltages
$V_1^{f-} = -Z_{1K}^{-} I_K^{f-}$
$V_K^{f-} = -Z_{KK}^{-} I_K^{f-}$
$V_n^{f-} = -Z_{nK}^{-} I_K^{f-}$
Post fault zero sequence bus voltages
$V_1^{f0} = V_{p.f} - Z_{1K}^{0} I_K^{f0}$
$V_K^{f0} = V_{p.f} - Z_{KK}^{0} I_K^{f0}$
$V_K^{f0} = V_{p.f} - Z_{nK}^{0} I_K^{f0}$
Positive sequence line current
$I_{ij}^{f+} = \frac{V_i^{f+} - V_j^{f+}}{Z_{ij}^{+}}$
Negative sequence line current
$I_{ij}^{f-} = \frac{V_i^{f-} - V_j^{f-}}{Z_{ij}^{-}}$
Zero sequence line current
$I_{ij}^{j0} = \frac{V_i^{f0} - V_j^{f0}}{Z_{ij}^{0}}$
Phase voltages
$[V_p] = [T]\,[V_s]$
Phase current
$[I_p] = [T]\,[I_s]$
Print all results
End

STABILITY ANALYSIS

Importance of stability analysis in power system planning and operation - classification of power system stability - angle and voltage stability – simple treatment of angle stability into small-signal and large-signal (transient) stability Single Machine Infinite Bus (SMIB) system: Development of swing equation - equal area criterion - determination of critical clearing angle and time by using modified Euler method and Runge-Kutta second order method. Algorithm and flow chart.

PART – A

Importance of stability analysis in power system planning and operation- classification of power system stability - angle and voltage stability

1. Define stability and power system stability.

The stability of a system is defined as the ability of power system to return to stable operation when it is subjected to a disturbance.

Power system stability (M/J 07)

Power system stability is the property of the system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance.

2. How power system stability is classified?

- Angle stability
- Voltage stability.
- Small signal stability
- Large signal stability
- Mid term stability
- Long term stability
- Transient stability
- Oscillatory stability
- Non- Oscillatory stability

3. How the stability studies are classified, what are they?

Depending on the nature of disturbance the stability can be classified into the following three types,

i) Steady state stability

ii) Dynamic stability

iii) Transient stability

4. How do you classify steady state stability limit. Define them.

Depending on the nature of the disturbance, the steady state stability limit is classified into,

- Static stability limit
- Dynamic stability limit

Static stability limit refers to steady state stability limit that prevails without the aid of regulating devices.

Dynamic stability limit refers to steady state stability limit prevailing in an unstable system with the help of regulating devices such as speed governors, voltage regulators, etc.

5. Define steady state stability and Steady state stability limit . (A/M 10)

It is the ability of the power system to bring it to a stable condition after a small disturbance such as gradual infinitesimal variations in system variables like rotor angle, voltage, etc

Steady state stability limit (Nov/Dec- 14)

When the load on the system is increased gradually, maximum power that can be transmitted without losing synchronism is termed as steady state stability limit. In steady state, the power transferred by synchronous machine of a power system is always less than the steady state stability limit.

6. What is rotor angle stability and voltage stability?

Rotor angle stability

- Rotor angle stability is the ability of inter-connected synchronous machines of a power system to remain in synchronism
- Torque balance of synchronous machines (Input turbine and output generator)

Voltage stability

It is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance.

7. State the causes of voltage instability.

A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable drop in voltage

The main factor causing instability is the inability of the power system to meet the demand for reactive power.

8. What is small signal stability and how it is analyzed?

- It is concerned with the maintenance of stability of a synchronous machine or a group of synchronous machines when subjected to a small disturbance.
- Analyzed by – Linearizing the differential equation that describe the swing of the machines around an operating point determined by initial power flow voltage conditions.

9. Define transient stability and dynamic stability. (May/June -14)

Transient stability

It is the ability of the system to bring it to a stable condition after a large disturbance. Large disturbance can occur due to the occurrence of fault, sudden outage of a line, sudden loss of excitation, sudden application or removal of loads, etc.

Dynamic stability

It is the ability of a power system to remain in synchronism after the initial swing (transient stability period) until the system has settled down to the new steady state equilibrium condition

10. Define Transient stability limit: (M/J 12)

The maximum power which can be transmitted between the given pair of buses such that the system does not become unstable when it is subjected to a specified sudden large disturbances under specified initial condition.

(or)

When the load on the system is increased suddenly, maximum power that can be transmitted without losing synchronism is termed as transient state stability limit. Normally, steady state stability limit is greater than transient state stability limit.

11. Write any three assumptions upon transient stability.

The assumptions for transient stability are given as follows.

- Rotor speed is assumed to be synchronous. In fact, it varies insignificantly during the course of the stability study.

- Shunt capacitances are not difficult to account for in a stability study.
- Loads are modeled as constant admittances.

12. How to improve the transient stability limit of power system?

The transient stability limit of power system can be improved by following methods.

- Increase of system voltages
- Use of high speed excitation systems.
- Reduction in system transfer reactance
- Use of high speed reclosing breakers.

13. What are the numerical integration methods of power system stability?

The numerical integration methods of power system stability are as follows.

- Point by point method or step by step method
- Euler method
- Modified Euler method
- Runge-Kutta method(R-K method)

14. What are the machine problems seen in the stability study?

The major problem seen in the machine during the stability study are given as follows

- Those having one machine of finite inertia machines swinging with respect to an infinite bus
- Those having two finite inertia machines swinging with respect to each other.

15. What are the causes of oscillatory and non-oscillatory instabilities in power systems? (A/M 10)

The causes of oscillatory and non-oscillatory instabilities in power systems are as follows.

Oscillatory :

- Due to insufficient damping torque
- Due to unstable control action

Non – oscillatory :

- Due to insufficient synchronous torque

16. Differentiate between voltage stability and rotor angle stability. (N/D 2013)

Voltage Stability	Rotor angle stability
Ability of power system to maintain steady acceptable voltages at all buses in power system under normal operating conditions and after being subjected to a disturbance.	Ability of inter – connected synchronous machines of a power system to remain in synchronism.
Reactive power balance	Torque balance of synchronous machines

Simple treatment of angle stability into small-signal and large-signal (transient) stability

Single Machine Infinite Bus (SMIB) system

17. State the assumptions made in stability studies.

The assumptions made for stability studies are listed as follows.

- Machines represents by classical model
- The losses in the system are neglected (all resistance are neglected)
- The voltage behind transient reactance is assumed to remain constant.
- Controllers are not considered (Shunt and series capacitor)
- Effect of damper winding is neglected.

18. Give the control schemes included in stability control techniques.

The control schemes included in the stability control techniques are:

- Excitation systems
- Turbine valve control
- Single pole operation of circuit breakers
- Faster fault clearing times

19. What are the assumptions that are made in order to simplify the computational task in stability studies?

The assumptions are,

- The D.C offset currents and harmonic components are neglected. The currents and voltages are assumed to have fundamental component alone.
- The symmetrical components are used for the representation of unbalanced faults.
- It is assumed that the machine speed variations will not affect the generated voltage.

20. Explain the concept synchronous speed.

The mechanical torque Tm and the electrical torque Te are considered positive for synchronous generator. Tm is the resultant shaft torque which tends to accelerate the rotor in the positive θ_m direction of rotation . Under steady-state operation of the generator Tm and Te are equal and the accelerating torque Ta is zero. Hence there is no acceleration of deceleration of the rotor, masses and the resultant constant speed is the synchronous speed.

21. Write the power angle equation of a synchronous machine connected to an infinite bus and also the expression for maximum power transferable to the bus.

$$P_1 = P_e = |E'|G_{11} + \frac{|E'||V|}{X_{12}} \sin\delta$$

$$P_e = P_C + P_{\max} \sin\delta$$

This equation is called power angle equation

$$M_{eq} = \frac{M_1 S_1}{S_b} + \frac{M_2 S_2}{S_b}$$

Expression for Maximum Power transfer:-

$$P_{\max} = \frac{|E'||V|}{X_{12}} \sin\delta$$

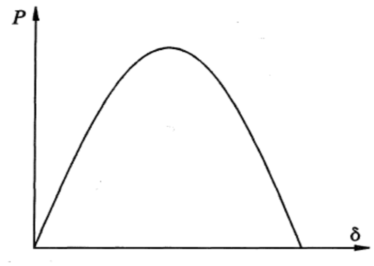
22.Define infinite bus in a power system. (M/J 13,08)

The substation bus voltage and frequency is assumed to remain constant. This is called as infinite bus, since its characterized do not change regardless of the power supplied or consumed by any device connected to it.

23. What is meant by power angle curve? (M/J 13)

$$P_e = \frac{|E'||V|}{X_{12}} \sin\delta = P_{\max} \sin\delta$$

Power transmitted depends on the transfer reactance X_{12} and the angle between the voltages E' and V i.e., (δ). The curve P_C versus δ is known as power angle curve.



24. Define small disturbance and large disturbance.

Small disturbance

The disturbances that cause small and gradual infinitesimal variation in system variables such as rotor angle, voltage, etc., are classified as small disturbance.

Large disturbance

- Any disturbance that causes a change in the admittance matrix encountered in stability is classified as large disturbance
  Eg – Fault occurring, removal of line

25. What is meant by synchronism and damping torques?

The component of electrical torque proportional to rotor angle deviation from initial value is referred to as synchronizing torque and that proportional to speed deviation from initial value is called damping torque.
Assume initially, the machine is in steady state, then
Machine speed = Rated speed = synchronous speed
Then Initial speed deviation = 0

26. State the causes of voltage instability.

The various causes for voltage instability are listed as follows.

- At the time of disturbance occurs
- Increase in load demand
- Inability of power system to meet the demand for reactive power

- Voltage drop occurs when active power and reactive power flow through inductive load

27. State the assumption made in stability studies .

The assumptions made in stability studies are stated as follows.

- Machine represented by classical model
- Controllers are not considered
- Loads are constants
- Voltage and current are sinusoidal.

28. Write the expression for maximum power transfer.

$$P_{max} = \frac{|E'||V|}{X_{12}} \sin\delta$$

$$\begin{aligned} where\ X_{12} &= Transient\ reactance \\ E' &= Transient\ internal\ source\ voltage. \\ V &= Infinite\ bus\ voltage. \end{aligned}$$

29. What are the methods to improve steady state stability.

- Reduce the reactance. Steady state stability limit can be improved by using two parallel lines which increases reliability of the system.
- Increase either of both |E| and |V|. Series capacitors are included in lines to get better voltage regulation by decreasing X.
- Higher excitation voltages and quick excitation system are also employed.

30. What is synchronizing power coefficient?

The quantity $P_S = P_{max} \cos\delta_0$ is the slope of the power angle at δ_0

$P_{e=} P_{max} \sin \delta_0$

$$P_s = \left.\frac{dP_e}{d\delta}\right|_{\delta_0} = P_{max}\cos\delta_0 = \frac{E'V\cos\delta_0}{X}$$

$where\ P_S\ is\ known\ as\ synchronising\ power.$

Co-efficient or stiffness of synchronous machine.

31. What are the assumptions made to simplify the transient stability problem?

- Neglecting the saliency of synchronous machine
  $X_d = X_q$
  $X'_d = X'_q$
- Synchronous machine are represented by constant terminal voltage
- Neglecting governor action for turbine
- Resistances are neglected
- Damping is neglected
- Loads are represented by common admittance.

32. What are the assumptions made to solve swing equation?

- Mechanical power input P_m is constant during the period of electromechanical transient
- Rotor speed changes are insignificant
- The generated machine e.m.f remains constant.
- Effect of voltage regulation loop is neglected.

33. Difference between steady state and transient state

Steady State	Transient State
• A power system is in steady state means all the measured quantities are in operating condition • Steady state – when it occurs disturbance, and it returns to same steady state condition. • Analysed by linear equation, non linear equation are replaced by linear equation.	• A power system is in transient state if the measured quantities are not in constant. • Transient state – large disturbance occurs change in operating condition occurs. • Analysed by using non linear equation

34. What is the importance of stability analysis in power system planning and operation?

- Transient stability studies give the information of magnitude of voltage and frequency
- It deals with the stability of the system
- Transient stability steady is needed when the new generating station and transmission facilities are planned
- Stability system is need to determine the nature of relaying system, critical clearing time of circuit breaker.
- More helpful in determining power transfer capability between two difference systems.

35. What are the different mode of small signal stability?

- Local plant mode
- Inter area mode
- Control mode
- Torsional mode

36. What is meant by local modes and Inter-area mode ?

local modes

Local modes are associated with swinging of unit at a generating station with respect to the rest of the power system. The term local is used because the oscillation are localized at one station or a small part of the power system.

Inter-area mode

Inter area mode is associated with the swinging of many machines in one part of the system against machines in other parts. They are caused by two or more groups of closely coupled machines being interconnected by weak ties.

37. What is meant by control modes and Torsional mode?

Control modes

Control modes are associated with generating units and other controls. Poorly tuned exciters, speed governor, HVDC converters and statics VAR compensators are the usual causes of instability of these modes.

Torsional mode

Torsional modes are associated with the turbine – generator shaft system rotational components. Instability of torsional modes may be caused by interaction with excitation controls, speed governors, HVDC controls, and series capacitor-compensated lines.

38. Write down the units of inertia constants M and H and their interrelationship.

The unit of M is MJ-s/elec.rad or MJ-s/mech-rad.

The unit of H is MJ/MVA or MW-s/MVA

The M and H are related by the equation,

$$M = \frac{HS}{\pi f}$$

Where, S = MVA rating of Machine

F = Frequency in Hz

39. If two machines are swinging coherently with inertia M_1 and M_2 what will be the inertia of the equivalent machine?

The equivalent moment of inertia,

$$M_{eq} = \frac{M_1 S_1}{S_b} + \frac{M_2 S_2}{S_b}$$

Where, S_1 & S_2 = MVA rating of machine 1 & 2 respectively

S_b = Base MVA or MVA rating of system.

40. What are the systems design strategies aimed at lowering system reactance?

The system design strategies aimed at lowering system reactance are:

- Minimum transformer reactance
- Series capacitor compensation of lines
- Additional transmission lines.

41. List the method of improving the transient stability limit of a power system.

The various methods to improve transient stability limit are given as follows.

- Increase of the system voltage and use of AVR
- Use of high speed excitation systems.
- Reduction in system transfer reactance
- Use of high speed reclosing

Swing equation

42. What is Multimachine stability?

If a system has any number of machines, then each machine is listed for stability by advancing the angular position, δ of its internal voltage and noting whether the electric power output of the machine increases (or) decreases. If it increases,

i.e if $\partial P_n / \partial \delta_n > 0$

then machine n is stable. If every machine is stable, then the system having any number of machine is stable.

43. List the assumptions made in multimachine stability studies.

The assumptions made are,

- The mechanical power input to each machine remains constant during the entire period of the swing curve computation
- Damping power is negligible
- Each machine may be represented by a constant transient reactance in series with a constant transient voltage.
- The mechanical rotor angle of each machine coincides with δ, the electrical phase angle of the transient internal voltage.

44. Define swing curve. What is the use of this curve? (N/D 2013)

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_{m(p.u)} - P_{e(p.u)}$$

The graphical display of δ versus *t* is called the swing curve. The plot of swing curves of all machines tells us whether machines will remain in synchronism after a disturbance.

The swing curve is the plot or graph between the power angle δ, and time, t. It is usually plotted for a transient state to study the nature of variation in δ for a sudden large disturbance.

From the nature of variations of δ, the stability of a system for any disturbance can be determined.

45. Give an example for swing equation. Explain each term along with their units. (N/D 11)

Eg : Turbo generator, water wheel generator, etc

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_{m(p.u)} - P_{e(p.u)}$$

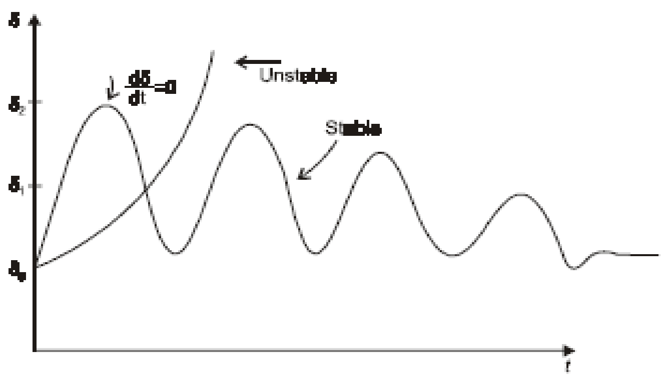
$$\begin{aligned} Where \quad H &= p.u.inertia\ constant \\ f &= Frequency \\ \delta &= Power\ angle \end{aligned}$$

46. Write swing equation. (A/M 11)

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_{m(p.u)} - P_{e(p.u)}$$

$$\begin{aligned} Where \quad H &= p.u.inertia\ constant \\ f &= Frequency \\ \delta &= Power\ angle \end{aligned}$$

47. Plot the swing curve.



48. What are the assumptions made in solving swing equation?

- Mechanical power input to the machine remains constant during the period of electromechanical transient of interest.
- Rotor speed changes are insignificant that had already been ignored in formulating the swing equations.
- Effect of voltage regulating loop during the transient.

49. Write the swing equation and explain the terms involved in it. (N/D 07)

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_{m(p.u)} - P_{e(p.u)}$$

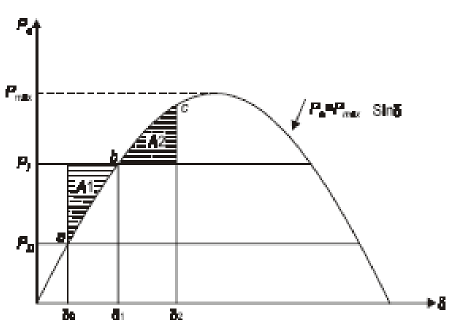
$$\begin{aligned} Where \quad H &= p.u.inertia\, constant \\ f &= Frequency \\ \delta &= Power\ angle \end{aligned}$$

Equal area criterion

50. State equal area criterion. (N/D 11) (M/J 09, 07)

- The equal area criterion for stability states that the system is stable if the area under $P_a - \delta$ curve reduced to zero at some value of δ.
- This is possible if the positive (acceleration) are under $P_a - \delta$ curve is equal to the negative (deceleration) area under $P_a - \delta$ curve for a finite change in δ. Hence the stability criteria is called equal area criterion.

51. Draw the figure for equal area criterion



52. What are various faults that increase severity of equal area criterion?

The various faults that increases severity of equal area criterion are,

- Single line to ground fault
- Line to line fault
- Double line to ground fault
- Three phase fault

53. State the application of equal area criterion.

We apply the equal area criterion to two different systems of operation

i) Sustained line fault

ii) line fault cleared after sometime by the simultaneous tripping of the breakers at both the end

54.List the types of disturbances that may occur in a single machine infinite bus bar system of the equal area criterion stability

The types of disturbances that may occur are,

- Sudden change in mechanical input
- Effect of clearing time on stability
- Sudden loss of one of parallel lines
- Sudden short circuit on one of parallel lines
  - Short circuit at one end of line
  - Short circuit away from line ends
  - Reclosure of lines.

Determination of critical clearing angle and time

55. Define critical clearing angle. (A/M 11)

The critical clearing angle, is the maximum allowable change in the power angle δ before clearing the fault, without loss of synchronism. The time corresponding to this angle is called critical clearing time, t_{cc}. It can be defined as the maximum time delay that can be allowed to clear a fault without loss of synchronism.

56. Define critical clearing time and critical clearing angle. (N/D- 14,12,08) (M/J – 12)

Critical clearing angle :

For any given initial load in the case of a fault clearance on a synchronous machine connected to an infinite bus bar, there is a critical clearing angle. If the actual clearing angle is greater than the critical value, the system is unstable, other wise the system is stable. Maximum allowable angle for a system to remain stable.

Critical clearing time :

Maximum allowable time for a system to remain stable are known as critical clearing time.

57. Give the expression for critical clearing time. (N/D 07)

Critical time margin = critical clearing time – clearing time specified

$$= t_{cr(critical)} - t_{spec}$$
$$where$$
$$t_{spec} = Specified\ clearing\ time$$

58. On what basis do you conclude that a given synchronous machine has lost stability? (A/M 08)

Unstable System : If the system is unstable, δ continues to increase with time and the machine loses synchronism.

From this we can easily able to conclude that the given synchronous machine has lost its stability.

59. What are coherent machines? (APR/MAY 2004)

Machines which swing together are called coherent machines. When both ωs and δ are expressed in electrical degrees or radians, the swing equations for coherent machines can be combined together even though the rated speeds are different. This is used in stability studies involving many machines.

60. What will happen if there a loss of excitation?

- It operates as an induction generator running above synchronous speed.
- The excitation is supplied from the power system and hence the machine draws reactive power from the system.
- It may cause severe system voltage reductions.
- The stator current may 2 to 3 times full load current causing excessive stator heating.

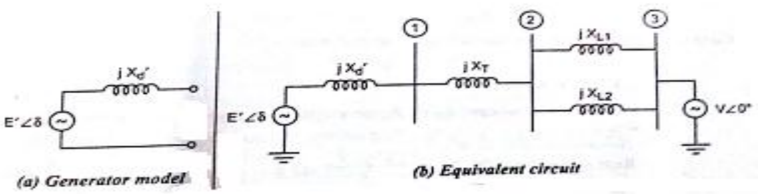
61. Define inertia constant (M).

M-Constant or inertia constant is defined as the angular momentum at synchronous speed. If energy is measured in Joules and speed in mechanical radians per second. Unit of M is Joule-sec/Mechanical radian.

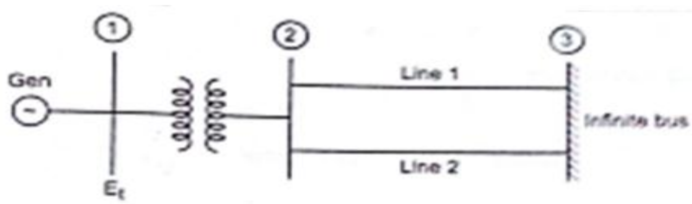
62. What happen if there exist of load rejection?

When there is a load rejection in the system, the speed of the generators will increase suddenly and hence the system frequency will rise. The speed governing systems will respond by reducing the mechanical power generated by the turbines.

63. Draw the equivalent circuit model of SMIB.



64. Draw the synchronous machine represented in classical model.

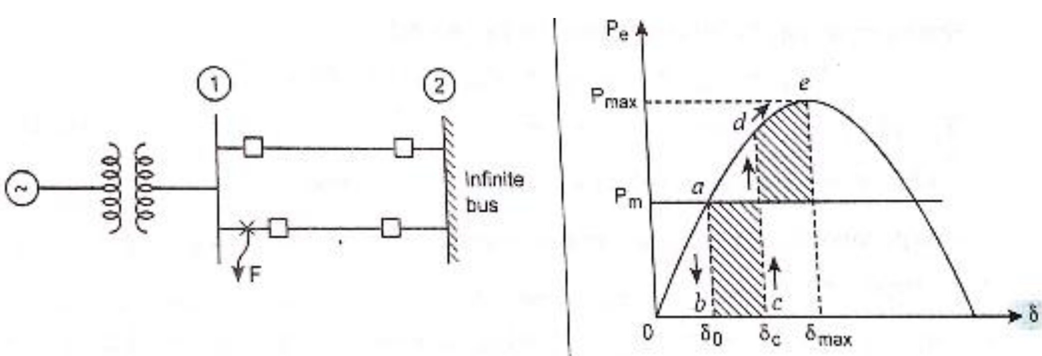


Part – B

1.Explain the equal area criteria for the following application : (16) (N/D'14)

- **i. Sustained fault**
- **ii. Fault with subsequent clearing.**

A three phase fault is occurred at point F of the outgoing radial line at bus 1 is shown in figure. The accelerating area A_1 begins to increase and point moves along *bc*. At time t_c (clearing time) corresponding to angle δc (clearing angle), the faulted line is cleared by opening of the circuit breaker. The rotor is now decelerated and the decelerating area A_2 begins, while the point moves along *de* and the path is retraced along the curve.



(6)

If an angle δ_1 can be found that area A_1 = Area A_2 the system is found to be stable. The system finally settles down to be the steady state operating point at *a* in an oscillatory manner because of inherent damping. At point *a*, $P_m = P_e$

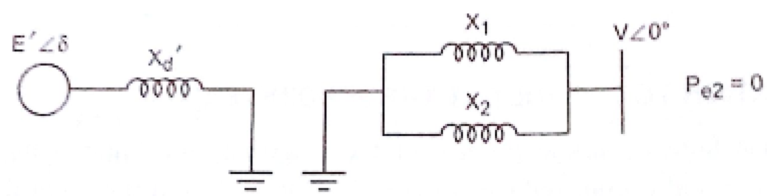
Prefault condition: (2)

Power angle equation is given by

$$P_{e1} = \frac{|E'||V|}{X_d' + \left[\frac{X_1 X_2}{X_1 + X_2}\right]} \sin\delta = P_{\max 1} \sin\delta$$

During Fault condition :

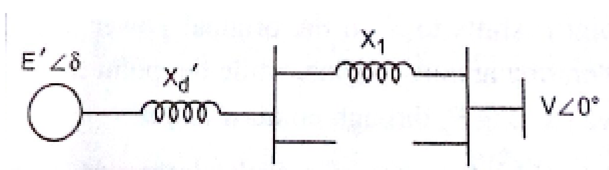
The generator gets isolated from power system for purpose of power flow as shown in figure.



(4)

Post fault condition:

The circuit breaker at two ends of the faulted line open at time t_{cr} disconnecting the faulted line. The circuit is as shown in figure.



Power angle equation is given by

$$P_{e3} = \frac{|E'||V|}{X_d' + X_1} \sin\delta = P_{\max 3} \sin\delta$$ (4)

2.Derive the swing equation from the basic principles. Why it is non-linear?

(16)(N/D'14) (M/J'07,14)

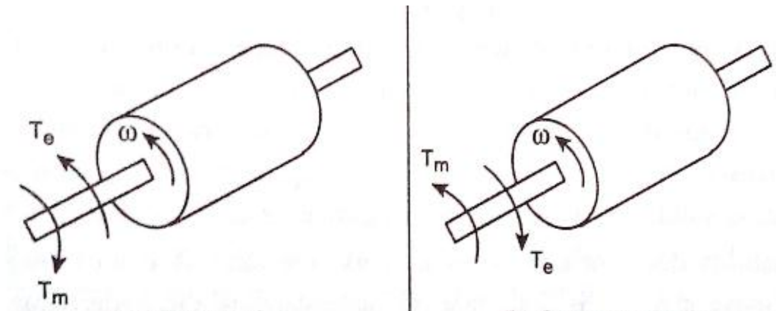
Let T_m be the driving mechanical torque (6)

T_e be the electrical torque

The motor action and generator action is shown in figure.

For generator action, T_m and T_e are positive

θ_m is positive



(a) Motor action (b) Generator action

Under steady state with losses neglected.

$$T_m = T_e$$

Acceleration torque $T_a = T_m - T_e = 0$

i.e. no accelerating torque

$$T_a = T_m - T_e$$

Let J be the moment of inertia of the prime mover and generator.

From Law's of rotation,

$$Acceleration\ \alpha = \frac{d^2\theta_m}{dt^2}$$

$$Acceleration\ torque\ T_a = J\alpha$$

$$\therefore J\frac{d^2\theta_m}{dt^2} = T_m - T_e \qquad (1)$$

Where θ_m is the angular displacement of the rotor with respect to the stationary reference axis on stator. (5)

θ_m increase with time even at constant synchronous speed.

$$\therefore \theta_m = \omega_{sm}t + \delta_m \qquad (2)$$

$where\ \delta_m = Angular\ displacement\ of\ rotor$
$before\ disturbance\ in\ mechancal\ radians.$

$\omega_{sm}t = Cons\tan t\ angular\ velocity$

$Diff.eq.(2), wrt\ t, we\ get$

$$\omega_m = \frac{d\theta_m}{dt} = \omega_{sm}t + \frac{d\delta_m}{dt} \qquad (3)$$

Diff .eq.(3), *wrt t*, *rotor acceleration is*

$$\frac{d^2\theta_m}{dt^2} = \frac{d^2\delta_m}{dt^2}$$

Substituting in eq(1) *we get*,

$$J\,\frac{d^2\delta_m}{dt^2} = T_m - T_e$$

Multiplying by ω_m *on both side*,

$$J\omega_m\,\frac{d^2\delta_m}{dt^2} = \omega_m T_m - \omega_m T_e$$

Inertia constant

$M = J\omega_m$ *is the inertia constant*

i.e. Angular momentum of the rotor at synchronous speed.

$$M\,\frac{d^2\delta_m}{dt^2} = P_m - P_e \quad (P = \omega T) \qquad (4)$$

p.u. Inertia Contant

Kinetic Energy of rotating masses $W_K = \frac{1}{2}J\omega_m^2$

$$p.u. of\ H = \frac{\text{Stored kinetic energy in mega joules of turbine, alternator and exciter rotor at synchronous speed}}{\text{Machine rating in MVA}}$$

$$H = \frac{\frac{1}{2}J\omega_{sm}^2}{S_B}\sec \qquad (6)$$

$$J\omega_{sm}^2 = \frac{2HS_B}{\omega_{sm}} = M$$

Substituting in eq(4)

$$\frac{2HS_B}{\omega_{sm}}\frac{d^2\delta_m}{dt^2} = P_m - P_e \qquad (5)$$

by solving we get

$$\frac{HS_B}{\pi f}\frac{d^2\delta_m}{dt^2} = P_m - P_e \qquad (6)$$

Dividing by MVA rating S_B *on both side we get,*

$$\frac{H}{\pi f}\frac{d^2\delta_m}{dt^2} = \frac{P_m}{S_B} - \frac{P_e}{S_B}$$

$$\frac{P_m}{S_B} = p.u. mechanical\ power$$

$$\frac{P_e}{S_B} = p.u. electrical\ power$$

$$\frac{H}{\pi f}\frac{d^2\delta_m}{dt^2} = P_{m(p.u)} - P_{e(p.u)} = P_{m(p.u)} - P_{\max}\sin\delta \quad (7)$$

$$M_{(p.u)}\frac{d^2\delta}{dt^2} = P_{m(p.u)} - P_{e(p.u)}$$

$$where\ M_{(p.u)} = \frac{H}{\pi f}, \delta\ in\ radians$$

If δ *expressed in electrical degrees,*

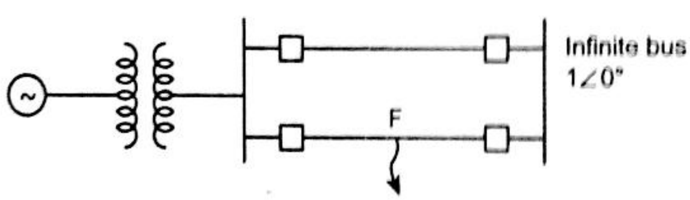
$$\frac{H}{180 f}\frac{d^2\delta}{dt^2} = P_{m(p.u)} - P_{e(p.u)}$$

These equation are called as **Swing Equation**

3. Describe the algorithm for modified Euler method of finding solution for power system stability problem studies. (16) (M/J'14)

Numerical integration techniques can be applied to obtain approximate solutions of non-linear differential equations. (5)

Consider a generator connected to an infinite bus through two parallel lines and a 3ϕ fault occurs at the middle of line 2 as shown in figure.



Let P_m be the input power which is a constant.

Prefault Condition: Under steady state operation,

Power transfer from generator to an infinite bus,

$P_e = P_m$

$$\frac{E'V}{X_1}\sin\delta_0 = P_{\max 1}\sin\delta_0 = P_m$$

$$\sin\delta_0 = \frac{P_m}{P_{\max 1}} \Rightarrow \delta_0 = \sin^{-1}\left[\frac{P_m}{P_{\max 1}}\right] \qquad (1)$$

$$where\ P_{\max 1} = \frac{E'V}{X_1}$$

$X_1 = Transfer\ reactance\ for\ the\ prefault\ condition$

$The\ rotor\ is\ running\ at\ synchronous\ speed,$

$\omega_0 = 2\pi f$

$Change\ in\ angular\ velocity\ is\ zero.$ (5)

$i.e., \Delta\omega_0 = 0$

During the fault : Consider a 3ϕ fault occurs at the middle of one line 2 as shown in fig.

$$P_{e2} = \frac{|E'||V|}{X_{II}}\sin\delta_1 = P_{\max 2}\sin\delta$$

$$where\ P_{\max 2} = \frac{|E'||V|}{X_{II}}$$

$X_{II} = Transef\ reactance\ during\ the\ fault$

$the\ swing\ eq.\ is\ given\ by,$

$$\frac{d^2\delta_m}{dt^2} = \frac{\pi f}{H}\left[P_m - P_{\max 2}\sin\delta\right] = \frac{\pi f}{H}P_a$$

$the\ above\ eq.\ can\ be\ transformed\ into\ the\ state\ variable\ form,$

$$\frac{d\delta^{(1)}}{dt} = \Delta\omega \qquad (2)$$

$$\frac{d^2\delta_m}{dt^2} = \frac{d\Delta\omega^{(1)}}{dt} = \frac{\pi f}{H}P_a \quad (3)$$

$Compute\ the\ first\ estimate\ at\ t_1 = t_0 + \Delta t.$

$$\delta_{i+1}^P = \delta_i + \left.\frac{d\delta^{(1)}}{dt}\right|_{\Delta\omega_i}.\Delta t \qquad (4) \qquad\qquad (6)$$

$$\Delta\omega_{i+1}^P = \Delta\omega_i + \left.\frac{d\Delta\omega^{(1)}}{dt}\right|_{\delta_i}.\Delta t \qquad (5)$$

Compute the derivatives : Using the predicted value, determine the derivatives at the end of iteration.

$$\left.\frac{d\delta^{(2)}}{dt}\right|_{\Delta\omega_{i+}^P} = \Delta\omega_{i+1}^P \qquad (6)$$

$$\left.\frac{d\Delta\omega^{(2)}}{dt}\right|_{\delta_{i+1}^{P}} = \frac{\pi f}{H} P_a\Big|_{\delta_{i+1}^{P}} \qquad (7)$$

Computing the final estimated corrected value,

$$\delta_{i+1}^{C} = \delta_i + \left[\frac{\left.\frac{d\delta}{dt}\right|_{\Delta\omega_i} + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_{i+1}^{P}}}{2}\right]\Delta t \qquad (8)$$

$$\Delta\omega_{i+1}^{C} = \Delta\omega + \left[\frac{\left.\frac{d\Delta\omega}{dt}\right|_{\delta_i} + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_{i+1}^{P}}}{2}\right]\Delta t \qquad (9)$$

4. Explain the methods of improving power system stability. (16) (N/D'13,11)

Methods of Improving transient Stabiltiy:- (4)

- Reducing in the disturbing influence by minimizing the fault severity and duration
- Increasing the restorating synchronizing forces.
- Reduction of acceleration torque through control of prime mover mechanical power.
- Reduction of accelerating torque by applying artificial load.

Traditional approach to transient stability problems. (6)

- Increasing system voltage by using automatic voltage regulator.
- Using high speed excitation system to increase the voltage profile.
- Reducing the transfer reactance.
- Using high speed reclosing breakers. (employing single-pole operation of reclosing circuit breakers).
- Reducing inertia constant.
- Single pole operation of reclosing circuit breakers
- Use of bundled conductors
- High speed fault clearing
- Increasing no .of parallel lines between points
- Regulated shunt compensation
- Dynamic breaking
- Single pole switching
- Generator tripping.

Increasing system voltage by AVR

When a fault occurs, the bus voltages are reduced. In generator terminals, the terminal voltage is maintained by the automatic voltage regulators or by using high speed excitation system.

Reducing the transfer reactance: (3)

Maximum power transfer, $P_{max} = \frac{|E'||V|}{X}$

By reducing reactance, system voltage profile increases and P_{max} increases.

$$\text{Inductance } L = 0.2 \ln\left[\frac{D}{r'}\right]$$

Where D = spacing

r' = Geometric mean radius

$$\text{Reactance } X = \omega L$$

Reactance can be decreased by reducing conductor spacing or by increasing conductor diameter.

Series reactance may be reduced by using bundled conductors.

For long transmission lines, series capacitors are added to the line for compensation is used to reduce reactance and increase the stability limit.

Switched series capacitors decreases load voltage fluctuations and raise the transient stability limit almost equal to steady state stability limit.

Transfer reactance is reduced by increasing the number of parallel lines.

Using High speed reclosing breakers: (3)

Most of the faults are transient in nature. Rapid switching and isolation of unhealthy lines followed by reclosing is used to improve the stability margin.

Most occurring fault like L.C. fault, the use of single pole opening and reclosing improves stability limit.

There will be a definite power transfer because one line is opened during the fault. Power transfer takes place in other two lines. But using these poles switching, the power transfer becomes zero.

Recent trends :-

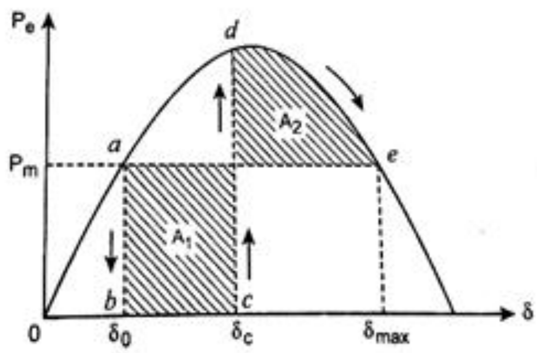
- HVDC links

- Use of breaking resistors
- Short circuit current limiters
- Turbine fast valving of bypassing valve
- Full load rejection technique.

5. Explain the term critical clearing angle and critical clearing time in connection with the transient stability of a power system. (16) (A/M'11)(N/D'07,13)

Obviously $P_{max2} < P_{max1}$ (8)

The critical clearing angle is reached when any further increase in δ_c causes the Area A_2 < Area A_1. This occurs when δ_{max} or point *e* is at the intersection of line P_m and curve P_e as shown in figure.



Apply equal area criterion. Area A_1 = Area A_2

$$\int_{\delta_0}^{\delta_c} P_m d\delta = \int_{\delta_c}^{\delta_{\max}} (P_{\max}\sin\delta - P_m)d\delta$$

$$P_m\left[\delta\right]_{\delta_0}^{\delta_c} = P_m(-\cos\delta) - P_m\delta]_{\delta_c}^{\delta_{\max}}$$

solving for δ_c, *we get*

$$P_{\max}\cos\delta_c = P_m(\delta_{\max} - \delta_0) + P_m\cos\delta_{\max}$$

Dividing by $P_{\max}$,

$$\cos\delta_c = \frac{P_m}{P_{\max}}(\delta_{\max} - \delta_0) + \cos\delta_{\max}$$

For a stable system,

$$\cos\delta_c = \frac{P_m}{P_{\max}}(\delta_{\max} - \delta_0) + \cos\delta_{\max} \qquad (1)$$

During a 3φ fault, $P_e = 0$, therefore the swing equation becomes (8)

$$\frac{H}{\pi f}\frac{d^2\delta}{dt^2} = P_m$$

$$\frac{d^2\delta}{dt^2} = \frac{\pi f}{H} P_m$$

Intergrating both side,

$$\frac{d^2\delta}{dt^2} = \frac{\pi f}{H} P_m \int_0^t dt = \frac{\pi f\, P_m t}{H}$$

$$At\,\delta = \frac{\pi f\, P_m}{H}\int_0^t t dt = \frac{\pi f\, P_m t^2}{2H} + \delta_0$$

$$\delta = \delta_{cr}, t = t_{cr}$$

$$\therefore \delta_{cr} = \frac{\pi f\, P_m t_{cr}^2}{2H} + \delta_0 \qquad (2)$$

$$t_{cr}^2 = \frac{2H}{\pi f P_m}(\delta_{cr} - \delta_0)$$

$$t_{cr} = \sqrt{\frac{2H}{\pi f\, P_m}(\delta_{cr} - \delta_0)} \qquad (3)$$

Where H= p.u. inertia constant.

f= frequency

P_m= Mechanical Power

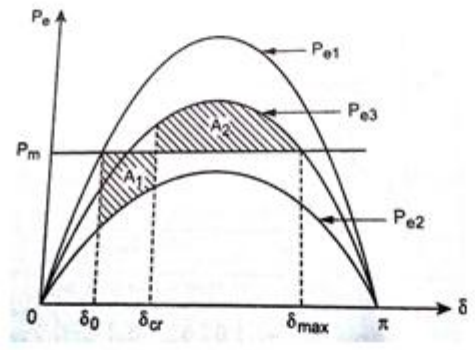
δ_{cr} = Critical clearing angle

δ_0 = Rotor angle

6. A generator is operating at 50 Hz delivers 1 p.u. power to an infinite bus through a transmission circuit in which resistance is ignored. A fault takes place reducing the maximum power transferable to 0.4 p.u., whereas before the fault, this power was 1.6 p.u. and after the clearance of the fault, it is 1.2 p.u. By the use of equal area criterion, determine the critical clearing angle. (16) (N/D'11)

Solution:

The power angle curve is as shown in fig. (6)



P_{e1}= 1.6 sin δ (5)

P_{max1}= 1.6 p.u.

P_{e2}= 0.4 sin δ

P_{max2}= 0.4 p.u.

P_{e3}= 1.2 sin δ

P_{max3}= 1.2 p.u.

Initial loading $P_m = \sin \delta_0 = 1/1.6$

$$\delta_0 = \sin^{-1}\left[\frac{1}{1.6}\right] = 0.675\,rad$$

$$\delta_{\max} = \pi - \sin^{-1}\left[\frac{P_m}{P_{\max 3}}\right]$$

$$= \pi - \sin^{-1}\left[\frac{1}{1.2}\right] = 2.156\,rad$$

Applying equal area criterion, (5)

Area A_1 = Area A_2

$$P_m(\delta_{cr} - \delta_0) - \int_{\delta_0}^{\delta_{cr}} P_{e2}\,d\delta = \int_{\delta_{cr}}^{\delta_{\max}} P_{e3}\,d\delta - P_m(\delta_{\max} - \delta_{cr})$$

$$\Rightarrow \cos\delta_{cr} = \frac{P_m(\delta_{\max} - \delta_{cr}) - P_{\max 2}\cos\delta_0 + P_{\max 3}\cos\delta_{\max}}{P_{\max 3} - P_{\max 2}}$$

$$= \frac{1.0(2.156 - 0.675) - 0.4\cos 0.675 + 1.2\cos 2.156}{1.2 - 0.4}$$

$$\cos\delta_{cr} = 0.632\,rad$$

$$\delta_{cr} = \cos^{-1} 0.632 = 0.887\,rad = 50.82°$$

7. Derive the swing equation of a single machine connected to an infinite bus system and explain the steps of solution by Runge-Kutta method. (16) (N/D '08,11)

Runge – Kutta method

The following steps involved in Runge-Kutta method to determine stability.

I estimates :

$$K_1 = \left.\frac{d\delta}{dt}\right|_{\Delta\omega_i} \times \Delta t = \Delta\omega_i \times \Delta t \qquad (1)$$

$$l_1 = \left.\frac{d\Delta\omega}{dt}\right|_{\delta i} \times \Delta t = \frac{\pi f}{H}\left[P_m^{'} - P_{e(\delta i)}\right] \times \Delta t \qquad (2)$$

$II \ \ estimates:$

$$K_2 = \left[\Delta\omega_i + \frac{l_1}{2}\right]\Delta t \qquad (3)$$

$$l_2 = \frac{\pi f}{H}\left[P'_m - P_{e(\delta_i + (K_1/2))}\right] \times \Delta t \qquad (4)$$

$III \ \ estimates:$

$$K_3 = \left[\Delta\omega_i + \frac{l_2}{2}\right]\Delta t \qquad (5)$$

$$l_3 = \frac{\pi f}{H}\left[P'_m - P_{e(\delta_i + (K_2/2))}\right] \times \Delta t \qquad (6)$$

$IV \ \ estimates:$

$$K_4 = (\Delta\omega_i + l_3) \times \Delta t \qquad (7)$$

$$l_4 = \frac{\pi f}{H}\left[P'_m - P_{e(\delta_i + (K_3)}\right] \times \Delta t \qquad (8)$$

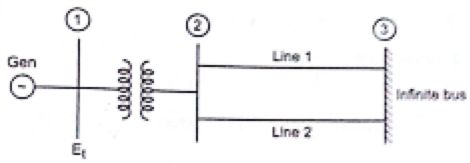
$Final\, estimates\, at\, t = t_1$

$$\delta_{i+1} = \delta_i + \frac{1}{6}\left[K_1 + 2K_2 + 2K_3 + K_4\right] \qquad (9)$$

$$\Delta\omega_{i+1} = \Delta\omega_i + \frac{1}{6}\left[l_1 + 2l_2 + 2l_3 + l_4\right] \qquad (10)$$

8.(i). Write the swing equation describing the rotor dynamic of a synchronous machine connected to infinite bus through a double circuit transmission line. (10)

Consider a generator connected to an infinite bus through a double transmission line as shown in fig.

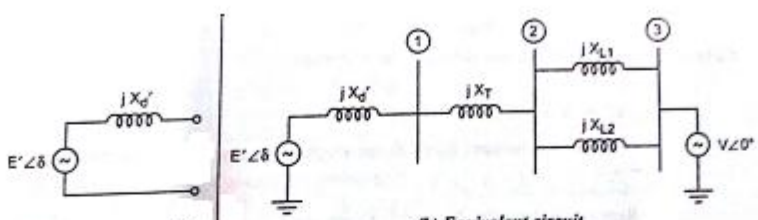


(5)

Infinite Bus

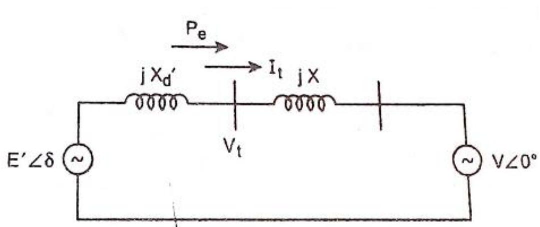
The substation bus voltage and frequency is assumed to remain constant. This is called as infinite bus, since its characteristics do not change regardless of the power supplied or consumed by any device connected to it.

The generator model is shown below and the equivalent circuit diagram also represented a classical model and all resistance are neglected is as shown in figure.



(a) Generator model (b) Equivalent circuit

The simplified equivalent circuit is as shown in Fig.



$$Now\, X = \frac{X_{L1} \times X_{L2}}{X_{L1} + X_{L2}} + X_T$$

Let E'_t *be the terminal voltage magnitude.*

Let P_e, Q_e *be the real and reactive power output power* (5)

Case (i): *Assume* V_t *as reference.*

$i.e., V_t = |V_t| \angle 0°$

Voltage behind transient reactance E'.

$$E' = V_t + jX'_d\, I_t \qquad (1)$$

$$where\; I_t = Stator\ current = \frac{S^*}{V_i^*} = \frac{P_e - jQ_e}{|V_t|\angle 0^\circ}$$

$$= \frac{P_e}{|V_t|} - j\frac{Q_e}{|V_t|} = I_{\text{Re}} - j\, I_{\text{Im}} \qquad (2)$$

Sub.eq.(2) *in* (1), *we get*

$$\therefore E' = V_t + jX'_d\left[I_{\text{Re}} - j\, I_{\text{Im}}\right] = |E'|\angle\beta \qquad (3)$$

Voltage of infinite bus,

$$V = V_t - jXI_t$$

$$= V_t - jX\left[I_{\text{Re}} - j\, I_{\text{Im}}\right] = |V|\angle\gamma \qquad (4)$$

angle between E' *and* V, $\delta = \beta - \gamma \qquad (5)$

Voltage at bus (2) *or voltage at high voltage side of transformer*.

$$E_{HV} = V_t - jX_T \times I_t$$

Case (ii) :Assume infinite bus voltage V as reference.

$$V = |V|\angle 0^\circ$$

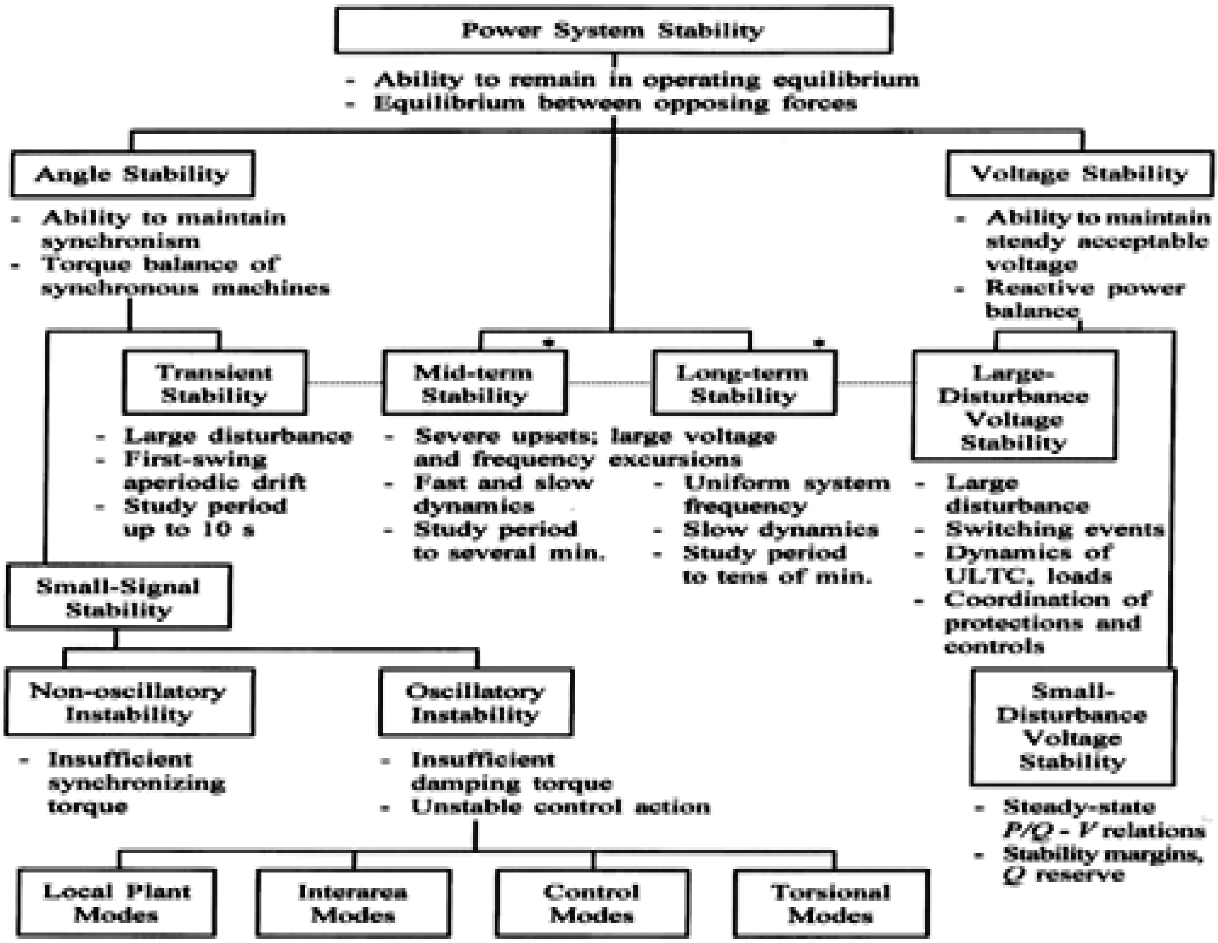
$$E' = V + jXI_t ;\; E' = |E'|\angle\delta$$

Where δ = Rotor angle with respect to synchronous rotating reference phasor $V\angle 0^\circ$ E' leads V by δ

$$\text{Re}al\ Power\ tranasfer\ P_e = \frac{|E'||V|}{X}\sin\delta \qquad (6)$$

$$= P_{\max}\sin\delta$$

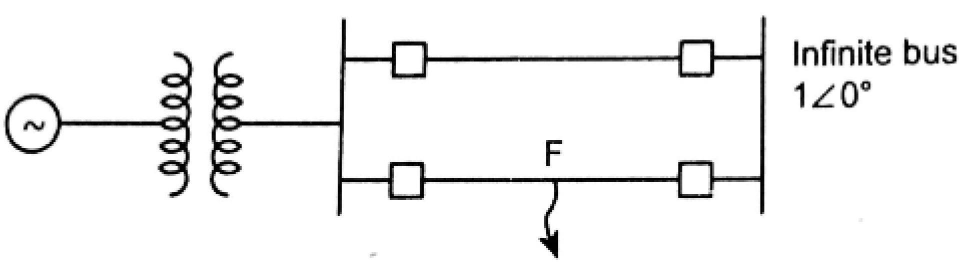
8.(i). Sketch the classifications of Power system stability. (6)



9. Explain the step-wise procedure of determining the swing curve of the above system using modified Euler's method. (16) (N/D'08)

Numerical integration techniques can be applied to obtain approximate solutions of non-linear differential equations. (5)

Consider a generator connected to an infinite bus through two parallel lines and a 3ϕ fault occurs at the middle of line 2 as shown in figure.



Let P_m be the input power which is a constant.

Prefault Condition: Under steady state operation,

Power transfer from generator to an infinite bus,

$P_e = P_m$

$$\frac{E'V}{X_1}\sin\delta_0 = P_{\max 1}\sin\delta_0 = P_m$$

$$\sin\delta_0 = \frac{P_m}{P_{\max 1}} \Rightarrow \delta_0 = \sin^{-1}\left[\frac{P_m}{P_{\max 1}}\right] \qquad (1)$$

$$where\ P_{\max 1} = \frac{E'V}{X_1} \qquad (5)$$

$X_1 = Transfer\ reactance\ for\ the\ prefault\ condition$

The rotor is running at synchronous speed,

$\omega_0 = 2\pi f$

Change in angular velocity is zero.

$i.e., \Delta\omega_0 = 0$

During the fault : Consider a 3ϕ fault occurs at the middle of one line 2 as shown in fig.

$$P_{e2} = \frac{|E'||V|}{X_{II}}\sin\delta_1 = P_{\max 2}\sin\delta$$

$$where\ P_{\max 2} = \frac{|E'||V|}{X_{II}}$$

$X_{II} = Transef\ reactance\ during\ the\ fault$

the swing eq. is given by,

$$\frac{d^2\delta_m}{dt^2} = \frac{\pi f}{H}\left[P_m - P_{\max 2}\sin\delta\right] = \frac{\pi f}{H}P_a$$

the above eq. can be transformed into the state variable form,

$$\frac{d\delta^{(1)}}{dt} = \Delta\omega \qquad (2)$$

$$\frac{d^2\delta_m}{dt^2} = \frac{d\Delta\omega^{(1)}}{dt} = \frac{\pi f}{H}P_a \quad (3)$$

Compute the first estimate at $t_1 = t_0 + \Delta t.$

$$\delta_{i+1}^P = \delta_i + \left.\frac{d\delta^{(1)}}{dt}\right|_{\Delta\omega_i} .\Delta t \qquad (4) \qquad (6)$$

$$\Delta\omega_{i+1}^P = \Delta\omega_i + \left.\frac{d\Delta\omega^{(1)}}{dt}\right|_{\delta_i} .\Delta t \qquad (5)$$

Compute the derivatives : Using the predicted value, determine the derivatives at the end of iteration.

$$\left.\frac{d\delta^{(2)}}{dt}\right|_{\Delta\omega_{i+}^{P}} = \Delta\omega_{i+1}^{P} \qquad (6)$$

$$\left.\frac{d\Delta\omega^{(2)}}{dt}\right|_{\delta_{i+1}^{P}} = \frac{\pi f}{H} P_a\big|_{\delta_{i+1}^{P}} \qquad (7)$$

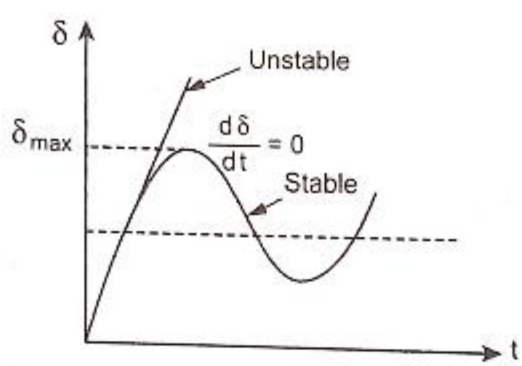
Computing the final estimated corrected value,

$$\delta_{i+1}^{C} = \delta_i + \left[\frac{\left.\frac{d\delta}{dt}\right|_{\Delta\omega_i} + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_{i+1}^{P}}}{2}\right]\Delta t \qquad (8)$$

$$\Delta\omega_{i+1}^{C} = \Delta\omega + \left[\frac{\left.\frac{d\Delta\omega}{dt}\right|_{\delta_i} + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_{i+1}^{P}}}{2}\right]\Delta t \qquad (9)$$

10. State and explain equal area criterion and discuss how you will apply it to find the maximum additional load that can be suddenly added. (16) (M/J'13) (N/D'12)

The equal area criteria for the stability states that the system is stable if the area under P_a-δ Curve reduces to Zero at some values of δ. (5)



This is possible if the positive (accelerating) area under P_a-δc curve is equal to negative (decelerating) area under P_a-δ curve for a finite change in δ. Hence the stability criterion is called equal area criterion.

This method is only applicable to a one machine connected to an infinite bus or two machine system.

Stability Criterion :

Stable system: If the system is stable, δ(t) perform oscillations whose amplitude decreases in actual practice.

At some time $\frac{d\delta}{dt} = 0$

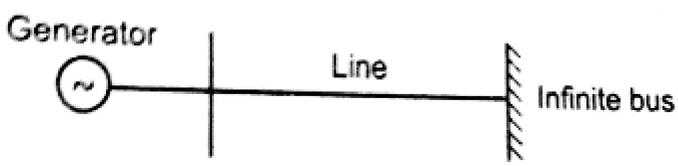
δ reaches maximum and will starts to reduce.

Unstable System : (5)

If the system is unstable, δ continues to increase with time and the machine loses synchronism.

$\frac{d\delta}{dt} > 0$ for a sufficiently long time.

Consider a synchronous machine connected to an infinite bus as shown in fig.



The swing eq. is given by

$$\frac{H}{180\,f}\frac{d^2\delta}{dt^2} = P_{m(p.u)} - P_{e(p.u)}$$

$$\frac{d^2\delta}{dt^2} = \frac{\pi f}{H}\left[P_m - P_e\right] \qquad (1)$$

Multiplying eq.(1) by $2\frac{d\delta}{dt}$ *on both sides, we get* (6)

$$2\frac{d\delta}{dt}\frac{d^2\delta}{dt^2} = 2\frac{d\delta}{dt}\frac{\pi f}{H}\left[P_m - P_e\right]$$

This may be written as,

$$d\left[\frac{d\delta}{dt}\right]^2 = \frac{2\pi f}{H}\left[P_m - P_e\right]d\delta \qquad (2)$$

Integrating equation (2) on both sides, we get,

$$\left[\frac{d\delta}{dt}\right]^2 = \frac{2\pi f}{H}\int_{\delta_0}^{\delta}\left[P_m - P_e\right]d\delta$$

Relative speed of machine with respect to sync.revolving ref.frame,

$$\frac{d\delta}{dt} = \sqrt{\frac{2\pi f}{H}\int_{\delta_0}^{\delta}\left[P_m - P_e\right]d\delta} \qquad (3)$$

For stable system, this speed must become zero at some time after the disturbance.

$$\frac{d\delta}{dt} = 0, \int_{\delta_0}^{\delta}(P_m - P_e)d\delta = 0$$

$$\int_{\delta_0}^{\delta} P_a\, d\delta = 0 \qquad (4)$$

Where P_a = Accelerating power

The condition of stability can be stated as the positive (accelerating) area under P_a Vs δ curve must be equal to the negative (decelerating) area and hence the name equal area criterion of stability.

11. With a neat flowchart, explain how the transient stability can be made by modified Euler method. (16) (N/D'12)

Numerical integration techniques can be applied to obtain approximate solutions of non-linear differential equations. (5)

Consider a generator connected to an infinite bus through two parallel lines and a 3ϕ fault occurs at the middle of line 2 as shown in figure.

Let P_m be the input power which is a constant.

Prefault Condition: Under steady state operation,

Power transfer from generator to an infinite bus,

$P_e = P_m$

$$\frac{E'V}{X_1}\sin\delta_0 = P_{\max 1}\sin\delta_0 = P_m$$

$$\sin\delta_0 = \frac{P_m}{P_{\max 1}} \Rightarrow \delta_0 = \sin^{-1}\left[\frac{P_m}{P_{\max 1}}\right] \qquad (1)$$

$$where\ P_{\max 1} = \frac{E'V}{X_1}$$

$X_1 = Transfer\ reactance\ for\ the\ prefault\ condition$

$The\ rotor\ is\ running\ at\ synchronous\ speed,$

$\omega_0 = 2\pi f$

$Change\ in\ angular\ velocity\ is\ zero.$

$i.e., \Delta\omega_0 = 0$

During the fault : Consider a 3ϕ fault occurs at the middle of one line 2 as shown in fig.

(5)

$$P_{e2} = \frac{|E'||V|}{X_{II}}\sin\delta_1 = P_{\max 2}\sin\delta$$

$$where\ P_{\max 2} = \frac{|E'||V|}{X_{II}}$$

$X_{II} = Transef\ reactance\ during\ the\ fault$

$the\ swing\ eq.\ is\ given\ by,$

$$\frac{d^2\delta_m}{dt^2} = \frac{\pi f}{H}\left[P_m - P_{\max 2}\sin\delta\right] = \frac{\pi f}{H}P_a$$

$the\ above\ eq.\ can\ be\ transformed\ into\ the\ state\ variable\ form,$

$$\frac{d\delta^{(1)}}{dt} = \Delta\omega \qquad (2)$$

$$\frac{d^2\delta_m}{dt^2} = \frac{d\Delta\omega^{(1)}}{dt} = \frac{\pi f}{H}P_a \quad (3)$$

$Compute\ the\ first\ estimate\ at\ t_1 = t_0 + \Delta t.$

$$\delta_{i+1}^P = \delta_i + \left.\frac{d\delta^{(1)}}{dt}\right|_{\Delta\omega_i}.\Delta t \qquad (4)$$

$$\Delta\omega_{i+1}^P = \Delta\omega_i + \left.\frac{d\Delta\omega^{(1)}}{dt}\right|_{\delta_i}.\Delta t \qquad (5)$$

Compute the derivatives : Using the predicted value, determine the derivatives at the end of iteration.

$$\left.\frac{d\delta^{(2)}}{dt}\right|_{\Delta\omega_{i+}^{P}} = \Delta\omega_{i+1}^{P} \qquad (6)$$

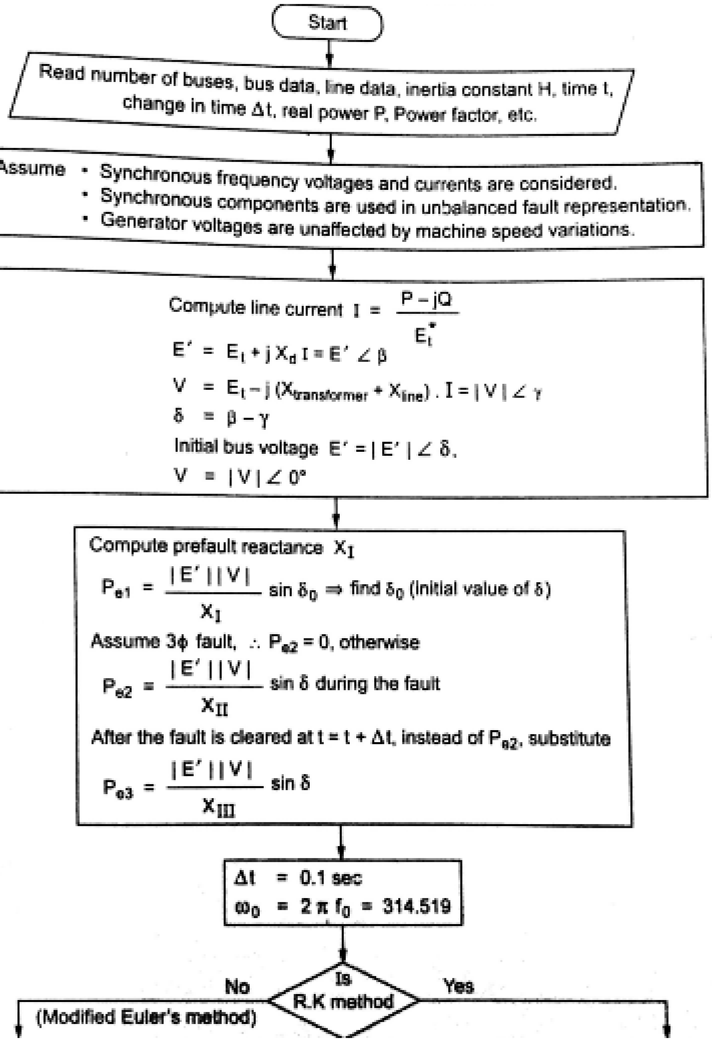
$$\left.\frac{d\Delta\omega^{(2)}}{dt}\right|_{\delta_{i+1}^{P}} = \frac{\pi f}{H} P_a\Big|_{\delta_{i+1}^{P}} \qquad (7)$$

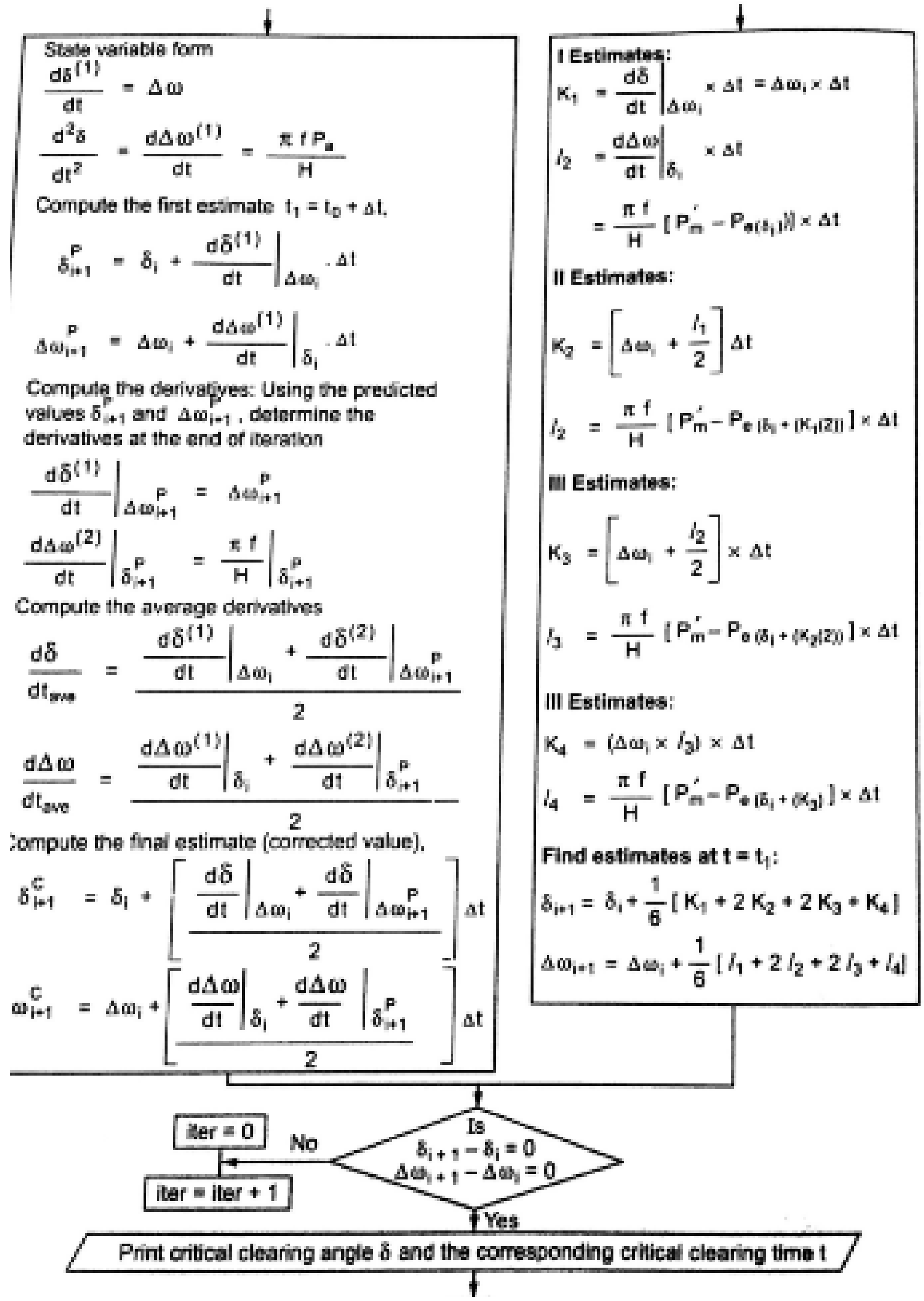
Computing the final estimated corrected value,

$$\delta_{i+1}^{C} = \delta_i + \left[\frac{\left.\frac{d\delta}{dt}\right|_{\Delta\omega_i} + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_{i+1}^{P}}}{2}\right]\Delta t \qquad (8)$$

$$\Delta\omega_{i+1}^{C} = \Delta\omega + \left[\frac{\left.\frac{d\Delta\omega}{dt}\right|_{\delta_i} + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_{i+1}^{P}}}{2}\right]\Delta t \qquad (9)$$

Flow Chart :- (6)

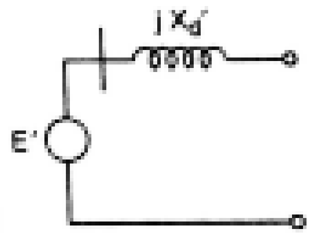

Start
Read number of buses, bus data, line data, inertia constant H, time t, change in time Δt, real power P, Power factor, etc.
Assume • Synchronous frequency voltages and currents are considered.
• Synchronous components are used in unbalanced fault representation.
• Generator voltages are unaffected by machine speed variations.
Compute line current I = (P − jQ) / E_t*
E′ = E_t + j X_d I = E′ ∠ β
V = E_t − j (X_transformer + X_line) . I = |V| ∠ γ
δ = β − γ
Initial bus voltage E′ = |E′| ∠ δ,
V = |V| ∠ 0°
Compute prefault reactance X_I
P_e1 = |E′||V| / X_I sin δ_0 ⇒ find δ_0 (Initial value of δ)
Assume 3ϕ fault, ∴ P_e2 = 0, otherwise
P_e2 = |E′||V| / X_II sin δ during the fault
After the fault is cleared at t = t + Δt, instead of P_e2, substitute
P_e3 = |E′||V| / X_III sin δ
Δt = 0.1 sec
ω_0 = 2 π f_0 = 314.519
Is R.K method
No
(Modified Euler's method)
Yes


State variable form
$\frac{d\delta^{(1)}}{dt} = \Delta\omega$
$\frac{d^2\delta}{dt^2} = \frac{d\Delta\omega^{(1)}}{dt} = \frac{\pi f P_a}{H}$
Compute the first estimate $t_1 = t_0 + \Delta t$,
$\delta_{i+1}^P = \delta_i + \frac{d\delta^{(1)}}{dt}\Big|_{\Delta\omega_i} . \Delta t$
$\Delta\omega_{i+1}^P = \Delta\omega_i + \frac{d\Delta\omega^{(1)}}{dt}\Big|_{\delta_i} . \Delta t$
Compute the derivatives: Using the predicted values δ_{i+1}^P and $\Delta\omega_{i+1}^P$, determine the derivatives at the end of iteration
$\frac{d\delta^{(1)}}{dt}\Big|_{\Delta\omega_{i+1}^P} = \Delta\omega_{i+1}^P$
$\frac{d\Delta\omega^{(2)}}{dt}\Big|_{\delta_{i+1}^P} = \frac{\pi f}{H}\Big|_{\delta_{i+1}^P}$
Compute the average derivatives
$\frac{d\delta}{dt_{ave}} = \frac{\frac{d\delta^{(1)}}{dt}\Big|_{\Delta\omega_i} + \frac{d\delta^{(2)}}{dt}\Big|_{\Delta\omega_{i+1}^P}}{2}$
$\frac{d\Delta\omega}{dt_{ave}} = \frac{\frac{d\Delta\omega^{(1)}}{dt}\Big|_{\delta_i} + \frac{d\Delta\omega^{(2)}}{dt}\Big|_{\delta_{i+1}^P}}{2}$
Compute the final estimate (corrected value),
$\delta_{i+1}^C = \delta_i + \left[\frac{\frac{d\delta}{dt}\Big|_{\Delta\omega_i} + \frac{d\delta}{dt}\Big|_{\Delta\omega_{i+1}^P}}{2}\right]\Delta t$
$\omega_{i+1}^C = \Delta\omega_i + \left[\frac{\frac{d\Delta\omega}{dt}\Big|_{\delta_i} + \frac{d\Delta\omega}{dt}\Big|_{\delta_{i+1}^P}}{2}\right]\Delta t$
I Estimates:
$K_1 = \frac{d\delta}{dt}\Big|_{\Delta\omega_i} \times \Delta t = \Delta\omega_i \times \Delta t$
$l_2 = \frac{d\Delta\omega}{dt}\Big|_{\delta_i} \times \Delta t$
$= \frac{\pi f}{H}[P_m' - P_{e(\delta_i)}] \times \Delta t$
II Estimates:
$K_2 = \left[\Delta\omega_i + \frac{l_1}{2}\right]\Delta t$
$l_2 = \frac{\pi f}{H}[P_m' - P_{e(\delta_i + (K_1/2))}] \times \Delta t$
III Estimates:
$K_3 = \left[\Delta\omega_i + \frac{l_2}{2}\right] \times \Delta t$
$l_3 = \frac{\pi f}{H}[P_m' - P_{e(\delta_i + (K_2/2))}] \times \Delta t$
III Estimates:
$K_4 = (\Delta\omega_i \times l_3) \times \Delta t$
$l_4 = \frac{\pi f}{H}[P_m' - P_{e(\delta_i + (K_3))}] \times \Delta t$
Find estimates at $t = t_1$:
$\delta_{i+1} = \delta_i + \frac{1}{6}[K_1 + 2K_2 + 2K_3 + K_4]$
$\Delta\omega_{i+1} = \Delta\omega_i + \frac{1}{6}[l_1 + 2l_2 + 2l_3 + l_4]$
iter = 0
iter = iter + 1
No
Is $\delta_{i+1} - \delta_i = 0$ $\Delta\omega_{i+1} - \Delta\omega_i = 0$
Yes
Print critical clearing angle δ and the corresponding critical clearing time t

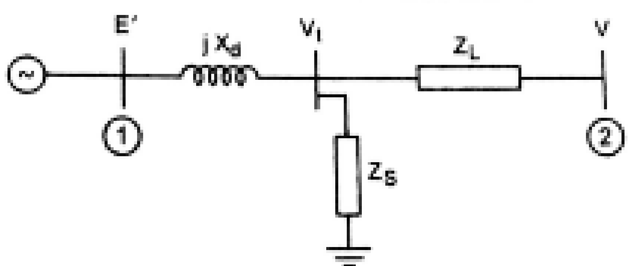
12. Derive a power angle equation for a

i. SMIB system. Also draw the power-angle curve. (16)

The equation relating the electrical power generated (P_e) to the angular displacement of the rotor (δ) is called power angle equation. Here the synchronous machine represented by a constant voltage E' behind the direct axis transient reactance X'_d as shown in fig. (5)

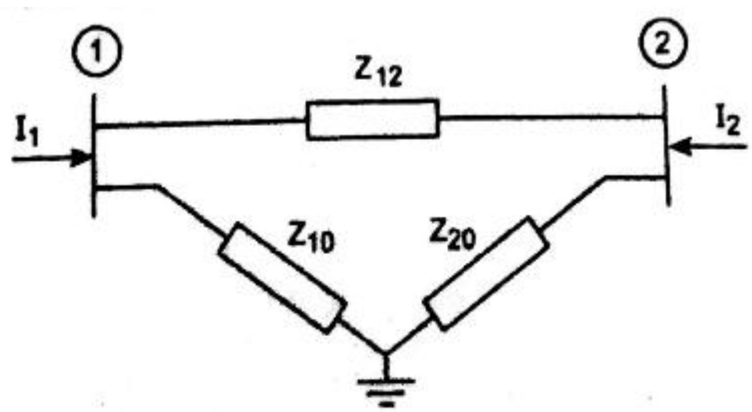


Consider a generator connected to a major substation of a very large system (Infinite bus) through a transmission line as shown in fig.



(5)

Eliminate the generator terminal voltage (V_t) node by using Y-Δ transformation as shown in fig.



$$z_{12} = \frac{jX'_d\, z_L + jX'_d\, z_L + z_L z_S}{z_S};\ z_{10} = \frac{jX'_d\, z_L + jX'_d\, z_S + z_L z_S}{z_L}$$

$$z_{20} = \frac{jX'_d\, z_L + jX'_d\, z_S + z_L z_S}{jX_d}$$

Nodal Equations : (6)

$$Node1: I_1 = \left[\frac{1}{z_{12}} + \frac{1}{z_{10}}\right]E' - \frac{1}{z_{12}}V$$

$$Node2: I_2 = -\frac{1}{z_{12}}E' + \left[\frac{1}{z_{12}} + \frac{1}{z_{20}}\right]V$$

$$\therefore \vec{I_1} = \vec{Y_{11}}\vec{E'} + \vec{Y_{12}}\vec{V} \qquad (1)$$

$$\vec{I_2} = \vec{Y_{21}}\vec{E'} + \vec{Y_{22}}\vec{V} \qquad (2)$$

Power injected at bus 1,

$$P_1 + jQ_1 = E'I^*$$

$$= \vec{E'}\left[\vec{Y_{11}}\vec{E'}\right]^* + \vec{E'}\left[\vec{Y_{12}}\vec{V}\right]^*$$

$$= |E'|\angle\delta\left[|Y_{11}|\angle-\theta_{11}|E'|\angle-\delta\right] + |E'|\angle\delta \times \left[|Y_{12}|\angle-\theta_{12}|V|\angle 0°\right]$$

$$= |E'|^2|Y_{11}|\angle-\theta_{11} + |E'||V||Y_{12}|\angle\delta-\theta_{12}$$

$$P_1 = \text{Re}\{P_1 + jQ_1\}$$

$$P_1 = |E'|^2|G_{11}| + |E'||V||Y_{12}|\cos(\delta - \theta_{12}) \qquad (3)$$

Mostly z_L and z_s are inductive. so resistance are neglected.

$$\theta_{12} = 90°, |Y_{12}| = \frac{1}{|X_{12}|}$$

$$P_1 = P_e = |E'|G_{11} + \frac{|E'||V|}{X_{12}}\sin\delta \qquad (4)$$

$$P_e = P_C + P_{\max}\sin\delta$$

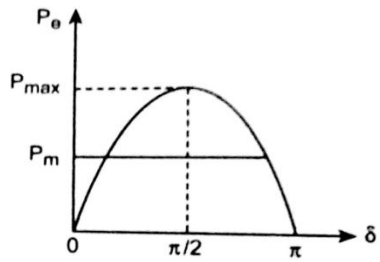
This equation is called as **Power angle Equation.**

Power angle curve:

All the elements are susceptance, then $G_{11} = 0$.

$$\therefore P_e = \frac{|E'||V|}{X_{12}}\sin\delta = P_{\max}\sin\delta$$

Power transmitted depends on the transfer reactance X_{12} and the angle between the voltages E' and V i.e., (δ). The curve P_e versus δ is known as power angle curve. The Power angle curve is as shown in fig.

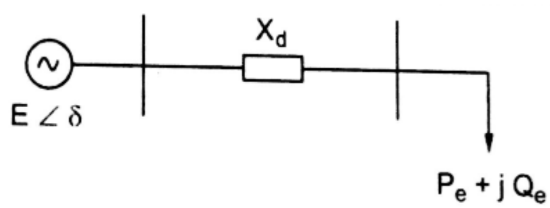


13.(i). A generator having X_d= 0.7 p.u deliver rated load at a power factor of 0.8 lagging. Find P_e, Q_e and E and δ. (8) (M/J'12)

X_d = 0.7 p.u

P.f = 0.8 lag

P_e, Q_e E and δ.= ?



$$S = \frac{1\angle 36.87}{0.8} = 1.25\angle 36.87$$

$$I_a = S^*/V^*$$
$$= 1.25\angle -36.87$$

$$E' = V + jX'_d \times I_a = 1.0 + j0.7 \times 1.25\angle -36.87$$
$$= 0.35 + j0.59 = 0.69\angle 1.03$$

$$|E'| = 0.69, \delta = 1.03$$

$$P_e = \frac{|E'||V|\sin\delta}{X'_d}$$

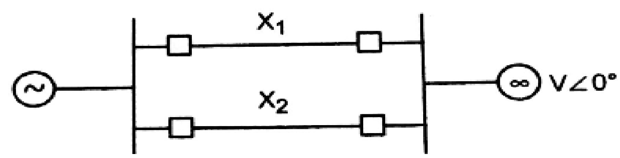
$$= \frac{0.69 \times 1\sin 1.03}{0.7} = 0.845$$

$$Q_e = \frac{|E'||V|\cos\delta}{X'_d} - \frac{|V|^2}{X'_d}$$

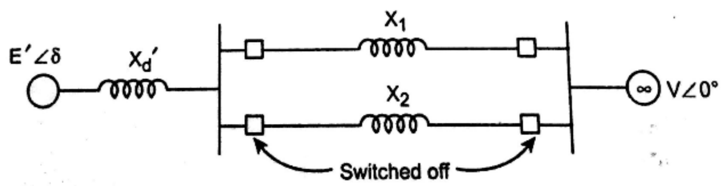
$$= \frac{0.69 \times 1\cos 1.03}{0.7} - \frac{1}{0.7} = -0.92\ p.u$$

13.ii. Using equal area criteria, derive an expression for critical clearing angle for a system having a generator feeding a large system through a double circuit line (8)

Consider a single machine connected to infinite bus through two parallel lines as shown in fig.



The equivalent circuit is shown in Fig.



Consider one of the line is suddenly switched off with system operating at a steady load.

Prefault condition (Before Switching off)

Power angel curve is given by

$$P_{e1} = \frac{|E'||V|}{X'_d + \left[\frac{X_1 X_2}{X_1 + X_2}\right]} \sin\delta = P_{\max 1} \sin\delta \quad (1)$$

$$During\ fault\ P_{e2} = 0$$

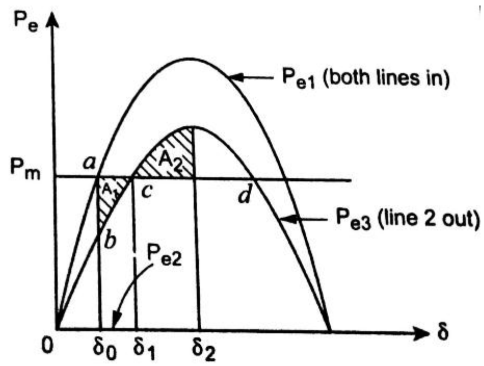
The rotor therefore accelerate and angle δ increases. Synchronism will be lost unless the fault is cleared in time.

Post fault (Immediately on switching off line 2):

Power angle curve is given by,

$$P_{e3} = \frac{|E'||V|}{X'_d + X_1} \sin\delta = P_{\max 2} \sin\delta \quad (2)$$

The power angle curves are drawn as shown in fig.



$$As\ X'_d + X_1 > X'_d + \left[\frac{X_1 X_2}{X_1 + X_2}\right]$$

$$\therefore P_{e2} < P_{e1}$$

The system is operating initially with steady power transfer P_m at a torque angle δ_0 on curve 1. Immediately on switching off line 2, the electrical operating point shifts to curve 2 (point b).

Accelerating energy corresponding to area A_1 is followed by decelerating energy for $\delta > \delta_1$, Apply equal area criterion, for stable system

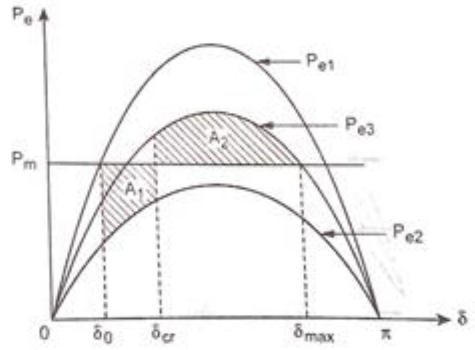
Area A_1 = Area A_2

The system will finally operate at *c* corresponding to a new rotor angle $\delta > \delta_0$. This is because a single line offers larger reactance and larger rotor angel to transfer the same steady power.

(i.e., $\delta_1 = \delta_{max} = \pi - \delta_0$)

14. A 3 ph generator delivers 1.0 p.u. power to an infinite bus through a transmission network when a fault occurs. The maximum power which can be transferred during prefault, during fault and post fault conditions is 1.75 p.u., 0.4 p.u, 1.25 p.u. Find critical clearing angle. (16) (M/J'12)

The power angle curve is as shown in fig. (6)



P_{e1}= 1.75 sin δ

P_{max1}= 1.75 p.u.

P_{e2}= 0.4 sin δ

P_{max2}= 0.4 p.u.

P_{e3}= 1.25 sin δ

P_{max3}= 1.25 p.u.

Initial loading P_m =1.0 p.u. (5)

$$1.75 \sin \delta_0 = P_m \Rightarrow \sin \delta_0 = \frac{1}{1.75}$$

$$\delta_0 = \sin^{-1} \frac{1}{1.75} = 0.608 \; rad$$

$$\delta_{\max} = \pi - \sin^{-1}\left[\frac{P_m}{P_{\max 3}}\right]$$

$$= \pi - \sin^{-1}\left[\frac{1}{1.25}\right] = 2.214 \, rad$$

Applying equal area criterion, (5)

Area A_1 = Area A_2

$$P_m(\delta_{cr} - \delta_0) - \int_{\delta_0}^{\delta_{cr}} P_{e2} d\delta = \int_{\delta_{cr}}^{\delta_{\max}} P_{e3} d\delta - P_m(\delta_{\max} - \delta_{cr})$$

$$\Rightarrow \cos \delta_{cr} = \frac{P_m(\delta_{\max} - \delta_{cr}) - P_{\max 2} \cos \delta_0 + P_{\max 3} \cos \delta_{\max}}{P_{\max 3} - P_{\max 2}}$$

$$= \frac{1.0(2.214 - 0.608) - 0.4 \cos 0.608 + 1.25 \cos 2.214}{1.25 - 0.4}$$

$$\cos \delta_{cr} = 0.6212 \, rad$$

$$\delta_{cr} = \cos^{-1} 0.6212 = 0.9 \, rad = 51.57°$$

$$\boxed{\delta_{cr} = 0.9 \, rad = 51.57°}$$

15. Derive the Runge-Kutta method of solution of swing equation for multi-machine systems. (16) (A/M'11'08)

In this method, the accuracy is of the order of (Δt). Swing equation of one machine connected to infinite bus.

$$\frac{d\delta}{dt} = \Delta\omega$$

$$\frac{d\Delta\omega}{dt} = \frac{\pi f_0}{H}(p_m - p_e) = \frac{\pi f_0}{H}(p_m - p_{\max}\sin\delta) \quad (5)$$

Value of $p_e = p_{\max}\sin\delta$

Initial value of $\delta_0 = \sin^{-1}\left[\frac{p_m}{p_{\max}}\right]$

I estimates:

$$K_1 = \left.\frac{d\delta}{dt}\right|_{\Delta\omega_i} \times \Delta t = \Delta\omega_i \times \Delta t$$

$$l_1 = \left.\frac{d\Delta\omega}{dt}\right|_{\delta_i} \times \Delta t = \frac{\pi f}{H}[P_m^{'} - P_{e(\delta_i)}] \times \Delta t$$

II estimates: (5)

$$K_2 = \left[\Delta\omega_i + \frac{l_1}{2}\right]\Delta t$$

$$l_2 = \frac{\pi f}{H}[P_m^{'} - P_{e(\delta_i + (K_1/2))}] \times \Delta t$$

III estimates:

$$K_3 = \left[\Delta\omega_i + \frac{l_2}{2}\right]\Delta t$$

$$l_3 = \frac{\pi f}{H}[P_m^{'} - P_{e(\delta_i + (K_2/2))}] \times \Delta t$$

IV estimates:

$$K_4 = [\Delta\omega_i + l_3]\Delta t$$

$$l_4 = \frac{\pi f}{H}[P_m^{'} - P_{e(\delta_i + K_3)}] \times \Delta t$$

Final estimates at t=t_1:

$$\delta_{i+1} = \delta_i + \frac{1}{6}[K_1 + 2K_2 + 2K_3 + K_4]$$
$$\Delta\omega_{i+1} = \Delta\omega_i + \frac{1}{6}[l_1 + 2l_2 + 2l_3 + l_4] \quad (6)$$

In the final estimates, the value ofδ' andΔω' for the first iterations are updated.

Replace δ° and Δω° by δ' and Δω'recalculate the values of k_1,k_2,k_3,k_4, l_1,l_2,l_3,l_4.

Compute

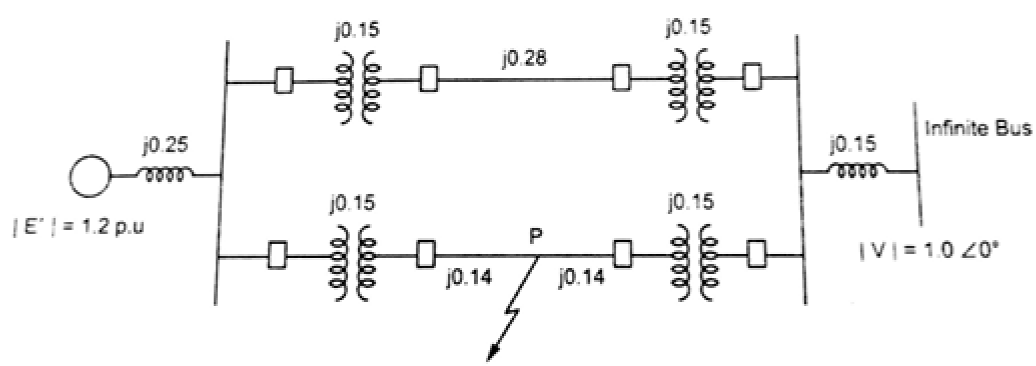
$$\delta_{i+1} = \delta_i + \frac{1}{6}[k_1 + 2k_2 + 2k_3 + k_4]$$
$$\Delta\omega_{i+1} = \Delta\omega_i + \frac{1}{6}[l_1 + 2l_2 + 2l_3 + l_4]$$

Where i=1,2,……………….,n (i.e., number of generators)

Check for convergence: If $\delta_{i+1} - \delta_I = 0$ and $\Delta\omega_{i+1} - \Delta\omega_I = 0$ are satisfied, then note down critical clearing angle δ and the critical clearing time t.

Otherwise repeat the process and do it for each and every machine.

16.As shown in given figure the three phase fault is applied at point 'p'. Find the critical clearing angle for clearing the fault with simultaneous opening of the breaker 1 and 2.The reactance values of various components are indicated on the diagram. The generator is delivering 1.0 p.u power at the instant proceeding the fault. (16) (M/J'09)



Normal operation (Prefault) (5)

$$X_1 = 0.25 + \frac{0.5 \times 0.4}{0.5 + 0.4} + 0.05$$
$$= 0.522 \; p.u.$$
$$P_{e1} = \frac{|E'||V|}{X_1}\sin\delta = \frac{1.2 \times 1}{0.522}\sin\delta$$
$$= 2.3\sin\delta$$

Prefault operating power angel is given by

$1.0 = 2.3 \sin \delta_0$

$\delta_0 = 25.8^o = 0.45$ radians

(ii) During Fault: No power is transferred during fault (5)

$P_{e2} = 0$

(iii) Post fault operational (fault cleared by opening the faulted line)

$X_{III} = 0.25 + 0.5 + 0.05 = 0.8$

$$P_{e3} = \frac{1.2 \times 1}{0.8} \sin\delta = 1.5 \sin\delta$$

$$\delta_{\max} = \pi - \sin^{-1}\left[\frac{P_m}{P_{\max 3}}\right]$$

$$= \pi - \sin^{-1}\left[\frac{1}{0.5}\right] = 2.41 rad$$

$$\boxed{\delta_{\max} = 2.41 rad}$$

Applying equal area criterion for critical clearing angle δ_C (6)

$$A_1 = P_m(\delta_{cr} - \delta_0)$$
$$= 1.0(\delta_{cr} - 0.45) = \delta_{cr} - 0.45$$

$$A_2 = \int_{\delta_{cr}}^{\delta_{\max}} (P_{e3} - P_m) d\delta$$

$$= \int_{\delta_{cr}}^{2.41} (1.5 \sin\delta - 1) d\delta$$

$$= \int_{\delta_{cr}}^{2.41} (1.5 \sin\delta - 1) d\delta$$

$$= -1.5 \cos\delta - \delta \Big|_{\delta_{cr}}^{2.41}$$
$$= 1.5 \cos\delta_{cr} + \delta_{cr} - 1.293$$

Setting $A_1 = A_2$ *and solving*

$$\delta_{cr} - 0.45 = 1.5 \cos\delta_{cr} - 1.293$$
$$\delta_{cr} = 55.8°$$

$$\boxed{\delta_{cr} = 55.8°}$$

17. State and explain 'equal area criteria' in connection with transient stability analysis. What are the advantages and limitations of this method? (16) (A/M'08,12)

Swing equation for a single synchronous machine connected to infinite bus is given by

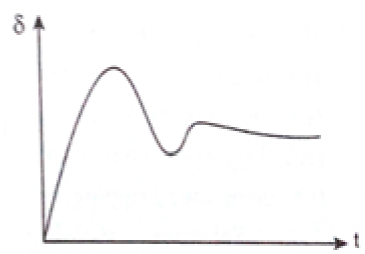
$$\frac{H}{\pi f}\frac{d^2\delta_m}{dt^2} = P_m - P_e$$
$$where\; P_e = P_{\max}\sin\delta$$

If $P_m = 0$, then swing equation can be solved easily.

For small disturbance, the equation can be liberalized using steady state stability concept.

For large disturbance, numerical methods are used to solve transient stability problem.

Numerical solution of the swing equation is obtained, giving a plot of δ Vs t is called swing curve as shown in Fig.



If δ value decreased after reaching a maximum value, then the system is stable otherwise the system is unstable.

Most of the line faults are transient in nature and get cleared immediately an opening the line. Auto reclose breaker are used for automatically close after the fault is cleared. If the fault is severe, the circuit breaker opens and lock permanently till the fault is cleared manually. Mostly the first reclosure will be sufficient, the system stability can be maintained by auto reclose breakers.

For a single machine connected to infinite bus system, stability can be determined by the equal area criterion.

18.Explain the modified Euler method of analyzing multi machine power stability, with neat flow chart. (16) (M/J'07,14)

Step by step procedure:

1. Perform load flow study for prefault condition and determine initial bus voltage magnitudes and angles. (5)
2. Calculate prefault generator current,

$$I_i^\circ = \frac{S_i^o}{\left|V_i^o\right|^2}$$

3. Compute $E_i^{'}$

$$E_i^{'} = V_i^o + j(X_d^{'} + X_L)I_i$$

$$E_i^{'} = \left|E_i^{'}\right| \angle \delta_i$$

Define initial rotor angle $\overset{o}{X}$.

4. Compute Y-bus matrix during the fault and post fault condition.
5. Set time count r=0.
6. Calculate generator power output P_{ei}. (5)

$$P_{ei}^r\Big|_{t=t^r} = \sum_{j=1}^{m} \left|E_i^{'}\right|\left|E_j^{'}\right|\left|Y_{ij}\right| \cos(\theta_{ij} + \delta_j - \delta_i)$$

7. Assume uniform discrete time interval Δt.

   Solve swing equation during the fault upto the fault clearing time and repeat the steps for post fault condition.
8. Compute $\left[\left(\overset{\bullet r}{x}_{1i}, \overset{\bullet r}{x}_{2i}\right), i = 1, 2, ..., m\right]$

   Using $\overset{\bullet}{x}_{1i} = x_{2i}$

$$\overset{\bullet}{x}_{2i} = \frac{\pi f_0}{H_i}\left(P_m - P_{ei}\right), i = 1, 2, ..., m$$

9. Compute the first state estimates for t=t^{r+1} as

$$x_{1i}^{r+1} = x_{1i}^{r} + \overset{\bullet r}{x}_{1i}.\Delta t; i = 1, 2, ..., m$$

$$x_{2i}^{r+1} = x_{2i}^{r} + \overset{\bullet r}{x}_{2i}.\Delta t$$

10. Compute the first estimates of E_i^{r+1}. (6)

$$E_i^{r+1} = E_i^{o}(\cos x_{1i}^{r+1} + j \sin x_{1i}^{r+1})$$

11. Compute $P_{ei}^{r+1} and \delta_n$,

$$\Delta\delta_n = \Delta\delta_{n-1} + \frac{(\Delta t)^2}{M} P_{a(n-1)}$$

$$\delta_n = \delta_{n-1} + \Delta\delta_n$$

12. Compute $\left(\overset{\bullet r+1}{x}_{1i}, \overset{\bullet r+1}{x}_{2i}\right), i = 1, 2, ..., m$

$$\overset{\bullet r+1}{x}_{1i} = \overset{\bullet r+1}{x}_{2i}$$

$$\overset{\bullet r+1}{x}_{2i} = \frac{\pi f_o}{H_i}(P_m - P_{ei}^{r+1}); i = 1, 2, ..., m$$

13. Compute the average values of state derivatives.

$$\overset{\bullet r}{x}_{1i\ \text{average}} = \frac{1}{2}\left[\overset{\bullet r}{x}_{1i} + \overset{\bullet r+1}{x}_{1i}\right]$$

$$\overset{\bullet r}{x}_{2i\ \text{average}} = \frac{1}{2}\left[\overset{\bullet r}{x}_{2i} + \overset{\bullet r+1}{x}_{2i}\right]$$

14. Compute the final state estimates for $t=t^{r+1}$.

$$x_{1i}^{r+1} = x_{1i}^{r} + \overset{\bullet r}{x}_{1i\ average}.\Delta t$$

$$x_{2i}^{r+1} = x_{2i}^{r} + \overset{\bullet r}{x}_{2i\ average}.\Delta t$$

15. Compute the final estimate for E_i at $t=t^{r+1}$.

$$E_i^{r+1} = \left|E_i^{o}\right| \cos x_{1i}^{r+1} + j \sin x_{1i}^{r+1}$$

16. Print $x_{1i}^{r+1}, x_{2i}^{r+1}$.

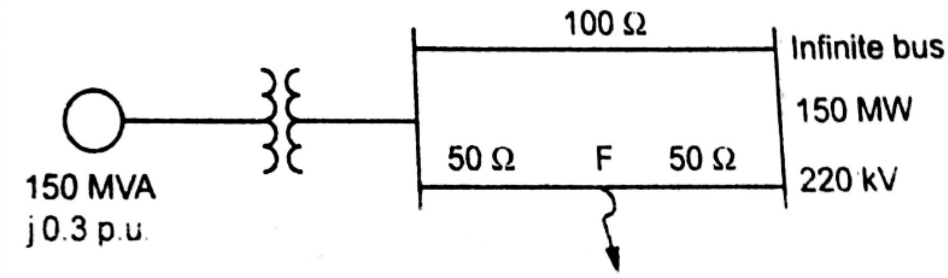
17. If $r > r_{final}$, stop.

Otherwise r = r+1 (Increment r) and repeat from step(6).

18. Examine δ Vs t plot (swing curve) to determine stability of the system.

19. A 150 MVA generator transformer unit having an overall reactance of 0.3 p.u. is delivering 150 MW to infinite bus bar over a double circuit 220 KV line having reactance per phase per circuit of 100 ohms. A three phase fault occurs midway along one of the

transmission lines. Calculate the maximum angle of swing that the generator may achieve before the fault is cleared without loss of stability. (16) (N/D '07)

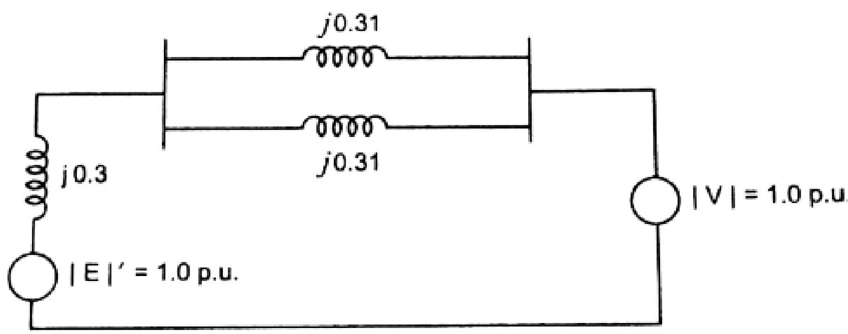


Solution

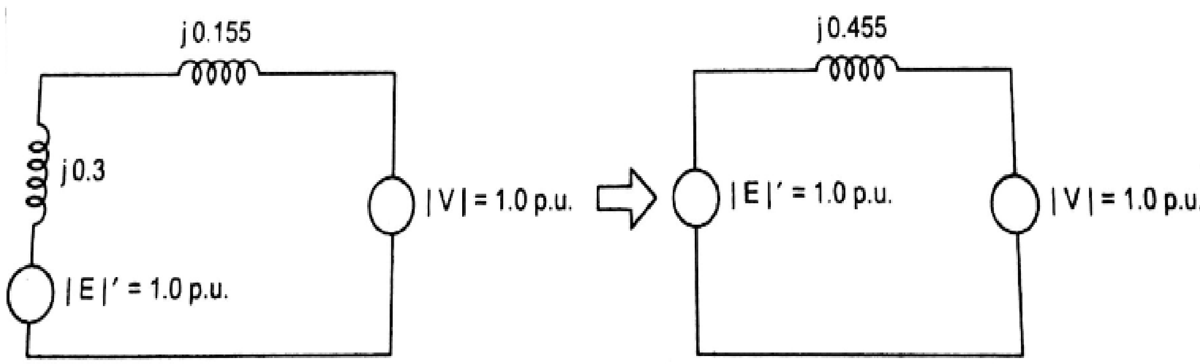
$$Reactance\ of\ line\ X_{p.u.} = \frac{X_{actual}}{(KV_b)^2} \times MVA_b \qquad (5)$$

$$= \frac{100}{220^2} \times 150 = j0.31 p.u.$$

Prefault condition : Impedance diagram for prefault condition is as shown in fig.



j0.31 is in parallel with j0.31



$$P_{e1} = \frac{|E'||V|}{X_1} \sin\delta = \frac{1.0 \times 1.0}{0.455} \sin\delta = 2.198 \sin\delta$$

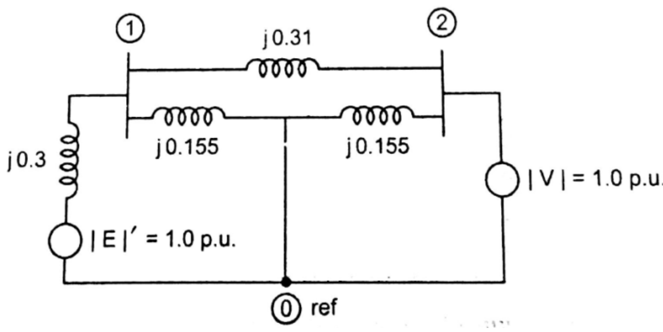
$$operating\ power\ angle\ \delta_0\ is\ given\ by$$

$$2.198 \sin\delta_0 = 1.0$$

$$\delta_0 = \sin^{-1}\left[\frac{1.0}{2.198}\right] = 27.06° = 0.472\,rad$$

$$\boxed{\delta_0 = 27.06° = 0.472\,rad}$$

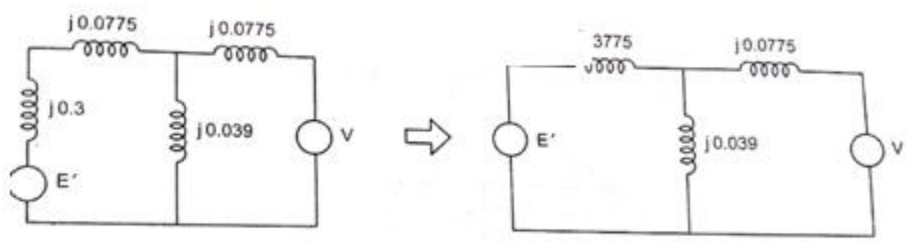
During the fault : Positive sequence reactance diagram



Using Delta-star conversion, the circuit becomes (5)

$$Z_{IN} = \frac{Z_{12} \times Z_{10}}{Z_{12} + Z_{10} + Z_{20}} = \frac{j0.31 \times j0.155}{j0.31 + j0.155 + j0.155} = j0.0775\, p.u.$$

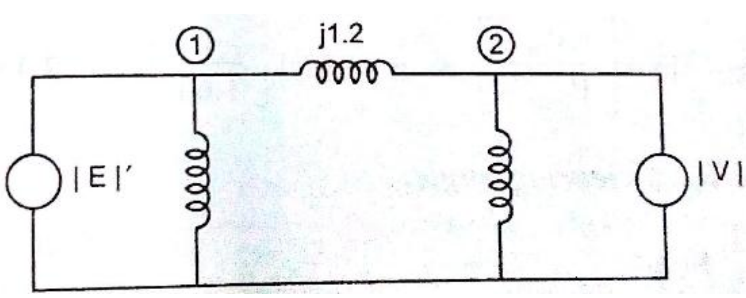
$$Z_{0N} = \frac{Z_{10} \times Z_{20}}{Z_{12} + Z_{10} + Z_{20}} = \frac{j0.155 \times j0.155}{j0.31 + j0.155 + j0.155} = j0.039\, p.u$$



Using star – Delta conversion,

$$Z_{12} = \frac{Z_{IN}Z_{N0} + Z_{N0}Z_{2N} + Z_{IN}Z_{N2}}{Z_{N0}}$$

$$= \frac{j0.3775 \times j0.039 + j0.039 \times j0.0775 + j0.3775 \times j0.0775}{j0.039} = j1.2$$



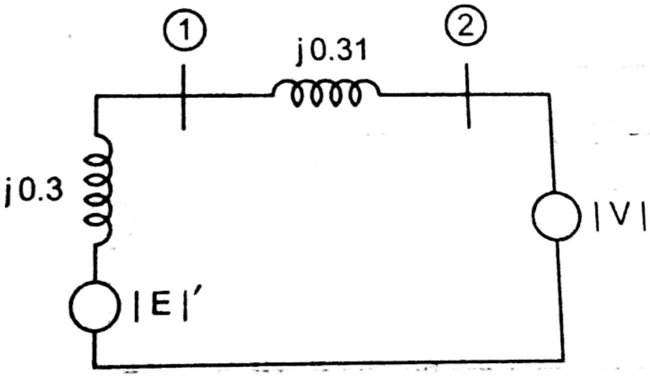
Power transfer during fault

$$P_{e2} = \frac{|E'||V|}{X_{12}} \sin\delta$$

$$= \frac{1.0 \times 1.0}{1.2} \sin\delta = 0.833 \sin\delta \, p.u.$$

Post fault condition: Faulted line is removed by opening the circuit breaker at ends.

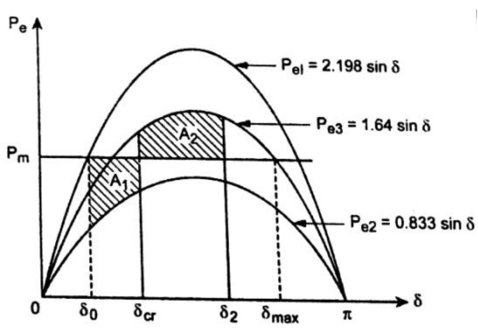
Impedance diagram for postfault is as shown in fig. (6)



$$Z = X_{III} = 0.3 + 0.31 = 0.61 \, p.u$$

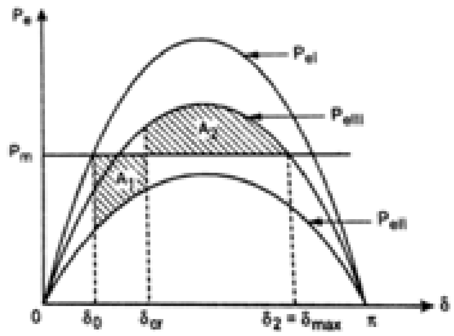
$$P_{e3} = \frac{|E'||V|}{X_{III}} \sin\delta = \frac{1.0 \times 1.0}{0.61} \sin\delta = 1.64 \sin\delta \, p.u.$$

Power angle curve is as shown in fig.



$$\delta_{\max} = \pi - \sin^{-1}\left[\frac{P_m}{P_{\max 3}}\right] = \pi - \sin^{-1}\left[\frac{1}{1.64}\right] = 3.14 - 0.656 = 2.48 \, rad$$

Determining of critical clearing angle:



$$Area\ A_1 = 1.0[\delta_{cr} - \delta_0] - \int_{\delta_0}^{\delta_{cr}} P_{e2} d\delta$$

$$Area\ A_2 = \int_{\delta_{cr}}^{\delta_{\max}} P_{e3}\, d\delta - P_m[\delta_{\max} - \delta_{cr}]$$

$$= \int_{\delta_{cr}}^{\delta_{\max}} 1.5 \sin\delta\, d\delta - 1.0 \times [2.4 - \delta_{cr}]$$

Applying equal area criteria $A_1 = A_2$

$$\delta_{cr} - 0.472 + \int_{0.472}^{\delta_{cr}} 0.833 \sin\delta = \int_{\delta_{cr}}^{2.48} 1.64 \sin\delta - (2.48 - \delta_{cr})$$

$$-0.472 + 0.833 \cos\delta\Big]_{0.472}^{\delta_{cr}} = -1.64 \cos\delta\Big]_{\delta_{cr}}^{2.48} - 2.48$$

$$-0.472 + 0.833 \cos\delta_{cr} - 0.393 = 1.294 + 1.64 \cos\delta_{cr} - 2.48$$

$$\cos\delta_{cr}(0.833 - 1.64) = 1.294 - 2.48 + 0.472 + 0.393$$

$$-0.807 \cos\delta_{cr} = -0.321$$

$$\cos\delta_{cr} = 0.398$$

$$\delta_{cr} = 1.16\, rad$$

$$\boxed{\delta_{cr} = 1.16\, rad}$$

20.A 50 Hz, 500 MVA, 400 KV generator (with transformer) is connected to a 400 KV infinite bus bar through an interconnector. The generator has H=2.5 MJ/MVA , voltage behind transients reactance of 450 KV and is loaded 460 MW. The transfer reactance between generator and bus under various conditions are:

Prefault : 0.5 p.u; During fault: 1.0 p.u; Post fault: 0.75 p.u

Calculate the swing curve using intervals of 0.05 sec and assuming that the fault is cleared at 0.15 sec. (16) (N/D'07)

Solution:

KVb = 400 (5)

V = $\frac{400}{400}$ = 1 p.u.

E' = $\frac{450}{400}$ = 1.125 p.u.

P_{e1} = $\frac{460}{400}$

Prefault, X_1 = 0.5 p.u.

$$P_{e1} = \frac{|E'||V|}{X_1}\sin\delta_0 = 0.92$$

$$\frac{1.125\times1}{0.5}\sin\delta_0 = 0.92$$
$$\delta_o = 0.42 rad$$

Assume 3ϕ fault occurs, P_{e2} = 0

Post fault condition, $P_{e3} = \frac{|E'||V|}{X_{111}}\sin\delta$

$$P_{e3} = \frac{1.125\times1}{0.75}\sin\delta = 1.5\sin\delta$$

Using modified Euler's method:

$\omega_0 = 2\pi f = 2\pi\times50 = 314.159$

Δt = 0.05 sec

Iteration 1: t = 0, (5)

$$\left.\frac{d\delta}{dt}\right|_{\Delta\omega_o} = \Delta\omega_o = \omega_o - 2\pi f = 0$$

$$\left.\frac{d\Delta\omega}{dt}\right|_{\delta_o} = \frac{\pi f}{H}\left[P_m^{'} - P_{e(\delta_o)}\right]$$

$$\left.\frac{d\Delta\omega}{dt}\right|_{\delta_o} = \frac{\pi \times 50}{2.5}\left[0.92 - 0\right] = 57.8$$

End of the first step at t=0.05 sec

Predicted values are

$$\delta_{0.05}^{P} = \delta_0 + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_o} \times \Delta t$$

$$\delta_{0.05}^{P} = 0.42 + (0 \times 0.05) = 0.42$$

$$\Delta\omega_{0.05}^{P} = \Delta\omega_0 + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_o} \times \Delta t$$

$$\Delta\omega_{0.05}^{P} = 0 + (57.8 \times 0.05) = 2.89 rad/\sec$$

$$\boxed{\Delta\omega_{0.05}^{P} 2.89 rad/\sec}$$

Derivation at the end of t =0.05.

$$\left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.05}^{P}} = \Delta\omega_{0.05}^{P} = 2.89 rad/\sec$$

$$\left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.05}^{P}} = \frac{\pi f}{H}[P_m^{'} - P_{e(\delta_{0.05}^{P})}]$$

$$\left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.05}^{P}} = \frac{\pi \times 50}{2.5}[0.92 - 0] = 57.8$$

Corrected values,

$$\delta_{0.05}^{C} = \delta_0 + \frac{\Delta t}{2}\left[\left.\frac{d\delta}{dt}\right|_{\Delta\omega_0} + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.05}^{P}}\right]$$

$$\delta_{0.05}^{C} = 0.42 + \frac{0.05}{2}[0 + 2.89]$$

$$\delta_{0.05}^{C} = 0.492 rad$$

$$\Delta\omega_{0.05}^{C} = \Delta\omega_0 + \frac{\Delta t}{2}\left[\left.\frac{d\Delta\omega}{dt}\right|_{\delta_0} + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.05}^{P}}\right]$$

$$\Delta\omega_{0.05}^{C} = 0 + \frac{0.05}{2}[57.8 + 57.8]$$

$$\Delta\omega_{0.05}^{C} = 2.89 rad/\sec$$

$$\boxed{\Delta\omega_{0.05}^{C} = 2.89 rad/\sec}$$

Iteration 2: (6)

$$\left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.05}^{C}} = \Delta\omega_{0.05}^{C} = 2.89$$

$$\left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.05}^{C}} = \frac{\pi\times 50}{2.5}[0.92-0] = 57.8$$

At t=0.1, predicted values are

$$\delta_{0.1}^{P} = \delta_{0.05}^{C} + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.05}^{C}} \times \Delta t$$

$$\delta_{0.1}^{P} = 0.492 + 2.89\times 0.05$$

$$\delta_{0.1}^{P} = 0.637 rad$$

$$\Delta\omega_{0.1}^{P} = \Delta\omega_{0.05}^{C} + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.05}^{C}} \times \Delta t$$

$$\Delta\omega_{0.1}^{P} = 2.89 + 57.8\times 0.05 = 5.78$$

$$\left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.1}^{P}} = \Delta\omega_{0.1}^{P} = 5.78 rad/\sec$$

$$\left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.1}^{P}} = \frac{\pi\times 50}{2.5}[0.92-0] = 57.8$$

$$\delta_{0.1}^{C} = \delta_{0.05}^{C} + \frac{\Delta t}{2}\left[\left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.05}^{C}} + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.1}^{P}}\right]$$

$$\delta_{0.1}^{C} = 0.492 + \frac{0.05}{2}[2.89 + 5.78] = 0.709 rad$$

$$\Delta\omega_{0.1}^{C} = \Delta\omega_{0.05}^{C} + \frac{\Delta t}{2}\left[\left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.05}^{C}} + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.1}^{P}}\right]$$

$$\Delta\omega_{0.1}^{C} = 2.89 + \frac{0.05}{2}[57.8 + 57.8] = 5.78 rad/\sec$$

$$\boxed{\Delta\omega_{0.1}^{C} = 5.78 rad/\sec}$$

Iteration 3: t=0.1 sec

$$\left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.1}^{C}} = \Delta\omega_{0.1}^{C} = 5.78$$

$$\left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.1}^{C}} = \frac{\pi\times 50}{2.5}[0.92-0] = 57.8$$

End of the third step at t=0.15 , predicted values are,

$$\delta_{0.15}^{P} = \delta_{0.1}^{C} + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.1}^{C}} \times \Delta t$$

$$\delta_{0.15}^{P} = 0.709 + 5.78\times 0.05 = 0.998 rad$$

$$\Delta\omega_{0.15}^{P} = \Delta\omega_{0.1}^{C} + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.1}^{C}} \times \Delta t$$

$$\Delta\omega_{0.15}^{P} = 5.78 + 57.8\times 0.05 = 8.67 rad/\sec$$

Derivation at the end of t=0.15 sec

$$\left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.15}^{P}} = \Delta\omega_{0.15}^{P} = 8.67 rad/\sec$$

$$\left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.15}^{P}} = \frac{\pi\times 50}{2.5}[0.92-0] = 57.8$$

Corrected values:

$$\delta_{0.15}^{C} = \delta_{0.1}^{C} + \frac{\Delta t}{2}\left[\left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.1}^{C}} + \left.\frac{d\delta}{dt}\right|_{\Delta\omega_{0.15}^{P}}\right]$$

$$\delta_{0.15}^{C} = 0.709 + \frac{0.05}{2}[5.78 + 8.67]$$

$$\delta_{0.15}^{C} = 1.07 rad$$

$$\Delta\omega_{0.15}^{C} = \Delta\omega_{0.1}^{C} + \frac{\Delta t}{2}\left[\left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.1}^{C}} + \left.\frac{d\Delta\omega}{dt}\right|_{\delta_{0.15}^{P}}\right]$$

$$\Delta\omega_{0.15}^{C} = 5.78 + \frac{0.05}{2}[57.8 + 57.8]$$

$$\Delta\omega_{0.15}^{C} = 8.67 rad/\sec$$

Post fault condition, $P_e = 1.5 \sin \delta$

Calculate $\delta_{0.2}^{C}$ and $\Delta\omega_{0.2}^{C}$ using $P_e = 1.5 \sin \delta$

QUESTION BANK
with SOLVED 2 MARK Qs

POWER SYSTEM ANALYSIS
UNIT 1: INTRODUCTION

1. Explain the requirements of planning the operation of a power system.

Planning the operation of a power system requires load studies, fault calculations, the design of means for protecting the system against lightning and switching surges and against short circuits, and studies of the stability of the system.

2. Define steady state operating condition.

A power system is said to be in a steady state operating condition, if all the measured(or calculated) physical quantities describing the operating condition of the system can be considered constant for the purpose of analysis.

3. What is a disturbance and what are the two types of disturbances?

If a sudden change or sequence of changes occurs in one or more of the system parameters or one or more of its operating quantities, the system is said to have undergone a disturbance from its steady state operating condition.

The two types of disturbances in a power system are,

i) Large disturbance ii) Small disturbance

4. What is a small disturbance? Give example.

If the power system is operating in a steady state condition and it undergoes change, which can be properly analyzed by linearized versions of its dynamic and algebraic equations, a small disturbance is said to have occurred.

Example of small disturbance is a change in the gain of the automatic voltage regulator in the excitation system of a large generating unit.

5. What is a large disturbance? Give some examples.

A large disturbance is one for which the nonlinear equations describing the dynamics of the power system cannot be validly linearized for the purpose of analysis.

Examples of large disturbances are transmission system faults, sudden load changes, loss of generating units and line switching.

6. When is a power system said to be steady-state stable?

The power system is steady state stable for a particular steady-state operating condition if, following a small disturbance, it returns to essentially the same steady state condition of operation.

7. When is a power system said to be transiently stable?

If the machines of the system are found to remain essentially in synchronism within the first second following a system fault or other large disturbance, the system is considered to be transiently stable.

8. What is transient state of the power system?

The state of the system in the first second following a system fault or large disturbance is called the transient state of the power system.

9. Give the formula to calculate base current, I_b and base impedance of a three-phase system.

The equation for base current I_b is,

$$I_b = \frac{kVA_b}{\sqrt{3}\, kV_b}$$

The equation for base impedance is,

$$Z_b = \frac{kV_b\, x1000}{\sqrt{3}\, I_b}$$

Where,

I_b = Line value of base current.

kVA_b = 3-phase base KVA

kV_b = line to line base kV

Z_b = Base impedance per phase.

10.Give the equation for load impedance and load admittance per phase of a balanced star connected load.

Load impedance per phase, $Z = \frac{|V_L|^2}{P - jQ}$

Load admittance per phase, $Y = \frac{1}{Z} = \frac{P - jQ}{|V_L|^2}$

Where,

P = Three phase active power of star connected load in watts.

Q = Three phase reactive power of star connected load in VARs.

V_L = Line voltage of load.

11. Give the equation for load impedance and load admittance per phase of a balanced delta connected load.

Load impedance per phase, $Z = \frac{3|V_L|^2}{P - jQ}$

Load admittance per phase, $Y = \frac{1}{Z} = \frac{P - jQ}{3|V_L|^2}$

Where,

P = Three phase active power of delta connected load in watts.

Q = Three phase reactive power of delta connected load in VARs.

V_L = Line voltage of load.

12. What is the advantage of per unit method over percent method?

The advantage of per unit method over percent method is that the product of two quantities expressed in per unit is expressed in per unit itself, but the product of two quantities expressed in percent must be divided by 100 to obtain the result in percent.

13. Define base impedance and base kilovoltamperes.

The base impedance is the impedance which will have a voltage drop across it equal to the base voltage when the current flowing in the impedance is equal to the base value of the current.

$$Z_b = \frac{(kV_b)^2 \; x1000}{kVA_b}$$

The base kilovoltamperes in single-phase systems is the product of base voltage in kilovolts and base current in amperes.

$$kVA_b = kV_b \; x \; I_b$$

14.Define per unit value of any electrical quantity.

The per unit value of any electrical quantity is defined as the ratio of the actual value of the quantity to its base value expressed as a decimal.

$$Perunitvalue = \frac{Actual\ value}{Base\ value}$$

15. What are the quantities whose base values are required to represent the power system by reactance diagram?

The base value of voltage, current, power and impedance are required to represent the power system by reactance diagram. Selection of base values for any two of them determines the base values of the remaining two. Usually the base values of voltage and power are chosen in kilovolt and kVA or mVA respectively. The base values of current and impedance are calculated using the chosen bases.

16. What is the need for base values?

The components of various sections of power system may operate at different voltage and power levels. It will be convenient for analysis of power system if the voltage, power, current and impedance ratings of power system components are expressed with reference to a common value called base value. Then all the voltages, power, current and impedance ratings of the components are expressed as a percent or per unit of the base value.

17. Write the equation for converting the per unit impedance expressed in one base to another.

$$Z_{p.u,new} = Z_{p.u,old} \; x \left(\frac{kV_{b,old}}{kV_{b,new}} \right)^2 x \left(\frac{MVA_{b,new}}{MVA_{b,old}} \right)$$

18. List the advantages of per unit computations.

(1) The per unit impedance referred to either side of a single phase transformer is the same.

(2) The per unit impedance referred to either side of a three phase transformer is the same regardless of the three phase connections whether they are Y-Y, Δ-Δ or

Δ-Y

(3) The chance of confusion between the line and phase quantities in a three phase balanced system is greatly reduced.
(4) The manufacturers usually provide the impedance values in per unit.
(5) The computational effort in power system is very much reduced with the use of per unit quantities.

19. What are the factors that affect the transient stability?

The transient stability is generally affected by two factors namely,
(1) Type of fault (2) Location of fault.

20. List the methods of improving the transient stability limit of a power system.

(1) Increase of system voltage, use of AVR.
(2) Use of high speed excitation systems.
(3) Reduction in system transfer reactance.
(4) Use of high speed reclosing breakers.

21. What is meant by stability study?

The procedure of determining the stability of a system upon occurrence of a disturbance followed by various switch off and switch on actions is called a stability study.

22. What is meant by short circuit fault?

Short circuit faults involve power conductor or conductors-to-ground or short circuit between conductors. These faults are characterized by increase in current and fall in voltage and frequency.

23. What is a reactor?

Reactor is a coil, which has high inductive reactance as compared to its resistance and is used to limit the short circuit current during fault conditions.

24. Give the equation for transforming base kV on LV side to HV side of a transformer and vice versa.

$$\text{Base kV on HV side} = \text{Base kV on LV side} \times \frac{\text{HV rating}}{\text{LV rating}}$$

$$\text{Base kV on LV side} = \text{Base kV on HV side} \times \frac{\text{LV rating}}{\text{HV rating}}$$

25.Give the equation for base current and base impedance of a balanced three phase circuit.

$$Base\ current,\ A = \frac{base\ kVA\ 3\varphi}{\sqrt{3}\ x\ base\ voltage,\ kV_{LL}}$$

$$Base\ impedance = \frac{(base\ voltage,\ kV_{LL})^2}{base\ MVA_{3\varphi}}$$

26. Why the line value of voltage directly used for per unit calculation in three phase systems?

The per unit value of a line-to-neutral(V_{LN}) on the line-to-neutral voltage base($V_{b,LN}$) is equal to the per unit value of the line-to-line voltage(V_{LL}) at the same point on the line-to-line voltage base($V_{b,LL}$) if the system is balanced.

$$i.e., \frac{V_{LN}}{V_{b,LN}} = \frac{V_{LL}}{V_{b,LL}}$$

27. Why the three phase kVA directly used for per unit calculation in three phase systems?

The per unit value of a 3-phase kVA on the 3-phase kVA base is identical to the per unit value of kVA per phase on the kVA per phase base.

$$i.e., \frac{3-phase\ kVA}{3-phase\ base\ kVA} = \frac{kVA\ per\ phase}{Base\ kVA\ per\ phase}$$

Therefore in 3 phase systems, the line value of voltage and 3 phase kVA are directly used for per unit calculations.

Possible 16-mark questions and answers

1. What is the need for system analysis in planning and operation of power system? Explain. (APR/MAY 2004)

2. Explain the advantages of the p.u form of representation?
3. Define the per unit value of a quantity. How will you change the base impedance from one set of base values to another set?
4. Explain the steady state and transient state with the help of a RL circuit.
5. Why is Per phase analysis done in a symmetrical three-phase system.
6. What are the advantages of using per unit system?
7. Explain the per phase generator model with required diagrams.
8. With neat diagrams, explain the transformer model used for per phase analysis.
9. Discuss in detail about the modeling of transmission lines.
10. Clearly explain the basic components of a power system.

Reference books:

R1 – Hadi saadat, "Power System Analysis", Tata McGraw Hill

R2 – I J Nagarath, D P Kothari 'Modern Power system Analysis', TMH Pub. Co. Ltd., 1994.

R3 – Nagoor Kani, "Power System Analysis"\

1.The equation for base current I_b is,

$$I_b = \frac{kVA_b}{\sqrt{3}\, kV_b}$$

2.The equation for base impedance is,

$$Z_b = \frac{kV_b \, x1000}{\sqrt{3}\, I_b}$$

3.The equation for base current I_b is,

$$I_b = \frac{kVA_b}{\sqrt{3}\, kV_b}$$

4.The equation for base impedance is,

$$Z_b = \frac{kV_b \, x1000}{\sqrt{3}\, I_b}$$

5.The base impedance is

$$Z_b = \frac{(kV_b)^2 \, x1000}{kVA_b}$$

6.The base kilovolt amperes is

$$kVA_b = kV_b \; x \; I_b$$

7.The equation for converting the per unit impedance expressed in one base to another.

$$Z_{p.u,new} = Z_{p.u,old} \; x \left(\frac{kV_{b,old}}{kV_{b,new}} \right)^2 x \left(\frac{MVA_{b,new}}{MVA_{b,old}} \right)$$

8.The equation for transforming base kV on LV side to HV side of a transformer and vice versa.

Base kV on HV side = Base kV on LV side

side

Base kV on LV side = Base kV on HV

$$\times \frac{\text{HV rating}}{\text{LV rating}}$$

$$\times \frac{\text{LV rating}}{\text{HV rating}}$$

9.The equation for base current and base impedance of a balanced three-phase circuit.

$$\text{Base current, } A = \frac{\text{base kVA } 3\varphi}{\sqrt{3} \text{ x base voltage, } kV_{LL}}$$

$$\text{Base impedance} = \frac{(\text{base voltage, } kV_{LL})^2}{\text{base } MVA_{3\varphi}}$$

10.3-phase kVA base is identical to the per unit value of kVA per phase on the kVA per phase base.

$$i.e., \frac{3 - \text{phase kVA}}{3 - \text{phase base kVA}} = \frac{\text{kVA per phase}}{\text{Base kVA per phase}}$$

11.The line-to-line voltage base ($V_{b,LL}$) if the system is balanced.

$$i.e., \frac{V_{LN}}{V_{b,LN}} = \frac{V_{LL}}{V_{b,LL}}$$

12.The per unit impedance referred to either side of a single-phase transformer is the same.

13.The per unit impedance referred to either side of a three phase transformer is the same regardless of the three phase connections whether they are Y-Y, Δ-Δ or Δ-Y

14.The chance of confusion between the line and phase quantities in a three phase balanced system is greatly reduced.

15.The manufacturers usually provide the impedance values in per unit.

16.The computational effort in power system is very much reduced with the use of per unit quantities.

17. The transient stability is generally affected by two factors namely,

(1) Type of fault

(2) Location of fault.

UNIT 2:MODELLING OF VARIOUS COMPONENTS

Possible 2-mark questions and answers

1. Write the most important mode of operation of power system and mention the major problems encountered with it.

Symmetrical steady state is the most important mode of operation of power system. Three major problems are encountered in this mode of operation. They are,

1) Load flow problem
2) Optimal load scheduling problem
3) Systems control problem

2.Why power flow analysis is made?

Power flow analysis is performed to calculate the magnitude and phase angle of voltages at the buses and also the active power and reactive voltamperes flow for the given terminal or bus conditions. The variables associated with each bus or node are,

a. Magnitude of voltage |V|
b. Phase angle of voltage δ
c. Active power, P
d. Reactive voltamperes, Q

3. What is power flow study or load flow study?

The study of various methods of solution to power system network is referred to as load study. The solution provides the voltages at various buses, power flowing in Various lines and line losses.

4. What are the information that are obtained from a load flow study?

The information obtained from a load flow study are magnitude and phase angles of bus voltages, real and reactive power flowing in each line and line losses. The load flow solution also gives the initial conditions of the system when the transient behavior of the system is to be studied.

5. What is the need for load flow study? (MAY/JUNE 2006)

The load flow study of a power system is essential to decide the best operation of existing system and for planning the future expansion of the system. It is also essential for designing a new power system.

6. What are the works involved in a load flow study? (NOV/DEC 2004)

The following has to be performed for a load flow study.

a. Representation of the system by single line diagram.
b. Formation of impedance diagram using the information in single line diagram.
c. Formulation of network equations
d. Solution of network equations.

7. What are the different types of buses in a power system?

The buses of a power system can be classified into three types based on the quantities being specified for the buses, which are as follows:

a. Load bus or PQ bus (P and Q are specified)
b. Generator bus or voltage controlled bus or PV bus (P and V are specified)
c. Slack bus or swing bus or reference bus (|V| and δ are specified)

8. Define voltage controlled bus(generator bus/PV bus).

A bus is called voltage controlled bus if the magnitude of voltage |V| and real power (P) are specified for it. In a voltage controlled bus, the magnitude of the voltage is not allowed to change. Voltage controlled bus is also called as Generator bus and PV bus.

9. What is PQ bus(load bus)? (APR/MAY 2005)

A bus is called PQ bus or load bus when real and reactive components of power are specified for the bus. In a load bus, the voltage is allowed to vary within permissible limits.

10.What is swing bus(slack bus/reference bus)?

A bus is called swing bus when the magnitude and phase of bus voltage are specified for it. The swing bus is the reference bus for load flow solution and it is required for accounting for the line losses. Usually one of the generator bus is selected as the swing bus.

11. What is the need for slack bus? (APR/MAY 2004),(NOV/DEC 2004)

The slack bus is needed to account for transmission line losses. In a power system, the total power generated will be equal to sum of power consumed by loads and losses. In a power system, only the generated power and load power are specified for the buses. The slack bus is assumed to generate the power required for losses. Since the losses are unknown, the real and reactive power are not specified for slack bus. They are estimated through the solution of line flow equations.

12. List the quantities specified and the quantities to be determined from load flow study for various types of buses. (MAY/JUNE 2006)

The following table shows the quantities specified and the quantities to be obtained for various types of buses.

Bus type	**Quantities specified**	**Quantities to be obtained**
Load Bus	P,Q	|V|, δ
Generator Bus	P, |V|	Q, δ
Slack Bus	|V|, δ	P, Q

13. Write the load flow equation of Gauss and Gauss-Seidel method.

The load flow equation of Gauss method is given by,

$$V_p^{K+1} = \frac{1}{Y_{pp}}\left[\frac{P_p - jQ_p}{\left(V_p^K\right)^*} - \sum_{\substack{q=1 \\ q \neq p}}^{n} Y_{pq} V_q^K\right]$$

The load flow equation of Gauss-Seidel method is given by,

$$V_p^{K+1} = \frac{1}{Y_{pp}}\left[\frac{P_p - jQ_p}{\left(V_p^K\right)^*} - \sum_{q=1}^{p-1} Y_{pq} V_q^{K+1} - \sum_{q=p+1}^{n} Y_{pq} V_q^K\right]$$

V_p^{K+1} and V_p^K = (K+1) and K[th] iteration voltage of bus 'p' respectively.
V_q^{K+1} and V_q^K = (K+1) and K[th] iteration voltage of bus 'q' respectively.

14. Write the load flow equation of Newton-Raphson method.

The load flow equation of Newton Raphson method is given by,

$$P_p = \sum_{q=1}^{n} \left[e_p (e_q G_{pq} + f_q B_{pq}) + f_p (f_q G_{pq} - e_q B_{pq}) \right]$$

$$Q_p = \sum_{q=1}^{n} \left[f_p (e_q G_{pq} + f_q B_{pq}) - e_p (f_q G_{pq} - e_q B_{pq}) \right]$$

$$\left|V_p\right|^2 = e_p^2 + f_p^2$$

15. Discuss the effect of acceleration factor in the load flow solution algorithm. (APR/MAY 2004)

In load flow solution by iterative methods, the number of iterations can be reduced if the correction voltage at each bus is multiplied by some constant. The multiplication of the constant will increase the amount of correction to bring the voltage closer to the value it is approaching. The multipliers that accomplish this improved converged are called acceleration factors. An acceleration factor of 1.6 is normally used in load flow problems.

16. How will you account for voltage controlled buses in the load flow algorithm?

The acceleration factor is a real quantity and it modifies the magnitude of bus voltage alone. Since in voltage controlled bus, the magnitude of bus voltage is not allowed to change, the acceleration factor is not used for voltage controlled bus.

17. Why do we go for iterative methods to solve load flow problems?

The load (or power) flow equations are nonlinear algebraic equations and so explicit solution is not possible. The solution of nonlinear equations can be obtained only by iterative numerical techniques.

18. What do you mean by a flat voltage start?

In iterative methods of load flow solution, the initial voltage of all buses except slack bus are assumed as 1+j0 p.u. This is referred to as flat voltage start.

19.When the generator bus is treated as load bus? What will be the reactive power and bus voltage when the generator bus is treated as load bus?

If the reactive power of a generator bus violates the specified limits, then the generator bus is treated as load bus. The reactive power of that particular bus is equated to the limit it has violated and the previous iteration value of bus voltage is used for calculating current iteration value.

20. What are the advantages of Gauss-Seidel method?

The advantages of Gauss-Seidel method are,

a. Calculations are simple and so the programming task is less
b. The memory requirement is less
c. Useful for small systems.

21.What are the disadvantages of Gauss-Seidel method?

The disadvantages of Gauss-Seidel method are,

a. Requires large number of iterations to reach convergence.
b. Not suitable for large systems.
c. Convergence time increases with size of the system.

22.How approximation is performed in Newton-Raphson method?

In Newton-Raphson method, the set of non-linear simultaneous (load flow) equations are approximated to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to first order approximation.

23. What is Jacobian matrix? How the elements of Jacobian matrix are computed?

The matrix formed from the derivates of load flow equations is called Jacobian matrix and it is denoted by J.

The elements of Jacobian matrix will change in every iteration. In each iteration, the elements of the Jacobian matrix are obtained by partially differentiating the load flow equations with respect o unknown variable and then evaluating the first derivates using the solution of previous iteration.

24.What are the advantages of Newton-Raphson method?

The advantages of Newton-Raphson method are,

a. This load flow method is faster, more reliable and he results are accurate.
b. Requires less number of iterations for convergence.
c. The number of iterations are independent of the size of the system.

d. Suitable for large system.

25.What are the disadvantages of Newton-Raphson method?

The disadvantages of Newton-Raphson method are,

a. Programming is more complex.
b. The memory requirement is more.
c. Computational time per iteration is higher due to larger number of calculations per iteration.

26.Mention (any) three advantages of N-R method over G-S method?

The three advantages of N-R method over G-S method are,

a. The N-R method has quadratic convergence characteristics and so converges faster than G-S method.
b. The number of iterations for convergence is independent of the system in N-R method.
c. In N-R method, the convergence is not affected by the choice of slack bus.

27.Compare G-S method and N-R methods of load flow solutions.

G-S method	N-R method
1. The variables are expressed in rectangular co-ordinates.	1. Variables are expressed in polar co-ordinates.
2. Computation time per iteration is less.	2. Computation time per iteration is more
3. It has linear convergence characteristics.	3. It has quadratic convergence characteristics.
4. The number of iterations required for convergence increase with size of the system.	4.The number of iterations are independent of the size of the system.
5.The choice of slack bus is critical.	5. The choice of slack bus is arbitrary.

28.How the convergence of N-R method is speeded up?

The convergence can be speeded up in N-R method by using Fast Decoupled Load Flow (FDLF) algorithm. In FDLF method, the weak coupling between P-δ and Q-V are decoupled and then the equations are further simplified using the knowledge of practical operating conditions of a power system.

29. How the disadvantages of N-R method are overcome?

The disadvantage of large memory requirement can be overcome by decoupling the weak coupling between P-δ and Q-V (i.e., using decoupled load flow algorithm). The disadvantage of large computational time per iteration can be reduced by simplifying the decoupled load flow equations. The simplifications are based on the practical operating conditions of a power system.

30. Write the equation for power flow in the transmission line.

The equation for power low in the transmission line (say p-q) at bus 'p' is given by,

$$S_{pq} = P_{pq} - jQ_{pq}$$
$$= E_p^* \, i_{pq}$$

$= E_p^* [E_p - E_q] Y_{pq} + E_p^* E_p . (Y_{pq}'/2)$

$S_{qp} = P_{qp} - jQ_{qp}$

$= E_q^* i_{qp}$

$\mathbf{= E_q^* [E_q - E_p] Y_{pq} + E_q^* E_q . (Y_{pq}'/2)}$

31.Define primitive network.

Primitive network is a set of unconnected elements which provides information regarding the characteristics of individual elements only. The performance equations of primitive network are given below.

V + E = ZI (In Impedance form)

I + J = YV (In Admittance form)

where V and I are the element voltage and current vectors respectively.

J and E are source vectors.

Z and Y are the primitive Impedance and Admittance matrices respectively.

32. What is a bus?

The meeting point of various components in a power system is called a bus. The bus is a conductor made of copper (or) aluminium having negligible resistance. The buses are considered as points of constant voltage in a power system.

33.Explain bus incidence matrix.

For the specific system, we can obtain the following relation (relation between element voltage and bus voltage).

$V = A\ V_{BUS}$

where A is the bus incidence matrix, which is a rectangular and singular matrix. Its elements are found as per the following rules.

a_{ik} = 1, if i^{th} element is incident to and oriented away from the k^{th} node (bus).

= -1, if i^{th} element is incident to but oriented towards the k^{th} node.

= 0, if i^{th} element is not incident to the k^{th} node.

34. What is bus admittance matrix? (MAY/JUNE 2006)

The matrix consisting of the self and mutual admittance of the power system network is called bus admittance matrix. It is given by the admittance matrix Y in the node basis matrix equation of a power system and it is denoted as Y_{bus}. Bus admittance matrix is a symmetrical matrix.

35. Write the equation for the bus admittance matrix.

The equation for bus admittance matrix is,

$Y_{bus}V = I$

where

Y_{bus} = Bus admittance matrix of order (n x n)

V = Bus voltage matrix of order (n x1)

I = Current source matrix of order (n x1)

n = Number of independent buses in the system

36. Give the matrix notation of $Y_{bus}V = I$

$$\begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & \cdots & Y_{1n} \\ Y_{21} & Y_{22} & Y_{23} & \cdots & Y_{2n} \\ Y_{31} & Y_{32} & Y_{33} & \cdots & Y_{3n} \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ Y_{n1} & Y_{n2} & Y_{n3} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \cdot \\ \cdot \\ \cdot \\ V_n \end{bmatrix} = \begin{bmatrix} I_{11} \\ I_{22} \\ I_{33} \\ \cdot \\ \cdot \\ \cdot \\ I_{nn} \end{bmatrix}$$

37. Give the equation to find the k^{th} bus voltage.

The equation to find the k^{th} bus voltage is,

$$V_k = \frac{1}{\Delta}\left[\Delta_{1k} I_{11} + \Delta_{2k} I_{22} + \Delta_{3k} I_{33} + \ldots + \Delta_{nk} I_{nn}\right]$$

$$V_k = \frac{1}{\Delta} \sum_{j=1}^{n} \Delta_{jk} I_{jj}$$

where Δ = Determinant of Y_{bus} matrix.

Ijj = Sum of the currents injecting current to node j.

Δ_{jk} = Cofactor of the element Y_{jk} of bus admittance matrix.

38.Mention the advantages of bus admittance matrix, Y_{bus}.

i) Data preparation is simple.
ii) Formation and modification is easy.
iii) Since the bus admittance matrix is sparse matrix(i.e., most of its elements are zero), the computer memory requirements are less.

<u>Possible 16-mark questions and answers</u>

1.With the help of a neat flow chart, explain the Newton-Raphson method of load flow solution when the system contains voltage controlled busses in addition to swing bus and load bus.
(APR/MAY 2004)

2.Compare Gauss-Seidel method and Newton-Raphson method of load flow studies
(NOV/DEC 2004)

3.Explain clearly with detailed flowchart, the computational procedure for load flow solution using N-R method when the system contains all types of buses.
(NOV/DEC 2004)

4.Explain the step by step computational procedure for the Newton-Raphson method of load flow studies.
(APR/MAY 2005)

5. Explain bus classification in power flow analysis with their known and unknown

quantities.

6. Derive the static load flow equations of n-Bus system.
(APR/MAY 2005)

7. Explain the step by step computational procedure for the Gauss-Seidel method of load flow studies (MAY/JUNE 2006)

8. Derive the basic equations for the load flow study using Gauss-Seidel method. With respect to this method, explain the following:

a. Acceleration factor.
b. Handling of PV buses.

9. Draw the representation schemes for

a. Phase shifting transformer
b. Tap changing transformer

10. Draw the mathematical model of phase shifting transformer to be used in power flow analysis.

11. Give the advantages and disadvantages of Gauss-Seidel method and Newton-Raphson method of load flow analysis.

12. Write the equations to calculate Slack bus power, Transmission losses and Line flows.

Reference books:

R1 – Hadi saadat, "Power System Analysis", Tata McGraw Hill
R2 – I J Nagarath , D P Kothari 'Modern Power system Analysis', TMH Pub. Co. Ltd., 1994.
R3 – Nagoor Kani, "Power System Analysis"

UNIT 3:POWER FLOW ANALYSIS

Possible 2 mark questions:

1. What is the need for short circuit studies or fault analysis?

The short circuit studies are essential in order to design or develop the protective schemes for various parts of the system. The protective scheme consists of current and voltage sensing devices, protective relays and circuit breakers. The selection of these devices mainly depends on various currents that may flow in the fault conditions.

2. What is the reason for transients during short circuits?

The faults or short circuits are associated with sudden change in currents. Most of the components of the power system have inductive property which opposes any sudden change in currents, so the faults are associated with transients.

3. What is meant by a fault?

A fault in a circuit is any failure which interrupts with the normal flow of current. The faults are associated with abnormal change in current, voltage and frequency of the power system. The faults may cause damage to the equipments, if it is allowed to persist for a long time. Hence every part of a system has been protected by means of relays and circuit breakers to sense the faults and to isolate the faulty part from the healthy part of the network in the event of fault

4. Why faults occur in a power system?

Faults occur in a power system due to insulation failure of equipments, flashover of lines initiated by a lightening stroke, permanent damage to conductors and towers or accidental faulty operations.

5. How are the faults classified?

In one method, the faults are classified as,

1. Shunt faults - due to short circuits in conductors

2. Series faults - due to open conductors.

In another method,

1. Symmetrical faults - fault currents are equal in all the phases and can be analyzed on per phase basis

2. Unsymmetrical faults – fault currents are unbalanced and so they can be analyzed only using symmetrical components.

6. List the various types of shunt and series faults.

Various types of shunt faults are

1. Single line-to-ground fault
2. Line-to-line fault

3. Double line-to-ground fault
4. Three phase fault

Various types of series faults are,

1. One open conductor fault
2. Two open conductor fault

7. What is meant by symmetrical fault?

The fault is called symmetrical fault if the fault current is equal in all the phases. This fault conditions are analyzed on per phase basis using Thevenin's theorem or using bus impedance matrix. The three-phase fault is the only symmetrical fault.

8. List out the differences in representing the power system for load flow and short circuit studies.

Load flow studies	Fault analysis
1. Both resistances and reactances are Considered.	Resistances are neglected.
2. Bus admittance matrix is useful.	Bus impedance matrix is used.
3. The exact voltages and currents are to be determined.	The voltages can be safely assumed as 1 p.u. and the prefault current can be neglected.

9. For a fault at a given location, rank the various faults in the order of severity.

In a power system, the most severe fault is three phase fault and less severe fault is open conductor fault. The various faults in the order of decreasing severity are,

1) 3 phase fault
2) Double line-to-ground fault
3) Line-to-line fault
4) Single line-to-ground fault
5) Open conductor fault

10. What is meant by fault calculations?

The fault condition of a power system can be divided into sub transient, transient, and steady state periods. The currents in the various parts of the system and in the fault locations are different in these periods. The estimation of these currents for various types of faults at various locations in the system is commonly referred to as fault calculations.

11. What are the assumptions made in short circuit studies of a large power system network? (APR/MAY 2005)

1) The phase to neutral emfs of all generators remain constant, balanced and unaffected by the faults.
2) Each generator is represented by an emf behind either the subtransient or transient reactance depending upon whether the short circuit current is to be found immediately after the short circuit or after about 3 – 4 cycles.
3) Load currents may often be neglected in comparison with fault currents.
4) All network impedances are purely reactive. Thus the series resistances of lines and transformers are neglected in comparison with their resistances.

5) Shunt capacitances and shunt branches of transformers are neglected. Hence, transformer reactances are taken as their leakage reactances.

12. What is synchronous reactance?

The synchronous reactance is the ratio of induced emf and the steady state rms current (i.e., it is the reactance of a synchronous machine under steady state condition). It is the sum of leakage reactance and the reactance representing armature reaction. It is given by,

$X_s = X_l + X_a$

Where,

X_s = Synchronous reactance
X_l = Leakage reactance
X_a = Armature reaction reactance.

13. Define subtransient reactance.(APR/MAY 2004)

The subtransient reactance is the ratio of induced emf on no-load and the subtransient symmetrical rms current, (i.e., it is the reactance of a synchronous machine under subtransient condition). It is given by,

Subtransient reactance, $$X_d'' = \frac{E_g}{I''} = X_l + \frac{1}{\frac{1}{X_a} + \frac{1}{X_f} + \frac{1}{X_{dw}}}$$

Where

X_l = Leakage reactance
X_a = Armature reaction reactance
X_f = Field winding reactance
X_{dw} = Damper winding reactance.

14. Define transient reactance.

The transient reactance is the ratio of induced emf on no-load and the transient symmetrical rms current. (i.e.,it is the reactance of synchronous machine under transient condition). It is given by,

Transient reactance, $$X_d' = \frac{E}{I'} = X_l + \frac{1}{\frac{1}{X_a} + \frac{1}{X_f}}$$

Where

X_l = Leakage reactan X_a = Armature reaction reactance X_f = Field winding reactance

15.What is the significance of subtransient reactance and transient reactance in short circuit studies?

The subtransient reactance can be used to estimate the initial value of fault current immediately on the occurrence of the fault. The maximum momentary short circuit current rating of the circuit breaker used for protection or fault clearing should be less than this initial fault current.

The transient reactance is used to estimate the transient state fault current. Most of the circuit breakers open their contacts only during this period. Therefore for a circuit breaker used for fault clearing (or protection), its interrupting short circuit current rating should be less than the transient fault current.

16. Write down the equation determining fault current in a generator when its reactance is known.

The equation is,

$$|I| = \frac{|E_g|}{X_d} \quad , \quad |I'| = \frac{|E_g|}{X_d'}$$

where

$|I|$ = Steady state symmetrical fault current

$|I'|$ = Transient symmetrical fault current

X_d = Direct axis synchronous reactance

X_d' = Direct axis transient reactance

$|E_g|$ = RMS voltage from one terminal to neutral at no load.

17.Write the equation for subtransient and transient internal voltage of the generator.

The equation for subtransient internal voltage is,

$$E_g'' = V_t + jI_L X_d''$$

Transient internal voltage is,

$$E_g' = V_t + jI_L X_d'$$

where

E_g'' = Subtransient internal voltage of generator
E_g' = Transient internal voltage of generator
V_t = Terminal voltage
I_L = Load current
X_d'' =Direct axis subtransient reactance
X_d' =Direct axis transient reactance

18.Write the equation for subtransient and transient internal voltage of the motor.

The equation for subtransient internal voltage is,

$$E_m'' = V_t - jI_L X_d''$$

Transient internal voltage is,

$$E_m' = V_t - jI_L X_d'$$ s

where

E_m'' = Subtransient internal voltage of generator

E_m' = Transient internal voltage of generator
V_t = Terminal voltage
I_L = Load current
X_d'' =Direct axis subtransient reactance

X_d' =Direct axis transient reactance

19. How symmetrical faults are analyzed?

The symmetrical faults are analyzed using per unit reactance diagram of the power system. Once the reactance diagram is formed, then the fault is simulated by short circuit or by connecting the fault impedance at the fault point. The currents and voltages at various parts of the system can be estimated by any of the following methods.

1) Using Kirchoff's laws
2) Using Thevenin's theorem
3) By forming bus impedance matrix.

20. Define doubling effect and DC off-set current.

Doubling effect:

If a symmetrical fault occurs when the voltage wave is going through zero then the maximum momentary short circuit current will be double the value of maximum symmetrical short circuit current. This effect is called doubling effect.

DC off-set current:

The unidirectional transient component of short circuit current is called DC off-set current.

21.Differentiate between subtransient and transient reactance.

Subtransient reactance	Transient reactance
1) This is the ratio of induced emf and subtransient current. 2) Flux created by induced currents in the damper winding is included. 3) This is the smallest reactance among the reactance values. 4) This cannot be extrapolated.	1) This is the ratio of induced emf and transient current. 2) There is no damper winding and hence no flux is created. 3) This is larger than the subtransient reactance. 4) This can be extrapolated backwards in time

22.What are symmetrical components?

An unbalanced system of N related vectors can be resolved into N systems of balanced vectors called symmetrical components. Positive sequence components
Negative sequence components
Zero sequence components.

23. Write the symmetrical components of three phase system.

In a 3-phase system, the three unbalanced vectors (either current or voltage vectors) can be resolved into three balanced system of vectors. They are,

1) Positive sequence components
2) Negative sequence components
3) Zero sequence components.

24. Define negative sequence and zero sequence components.

Negative sequence components consist of three phasors equal in magnitude, displaced from each other by 120^o in phase, and having the phase sequence opposite to that of the original phasors. V_{a2}, V_{b2} and V_{c2} are the negative sequence components of V_a, V_b and v_c.

Zero sequence components consist of three phasors equal in magnitude and with zero phase displacement from each other. V_{ao}, V_{bo} and V_{co} are the zero sequence components of V_a, V_b and V_c.

25.Express the unbalanced voltages V_a, V_b and V_c in terms of symmetrical components V_{a1}, V_{a2} and V_{a0}.

The expression of unbalanced voltages in terms of symmetrical components are,

$$V_a = V_{ao} + V_{a1} + V_{a2}$$

$$V_b = V_{ao} + a^2 V_{a1} + aV_{a2}$$

$$V_c = V_{ao} + aV_{a1} + a^2 V_{a2}$$

(Or)

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$

26. Express the symmetrical components V_{a1}, V_{a2} and V_{a0} in terms of unbalanced vectors V_a, V_b and V_c.

The expression of symmetrical components in terms of unbalanced vectors are,

$$V_{ao} = \frac{1}{3}(V_a + V_b + V_c)$$

$$V_{a1} = \frac{1}{3}(V_a + aV_b + a^2 V_c)$$

$$V_{a2} = \frac{1}{3}(V_a + a^2 V_b + aV_c)$$

(Or)

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ \ldots \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ \ldots & & \ldots^2 \end{bmatrix} \begin{bmatrix} V_a \\ \ldots \\ V_{a2} \end{bmatrix}$$

$$3\begin{bmatrix} 1 & a & a \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V_b \\ V_c \end{bmatrix}$$

27. Define the operator 'a' and express the value of 'a' and 'a^2' in both polar and rectangular form.

An operator which causes a rotation of 120^o in the anticlockwise direction is known as operator 'a'. The value of 'a' is $1\angle 120^o$.

The polar form and rectangular form of operator 'a' is given by,

$a = 1\angle 120^o$ --------polar form

$= -0.5 + j0.806$ ----------rectangular form

The polar form and rectangular form of operator 'a^2' is given by,

$a^2 = 1\angle 240^o$ --------polar form

$= -0.5 - j0.806$ ----------rectangular form

28.what are sequence impedances and sequence networks?

The sequence impedances are the impedances offered by the devices or components for the like sequence component of the current.

The single phase equivalent circuit of a power system consisting of impedances to current of any one sequence only is called **sequence network**.

29. What assumption is made at the star / delta transformer?

It is that the positive sequence quantities on the HV side lead their corresponding positive sequence quantities on the LV side by 30^o. The reverse is the case for negative sequence quantities wherein HV quantities lag the corresponding LV quantities by 30^o.

30.What is an unsymmetrical fault? List the various unsymmetrical faults.

The fault is called unsymmetrical fault if the fault current is not equal in all the phases. The unsymmetrical faults in a power system are,

1) Single line-to-ground fault.
2) Line-to-line fault.
3) Double line-to-ground fault
4) Open conductor fault.

31.Define positive sequence and negative sequence impedances.

The positive sequence impedance of an equipment is the impedance offered by the equipment to the flow of positive sequence current.

The negative sequence impedance of an equipment is the impedance offered by the equipment to the flow of negative sequence current.

Possible 16 marks:

1. Explain the need for short circuit studies.
2. Draw the relationship between the phase components and the sequence components.
3. The phase ‘b’ of a three phase circuit is open. The currents in phases ‘c’ and ‘a’ are I and –I respectively. Determine the positive, negative and zero sequence components of the current in phase ‘a’.
4. With the help of a detailed flow chart, explain how a symmetrical fault can be analysed using Z_{Bus}.
5. What are the various types of faults? Discuss their frequency of occurrence and severity? Find the fault current when an L-L-G fault occurs at the terminals of an unloaded generator.
6. Derive an expression for the positive sequence current I_{a1} of an unloaded generator when it is subjected to a double line to ground fault.(APR/MAY 2004).
7. Explain the short circuit model of a synchronous machine under short circuit conditions.
8. What symmetrical components? Explain the symmetrical component transformation.
9. What is meant by sequence impedance? Explain the sequence network of an unloaded generator.
10. Explain the procedure for making short circuit studies of a large power system using digital computer. Illustrate the answer by considering a symmetrical fault. **(**NOV/DEC 2004)

Reference books:

R1 **–** Hadi saadat, “Power System Analysis”, Tata McGraw Hill

R2 – I J Nagarath , D P Kothari ’Modern Power system Analysis’, TMH Pub. Co. Ltd., 1994.

R3 **–** Nagoor Kani, “Power System Analysis**”**

UNIT 4: SHORT CIRCUIT ANALYSIS

Possible 2 mark questions:

1. What is meant by a fault?

A fault in a circuit is any failure which interrupts with the normal flow of current. The faults are associated with abnormal change in current, voltage and frequency of the power system. The faults may cause damage to the equipments, if it is allowed to persist for a long time.

2. Give the reason for faults in power system?

Faults occur in a power system due to insulation failure of equipments, flashover of lines initiated by a lightening stroke, permanent damage to conductors and towers or accidental faulty operations.

3. List the various types of symmetrical and unsymmetrical faults. (MAY/JUNE 2006)

Symmetrical fault:

5. Three phase fault

Unsymmetrical faults:

6. Single line-to-ground fault
7. Line-to-line fault
8. Double line-to-ground fault

4. For a fault at a given location, rank the various faults in the order of severity.

In a power system, the most severe fault is three phase fault and less severe fault is open conductor fault. The various faults in the order of decreasing severity are,

6) 3 phase fault
7) Double line-to-ground fault
8) Line-to-line fault
9) Single line-to-ground fault
10) Open conductor fault

5. What is meant by fault calculations?

The fault condition of a power system can be divided into subtransient, transient, and steady state periods. The currents in the various parts of the system and in the fault locations are different in these periods. The estimation of these currents for various types of faults at various locations in the system is commonly referred to as fault calculations.

6. What is synchronous reactance?

The synchronous reactance is the ratio of induced emf and the steady state rms current (i.e., it is the reactance of a synchronous machine under steady state condition). It is the sum of leakage reactance and the reactance representing armature reaction. It is given by,

$X_s = X_l + X_a$

Where,

X_s = Synchronous reactance
X_l = Leakage reactance
X_a = Armature reaction reactance.

7. Define subtransient reactance.(APR/MAY 2004)

The subtransient reactance is the ratio of induced emf on no-load and the subtransient symmetrical rms current, (i.e., it is the reactance of a synchronous machine under subtransient condition). It is given by,

Subtransient reactance, $$X_d'' = \frac{E_g}{I''} = X_l + \frac{1}{\frac{1}{X_a} + \frac{1}{X_f} + \frac{1}{X_{dw}}}$$

Where

X_l = Leakage reactance
X_a = Armature reaction reactance
X_f = Field winding reactance
X_{dw} = Damper winding reactance.

8. Define transient reactance.

The transient reactance is the ratio of induced emf on no-load and the transient symmetrical rms current. (i.e.,it is the reactance of synchronous machine under transient condition). It is given by,

Transient reactance, $$X_d' = \frac{E}{I'} = X_l + \frac{1}{\frac{1}{X_a} + \frac{1}{X_f}}$$

Where X_l = Leakage reactance X_a = Armature reaction reactance
X_f = Field winding reactance

9.What is the significance of subtransient reactance and transient reactance in short circuit studies?

The subtransient reactance can be used to estimate the initial value of fault current immediately on the occurrence of the fault. The maximum momentary short circuit current rating of the circuit breaker used for protection or fault clearing should be less than this initial fault current.

The transient reactance is used to estimate the transient state fault current. Most of the circuit breakers open their contacts only during this period. Therefore for a circuit breaker used for fault clearing (or protection), its interrupting short circuit current rating should be less than the transient fault current.

10. Write down the equation determining fault current in a generator when its reactance is known.

The equation is,

$$|I| = \frac{|E_g|}{X_d} \quad , \quad |I'| = \frac{|E_g|}{X_d'}$$

where

$|I|$ = Steady state symmetrical fault current

$|I'|$ = Transient symmetrical fault current

$X_{d,}$ = Direct axis synchronous reactance

X_d = Direct axis transient reactance

$|E_g|$ = RMS voltage from one terminal to neutral at no load.

11.Write the equation for subtransient and transient internal voltage of the generator.

The equation for subtransient internal voltage is,

$$E_g'' = V_t + jI_L X_d''$$

Transient internal voltage is,

$$E_g' = V_t + jI_L X_d'$$

where

$E_{g,}''$ = Subtransient internal voltage of generator

E_g = Transient internal voltage of generator

V_t = Terminal voltage

I_L = Load current

$X_{d,}''$ =Direct axis subtransient reactance

X_d =Direct axis transient reactance

12.Write the equation for subtransient and transient internal voltage of the motor.

The equation for subtransient internal voltage is,

$$E_m'' = V_t - jI_L X_d''$$

Transient internal voltage is,

$$E_m' = V_t - jI_L X_d' \text{ s}$$

where

E_m'' = Subtransient internal voltage of generator

E_m' = Transient internal voltage of generator
V_t = Terminal voltage
I_L = Load current
X_d'' =Direct axis subtransient reactance

$X_d{}'$ =Direct axis transient reactance

13. Define doubling effect and DC off-set current.

Doubling effect:

If a symmetrical fault occurs when the voltage wave is going through zero then the maximum momentary short circuit current will be double the value of maximum symmetrical short circuit current. This effect is called doubling effect.

DC off-set current:

The unidirectional transient component of short circuit current is called DC off-set current.

14.Differentiate between subtransient and transient reactance.

Subtransient reactance	Transient reactance
1) This is the ratio of induced emf and subtransient current. 2) Flux created by induced currents in the damper winding is included. 3) This is the smallest reactance among the reactance values. 4) This cannot be extrapolated.	1) This is the ratio of induced emf and transient current. 2) There is no damper winding and hence no flux is created. 3) This is larger than the subtransient reactance. 4) This can be extrapolated backwards in time

15.What are symmetrical components?

An unbalanced system of N related vectors can be resolved into N systems of balanced vectors called symmetrical components. Positive sequence components Negative sequence component Zero sequence components.

16. Write the symmetrical components of three phase system. (MAY/JUNE 2006)

In a 3-phase system, the three unbalanced vectors (either current or voltage vectors) can be resolved into three balanced system of vectors. They are,

4) Positive sequence components
5) Negative sequence components
6) Zero sequence components.

17. Define negative sequence and zero sequence components.

Negative sequence components consist of three phasors equal in magnitude, displaced from each other by 120^o in phase, and having the phase sequence opposite to that of the original phasors. V_{a2}, V_{b2} and V_{c2} are the negative sequence components of V_a, V_b and v_c.

Zero sequence components consist of three phasors equal in magnitude and with zero phase displacement from each other. V_{ao}, V_{bo} and V_{co} are the zero sequence components of V_a, V_b and V_c.

18.Express the unbalanced voltages V_a, V_b and V_c in terms of symmetrical components V_{a1}, V_{a2} and V_{a0}.

The expression of unbalanced voltages in terms of symmetrical components are,

$$V_a = V_{ao} + V_{a1} + V_{a2}$$

$$V_b = V_{ao} + a^2 V_{a1} + aV_{a2}$$

$$V_c = V_{ao} + aV_{a1} + a^2 V_{a2}$$

(Or)

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$

19. Express the symmetrical components V_{a1}, V_{a2} and V_{a0} in terms of unbalanced vectors V_a, V_b and V_c.

The expression of symmetrical components in terms of unbalanced vectors are,

$$V_{ao} = \frac{1}{3}(V_a + V_b + V_c)$$

$$V_{a1} = \frac{1}{3}(V_a + aV_b + a^2 V_c)$$

$$V_{a2} = \frac{1}{3}(V_a + a^2 V_b + aV_c)$$

(Or)

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

20. Define the operator 'a' and express the value of 'a' and 'a^2' in both polar and rectangular form.

An operator which causes a rotation of 120^o in the anticlockwise direction is known as operator 'a'. The value of 'a' is $1\angle 120^o$.

The polar form and rectangular form of operator 'a' is given by,

a = $1\angle 120^o$ --------polar form

= -0.5 + j0.806 ----------rectangular form

The polar form and rectangular form of operator 'a^2' is given by,

$a^2 = 1\angle 240^o$ --------polar form

$= -0.5 - j0.806$ ----------rectangular form

<u>Possible 16 marks</u>:

11. Draw the relationship between the phase components and the sequence components..

12. Derive the expression for fault current for a double line to ground fault in an unloaded generator in terms of symmetrical components. **(MAY/JUNE 2006)**

13. Derive the expression for fault current for a single line-to-ground fault in a power system faulted through fault impedance Z_f.

14. Explain the need for short circuit studies

15. The phase 'b' of a three phase circuit is open. The currents in phases 'c' and 'a' are I and –I respectively. Determine the Fpositive, negative and zero sequence components of the current in phase 'a'.

16. What are the various types of faults? Discuss their frequency of occurrence and severity?

17. Find the fault current when an L-L-G fault occurs at the terminals of an unloaded generator. Derive an expression for the positive sequence current I_{a1} of an unloaded generator when it is subjected to a double line to ground fault. **(APR/MAY 2004).**

18. Explain the short circuit model of a synchronous machine under short circuit conditions. What symmetrical components? Explain the symmetrical component transformation.

19. Write about the impedances in phase and sequence form.

20. What is meant by sequence impedance? Explain the sequence network of an unloaded generator.

21. Explain the procedure for making short circuit studies of a large power system using digital computer. Illustrate the answer by considering a symmetrical fault. (NOV/DEC 2004)

UNIT 5:STABILITY ANALYSIS

Possible 2 marks

1.Define Stability.

The stability of a system is defined as the ability of power system to return to a stable operation in which various synchronous machines of the system remain in synchronism or 'in step' with each other, when it is subjected to a disturbance.

2. Define steady state stability.

The steady state stability is defined as the ability of a power system to remain stable i.e., without loosing synchronism for small disturbances.

3. Define transient stability.

The transient stability is defined as the ability of a power system to remain stable i.e., without loosing synchronism for large disturbances.

4.Write any three assumptions upon transient stability.

a. Rotor speed is assumed to be synchronous. In fact, it varies insignificantly during the course of the stability study.
b. Shunt capacitances are not difficult to account for in a stability study.
c. Loads are modeled as constant admittances.

5. What is meant by steady state stability limit?

When the load on the system is increased gradually,maximum power that can be transmitted without losing synchronism is termed as steady state stability limit. In steady state, the power transferred by synchronous machine of a power system is always less than the steady state stability limit.

6. What is transient stability limit?

When the load on the system is increased suddenly, maximum power that can be transmitted without losing synchronism is termed as transient state stability limit.

Normally, steady state stability limit is greater than transient state stability limit.

7. How to improve the transient stability limit of power system?

a. Increase of system voltages
b. Use of high speed excitation systems.
c. Reduction in system transfer reactance
d. Use of high speed reclosing breakers.

8. What is stability study?

The procedure of determining the stability of a system upon occurrence of a disturbance followed by various switching off and switching on actions is called stability study.

9.How do you classify steady state stability limit. Define them.

Depending on the nature of the disturbance, the steady state stability limit is classified into,

a. **Static stability limit** refers to steady state stability limit that prevails without the aid of regulating devices.

b. Dynamic stability limit refers to steady state stability limit prevailing in an unstable system with the help of regulating devices such as speed governors, voltage regulators, etc.

10.What are the machine problems seen in the stability study.

1. Those having one machine of finite inertia machines swinging with respect to an infinite bus
2. Those having two finite inertia machines swinging with respect to each other.

11. Give the expression for swing equation. Explain each term along with their units.(APR/MAY 2005)

Where H = Inertia constant in MJ/MVA.

f = Frequency in Hz.

M = Inertia constant in p.u.

P_m= Mechanical power input to the system (neglecting mechanical losses) in p.u.

P_e = Electrical power output of the system (neglecting electrical losses) in p.u.

12. What are the assumptions made in solving swing equation?

1) Mechanical power input to the machine remains constant during the period of electromechanical transient of interest.
2) Rotor speed changes are insignificant that had already been ignored in formulating the swing equations.
3) Effect of voltage regulating loop during the transient are ignored.

13. Define swing curve. What is the use of swing curve?

The swing curve is the plot or graph between the power angle δ, and time, t.

It is usually plotted for a transient state to study the nature of variation in δ for a sudden large disturbance. From the nature of variations of δ, the stability of a system for any disturbance can be determined.

14.Give the control schemes included in stability control techniques?

The control schemes included in the stability control techniques are:

a. Excitation systems

b.Turbine valve control

c.Single pole operation of circuit breakers

d.Faster fault clearing times

15.What are the systems design strategies aimed at lowering system reactance?

The system design strategies aimed at lowering system reactance are:

a. Minimum transformer reactance

b.Series capacitor compensation of lines

c.Additional transmission lines.

16.What are coherent machines? (APR/MAY 2004)

Machines which swing together are called coherent machines. When both ωs and δ are expressed in electrical degrees or radians, the swing equations for coherent machines can be combined together even though the rated speeds are different. This is used in stability studies involving many machines.

17.State equal area criterion. (NOV/DEC 2004)

In a two machine system under the usual assumptions of constant input , no damping and constant voltage being transient reactance , the angle between the machines either increases or else, after all disturbances have occurred oscillates with constant amplitude. There is a simple graphical method of determining whether the system comes to rest with respect to each other. This is known as equal area criterion

18.What are various faults that increase severity of equal area criterion?

The various faults that increases severity of equal area criterion are,

A Single line to ground fault

A Line to line fault

A Double line to ground fault

A Three phase fault

19.Give the expression for critical clearing time

The expression for the critical clearing time t_{cr} is given by

$t_{cr} =$

Where, H is the constant

δcr is the critical clearing angle

δo is the rotor angle

Pm is the mechanical power

ωs is the synchronous speed

20.List the types of disturbances that may occur in a single machine infinite bus bar system of the equal area criterion stability

The types of disturbances that may occur are,

Sudden change in mechanical input

Effect of clearing time on stability

Sudden loss of one of parallel lines

Sudden short circuit on one of parallel lines

i) Short circuit at one end of line

ii) Short circuit away from line ends

iii) Reclosure

21.Define critical clearing angle

The critical clearing angle δcc is the maximum allowable change in the power angle δ before clearing the fault , without loss of synchronism.

22. Define critical clearing time.

The critical clearing time , tcc can be defined as the maximum time delay that can be allowed to clear a fault without loss of synchronism . The time corresponding to the critical clearing angle is called critical clearing time tcc.

23. What are the assumptions that are made inorder to simplify the computational task in stability studies?

The assumptions are,

- The D.C offset currents and harmonic components are neglected. The currents and voltages are assumed to have fundamental component alone.
- The symmetrical components are used for the representation of unbalanced faults.
- It is assumed that the machine speed variations will not affect the generated voltage.

24.What is Multimachine stability?

If a system has any number of machines, then each machine is listed for stability by advancing the angular position, δ of its internal voltage and noting whether the electric power output of the machine increases (or) decreases. If it increases,

i.e if $\partial Pn / \partial \delta n > 0$

then machine n is stable. If every machine is stable, then the system having any number of machine is stable.

25. What is meant by an infinite bus?

The connection or disconnection of a single small machine on a large system would not affect the magnitude and phase of the voltage and frequency. Such a system of constant voltage and constant frequency regardless of the load is called infinite bus bar system or infinite bus.

26.List the assumptions made in multimachine stability studies.

The assumptions made are,

- The mechanical power input to each machine remains constant during the entire period of the swing curve computation
- Damping power is negligible
- Each machine may be represented by a constant transient reactance in series with a constant transient voltage.
- The mechanical rotor angle of each machine coincides with δ , the electrical phase angle of the transient internal voltage.

27. Explain the concept synchronous speed.

The mechanical torque Tm and the electrical torque Te are considered positive for synchronous generator. Tm is the resultant shaft torque which tends to accelerate the rotor in the positive θm direction of rotation . Under steady-state operation of the generator Tm and Te are equal and the accelerating torque Ta is zero. Hence there is no acceleration of deceleration of the rotor, masses and the resultant constant speed is the synchronous speed.

Possible 16 marks

1. Derive the swing equation for a single machine connected to infinite bus system. State the assumptions if any and state the usefulness of this equation. Neglect the damping.
   R4-Pg.No 246

2.Discuss the various factors affecting the transient stability of the system.
   R1-Pg.No 5.42

3. With the help of a neat flowchart, explain the modified Euler method of solving the swing equations.
   R1-Pg.No 5.69

4.State the bad effects of instability. Distinguish between steady state and transient stability.
   R1-Pg.No5.6

5.Write short notes on assumptions made in deducing equal area criterion.
   R1-Pg.No5.45, R2 - 346

6. State and explain equal area criterion. How do you apply equal area criterion to find the maximum additional load.
   R1-Pg.No5.47, R4-256

7. Describe the equal area criterion for transient stability analysis of a system.
   R1-Pg.No5.45 APR/MAY 2004

8. Mention the assumptions clearly and developing necessary equations, describe the step by step solution of swing bus.
   R1-Pg.No5.28 APR/MAY 2004

9. Derive the swing equation of a synchronous machine swinging against an infinite bus. Clearly state the assumptions in deducing the swing equation.
   R1-Pg.No5.8 NOV/DEC 2004

10. Derive the swing equation for a synchronous machine.
   R1-Pg.No5.8 APR/MAY 2005.

11. Explain critical clearing time and critical clearing angle, deriving the expressions.
   R1-Pg.No5.54, Pg.No5.60 APR/MAY 2006

12.Explain the solution of swing equation by Runge Kutta Method..
   R1-Pg.No5.63

Book:

R1. Power System Analysis – K.B. Hemalatha, S.T. JayaChrista.
R2 – Hadi saadat, “Power System Analysis”, Tata McGraw Hill
R3 – I J Nagarath , D P Kothari ’Modern Power system Analysis’, TMH Pub. Co. Ltd., 1994.
R4 – Nagoor Kani, “Power System Analysis”

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE3591- POWER ELECTRONICS

SEMESTER V

REGULATIONS 2021

NOTES

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QUESTION BANK

EE3591	POWER ELECTRONICS	L T P C
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COURSE OBJECTIVES:

- To understand the various applications of power electronic devices for conversion, control and conditioning of the electrical power and to get an overview of different types of power semiconductor devices and their dynamic characteristics.
- To understand the operation, characteristics and performance parameters of controlled rectifiers
- To study the operation, switching techniques and basic topologies of DC-DC switching regulators.
- To learn the different modulation techniques of pulse width modulated inverters and to understand harmonic reduction methods.
- To study the operation of AC voltage controller and various configurations of AC voltage controller.

UNIT I SWITCHING POWER SUPPLIES 9

MOSFET dynamic behavior - driver and snubber circuits - low power high switching frequency switching Power supplies, buck, boost, buck-boost converters – Isolated topologies – resonant converters - switching loss calculations and thermal design.

UNIT II INVERTERS 9

IGBT: Static and dynamic behavior - single phase half bridge and full bridge inverters - VSI :(1phase and three phase inverters square wave operation) - Voltage control of inverters single, multi pulse, sinusoidal, space vector modulation techniques- various harmonic elimination techniques-CSI

UNIT III UNCONTROLLED RECTIFIERS 9

Power Diode – half wave rectifier – mid-point secondary transformer based full wave rectifier – bridge rectifier – voltage doubler circuit – distortion factor – capacitor filter for low power rectifiers – LC filters – Concern for power quality – three phase diode bridge.

UNIT IV CONTROLLED RECTIFIERS 9

SCR-Two transistor analogy based turn- ON – turn ON losses – thermal protection – controlled converters (1 pulse, 2 pulse, 3 pulse, 6 pulse) - displacement factor – ripple and harmonic factor - power factor mitigation, performance parameters – effect of source inductance - inverter angle limit.

UNIT V AC PHASE CONTROLLERS 9

TRIAC triggering concept with positive and negative gate pulse triggering, TRIAC based phase controllers - various configurations for SCR based single and three phase controllers.

TOTAL: 45 PERIODS

COURSE OUTCOMES:

Upon the successful completion of the course, students will be able to:

CO1: Understand the operation of semiconductor devices and dynamic characteristics and to design &analyze the low power SMPS

CO2: Analyze the various uncontrolled rectifiers and design suitable filter circuits

CO3: Analyze the operation of the n-pulse converters and evaluate the performance parameters

CO4: Understand various PWM techniques and apply voltage control and harmonic elimination methods to inverter circuits.

CO5: Understand the operation of AC voltage controllers and its applications.

TEXT BOOKS:

1. Ned Mohan, T.M.Undeland, W.P.Robbins, ”Power Electronics: Converters, applications anddesign”, John Wiley and Sons, 3rd Edition (reprint), 2009
2. Rashid M.H., Power Electronics Circuits, Devices and Applications, Prentice Hall India,
3. 3rdEdition, New Delhi, 2004.

REFERENCES:

1. Cyril. W.Lander, Power Electronics, McGraw Hill International, Third Edition, 1993.
2. P.S.Bimbhra, Power Electronics, Khanna Publishers, Third Edition 2003
3. Philip T.Krein, Elements of Power Electronics, Oxford University Press, 2013.
4. P.C.Sen, Power Electronics, Tata McGraw-Hill, 30th reprint, 2008.

UNIT 1
SWITCHING POWER SUPPLIES

DC chopper which converts fixed DC to variable DCis a power electronic circuit which is DC equivalent of transformer. Using chopper the input can be stepped up and stepped down as per the requirement of application.

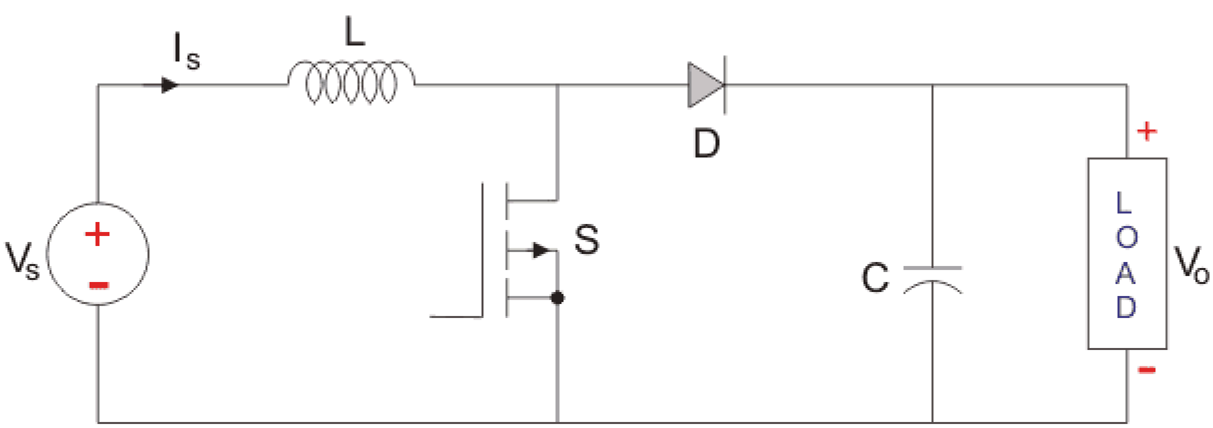
Applications of DC Chopper

DC chopper can be used for following applications like

(i) Electric locomotives (ii) Battery operated cars. (iii) Power supplies etc.,.

principle of operation of step up converter:

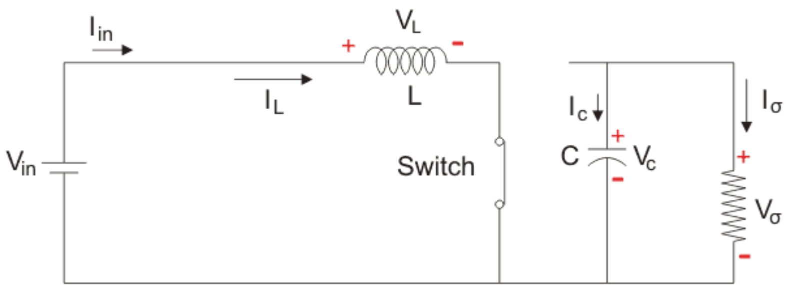
DC-DC converters are also known as Choppers. Here we will have a look at the **Step Up Chopper or Boost converter** which increases the input DC voltage to a specified DC output voltage.



The input voltage source is connected to an inductor. The solid-state device which operates as a switch is connected across the source. The second switch used is a diode. The diode is connected to a capacitor, and the load and the two are connected in parallel as shown in the figure above.

The inductor connected to input source leads to a constant input current, and thus the Boost converter is seen as the constant current input source. And the load can be seen as a constant voltage source. The controlled switch is turned on and off by using Pulse Width Modulation(PWM). PWM can be time-based or frequency based. Frequency-based modulation has disadvantages like a wide range of frequencies to achieve the desired

control of the switch which in turn will give the desired output voltage. Time-based Modulation is mostly used for DC-DC converters. It is simple to construct and use. The frequency remains constant in this type of PWM modulation. The **Boost converter** has two modes of operation. The first mode is when the switch is on and conducting.
Mode I : Switch is ON, Diode is OFF



The Switch is ON and therefore represents a short circuit ideally offering zero resistance to the flow of current so when the switch is ON all the current will flow through the switch and back to the DC input source. Let us say the switch is on for a time TON and is

off for a time TOFF. We define the time period, T, as and the switching frequency,

$$f_{switching} = \frac{1}{T}$$

and the duty cycle, $D = \frac{T_{ON}}{T}$

Let us analyze the Boost converter in steady state operation for this mode using KVL.

$$\therefore V_{in} = V_L$$

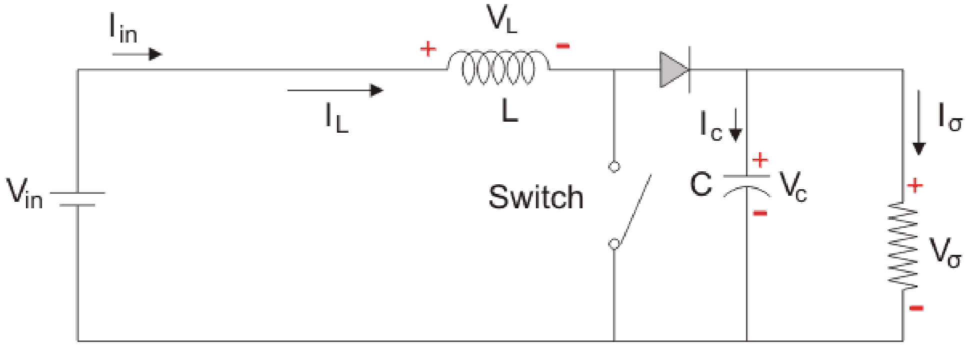
$$\therefore V_L = L\frac{di_L}{dt} = V_{in}$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{DT} = \frac{V_{in}}{L}$$

Since the switch is closed for a time TON = DT we can say that Δt = DT.

$$(\Delta i_L)_{closed} = \left(\frac{V_{in}}{L}\right) DT$$

Mode II : Switch is OFF, Diode is ON



In this mode, the polarity of the inductor is reversed. The energy stored in the inductor is released and is ultimately dissipated in the load resistance, and this helps to maintain the flow of current in the same direction through the load and also step-up the output voltage as the inductor is now also acting as a source in conjunction with the input source. But for analysis, we keep the original conventions to analyze the circuit using KVL.

Let us now analyse the **Boost converter** in steady state operation for Mode II using KVL.

$$\therefore V_{in} = V_L + V_o$$

$$\therefore V_L = L\frac{di_L}{dt} = V_{in} - V_o$$

$$\frac{di_L}{dt} = \frac{\Delta i_L}{\Delta t} = \frac{\Delta i_L}{(1-D)T} = \frac{V_{in} - V_o}{L}$$

Since the switch is open for a time $T_{OFF} = T - T_{ON} = T - DT = (1-D)T$ we can say that $\Delta t = (1-D)T$

It is already established that the net change of the inductor current over any one complete cycle is zero.

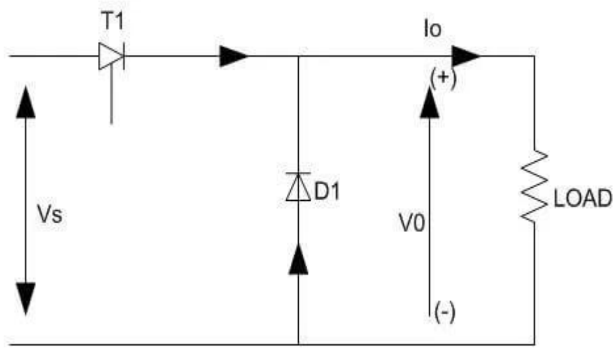
$$\therefore (\Delta i_L)_{closed} + (\Delta i_L)_{open} = 0$$

$$\left(\frac{V_{in} - V_o}{L}\right)(1-D)T + \left(\frac{-V_o}{L}\right)DT = 0$$

$$\frac{V_o}{V_{in}} = \frac{1}{1-D}$$

Control strategies applied to dc chopper:

A basic dc chopper circuit is shown in the below figure.



Here the SCR (T1) acts alike a static switch. The SCR can be turned ON and turned OFF with the help of triggering and commutating circuits respectively. If TON and TOFF are the ON time and OFF time respectively for the chopper, then the chopper duty cycle is given by

$$DutyCycle = \frac{T_{ON}}{T}$$

where T = TON + TOFF

The load voltage of the chopper is given by

$$V_L = V_{DC} \cdot \left(\frac{T_{ON}}{T}\right)$$

From the above equation it is clear that the load voltage depends on two factors

The supply voltage (Vs)

The duty cycle of the chopper (D)

Since the supply voltage is constant, the load voltage is governed by the duty cycle of the chopper.

In other words the load voltage is dependent on two factors TON and TOFF. So the average load voltage can be controlled by varying the values of the TON and TOFF in the following two ways.

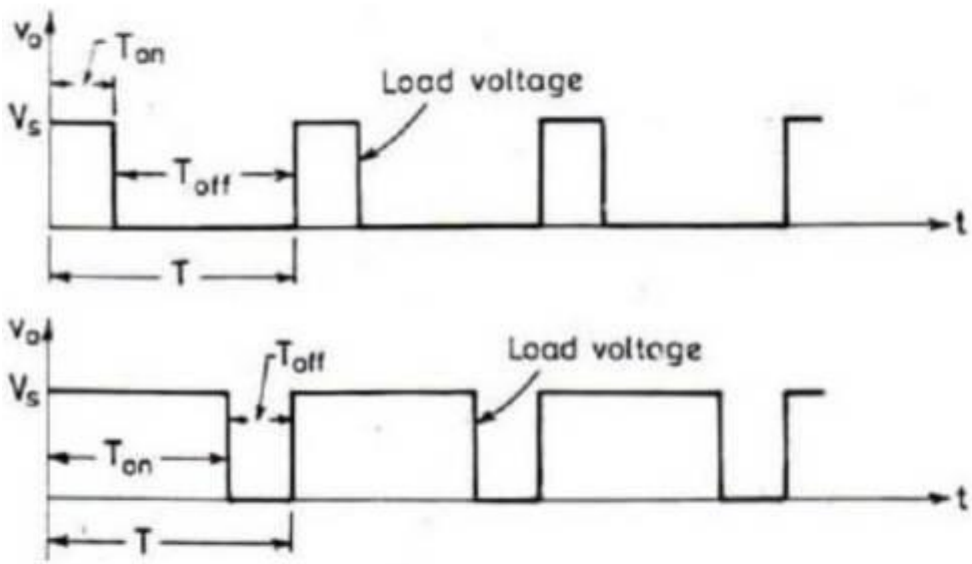
- Varying TON and keeping the time period (T) constant. This is called as constant frequency system
- Either keeping TON constant and varying TOFF or keeping TOFF constant and varying TON. This is called as variable frequency system.

The summary is

In chopper circuits,The average value of the output voltage VO can be controlled by opening and closing the semiconductor switch periodically.
The various control strategies for varying duty cycle are as follows:

- Constant Frequency System (Pulse Width Modulation)
- Variable Frequency System (Frequency Modulation)

Constant Frequency System:



It is also referred as Time-ratio control (TRC)

In this scheme, the on-time TON is varied but the chopping period T is kept constant

Variation of TON means adjustment of pulse width. So this method is also known as pulse-width modulation scheme.

Disadvantages of Constant Frequency Technique:

The limitations of pulse width modulation scheme is given below:

- In this technique, TON cannot be reduced to near zero for most of the commutation circuits used in choppers.
- As such, low range of a control is not possible in PWM. This can be achieved by increasing the chopping period (or decreasing the chopping frequency) of the chopper.
- Variable Frequency System:

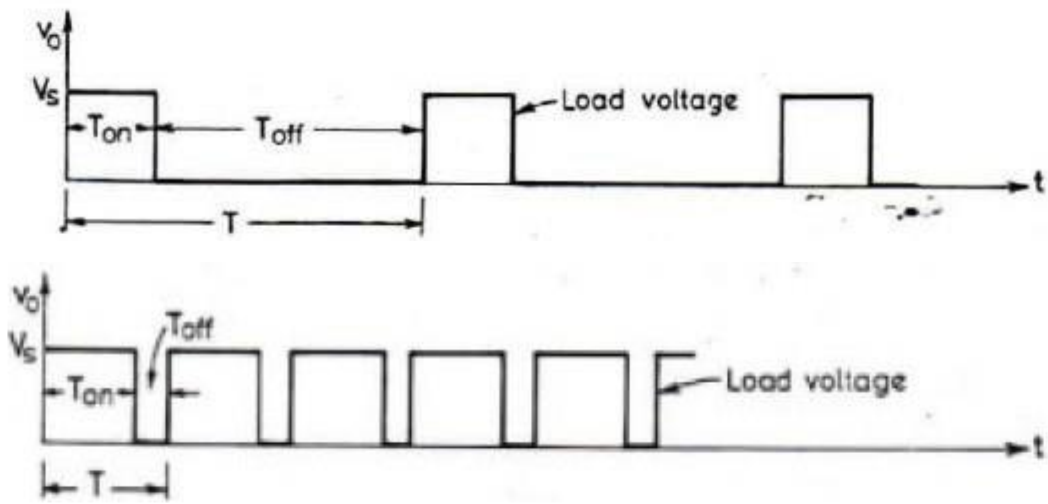
- In this scheme, the chopping period T is varied and either

  (i) On-time TON is kept constant

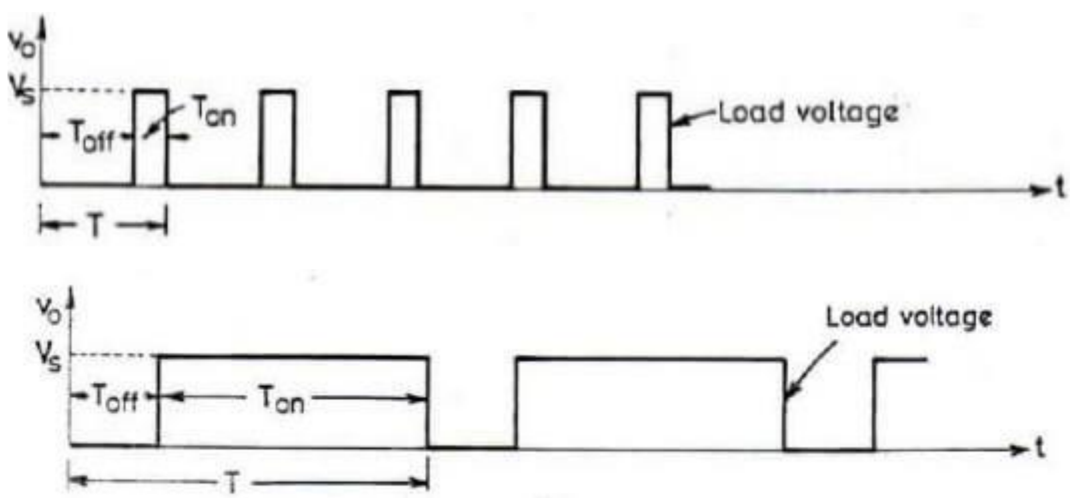
  (ii) Off-time TOFF is kept constant.

  This method of controlling duty cycle is also called as frequency-modulation scheme.

Case-1: Ton is kept constant but T is varied. Ton = 1/4 T so that Duty cycle = 0.25. In the next figure Ton = 3/4 T so that Duty cycle = = 0.75



Case-2: Toff is kept constant and Ton is varied. Ton = 1/4 T so that Duty cycle = 0.25 and in the lower diagram Ton = 3/4 T.so that Duty cycle = 0.75.

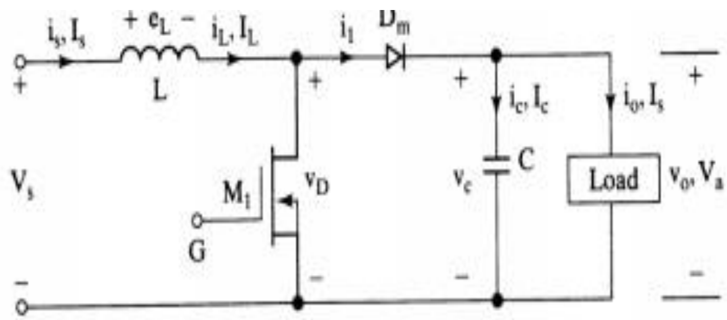


Disadvantages of Variable Frequency Technique:

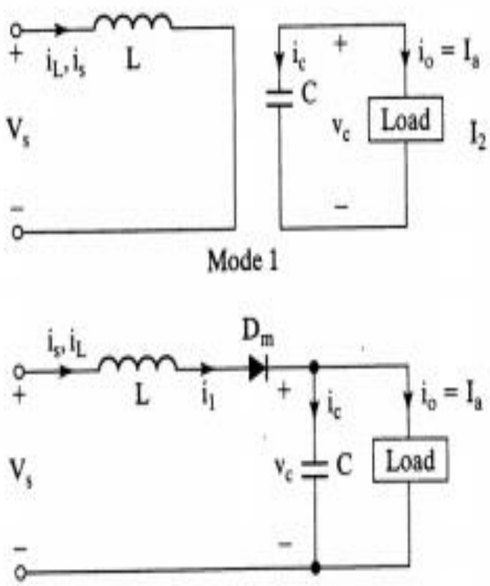
The frequency modulation method has some disadvantages as compared to pulse-width modulation scheme.They are

- The chopping frequency has to be varied over a wide range for the control of output voltage in frequency modulation.
- Filter design for such wide frequency variation is quite difficult.
- For the control of a, frequency variation would be wide. As such, there is possibility of interference with signalling and telephone lines in this scheme.
- The large off-time in frequency modulation scheme may make the load current discontinuous which is undesirable.

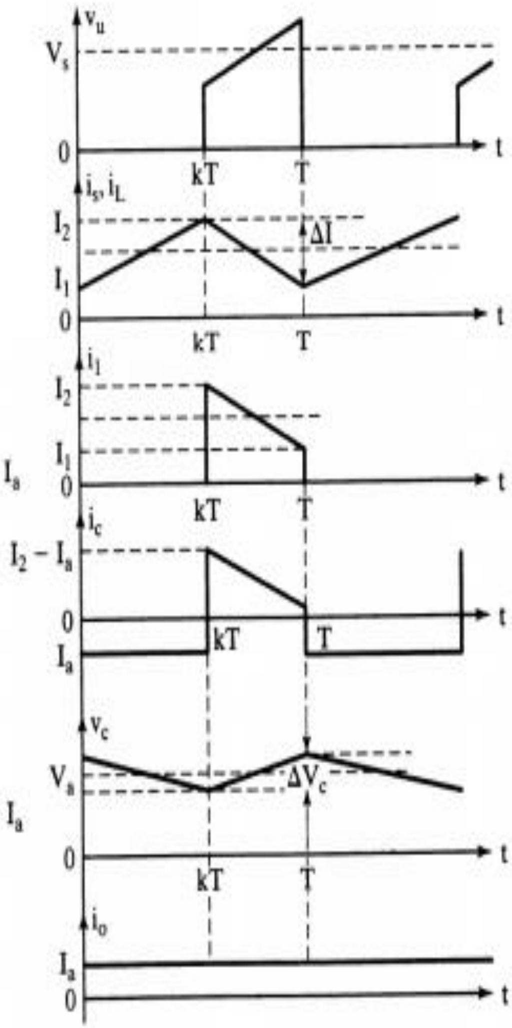
Boost Converter



(a) Circuit diagram

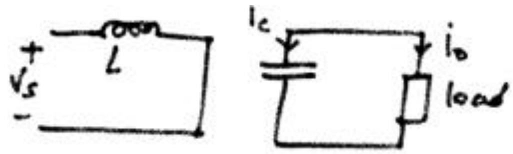


(b) Equivalent circuits



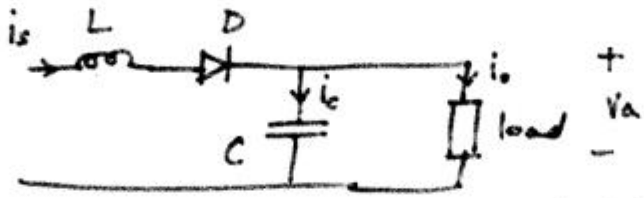
(c) Waveforms

Mode 1



- Mosfet M1 is switched on at $t = 0$
- Input current flows through M1, L
- Inductor current rises

Mode 2.



- Current flows through L, D and C ; L, D and load.
- Inductor current falls
- Energy stored in L is transferred to load

For **Mode 1** if switch M is closed for period t_1

$$V_s = \frac{L(I_2 - I_1)}{t_1} = \frac{L\Delta I}{t_1}$$

$$t_1 = \frac{L\Delta I}{V_s} \quad ; \Delta I = I_2 - I_1$$

For **Mode 2**

$$V_s - V_a = \frac{-L\Delta I}{t_2}$$

; $\Delta I = I_2 - I_1$ = Inductor Ripple current

$$t_2 = \frac{-L\Delta I}{V_s - V_a} = \frac{L\Delta I}{V_a - V_s}$$

$$\Delta I = \frac{V_s t_1}{L} = \frac{(V_a - V_s)\, t_2}{L}$$

$$t_1 = k.T$$

$$t_2 = (1-k)\,T$$

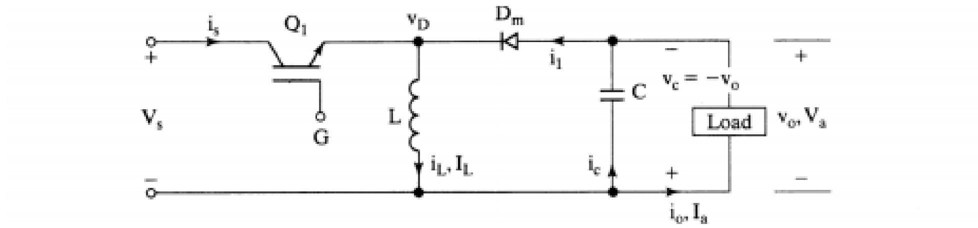
$$V_s t_1 = (V_a - V_s)\, t_2$$

$$V_s(t_1 + t_2) = V_a t_2$$

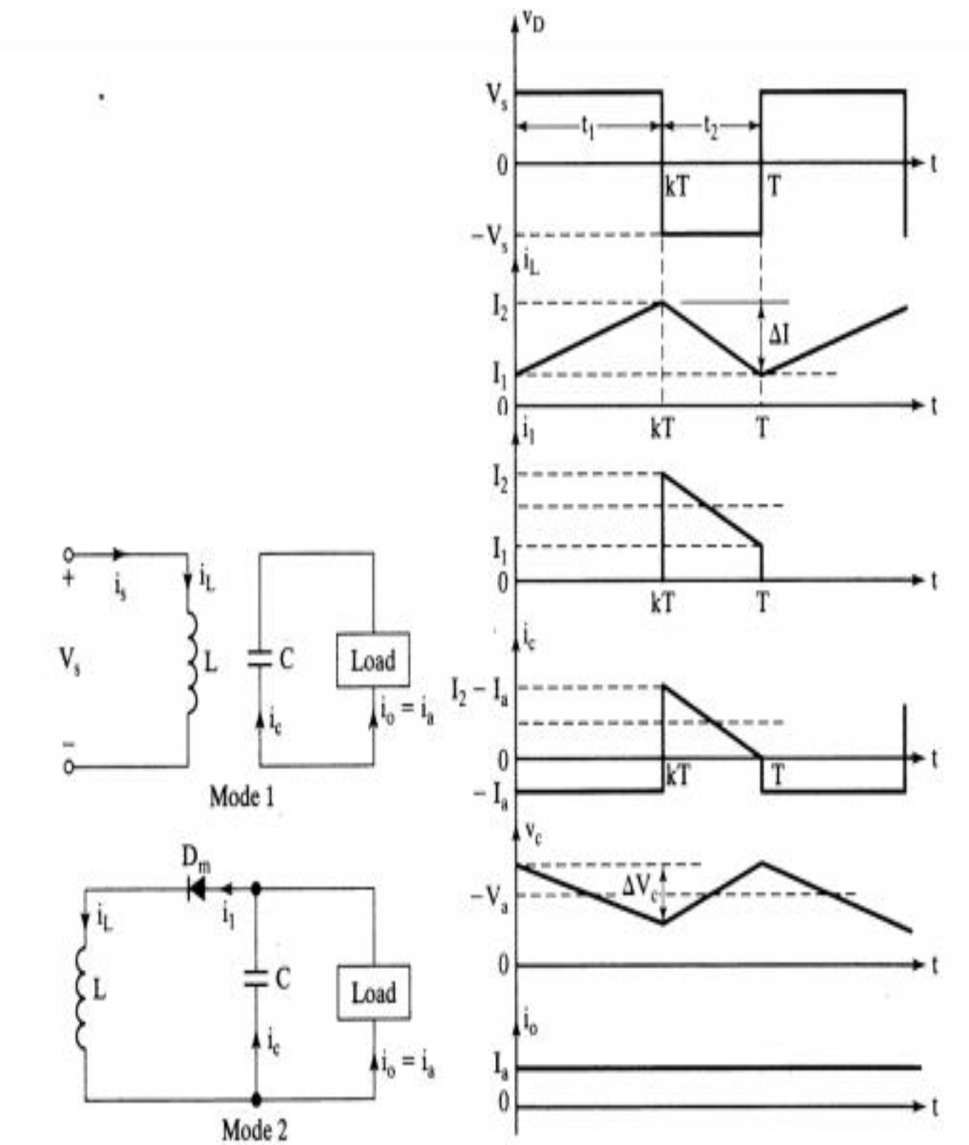
$$V_a = \frac{V_s (t_1 + t_2)}{t_2} = \frac{V_s}{1-k}$$

\

Buck-Boost Converter



(a) Circuit diagram



(b) Equivalent circuits

(c) Waveforms

Mode 1 : Q_1 is on

D is reverse biased

Input current flows through L, Q_1

Inductor current rises

Mode 2 : Q_1 is turned off

Current flowing through inductor flows through L, C, D and load.

Energy stored in inductor is transferred to the load

Inductor current falls

For Mode 1 : $V_s = L \cdot \frac{I_2 - I_1}{t_1} = \frac{L \Delta I}{t_1}$; $t_1 = \frac{L \Delta I}{V_s}$

For Mode 2 : Inductor current falls from I_2 to I_1 in time t_2

Output voltage $V_a = -\frac{L \Delta I}{t_2}$; $t_2 = -\frac{L \Delta I}{V_a}$

$\Delta I = I_2 - I_1$

$$\Delta I = \frac{V_s t_1}{L} = \frac{-V_a t_2}{L}$$

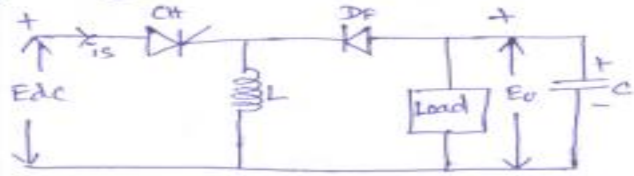
$t_1 = KT$; $t_2 = (1-K)T$

$$V_a = \frac{-V_s t_1}{t_2} = \frac{-V_s KT}{(1-K)T} = \frac{-V_s K}{1-K}$$

Operation ac chopper

Step up/down Chopper:-

→ Chopper can also be used both in step up & step down modes by varying duty cycle α.



→ When the chopper is ON, diode D_F is off, the supply flows through the path E_{dc+} — CH — L — E_{dc-}.

→ Inductor L stores energy

→ When chopper is off, the polarity of emf induced in L is reversed as inductor current tends to decrease so Inductor discharges, the path is L_+ — Load — D — L_-

→ During T_{on}, the energy stored in the inductor is

$$W_i = E_{dc} I_s T_{on}$$

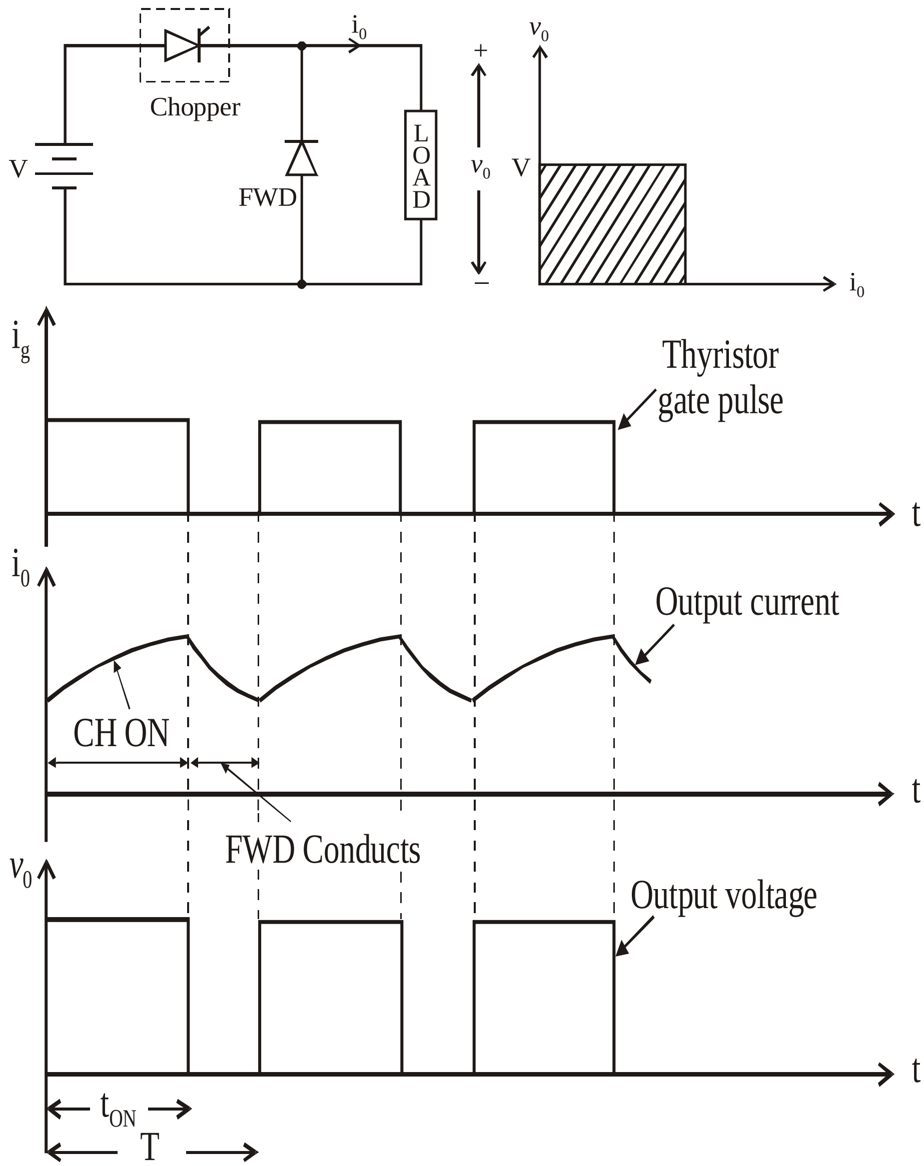
→ During T_{off}, the energy fed to the load is

$$W_o = E_o I_s T_{off}$$

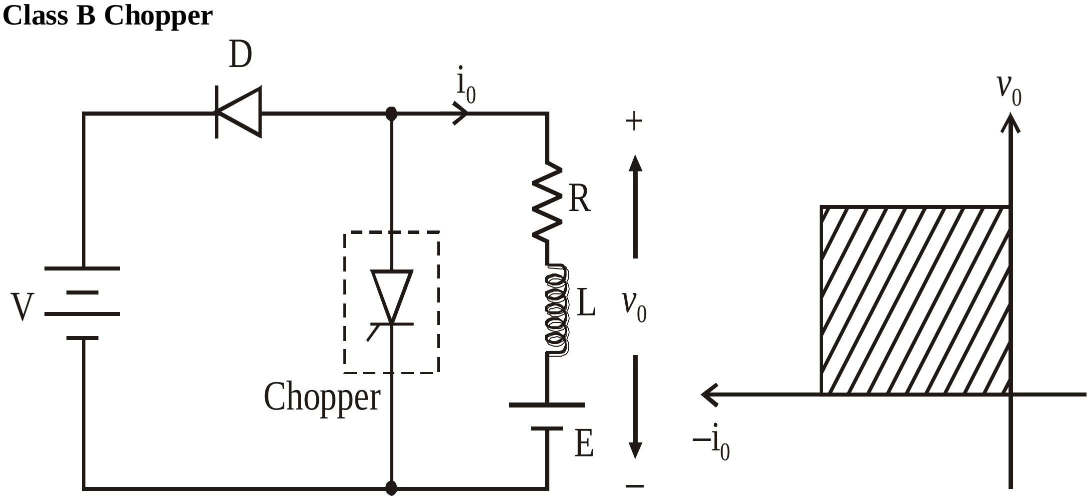
CLASSIFICATION OF CHOPPERS

Class A chopper

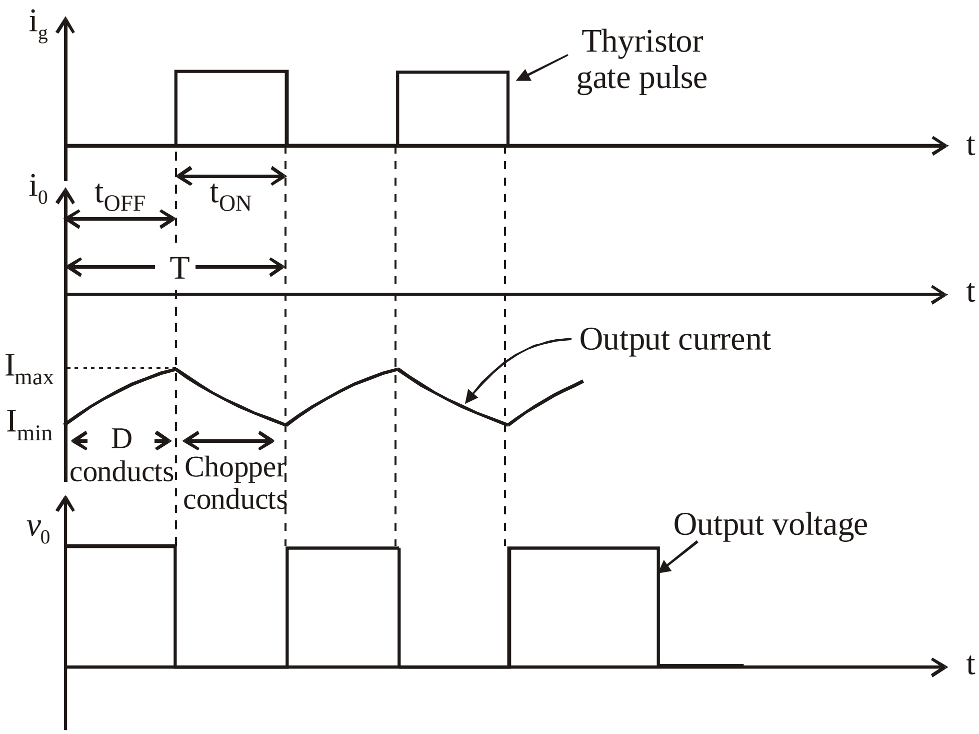
- When chopper is *ON*, supply voltage *V* is connected across the load.
- When chopper is OFF, $v_O = 0$ and the load current continues to flow in the same direction through the FWD.
- The average values of output voltage and current are always positive.
- *Class A Chopper* is a first quadrant chopper .
- *Class A Chopper* is a step-down chopper in which power always flows form source to load.
- It is used to control the speed of dc motor.
- The output current equations obtained in step down chopper with *R-L* load can be used to study the performance of *Class A Chopper.*



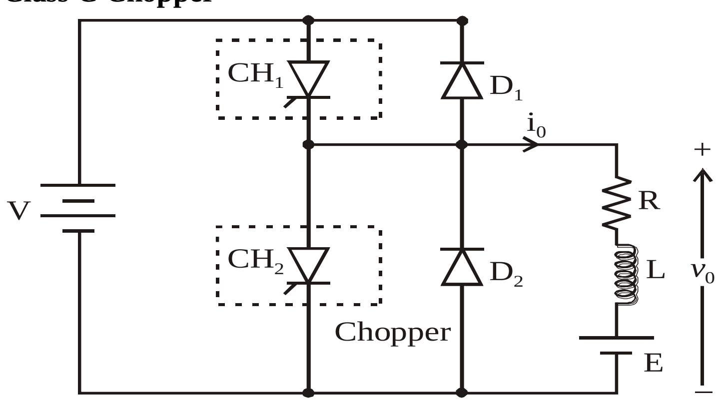
Class B Chopper

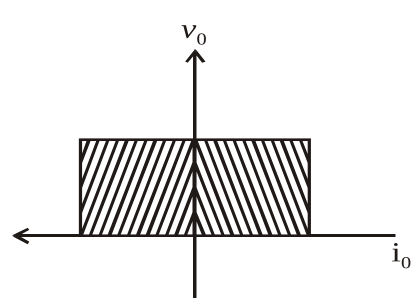


- When chopper is ON, *E* drives a current through *L* and R in a direction opposite to that shown in figure.
- During the ON period of the chopper, the inductance *L* stores energy.
- When Chopper is OFF, diode *D* conducts, and part of the energy stored in inductor *L* is returned to the supply.
- Average output voltage is positive.
- Average output current is negative.
- Therefore C*lass B Chopper* operates in second quadrant.
- In this chopper, power flows from load to source.
- *Class B Chopper* is used for regenerative braking of dc motor.
- *Class B Chopper* is a step-up chopper.



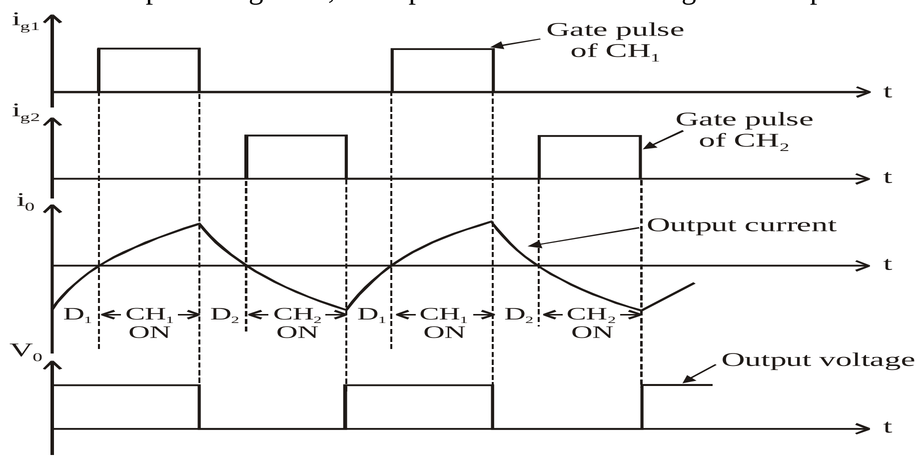
Class C Chopper



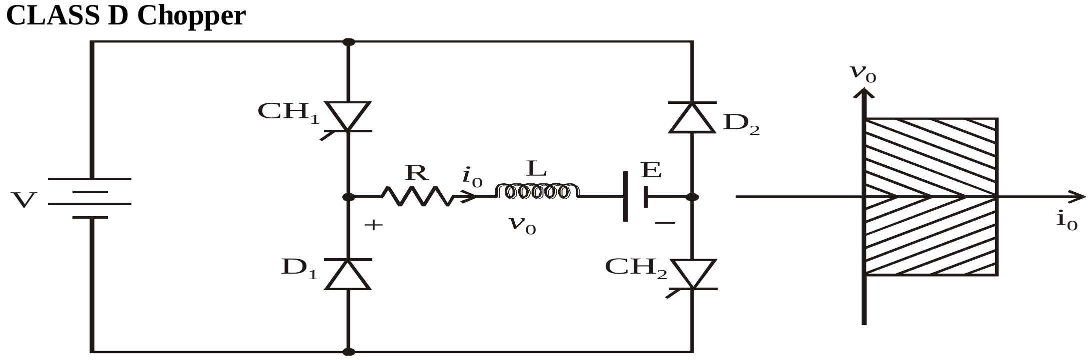


- *Class C Chopper* is a combination of *Class A* and *Class B Choppers*.
- For first quadrant operation, CH_1 is ON or D_2 conducts.

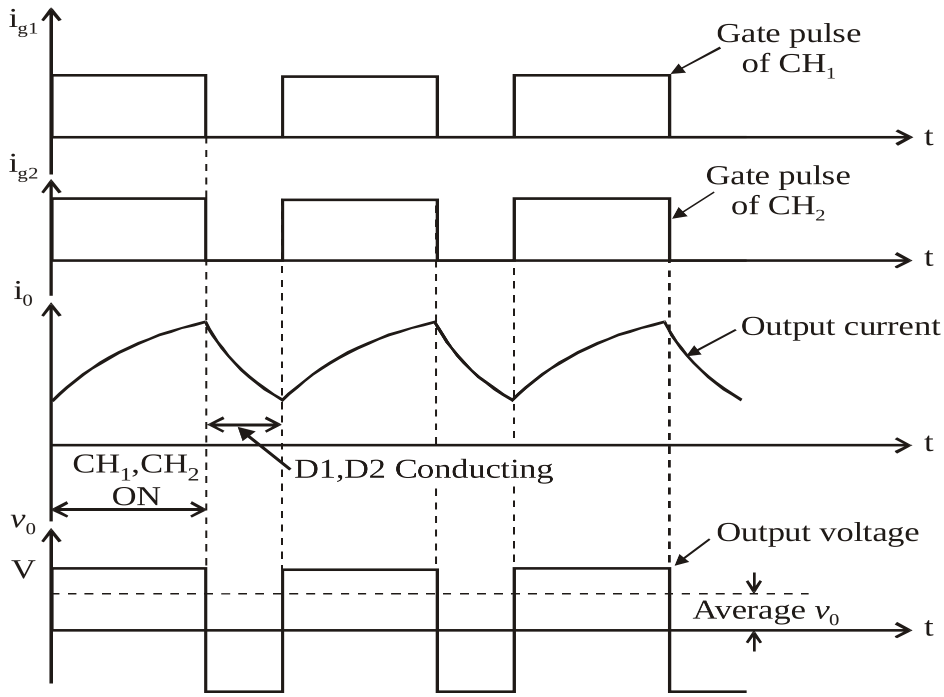
- For second quadrant operation, CH_2 is ON or D_1 conducts.
- When CH_1 is ON, the load current is positive.
- The output voltage is equal to *'V'* & the load receives power from the source.
- When CH_1 is turned OFF, energy stored in inductance *L* forces current to flow through the diode D_2 and the output voltage is zero.
- Current continues to flow in positive direction.
- When CH_2 is triggered, the voltage *E* forces current to flow in opposite direction through L and CH_2 .
- The output voltage is zero.
- On turning OFF CH_2 , the energy stored in the inductance drives current through diode D_1 and the supply
- Output voltage is *V*, the input current becomes negative and power flows from load to source.

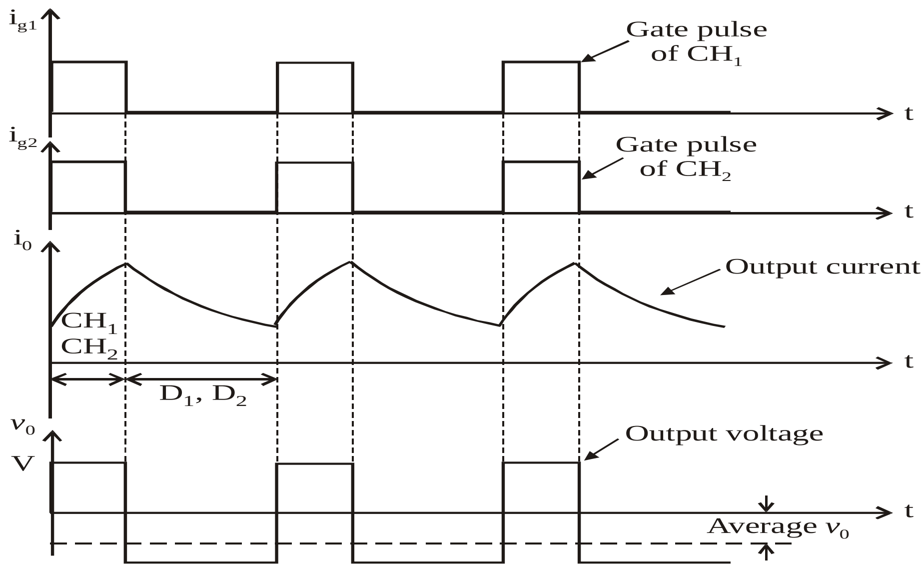


CLASS D Chopper

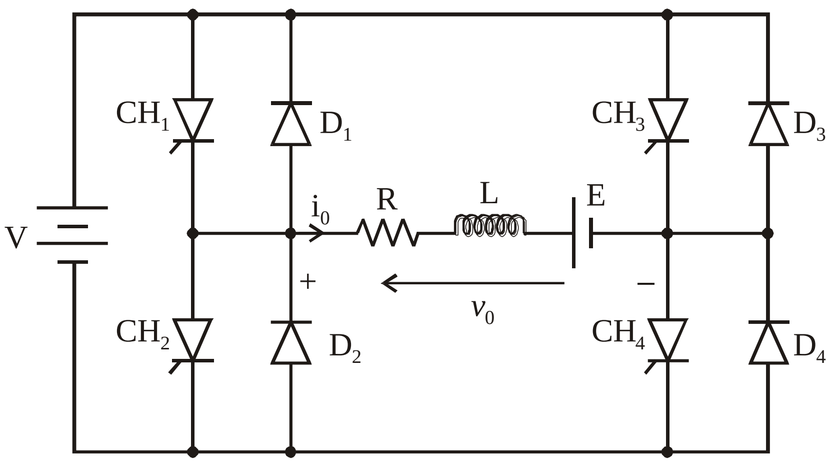


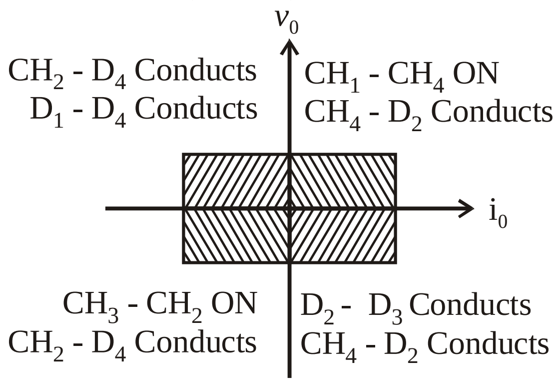
- Class D is a two quadrant chopper.
- When both CH_1 and CH_2 are triggered simultaneously, the output voltage $v_O = V$ and output current flows through the load.
- When CH_1 and CH_2 are turned OFF, the load current continues to flow in the same direction through load, D_1 and D_2 , due to the energy stored in the inductor L.
- Output voltage $v_O = - V$.
- Average load voltage is positive if chopper ON time is more than the OFF time
- Average output voltage becomes negative if $t_{ON} < t_{OFF}$.
- Hence the direction of load current is always positive but load voltage can be positive or negative.





CLASS E CHOPPER





- Class E is a four quadrant chopper
- When CH_1 and CH_4 are triggered, output current i_O flows in positive direction through CH_1 and CH_4, and with output voltage $v_O = V$.
- This gives the first quadrant operation.
- When both CH_1 and CH_4 are OFF, the energy stored in the inductor L drives i_O through D_2 and D_3 in the same direction, but output voltage $v_O = -V$.
- Therefore the chopper operates in the fourth quadrant.
- When CH_2 and CH_3 are triggered, the load current i_O flows in opposite direction & output voltage $v_O = -V$.

Since both i_O and v_O are negative, the chopper operates in third quadrant.

Resonant switching:

A **resonant converter** is a type of electric power converter that contains a network of inductors and capacitors called a "resonant tank", tuned to resonate at a specific frequency. They find applications in electronics, in integrated circuits.

There are multiple types of resonant converter:

- Series resonant inverter

- Parallel resonant inverter
- Class E Resonant Converter
- Class E Resonant Rectifier
- Zero Voltage Switching Resonant Converter
- Zero Current Switching Resonant Converter
- Two Quadrant ZVS Resonant Converter
- Resonant dc-link inverter

Resonant power converters contain resonant L-C networks whose voltage and current waveforms vary sinusoidally during one or more subintervals of each switching period. These sinusoidal variations are large in magnitude, and the small ripple approximation does not apply

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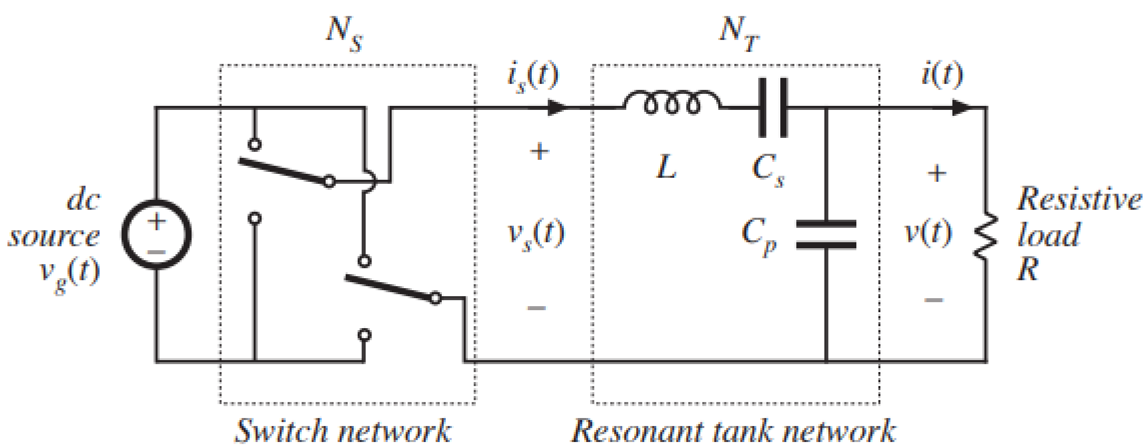
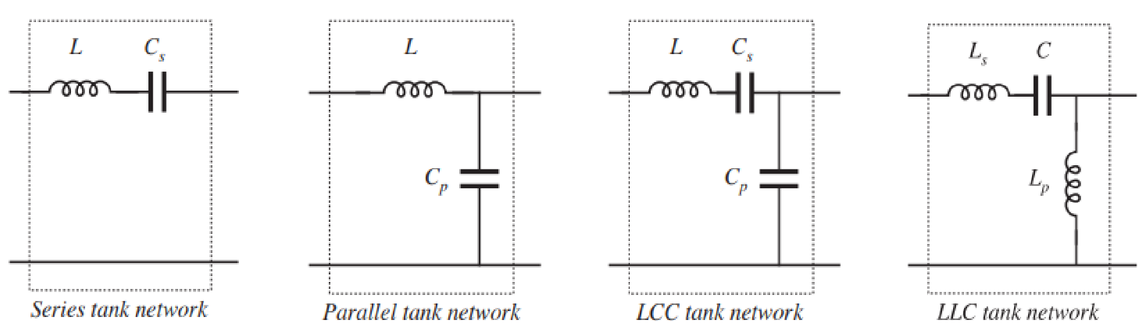


Several resonant tank networks



In PWM converters, the switching of semiconductor devices normally occurs at high current levels. Therefore, when switching at high frequencies these converters are associated with high power dissipation in their switching devices. • Furthermore, the PWM converters suffer from EMI caused by high frequency harmonic components associated with their quasi-square switching current and/or voltage waveforms. • In the resonant techniques, the switching losses in the semiconductor devices are avoided due to the fact that current through or voltage across the switching device at the switching point is equal to or near zero. • Compared to the PWM converters, the resonant converters show a promise of achieving the design of small size and weight converters. • Another advantage of resonant converters over PWM converters is the decrease of the harmonic content in the converter voltage and current waveforms.

Classification of soft-Switching Resonant Converters

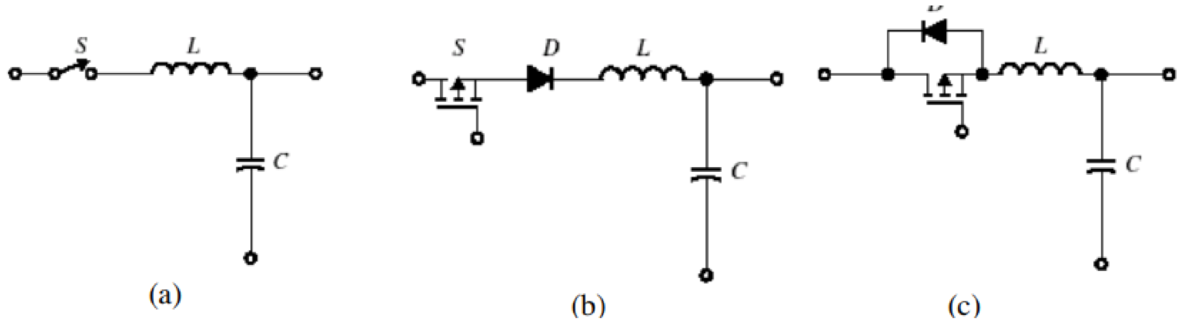
• Quasi-resonant converters (single-ended) – Zero-current switching (ZCS) – Zero-voltage switching (ZVS)

• Full-resonance converters (conventional) – Series resonant converter (SRC) – Parallel resonant converter (PRC)

• Quasi-squarewave (QSW) converters – Zero-current switching (ZCS) – Zero-voltage switching (ZVS)

• Zero Transition Topologies – Zero-voltage transition (ZVT) – Zero- current transition (ZCT)

Zero-Current Switching Topologies The Resonant Switch • Depending on the inductor-capacitor arrangements, there are two possible types of resonant switch arrangements • The switch is either an L-type or an M-type and can be implemented as a halfwave or a full-wave, i.e. unidirectional or bi-directional • LC tank forms the resonant tank that causes ZCS to occur.



Resonant switch. (a) L-type switch. (b) Half-wave implementation. (c) Full-wave implementation.

ZCS and ZVS resonant converter:

ZCS can eliminate the switching losses at turnoff and reduce the switching losses at turn-on. As a relatively large capacitor is connected across the output diode during resonance, the converter operation becomes insensitive to the diode's junction capacitance. When power MOSFETs are zero-current switched on, the energy stored in the device's capacitance will be dissipated. This capacitive turn-on loss is proportional to the switching frequency. During turn-on, considerable rate of change of voltage can be coupled to the gate drive circuit through the Miller capacitor, thus increasing switching loss and noise. Another limitation is that the switches are under high current stress, resulting in higher conduction loss. However, it should be noted that ZCS is particularly effective in reducing switching loss for power devices (such as IGBT) with large tail current in the turn-off process.

ZVS eliminates the capacitive turn-on loss. It is suitable for high-frequency operation. For single-ended configuration, the switches could suffer from excessive voltage stress, which is proportional to the load. It will be shown in Section 12.5 that the maximum voltage across switches in half-bridge and full-bridge configurations is clamped to the input voltage.

For both ZCS and ZVS, the output regulation of the resonant converters can be achieved by variable frequency control. ZCS operates with constant on-time control, while ZVS operates with constant off-time control. With a wide input and load range, both techniques have to operate with a wide switching frequency range, making it not easy to design resonant converters optimally.

Application:

Battery operated vehicle:

A battery electric vehicle (BEV), pure electric vehicle, only-electric vehicle or all-electric vehicle is a type of electric vehicle (EV) that uses chemical energy stored in rechargeable battery packs. BEVs use electric motors and motor controllers instead of internal combustion engines (ICEs) for propulsion. They derive all power from battery packs and thus have no internal combustion engine, fuel cell, or fuel tank. BEVs include - but are not limited to - motorcycles, bicycles, scooters, skateboards, rail cars, watercraft, forklifts, buses, trucks, and cars.

A battery-powered electric car is an automobile which is propelled by electric motors.

Although electric cars often give good acceleration and have generally acceptable top speed, the lower specific energy of production batteries available in 2015 compared with carbon-based fuels means that electric cars need batteries that are fairly large fraction of the vehicle mass but still often give relatively low range between charges. Recharging can also take significant lengths of time. For journeys within a single battery charge, rather than long journeys, electric cars are practical forms of transportation and can be recharged overnight.

Electric cars can significantly reduce city pollution by having zero tail pipe emissions. Vehicle greenhouse gas savings depend on how the electricity is generated. With the current US energy mix, using an electric car would result in a 30 percent reduction in carbon dioxide emissions. Given the current energy mixes in other countries (that are transiting to more renewables), it has been predicted that such emissions would decrease by 40 percent in the UK, 19 percent in China, and as little as 1 percent in Germany.

Electric cars are having a major impact in the auto industry given advantages in city pollution, less dependence on oil and combustion, and scarcity and expected rise in gasoline prices. World governments are pledging billions to fund development of electric vehicles and their components. The US has pledged US$2.4 billion in federal grants for electric cars and batteries. China has announced it will provide US$15 billion to initiate an electric car industry.

In 2015, it was the first time BYD also ranked first in accumulated global sales throughout an entire year – with a total of over 43,073 NEVs sold (a >220% surge compared to last year), exceeding all American, Japanese and European leaders to date.

Cumulative global sales of highway-capable battery electric cars and vans passed the 1 million unit milestone in September 2016. The Renault-Nissan Alliance is the leading all-electric vehicle manufacturer. The Alliance achieved the sales milestone of 350,000 all-electric vehicles delivered globally in August 2016. Ranking second is Tesla Motors with over 139,000 electric cars sold between 2008 and June 2016.

As of December 2016, the world's top selling highway capable all-electric car in history is the Nissan Leaf, released in December 2010, with global sales of more than 250,000 units, followed by the Tesla Model S with more than 158,000 units delivered worldwide. Ranking next are the BMW i with about 65,500 units, and the Renault Zoe with 61,205 units, both through December 2016.[6] Until June 2016 the Mitsubishi i-MiEV family ranked fifth with about 37,600 units delivered globally. The Renault Kangoo

Z.E. utility van is the leader of the light-duty all-electric segment with global sales of 25,205 units through December 2016.

Formula E is a fully electric international single seater championship. The series was conceived in 2012, and the inaugural championship started in Beijing on 13 September 2014. The series is sanctioned by the FIA. Alejandro Agag is the current CEO of Formula E.

The Formula E championship is currently contested by ten teams with two drivers each (after the withdrawal of Team Trulli, there are temporarily only nine teams competing). Racing generally takes place on temporary city-center street circuits which are approximately 2 to 3.4 km (1.2 to 2.1 mi) long. Currently, only the Mexico City ePrix takes place on a road course, a modified version of the Autódromo Hermanos Rodríguez.

Environmental benefits of the use of electric vehicles

Electric vehicles produce no GHG emissions, at the tailpipe. So they are considered 'green' because they have no emissions in the place where they are used. However, battery electric vehicles can be considered Zero emission engines only locally, because they generally produce GHG in the power plants where electricity is generated. The two factors driving these GHG emissions of Battery Electric Vehicles are:

- the Carbon intensity of the electricity used to recharge the Electric Vehicle (commonly expressed in grams of CO2 per kWh)
- the consumption of the specific vehicle (in kilometers/kWh)

The Carbon Intensity of electricity can largely vary, depending on the electricity mix of the geographic region where electricity is consumed (a Country with high shares of renewables in his electricity mix will have a low C.I.). In the European Union, in 2013, the Carbon Intensity had a strong geographic variability, but in almost all the Member States Electric vehicles were "greener" than conventional ones. On average, Electric car saved 50%-60% of CO2 emissions compared to diesel and gasoline fuelled engines. Moreover, the de-carbonisation process is constantly reducing the GHG emissions due to the use of Electric Vehicles. In the European Union, on average, between 2009 and 2013 there was a reduction of the electricity Carbon Intensity of 17%. In a Life-cycle assessment perspective, considering the GHG necessary to build the battery and its end-of-life, the GHG savings are 10-13% lower.

Motor controllers

The motor controller receives a signal from potentiometers linked to the accelerator pedal, and it uses this signal to determine how much electric power is needed. This DC power is supplied by the battery pack, and the controller regulates the power to the motor, supplying either variable pulse width DC or variable frequency variable amplitude AC, depending on the motor type. The controller also handles regenerative braking, whereby electrical power is gathered as the vehicle slows down and this power recharges the battery.[72] In addition to power and motor management, the controller performs various safety checks such as anomaly detection, functional safety tests and failure diagnostics.

Battery Pack

Most electric vehicles today use an electric battery, consisting of electrochemical cells with external connections in order to provide power to the vehicle. Battery technology for EVs has developed from early lead-acid batteries used in the late 19th Century to the 2010s, to lithium-ion batteries which are found in most EVs today. The overall battery is referred to as a battery pack, which is a group of multiple battery modules and cells. The battery pack powering modern EVs can have as little as 96 battery cells to as many as 2,976 cells.

Motors

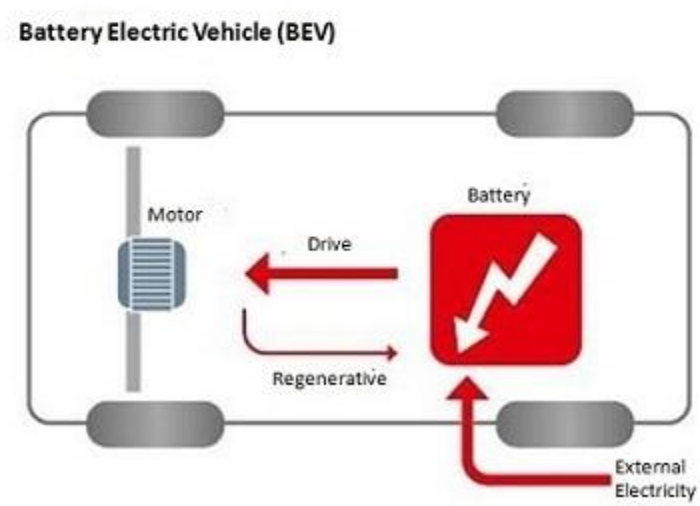
Electric cars have traditionally used series wound DC motors, a form of brushed DC electric motor. Separately excited and permanent magnet are just two of the types of DC motors available. More recent electric vehicles have made use of a variety of AC motor types, as these are simpler to build and have no brushes that can wear out. These are usually induction motors or brushless AC electric motors which use permanent magnets. There are several variations of the permanent magnet motor which offer simpler drive schemes and/or lower cost including the brushless DC electric motor.

Once electric power is supplied to the motor (from the controller), the magnetic field interaction inside the motor will turn the drive shaft and ultimately the vehicle's wheels.

Principle of operation of battery operated vehicles:

A Battery Electric Vehicle (BEV), also called All-Electric Vehicle (AEV), runs entirely on a battery and electric drive train. This type of electric cars does not have an ICE. Electricity is stored in a large battery pack that is charged by plugging into the electricity grid. The battery pack, in turn, provides power to one or more electric motors to run the electric car.

Architecture and Main Components of



Components of BEV

- Electric motor
- Inverter
- Battery
- Control Module
- Drive train

Working Principles of BEV

- Power is converted from the DC battery to AC for the electric motor
- The accelerator pedal sends a signal to the controller which adjusts the vehicle's speed by changing the frequency of the AC power from the inverter to the motor
- The motor connects and turns the wheels through a cog
- When the brakes are pressed or the electric car is decelerating, the motor becomes an alternator and produces power, which is sent back to the battery

DC-DC converters are used in battery operated vehicle:

The different configurations of EV power supply show that at least one DC/DC converter is necessary to interface the FC, the Battery or the Supercapacitors module to the DC-link.

In electric engineering, a DC to DC converter is a category of power converters and it is an electric circuit which converts a source of direct current (DC) from one voltage level to another, by storing the input energy temporarily and then releasing that energy to the output at a different voltage. The storage may be in either magnetic field storage components (inductors, transformers) or electric field storage components (capacitors).

DC/DC converters can be designed to transfer power in only one direction, from the input to the output. However, almost all DC/DC converter topologies can be made bi-directional. A bi-directional converter can move power in either direction, which is useful in applications requiring regenerative braking.

The amount of power flow between the input and the output can be controlled by adjusting the duty cycle (ratio of on/off time of the switch). Usually, this is done to control the output voltage, the input current, the output current, or to maintain a constant power. Transformer-based converters may provide isolation between the input and the output. The main drawbacks of switching converters include complexity, electronic noise and high cost for some topologies. Many different types of DC/DC power converters are proposed in literature. The most common DC/DC converters can be grouped as follows:

Non-isolated converters

The non-isolated converters type is generally used where the voltage needs to be stepped up or down by a relatively small ratio (less than 4:1). And when there is no problem with the output and input having no dielectric isolation. There are five main types of converter in this non-isolated group, usually called the buck, boost, buck-boost, Cuk and charge-pump converters. The buck converter is used for voltage step-down, while the boost converter is used for voltage step-up. The buck-boost and Cuk converters can be used for either step-down or step-up. The charge-pump converter is used for either voltage step-up or voltage inversion, but only in relatively low power applications.

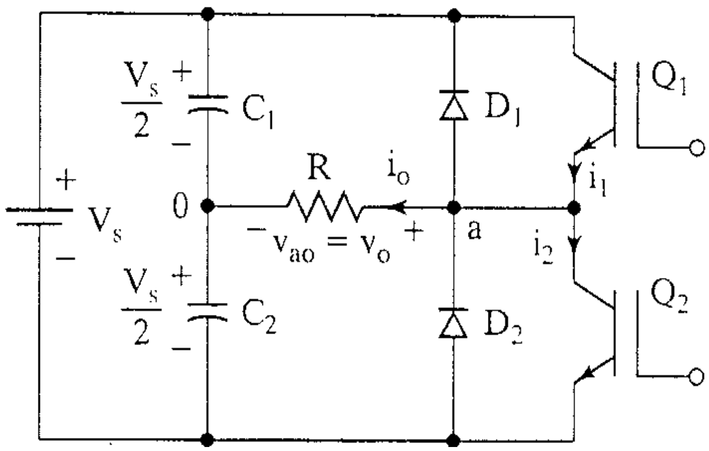
Isolated converters

Usually, in this type of converters a high frequency transformer is used. In the applications where the output needs to be completely isolated from the input, an isolated converter is necessary. There are many types of converters in this group such as Half-Bridge, Full-Bridge, Fly-back, Forward and Push-Pull DC/DC converters . All of these converters can be used as bi-directional converters and the ratio of stepping down or stepping up the voltage is high.

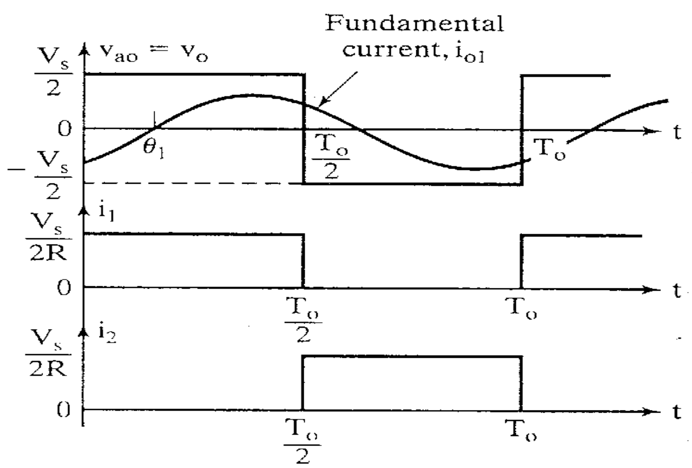
UNIT-II

INVERTER

Half bridge inverter



- Consists of 2 choppers, 3-wire DC source
- Transistors switched on and off alternately
- Need to isolate the gate signal for Q_1 (upper device)
- Each provides opposite polarity of $V_s/2$ across the load



Operation Of Single-Phase Voltage-Source Inverter Bridge.

Inverter is the conversion of dc power to ac power at a desired output voltage or current and frequency. The term voltage-fed and current-fed are used in connection with the output from inverter circuits.

A voltage-source inverter (VSI)is one in which the dc input voltage is essentially constant and independent of the load current drawn. The inverter specifies the load voltage while the drawn current shape is dictated by the load.

A current-source inverter (CSI)is one in which the source, hence the load current is predetermined and the load impedance determines the output voltage. The supply current cannot change quickly. This current is controlled by series dc supply inductance which prevents sudden changes in current. The load current magnitude is controlled by varying the input dc voltage to the large inductance; hence inverter response to load changes is slow.

Voltage control may be required to maintain a fixed output voltage when the dc input voltage regulation is poor, or to control power to a load. The inverter and its output can be single-phase, three-phase or multi-phase.

Variable output frequency may be required for ac motor speed control where, in conjunction with voltage or current control, constant motor flux can be maintained. Inverter output waveforms (either voltage or current) are usually rectilinear in nature and as such contain harmonics which may lead to reduced load efficiency and performance.

Load harmonic reduction can be achieved by either filtering, selected harmonic-reduction chopping or pulse-width modulation.The quality of an inverter output is normally evaluated in terms of its harmonic factor(ρ), distortion factor(μ), and total harmonic distortion(THD).

Figure 1.a shows an H-bridge inverter (VSI) for producing an ac voltage and employing switches which may be transistors (MOSFET or IGBT), or at high powers, thyristors (GTO or GCT).

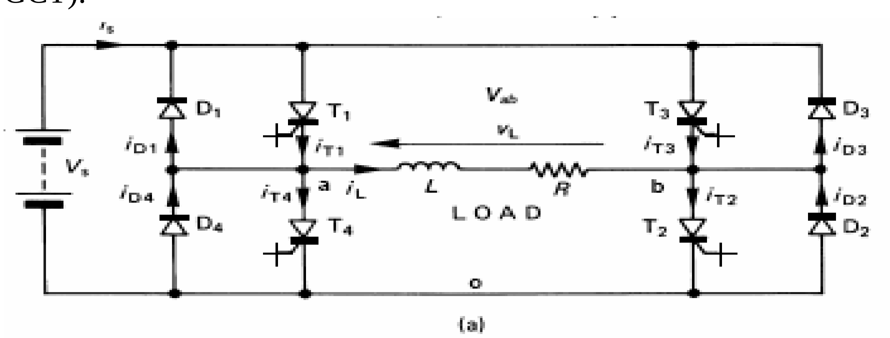


Figure 1.a Single phase H-bridge inverter (VSI)

Device conduction patterns are also shown in figure 1.b. With inductive loads (not purely resistive), stored energy at turn-off is fed through the bridge reactive feedback or freewheel diodes D1 to D4. These four diodes clamp the load voltage to within the dc supply voltage rails (0 to *Vs*).

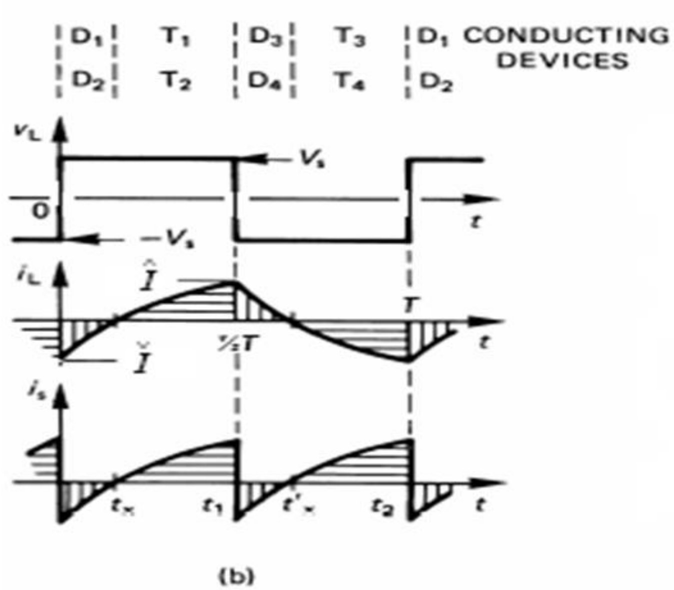


Fig 1.b Device conduction patterns waveform with square wave output voltage

Figure 1.b shows waveforms for a square-wave output (2*t1* = *t2*) where each device is turned on as appropriate for 180°, (that is π) of the output voltage cycle (state sequence 10, 01, 10, ..). The load current $i_L$grows exponentially through T1 and T2 (state 10) according to

$$V_S = L\frac{di_L}{dt} + i_L R \qquad --- \ (1)$$

When T1 and T2 are turned off, T3 and T4 are turned on (state 01), thereby reversing the load voltage polarity. Because of the inductive nature of the load, the load current cannot reverse instantaneously and load reactive energy flows back into the supply via diodes D3 and D4 (which are in parallel with T3 and T4 respectively) according to

$$-V_S = L\frac{di_L}{dt} + i_L R$$

The load current falls exponentially and at zero, T3 and T4 become forward-biased and conduct load current, thereby feeding power to the load. The output voltage is a square wave of magnitude ± *Vs*, figure 1.b, has an rms value of *Vs*.

For a simple *R-L* load, with time constant *τ* = *L* /*R*, during the first cycle with no initial load current, solving equation (1) yields a load current

$$i_L(t) = \frac{V_S}{R}(1 - e^{\frac{-t}{\tau}})$$

Under steady-state load conditions, the initial current is *I*as shown in figure 1.b, and equation (1) yields

$$i_L(t) = \frac{V_S}{R} - \left(\frac{V_S}{R} - \check{I}\right) e^{\frac{-t}{\tau}} \qquad 0 \le t \le t_2 = \frac{1}{2}T$$

The Methods Of Voltage Control Of Inverters

An inverter may require voltage control to:

- Cope with the variations in the input dc voltage
- Compensate the voltage regulation of the inverter switches and transformer
- Provide variable or adjustable voltage to the load.

Certain loads, such as variable frequency induction motor drive, require simultaneous control of frequency and voltage. Controlling the conduction intervals of the inverter switches can control frequency of the inverter output.

Voltage control may be done by any of the following techniques:

1. Control of input dc voltage
2. External control of inverter ac output voltage
3. Internal control of inverter.

CONTROL OF INPUT DC VOLTAGE:

The output voltage of an inverter may be controlled by controlling the input dc voltage supplied to the inverter.

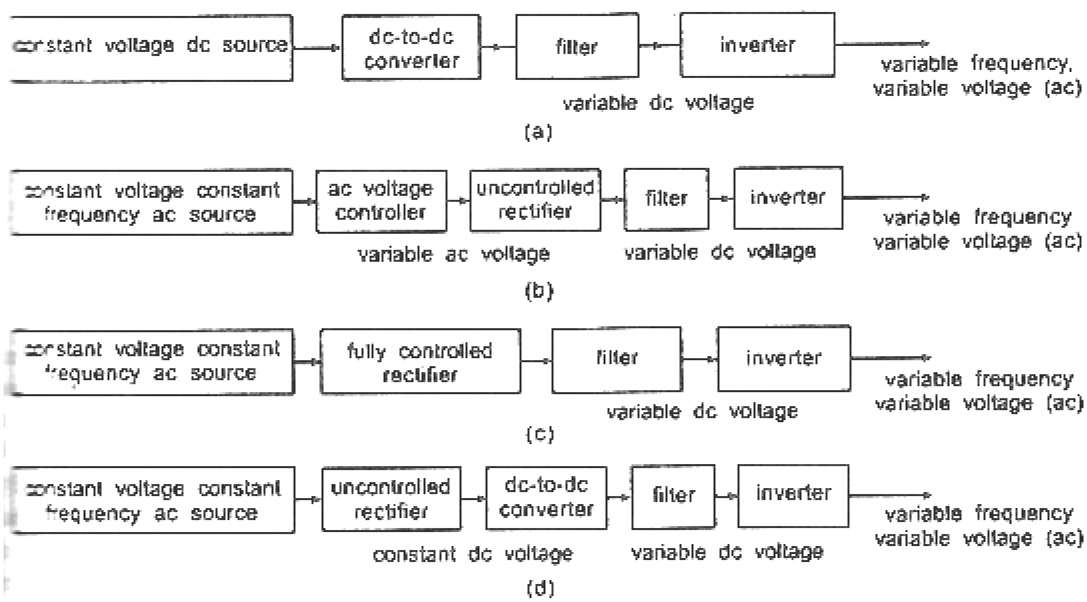


Fig 2.1 Inverter voltage control by control of dc input voltage.

Figure 2.1 shows the various schemes used to control the input dc voltage. If the basic source is dc, variable dc voltage may be obtained using a chopper or a dc-to-dc converter, as shown in Fig. 2.1(a).

If the basic source is ac, variable dc voltage may be obtained using any of the schemes shown in Fig. 2.1(b),In the scheme, the input ac voltage is first converted into a variable ac voltage using an ac voltage controller and then it is converted into dc with the help of an uncontrolled rectifier. In this system, variable voltage, variable frequency ac is obtained after three conversion stages. Obviously, efficiency of the system is poor. Moreover, the input power factor becomes poor at low voltages.

Figure 2.1.c shows an improved scheme. In this scheme, variable dc voltage is obtained using a controlled rectifier. As only two conversion stages are required, the efficiency of system is better than that for the previous scheme. At low output voltages, the input power factor is poor.

Another drawback of the scheme is that the output of the controlled rectifier contains appreciable amount of low-frequency harmonics. Therefore, large size filter components are required. This makes the system response sluggish.

Drawbacks of the system of Fig.2.1(c) are removed in the system shown in Fig. 2.1(d). This system converts the input voltage into dc using an uncontrolled rectifier. The constant dc voltage is then converted into a variable dc using a high-frequency (dc-to-dc converter). As the chopper operates at a high frequency, its output contains harmonics at very high frequencies. Thus the size of filter components is reduced.

Moreover, the fundamental input power factor remains unity under all conditions of operation. However, losses in the system increase due to use of an additional converter.

EXTERNAL CONTROL OF AC OUTPUT VOLTAGE:

The constant ac output voltage (rms) from an inverter may be controlled using an ac regulator (ac phase control). This method introduces a large harmonic content in the output voltage. Moreover, the method can be used only for small power applications.

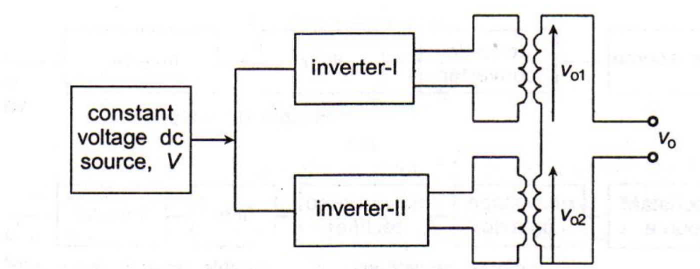


Figure 2.2 Series-connected inverters.

For high-power applications, two square-wave inverters may be connected in series to variable ac voltage, as shown in Fig. 6.

- The output voltages of the inverter I and inverter II are given to the primaries of the two transformers, whose secondary windings are connected in series.
- The output voltages of the two transformers, v_{01} and v_{02} have same magnitude. The phase angle between v_{01} and v_{02} , ϕ, can be controlled by controlling the phase angle between the control signals of the two inverters.
- The resultant output voltage (v_0) has a constant magnitude 2V (double the peak of v_{01} and v_{02}) and a variable pulse width, π-ϕ, as shown in Fig.2.3.
- By varying ϕ from 0 to π, the width of output pulses may be varied from π to 0 and hence the output voltage may be controlled from 2V to zero.

- At low voltages, it becomes a thin pulse, the harmonic contents in the output voltage become large. Therefore, this method of voltage control is used for voltage control (lower side) up to 25 to 30 per cent of the rated voltage.$\varphi\omega$ω

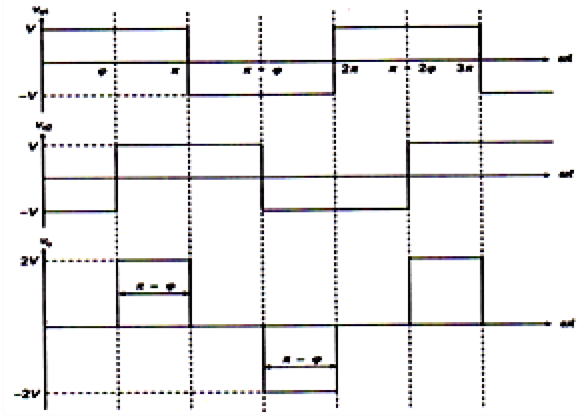


Figure 2.3 Waveforms of series-connected inverters.

INTERNAL CONTROL OF INVERTERS:

In this technique, the voltage control is obtained within the inverter. The output of the inverter is in the form of a pulse width modulated wave. Controlling the width of output pulses, controls the output voltage.

This method not only provides variable output voltage but also eliminates certain low frequency harmonics, which are responsible for poor performance.

This method is therefore, the most popular method of voltage control of inverter. Depending on the required range of voltage control and required performance, a suitable PWM technique may be used.

The square-wave inverters suffer from two major drawbacks:

1. For fixed-source voltage, the output voltage of the inverter cannot be controlled. To achieve voltage control, the inverter must be fed either from a controlled ac-dc or dc-dc converter.

2. The output voltage contains appreciable harmonics (low-frequency range). THD is also very high (48.34%).

To achieve voltage control within the inverter and to reduce the harmonic contents in the output voltage, pulse-width modulated (PWM) inverters are used. In PWM inverters, widths of output pulses are modulated to achieve the voltage control.

Among the large number modulation techniques, simple modulation techniques are:

(a) Single pulse-width modulation (SPWM)

(b) Multiple or uniform pulse-width modulation (UPWM)

(c) Sinusoidal pulse-width modulation (sine-PWM).

SINGLE PULSE WIDTH MODULATION:

- In single-pulse width modulation control, there is only one pulse per half-cycle and the width of the pulse is varied to control the inverter output voltage.
- The generation of gating signals and output voltage of single-phase full bridge inverters is shown in Fig. 3.1, the gating signals are generated by comparing a rectangular reference signal of amplitude.E_R, with a triangular carrier wave of amplitude E_c.
- The fundamental frequency of output voltage is determined by the frequency of the reference signal. The pulse-width, *P,* can be varied from 0° to 180° by varying $E_R$from 0 to E_c.
- The ratio of $E_R$to $E_c$is the control variable and is defined as the *amplitude modulation index.* The amplitude modulation index, or simply modulation index is

$$m = \frac{E_R}{E_C}$$

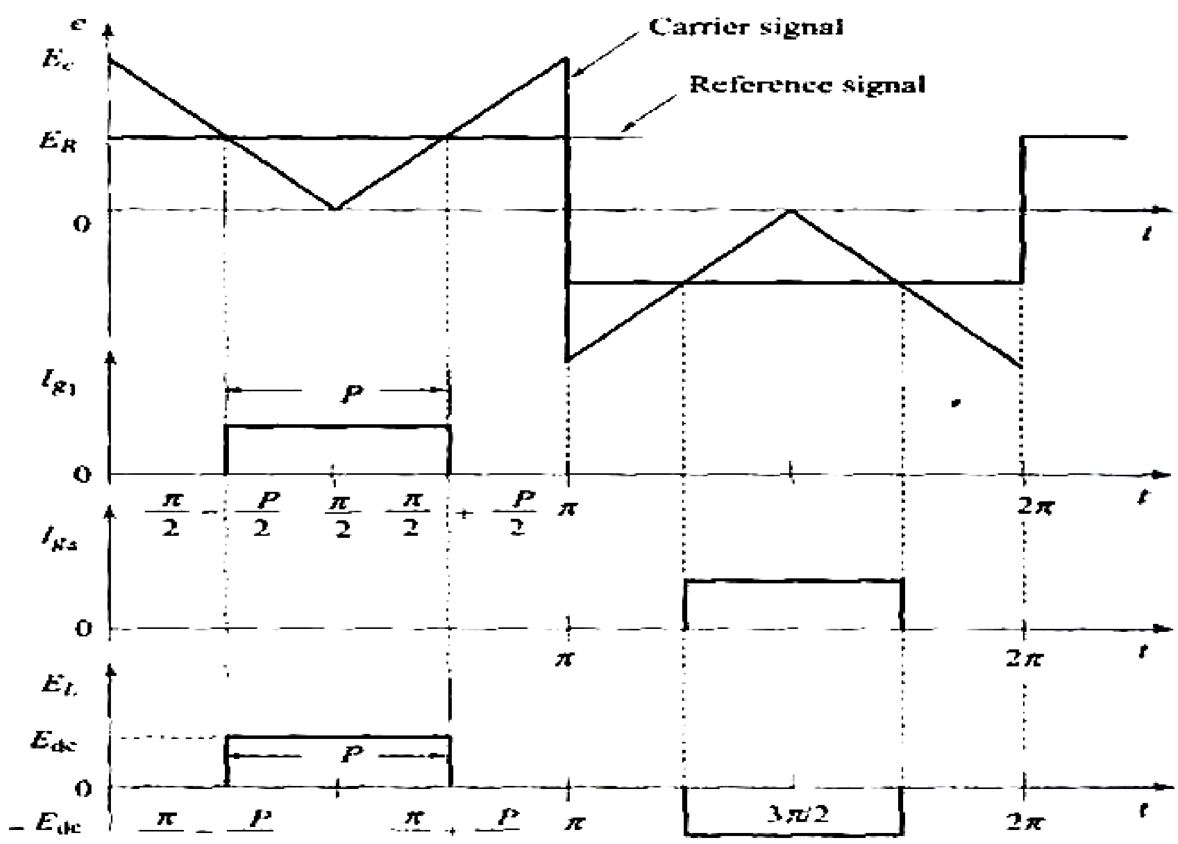


Fig 3.1 Single pulse-width modulation

The following fourier series describes the waveform of E_L as

$$E_L = \sum_{n=1,3,5,....}^{\infty} A_n \sin n\omega t + \sum_{n=1,3,5,....}^{\infty} B_n \sin n\omega t$$

Where

$$A_n = \frac{2}{\pi}\int_0^{\pi} E_{dc} \sin n\omega t \; d(\omega t)$$

$$= \frac{2}{\pi}\int_{\pi/_2 - p}^{\pi/_2 + p} \sin n\omega t \; d(\omega t)$$

$$= \frac{4E_{dc}}{5\pi} sin \frac{np}{2}$$

And,

$$Bn = \frac{2Edc}{\pi}\int_{(\pi-p)/2}^{(\pi+p/2)} \cos n \; \omega t \;\; d \; (\omega t)$$

Thus, $E_L = \sum_{n=1,3,5}^{\infty} \frac{4Edc}{n\pi} \sin \frac{np}{2} \sin n \; \omega t$

When pulse-width P is equal to its maximum value of *7t* radians, then the fundamental component
of output voltage E_L, from Eq. (9.33), has the peak value of

The RMS output voltage can be found from

$$E_{Lrms} = \left[\frac{2}{\pi} \int_{(\pi-p/2)}^{(\pi+p/2)} E_{dc}^2 \; d(\omega t)\right]^{1/_2}$$

$$= E_{dc} \cdot \sqrt{\frac{p}{\pi}} \quad --- (9.35)$$

The peak value of the n^{th} harmonic component from eqn. 9.33 is given by

$$E_{Lrms} = \frac{4E_{dc}}{n\pi} \sin \frac{np}{2} \quad ----(9.36)$$

From Eqs (9.34) and (9.36), $\frac{\text{ELnm}}{\text{ELlm}} = \frac{\sin \text{np}/2}{\text{n}} \quad ------(9.37)$

The ratio as given by Eq. (9.37) is plotted in Fig. 3.2 for n = 1, n = 3, n = 5 for different pulse

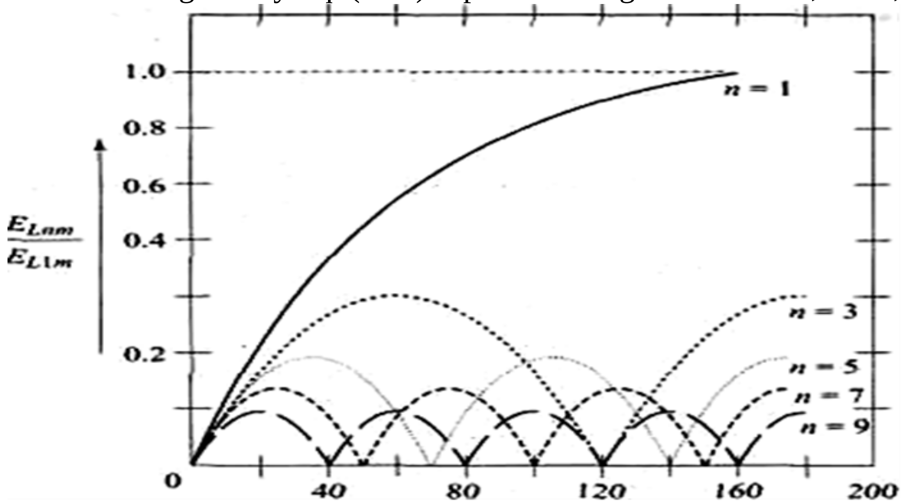


Fig 3.2 Graph for the ratio E_{Lnm} / E_{Llm}

From these curves it may be observed that when the fundamental component is reduced to Nearly0.33, the amplitude of the third harmonic is also 0.33.

When fundamental component is reduced to about 0.143, all the three harmonics (3, 5, 7) become almost equal to the fundamental.

This shows that in this type of voltage control scheme, as great deal of harmonic content is introduced in the output voltage, particularly at low output voltage levels.

MULTIPLE PULSE WIDTH MODULATION

- In this method of pulse-width modulation, the harmonic content can be reduced using several pulses in each half-cycle of output voltage.
- By comparing a reference signal with a triangular carrier wave, the gating signals are generated for turning-on and turning-off of a thyristor, as shown in Fig.3.3.
- The carrier frequency, f_c, determines the number of pulses per half-cycle, m, whereas the frequency of reference signal sets the output frequency.
- The modulation index controls the output voltage. This type of modulation is also known as symmetrical pulse width modulation (SPWM). The number of pulses N per half-cycle is found from the expression

$$Np = \frac{fc}{2fo} = \frac{mf}{2} \text{ where } mf = \frac{fc}{fo} \text{ is the frequency modulation ratio.}$$

- The variation of modulation index (M) from 0 to 1 varies the pulse width from 0 to $\pi l N_P$ and the output voltage from 0 to E_{dc}.

Output voltage :

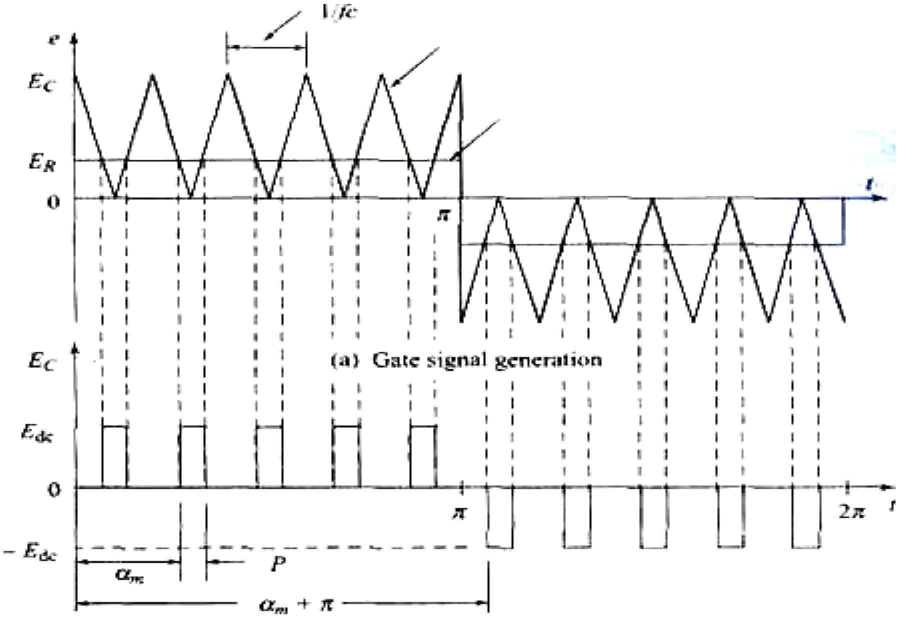


Fig 3.3 Multiple-pulse width modulation

If P is the width of each pulse, the RMS output voltage can be obtained from the following expression:

$$E_{Lrms} = \left[\frac{2N_p}{2\pi} \int_{(\pi/N_P-P)/2}^{(\pi/N_P+P)/2} E_{dc}^2 \, d(\omega L)\right]^{1/2} = E_{dc}\sqrt{\frac{N_p.P}{\pi}} \quad ----(9.39)$$

With this method, since voltage control is achieved with a simultaneous reduction of lower order harmonics, this scheme is comparatively advantageous over single-pulse modulation,

However, due to larger number of pulses per half-cycle, frequent turning-on andturning-off of thyristors is required which increases the switching losses. Also, for this scheme inverter-grade thyristors are required which are costly.

SINUSOIDAL PULSE WIDTH MODULATION: -MAY/JUNE-2013,18, NOV/DEC-2013

- In this method of modulation, several pulses per half-cycle are used
- The width of each pulse is varied proportional to the amplitude of a sine-wave evaluated at the centre of the same pulse.
- By comparing a sinusoidal reference signal with a triangular carrier wave of frequency f_c, the gating signals are generated, as shown in Fig. 3.5(a).
- The frequency of reference signal determine the inverter output frequencyf_0, and its peak amplitude, $E_n$controls the modulation index, A and then in turn the RMS output voltage, E_L.
- The number of pulses per half-cycle depends on the carrier frequency. Within the constraint that two thyristors of the same arm (T_1, T_4) cannot conduct at the same time, the instantaneous output voltage is shown in Fig.3.5(a).
- The same gating signals can be generated using unidirectional triangular carrier-wave as shown in Fig. 3.5(b).
- By varying the modulation index *M*, the RMS output voltage can be varied. If $P_m$is the width of the mth pulse, Eq. (9.39) can be extended to find the rms output voltage

$$E_L = E_{dc}\left(\sum_{m=1}^{N_p}\frac{P_m}{\pi}\right)^{1/2} \qquad ------------ (9.42)$$

Harmonic analysis of the output modulated voltage wave reveals that SPWM has the following important features:

(i) For modulation index less than one, the largest harmonic amplitudes in the output voltage are associated with harmonics of order $f_c/f_r \pm 1$ or $2N_p \pm 1$, where $N_p$is the number of pulses per half-cycle.

By increasing the number of pulses per half-cycle, the order of dominantHarmonic frequency can be raised, which can then be filtered out easily.

For Np = 5, harmonics of the order of 9 and 11 become significant in the output voltage. It may be noted that the highest order of significant harmonic of modulated voltage-wave is centered around the carrier frequency, fc.

(ii) For modulation index greater than one, lower order harmonics appear.

modulation index greater than one, pulse width is no longer a sinusoidal function of the angular position of the pulse.

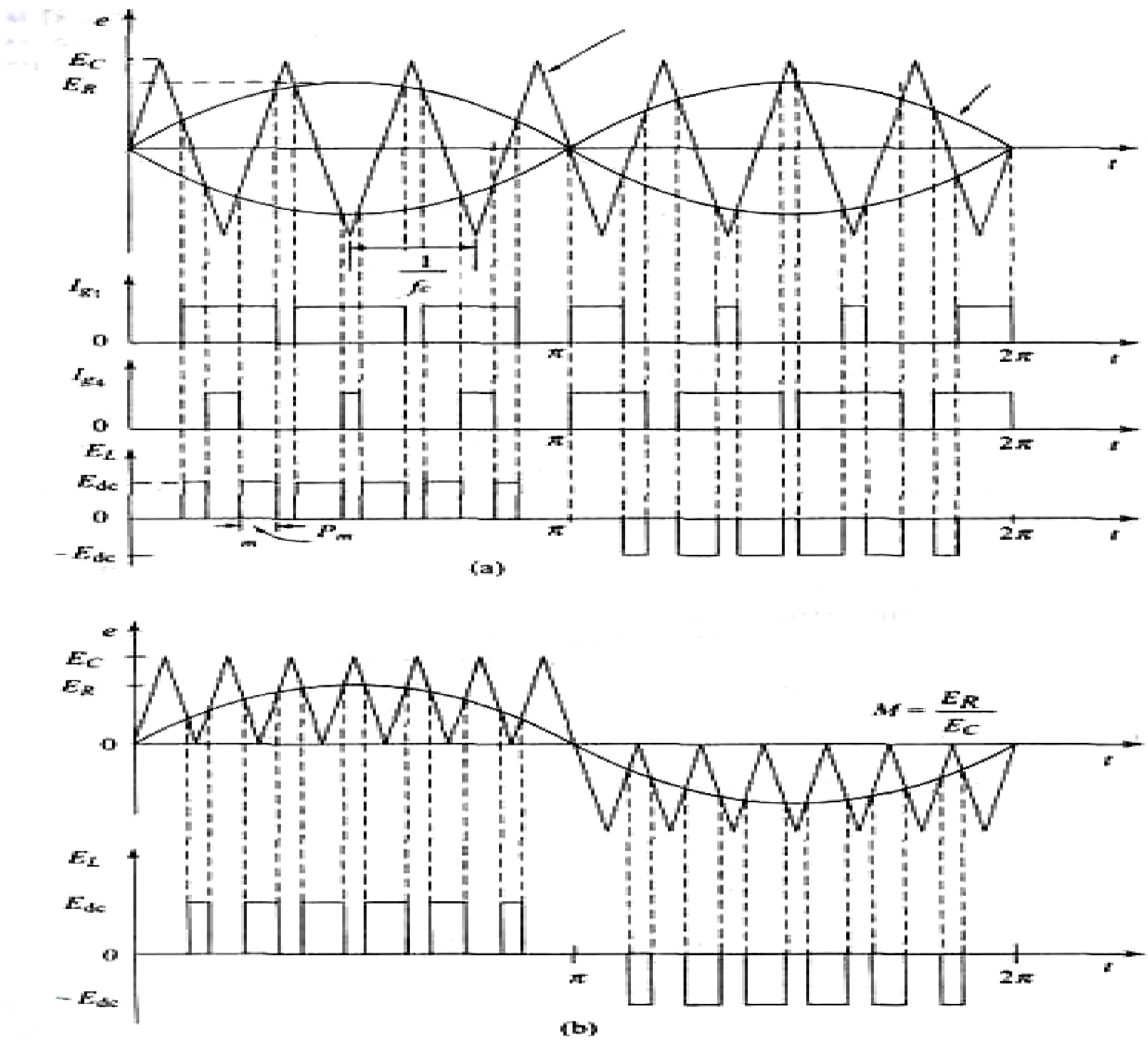
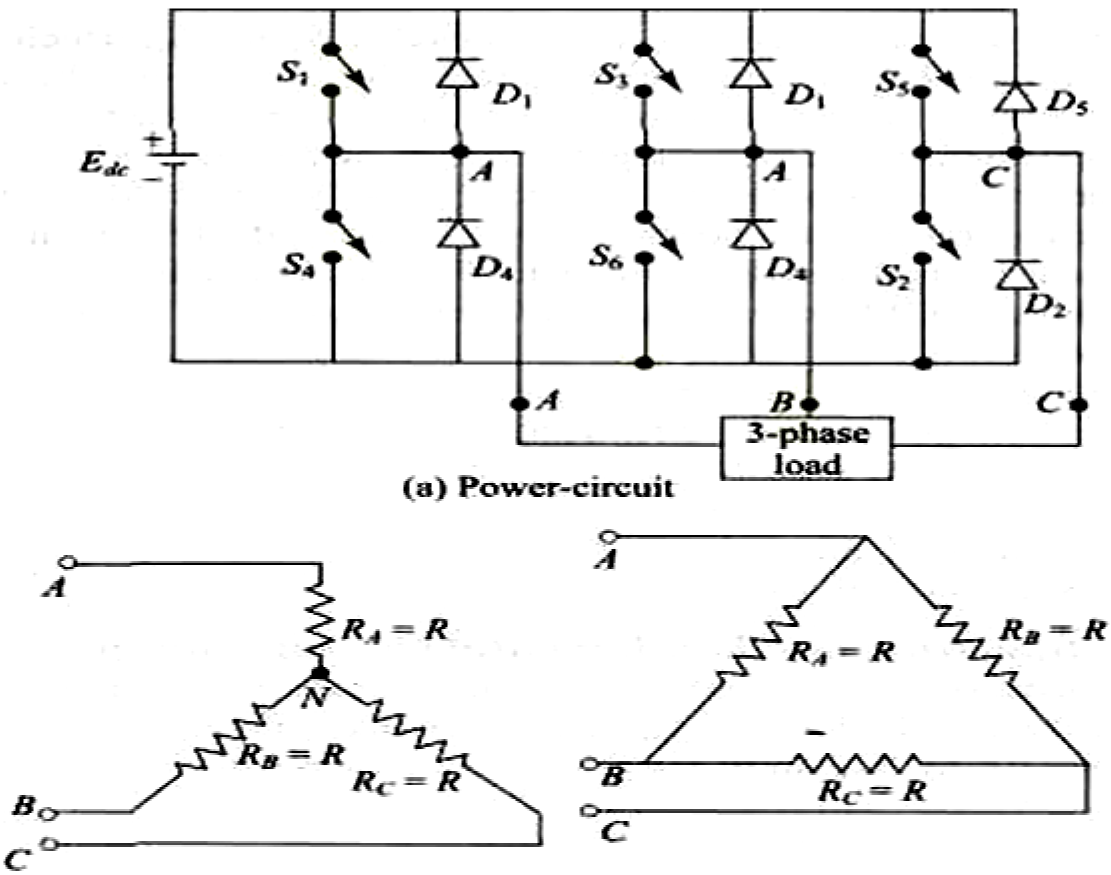


Fig 3.5 Sinusoidal pulse – width modulation

Working Of Three Phase Bridge Inverter In 180 Degree

Three-phase inverters are used for high-power applications such as ac motor drives, induction heating, uninterruptive power supplies. A three-phase inverter circuit changes DC input voltage to a three-phase variable frequency, variable-voltage output.

The input DC voltage can be from a DC source or a rectified AC voltage. A three-phase bridge inverter can be constructed by combining three-single-phase half-bridge inverters.



(b) Star-connected load (c) Delta-connected load

Fig.4.1Three-phase full-bridge inverter

- it consists of six power-switches with six associated Freewheeling diodes. The switches are opened and closed periodically in the proper output frequency of the inverter.
- Basically, there are two possible schemes of gating the devices. In one scheme, each device (switch) conducts for 180° and in the other scheme, each device conducts for 120°.
- But in both these schemes, gating signals are applied and removed at 60°intervals of the output voltage waveform.

180° CONDUCTION:

- In this control scheme, each switch conducts for a period of 180° or half-cycle electrical. Switches are triggered in sequence of their numbers with an interval of 60°.
- At a time, three switches (one from each leg) conduct. Thus, two switches of the same leg are prevented from conducting simultaneously. Theswitches are conducting—two from upper group and one from the lower group and vice-versa.
- One complete cycle is divided into six modes, each of 60° intervals. The operation of the circuit can be understood from the waveforms shown in Fig.4.3 and the operation Table 4.2
- Switch pair in each leg, i.e. S_1, S_4, S_3 S_6, and S_5, $S_2$are turned-on with a time interval of 180°. It means that switch S_1conducts for 180° and switch S_4 for the next 180° of a cycle.
- Switches, in the upper group, i.e. S_1, S_3, 5_5 conduct at an interval of 120°. It means that if 5] is fired at 0°, then—S_3 must be triggered at 120° and S_5at 240°. Same is true for lower group of switches.

Table 4.2Operation Table

S.No.	Interval	Device conducting	Incoming device	Outgoing device
1	I	5, 6, 1	1	4
2	II	6, 1, 2	2	5
3	III	1, 2,,3	3	6
4	IV	2, 3, 4	4	1
5	V	3, 4, 5	5	2
6	VI	4, 5, 6	6	3

The following points can be noted from the wave forms and the operating Table
(i) Each switch conducts for a period of 180°.
(ii) Switches are triggered in the sequence 1, 2, 3, 4, 5, and 6.
(iii) Phase shift between triggering the two adjacent switches is 60°.
(iv) From table, it is observed that in every step of 60° duration, only three
(v) The output voltage waveforms (E_{AB}, E_{BC}, E_{CA}) are quasi-square-wave with a peak-value of E_{dc}. The three-line voltages are mutually phase-shifted by 120°.
(vi) The three-phase-voltages E_{AN}, E_{BN}, and E_{CN} are six-step saves, with step heights E_{dc}.
(vii) Line voltage E_{AB} is leading the phase-voltage E_{AN} by 30°.In Fig.4.3, phase voltages E_{AN}, E_{BN} and E_{CN} have also been drawn for star Connected resistive load. For a star connected load, the line-to-neutral voltages must be determined to find the line or phase currents.

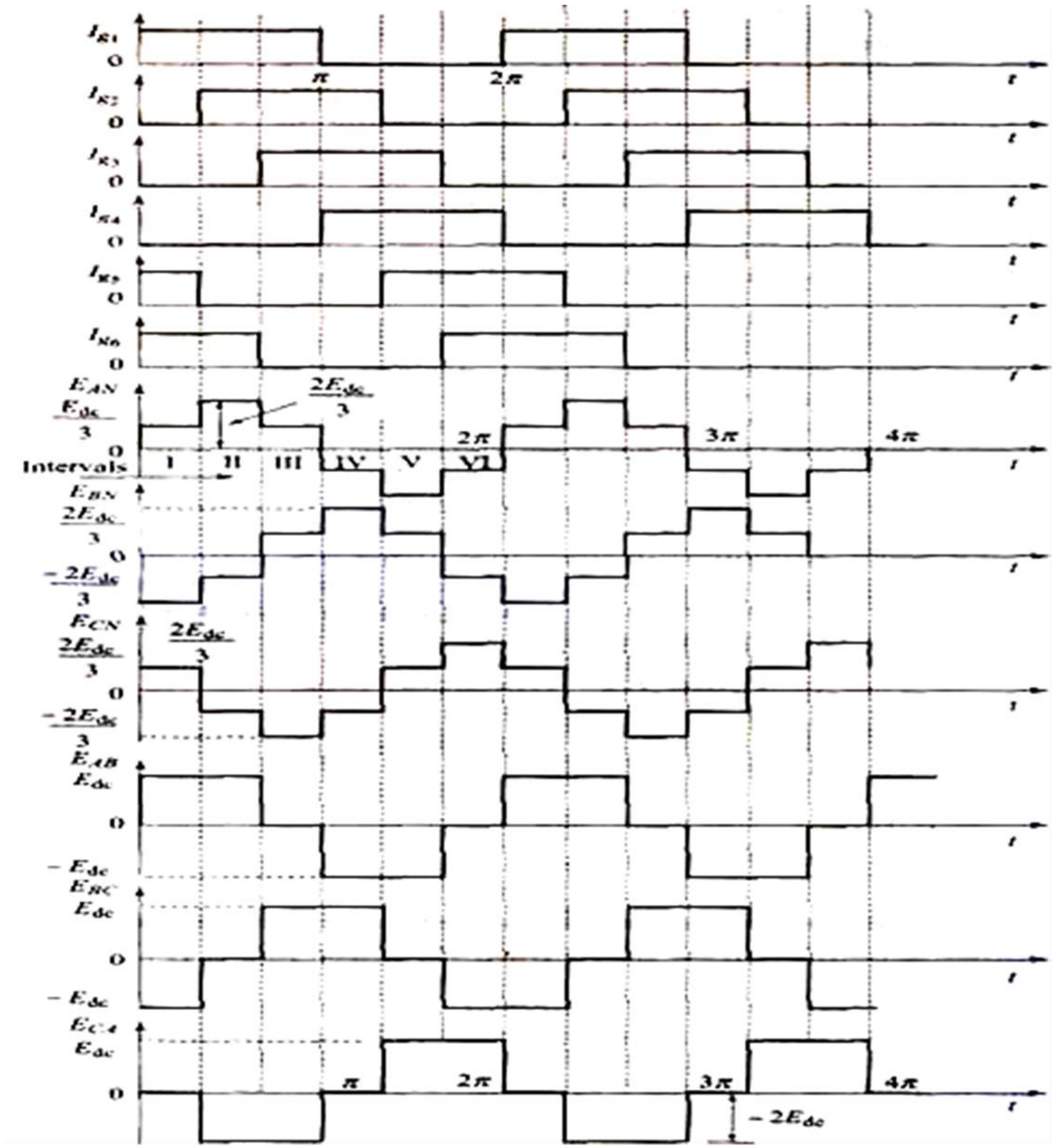


Fig. 4.3Voltage waveforms for 180° conductio

There are three modes of operation in a half-cycle and the equivalent circuits are shown in Fig.4.4 for a star-connected load.

(i) **During interval I for0** $\leq \boldsymbol{\omega t \omega} < \pi/3$

$$Req = R_B + (R_A II\ R_C)$$

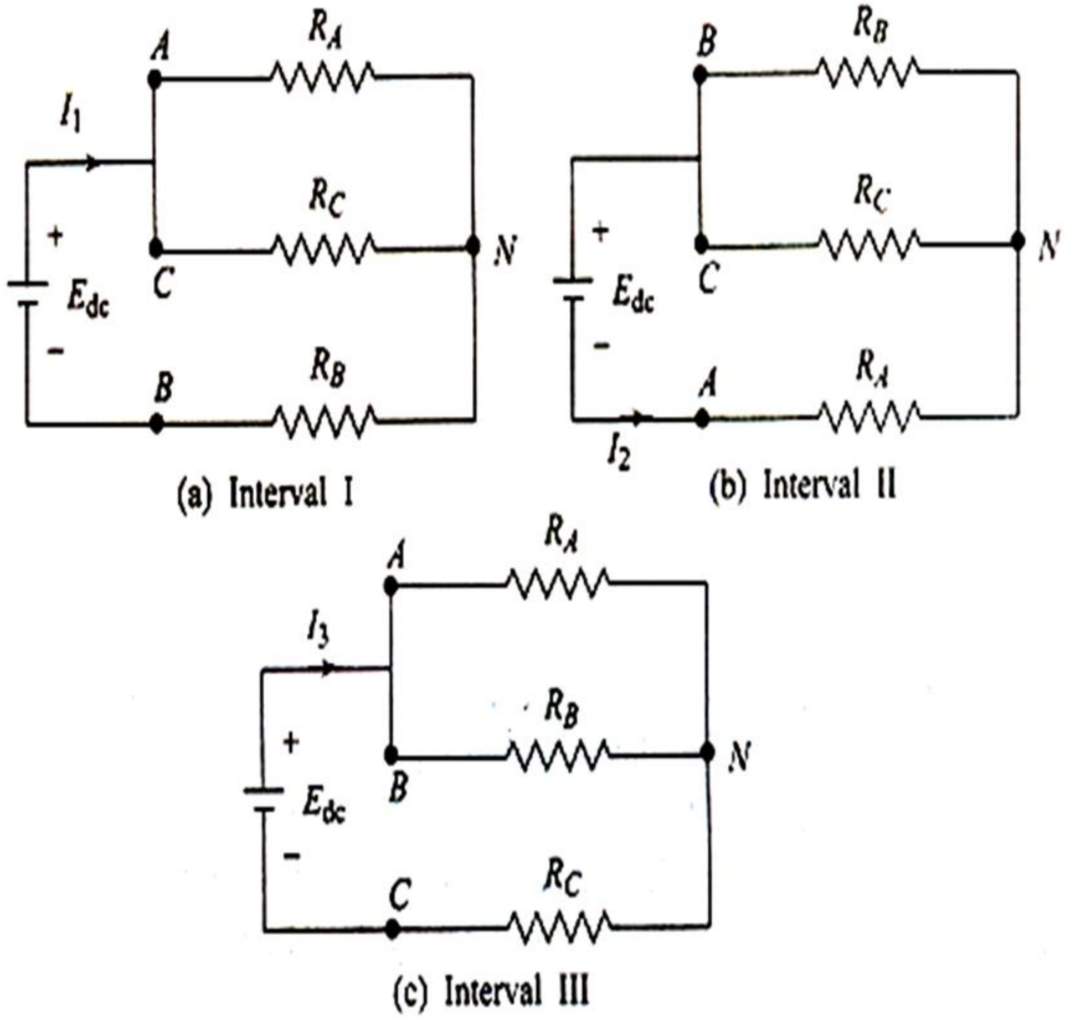


Fig. 9.26 *Equivalent circuits for star-connected resistive load*

$$= R + \frac{R}{2} = \frac{3R}{2} (SInce\ R_A = R_B = R_C)$$

$$Current, I_1 = \frac{E_{dc}}{Req} = \frac{2E_{dc}}{3R}$$

$$Now, E_{AN} = E_{CN} = \frac{I_1R}{2} = \frac{E_{dc}}{3} ------ (9.68)$$

$$Also, E_{BN} = -I_1R = \frac{-2E_{dc}}{3}$$

(ii) During intervalII for $\frac{\pi}{3} \leq \omega t < 2\pi/3$

$$Req = R + \frac{R}{2} = \frac{3R}{2}$$
$$Current, I_2 = \frac{E_{dc}}{Req} = \frac{2E_{dc}}{3R}$$
$$E_{AN} = I_2R = \frac{2E_{dc}}{3}$$
$$E_{BN} = E_{CN} = \frac{-I_2R}{2} = \frac{-E_{dc}}{3}$$

(iii) During interval III for $\frac{2\pi}{3} \leq \omega t < \pi$.

$$Req = R + \frac{R}{2} = \frac{3R}{2}$$
$$Current, I_3 = \frac{E_{dc}}{Req} = \frac{2E_{dc}}{3R}$$
$$E_{AN} = E_{BN} = \frac{I_3R}{2} = \frac{E_{dc}}{3}$$
$$E_{CN} = -I_3R = \frac{-2E_{dc}}{3}$$

The line voltage $E_{AB} = E_{AN} - E_{BN}$ is obtained by reversing E_{BN} and adding it to E_{AN} as shown in Fig 4.3. Similarly, line voltages $E_{BC} = E_{BN} - E_{CN}$ and $E_{CA} = E_{CN} - E_{AN}$.

It can be observed from Fig.4.3 that phase voltages have six steps per cycle and line voltages have one positive pulse and one negative pulse (each of 120° duration) per cycle. The phase as well as line-voltages is out of phase by 120°.

The instantaneous line-to-line voltage, E_{AB} can be expressed in a Fourier-series, recognizing that E_{AB} is shifted by Π / 6 and even harmonics are zero,

$$E_{AB} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4E_{dc}}{n\pi} cos\frac{n\pi}{6} \sin n(\omega t + {}^{\pi}/_{6}) \quad ----- (9.71)$$

E_{BC} $and E_{CA} can\ be\ found\ from\ eqn$ (9.71) $by\ phase\ shifting$ E_{AB} by $120°$ and $240°$ $respective;y$

$$E_{BC} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4E_{dc}}{n\pi} cos\frac{n\pi}{6} \sin n\left(\omega t - {}^{\pi}/_{2}\right) --------- (9.72)$$

$$E_{CA} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4E_{dc}}{n\pi} cos\frac{n\pi}{6} \sin n(\omega t - {}^{7\pi}/_{6}) \quad ------- (9.73)$$

For n=3,9,15,……cos$\frac{n\pi}{6} = 0$

Hence it is noted from eqn (9.71), (9.72) and (9.73) that the triple harmonics would be zero in the line to line voltages

The line to line rms voltage can be found from

$$E_L = \left[\frac{2}{\pi}\int_0^{2\pi/3} {E_{dc}}^2 d(\omega t)\right]^{1/2} = \sqrt{\frac{2}{3}} E_{dc} \qquad -------- (9.74)$$

$$E_{Ln} = \frac{4E_{dc}}{\sqrt{2}n\pi}\cos(n\pi/6)$$

Which for n=1

$$E_{L1} = \frac{4E_{dc}}{\sqrt{2}\,\pi}\cos\left(\frac{\pi}{6}\right) = 0.7797E_{dc}$$

$The\ rms\ value\ of\ line\ to\ neutral\ voltage\ can\ be\ found\ from\ the\ line\ voltages$

$$E_p = \frac{E_L}{\sqrt{3}} = \frac{\sqrt{2}E_{dc}}{3} = 0.4714E_{dc}$$

3 phase VSI in 120 degree operating mode:

In this type of conduction mode, each switch conducts for 120°. At any instant of time, only two switches remain on. Here also gate pulse indicates the conduction period of each switch.

- In this case also, six commutations per cycle are required. The gating signals and various voltage waveforms of three-phase bridge inverters with 120° conduction for each switch is shown in Fig.

- One period of inverter operation has been divided into six intervals. The firing sequence of six switches is prepared, as shown in Table 5.1.
- Like 180° mode, 120° mode inverter also requires six steps, each of 60° duration, for completing one cycle of the output a.c. voltage.

Table 9.3 Operation Table

S.No.	*Interval*	*Conducting devices*	*Incoming device*	*Outgoing device*
1	I	S_6, S_1	S_1	S_5
2	II	S_1, S_2	S_2	S_6
3	III	S_2, S_3	S_3	S_1
4	IV	S_3, S_4	S_4	S_2
5	V	S_4, S_5	S_5	S_3
6	VI	S_5, S_6	S_6	S_4

Following points can be noted from the waveforms and the operating Table:

(i) The base drives of two switches in the same-half-bridge have an inherent dead band of 60°. Hence, there is no possibility of cross conduction or shoot-through fault.

(ii) Conduction period for each switch is 120°.

(iii) The phase-shift between the triggering of every two adjacent switches is 60°.

(iv) Three line voltages, E_{AB}, E_{BC} and E_{CA} are six-step waves, with step heights, $E_{dc}/2$ and E_{dc}. The three-line voltages are mutually phase shifted by 120°.

(v) The three-phase voltages E_{AN} ,E_{BN} and E_{CN} are quasi-square-waves with peak values of $E_{dc}/2$. They are also mutually phase-shifted by 120°.

(vi) The line-voltage $E_{AB}$is leading the phase-voltage E_{AN} by 30°. From Fig.5.2 and 5.1 it is observed that two switches conduct at a time, one from the upper group and the other from the lower group.

(vii) There are three modes of operation in one half-cycle and the equivalent circuits for a star-connected load are shown in Fig.5.3.

During interval I, 0 ≤ ωt < π/3, switches S1 and S6 conduct.

$$E_{AN} = \frac{E_{DC}}{2} \ , E_{BN} = \frac{-E_{DC}}{2} \ , E_{CN} = 0$$

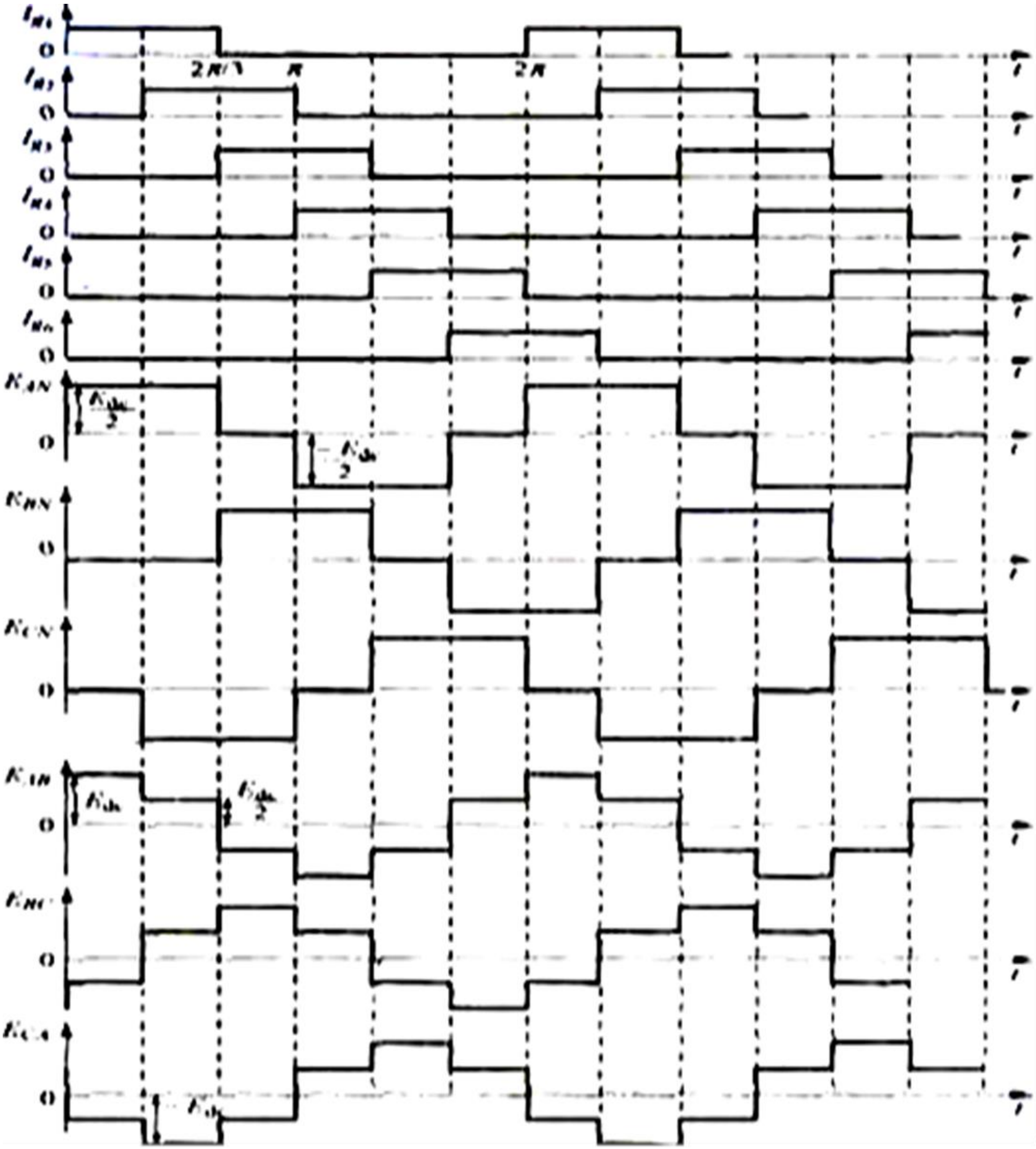


Fig 5.2 Gating signals and voltage waveform for 120° conduction

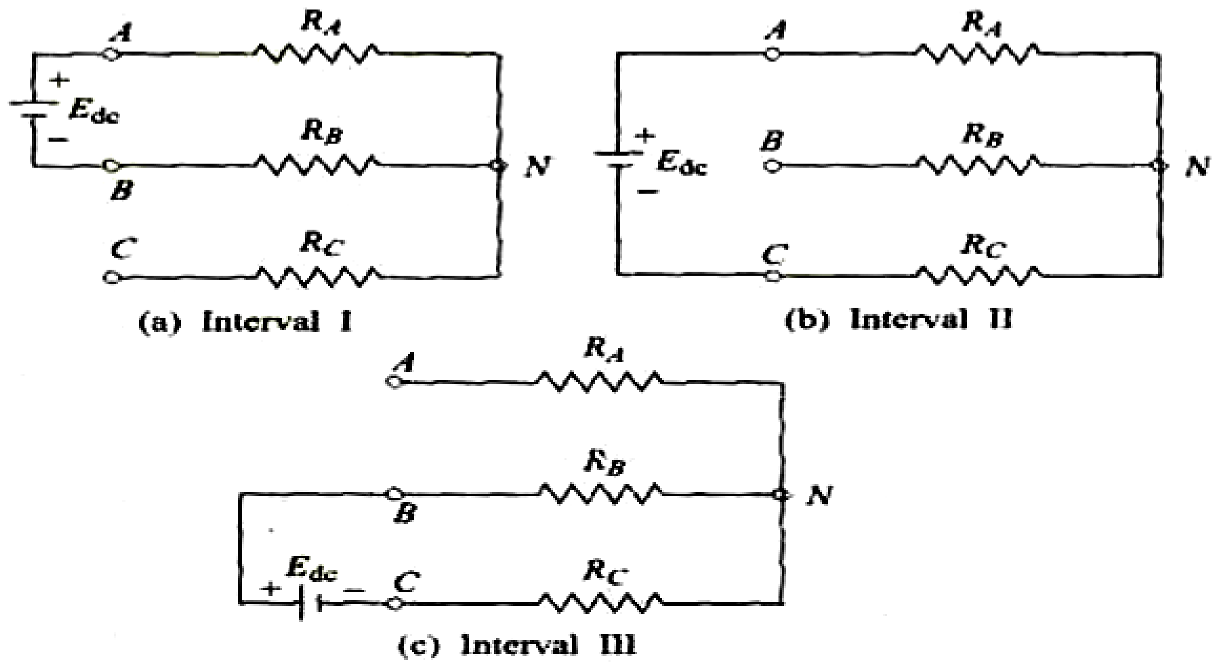


Fig. 9.29 *Equivalent circuits*

During interval II, for π/3 ≤ ωt ≤ 2π/3, switches S_1 and S_2 conduct.

$$\boldsymbol{E_{AN} = \frac{E_{dc}}{2}, E_{BN} = 0, E_{CN} = \frac{-E_{dc}}{2} \;--------\; (9.89)}$$

(iii) During interval III (for 2**π/3 ≤ ωt ≤ 3π/3**) switches S2 and S3 conducts

$$\boldsymbol{E_{AN} = 0, E_{BN} = \frac{E_{dc}}{2}, E_{CN} = \frac{-E_{dc}}{2} \;-----\; (9.90)}$$

In the fig 9.28 the line to neutran voltage are shown, which can be expressed in fourier series

$$E_{AN} = \sum_{n=1,3,5,....}^{\infty} \frac{2E_{dc}}{n\pi} cos\frac{n\pi}{6} \sin n(\omega t + {}^{\pi}/_{6}) ------(9.91)$$

$$E_{BN} = \sum_{n=1,3,5,....}^{\infty} \frac{2E_{dc}}{n\pi} cos\frac{n\pi}{6} \sin n(\omega t - {}^{\pi}/_{2}) \;-----\; (9.92)$$

$$E_{CN} = \sum_{n=1,3,5,....}^{\infty} \frac{2E_{dc}}{n\pi} cos\frac{n\pi}{6} \sin n(\omega t - 7\,{}^{\pi}/_{6}) \;-----\; (9.93)$$

The line voltage, E_{AB}=√3 $E_{AN}$with a phase advance $S_4$of 30°. There is a delay of π/6 between the turning-off of S_1 and turning-on of S_4. Thus, there should be no circuit of the d.c. supply through one upper and one lower switch.

At any-time, two load terminals are connected to the d.c. supply and the third one remains open. The potential of this open terminal will depend on the load characteristics and would be unpredictable.

Concept Space Vector Modulation.

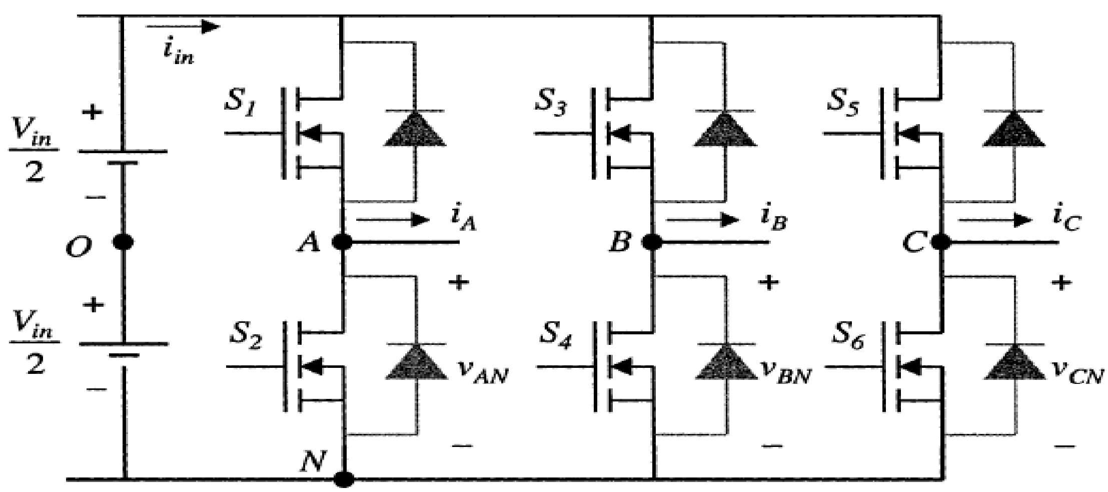
- This method has become extremely popular for 3-phase inverters in the low-to-medium power range. For 3-phase systems with no zero-sequence component,

$$v_z = \frac{(v_{AN} + v_{BN} + v_{CN})}{3} = 0$$

- The 3-phase quantities are linearly dependent and can be transformed to a 2-phase orthogonal system commonly called the *αβ* system.
- Quantities in the *αβ* system can be represented by complex numbers and as two-dimensional vectors in a plane, called *space vectors*. The transformation from the *abc* to *αβ* quantities is given by

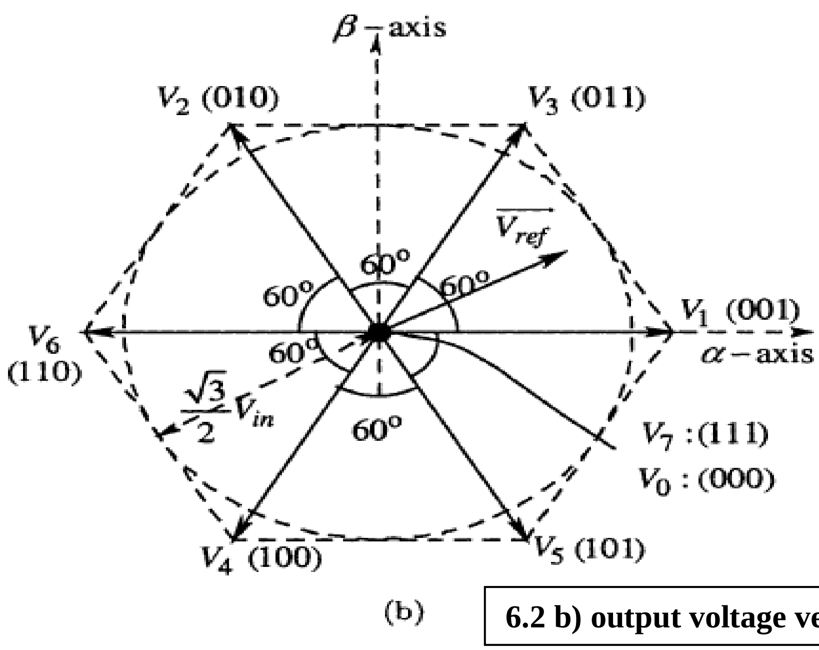
$$\vec{v}_{\alpha\beta}(t) = v_\alpha(t) + j.v_\beta(t) = e^{j0}.v_a(t) + e^{\frac{j2\pi}{3}}.v_b(t) + e^{\frac{j4\pi}{3}}.v_c(t)$$

- With negative sequence components absent, *α* and *β* components of steady-state sinusoidal *abc* quantities are also sinusoids with constant amplitude and a 90 degree phase difference between them.
- Under transient conditions they are arbitrary time-varying quantities. Thus, for balanced sinusoidal conditions, the space vector $V_{\alpha\beta}(t)$ rotates in counter clockwise direction with angular frequency equal to frequency of the *abc* voltages, and a circle of radius (3/2) ˆ*Vph*,
ˆ*Vph* = the peak of the phase voltage.



6.1 a)	3 Phase converter

- The instantaneous output voltages of the 3-phase inverter shown in Fig.6.1.*a* can assume eight different combinations based on which of the six MOSFETs are on.
- The space vectors for these eight combinations are shown in Fig 6.1*b*. For example, vector *V*4 denoted by (100) corresponds to switch states $V_{AN}=Vin$, $V_{BN}= 0$, and $V_{CN}= 0$. The vectors *V*0(000) and *V*7(111) have zero magnitude and are called *zero vectors*.
- Synthesis utilizing the idea of space vectors is done by dividing one switching time period intoseveral time intervals, for each of which a particular voltage vector is the output by the inverter.
- The time period is equal to the desired output voltage vector. For the reference voltage vector *ref* ,shown in Fig.6.1*b*, the nonzero vectors adjacent to it (*V*1 and *V*3), and the zero vectors (*V*0 and *V*7) are utilized as shown in Fig.6.1*c*.
- Relative values of time intervals *t*1 and *t*3 determine the direction, while ratio of t_0 to the switching time period determines the magnitude of the output vector synthesized.
- The maximum obtainable average vector lies along the hexagon connecting the six nonzero vectors.
- As stated earlier, balanced 3-phase sinusoidal quantities describe a circle in the *αβ* plane. Thus, to synthesize distortion-free and balanced 3-phase sinusoidal voltages the circle must be contained within the hexagon, that is, with a maximum radius of 3/2.V_{in}.



6.2 b) output voltage vector

- This gives the maximum peak value of line-to-line voltage obtained with SVM as $V_{LL}=Vin$. This is significantly higher than that obtained using sine triangle PWM: 3/2.V_{in}.

- Further, the sequence and choice of vectors applied can be optimized to minimize number of switching's and ripple in the resulting currents. There are several variations of SVM, each suited to a different application.
- Space vector modulation can be easily implemented digitally using microcontroller and digital signal processor (DSPs), and is extremely advantageous in control of 3-phase ac machines strategies using *vector control* and *direct*torque control(DTC).

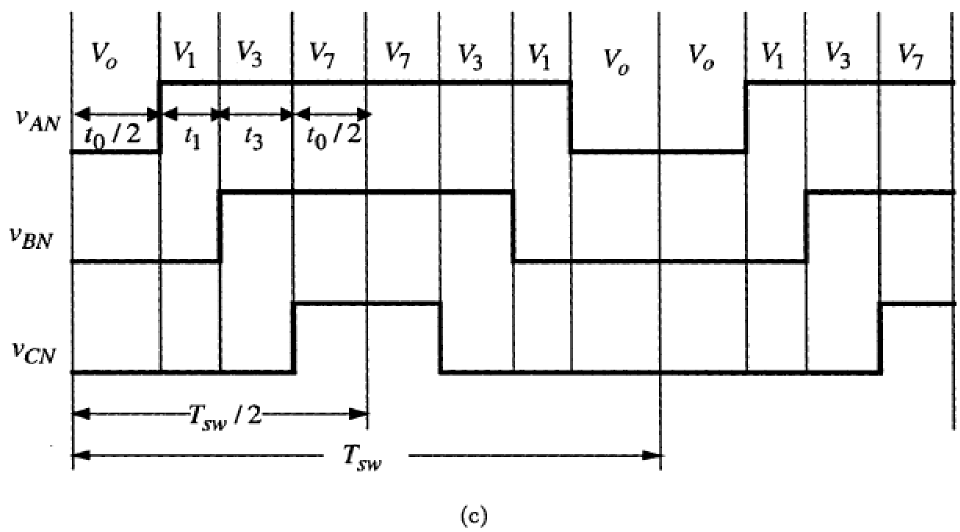


Fig 6.1, **(*c*) Instantaneous waveforms.**

working of series inverter

In some inverters, the commutating elements may come in series with the load or in parallel with the load during operation.

In this type of inverters, as indicated by the name, the commutating elements, viz. *L* and *C* are connected in series with the load. This constitutes a series *R-L-C* resonant circuit.

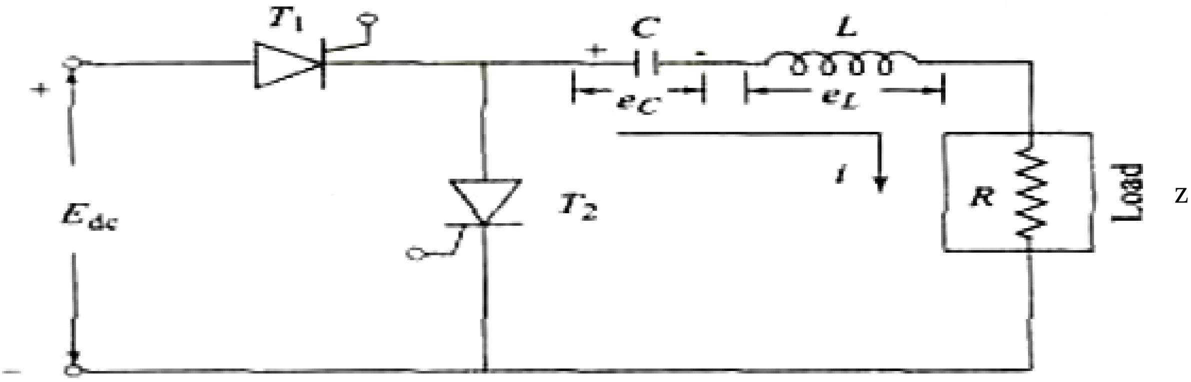
If the load is purely resistive, it only has resistance in the circuit. In case of load being inductive or capacitive in nature, its inductance or capacitance part is added to the commutating elements (beinginseries).Thistypeofthyristorisedinverterproducesanapproximatelysinusoidal waveform at a high output frequency , rangingfrom200 Hz to 100 kHz.

And is commonly used in relatively fixed output applications such as ultrasonic generators, induction heating, sonar transmitter, fluorescent lighting, etc. Due to the high-switching frequency, the size of commutating components is small.

Basic Series Inverter:

Figure shows the circuit diagram of basic series inverter. Two thyristors *T1* and $T_2$are used to produce the two halves (positive and negative respectively) in the output.

$$R^2 < \frac{4L}{C}$$



(a) Circuit diagram

The commutating elements *L* and *C* are connected in series with the load *R* to form the series *R-L-C* circuit. The values of E and *C* are chosen such that, they form an under damped circuit. This is necessary to produce the required oscillations. This condition is fulfilled by selecting *L* and C

The operation of a basic series inverter circuit can be divided into following three operating modes

Mode 1:

- This mode begins when a d.c. voltage E_{dc} is applied to the circuit and thyristor $T_1$is triggered by giving external pulse to its gate.
- As soon as SCR $T_1$is triggered, it starts conducting and resulting in some current to flow through the *R-L-C* series circuit. Capacitor C gets charged up to voltage, say, E_c, with positive polarity on its left plate and negative polarity on its right plate.
- The load current is of alternating nature. This is due to the underdamped circuit formed by the commutating elements.
- It starts building up in the positive half, goes gradually to its peak-value, then starts returning and again becomes zero, as shown in Fig.7.2 (b).
- When the current reaches its peak-value, the voltage across the capacitor is approximately the supply voltage E_{dc}. After this, the current starts decreasing but the capacitor voltage still increases and finally the current becomes zero but the capacitor retains the highest voltage, i.e. (E_{dc} + E_c), $E_c$is the initial voltage across the capacitor at the instant SCR r, was turned-on.
- At P, SCR T_1 is automatically turned-off because the current flowing through it becomes zero.

Mode 2:

- During this mode, the load current remains at zero for a sufficient time (T_{off}). Therefore, both the thyristors $T_1$and $T_2$are OFF. During this period *PQ*, capacitance voltage will be held constant.

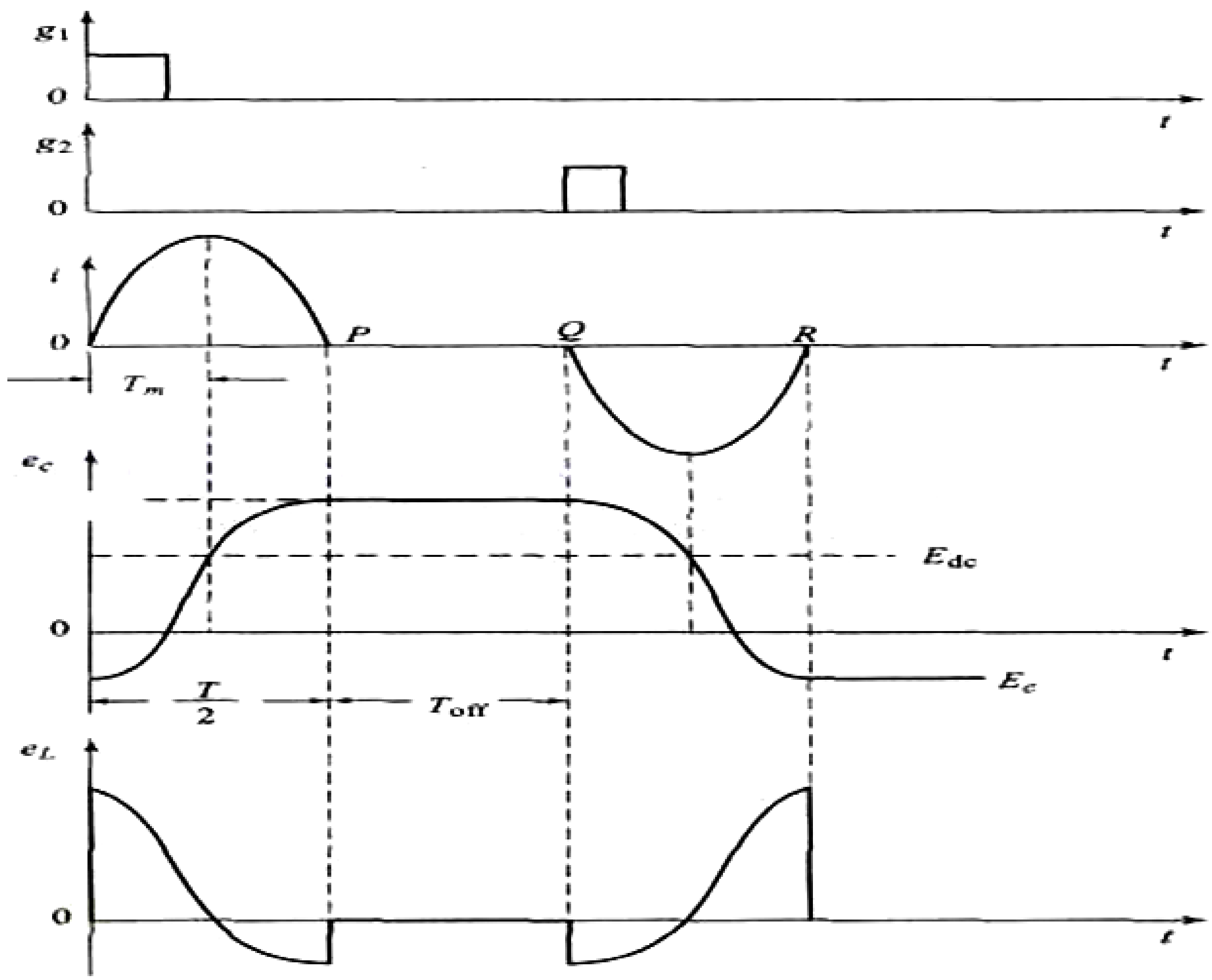


Fig. 7.2 b Voltage and current waveforms of Series inverter

Mode3:

- Since the positive polarity of the capacitor C appears on the anode of SCR T_2, it is in conducting mode and hence triggers immediately.
- At *Q*, SCR T_2 is triggered. When SCR T_2starts conducting, capacitor C gets discharged through it. Thus, the current through the load flows in the opposite direction forming the negative alternation. This current builds up to the negative maximum and then decreases to zero at point *R*.

- SCR T_2will then be turned-off. Now, the capacitor voltage reverses to some value depending upon the values of R, L and C.
- Again, after some time delay (T_{off}), SCR T_1, is triggered and in the same fashion other cycles are produced. This is a chain of process giving rise to alternating output almost sinusoidal in nature.
- One important point to be noted here is that the supply from the d.c. source is intermittent in nature. Positive alternation of the a.c. output is drawn from the d.c. input source, whereas for the negative alternation the current is drawn from the capacitor.
- It is necessary to maintain a time delay between the point when one SCR is turned-off and other SCR is triggered. If this is not done, both the SCRs will start conducting simultaneously resulting in a short circuit of the d.c. input source. This time delay *(T_{OFF})* must be more than the turn-off time of the SCRs. The output frequency is given by

$$F = \left[\frac{1}{T/2 + T_{off}}\right] Hz$$

Where$T$ is the time period for oscillations and is given by

$$\frac{T}{2} = \frac{\pi}{\sqrt{\frac{1}{LC} - R^2/4L^2}}$$

$T_{OS}$is the time-delay between tum-off of one SCR and turn-on of the other SCR.

Thus, by changing the value of T_{off}, frequency can be changed without changing the commutating elements.

The basic series inverter has the following drawbacks:

1. The load voltage waveform has more distortion due to the time delay. This distortion is specially high for frequencies less than the resonance frequency.

2. The maximum inverter frequency is limited to a value that is slightly less than the circuit ringing frequency. If the inverter frequency exceeds the circuit ringing frequency, the d.c. source will be short-circuited.

3. The commutating element must have high rating because these compo- nents carry the load current continuously and the capacitor supplies the load current in every alternate half-cycle.

4. Load current is drawn from the d.c. source only during one half-cycle and this increases the peak current rating of the d.c. source. Since the current drawn from the d.c. source is not continuous in nature, more

ripples are present in it.

5. The peak amplitude and duration of the load current in each half-cycle depends on load parameters, resulting in poor output regulation for the inverter.

current source inverter

A single-phase, controlled current-sourced bridge is shown in figure 8.1a and its near square-wave output current is shown in figure 8.1b. No freewheel diodes are required and the thyristors required forced commutation and have to withstand reverse voltages.

An inverter current path must be maintained at all times for the source controlled current. Consider thyristors T1 and T2 on and conducting the constant load current. The capacitors are charged with plates X and Y positive as a result of the previous commutation cycle.

MODE I:

- Thyristors T1 and T2 are commutated by triggering thyristors T3 and T4. The capacitors impress negative voltages across the respective thyristors to be commutated off, as shown in figure 8.2b.
- The load current is displaced from T1 and T2 via the path T3-C1-D1, the load and D2-C2-T4. The two capacitors discharge in series with the load, each capacitor reverse biasing the thyristor to be commutated, T1 and T2 as well as diodes D3 to D4. The capacitors discharge linearly (due to the constant current source).

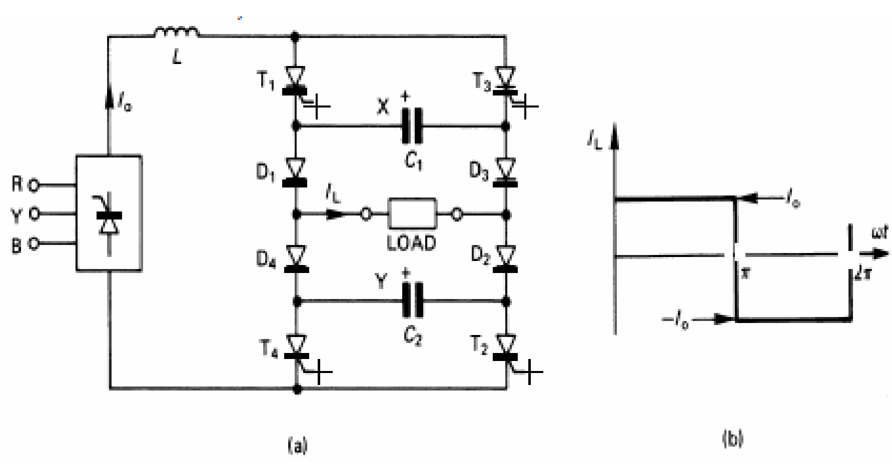


Figure 8.1.Single-phase controlled-current sourced bridge inverter:
(a) bridge circuit with a current source input and (b) load current waveform.

MODE II:

- When both capacitors are discharged, the load current transfers from D1 to D2 and from D3 to D4, which connects the capacitors in parallel with the load via diodes D1 to D2. The plates X and Y now charge negative, ready for the next commutation cycle, as shown in figure 8.2b.
- Thyristors T1 and T2 are now forward biased and must have attained forward blocking ability before the start of phase 2.
- The on-going thyristor automatically commutates the outgoing thyristor. This repeated commutation sequencing is a processed termed *auto-sequential thyristor commutation*.

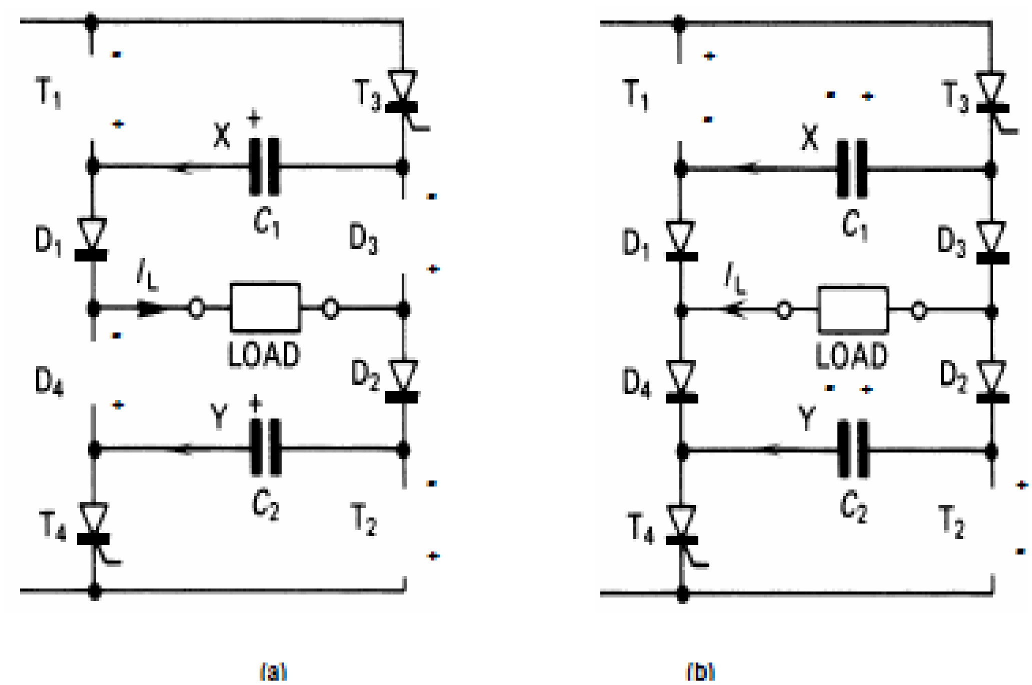


Figure 8.2. Controlled-current sourced bridge inverter showing commutation of T1 and T2 by T3 and T4: (a) capacitors C1 and C2 discharging and T1, T2, D3, and D4 reversed biased and(b) C1, C2, and the load in parallel with C1 and C2 charging.

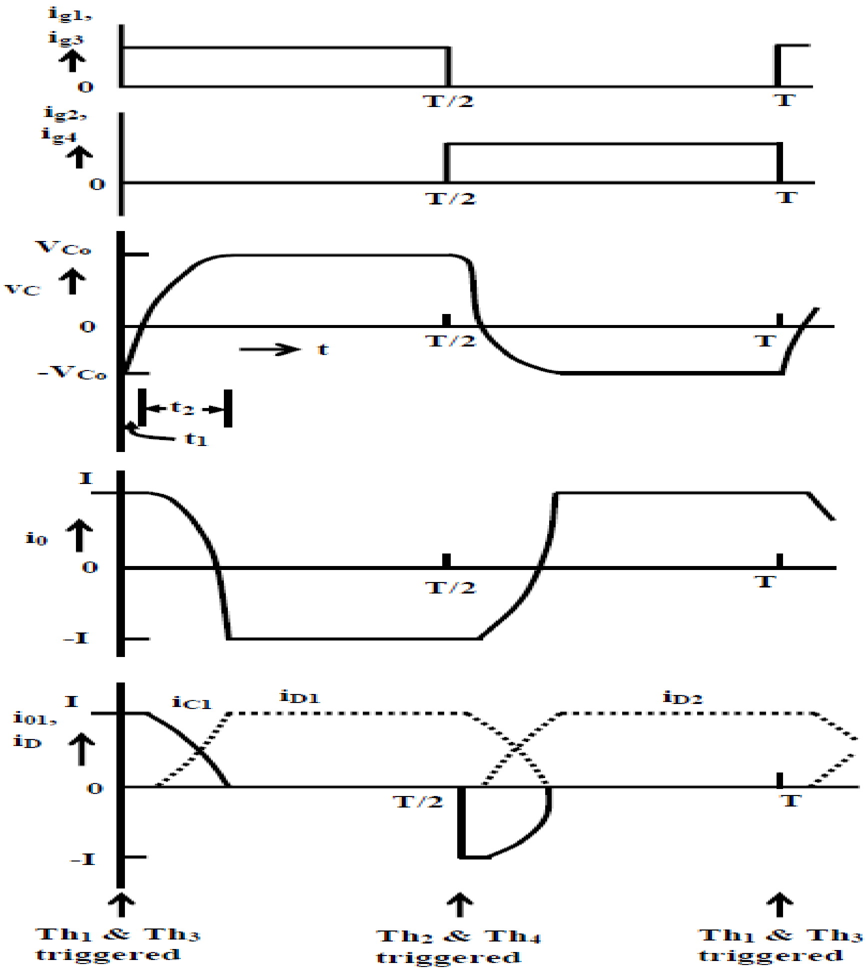
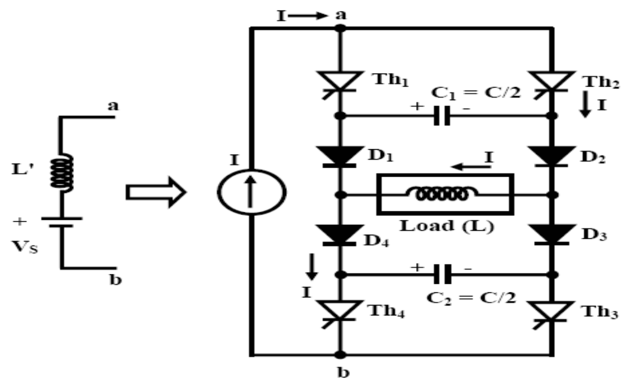


Fig. Voltage and current waveforms

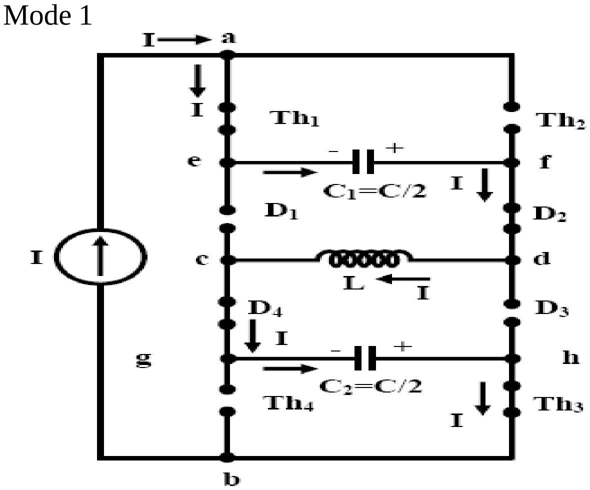
- The load voltage is load dependent and usually has controlled voltage spikes during commutation. Since the GTO and GCT both can be commutated from the gate, the two commutation capacitors C1 and C2 are not necessary. Commutation overlap is still essential.
- Also, if the thyristors have reverse blocking capability, the four diodes D1 to D4 are not necessary. IGBTs require series blocking diodes, which increases on-state losses.
- In practice, the current source inverter is only used in very high-power applications (>1MVA), and the ratings of the self-commutating thyristor devices can be greatly extended if the simple external capacitive commutation circuits shown in figure are used to reduce thyristor turn-off stresses.

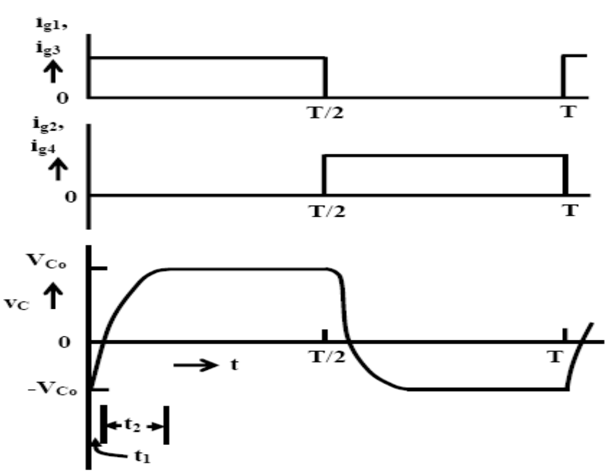
Single phase current source inverter.



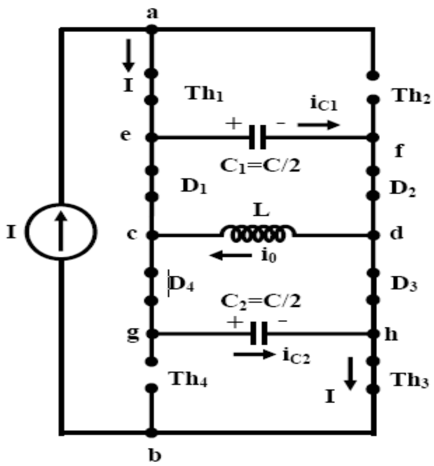
The thyristor pairs, Th_1 & Th_3, and Th_2 & Th_4, are alternatively turned ON to obtain a nearly square wave current waveform. Two commutating capacitors − C_1 in the upper half, and C_2 in the lower half, are used. Four diodes, D_1–D_4 are connected in series with each thyristor to prevent the commutating capacitors from discharging into the load. The output frequency of the inverter is controlled in the usual way, i.e., by varying the half time period, (T/2), at which the thyristors in pair are triggered by pulses being fed to the respective gates by the control circuit, to turn them ON, as can be observed from the waveforms (Fig. 39.2). The inductance (L) is taken as the load in this case, the reason(s) for which need not be stated, being well known. The operation is explained by two modes.

Mode 1

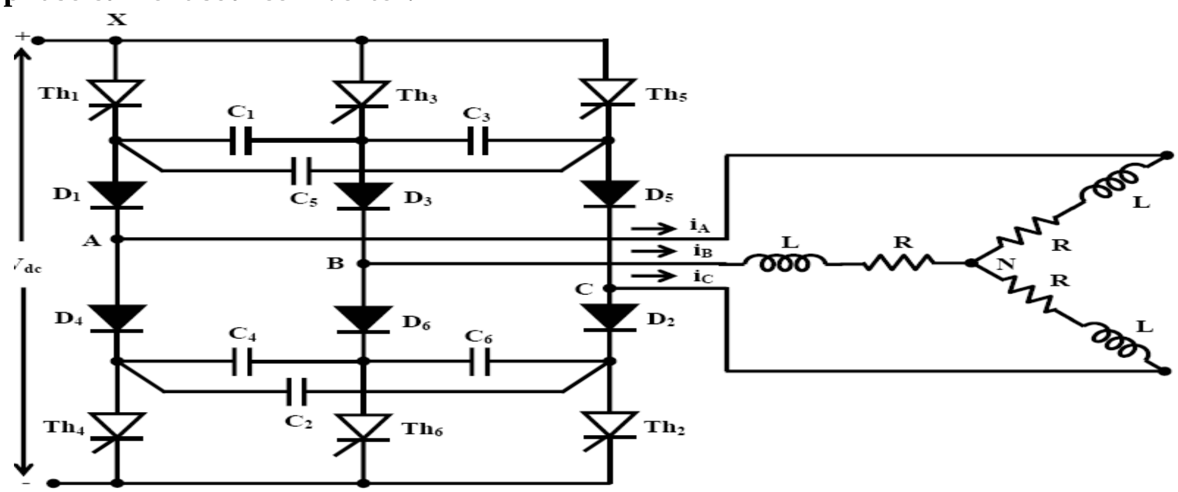




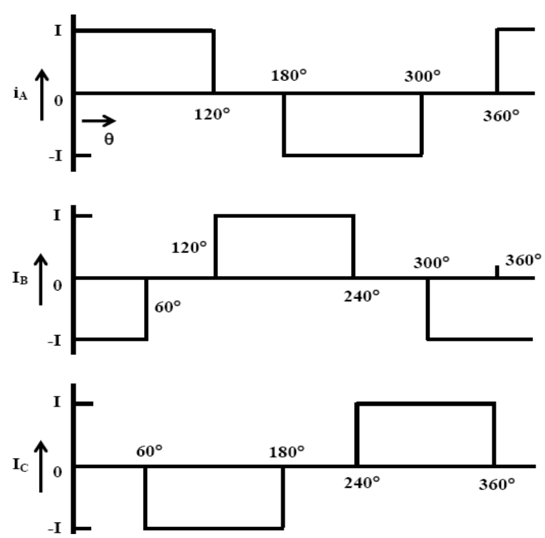
Mode 2



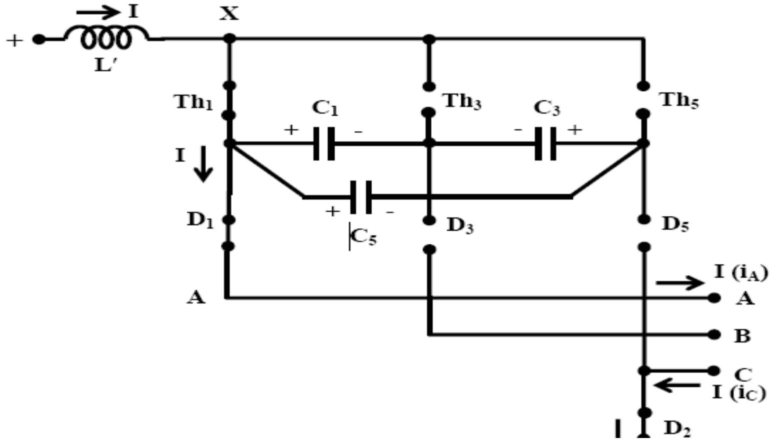
Three phase current source inverter.



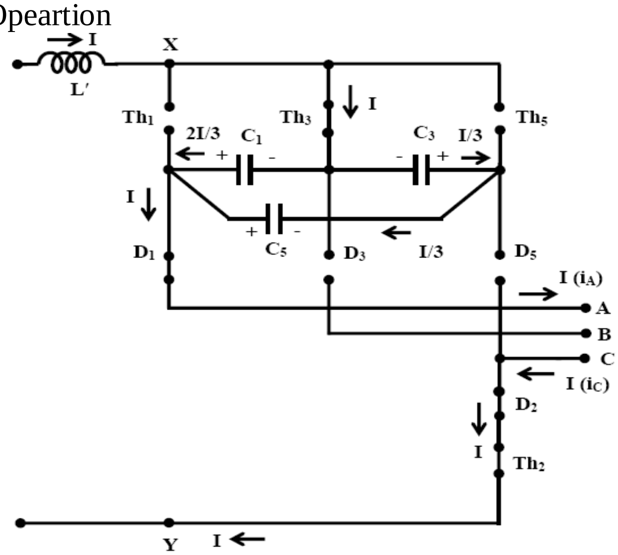
Thyristors being triggered in sequence



Mode 1 operation

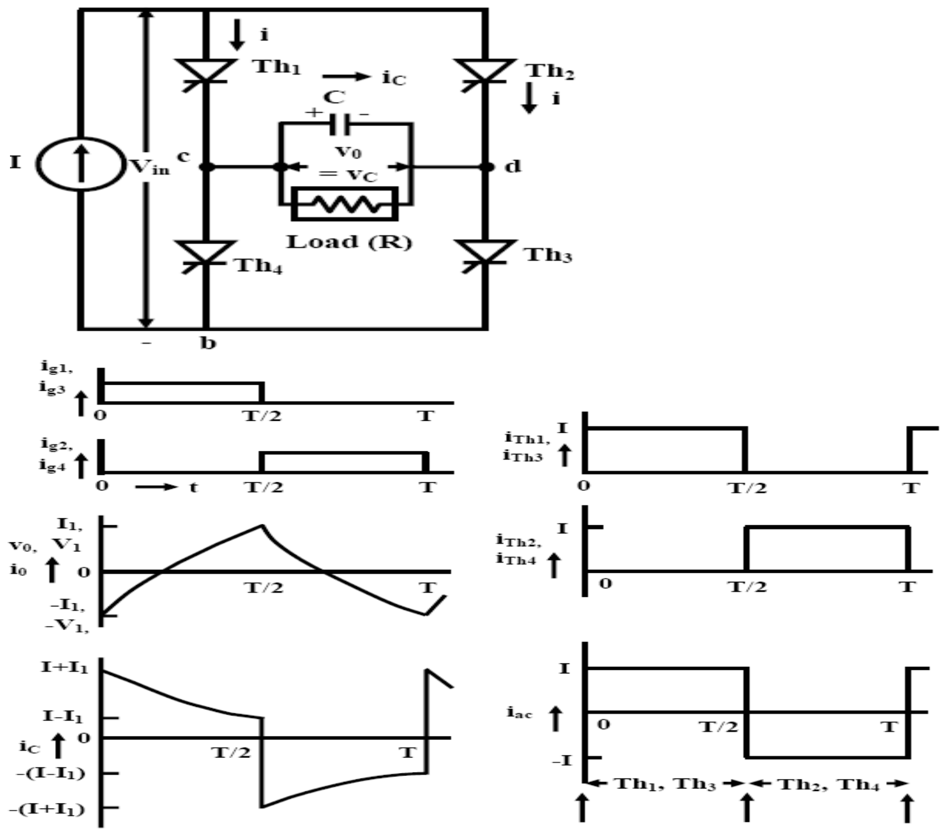


Mode 2 Opeartion



Load commutated current source inverter.

Two commutating capacitors, along with four diodes, are used in the above circuit for commutation from one pair of thyristors to the second pair. Earlier, also in VSI, if the load is capacitive, it was shown that forced commutation may not be needed. The operation of a single-phase CSI with capacitive load (Fig. 40.1) is discussed here. It may be noted that the capacitor, C is assumed to be in parallel with resistive load (R). The capacitor, C is used for storing the charge, or voltage, to be used to force-commutate the conducting thyristor pair as will be shown. As was the case in the last lesson, a constant current source, or a voltage source with large inductance, is used as the input to the circuit

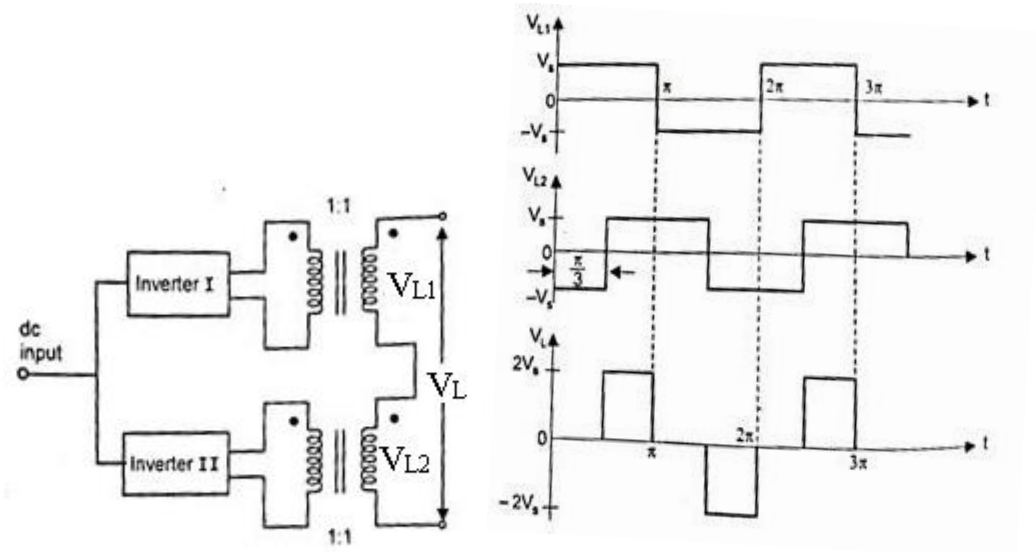


HARMONIC CONTROL OF INVERTER?

Harmonic reduction by Transformer connection

To get net output voltage with reduced harmonic content,

- Output voltage from two or more inverters can be obtained by means of transformers.
- The essential conditions of this scheme is that the output voltage waveforms from the inverter must be similar ***but phase shifted from each other***
- The below Fig. shows a scheme for connecting two inverters and two transformers for harmonic elimination



Their output voltage V_{L1} from inverter 1 and V_{L2} from inverter 2 are shown in waveform
V_{L2} is phase shifted by $\pi/3$ radians with respect to V_{L1}
By adding the magnitudes the resultant waveform is obtained

The absence of third harmonic in the output waveform V_L can be explained by writing the fourier series for V_{L1} and V_{L2}

$$V_{L_1} = A_1 sin\omega t + A_3 \sin 3\omega t + A_5 \sin 5\omega t + \cdots$$

$$V_{L_2} = A_1 \sin(\omega t - \frac{\pi}{3}) + A_3 \sin 3(\omega t - \frac{\pi}{3}) + A_5 \sin 5(\omega t - \frac{\pi}{3}) + \cdots$$

The resultant voltage VL is obtained by vector addition
VL=VL1+VL2

$$V_L = \sqrt{3}\left[A_1 \sin\left(\omega t - \frac{\pi}{6}\right) + \mathrm{A}_5 \sin 5\left(\omega t + \frac{\pi}{6}\right) + \cdots\right]$$

From the above expression of VL, it is observed that with the phase shifting of $\frac{\pi}{3}$ and combining voltages by transformer connection it is possible to eliminate 3rd Harmonics.
Also multiples of 3rd harmonics such as 9,12 , harmonics also eleimnated

Drawbacks: Needs more number of inverter and transformerof similar rating

HARMONIC REDUCTION BY MULTIPLE COMMUTATION IN EACH HALF CYCLE

This method is explained with respect to a single phase inverter.

Normally there is one commutation per half cycle at the end of each half cycleand this produces a square wave output

Instead of having commutation at the end of half cycle some more commutation can be created in the half cycle and the waveform is as shown

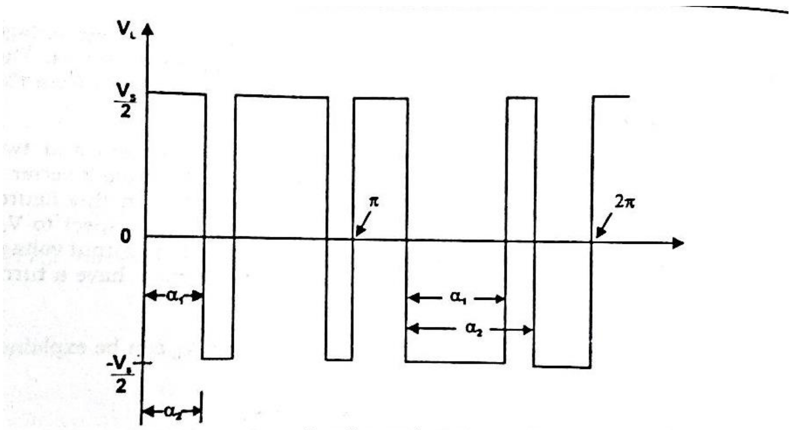


Figure 5.32: Harmonic reduction using four extra communication per cycle

By properly selecting the values of delay angle α_1 and α_2, any two unwanted lower order harmonics can be eliminated

Here waveform are drawn for single phase half bridge inverter

It employs 4 extra commutations per cycle instead of one

$$B_n = \frac{4V_S}{\pi}\left[\int_0^{\alpha_1} \sin n\omega t\ d(\omega t) - \int_{\alpha_1}^{\alpha_2} \sin n\omega t\ d(\omega t) + \int_{\alpha_2}^{\pi/2} \sin\ n\omega t(\omega t)\right]$$

$$= \frac{4V_S}{\pi}\left[\frac{1 - 2cosn\alpha_1 + 2cosn\alpha_2}{n}\right]$$

If the 3rd and 5th order harmonics are to be eliminated

Substituting n=3 and 5 in above eqn.

$$B_3 = \frac{4V_S}{\pi}\left[\frac{1 - 2Cos3\alpha_1 + 2Cos3\alpha_2}{3}\right] = 0$$

$$B_5 = \frac{4V_S}{\pi}\left[\frac{1 - 2Cos5\alpha_1 + 2Cos5\alpha_2}{5}\right] = 0$$

Or the numerators should be equal to zero

$1 - 2Cos3\alpha_1 + 2Cos3\alpha_2 = 0$ and

$1 - 2COS5\alpha\_1 + 2COS5\alpha\_2 = 0$

The above 2 simultaneous equations can be solved numerically to calculate $\alpha 1$ and $\alpha 2$ under the condition that $0<\alpha 1<90°$

Whcich gives $\alpha 1=23.62°$ and $\alpha 2=33.6°$

Similarly any 2 harmonics can be eliminated by calculating values of $\alpha 1$ and $\alpha 2$

Dis advantage

1. The inverter is derated by 16.1%
2. Need for additional 4 commutations per cycle, resulting in switching losses and hence efficiency

HARMONIC REDUCTION USING STEPPED WAVE INVERTER

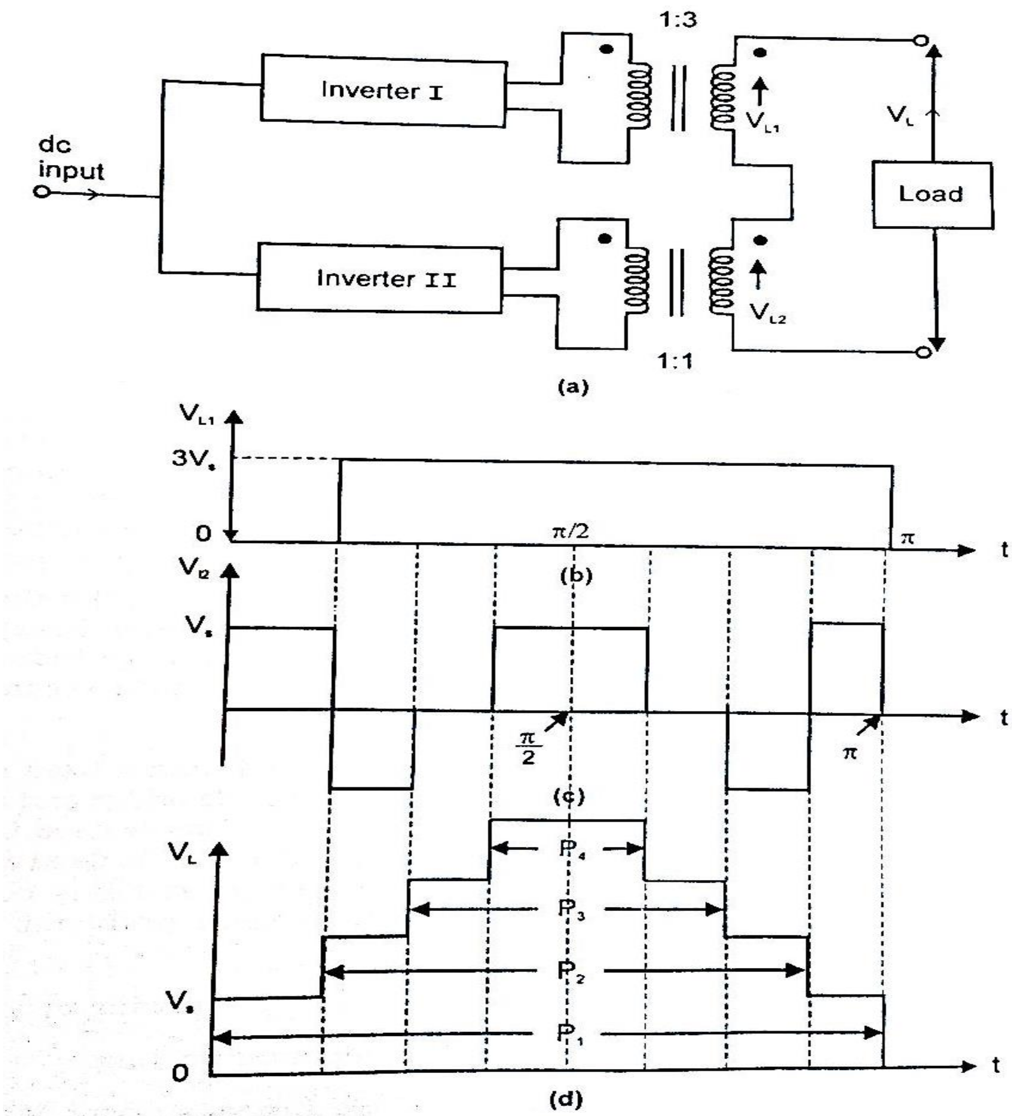


Figure 5.33: Stepped wave inverters

This method is also called as wave-stepping in which pulses of different widths and heights are added to produce a resultant stepped wave with reduced harmonic content

Fig 1 shows 2 stepped wave inverters fed from a common dc input voltage.These inverters are connected to a common load through transformers having turn ratio of 1:3 and 1:1 respectively

The inverter 1 is so operated that its output voltage is VL1 as shown

The output voltage level is either zero or positive during the first half cycle

During second half cycle the output voltage would be either zero or negative. This type of modulation in which the output voltage has only two levels during any half cycle is called as ***two level modulations***

The inverter II is so operated that its output voltage is VL2 as shown

Here the output voltage is positive , zero and negative during first half cycle. Therefore the inverter II is operated with three level modulation

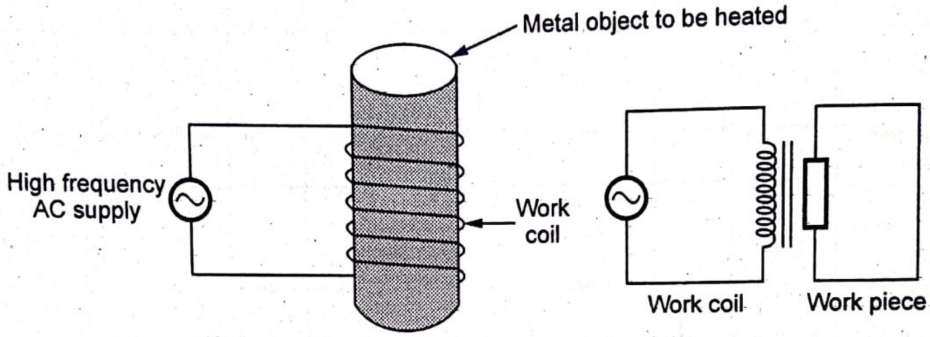
The resultant waveform is obtained by adding the magnitudes as shown in the waveform

By this method 3rd, 5th, and 7th harmonics can be decreases considerably

Applications-Induction heating, UPS.

Induction Heating

- Fig. 4.10.1 shows the induction heating setup used for metal object.



(a) Basic induction heating setup

(b) Equivalent circuit

Fig. 4.10.1 Principle of induction heating

- The high frequency AC supply drives the coil, which is wound around the object to be heated.
- When current flows through the coil, it induces magnetic flux in the metal object. This flux generates eddy currents in the metal object.
- The eddy currents flow in circular connected paths in the metal object. Due to internal resistance of the metal object, heat is produced. Thus the metal object starts heating.
- Fig. 4.10.1(b) shows an equivalent circuit of the induction heating. The work coil acts as primary and work piece acts as shorted secondary. The object heats up due to current flow in shorted path.

Advantages of Induction Heating

i) Induction heating provides very high heating ratios (up to 5 kW/cm^2).

ii) Temperature can be controlled automatically with the help of feedback.

iii) The heat transferred to the metal object can be controlled with the help of electronic timers

iv) Heat is not wasted since it is generated internally in the metal object.

v) Surface hardening of steel is possible due to skin effect of eddy currents.

vi) Induction heating can take place in vacuum, inert gases as well as other gases.

Disadvantages of Induction Heating

i) Heating is not even. It is more in regions that are closer to heating coil.

ii) The shape of the work piece and coil should match.

iii) Heating is more in the corners of work piece.

iv) Cost of the heating equipment is very high.

v) Efficiency of heating is poor.

Applications of Induction Heating

i) Surface hardening of steel.

ii) Soldering and brazing.

iii) Annealing of brass and bronze items.

iv) Induction cooking using metal pans and pots.

v) Drying points on metals, sintering powdered metals.

vi) Sterilizing surgical instruments.

vii) Welding and bonding clutch facing.

Uninterruptible Power Supply (UPS)

- An UPS is used to provide the power when mains is not available. In the present days of load shading, UPS is playing major role. UPS is being used along with computers.
- There are three types of UPS as follows

i) Online UPS

ii) Offline UPS

iii) Line interactive UPS

The block diagrams and working of these UPS is discussed next.

Online UPS

The online UPS is also called inverter preferred UPS. Fig. 4.10.2 shows the block diagram of online UPS. (See Fig. 4.10.2 on next page)

- When the main supply is present, the rectifier/charger provides power to an inverter as well as battery (See Fig. 4.10.3 (a)). The battery is charged. The inverter is on and feeds power to the load through UPS static switch.
- The UPS static switch is always on and connects load to inverter output.
- The mains static switch is always off. But when the UPS fails, then load is connected directly to the mains directly through mains static switch.

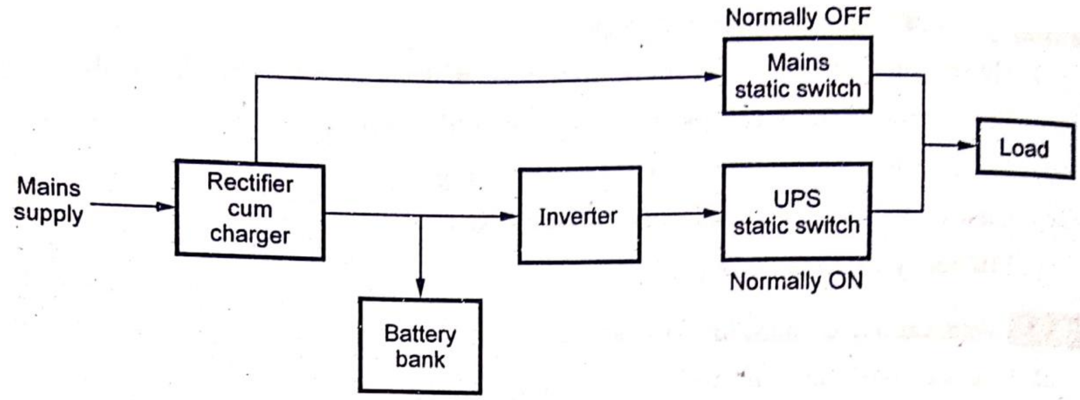
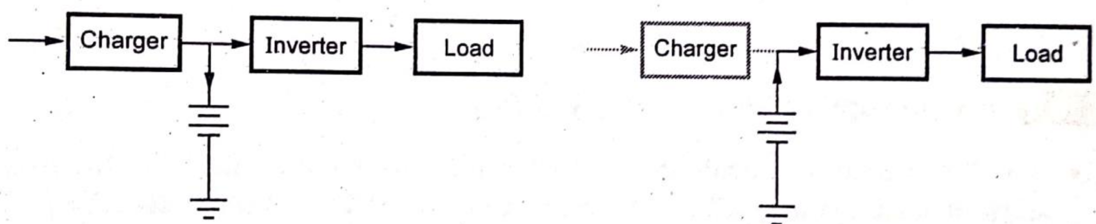


Fig. 4.10.2 Block diagram of online UPS system

- When the mains supply is not available, then battery bank supplies power to an inverter (See Fig. 4.10.3 (b)). Thus an inverter is always on and it takes power from rectifier or battery.
- Fig. 4.10.3 shows the power flow when mains is present and mains is absent.



(a) When mains is present **(b) When mains is absent**

Fig. 4.10.3 Power flow in online UPS

Offline UPS

The offline UPS is also called line preferred UPS. Fig. 4.10.4 shows the block diagram of an offline UPS. Observe that this diagram appears similar to that of online UPS, but it is functionally different.

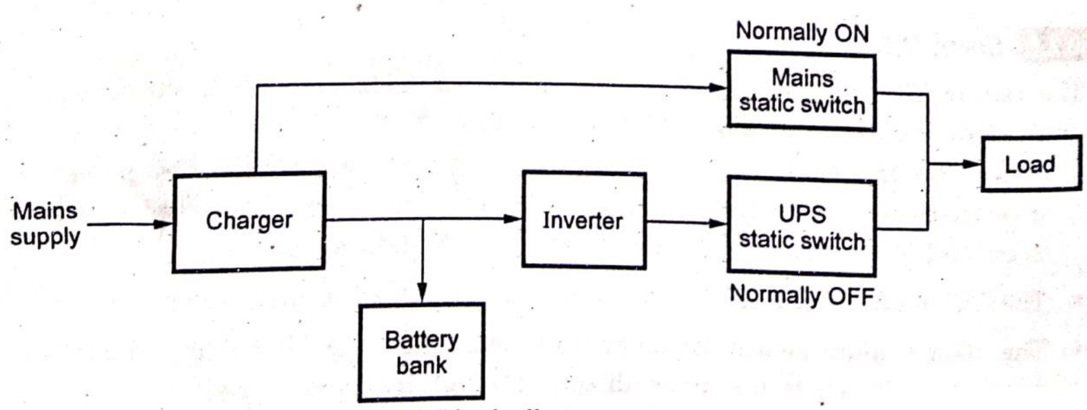
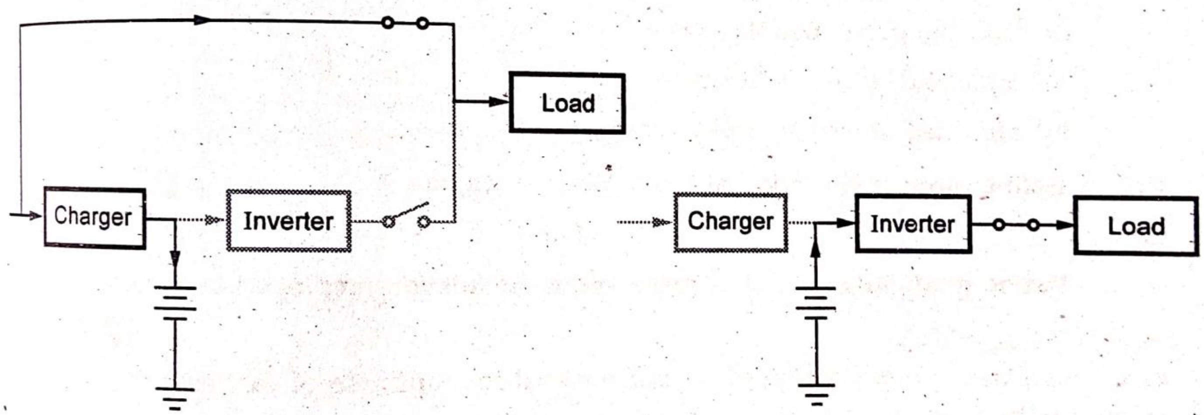


Fig. 4.10.4 Block diagram of offline UPS

- When mains supply is present, then charger charges the battery. Inverter is off and UPS static switch is off. The load is connected to mains through mains static switch. The power flow is shown in Fig. 4.10.5 (a).
- When mains supply is not available, then inverter is turned on.
- Inverter takes power from the battery. The load is connected to inverter output through UPS static switch. The power flow diagram is shown in Fig. 4.10.5 (b).
- The mains static switch is always on and keeps load connected to mains. The mains static switch is turned off when mains is not available.
- The charger feeds power only to the battery. Hence its power handling capacity is reduced.



(a) When mains is present (b) When mains is absent

Fig. 4.10.5 Power flow in offline UPS

UNIT III

UNCONTROLLED RECTIFIERS

INTRODUCTION

- AC voltage controllers (ac line voltage controllers) are employed to vary the RMS value of the alternating voltage applied to a load circuit by introducing Thyristors between the load and a constant voltage ac source.

- The RMS value of alternating voltage applied to a load circuit is controlled by controlling the triggering angle of the Thyristors in the ac voltage controller circuits.

- In brief, an ac voltage controller is a type of thyristor power converter which is used to convert a fixed voltage, fixed frequency ac input supply to obtain a variable voltage ac output.

- The RMS value of the ac output voltage and the ac power flow to the load is controlled by varying (adjusting) the trigger angle 'α'

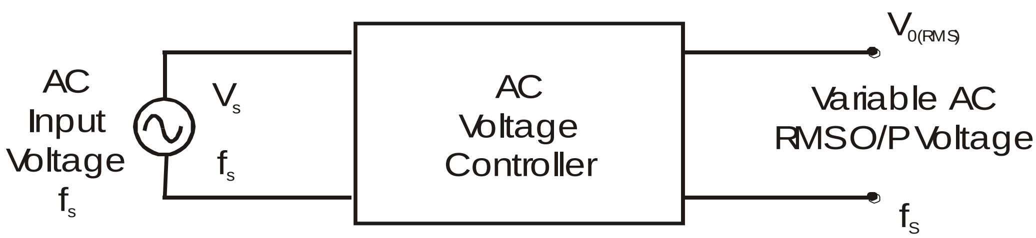


Fig.1

TYPE OF AC VOLTAGE CONTROLLER

- The ac voltage controllers are classified into two types based on the type of input ac supply applied to the circuit.
  - Single Phase AC Controllers.
  - Three Phase AC Controllers.
- Single phase ac controllers operate with single phase ac supply voltage of 230V RMS at 50Hz in our country.

- Three phase ac controllers operate with 3 phase ac supply of 400V RMS at 50Hz supply frequency.

- Each type of controller may be sub divided into

  - Uni-directional or half wave ac controller.
  - Bi-directional or full wave ac controller.
- In brief different types of ac voltage controllers are

  - Single phase half wave ac voltage controller (uni-directional controller).
  - Single phase full wave ac voltage controller (bi-directional controller).

- Three phase half wave ac voltage controller (uni-directional controller).
- Three phase full wave ac voltage controller (bi-directional controller).

AC VOLTAGE CONTROL TECHNIQUES

- There are two different types of thyristor control used in practice to control the ac power flow
  - Phase control
  - On-Off control
- These are the two ac output voltage control techniques.
- In On-Off control technique Thyristors are used as switches to connect the load circuit to the ac supply (source) for a few cycles of the input ac supply and then to disconnect it for few input cycles.
- The Thyristors thus act as a high speed contactor (or high speed ac switch).

PHASE CONTROL TECHNIQUE.

- In phase control the Thyristors are used as switches to connect the load circuit to the input ac supply, for a part of every input cycle.
- That is the ac supply voltage is chopped using Thyristors during a part of each input cycle.
- The thyristor switch is turned on for a part of every half cycle, so that input supply voltage appears across the load and then turned off during the remaining part of input half cycle to disconnect the ac supply from the load.
- By controlling the phase angle or the trigger angle 'α' (delay angle), the output RMS voltage across the load can be controlled.
- The trigger delay angle 'α' is defined as the phase angle (the value of ωt) at which the thyristor turns on and the load current begins to flow.
- Thyristor ac voltage controllers use ac line commutation or ac phase commutation.
- Thyristors in ac voltage controllers are line commutated (phase commutated) since the input supply is ac.
- When the input ac voltage reverses and becomes negative during the negative half cycle the current flowing through the conducting thyristor decreases and falls to zero.
- Thus the ON thyristor naturally turns off, when the device current falls to zero.

- ❖ Phase control Thyristors which are relatively inexpensive, converter grade Thyristors which are slower than fast switching inverter grade Thyristors are normally used.
- ❖ For applications up to 400Hz, if Triacs are available to meet the voltage and current ratings of a particular application, Triacs are more commonly used.
- ❖ Due to ac line commutation or natural commutation, there is no need of extra commutation circuitry or components and the circuits for ac voltage controllers are very simple.
- ❖ Due to the nature of the output waveforms, the analysis, derivations of expressions for performance parameters are not simple, especially for the phase controlled ac voltage controllers with RL load.
- ❖ But however most of the practical loads are of the RL type and hence RL load should be considered in the analysis and design of ac voltage controller circuits.

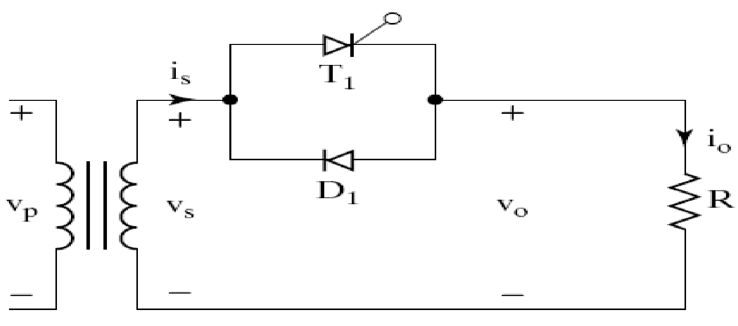
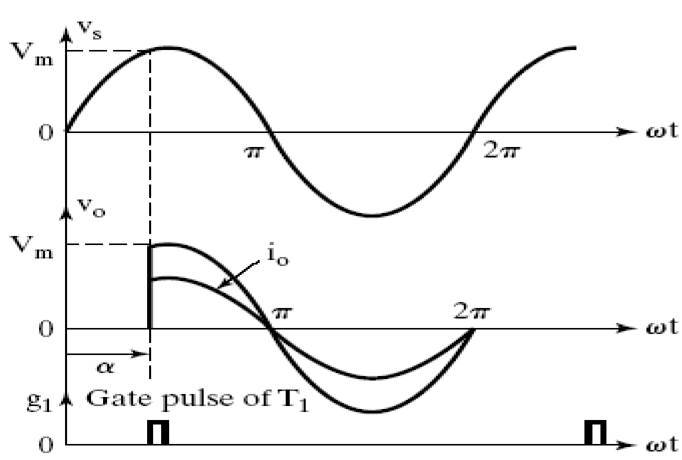


Fig.: Halfwave AC phase controller (Unidirectional Controller)



EQUATIONS:

- ❖ **Input AC Supply Voltage across the Transformer Secondary Winding:**

$$v_s = V_m \sin \omega t$$

$$V_S = V_{in(RMS)} = \frac{V_m}{\sqrt{2}}$$ = RMS value of secondary supply voltage.

- **Output Load Voltage:**

$v_o = v_L = 0$; for $\omega t = 0$ to α

$v_o = v_L = V_m \sin \omega t$; for $\omega t = \alpha$ to 2π.

- **Output Load Current:**

$i_o = i_L = \frac{v_o}{R_L} = \frac{V_m \sin \omega t}{R_L}$; for $\omega t = \alpha$ to 2π.

$i_o = i_L = 0$; for $\omega t = 0$ to α.

TO DERIVE AN EXPRESSION FOR RMS OUTPUT VOLTAGE: $V_{O(RMS)}$

$$V_{O(RMS)} = \sqrt{\frac{1}{2\pi}\left[\int_{\alpha}^{2\pi} V_m^{\,2} \sin^2 \omega t.d\left(\omega t\right)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^{\,2}}{2\pi}\left[\int_{\alpha}^{2\pi}\left(\frac{1-\cos 2\omega t}{2}\right).d\left(\omega t\right)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^{\,2}}{4\pi}\left[\int_{\alpha}^{2\pi}\left(1-\cos 2\omega t\right).d\left(\omega t\right)\right]}$$

$$V_{O(RMS)} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\left[\int_{\alpha}^{2\pi} d\left(\omega t\right) - \int_{\alpha}^{2\pi} \cos 2\omega t.d\omega t\right]}$$

$$V_{O(RMS)} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\left[\left(\omega t\right)\Big/_{\alpha}^{2\pi} - \left(\frac{\sin 2\omega t}{2}\right)\Big/_{\alpha}^{2\pi}\right]}$$

$$V_{O(RMS)} = \frac{V_m}{2\sqrt{\pi}}\sqrt{\left(2\pi-\alpha\right) - \left(\frac{\sin 2\omega t}{2}\right)\Big/_{\alpha}^{2\pi}}$$

$$V_{O(RMS)} = \frac{V_m}{2\sqrt{\pi}} \sqrt{(2\pi-\alpha) - \left\{\frac{\sin 4\pi}{2} - \frac{\sin 2\alpha}{2}\right\}} \qquad ; \sin 4\pi = 0$$

$$V_{O(RMS)} = \frac{V_m}{2\sqrt{\pi}} \sqrt{(2\pi-\alpha) + \frac{\sin 2\alpha}{2}}$$

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}\sqrt{2\pi}} \sqrt{(2\pi-\alpha) + \frac{\sin 2\alpha}{2}}$$

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}} \sqrt{\frac{1}{2\pi}\left[(2\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]}$$

$$V_{O(RMS)} = V_{i(RMS)} \sqrt{\frac{1}{2\pi}\left[(2\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]}$$

$$V_{O(RMS)} = V_S \sqrt{\frac{1}{2\pi}\left[(2\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]}$$

Where, $V_{i(RMS)} = V_S = \frac{V_m}{\sqrt{2}}$ = RMS value of input supply voltage (across the transformer secondary winding).

Note: Output RMS voltage across the load is controlled by changing $'\alpha'$ as indicated by the expression for $V_{O(RMS)}$

TO CALCULATE THE AVERAGE VALUE (DC VALUE) OF OUTPUT VOLTAGE:

$$V_{O(dc)} = \frac{1}{2\pi} \int_{\alpha}^{2\pi} V_m \sin \omega t . d(\omega t)$$

$$V_{O(dc)} = \frac{V_m}{2\pi} \int_{\alpha}^{2\pi} \sin \omega t . d(\omega t)$$

$$V_{O(dc)} = \frac{V_m}{2\pi} \left[-\cos \omega t \Big/_{\alpha}^{2\pi} \right]$$

$$V_{O(dc)} = \frac{V_m}{2\pi} \left[-\cos 2\pi + \cos \alpha \right] \qquad ; \cos 2\pi = 1$$

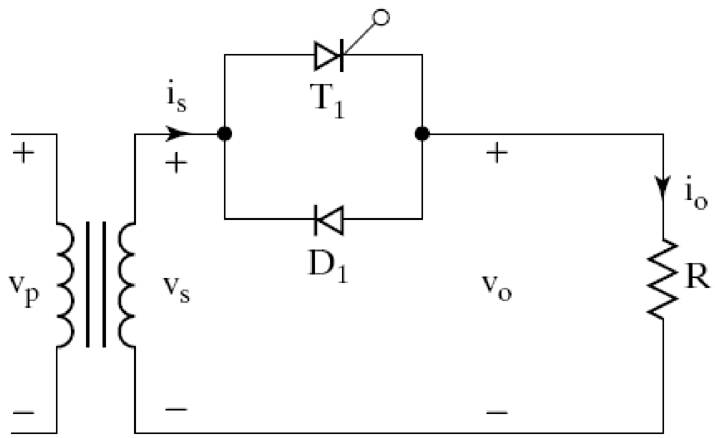
$$V_{dc} = \frac{V_m}{2\pi}\left[\cos\alpha - 1\right] \quad ; \; V_m = \sqrt{2}V_S$$

Hence $V_{dc} = \frac{\sqrt{2}V_S}{2\pi}\left(\cos\alpha - 1\right)$

When $'\alpha'$ is varied from 0 to π . V_{dc} varies from 0 to $\frac{-V_m}{\pi}$

Problem.1

- *A single phase half-wave ac voltage controller has a load resistance $R = 50\Omega$, input ac supply voltage is 230V RMS at 50Hz. The input supply transformer has a turns ratio of 1:1. If the thyristor T_1 is triggered at $\alpha = 60^0$. Calculate*
  - *RMS output voltage.*
  - *Output power.*
  - *RMS load current and average load current.*
  - *Input power factor.*
  - *Average and RMS thyristor current.*



GIVEN:

$V_p = 230V, RMS$ primary supply voltage.

$f =$ Input supply frequency = 50Hz.

$R_L = 50\Omega$

$\alpha = 60^0 = \frac{\pi}{3}$ radians.

$V_S =$ RMS secondary voltage.

$$\frac{V_p}{V_S} = \frac{N_p}{N_S} = \frac{1}{1} = 1$$

Therefore $V_p = V_S = 230V$

Where, N_p = Number of turns in the primary winding.

N_S = Number of turns in the secondary winding.

TO FIND:

- *RMS output voltage.*
- *Output power.*
- *RMS load current and average load current.*
- *Input power factor.*
- *Average and RMS thyristor current.*

SOLUTION:

- **RMS Value of Output (Load) Voltage** $V_{O(RMS)}$

$$V_{O(RMS)} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{2\pi} V_m^2 \sin^2 \omega t.d\left(\omega t\right)}$$

We have obtained the expression for $V_{O(RMS)}$ as

$$V_{O(RMS)} = V_S \sqrt{\frac{1}{2\pi}\left[\left(2\pi - \alpha\right)\right] + \frac{\sin 2\alpha}{2}}$$

$$V_{O(RMS)} = 230\sqrt{\frac{1}{2\pi}\left[\left(2\pi - \frac{\pi}{3}\right)\right] + \frac{\sin 120^0}{2}}$$

$$V_{O(RMS)} = 230\sqrt{\frac{1}{2\pi}\left[5.669\right]} = 230 \times 0.94986$$

$$V_{O(RMS)} = 218.4696\ V \approx 218.47\ V$$

- **RMS Load Current** $I_{O(RMS)}$

$$I_{O(RMS)} = \frac{V_{O(RMS)}}{R_L} = \frac{218.46966}{50} = 4.36939\ Amps$$

- **Output Load Power** P_O

$$P_O = I^2_{O(RMS)} \times R_L = (4.36939)^2 \times 50 = 954.5799\ Watts$$

$$P_O = 0.9545799\ KW$$

- **Input Power Factor**

$$PF = \frac{P_O}{V_S \times I_S}$$

V_S = RMS secondary supply voltage = 230V.

I_S = RMS secondary supply current = RMS load current.

$$\therefore I_S = I_{O(RMS)} = 4.36939\ Amps$$

$$\therefore PF = \frac{954.5799 \text{ W}}{(230 \times 4.36939) \text{ W}} = 0.9498$$

- **Average Output (Load) Voltage**

$$V_{O(dc)} = \frac{1}{2\pi}\left[\int_{\alpha}^{2\pi} V_m \sin\omega t.d(\omega t)\right]$$

We have obtained the expression for the average / DC output voltage as,

$$V_{O(dc)} = \frac{V_m}{2\pi}[\cos\alpha - 1]$$

$$V_{O(dc)} = \frac{\sqrt{2} \times 230}{2\pi}\left[\cos(60^0) - 1\right] = \frac{325.2691193}{2\pi}[0.5 - 1]$$

$$V_{O(dc)} = \frac{325.2691193}{2\pi}[-0.5] = -25.88409 \text{ Volts}$$

- **Average DC Load Current**

$$I_{O(dc)} = \frac{V_{O(dc)}}{R_L} = \frac{-25.884094}{50} = -0.51768 \text{ Amps}$$

- **Average & RMS Thyristor Currents**

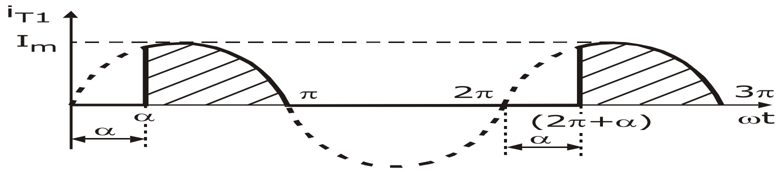


Fig.: Thyristor Current Waveform

Referring to the thyristor current waveform of a single phase half-wave ac voltage controller circuit, we can calculate the average thyristor current $I_{T(Avg)}$ as

$$I_{T(Avg)} = \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} I_m \sin\omega t.d\left(\omega t\right)\right]$$

$$I_{T(Avg)} = \frac{I_m}{2\pi}\left[\int_{\alpha}^{\pi} \sin\omega t.d\left(\omega t\right)\right]$$

$$I_{T(Avg)} = \frac{I_m}{2\pi}\left[\left(-\cos\omega t\right)\Big/_{\alpha}^{\pi}\right]$$

$$I_{T(Avg)} = \frac{I_m}{2\pi}\left[-\cos\left(\pi\right)+\cos\alpha\right]$$

$$I_{T(Avg)} = \frac{I_m}{2\pi}\left[1+\cos\alpha\right]$$

Where, $I_m = \frac{V_m}{R_L}$ = Peak thyristor current = Peak load current.

$$I_m = \frac{\sqrt{2}\times 230}{50}$$

$$I_m = 6.505382 \text{ Amps}$$

$$I_{T(Avg)} = \frac{V_m}{2\pi R_L}\left[1+\cos\alpha\right]$$

$$I_{T(Avg)} = \frac{\sqrt{2}\times 230}{2\pi\times 50}\left[1+\cos\left(60^0\right)\right]$$

$$I_{T(Avg)} = \frac{\sqrt{2} \times 230}{100\pi}[1+0.5]$$

$$I_{T(Avg)} = 1.5530 \text{ Amps}$$

- RMS thyristor current $I_{T(RMS)}$ can be calculated by using the expression

$$I_{T(RMS)} = \sqrt{\frac{1}{2\pi}\left[\int_{\alpha}^{\pi} I_m^2 \sin^2 \omega t.d(\omega t)\right]}$$

$$I_{T(RMS)} = \sqrt{\frac{I_m^2}{2\pi}\left[\int_{\alpha}^{\pi} \frac{(1-\cos 2\omega t)}{2}.d(\omega t)\right]}$$

$$I_{T(RMS)} = \sqrt{\frac{I_m^2}{4\pi}\left[\int_{\alpha}^{\pi} d(\omega t) - \int_{\alpha}^{\pi} \cos 2\omega t.d(\omega t)\right]}$$

$$I_{T(RMS)} = I_m \sqrt{\frac{1}{4\pi}\left[(\omega t)\Big/_{\alpha}^{\pi} - \left(\frac{\sin 2\omega t}{2}\right)\Big/_{\alpha}^{\pi}\right]}$$

$$I_{T(RMS)} = I_m \sqrt{\frac{1}{4\pi}\left[(\pi-\alpha) - \left\{\frac{\sin 2\pi - \sin 2\alpha}{2}\right\}\right]}$$

$$I_{T(RMS)} = I_m \sqrt{\frac{1}{4\pi}\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]}$$

$$I_{T(RMS)} = \frac{I_m}{\sqrt{2}} \sqrt{\frac{1}{2\pi}\left[(\pi-\alpha) + \frac{\sin 2\alpha}{2}\right]}$$

$$I_{T(RMS)} = \frac{6.50538}{\sqrt{2}} \sqrt{\frac{1}{2\pi}\left[\left(\pi - \frac{\pi}{3}\right) + \frac{\sin(120^0)}{2}\right]}$$

$$I_{T(RMS)} = 4.6\sqrt{\frac{1}{2\pi}\left[\left(\frac{2\pi}{3}\right) + \frac{0.8660254}{2}\right]}$$

$$I_{T(RMS)} = 4.6 \times 0.6342 = 2.91746A$$

$$I_{T(RMS)} = 2.91746 \text{ Amps}$$

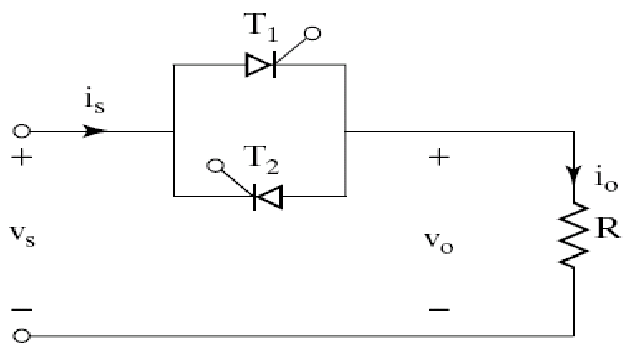
PRINCIPLE OF ON-OFF CONTROL TECHNIQUE (INTEGRALCYCLE CONTROL)

(OR)

OPERATION OF SINGLE PHASE FULL WAVE AC VOLTAGE CONTROLLER WITH R LOAD.

The basic principle of on-off control technique is explained with reference to a single phase full wave ac voltage controller circuit shown below.

- ❖ The thyristor switches T_1 and T_2 are turned on by applying appropriate gate trigger pulses to connect the input ac supply to the load for 'n' number of input cycles during the time interval t_{ON}.
- ❖ The thyristor switches T_1 and T_2 are turned off by blocking the gate trigger pulses for 'm' number of input cycles during the time interval t_{OFF}.
- ❖ The ac controller ON time t_{ON} usually consists of an integral number of input cycles.



$R = R_L$ = Load Resistance

Fig.2: Single phase full wave AC voltage controller circuit

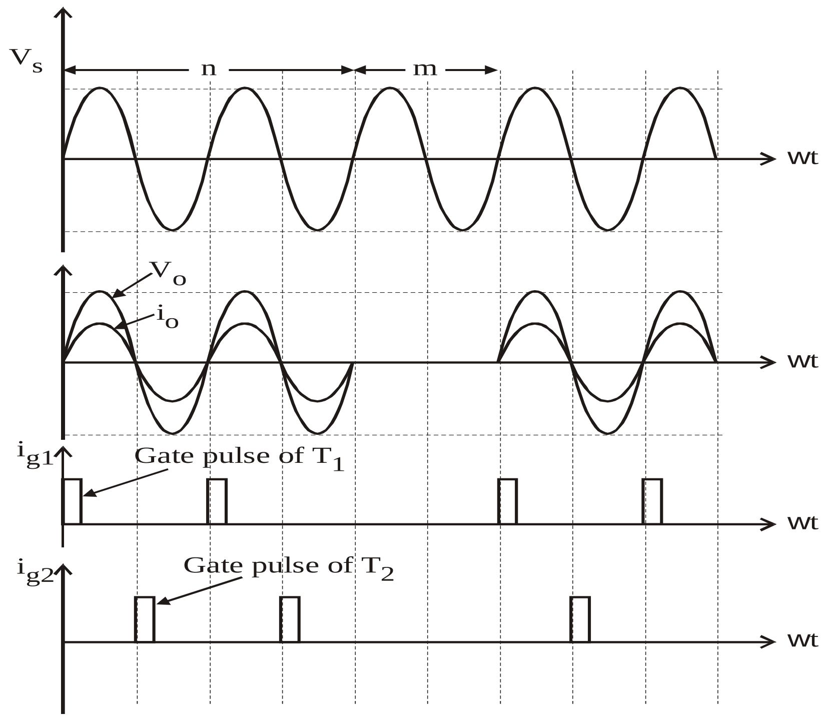


Fig.3: Waveforms

Example

- Referring to the waveforms of ON-OFF control technique in the above diagram,

$n =$ Two input cycles. Thyristors are turned ON during t_{ON} for two input cycles.

$m =$ One input cycle. Thyristors are turned OFF during t_{OFF} for one input cycle

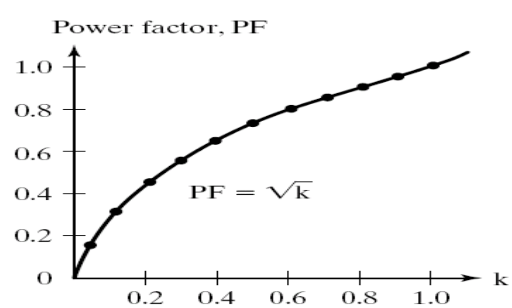


Fig.4: Power Factor

- Thyristors are turned ON precisely at the zero voltage crossings of the input supply.

- The thyristor T_1 is turned on at the beginning of each positive half cycle by applying the gate trigger pulses to T_1 as shown, during the ON time t_{ON} .
- The load current flows in the positive direction, which is the downward direction as shown in the circuit diagram when T_1 conducts.
- The thyristor T_2 is turned on at the beginning of each negative half cycle, by applying gating signal to the gate of T_2, during t_{ON}.
- The load current flows in the reverse direction, which is the upward direction when T_2 conducts.
- Thus we obtain a bi-directional load current flow (alternating load current flow) in a ac voltage controller circuit, by triggering the thyristors alternately.
- This type of control is used in applications which have high mechanical inertia and high thermal time constant (Industrial heating and speed control of ac motors).
- Due to zero voltage and zero current switching of Thyristors, the harmonics generated by switching actions are reduced.
- For a sine wave input supply voltage,

$$v_s = V_m \sin \omega t = \sqrt{2} V_S \sin \omega t$$

$V_S =$ RMS value of input ac supply = $\frac{V_m}{\sqrt{2}}$ = RMS phase supply voltage.

- If the input ac supply is connected to load for 'n' number of input cycles and disconnected for 'm' number of input cycles, then

$$t_{ON} = n \times T, \qquad t_{OFF} = m \times T$$

Where $T = \frac{1}{f}$ = input cycle time (time period) and

f = input supply frequency.

t_{ON} = controller on time = $n \times T$.

t_{OFF} = controller off time = $m \times T$.

T_O = Output time period = $\left(t_{ON} + t_{OFF}\right) = \left(nT + mT\right)$.

- We can show that, Output RMS voltage $V_{O(RMS)} = V_{i(RMS)} \sqrt{\frac{t_{ON}}{T_O}} = V_S \sqrt{\frac{t_{ON}}{T_O}}$

Where $V_{i(RMS)}$ is the RMS input supply voltage = V_S.

TO DERIVE AN EXPRESSION FOR THE RMS VALUE OF OUTPUT VOLTAGE, FOR ON-OFF CONTROL METHOD:

- Output RMS voltage $V_{O(RMS)} = \sqrt{\frac{1}{\omega T_O} \int_{\omega t=0}^{\omega t_{ON}} V_m^{\ 2} Sin^2 \omega t.d(\omega t)}$

$$V_{O(RMS)} = \sqrt{\frac{V_m^{\ 2}}{\omega T_O} \int_{0}^{\omega t_{ON}} Sin^2 \omega t.d(\omega t)}$$

- Substituting for $Sin^2\theta = \frac{1 - Cos 2\theta}{2}$

$$V_{O(RMS)} = \sqrt{\frac{V_m^{\ 2}}{\omega T_O} \int_{0}^{\omega t_{ON}} \left[\frac{1 - Cos 2\omega t}{2}\right] d(\omega t)}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^{\ 2}}{2\omega T_O} \left[\int_{0}^{\omega t_{ON}} d(\omega t) - \int_{0}^{\omega t_{ON}} Cos 2\omega t.d(\omega t)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^{\ 2}}{2\omega T_O} \left[(\omega t) \Big/_{0}^{\omega t_{ON}} - \frac{Sin 2\omega t}{2} \Big/_{0}^{\omega t_{ON}}\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^{\ 2}}{2\omega T_O} \left[(\omega t_{ON} - 0) - \frac{\sin 2\omega t_{ON} - \sin 0}{2}\right]}$$

Now t_{ON} = An integral number of input cycles; Hence

$t_{ON} = T, 2T, 3T, 4T, 5T, ...$ & $\omega t_{ON} = 2\pi, 4\pi, 6\pi, 8\pi, 10\pi, ...$

- Where T is the input supply time period (T = input cycle time period). Thus we note that $\sin 2\omega t_{ON} = 0$

$$V_{O(RMS)} = \sqrt{\frac{V_m^{\ 2} \not{\omega} t_{ON}}{2 \not{\omega} T_O}} = \frac{V_m}{\sqrt{2}} \sqrt{\frac{t_{ON}}{T_O}}$$

$$V_{O(RMS)} = V_{i(RMS)} \sqrt{\frac{t_{ON}}{T_O}} = V_S \sqrt{\frac{t_{ON}}{T_O}}$$

❖ Where $V_{i(RMS)} = \frac{V_m}{\sqrt{2}} = V_S =$ RMS value of input supply voltage;

$$\frac{t_{ON}}{T_O} = \frac{t_{ON}}{t_{ON} + t_{OFF}} = \frac{nT}{nT + mT} = \frac{n}{(n+m)} = k = \text{duty cycle (d).}$$

$$V_{O(RMS)} = V_S \sqrt{\frac{n}{(m+n)}} = V_S \sqrt{k}$$

PERFORMANCE PARAMETERS OF AC VOLTAGE CONTROLLERS:

1. **RMS Output (Load) Voltage:**

$$V_{O(RMS)} = \left[\frac{n}{2\pi(n+m)} \int_0^{2\pi} V_m^{\ 2} \sin^2 \omega t . d(\omega t) \right]^{1/2}$$

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}} \sqrt{\frac{n}{(m+n)}} = V_{i(RMS)} \sqrt{k} = V_S \sqrt{k}$$

$$V_{O(RMS)} = V_{i(RMS)} \sqrt{k} = V_S \sqrt{k}$$

Where $V_S = V_{i(RMS)}$ = RMS value of input supply voltage

2. **Duty Cycle:**

$$k = \frac{t_{ON}}{T_O} = \frac{t_{ON}}{(t_{ON} + t_{OFF})} = \frac{nT}{(m+n)T}$$

Where, $k = \frac{n}{(m+n)}$ = duty cycle (d).

3. **RMS Load Current:**

$$I_{O(RMS)} = \frac{V_{O(RMS)}}{Z} = \frac{V_{O(RMS)}}{R_L}; \quad \text{for a resistive load } Z = R_L.$$

4. **Output AC (Load) Power:**

$$P_O = I_{O(RMS)}^2 \times R_L$$

5. **Input Power Factor:**

$$PF = \frac{P_O}{VA} = \frac{\text{output load power}}{\text{input supply volt amperes}} = \frac{P_O}{V_S I_S}$$

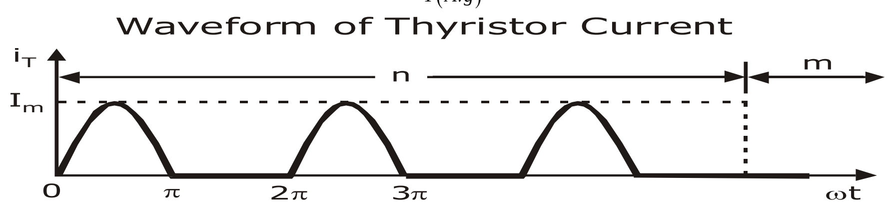
$$PF = \frac{I_{O(RMS)}^2 \times R_L}{V_{i(RMS)} \times I_{in(RMS)}};\qquad I_S = I_{in(RMS)} = \text{RMS input supply current.}$$

- The input supply current is same as the load current $I_{in} = I_O = I_L$
- Hence, RMS supply current = RMS load current; $I_{in(RMS)} = I_{O(RMS)}$.

$$PF = \frac{I_{O(RMS)}^2 \times R_L}{V_{i(RMS)} \times I_{in(RMS)}} = \frac{V_{O(RMS)}}{V_{i(RMS)}} = \frac{V_{i(RMS)}\sqrt{k}}{V_{i(RMS)}} = \sqrt{k}$$

$$PF = \sqrt{k} = \sqrt{\frac{n}{m+n}}$$

6. The Average Current of Thyristor : $I_{T(Avg)}$



$$I_{T(Avg)} = \frac{n}{2\pi(m+n)} \int_0^{\pi} I_m \sin\omega t.d(\omega t)$$

$$I_{T(Avg)} = \frac{nI_m}{2\pi(m+n)} \int_0^{\pi} \sin\omega t.d(\omega t)$$

$$I_{T(Avg)} = \frac{nI_m}{2\pi(m+n)} \left[-\cos\omega t \Big/_0^{\pi} \right]$$

$$I_{T(Avg)} = \frac{nI_m}{2\pi(m+n)} \left[-\cos\pi + \cos 0 \right]$$

$$I_{T(Avg)} = \frac{nI_m}{2\pi(m+n)} \left[-(-1) + 1 \right]$$

$$I_{T(Avg)} = \frac{n}{2\pi(m+n)} \left[2I_m \right]$$

$$I_{T(Avg)} = \frac{I_m n}{\pi(m+n)} = \frac{k.I_m}{\pi}$$

$$k = \text{duty cycle} = \frac{t_{ON}}{(t_{ON} + t_{OFF})} = \frac{n}{(n+m)}$$

$$I_{T(Avg)} = \frac{I_m n}{\pi(m+n)} = \frac{k.I_m}{\pi},$$

Where $I_m = \frac{V_m}{R_L}$ = maximum or peak thyristor current.

7. RMS Current of Thyristor $I_{T(RMS)}$

$$I_{T(RMS)} = \left[\frac{n}{2\pi(n+m)} \int_0^{\pi} I_m^2 \sin^2 \omega t.d(\omega t) \right]^{1/2}$$

$$I_{T(RMS)} = \left[\frac{nI_m^2}{2\pi(n+m)} \int_0^{\pi} \sin^2 \omega t.d(\omega t) \right]^{1/2}$$

$$I_{T(RMS)} = \left[\frac{nI_m^2}{2\pi(n+m)} \int_0^{\pi} \frac{(1-\cos 2\omega t)}{2} d(\omega t) \right]^{1/2}$$

$$I_{T(RMS)} = \left[\frac{nI_m^2}{4\pi(n+m)} \left\{ \int_0^{\pi} d(\omega t) - \int_0^{\pi} \cos 2\omega t.d(\omega t) \right\} \right]^{1/2}$$

$$I_{T(RMS)} = \left[\frac{nI_m^2}{4\pi(n+m)} \left\{ (\omega t) \Big/_0^{\pi} - \left(\frac{\sin 2\omega t}{2} \right) \Big/_0^{\pi} \right\} \right]^{1/2}$$

$$I_{T(RMS)} = \left[\frac{nI_m^2}{4\pi(n+m)} \left\{ (\pi - 0) - \left(\frac{\sin 2\pi - \sin 0}{2} \right) \right\} \right]^{1/2}$$

$$I_{T(RMS)} = \left[\frac{nI_m^2}{4\pi(n+m)} \{\pi - 0 - 0\} \right]^{1/2}$$

$$I_{T(RMS)} = \left[\frac{nI_m^2\pi}{4\pi(n+m)}\right]^{1/2} = \left[\frac{nI_m^2}{4(n+m)}\right]^{1/2}$$

$$I_{T(RMS)} = \frac{I_m}{2}\sqrt{\frac{n}{(m+n)}} = \frac{I_m}{2}\sqrt{k}$$

$$I_{T(RMS)} = \frac{I_m}{2}\sqrt{k}$$

PROBLEM 1

- *A single phase full wave ac voltage controller working on ON-OFF control technique has supply voltage of 230V, RMS 50Hz, load = 50Ω. The controller is ON for 30 cycles and off for 40 cycles. Calculate*
    1. *ON & OFF time intervals.*
    2. *RMS output voltage.*
    3. *Input P.F.*
    4. *Average and RMS thyristor currents.* ***NOV/DEC-12***

GIVEN:

F=50Hz, R= 50Ω. $V_{in(RMS)} = 230V$, $m = 40$ $n = 30$.

TO FIND:

1. ON & OFF time intervals.
2. RMS output voltage.
3. Input P.F.
4. Average and RMS thyristor currents

SOLUTION:

$V_{in(RMS)} = 230V$, $V_m = \sqrt{2}\times 230V = 325.269\,\text{V}$, $V_m = 325.269V$,

$$T = \frac{1}{f} = \frac{1}{50Hz} = 0.02\sec, \quad T = 20ms .$$

n = number of input cycles during which controller is ON; $n = 30$.

m = number of input cycles during which controller is OFF; $m = 40$.

$t_{ON} = n\times T = 30\times 20ms = 600ms = 0.6\sec$

$t_{ON} = n\times T = 0.6\sec$ = controller ON time.

$t_{OFF} = m\times T = 40\times 20ms = 800ms = 0.8\sec$

$t_{OFF} = m\times T = 0.8\sec$ = controller OFF time.

Duty cycle $k = \frac{n}{(m+n)} = \frac{30}{(40+30)} = 0.4285$

RMS output voltage:

$$V_{O(RMS)} = V_{i(RMS)} \times \sqrt{\frac{n}{(m+n)}}$$

$$V_{O(RMS)} = 230V \times \sqrt{\frac{30}{(30+40)}} = 230\sqrt{\frac{3}{7}}$$

$$V_{O(RMS)} = 230V\sqrt{0.42857} = 230 \times 0.65465$$

$$V_{O(RMS)} = 150.570V$$

$$I_{O(RMS)} = \frac{V_{O(RMS)}}{Z} = \frac{V_{O(RMS)}}{R_L} = \frac{150.570V}{50\Omega} = 3.0114A$$

$$P_O = I^2_{O(RMS)} \times R_L = 3.0114^2 \times 50 = 453.426498W$$

Input Power Factor: $P.F = \sqrt{k}$

$$PF = \sqrt{\frac{n}{(m+n)}} = \sqrt{\frac{30}{70}} = \sqrt{0.4285}$$

$$PF = 0.654653$$

Average Thyristor Current Rating:

$$I_{T(Avg)} = \frac{I_m}{\pi} \times \left(\frac{n}{m+n}\right) = \frac{k \times I_m}{\pi}$$

where $I_m = \frac{V_m}{R_L} = \frac{\sqrt{2} \times 230}{50} = \frac{325.269}{50}$

$I_m = 6.505382A$ = Peak (maximum) thyristor current.

$$I_{T(Avg)} = \frac{6.505382}{\pi} \times \left(\frac{3}{7}\right)$$

$I_{T(Avg)} = 0.88745A$

RMS Current Rating of Thyristor:

$$I_{T(RMS)} = \frac{I_m}{2}\sqrt{\frac{n}{(m+n)}} = \frac{I_m}{2}\sqrt{k} = \frac{6.505382}{2} \times \sqrt{\frac{3}{7}}$$

$$I_{T(RMS)} = 2.129386A$$

PROBLEM 2

A Single phase full wave AC voltage controller has an input voltage of 230V, 50Hz, and it is feeding resistive load of 10 Ω. If firing angle of thyristor is 110degree. Find the output rms voltage, Input Power Factor and Average current of thyristor. ***NOV/DEC-14***

GIVEN:

V_S =230 V, f = 50 HZ , α=110°, R=10Ω

TO FIND:

The output rms voltage, Input Power Factor and Average current of thyristor.

SOLUTION:

A Single phase full wave AC voltage controller V_S =230 V, f = 50 HZ , α=110°, R=10Ω

1. RMS output voltage ($V_o(rms)$)

$$V_o(rms) = V_S[1/\pi(\pi - \alpha + \frac{\sin 2\alpha}{2})]^{1/2}$$

$$= 230\left[1/\pi(\pi - \frac{11}{18}\pi) + \frac{\sin 2(110^\circ)}{2}\right]^{1/2}$$

$$= 230\left[\frac{1}{\pi}(\frac{7}{18}\pi) + (-0.3214)\right]^{1/2}$$

$$= 230[0.3889 - 0.3214]^{1/2}$$

$$= 230(0.0675)^{1/2}$$

RMS output voltage, $V_O(rms) = 59.76V$

2. Input Power Factor (PF)

$$I_O(rms) = \frac{V_O(rms)}{R} = \frac{59.76}{10}$$

RMS Load Current, $I_O(rms) = 5.98A$

$$P_o = I_O^{\,2}(rms).R$$

$$= (5.98)^2 \times 10$$

$$P_o = 357.6W$$

Since , input current is the same as the load current , the input V-A rating

$$VA = V_s I_s = V_S I_O = 230 \times 5.98 = 1375.4W$$

The input power factor,

$$PF = \frac{P_O}{VA} = \frac{V_O}{V_S} = \left[1/\pi(\pi - \alpha + \frac{Sin2\alpha}{2})\right]^{\frac{1}{2}}$$

$$= [0.3889 - 0.3214]^{1/2} = 0.2598 \ (Lagging)$$

3. Average current of thyristor

$$I_A = \frac{1}{2\pi R}\int_{\alpha}^{\pi} \sqrt{2} V_S Sin\omega t d(\omega t)$$

$$I_A = \frac{V_s\sqrt{2}}{2\pi R}(\cos\alpha + 1)$$

$$= \frac{\sqrt{2}}{2\pi} \times \frac{230}{10}(\cos 110^\circ + 1)$$

$$I_A = 3.41A$$

Phase Controlled Single-Phase AC Voltage Controller with RL load.

The basic power circuit of a single-phase ac-ac voltage controller, as shown in Fig. 16.1a, is composed of a pair of

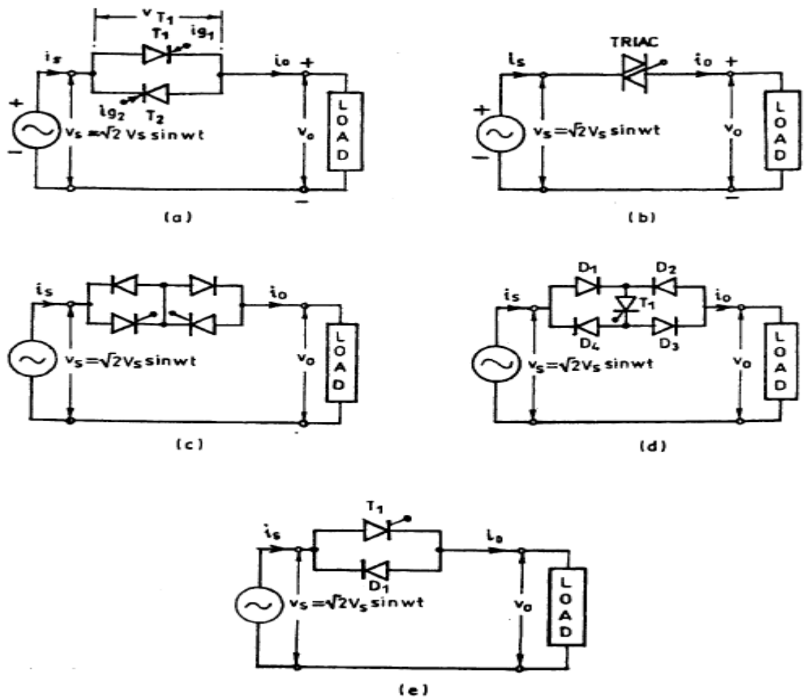


FIGURE 16.1 Single-phase ac voltage controllers: (a) full-wave, two SCRs in inverse parallel; (b) full-wave with Triac; (c) full wave with two SCRs and two diodes; (d) full wave with four diodes and one SCR; and (e) half wave with one SCR and one diode in antiparallel.

SCRs connected back-to-back (also known as inverse-parallel or antiparallel) between the ac supply and the load. This connection provides a bidirectional full-wave symmetrical control and the SCR pair can be replaced by a Triac (Fig. 16.1b) for low-power applications. Alternate arrangements are as shown in Fig. 16.1c with two diodes and two SCRs to provide a common cathode connection for simplifying the gating circuit without needing isolation, and in Fig. 16.1d with one SCR and four diodes to reduce the device cost but with increased device conduction loss. An SCR and diode combination, known as a thyrode controller, as shown in Fig. 16.1e, provides a unidirectional half-wave asymmetrical voltage control with device economy but introduces a dc component and more harmonics and thus is not very practical to use except for a very low power heating load. With phase control, the switches conduct the load current for a chosen period of each input cycle of voltage and with on=off control the switches connect the load either for a few cycles of input voltage and disconnect it for the next few cycles (integral cycle control) or the switches are turned on and off several times within alternate half-cycles of input voltage (ac chopper or PWM ac voltage controller).

Phase-Controlled Single-Phase AC Voltage Controller

For a full-wave, symmetrical phase control, the SCRs T1 and T2 in Fig. 16.1a are gated at α and π+α, respectively, from the zero crossing of the input voltage and by varying α, the power flow to the load is controlled through voltage control in alternate half-cycles. As long as one SCR is carrying current, the other SCR remains reverse-biased by the voltage drop across the conducting SCR. The principle of operation in each half-cycle is similar to that of the controlled half-wave rectifier and one can use the same approach for analysis of the circuit.

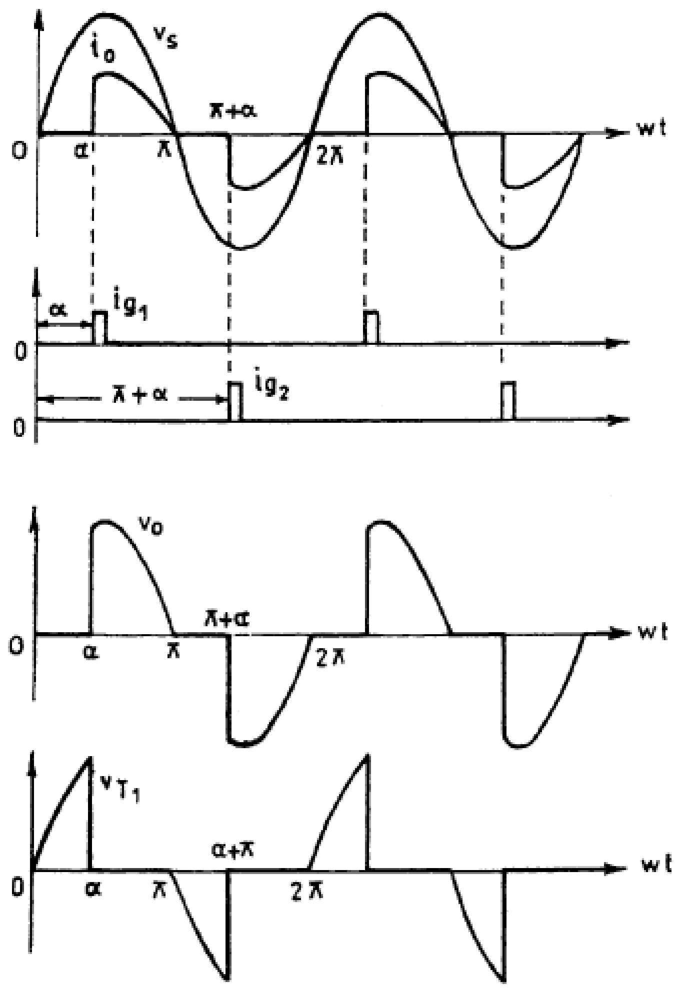


FIGURE 16.2 Waveforms for single-phase ac full-wave voltage controller with *R*-load.

Operation with R-load. Figure 16.2 shows the typical voltage and current waveforms for the single-phase bidirectional phase-controlled ac voltage controller of Fig. 16.1a with resistive load. The output voltage and current waveforms have half-wave symmetry and thus no dc component.

$$If\ V_s = \sqrt{2}V_s sin\omega t$$

is the source voltage, then the rms output voltage with T1 triggered at a can be found from the half-wave symmetry as

$$V_0 = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} 2Vs^2 sin^2\omega t\ d(\omega t)\right]^{\frac{1}{2}} = V_s\left[1 - \frac{\alpha}{\pi} + \frac{sin2\alpha}{2\pi}\right]^{\frac{1}{2}}$$

Note that Vo can be varied from Vs to 0 by varying α from 0 to π. The rms value of load current:

$$I_0 = \frac{V_0}{R}$$

The input power factor:

$$\frac{V_0}{PA} = \frac{V_0}{V_s} = \left[1 - \frac{\alpha}{\pi} + \frac{sin2\alpha}{2\pi}\right]^{\frac{1}{2}}$$

The average SCR current:

$$I_{A,SCR} = \frac{1}{2\pi R}\int_{\alpha}^{\pi} \sqrt{2}V_s sin\omega t\ d(\omega t)$$

As each SCR carries half the line current, the rms current in each SCR is

$$I_{0,SCR} = \frac{I_0}{\sqrt{2}}$$

Operation with RL Load.

Figure 16.3 shows the voltage and current waveforms for the controller in Fig. 16.1a with RL load. Due to the inductance, the current carried by the SCR T1 may not fall to zero at wt=α when the input voltage goes negative and may continue until wt=β, the extinction angle, as shown. The conduction angle

$$\Theta = \beta - \alpha$$

of the SCR depends on the firing delay angle a and the load impedance angle .

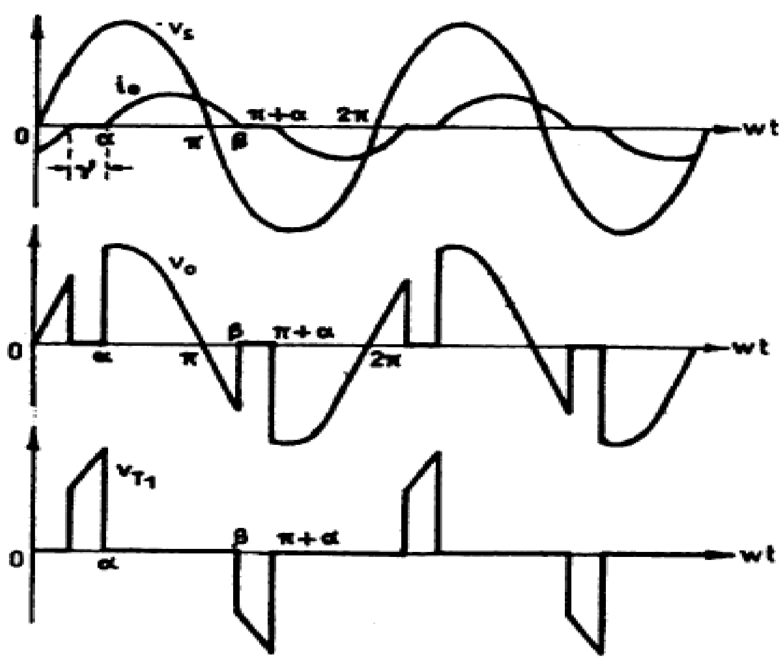


FIGURE 16.3 Typical waveforms of single-phase ac voltage controller with an R -load.

Three-Phase AC to AC Voltage Controllers

Phase-Controlled Three-Phase AC Voltage Controllers

Various Configurations. Several possible circuit configurations for three-phase phase-controlled ac regulators with staror delta-connected loads are shown in Fig. 16.11a–h. The configurations in Fig. 16.11a and b can be realized by three single-phase ac regulators operating independently of each other and they are easy to analyze.

In Fig. 16.11a, the SCRs are to be rated to carry line currents and withstand phase voltages, whereas in Fig. 16.11b they should be capable of carrying phase currents and withstand the line voltages. Also, in Fig. 16.11b the line currents are free from triplen harmonics while these are present in the closed delta.

The power factor in Fig. 16.11b is slightly higher. The firing angle control range for both these circuits is 0 to $180^0$for R-load. The circuits in Fig. 16.11c and d are three-phase three-wire circuits and are difficult to analyze. In both these circuits, at least two SCRs—one in each phase—must be gated simultaneously to get the controller started by establishing a current path between the supply lines.

This necessitates two firing pulses spaced at 60^0apart per cycle for firing each SCR. The operation modes are defined by the number of SCRs conducting in these modes. The firing control range is 0 to 150^0.

The triplen harmonics are absent in both these configurations. Another configuration is shown in Fig. 16.11e when the controllers are delta connected and the load is connected between the supply and the converter.

Here, current can flow between two lines even if one SCR is conducting, so each SCR requires one firing pulse per cycle. The voltage and current ratings of SCRs are nearly the same as those of the circuit in Fig. 6.11b.

It is also possible to reduce the number of devices to three SCRs in delta as shown in Fig. 16.11f connecting one source terminal directly to one load circuit terminal. Each SCR is provided with gate pulses in each cycle spaced 120^0 apart. In both Figs. 16.11e and f each end of each phase must be accessible.

The number of devices in Fig. 16.11f is fewer but their current ratings must be higher. As in the case of the single-phase phase-controlled voltage regulator, the total regulator cost can be reduced by replacing six SCRs by three SCRs and three diodes, resulting in threephase half-wave controlled unidirectional ac regulators as shown in Fig. 16.11g and h for star- and delta-connected loads.

The main drawback of these circuits is the large harmonic content in the output voltage, particularly the second harmonic because of the asymmetry. However, the dc components are absent in the line. The maximum firing angle in the half-wave controlled regulator is 210^0.

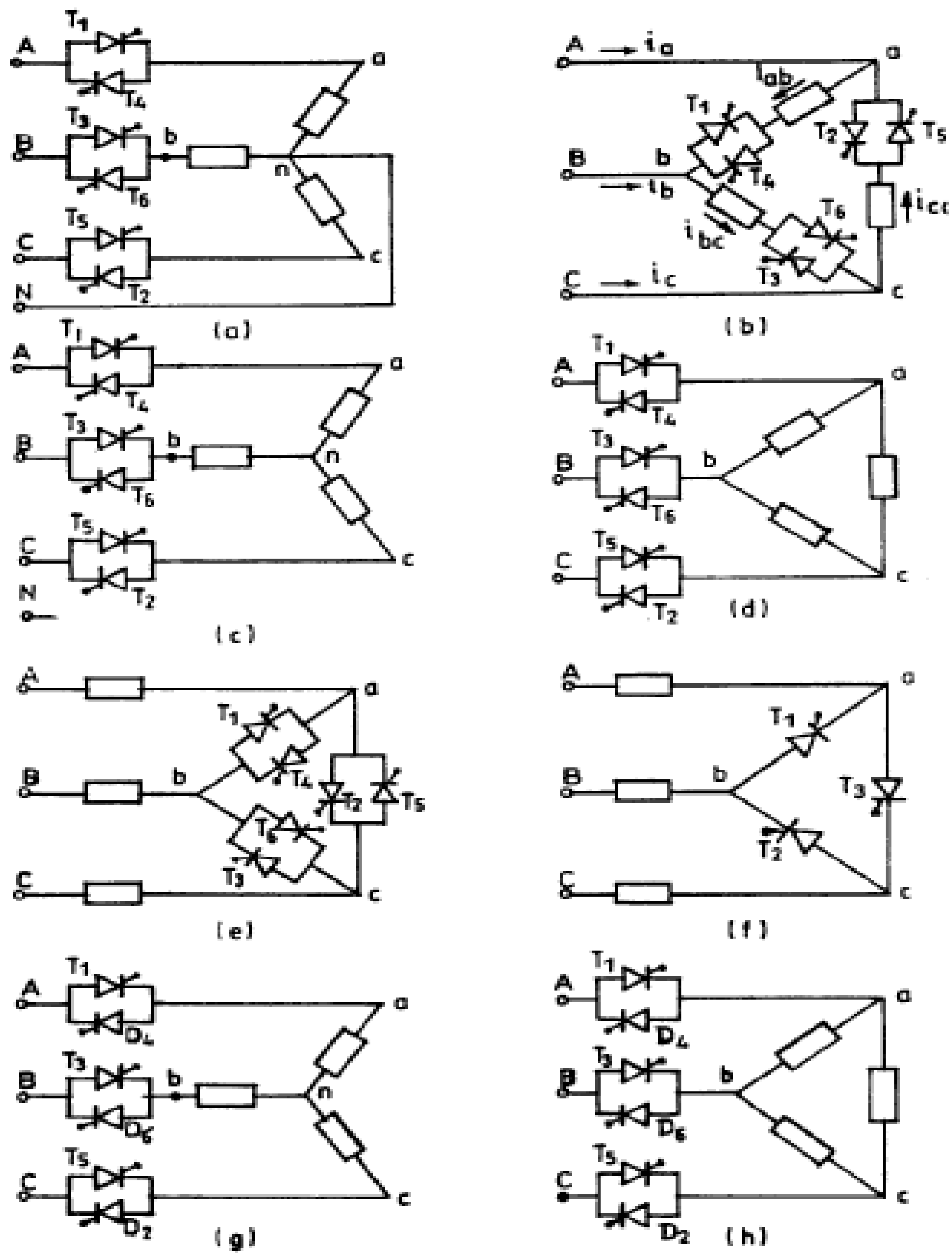


FIGURE 16.11 Three-phase ac voltage-controller circuit configurations.

Fully Controlled Three-Phase Three-Wire AC Voltage Controller Star-Connected Load with Isolated Neutral

The analysis of operation of the full-wave controller with isolated neutral as shown in Fig. 16.11c is, as mentioned, quite complicated in comparison to that of a single-phase controller, particularly for an RL or motor load.

As a simple example, the operation of this controller is considered here with a simple star-connected R-load. The six SCRs are turned on in the sequence 1-2-3-4-5-6 at 60^0 intervals and the gate signals are sustained throughout the possible conduction angle.

The output phase voltage waveforms for 30, 75, and 120^0 for a balanced three-phase R-load are shown in Fig. 16.12. At any interval, either three SCRs or two SCRs, or no SCRs may be on and the instantaneous output voltages to the load are either line-to-neutral voltages (three SCRs on), or one-half of the line-to-line voltage (two SCRs on) or zero (no SCR on). Depending on the firing angle a, there may be three operating modes.

Mode I (also known as Mode 2=3): 0^0 and 60^0. There are periods when three SCRs are conducting, one in each phase for either direction and periods when just two SCRs conduct. For example, with 30^0 in Fig. 16.12a, assume that at 0^0, SCRs T5 and T6 are conducting, and the current through the R-load in a-phase is zero making v_{an} 0 At 30^0, T1 receives a gate pulse and starts conducting; T5 and T6 remain on and van . v_{AN}.

The current in T5 reaches zero at 60^0, turning T5 off. With T1 and T6 staying on, van . $1=2v_{AB}$. At 90^0, T2 is turned on, the three SCRs T1, T2, and T6 are then conducting and van . v_{AN}. At 120^0, T6 turns off, leaving T1 and T2 on, so v_{AN} . $1=2v_{AC}$. Thus with the progress of firing in sequence until 60^0, the number of SCRs conducting at a particular instant alternates between two and three.

Mode II (also known as Mode 2/2): 60^0 to $90^{0.}$ Two SCRs, one in each phase, always conduct. For 75^0 as shown in Fig. 16.12b, just prior to a 75^0, SCRs T5 and T6 were conducting and v_{an} 0 At 75^0, T1 is turned on, T6 continues to conduct while T5 turns off as v_{CN} is negative; v_{an} . $1=2v_{AB}$. When T2 is turned on at 135^0, T6 is turned off and van . $1=2v_{AC}$. The next SCR to turn on is T3, which turns off T1 and van . 0. One SCR is always turned off when another is turned on in this range of a and the output is either one-half line-to-line voltage or zero.

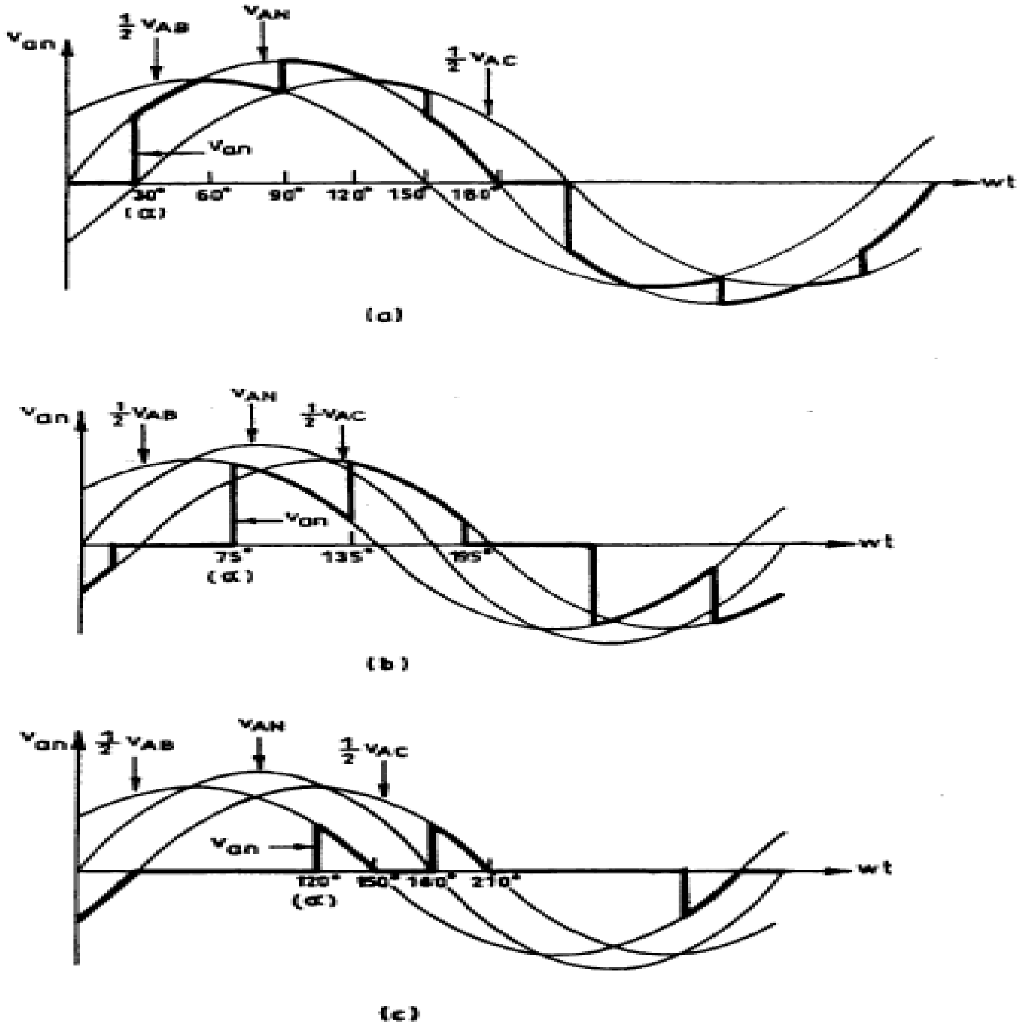


FIGURE 16.12 Output voltage waveforms for a three-phase ac voltage controller with star-connected R-load: (a) v_{an} for $\alpha = 30°$; (b) v_{an} for $\alpha = \ \ 5°$; and (c) $v_{an} = 120°$.

Mode III (also known as Mode 0/2): 90^0 to150^0. When none or two SCRs conduct. For 120^0 (Fig. 16.12c), earlier no SCRs were on and v_{an} 0. At 120^0 SCR T1 is given a gate signal while T6 has a gate signal already applied. As v_{AB} is positive, T1 and T6 are forward-biased and they begin to conduct and van . 1=2v_{AB}. Both T1 and T6 turn off when v_{AB} becomes negative. When a gate signal is given to T2, it turns on and T1 turns on again. For a > 150^0, there is no period when two SCRs are conducting and the output voltage is zero at 150^0.Thus, the range of the firing angle control is 0^0 to 150^0. For star-connected R-load, assuming the instantaneous phase voltages as

$$V_{AN} = \sqrt{2}V_s sin\omega t$$

$V_{BN} = \sqrt{2}V_s \sin(\omega t\text{-}120^0)$

$$V_{CN} = \sqrt{2}V_s \sin(\omega t\text{-}240^0)$$

The expressions for the rms output phase voltage V_0can be derived for the three modes as

$0 \leq \alpha \leq 60^0$ $\quad V_0 = V_s\left[1 - \frac{3\alpha}{2\pi} + \frac{3}{4\pi} sin2\alpha\right]^{\frac{1}{2}}$

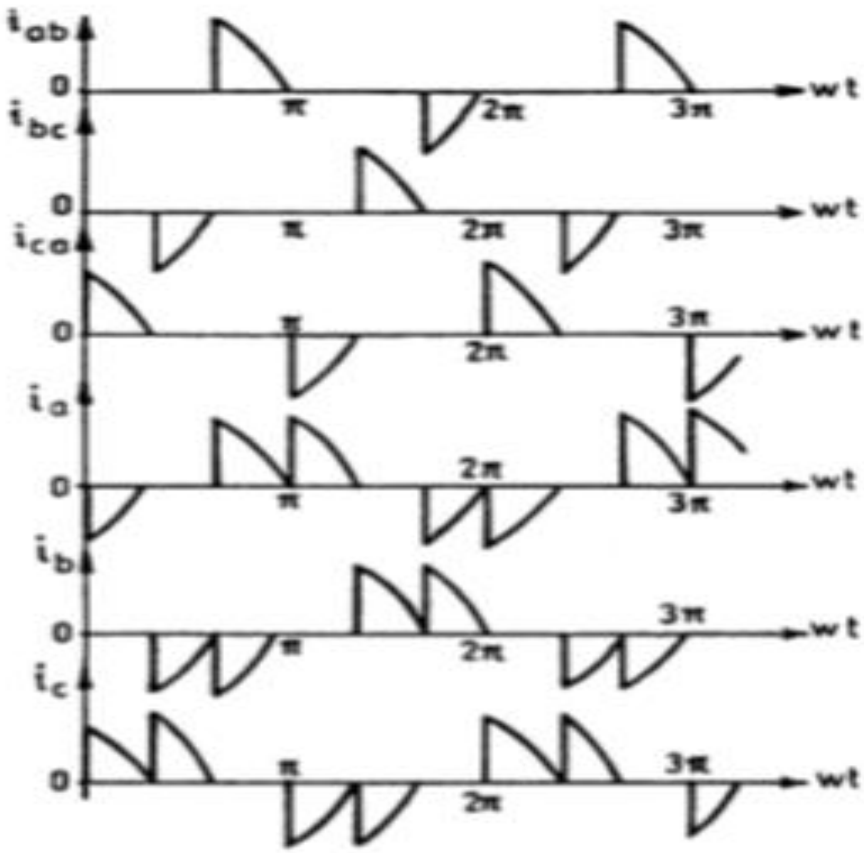
$60^0 \leq \alpha \leq 90^0$ $\quad V_0 = V_s\left[\frac{1}{2} + \frac{3}{4\pi} sin2\alpha + \frac{3}{4\pi}\sin(2\alpha + 60^0\right]^{\frac{1}{2}}$

$90^0 \leq \alpha \leq 150^0$ $\quad V_0 = V_s\left[\frac{5}{4} - \frac{3}{2\pi} + \frac{3}{4\pi}\sin(2\alpha + 60^0\right]^{\frac{1}{2}}$

For star-connect pure L-Load the effective control starts at α>90^0 and the expression for two ranges of α are

$90^0 \leq \alpha \leq 120^0$ $\quad V_0 = V_s\left[\frac{5}{2} - \frac{3\alpha}{\pi} + \frac{3}{2\pi}\sin(2\alpha)\right]^{\frac{1}{2}}$

$120^0 \leq \alpha \leq 150^0$ $\quad V_0 = V_s\left[\frac{5}{2} - \frac{3\alpha}{\pi} + \frac{3}{2\pi}\sin(2\alpha + 60^0\right]^{\frac{1}{2}}$



(a)

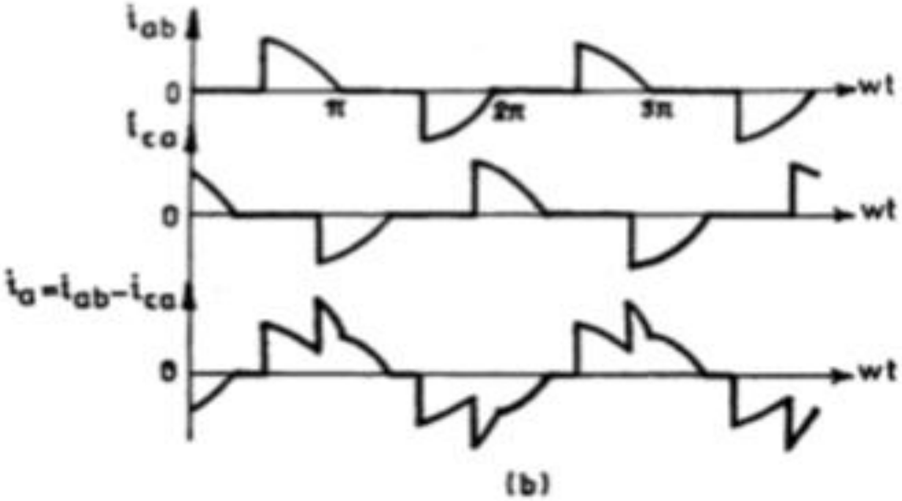


FIGURE 16.15 Waveforms of a three-phase ac voltage controller with a delta-connected R-load: (a) $\alpha = 120°$; (b) $\alpha = 0°$.

as the conduction angle varies from very small (large α) to 180° ($\alpha = 0$).

CYCLOCONVERTERS

- ❖ It is defined as conversion of fixed AC power into variable AC power with change in frequency.
- ❖ Traditionally, ac-ac conversion using semiconductor switches is done in two different ways:

1) In two stages (ac-dc and then dc-ac) as in dc link converters or
2) In one stage (ac-ac) cycloconverters (Fig. 1).

- ❖ Cycloconverters are used in high power applications driving induction and synchronous motors.
- ❖ They are usually phase-controlled and they traditionally use thyristors due to their ease of phase commutation.

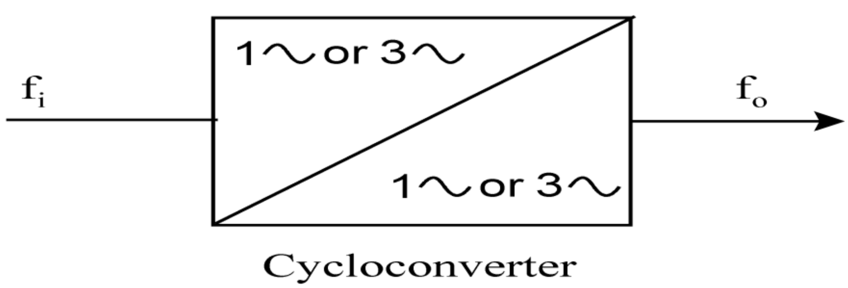


Fig.1 Block diagram of a cycloconverter

- There are other newer forms of cycloconversion such as ac-ac matrix converters and highfrequency ac-ac (hfac-ac) converters and these use self-controlled switches. These converters,however, are not popular yet.

CYCLOCONVERTERS:

- cycloconverter is another class of ac to ac converters. output frequency can also be varied.
- It is possible to obtain 3 phase to 1 phase regulator. in this section we will study some of these aspects.

TYPES OF CYCLOCONVERTER:

i) single phase cycloconverter

a) Step-up Cycloconverter

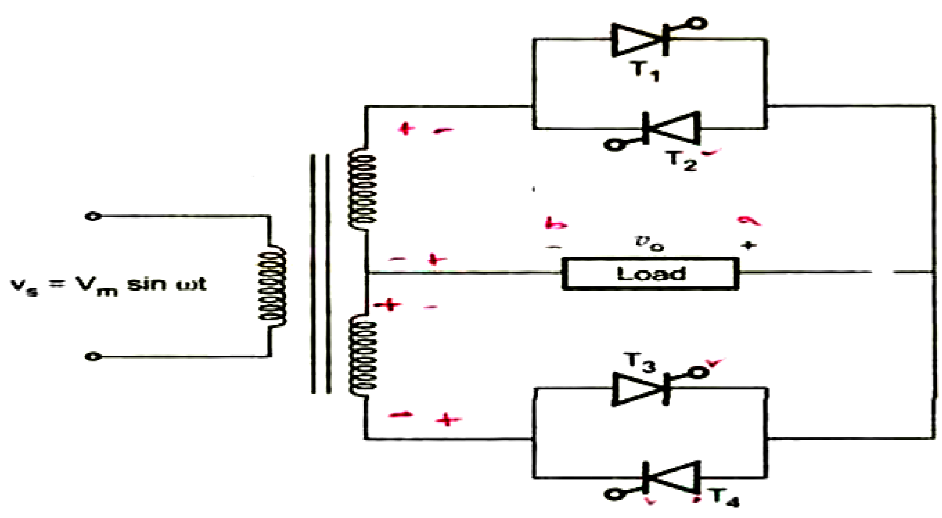
b) Step-down Cycloconverter

ii) 3 phase to 1 phaseCycloconverter

iii) 3 phase to 3 phaseCycloconverter

PRINCIPLE OF SINGLE-PHASE TO SINGLE-PHASE (1 Φ -1 Φ) CYCLOCONVERTER WITH POWER CIRCUIT AND WAVEFORMS/ STEP-UP CYCLOCONVERTER

- When the frequency of the output is higher than the frequency of input, then it is called step-up cycloconverter.
- Fig. 5.8.1 shows the midpoint type step-up cycloconverter.



Midpoint type cycloconverter

- The waveforms of this converter are shown in Fig. 5.8.2. In the positive half cycle, T_1 conducts from 0 to t_1, hence output voltage is positive.
- At t_1, T_1 is forced commutated and T_4 is triggered. Hence load voltage becomes negative as shown in Fig.

- Then at t_2, T_4 is forced commutated and $T_1$is turned-on again. Therefore output voltage is again positive.

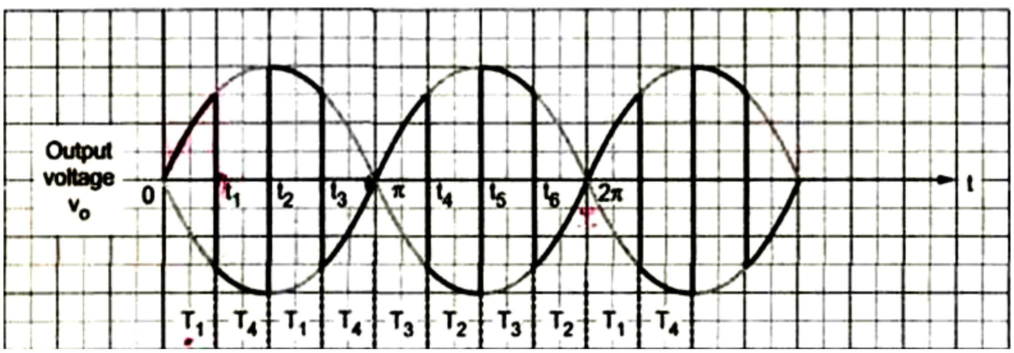
- At t_3, T_4 is turned-on and T_1 is forced commutated. Hence output voltage is negative. At π, T3 is turned on.

- Therefore output voltage is positive. At t_4,$T3$ is forced commutated and $T2$ is triggered. Hence the load voltage is negative.

- This sequence continues. Observe that output voltage waveform has the frequency of,

$$f_0 = \frac{1}{t_2 - t_1}$$

- This frequency is higher than supply frequency.



Waveforms of step-up cycloconverter

STEP-DOWN CYCLOCONVERTER (OR)

PRINCIPLE OF WORKING OF 1Φ-1Φ STEP DOWN CYCLOCONVERTER FOR A BRIDGE TYPE CONVERTER.ASSUME BOTH DISCONTINUOUS AND CONTINUOUS CONDUCTION CONDUCTION

- In the step-down cycloconverter, the output frequency is less than supply frequency.

- The midpoint cycloconverter of Fig. 5.8.1 can be operated as step-down cycloconverter. Fig. 5.8.3 shows the waveforms of this converter.

- These waveforms are shown for highly inductive load with continuous output current. Output voltage is also controlled by varying the firing angle 'α'.

- Consider that, the period of input supply is T. The period of output is 4T. Four cycles of supply voltage make one cycle of output. The dotted line shows equivalent output voltage waveform.

- ❖ Thus the supply frequency is divided by four. T1 and *T3* are triggered to obtain

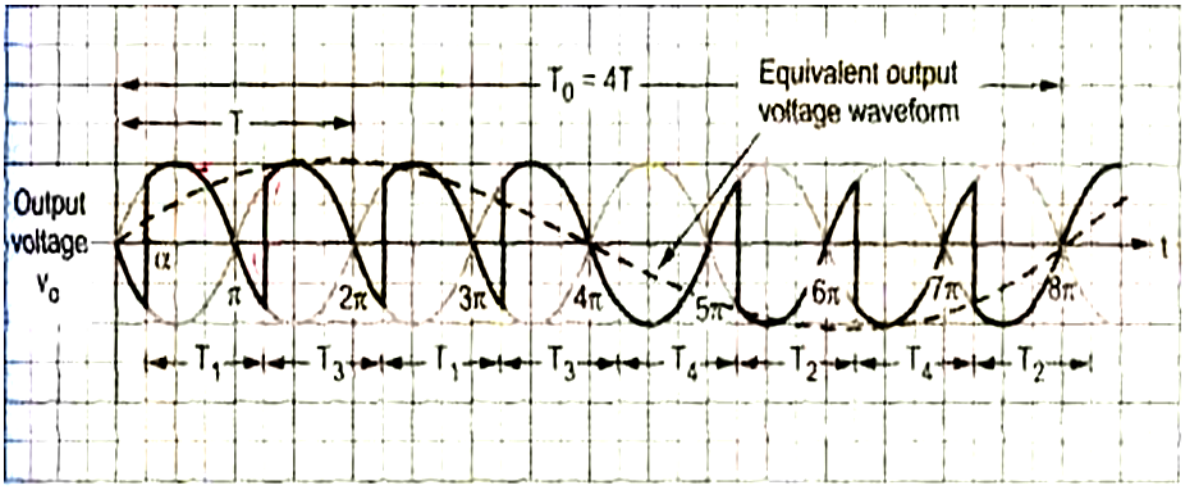


Fig. 5.8.3 Step-down cycloconverter

Output frequency will be,

$$f_0 = \frac{1}{T_0}$$

$$= \frac{1}{4T} = \frac{f}{4}$$

- ❖ Positive cycle of the output voltage. Similarly, T_2 and T_4 are triggered to obtain Negative half cycle of the output voltage.

1 Φ to 1 Φ Cycloconverters

The output and input, both are 1Φfor such converters. The cycloconvertersdiscussed in previous two subsections are also 1Φ to 1Φcycloconverters. Fig. 5.8.4 shows the circuit diagram of bridge type 1 Φ to 1 Φ cycloconverter.

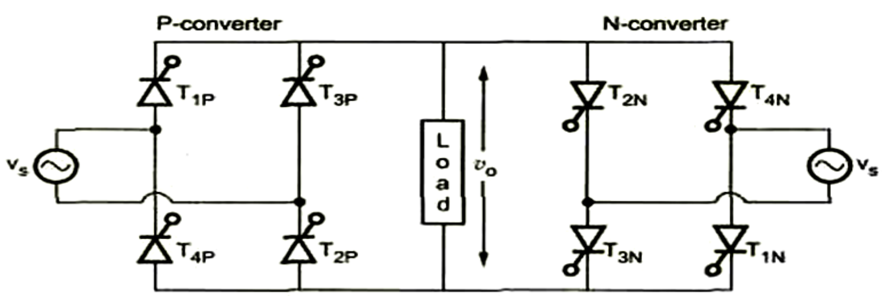


Fig. 5.8.4 1 Φ to 1 Φ bridge type cycloconverter

- ❖ Output waveform of the above cycloconverter will be similar to that of Fig. 5.8.3 for inductive load and continuous output current.

❖ Fig.5.8.5 shows the waveform ofabove converter for resistive load.

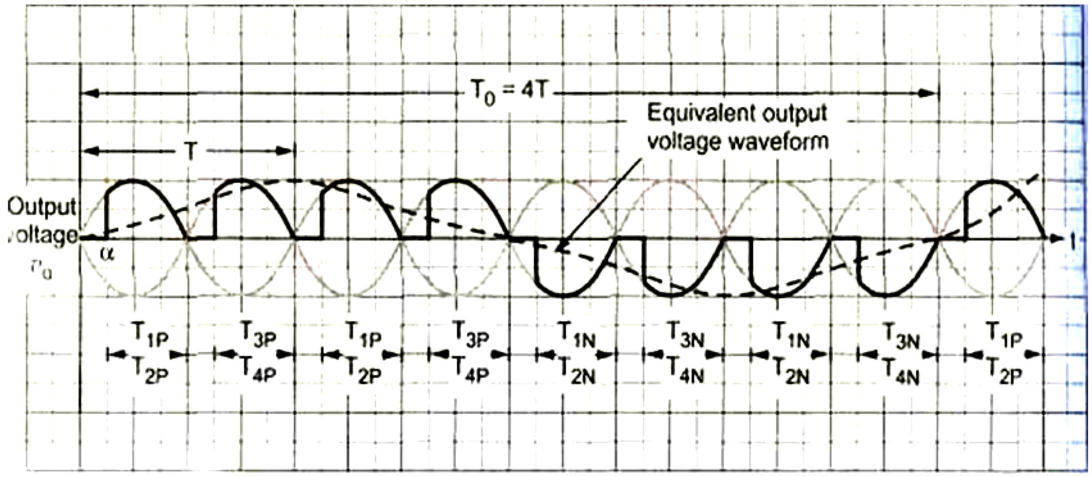


Fig. 5.8.5 Waveforms of 1 Φ to 1 Φ cycloconverter for resistive load

❖ Output voltage is positive, when SCRs of P-converter are conducting. Similarly the output voltage is negative when SCRs of N-converter are conducting.

❖ The firing angle of the SCRs is varied to control the output voltage. Above waveforms are shown for step-down operation.

❖ Step-up operation is also possible in this converter. Four cycles of input make one cycle of output. Hence output frequency is,

$$f_o = 1/T_o = 1/4T = f/4$$

OPERATION OF THREE-PHASE TO SINGLE-PHASE (3Φ-1Φ) CYCLOCONVERTER WITH NEAT CIRCUIT DIAGRAM AND WAVEFORMS.

There are two kinds of three-phase to single-phase **(3Φ-1Φ)**cycloconverters: **(3Φ-1Φ)** half-wave cycloconverter (Fig. 4) and **(3Φ-1Φ)** bridge cycloconverter (Fig. 5).

❖ Like the **(1Φ-1Φ)** case, the **(3Φ-1Φ)**cycloconverter applies rectified voltage to the load.

❖ Both positive and negative converters can generate voltages at either polarity, but the positive converter can only supply positive current and the negative converter can only supply negative current.

❖ Thus, the cycloconverter can operate in four quadrants: (+v, +i) and (-v, -i) rectification modes and (+v, -i) and (-v, +i) inversion modes.

❖ The modulation of the output voltage and the fundamental output voltage are shown in Fig. 6.

❖ Note that sinusoidally modulated over the cycle to generate a harmonically Optimum output voltage.

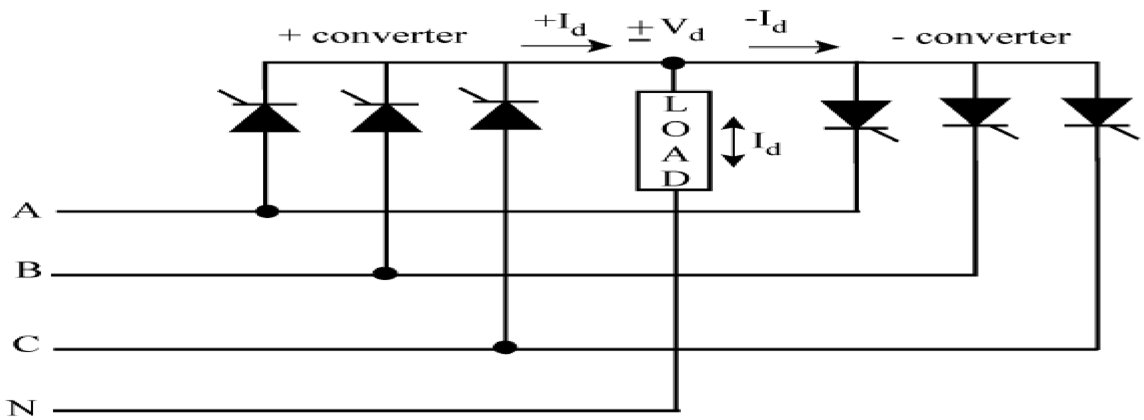


Fig. 4. 3 Φ -1 Φ half-wave cycloconverter

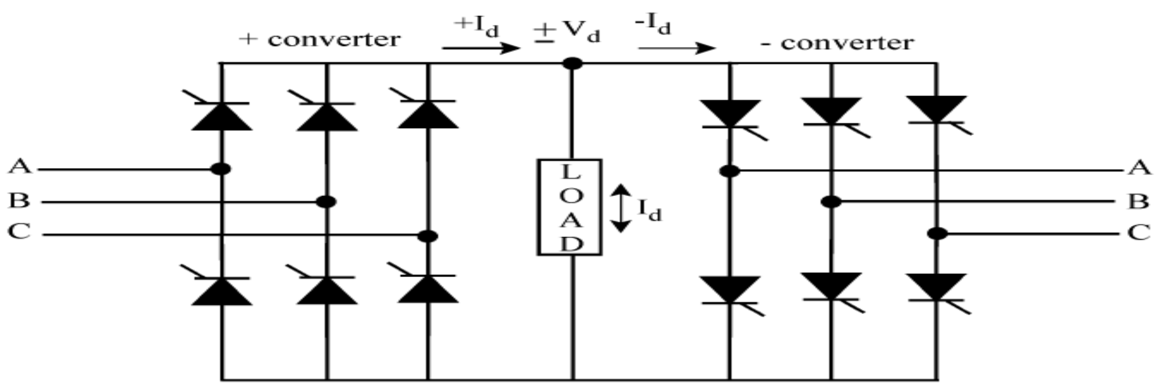


Fig. 5 3 Φ -1 Φ bridge cycloconverter

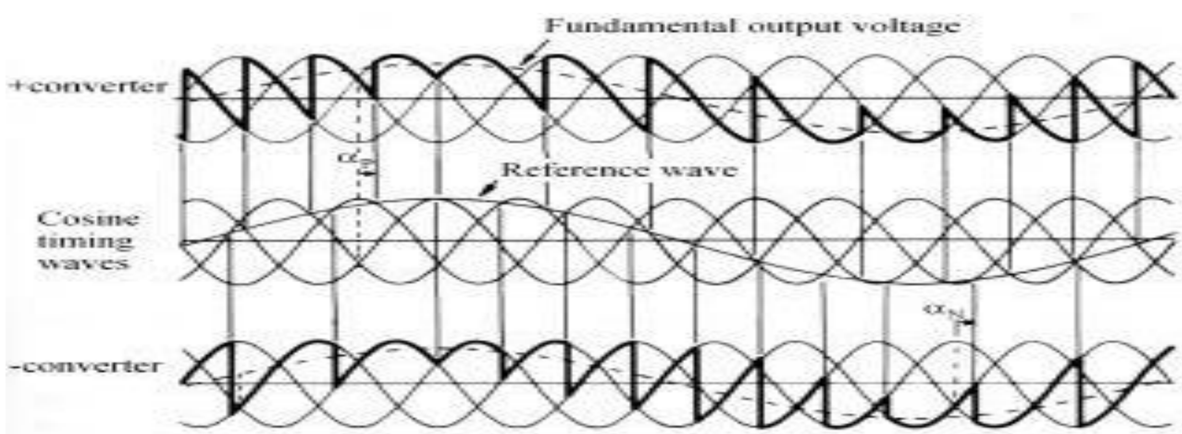


Fig. 6. 3 Φ -1 Φhalf-wave cycloconverter waveforms

a) + converter output voltage
b) cosine timing waves
c) – converter output voltage

- ❖ The polarity of the current determines if the positive or negative converter should be supplying power to the load.
- ❖ Conventionally, the firing angle for the positive converter is named +P, and that of the negative converter is named -N.
- ❖ When the polarity of the current changes, the converter previously supplying the current is disabled and the other one is enabled.
- ❖ The load always requires the fundamental voltage to be continuous. Therefore, during the current polarity reversal, the average voltage supplied by both of the converters should be equal.
- ❖ Otherwise, switching from one converter to the other one would cause an undesirable voltage jump.
- ❖ To prevent this problem, the converters are forced to produce the same average voltage at all times.
- ❖ Thus, the following condition for the firing angles should be met.

$$\alpha_P + \alpha_N = \pi$$

- ❖ The fundamental output voltage in Fig. 6 can be given as:

$$V_0(t) = \sqrt{2}V_0 sin\omega_0 t$$

where *Vo* is the rms value of the fundamental voltage

- ❖ At a time to the output fundamental voltage is

$$V_0(\,t_0) = \sqrt{2}V_0 sin\omega_0 t_0$$

- ❖ The positive converter can supply this voltage if satisfies the following condition.

$$V_0(\,t_0) = \sqrt{2}V_0 sin\omega_0 t_0 = \,V_{db}\cos\alpha_P$$

Where

$$V_{db} = \sqrt{2}V_0 \frac{P}{\pi}\sin\frac{\pi}{P}(p = 3\,for\;half\;wave\;converter\;and\;6\,for\;bridge\;converter)$$

- ❖ From the condition (3)

$$v_{01} = V_{d0}\cos\alpha_P = -V_{d0}\sin\alpha_N$$

- ❖ The firing angles at any instant can be found from (6) and (7).The operation of the 3 Φ -1 Φ bridge cycloconverter is similar to the above 3 Φ -1 Φ half-wave cycloconverter.

- ❖ Note that the pulse number for this case is 6.

OPERATION OF THREE-PHASE TO THREE-PHASE (3 Φ -3 Φ) CYCLOCONVERTER.

- If the outputs of 3 3Φ-1 Φ converters of the same kind are connected in wye or delta and if the output voltages are 2π/3 radians phase shifted from each other, the resulting converter is a threephase to three-phase (3 Φ -3 Φ) cycloconverter.
- The resulting cycloconverters are shown in Figs. 7 and 8 with wye connections. If the three converters connected are half-wave converters, then the new converter is called a 3 Φ -3 Φ half-wave cycloconverter.
- If instead, bridge converters are used, then the result is a 3 Φ -3 Φ bridge cycloconverter. 3 Φ -3 Φ half-wave cycloconverter is also called a 3-pulse cycloconverter or an 18-thyristor cycloconverter.
- On the other hand, the 3 Φ -3 Φ bridge cycloconverter is also called a 6-pulse cycloconverter or a 36-thyristor cycloconverter.
- The operation of each phase is explained in the previous section.

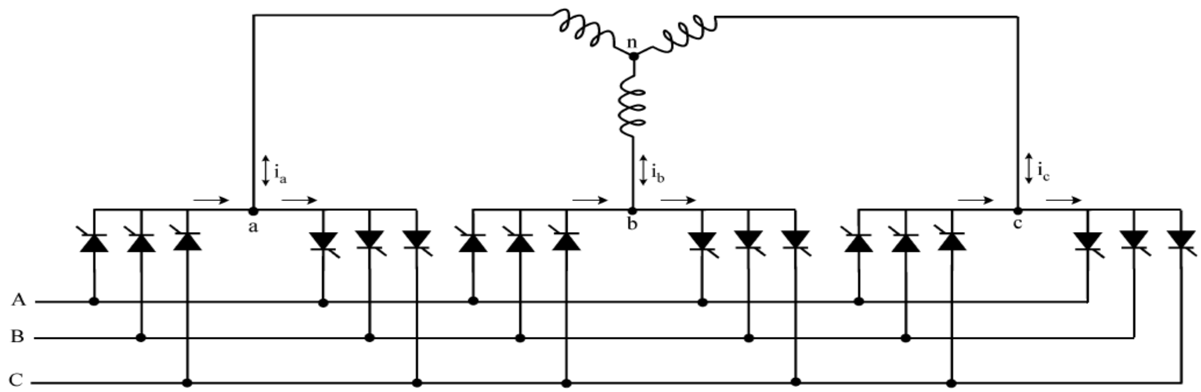


Fig. 7. 3 Φ -3 Φ half-wave cycloconverter

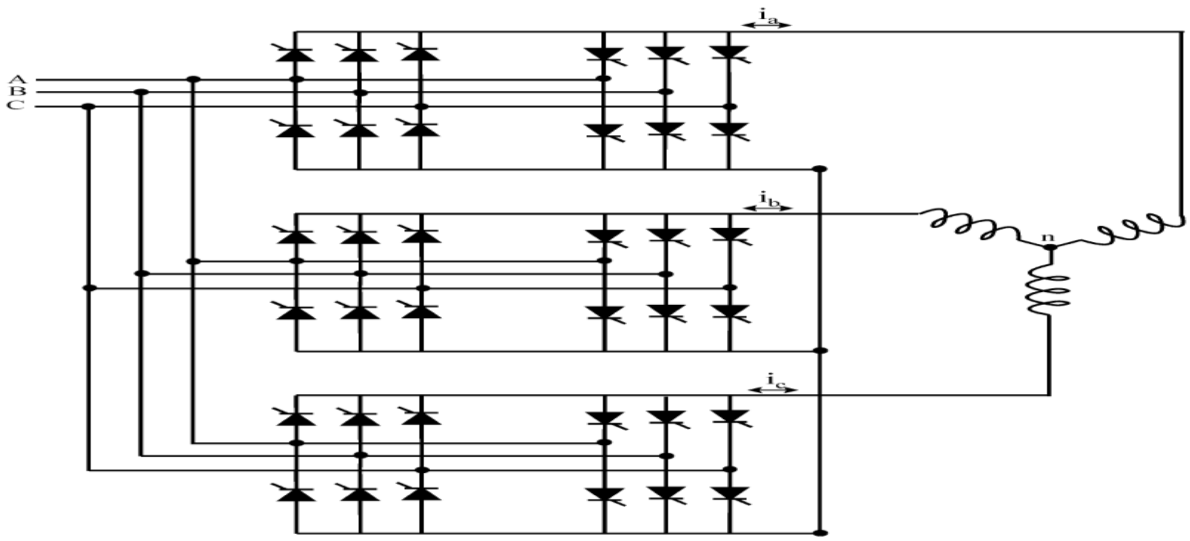


Fig. 8. 3 Φ -3 Φ bridge cycloconverter

- The three-phase cycloconverters are mainly used in ac machine drive systems running three phase synchronous and induction machines.
- They are more advantageous when used with a synchronous machine due to their output power factor characteristics.
- A cycloconverter can supply lagging, leading, or unity power factor loads while its input is always lagging.
- A synchronous machine can draw any power factor current from the converter. This characteristic operation matches the cycloconverter to the synchronous machine.
- On the other hand, induction machines can only draw lagging current, so the cycloconverter does not have an edge compared to the other converters in this aspect for running an induction machine.
- However, cycloconverters are used in Scherbius drives for speed control purposes driving wound rotor induction motors.
- Cycloconverters produce harmonic rich output voltages, which will be discussed in the following sections.
- When cycloconverters are used to run an ac machine, the leakage inductance of the machine filters most of the higher frequency harmonics and reduces the magnitudes of the lower order harmonics.

Blocked Mode and Circulating Current Mode:

- The operation of the cycloconverters is explained above in ideal terms. When the load current is positive, the positive converter supplies the required voltage and the negative converter is disabled.
- On the other hand, when the load current is negative, then the negative converter supplies the required voltage and the positive converter is blocked.
- This operation is called the blocked mode operation, and the cycloconverters using this approach are called blocking mode cycloconverters.
- However, if by any chance both of the converters are enabled, then the supply is short-circuited.
- To avoid this short circuit, an intergroup reactor (IGR) can be connected between the convertersas shown in Fig. 9.
- Instead of blocking the converters during current reversal, if they are both enabled, then a circulating current is produced.
- This current is called the circulating current. It is unidirectional because the thyristors allow the current to flow in only one direction.
- Some cycloconverters allow this circulating current at all times. These are called circulating current cycloconverters.

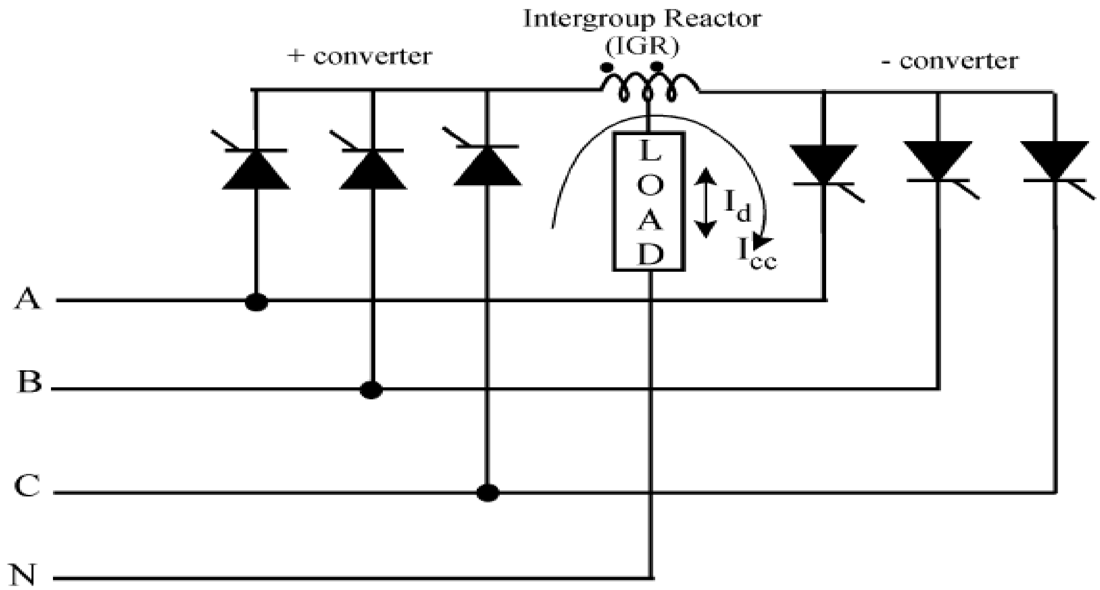


Fig. 9 Circulating current and IGR

Blocking Mode Cycloconverters:

- ❖ The operation of these cycloconverters was explained briefly before. They do not let circulating current flow, and therefore they do not need a bulky IGR.
- ❖ When the current goes to zero, both positive and negative converters are blocked.
- ❖ The converters stay off for a short delay time to assure that the load current ceases.
- ❖ Then, depending on the polarity, one of the converters is enabled. With each zero crossing of the current, the converter, which was disabled before the zero crossing, is enabled.
- ❖ A toggle flip-flop, which toggles when the current goes to zero, can beused for this purpose.
- ❖ The operation waveforms for a three-pulse blocking mode cycloconverter are given in Fig. 10.
- ❖ The blocking mode operation has some advantages and disadvantages over the circulating mode operation.
- ❖ During the delay time, the current stays at zero distorting the voltage and current waveforms.
- ❖ This distortion means complex harmonics patterns compared to the circulating mode cycloconverters.
- ❖ In addition to this, the current reversal problem brings more control complexity.

- ❖ However, no bulky IGRs are used, so the size and cost is less than that of the circulating current case.

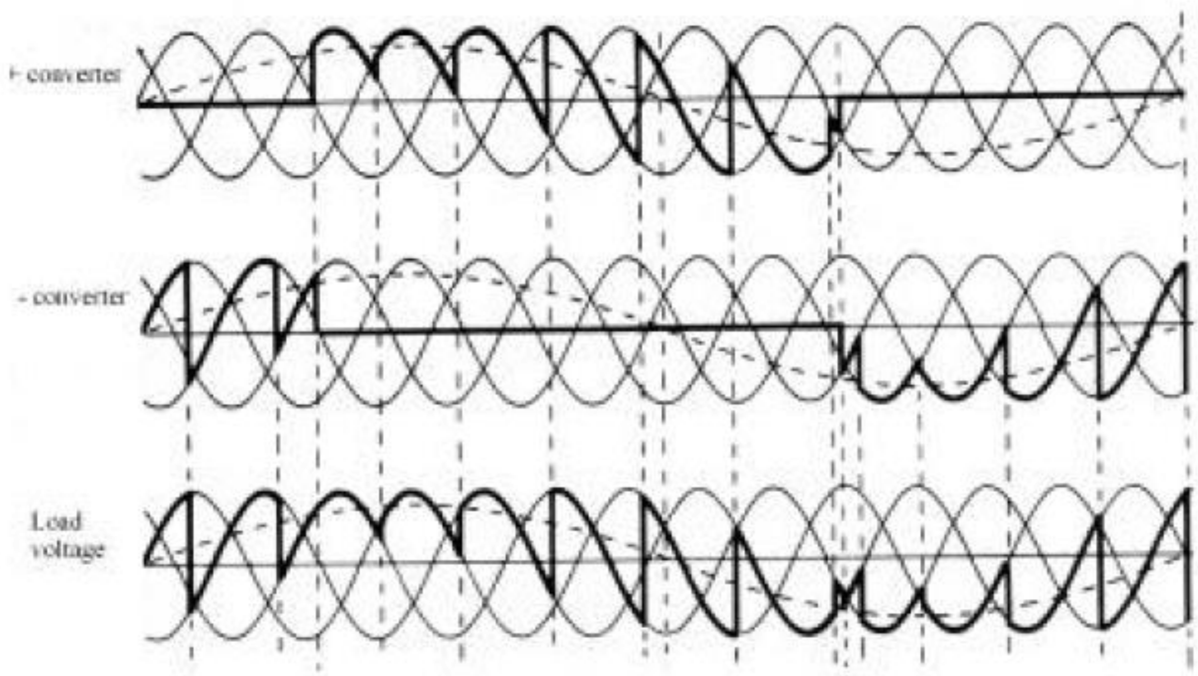


Fig. 10 Blocking mode operation waveforms

- ❖ Another advantage is that only one converter is in conduction at all times rather than two.
- ❖ This means less losses and higher efficiency.

a) + converter output voltage
b) – converter output voltage
c) load voltage

Circulating Current Cycloconverters:

- ❖ In this case, both of the converters operate at all times producing the same fundamental output voltage.
- ❖ The firing angles of the converters satisfy the firing angle condition (Eq. 3), thus when one converter is in rectification mode the other one is in inversion mode and vice versa.
- ❖ If both of the converters are producing pure sine waves, then there would not be any circulating current
- ❖ Because the instantaneous potential difference between the outputs of the converters would be zero.
- ❖ In reality, an IGR is connected between the outputs of two phase controlled converters (in either rectification or inversion mode). The voltage waveform across the IGR can be seen in Fig.11d.
- ❖ This is the difference of the instantaneous output voltages produced by the two converters.

- ❖ Note that it is zero when both of the converters produce the same instantaneous voltage.
- ❖ The center tap voltage of IGR is the voltage applied to the load and it is the mean

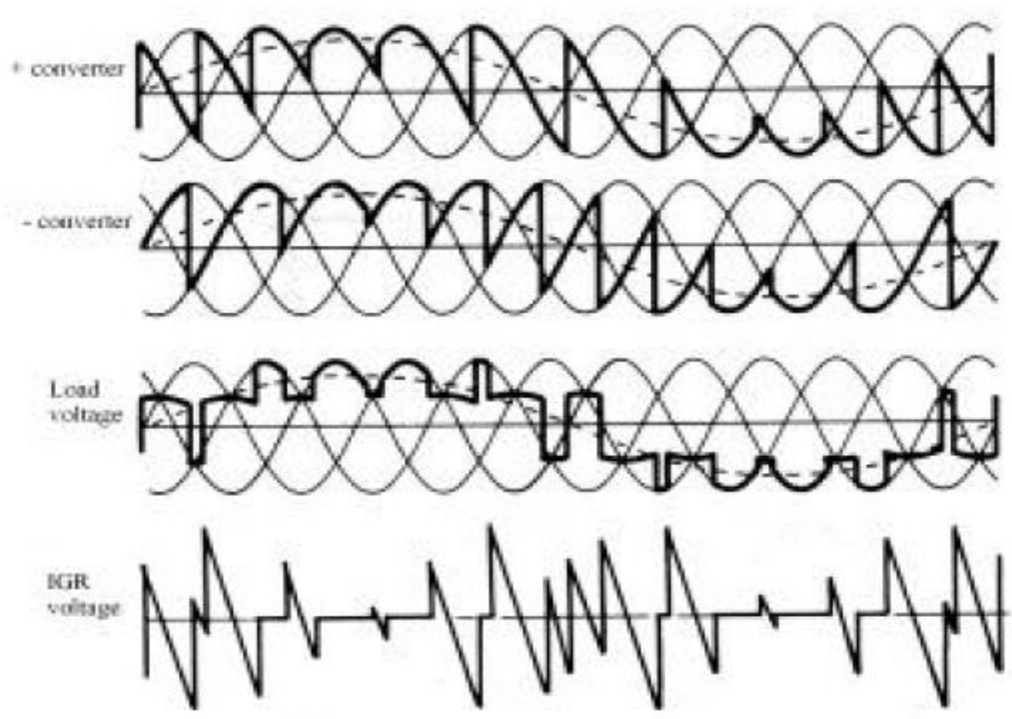


Fig.11.circulating mode operation waveforms

of the voltages applied to the ends of IGR, thus the load voltage ripple is reduced.

a) + converter output voltage
b) – converter output voltage
c) load voltage
d) IGR voltage

- ❖ The circulating current cycloconverter applies a smoother load voltage with less harmonics compared to the blocking mode case.
- ❖ Moreover, the control is simple because there is no current reversal problem. However, the bulky IGR is a big disadvantage for this converter.
- ❖ In addition to this, the number of devices conducting at any time is twice that of the blocking mode converter.
- ❖ Due to these disadvantages, this cycloconverter is not attractive. The blocked mode cycloconverter converter and the circulating current cycloconverter can be combined to give a hybrid system, which has the advantages of both.
- ❖ The resulting cycloconverter looks like a circulating mode cycloconverter circuit, but depending on the polarity of the output current only one converter is enabled and the other one is disabled as with the blocking mode cycloconverters.
- ❖ When the load current decreases below a threshold, both of the converters are enabled.
- ❖ Thus, the current has a smooth reversal. When the current increases above a threshold in the other direction, the outgoing converter is disabled.

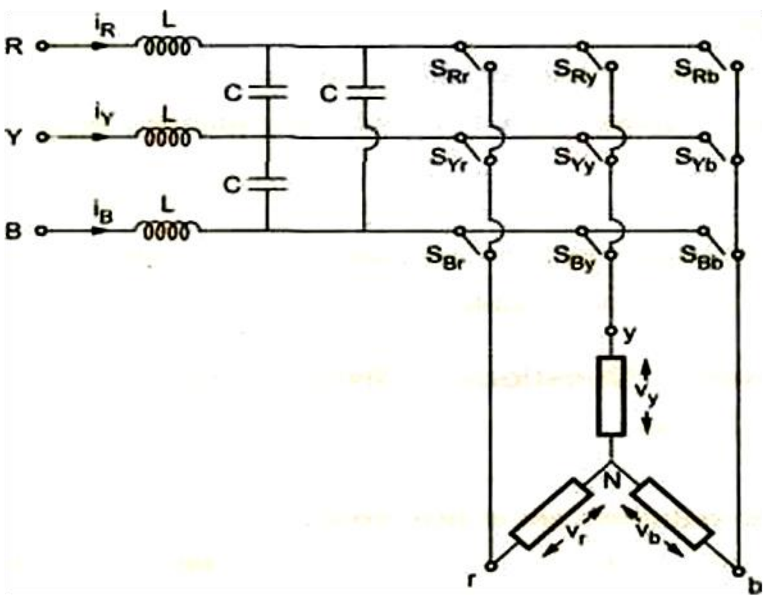
- This hybrid cycloconverter operates in the blocking mode most of the time so a smaller IGR can be used.
- The efficiency is slightly higher than that of the circulating current cycloconverter but much less than the blocking mode cycloconverter.
- Moreover, the distortion caused by the blocking mode operation disappears due to the circulating current operation around zero current.
- Moreover, the control of the converter is still less complex than that of the blocking mode cycloconverter.

MATRIX CONVERTERS FOR POWER FACTOR CONTROL:

Principle: The matrix converter uses the matrix of switches so that any of the input phase voltage can be connected to any of the output load phase. There is **exactly one** switch for each of the possible connections between supply and load.

Circuit diagram and operation

- As shown in this circuit diagram, S_{RR}, S_{YR} and S_{Br} are the switches that



Circuit diagram of matrix converter

connect any of the input to load phase *r*. Similarly the switches S_{RY}, S_{YY} and S_{By} connect any of the input to load phase *y*. And the switches S_{RB}, S_{YB}, and S_{BB} connect any of the input to load phase b.

- The input LC filter is used to eliminate harmonic currents in the input side.
- The switches $2^9 = 512$ combinations but only 9 combinations are used.
- The switches are controlled in such a way that there is no short circuit of the input supply. The load voltages $v_R v_Y$, v_B, are related to supply voltages V_R, V_Y and

$V_B$by following matrix equation

$$\begin{bmatrix} V_r \\ V_b \\ V_y \end{bmatrix} = \begin{bmatrix} SR_r & SY_r & SB_r \\ SR_y & SY_y & SB_y \\ SR_b & SY_b & SB_b \end{bmatrix} = \begin{bmatrix} V_R \\ V_Y \\ V_B \end{bmatrix}$$

The maximum voltage transfer ratio is 0.866

Advantages:

1. Inherent bidirectional power flow control.
2. Input-output waveforms are sinusoidal.
3. No dc-link is required, hence it is compact.
4. Power factor is controlled by independent control of load current.

Disadvantages:

1. The switches are not available for high powers.
2. Implementation is complex.
3. The maximum voltage transfer ratio is limited.
4. The switches required protection and commutation circuits which makes the converter bulley.

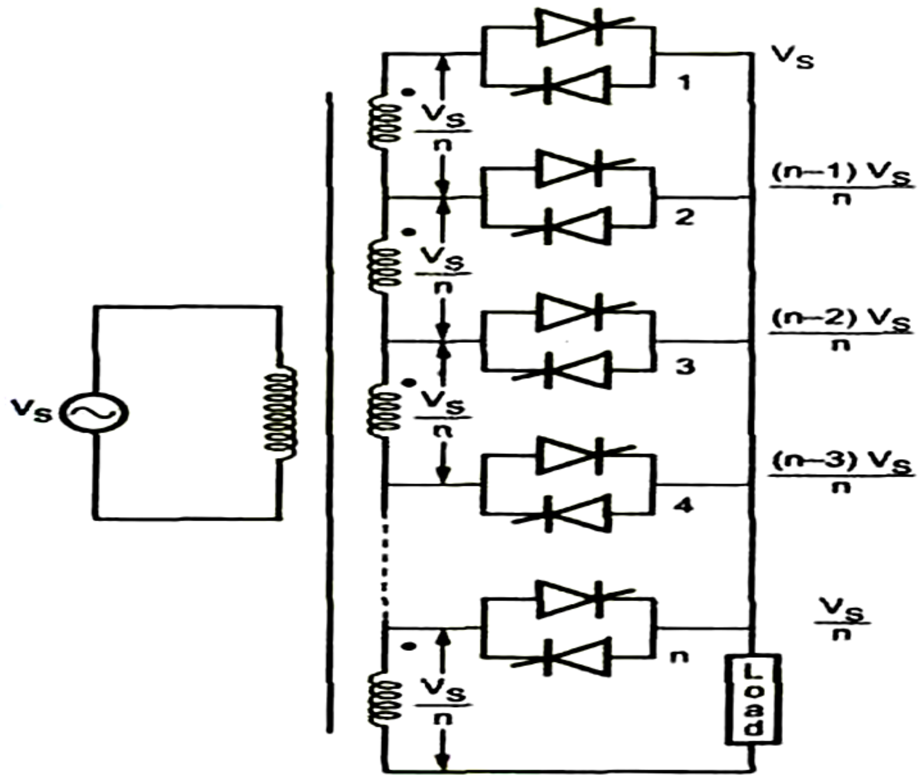
Applications:

1. Matrix converters are used for low power 3Φ AC controllers.
2. It is used for power factor control.

MULTI-STAGE SEQUENCE CONTROL OF VOLTAGE CONTROLLERS:

Principle: Multiple bidirectional voltage controllers are employed in parallel. Each is fed from the multiple tap transformers. Depending upon the desired output voltage, particular controllers are triggered.

Circuit diagram and operation



Multistage sequence controller

The circuit diagram of multistage sequence controller is shown in Fig. 5.6.1. The secondary of the transformer have *'n* taps. Each tap has the output voltage of V_S/n.When SCR pair 1 is triggered, the load voltage will be maximum, i.e. V_S. This is because voltages of all the taps are added. When the output voltage variation is required betwee $\frac{(n-1)V_s}{n}$ Vsthen SCR

Pair 2 is triggered at zero firing angle. This gives the load voltage of $\frac{(n-1)V_s}{n}$ and the Variation

above this voltage upto V_S is obtained by controlling the firing angle of SCR pair 1. Thus other pairs can be selected depending upon required output voltage.

Advantages

i) Because of multistage output control, the amplitude variations in output are reduced.
ii) Harmonic content is reduced.
iii) Failure of particular pair does not stop the operation completely, since other pairs keep on Working.

POWER FACTOR CONTROL IN AC VOLTAGE REGULATION

- The power factor of a nonlinear deserves a special discussion. Fig.2 shows the supply voltage and the non-sinusoidal load current.

- The fundamental load/supply current lags the supply voltage by the φ_1, 'Fundamental Power Factor' angle.
- $\cos\varphi_1$ is also called the 'Displacement Factor'. However this does not account for the total reactive power drawn by the system.
- This power factor is inspite of the actual load being resistive! The reactive power is drawn also y the trigger-angle dependent harmonics. now

$$Power\ factor = \frac{average\ power}{apparent\ voltamperes} = \frac{P}{VI_L}$$

$$= \frac{VI_{L1}\cos\phi 1}{VI_L}$$

$$distortion\ factor = \frac{I_{L1}}{I_L}$$

- The Average Power, P drawn by the resistive load is

$$P = \frac{1}{2\pi}\int_0^{2\pi} Vi_L\, d\omega t$$

$$= \frac{1}{\pi}\int_\alpha^{\pi} \frac{2V^2}{R} sin^2\omega t\, d\omega t$$

$$= \frac{2V^2}{R\pi}\left[\pi - \frac{\alpha}{2} + \frac{sin2\alpha}{2}\right]$$

- The portion within square brackets in Eq is identical to the first part of the expression within brackets in Eq., which is called the Fourier coefficient 'B1'

The rms load voltage can also be similarly obtained by integrating between α and π and the result can be combined with Eq to give

$$power\ \ factor = per-unit\ \ rms\ \ load-current$$

$$= \sqrt{per-unit\ \ load\ \ power}$$

$$= \sqrt{B_1\ \ p.u..}$$

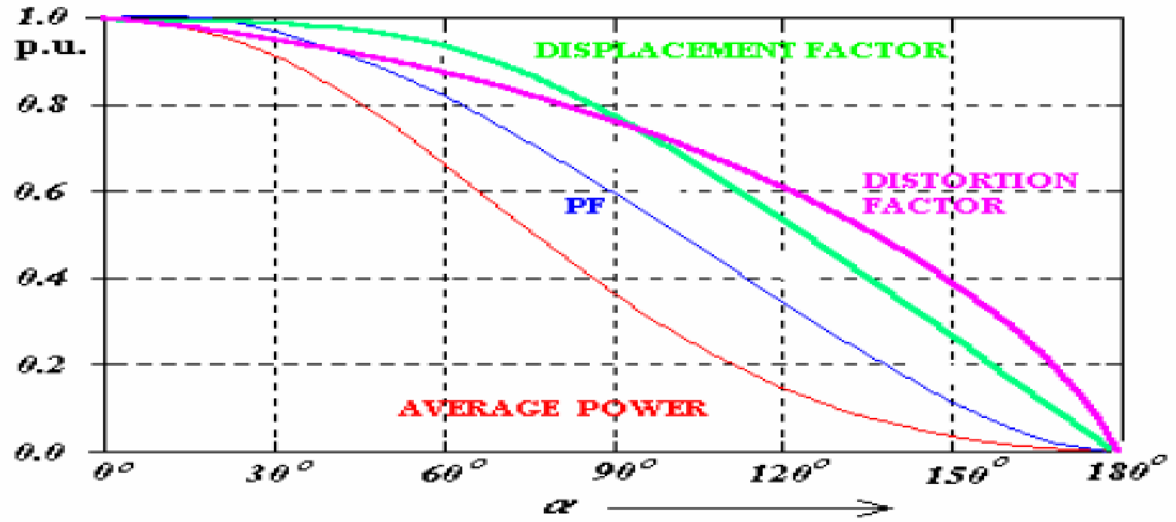


Fig.1 Variation of various performance parameters with triggering angle

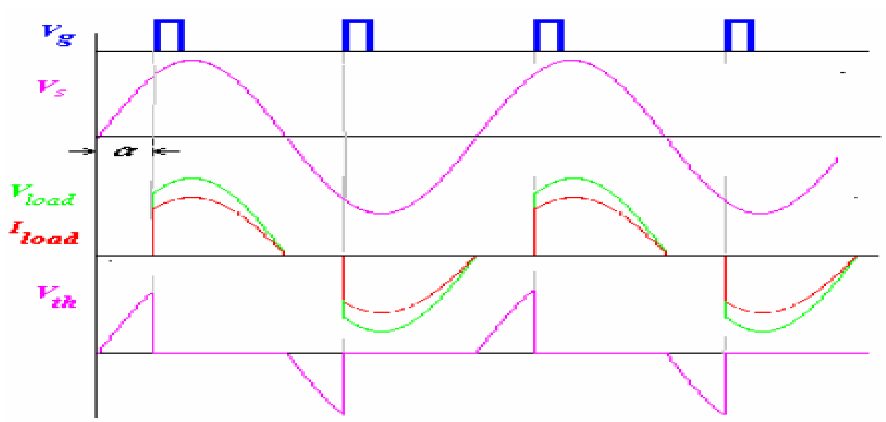


Fig. 2 Operation of a Phase Angle Controlled AC-AC converter with a resistive load

12. Applications –welding

Applications of AC to AC Converter in Welding

- Fig. 5.13.1 shows the use of AC regulators for welding purposes. The SCRs T_1 and T_2 control the voltage applied to the welding transformer primary.

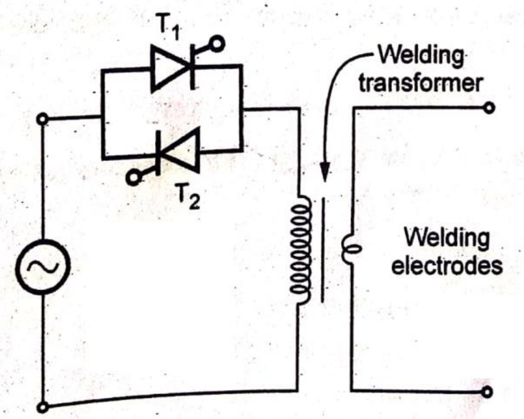


Fig. 5.13.1 : AC to AC converters for electric welding

- Hence the current in the secondary is controlled. The welding current can be increased or decreased depending upon the firing angle of T_1 and T_2.

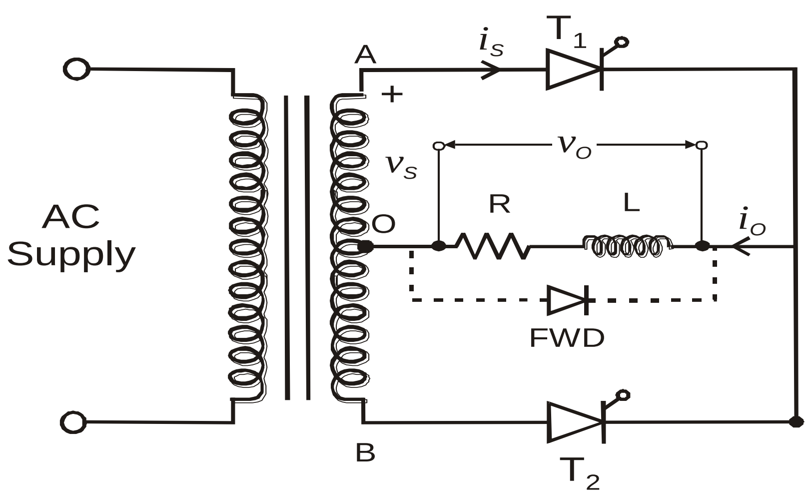
single phase full converter in the rectifier mode with RL load. Discuss how one pair of SCR is commutated by an incoming pair of SCR. Illustrate your answer with the waveforms of source voltage, load voltage and source current. Assume continuous and discontinuous conduction. Also derive the expressions for average and rms output voltage. *NOV/DEC-13,APRIL/MAY-2015*

Single phase full wave controlled rectifier circuit combines two half wave controlled rectifiers in one single circuit so as to provide two pulse output across the load. Both the half cycles of the input supply are utilized and converted into a uni-directional output current through the load so as to produce a two pulse output waveform. Hence a full wave controlled rectifier circuit is also referred to as a two pulse converter.

Single phase full wave controlled rectifiers are of various types

- Single phase full wave controlled rectifier using a center tapped transformer (two pulse converter with midpoint configuration).
- Single phase full wave bridge controlled rectifier
    - Half controlled bridge converter (semi converter).
    - Fully controlled bridge converter (full converter).

SINGLE PHASE FULL WAVE CONTROLLED RECTIFIER USING A CENTER TAPPED TRANSFORMER



v_S = Supply Voltage across the upper half of the transformer secondary winding

$v_S = v_{AO} = V_m \sin \omega t$

$v_{BO} = -v_{AO} = -V_m \sin \omega t =$ supply voltage across the lower half of the transformer secondary winding.

This type of full wave controlled rectifier requires a center tapped transformer and two thyristors T_1 and T_2. The input supply is fed through the mains supply transformer, the primary side of the transformer is connected to the ac line voltage which is available (normally the primary supply voltage is 230V RMS ac supply voltage at 50Hz supply frequency in India). The secondary side of the transformer has three lines and the center point of the transformer (center line) is used as the reference point to measure the input and output voltages.The upper half of the secondary winding and the thyristor T_1 along with the load act as a half wave controlled rectifier, the lower half of the secondary winding and the thyristor T_2 with the common load act as the second half wave controlled rectifier so as to produce a full wave load voltage waveform.

There are two types of operations possible.

- Discontinuous load current operation, which occurs for a purely resistive load or an RL load with low inductance value.
- Continuous load current operation which occurs for an RL type of load with large load inductance.

Discontinuous Load Current Operation (for low value of load inductance)

Generally the load current is discontinuous when the load is purely resistive or when the RL load has a low value of inductance.

During the positive half cycle of input supply, when the upper line of the secondary winding is at a positive potential with respect to the center point 'O' the thyristor T_1 is forward biased and it is triggered at a delay angle of α. The load current flows through the thyristor T_1, through the load and through the upper part of the secondary winding, during the period α to β, when the thyristor T_1 conducts.

The output voltage across the load follows the input supply voltage that appears across the upper part of the secondary winding from $\omega t = \alpha$ to β. The load current through the thyristor T_1 decreases and drops to zero at $\omega t = \beta$, where $\beta > \pi$ for RL type of load and the thyristor T_1 naturally turns off at $\omega t = \beta$.

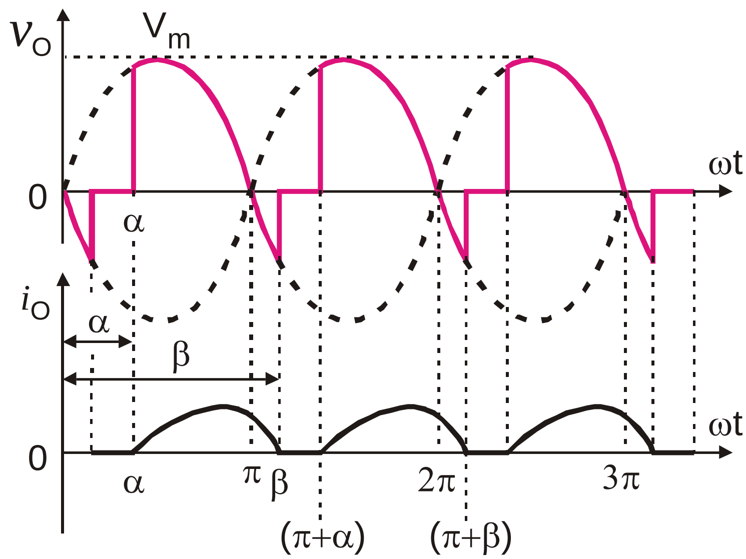


Fig.: Waveform for Discontinuous Load Current Operation without FWD

During the negative half cycle of the input supply the voltage at the supply line 'A' becomes negative whereas the voltage at line 'B' (at the lower side of the secondary winding) becomes positive with respect to the center point 'O'. The thyristor T_2 is forward biased during the negative half cycle and it is triggered at a delay angle of $(\pi+\alpha)$. The current flows through the thyristor T_2, through the load, and through the lower part of the secondary winding when T_2 conducts during the negative half cycle the load is connected to the lower half of the secondary winding when T_2 conducts.

For purely resistive loads when L = 0, the extinction angle $\beta=\pi$. The load current falls to zero at $\omega t=\beta=\pi$, when the input supply voltage falls to zero at $\omega t=\pi$. The load current and the load voltage waveforms are in phase and there is no phase shift between the load voltage and the load current waveform in the case of a purely resistive load.

For low values of load inductance the load current would be discontinuous and the extinction angle $\beta>\pi$ but $\beta<(\pi+\alpha)$.

For large values of load inductance the load current would be continuous and does not fall to zero. The thyristor T_1 conducts from α to $(\pi+\alpha)$, until the next thyristor T_2 is triggered. When T_2 is triggered at $\omega t=(\pi+\alpha)$, the thyristor T_1 will be reverse biased and hence T_1 turns off.

TO DERIVE AN EXPRESSION FOR THE DC OUTPUT VOLTAGE OF A SINGLE PHASE FULL WAVE CONTROLLED RECTIFIER WITH RL LOAD (WITHOUT FREE WHEELING DIODE (FWD))

The average or dc output voltage of a full-wave controlled rectifier can be calculated by finding the average value of the output voltage waveform over one output cycle (i.e., π radians) and note that the output pulse repetition time is $\frac{T}{2}$ seconds where T represents the input supply time period and $T = \frac{1}{f}$; where f = input supply frequency.

Assuming the load inductance to be small so that $\beta > \pi$, $\beta < (\pi + \alpha)$ we obtain discontinuous load current operation. The load current flows through T_1 form $\omega t = \alpha$ to β, where α is the trigger angle of thyristor T_1 and β is the extinction angle where the load current through T_1 falls to zero at $\omega t = \beta$. Therefore the average or dc output voltage can be obtained by using the expression

$$V_{O(dc)} = V_{dc} = \frac{2}{2\pi} \int_{\omega t = \alpha}^{\beta} v_O . d(\omega t)$$

$$V_{O(dc)} = V_{dc} = \frac{1}{\pi} \int_{\omega t = \alpha}^{\beta} v_O . d(\omega t)$$

$$V_{O(dc)} = V_{dc} = \frac{1}{\pi} \left[\int_{\alpha}^{\beta} V_m \sin \omega t . d(\omega t) \right]$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi} \left[-\cos \omega t \Big/_{\alpha}^{\beta} \right]$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi} (\cos \alpha - \cos \beta)$$

Therefore $V_{O(dc)} = \frac{V_m}{\pi} (\cos \alpha - \cos \beta)$**, for discontinuous load current operation,** $\pi < \beta < (\pi + \alpha)$**.**

When the load inductance is small and negligible that is $L \approx 0$, the extinction angle $\beta = \pi$ radians. Hence the average or dc output voltage for resistive load is obtained as

$$V_{O(dc)} = \frac{V_m}{\pi} (\cos \alpha - \cos \pi) \quad ; \ \cos \pi = -1$$

$$V_{O(dc)} = \frac{V_m}{\pi}\left(\cos\alpha - \left(-1\right)\right)$$

$$V_{O(dc)} = \frac{V_m}{\pi}\left(1+\cos\alpha\right)$$; For resistive load, when $L \approx 0$

Due to the presence of load inductance the output voltage reverses and becomes negative during the time period $\omega t = \pi$ to β. This reduces the dc output voltage. To prevent this reduction of dc output voltage due to the negative region in the output load voltage waveform, we can connect a free wheeling diode across the load. The output voltage waveform and the dc output voltage obtained would be the same as that for a full wave controlled rectifier with resistive load.

When the Free wheeling diode (FWD) is connected across the load

When T_1 is triggered at $\omega t = \alpha$, during the positive half cycle of the input supply the FWD is reverse biased during the time period $\omega t = \alpha$ to π. FWD remains reverse biased and cut-off from $\omega t = \alpha$ to π. The load current flows through the conducting thyristor T_1, through the RL load and through upper half of the transformer secondary winding during the time period α to π.

At $\omega t = \pi$, when the input supply voltage across the upper half of the secondary winding reverses and becomes negative the FWD turns-on. The load current continues to flow through the FWD from $\omega t = \pi$ to β.

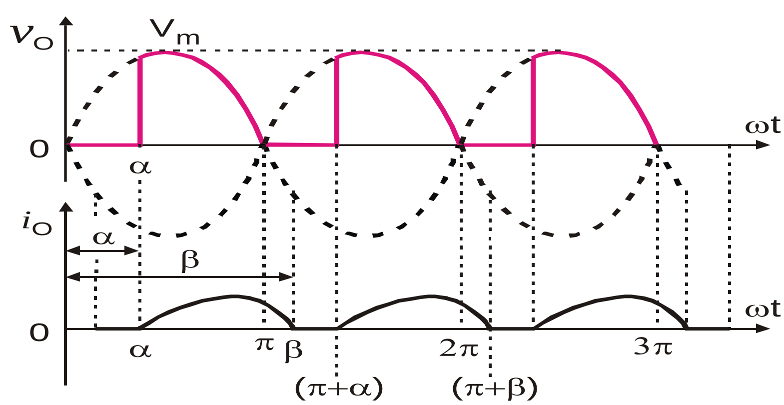


Fig.: Waveform for Discontinuous Load Current Operation with FWD

EXPRESSION FOR THE DC OUTPUT VOLTAGE OF A SINGLE PHASE FULL WAVE CONTROLLED RECTIFIER WITH RL LOAD AND FWD

$$V_{O(dc)} = V_{dc} = \frac{1}{\pi}\int_{\omega t=0}^{\pi} v_O . d\left(\omega t\right)$$

Thyristor T_1 is triggered at $\omega t = \alpha$. T_1 conducts from $\omega t = \alpha$ to π

Output voltage $v_O = V_m \sin\omega t$; for $\omega t = \alpha \ to \ \pi$

FWD conducts from $\omega t = \pi$ to β and $v_O \approx 0$ during discontinuous load current

Therefore $$V_{O(dc)} = V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t . d(\omega t)$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}\left[-\cos\omega t \Big/_{\alpha}^{\pi}\right]$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}\left[-\cos\pi + \cos\alpha\right] \quad ; \quad \cos\pi = -1$$

Therefore $$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}(1+\cos\alpha)$$

The DC output voltage V_{dc} is same as the DC output voltage of a single phase full wave controlled rectifier with resistive load. Note that the dc output voltage of a single phase full wave controlled rectifier is two times the dc output voltage of a half wave controlled rectifier.

CONTINUOUS LOAD CURRENT OPERATION (WITHOUT FWD)

For large values of load inductance the load current flows continuously without decreasing and falling to zero and there is always a load current flowing at any point of time. This type of operation is referred to as continuous current operation.

Generally the load current is continuous for large load inductance and for low trigger angles.

The load current is discontinuous for low values of load inductance and for large values of trigger angles.

The waveforms for continuous current operation are as shown.

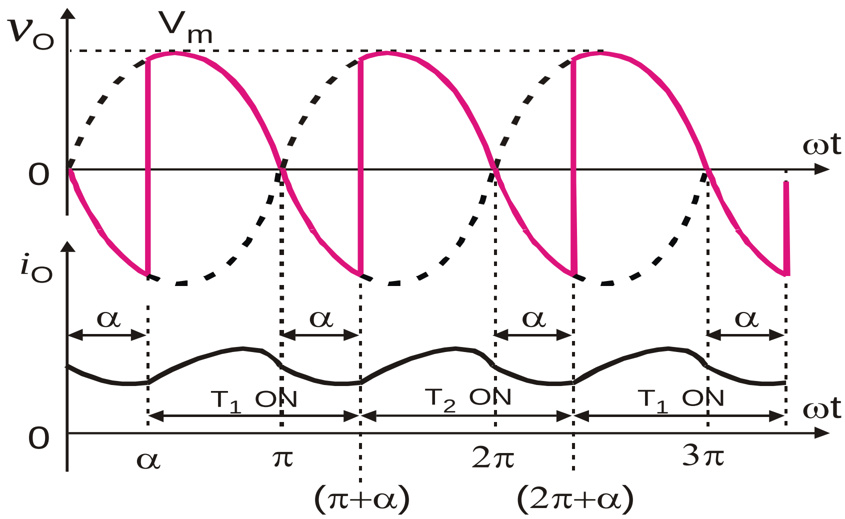


Fig.: Load voltage and load current waveform of a single phase full wave controlled rectifier with RL load & without FWD for continuous load current operation

In the case of continuous current operation the thyristor T_1 which is triggered at a delay angle of α, conducts from $\omega t = \alpha$ to $(\pi + \alpha)$. Output voltage follows the input supply voltage across the upper half of the transformer secondary winding $v_O = v_{AO} = V_m \sin \omega t$.

The next thyristor T_2 is triggered at $\omega t = (\pi + \alpha)$, during the negative half cycle input supply. As soon as T_2 is triggered at $\omega t = (\pi + \alpha)$, the thyristor T_1 will be reverse biased and T_1 turns off due to natural commutation (ac line commutation). The load current flows through the thyristor T_2 from $\omega t = (\pi + \alpha)$ to $(2\pi + \alpha)$. Output voltage across the load follows the input supply voltage across the lower half of the transformer secondary winding $v_O = v_{BO} = -V_m \sin \omega t$ .Each thyristor conducts for π radians (180^0) in the case of continuous current operation.

TO DERIVE AN EXPRESSION FOR THE AVERAGE OR DC OUTPUT VOLTAGE OF SINGLE PHASE FULL WAVE CONTROLLED RECTIFIER WITH LARGE LOAD INDUCTANCE ASSUMING CONTINUOUS LOAD CURRENT OPERATION.

$$V_{O(dc)} = V_{dc} = \frac{1}{\pi} \int_{\omega t = \alpha}^{(\pi+\alpha)} v_O . d(\omega t)$$

$$V_{O(dc)} = V_{dc} = \frac{1}{\pi} \left[\int_{\alpha}^{(\pi+\alpha)} V_m \sin \omega t . d(\omega t) \right]$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}\left[-\cos\omega t \Big/_{\alpha}^{(\pi+\alpha)}\right]$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}\left[\cos\alpha - \cos(\pi+\alpha)\right] \quad ; \qquad \cos(\pi+\alpha) = -\cos\alpha$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}\left[\cos\alpha + \cos\alpha\right]$$

$$\therefore \qquad V_{O(dc)} = V_{dc} = \frac{2V_m}{\pi}\cos\alpha$$

The above equation can be plotted to obtain the control characteristic of a single phase full wave controlled rectifier with RL load assuming continuous load current operation.

Normalizing the dc output voltage with respect to its maximum value, the normalized dc output voltage is given by

$$V_{dcn} = V_n = \frac{V_{dc}}{V_{dc(\max)}} = \frac{\frac{2V_m}{\pi}(\cos\alpha)}{\frac{2V_m}{\pi}} = \cos\alpha$$

Therefore $\qquad V_{dcn} = V_n = \cos\alpha$

Trigger angle α in degrees	$V_{O(dc)}$	**Remarks**
0	$V_{dm} = \left(\frac{2V_m}{\pi}\right)$	Maximum dc output voltage $V_{dc(\max)} = V_{dm} = \left(\frac{2V_m}{\pi}\right)$
30^0	0.866 V_{dm}	
60^0	0.5 V_{dm}	
90^0	0 V_{dm}	
120^0	-0.5 V_{dm}	

150^0	-0.866 V_{dm}
180^0	$-V_{dm} = -\left(\frac{2V_m}{\pi}\right)$

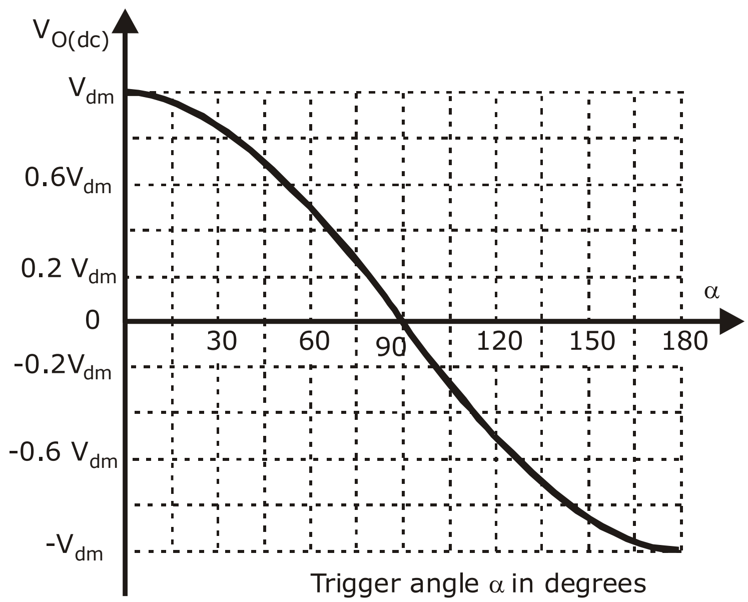


Fig.: Control Characteristic

We notice from the control characteristic that by varying the trigger angle α we can vary the output dc voltage across the load. Thus it is possible to control the dc output voltage by changing the trigger angle α. For trigger angle α in the range of 0 to 90 degrees $\left(i.e.,\ 0 \le \alpha \le 90^0\right)$, V_{dc} is positive and the circuit operates as a controlled rectifier to convert ac supply voltage into dc output power which is fed to the load.

For trigger angle $\alpha > 90^0, \cos\alpha$ becomes negative and as a result the average dc output voltage V_{dc} becomes negative, but the load current flows in the same positive direction. Hence the output power becomes negative. This means that the power flows from the load circuit to the input ac source. This is referred to as *line commutated inverter operation*. During the inverter mode operation for $\alpha > 90^0$ the load energy can be fed back from the load circuit to the input ac source.

TO DERIVE AN EXPRESSION FOR RMS OUTPUT VOLTAGE

The rms value of the output voltage is calculated by using the equation

$$V_{O(RMS)} = \left[\frac{2}{2\pi} \int_{\alpha}^{(\pi+\alpha)} v_O^2 . d(\omega t) \right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = \left[\frac{1}{\pi} \int_{\alpha}^{(\pi+\alpha)} V_m^2 \sin^2 \omega t . d(\omega t) \right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = \left[\frac{V_m^2}{\pi} \int_{\alpha}^{(\pi+\alpha)} \sin^2 \omega t . d(\omega t) \right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = \left[\frac{V_m^2}{\pi} \int_{\alpha}^{(\pi+\alpha)} \frac{(1-\cos 2\omega t)}{2} . d(\omega t) \right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = V_m \left[\frac{1}{2\pi} \left\{ \int_{\alpha}^{(\pi+\alpha)} d(\omega t) - \int_{\alpha}^{(\pi+\alpha)} \cos 2\omega t . d(\omega t) \right\} \right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = V_m \left[\frac{1}{2\pi} \left\{ (\omega t) \Big/_{\alpha}^{(\pi+\alpha)} - \left(\frac{\sin 2\omega t}{2} \right) \Big/_{\alpha}^{(\pi+\alpha)} \right\} \right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = V_m \left[\frac{1}{2\pi} \left\{ (\pi + \alpha - \alpha) - \left(\frac{\sin 2(\pi + \alpha) - \sin 2\alpha}{2} \right) \right\} \right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = V_m \left[\frac{1}{2\pi} \left\{ (\pi) - \left(\frac{\sin 2\pi \times \cos 2\alpha + \cos 2\pi \times \sin 2\alpha - \sin 2\alpha}{2} \right) \right\} \right]^{\frac{1}{2}}$$

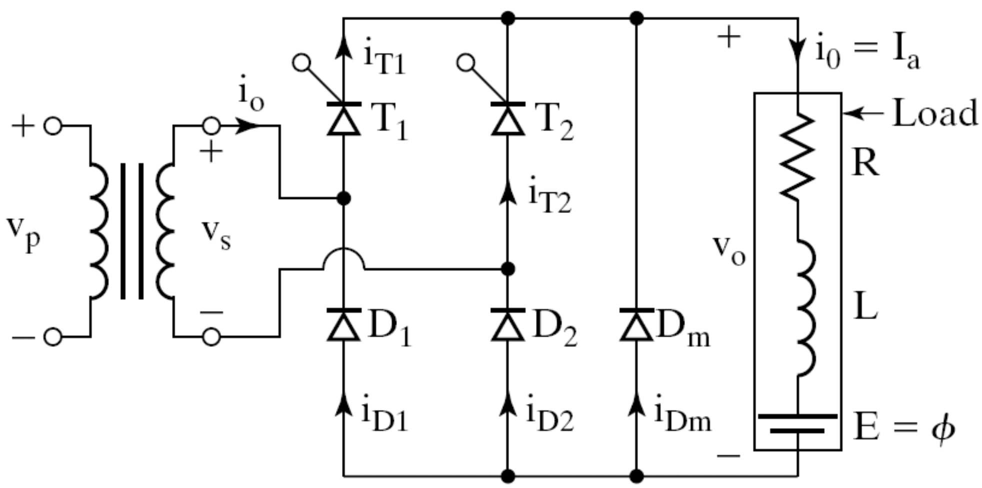
$$V_{O(RMS)} = V_m \left[\frac{1}{2\pi} \left\{ (\pi) - \left(\frac{0 + \sin 2\alpha - \sin 2\alpha}{2} \right) \right\} \right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = V_m \left[\frac{1}{2\pi} (\pi) \right]^{\frac{1}{2}} = \frac{V_m}{\sqrt{2}}$$

Therefore

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}}$$; The rms output voltage is same as the input rms supply voltage.

Single Phase Semi converters with RLE load and freewheeling diode



Errata: Consider diode D_2 as D_1 in the figure and diode D_1 as D_2

Single phase semi-converter circuit is a full wave half controlled bridge converter which uses two thyristors and two diodes connected in the form of a full wave bridge configuration.

The two thyristors are controlled power switches which are turned on one after the other by applying suitable gating signals (gate trigger pulses). The two diodes are uncontrolled power switches which turn-on and conduct one after the other as and when they are forward biased.

The circuit diagram of a single phase semi-converter (half controlled bridge converter) is shown in the above figure with highly inductive load and a dc source in the load circuit. When the load inductance is large the load current flows continuously and we can consider the continuous load current operation assuming constant load current, with negligible current ripple (i.e., constant and ripple free load current operation).

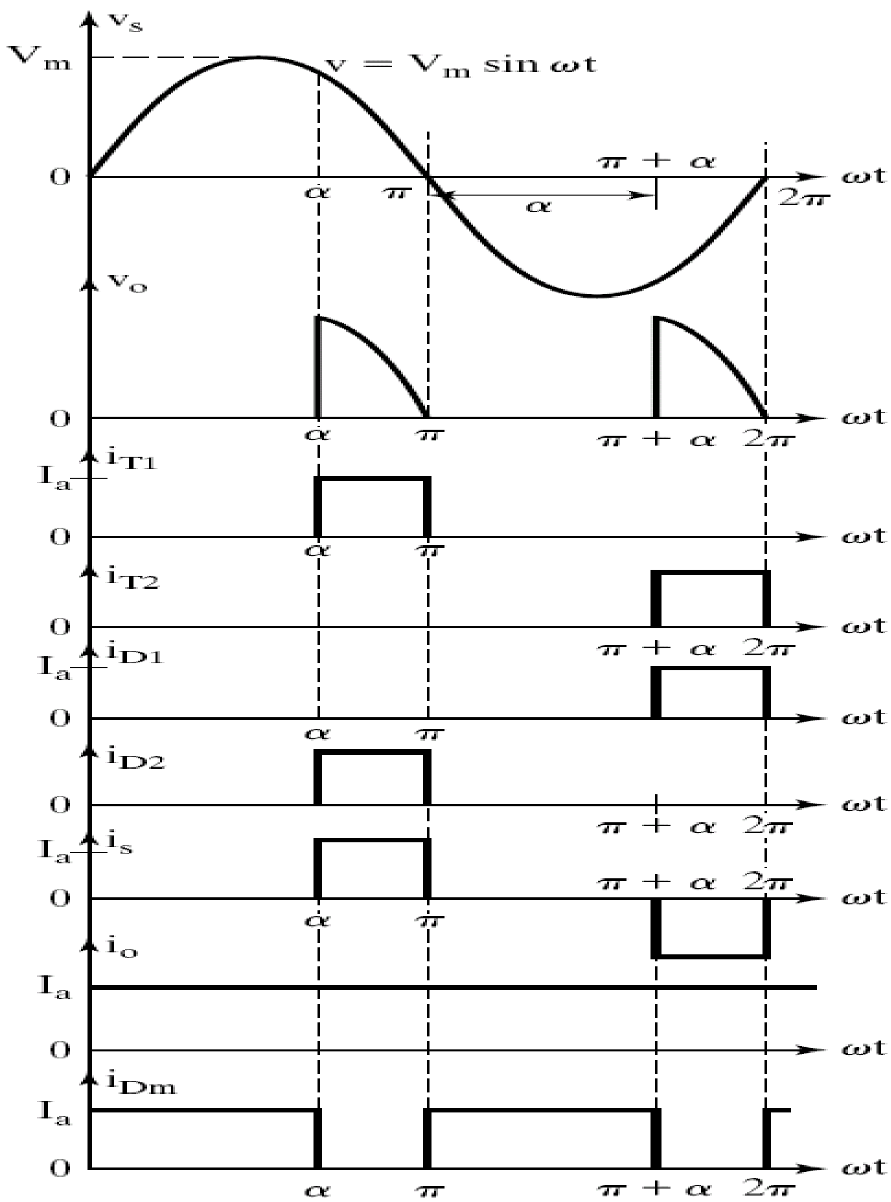
The ac supply to the semi converter is normally fed through a mains supply transformer having suitable turns ratio. The transformer is suitably designed to supply the required ac supply voltage (secondary output voltage) to the converter.

During the positive half cycle of input ac supply voltage, when the transformer secondary output line ‘A’ is positive with respect to the line ‘B’ the thyristor T_1 and the diode D_1 are both forward biased. The thyristor T_1 is triggered at $\omega t = \alpha$; $\left(0 \le \alpha \le \pi\right)$ by applying an appropriate gate trigger signal to the gate of T_1. The current in the circuit flows through the secondary line ‘A’, through T_1 , through the load in the downward direction, through diode D_1 back to the secondary line ‘B’. T_1 and D_1 conduct together from $\omega t = \alpha$ to π and the load is connected to the input ac supply. The output load voltage follows the input supply voltage (the secondary output voltage of the transformer) during the period $\omega t = \alpha$ to π .

At $\omega t = \pi$, the input supply voltage decreases to zero and becomes negative during the period $\omega t = \pi$ to $\left(\pi + \alpha\right)$. The free wheeling diode D_m across the load becomes forward biased and conducts during the period $\omega t = \pi$ to $\left(\pi + \alpha\right)$.

The load current is transferred from T_1 and D_1 to the FWD D_m. T_1 and D_1 are turned off. The load current continues to flow through the FWD D_m. The load current free wheels (flows continuously) through the FWD during the free wheeling time period π to $\left(\pi + \alpha\right)$.

During the negative half cycle of input supply voltage the secondary line ‘A’ becomes negative with respect to line ‘B’. The thyristor T_2 and the diode D_2 are both forward biased. T_2 is triggered at $\omega t = \left(\pi + \alpha\right)$, during the negative half cycle. The FWD is reverse biased and turns-off as soon as T_2 is triggered. The load current continues to flow through T_2 and D_2 during the period $\omega t = \left(\pi + \alpha\right)$ to 2π



Waveforms of single phase semi-converter for RLE load and constant load current for $\alpha > 90^0$

TO DERIVE AN EXPRESSION FOR THE AVERAGE OR DC OUTPUT VOLTAGE OF A SINGLE PHASE SEMI-CONVERTER

The average output voltage can be found from

$$V_{dc} = \frac{2}{2\pi} \int_{\alpha}^{\pi} V_m \sin \omega t . d(\omega t)$$

$$V_{dc} = \frac{2V_m}{2\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi}$$

$$V_{dc} = \frac{V_m}{\pi}\left[-\cos\pi + \cos\alpha\right] \ ; \ \cos\pi = -1$$

Therefore $$V_{dc} = \frac{V_m}{\pi}\left[1+\cos\alpha\right]$$

V_{dc} can be varied from $\frac{2V_m}{\pi}$ to 0 by varying α from 0 to π.

The maximum average output voltage is

$$V_{dc(\max)} = V_{dm} = \frac{2V_m}{\pi}$$

Normalizing the average output voltage with respect to its maximum value

$$V_{dcn} = V_n = \frac{V_{dc}}{V_{dm}} = 0.5\left(1+\cos\alpha\right)$$

The output control characteristic can be plotted by using the expression for V_{dc}

TO DERIVE AN EXPRESSION FOR THE RMS OUTPUT VOLTAGE OF A SINGLE PHASE SEMI-CONVERTER

The rms output voltage is found from

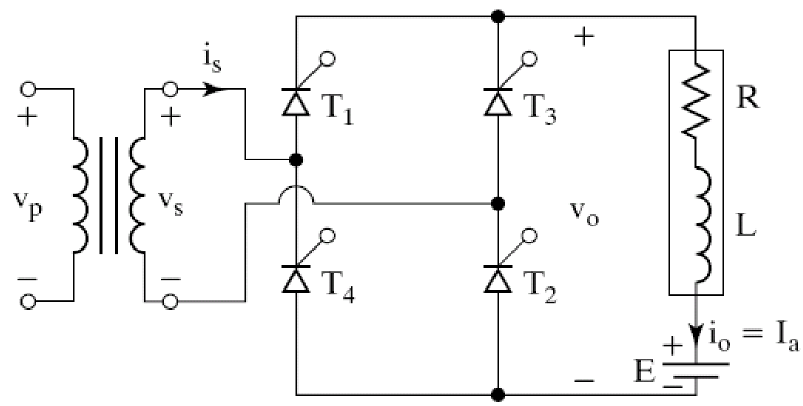
$$V_{O(RMS)} = \left[\frac{2}{2\pi}\int_{\alpha}^{\pi} V_m^2 \sin^2\omega t.d\left(\omega t\right)\right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = \left[\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi}\left(1-\cos 2\omega t\right).d\left(\omega t\right)\right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = \frac{V_m}{\sqrt{2}}\left[\frac{1}{\pi}\left(\pi-\alpha+\frac{\sin 2\alpha}{2}\right)\right]^{\frac{1}{2}}$$

SINGLE PHASE FULL CONVERTER (FULLY CONTROLLED BRIDGE CONVERTER).

1. Describe the operation of a 1 phase two pulse bridge converter in the inverter mode with RLE load.MAY/JUNE-2012,NOV/DEC-2009, APRIL/MAY-2016

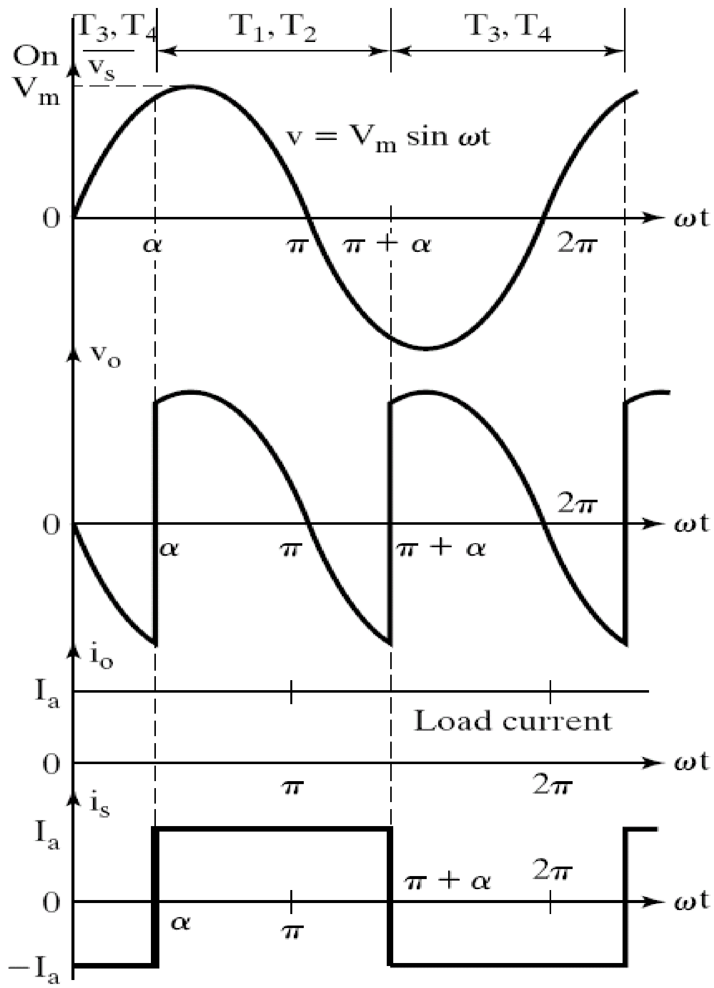


The circuit diagram of a single phase fully controlled bridge converter is shown in the figure with a highly inductive load and a dc source in the load circuit so that the load current is continuous and ripple free (constant load current operation).

The fully controlled bridge converter consists of four thyristors T_1, T_2, T_3 and T_4 connected in the form of full wave bridge configuration as shown in the figure. Each thyristor is controlled and turned on by its gating signal and naturally turns off when a reverse voltage appears across it. During the positive half cycle when the upper line of the transformer secondary winding is at a positive potential with respect to the lower end the thyristors T_1 and T_2 are forward biased during the time interval $\omega t = 0$ to π. The thyristors T_1 and T_2 are triggered simultaneously $\omega t = \alpha$; $\left(0 \le \alpha \le \pi\right)$, the load is connected to the input supply through the conducting thyristors T_1 and T_2. The output voltage across the load follows the input supply voltage and hence output voltage $v_O = V_m \sin \omega t$. Due to the inductive load T_1 and T_2 will continue to conduct beyond $\omega t = \pi$, even though the input voltage becomes negative. T_1 and T_2 conduct together during the time period α to $\left(\pi + \alpha\right)$, for a time duration of π radians (conduction angle of each thyristor = 180^0)

During the negative half cycle of input supply voltage for $\omega t = \pi$ to 2π the thyristors T_3 and T_4 are forward biased. T_3 and T_4 are triggered at $\omega t = \left(\pi + \alpha\right)$. As soon as the thyristors T_3 and T_4 are triggered a reverse voltage appears across the thyristors T_1 and T_2 and they naturally turn-off and the load current is transferred from T_1 and T_2 to the thyristors T_3 and

T_4. The output voltage across the load follows the supply voltage and $v_O = -V_m \sin \omega t$ during the time period $\omega t = (\pi + \alpha)$ to $(2\pi + \alpha)$. In the next positive half cycle when T_1 and T_2 are triggered, T_3 and T_4 are reverse biased and they turn-off. The figure shows the waveforms of the input supply voltage, the output load voltage, the constant load current with negligible ripple and the input supply current.



During the time period $\omega t = \alpha$ to π, the input supply voltage v_S and the input supply current i_S are both positive and the power flows from the supply to the load. The converter operates in the rectification mode during $\omega t = \alpha$ to π.

During the time period $\omega t = \pi$ to $(\pi + \alpha)$, the input supply voltage v_S is negative and the input supply current i_S is positive and there will be reverse power flow from the load circuit to the input supply. The converter operates in the inversion mode during the time period $\omega t = \pi$ to $(\pi + \alpha)$ and the load energy is fed back to the input source.

The single phase full converter is extensively used in industrial applications up to about 15kW of output power. Depending on the value of trigger angle α, the average output voltage may be either positive or negative and two quadrant operation is possible.

TO DERIVE AN EXPRESSION FOR THE AVERAGE (DC) OUTPUT VOLTAGE

The average (dc) output voltage can be determined by using the expression

$$V_{O(dc)} = V_{dc} = \frac{1}{2\pi}\left[\int_0^{2\pi} v_O.d(\omega t)\right] \;;$$

The output voltage waveform consists of two output pulses during the input supply time period between $0 \;\&\; 2\pi$ radians. In the continuous load current operation of a single phase full converter (assuming constant load current) each thyristor conduct for π radians (180^0) after it is triggered. When thyristors T_1 and T_2 are triggered at $\omega t = \alpha$ T_1 and T_2 conduct from α to $(\pi + \alpha)$ and the output voltage follows the input supply voltage. Therefore output voltage $v_O = V_m \sin \omega t$; for $\omega t = \alpha$ to $(\pi + \alpha)$

Hence the average or dc output voltage can be calculated as

$$V_{O(dc)} = V_{dc} = \frac{2}{2\pi}\left[\int_\alpha^{\pi+\alpha} V_m \sin \omega t.d(\omega t)\right]$$

$$V_{O(dc)} = V_{dc} = \frac{1}{\pi}\left[\int_\alpha^{\pi+\alpha} V_m \sin \omega t.d(\omega t)\right]$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}\left[\int_\alpha^{\pi+\alpha} \sin \omega t.d(\omega t)\right]$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}\left[-\cos \omega t\right]_\alpha^{\pi+\alpha}$$

$$V_{O(dc)} = V_{dc} = \frac{V_m}{\pi}\left[-\cos(\pi + \alpha) + \cos \alpha\right] \quad ; \quad \cos(\pi + \alpha) = -\cos \alpha$$

Therefore $\quad V_{O(dc)} = V_{dc} = \dfrac{2V_m}{\pi}\cos \alpha$

The dc output voltage V_{dc} can be varied from a maximum value of $\frac{2V_m}{\pi}$ for $\alpha = 0^0$ to a minimum value of $\frac{-2V_m}{\pi}$ for $\alpha = \pi$ radians $= 180^0$

The maximum average dc output voltage is calculated for a trigger angle $\alpha = 0^0$ and is obtained as

$$V_{dc(\max)} = V_{dm} = \frac{2V_m}{\pi} \times \cos(0) = \frac{2V_m}{\pi}$$

Therefore $V_{dc(\max)} = V_{dm} = \frac{2V_m}{\pi}$

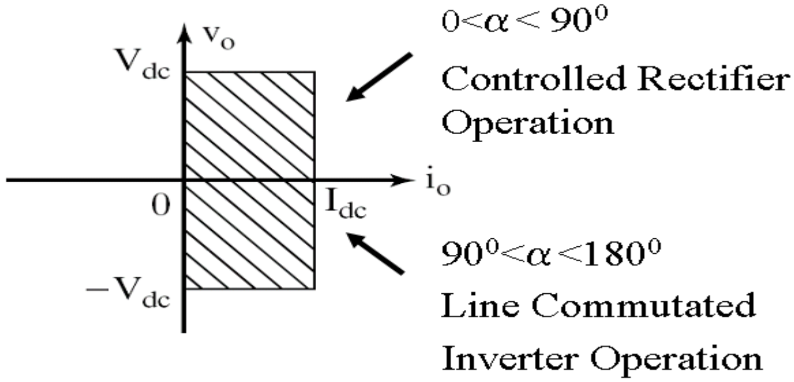
The normalized average output voltage is given by

$$V_{dcn} = V_n = \frac{V_{O(dc)}}{V_{dc(\max)}} = \frac{V_{dc}}{V_{dm}}$$

$$V_{dcn} = V_n = \frac{\frac{2V_m}{\pi}\cos\alpha}{\frac{2V_m}{\pi}} = \cos\alpha$$

Therefore $V_{dcn} = V_n = \cos\alpha$; for a single phase full converter assuming continuous and constant load current operation.

TWO QUADRANT OPERATION OF A SINGLE PHASE FULL CONVERTER



The above figure shows the two regions of single phase full converter operation in the V_{dc} versus I_{dc} plane. In the first quadrant when the trigger angle α is less than 90^0, V_{dc} and I_{dc}

are both positive and the converter operates as a controlled rectifier and converts the ac input power into dc output power. The power flows from the input source to the load circuit. This is the normal controlled rectifier operation where P_{dc} is positive.

When the trigger angle is increased above 90^0, V_{dc} becomes negative but I_{dc} is positive and the average output power (dc output power) P_{dc} becomes negative and the power flows from the load circuit to the input source. The operation occurs in the fourth quadrant where V_{dc} is negative and I_{dc} is positive. The converter operates as a line commutated inverter.

TO DERIVE AN EXPRESSION FOR THE RMS VALUE OF THE OUTPUT VOLTAGE

The rms value of the output voltage is calculated as

$$V_{O(RMS)} = \sqrt{\frac{1}{2\pi}\left[\int_0^{2\pi} v_O^2.d(\omega t)\right]}$$

The single phase full converter gives two output voltage pulses during the input supply time period and hence the single phase full converter is referred to as a two pulse converter. The rms output voltage can be calculated as

$$V_{O(RMS)} = \sqrt{\frac{2}{2\pi}\left[\int_\alpha^{\pi+\alpha} v_O^2.d(\omega t)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{1}{\pi}\left[\int_\alpha^{\pi+\alpha} V_m^2 \sin^2 \omega t.d(\omega t)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^2}{\pi}\left[\int_\alpha^{\pi+\alpha} \sin^2 \omega t.d(\omega t)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^2}{\pi}\left[\int_\alpha^{\pi+\alpha} \frac{(1-\cos 2\omega t)}{2}.d(\omega t)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^2}{2\pi}\left[\int_\alpha^{\pi+\alpha} d(\omega t) - \int_\alpha^{\pi+\alpha} \cos 2\omega t.d(\omega t)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^2}{2\pi}\left[\left(\omega t\right)\Big/_{\alpha}^{\pi+\alpha} - \left(\frac{\sin 2\omega t}{2}\right)\Big/_{\alpha}^{\pi+\alpha}\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^2}{2\pi}\left[\left(\pi+\alpha-\alpha\right)-\left(\frac{\sin 2\left(\pi+\alpha\right)-\sin 2\alpha}{2}\right)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^2}{2\pi}\left[\left(\pi\right)-\left(\frac{\sin\left(2\pi+2\alpha\right)-\sin 2\alpha}{2}\right)\right]} \quad ; \quad \sin\left(2\pi+2\alpha\right)=\sin 2\alpha$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^2}{2\pi}\left[\left(\pi\right)-\left(\frac{\sin 2\alpha-\sin 2\alpha}{2}\right)\right]}$$

$$V_{O(RMS)} = \sqrt{\frac{V_m^2}{2\pi}\left(\pi\right)-0} = \sqrt{\frac{V_m^2}{2}} = \frac{V_m}{\sqrt{2}}$$

Therefore $\quad V_{O(RMS)} = \frac{V_m}{\sqrt{2}} = V_S$

Hence the rms output voltage is same as the rms input supply voltage

The rms Thyristors current can be calculated as

Each thyristor conducts for π radians or 180^0 in a single phase full converter operating at continuous and constant load current.

Therefore rms value of the thyristor current is calculated as

$$I_{T(RMS)} = I_{O(RMS)}\sqrt{\frac{\pi}{2\pi}} = I_{O(RMS)}\sqrt{\frac{1}{2}}$$

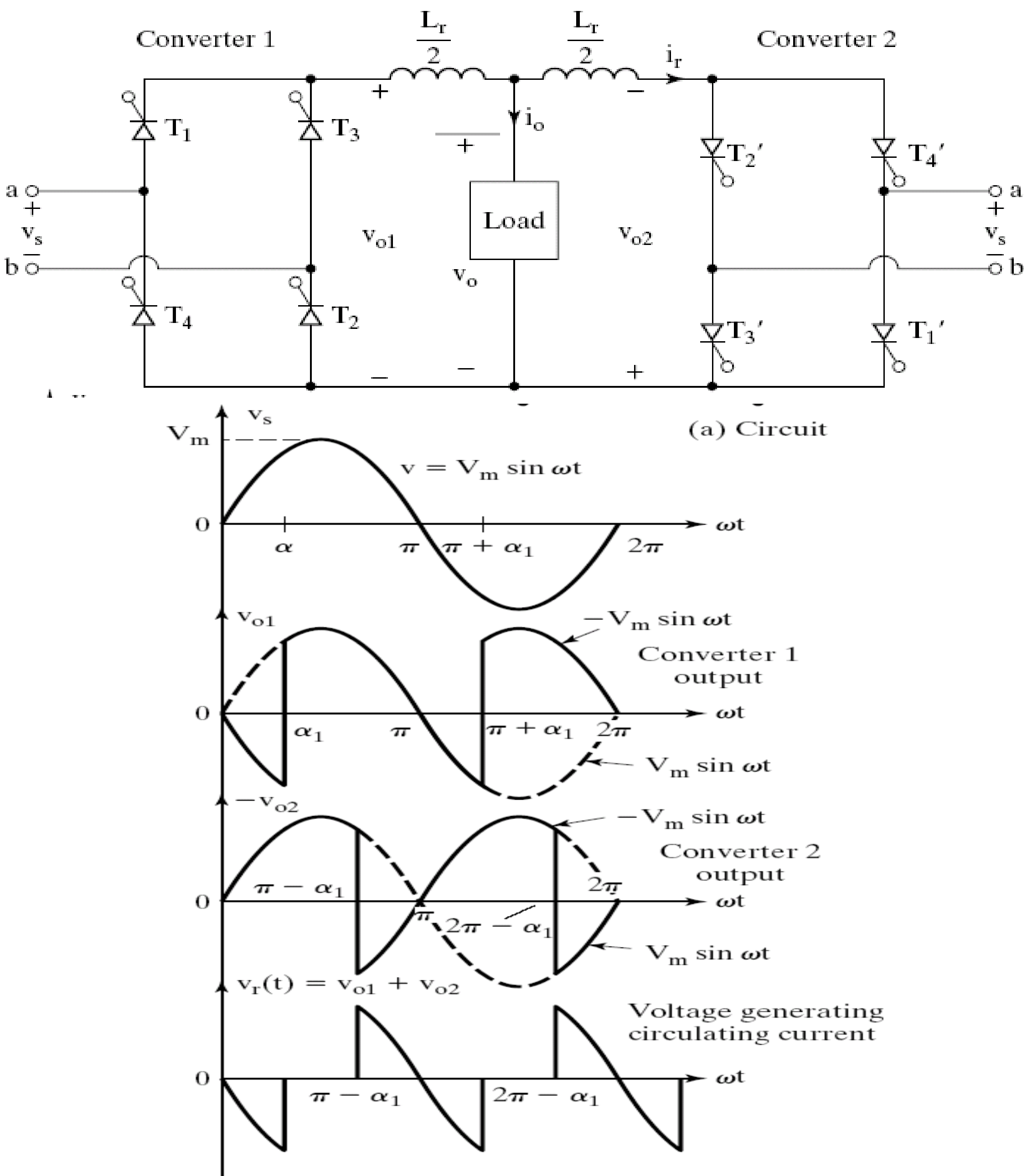
$$I_{T(RMS)} = \frac{I_{O(RMS)}}{\sqrt{2}}$$

The average thyristor current can be calculated as

$$I_{T(Avg)} = I_{O(dc)} \times \left(\frac{\pi}{2\pi}\right) = I_{O(dc)} \times \left(\frac{1}{2}\right)$$

$$I_{T(Avg)} = \frac{I_{O(dc)}}{2}$$

single phase dual converter



(b) Waveforms

We have seen in the case of a single phase full converter with inductive loads the converter can operate in two different quadrants in the V_{dc} versus I_{dc} operating diagram. If two single phase full converters are connected in parallel and in opposite direction (connected in back to back) across a common load four quadrant operation is possible. Such a converter is called as a dual converter which is shown in the figure.

The dual converter system will provide four quadrant operation and is normally used in high power industrial variable speed drives. The converter number 1 provides a positive dc output voltage and a positive dc load current, when operated in the rectification mode.

The converter number 2 provides a negative dc output voltage and a negative dc load current when operated in the rectification mode. We can thus have bi-directional load current and bi-directional dc output voltage. The magnitude of output dc load voltage and the dc load current can be controlled by varying the trigger angles α_1 & α_2 of the converters 1 and 2 respectively.

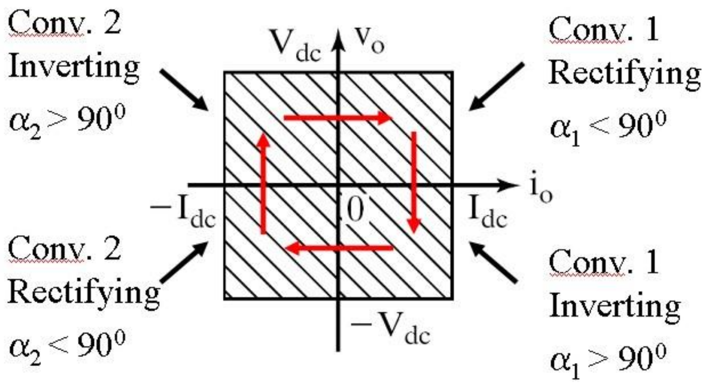


Fig.: Four quadrant operation of a dual converter

There are two modes of operations possible for a dual converter system.

- Non circulating current mode of operation (circulating current free mode of operation).
- Circulating current mode of operation.

NON CIRCULATING CURRENT MODE OF OPERATION (CIRCULATING CURRENT FREE MODE OF OPERATION)

In this mode of operation only one converter is switched on at a time while the second converter is switched off. When the converter 1 is switched on and the gate trigger signals are released to the gates of thyristors in converter 1, we get an average output voltage across the load, which can be varied by adjusting the trigger angle α_1 of the converter 1. If α_1 is less than 90^0, the converter 1 operates as a controlled rectifier and converts the input ac power into dc output power to feed the load. V_{dc} and I_{dc} are both positive and the operation occurs in the first quadrant. The average output power $P_{dc} = V_{dc} \times I_{dc}$ is positive. The power flows from the input ac supply to the load. When α_1 is increased above 90^0 converter 1 operates as a line commutated inverter and V_{dc} becomes negative while I_{dc} is positive and the output power P_{dc} becomes negative. The power is fed back from the load circuit to the input ac source through the converter 1. The load current falls to zero when the load energy is utilized completely.

The second converter 2 is switched on after a small delay of about 10 to 20 mill seconds to allow all the thyristors of converter 1 to turn off completely. The gate signals are released to the thyristor gates of converter 2 and the trigger angle α_2 is adjusted such that $0 \le \alpha_2 \le 90^0$ so that converter 2 operates as a controlled rectifier. The dc output voltage V_{dc} and I_{dc} are both negative and the load current flows in the reverse direction. The magnitude of V_{dc} and I_{dc} are controlled by the trigger angle α_2. The operation occurs in the third quadrant where V_{dc} and I_{dc} are both negative and output power P_{dc} is positive and the converter 2 operates as a controlled rectifier and converts the ac supply power into dc output power which is fed to the load.

When we want to reverse the load current flow so that I_{dc} is positive we have to operate converter 2 in the inverter mode by increasing the trigger angle α_2 above 90^0. When α_2 is made greater than 90^0, the converter 2 operates as a line commutated inverter and the load power (load energy) is fed back to ac mains. The current falls to zero when all the load energy is utilized and the converter 1 can be switched on after a short delay of 10 to 20 milli seconds to ensure that the converter 2 thyristors are completely turned off.

The advantage of non circulating current mode of operation is that there is no circulating current flowing between the two converters as only one converter operates and conducts at a time while the other converter is switched off. Hence there is no need of the series current limiting inductors between the outputs of the two converters. The current rating of thyristors is low in this mode.

But the disadvantage is that the load current tends to become discontinuous and the transfer characteristic becomes non linear. The control circuit becomes complex and the output response is sluggish as the load current reversal takes some time due to the time delay between the switching off of one converter and the switching on of the other converter. Hence the output dynamic response is poor. Whenever a fast and frequent reversal of the load current is required, the dual converter is operated in the circulating current mode.

CIRCULATING CURRENT MODE OF OPERATION

In this mode of operation both the converters 1 and 2 are switched on and operated simultaneously and both the converters are in a state of conduction. If converter 1 is operated as a controlled rectifier by adjusting the trigger angle α_1 between 0 to 90^0 the second converter 2 is operated as a line commutated inverter by increasing its trigger angle α_2 above 90^0. The trigger angles α_1 and α_2 are adjusted such that they produce the same average dc output voltage across the load terminals.

The average dc output voltage of converter 1 is

$V_{dc1} = \frac{2V_m}{\pi}\cos\alpha_1$

The average dc output voltage of converter 2 is

$V_{dc2} = \frac{2V_m}{\pi}\cos\alpha_2$

In the dual converter operation one converter is operated as a controlled rectifier with $\alpha_1 < 90^0$ and the second converter is operated as a line commutated inverter in the inversion mode with $\alpha_2 > 90^0$.

$$V_{dc1} = -V_{dc2}$$

$$\frac{2V_m}{\pi}\cos\alpha_1 = \frac{-2V_m}{\pi}\cos\alpha_2 = \frac{2V_m}{\pi}\left(-\cos\alpha_2\right)$$

Therefore $\cos\alpha_1 = -\cos\alpha_2$ or $\cos\alpha_2 = -\cos\alpha_1 = \cos\left(\pi - \alpha_1\right)$

Therefore $\alpha_2 = \left(\pi - \alpha_1\right)$ or $\left(\alpha_1 + \alpha_2\right) = \pi$ radians

Which gives $\alpha_2 = \left(\pi - \alpha_1\right)$

When the trigger angle α_1 of converter 1 is set to some value the trigger angle α_2 of the second converter is adjusted such that $\alpha_2 = \left(180^0 - \alpha_1\right)$. Hence for circulating current mode of operation where both converters are conducting at the same time $\left(\alpha_1 + \alpha_2\right) = 180^0$ so that they produce the same dc output voltage across the load.

When $\alpha_1 < 90^0$ (say $\alpha_1 = 30^0$) the converter 1 operates as a controlled rectifier and converts the ac supply into dc output power and the average load current I_{dc} is positive. At the same time the converter 2 is switched on and operated as a line commutated inverter, by adjusting the trigger angle α_2 such that $\alpha_2 = \left(180^0 - \alpha_1\right)$, which is equal to 150^0 , when $\alpha_1 = 30^0$. The converter 2 will operate in the inversion mode and feeds the load energy back to the ac supply. When we want to reverse the load current flow we have to switch the roles of the two converters.

When converter 2 is operated as a controlled rectifier by adjusting the trigger angle α_2 such that $\alpha_2 < 90^0$, the first converter1 is operated as a line commutated inverter, by adjusting the trigger angle α_1 such that $\alpha_1 > 90^0$. The trigger angle α_1 is adjusted such that $\alpha_1 = \left(180^0 - \alpha_2\right)$ for a set value of α_2.

In the circulating current mode a current builds up between the two converters even when the load current falls to zero. In order to limit the circulating current flowing between the two converters, we have to include current limiting reactors in series between the output terminals of the two converters.

The advantage of the circulating current mode of operation is that we can have faster reversal of load current as the two converters are in a state of conduction simultaneously. This greatly improves the dynamic response of the output giving a faster dynamic response. The output voltage and the load current can be linearly varied by adjusting the trigger angles α_1 & α_2 to obtain a smooth and linear output control. The control circuit becomes relatively simple. The transfer characteristic between the output voltage and the trigger angle is linear and hence the output response is very fast. The load current is free to flow in either direction at any time. The reversal of the load current can be done in a faster and smoother way.

The disadvantage of the circulating current mode of operation is that a current flows continuously in the dual converter circuit even at times when the load current is zero. Hence we should connect current limiting inductors (reactors) in order to limit the peak circulating current within specified value. The circulating current flowing through the series inductors gives rise to increased power losses, due to dc voltage drop across the series inductors which decreases the efficiency. Also the power factor of operation is low. The current limiting series inductors are heavier and bulkier which increases the cost and weight of the dual converter system.

The current flowing through the converter thyristors is much greater than the dc load current. Hence the thyristors should be rated for a peak thyristor current of $I_{T(\max)} = I_{dc(\max)} + i_{r(\max)}$, where $I_{dc(\max)}$ is the maximum dc load current and $i_{r(\max)}$ is the maximum value of the circulating current.

TO CALCULATE THE CIRCULATING CURRENT

As the instantaneous output voltages of the two converters are out of phase, there will be an instantaneous voltage difference and this will result in circulating current between the two converters. In order to limit the circulating current, current limiting reactors are connected in series between the outputs of the two converters. This circulating current will not flow through the load and is normally limited by the current reactor L_r .

If v_{O1} and v_{O2} are the instantaneous output voltages of the converters 1 and 2, respectively the circulating current can be determined by integrating the instantaneous voltage difference (which is the voltage drop across the circulating current reactor L_r), starting from $\omega t = (2\pi - \alpha_1)$. As the two average output voltages during the interval $\omega t = (\pi + \alpha_1)$ to $(2\pi - \alpha_1)$ are equal and opposite their contribution to the instantaneous circulating current i_r is zero.

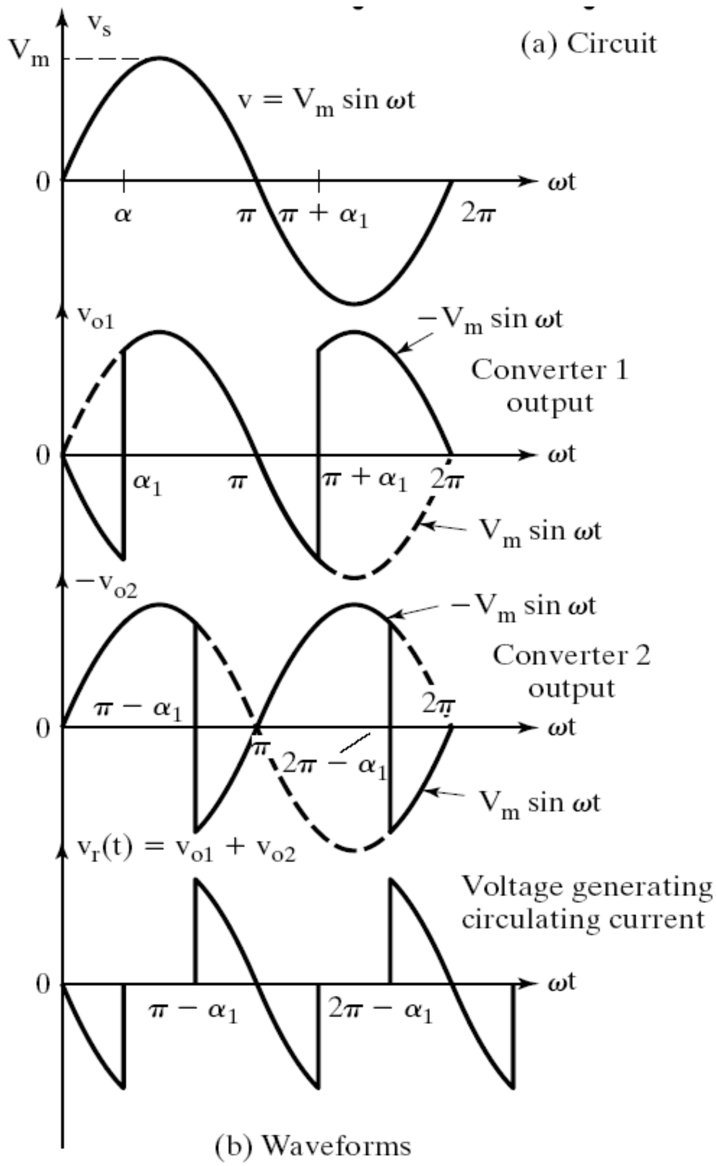


Fig.: Waveforms of dual converter

$$i_r = \frac{1}{\omega L_r}\left[\int_{(2\pi-\alpha_1)}^{\omega t} v_r.d(\omega t)\right]; \quad v_r = (v_{O1} - v_{O2})$$

As the output voltage v_{O2} is negative

$$v_r = (v_{O1} + v_{O2})$$

Therefore $$i_r = \frac{1}{\omega L_r}\left[\int_{(2\pi-\alpha_1)}^{\omega t}(v_{O1}+v_{O2}).d(\omega t)\right];$$

$$v_{O1} = -V_m \sin\omega t \text{ for } (2\pi-\alpha_1) \text{ to } \omega t$$

$$i_r = \frac{V_m}{\omega L_r}\left[\int_{(2\pi-\alpha_1)}^{\omega t} -\sin\omega t.d(\omega t) - \int_{(2\pi-\alpha_1)}^{\omega t} \sin\omega t.d(\omega t)\right]$$

$$i_r = \frac{V_m}{\omega L_r}\left[(\cos\omega t)\Big/_{(2\pi-\alpha_1)}^{\omega t} + (\cos\omega t)\Big/_{(2\pi-\alpha_1)}^{\omega t}\right]$$

$$i_r = \frac{V_m}{\omega L_r}\left[(\cos\omega t)-\cos(2\pi-\alpha_1)+(\cos\omega t)-\cos(2\pi-\alpha_1)\right]$$

$$i_r = \frac{V_m}{\omega L_r}\left[2\cos\omega t - 2\cos(2\pi-\alpha_1)\right]$$

$$i_r = \frac{2V_m}{\omega L_r}(\cos\omega t - \cos\alpha_1)$$

The instantaneous value of the circulating current depends on the delay angle.

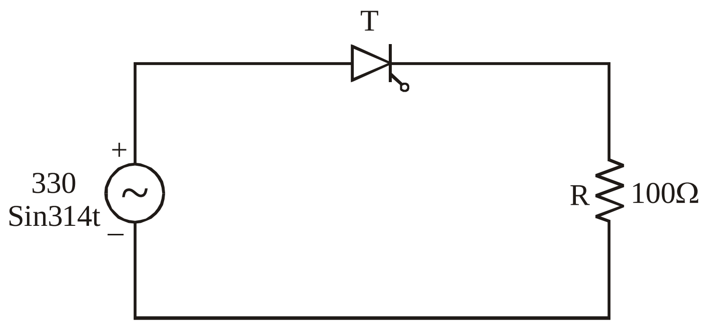
For trigger angle (delay angle) $\alpha_1 = 0$, its magnitude becomes minimum when $\omega t = n\pi,\ n = 0, 2, 4, ...$ and magnitude becomes maximum when $\omega t = n\pi,\ n = 1, 3, 5, ...$

If the peak load current is I_p, one of the converters that controls the power flow may carry a peak current of $$I_p + \frac{4V_m}{\omega L_r},$$

Where $$I_p = I_{L(\max)} = \frac{V_m}{R_L}, \ \& \ i_{r(\max)} = \frac{4V_m}{\omega L_r}$$

Problems

1. What will be the average power in the load for the circuit shown, when $\alpha = \frac{\pi}{4}$. Assume SCR to be ideal. Supply voltage is 330 sin314t. Also calculate the RMS power and the rectification efficiency.



GIVEN:

$\alpha = \frac{\pi}{4}$

V_S=330 sin314t

TO FIND:

RMS power and the rectification efficiency.

SOLUTION:

The circuit is that of a single phase half wave controlled rectifier with a resistive load

$$V_{dc} = \frac{V_m}{2\pi}(1+\cos\alpha) \quad ; \quad \alpha = \frac{\pi}{4} \; radians$$

$$V_{dc} = \frac{330}{2\pi}\left(1+\cos\left(\frac{\pi}{4}\right)\right)$$

$$V_{dc} = 89.66 \text{ Volts}$$

$$\text{Average Power} \quad = \frac{V_{dc}^2}{R} = \frac{89.66^2}{100} = 80.38 \text{ Watts}$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{89.66}{100} = 0.8966 \text{ Amps}$$

$$V_{RMS} = \frac{V_m}{2}\left[\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)\right]^{\frac{1}{2}}$$

$$V_{RMS} = \frac{330}{2}\left[\frac{1}{\pi}\left(\pi - \frac{\pi}{4} + \frac{\sin 2 \times \frac{\pi}{4}}{2}\right)\right]^{\frac{1}{2}}$$

$$V_{RMS} = 157.32\ V$$

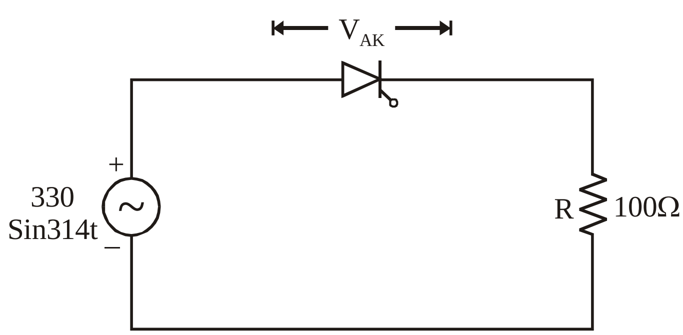
RMS Power (AC power)

$$= \frac{V_{RMS}^2}{R} = \frac{157.32^2}{100} = 247.50 \text{ Watts}$$

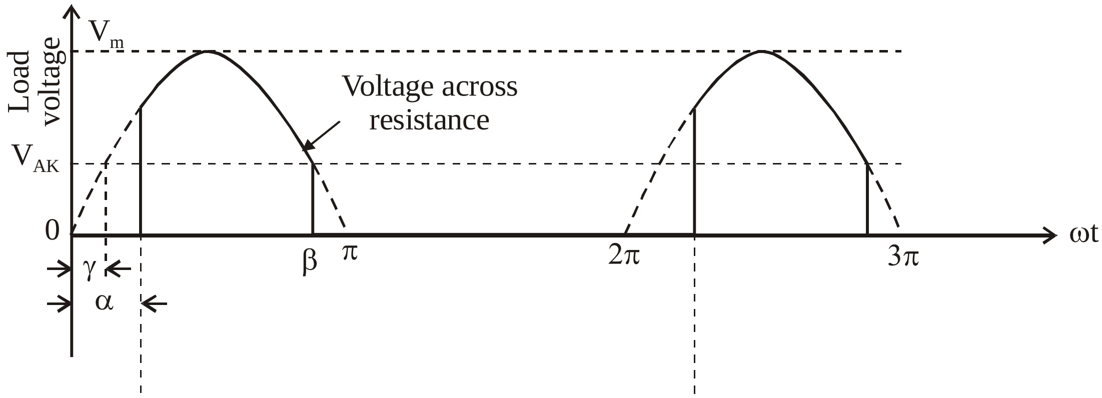
$$\text{Rectification Efficiency } = \frac{\text{Average power}}{\text{RMS power}}$$

$$= \frac{80.38}{247.47} = 0.3248$$

2. In the circuit shown find out the average voltage across the load assuming that the conduction drop across the SCR is 1 volt. Take $\alpha = 45^0$.



The wave form of the load voltage is shown below (not to scale).



It is observed that the SCR turns off when $\omega t = \beta$, where $\beta = (\pi - \gamma)$ because the SCR turns-off for anode supply voltage below 1 Volt.

$$V_{AK} = V_m \sin\gamma = 1 \text{ volt (given)}$$

Therefore $$\gamma = \sin^{-1}\left(\frac{V_{AK}}{V_m}\right) = \sin^{-1}\left(\frac{1}{330}\right) = 0.17^0 \left(0.003 \text{ radians}\right)$$

$$\beta = \left(180^0 - \gamma\right) \quad ; \text{ By symmetry of the curve.}$$

$$\beta = 179.83^0 \quad ; 3.138 \text{ radians.}$$

$$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\beta}\left(V_m \sin\omega t - V_{AK}\right) d\left(\omega t\right)$$

$$V_{dc} = \frac{1}{2\pi}\left[\int_{\alpha}^{\beta} V_m \sin\omega t . d\left(\omega t\right) - V_{AK}\int_{\alpha}^{\beta} d\left(\omega t\right)\right]$$

$$V_{dc} = \frac{1}{2\pi}\left[V_m\left(-\cos\omega t\right)\Big/_{\alpha}^{\beta} - V_{AK}\left(\omega t\right)\Big/_{\alpha}^{\beta}\right]$$

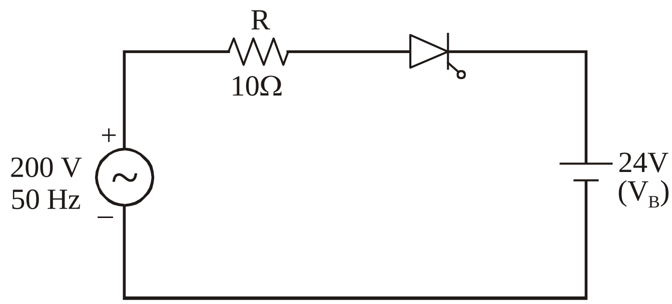
$$V_{dc} = \frac{1}{2\pi}\left[V_m\left(\cos\alpha - \cos\beta\right) - V_{AK}\left(\beta - \alpha\right)\right]$$

$$V_{dc} = \frac{1}{2\pi}\left[330\left(\cos 45^0 - \cos 179.83^0\right) - 1\left(3.138 - 0.003\right)\right]$$

$$V_{dc} = 89.15 \text{ Volts}$$

Note: β and α values should be in radians

3. In the figure find out the battery charging current when $\alpha = \frac{\pi}{4}$. Assume ideal SCR.



GIVEN:

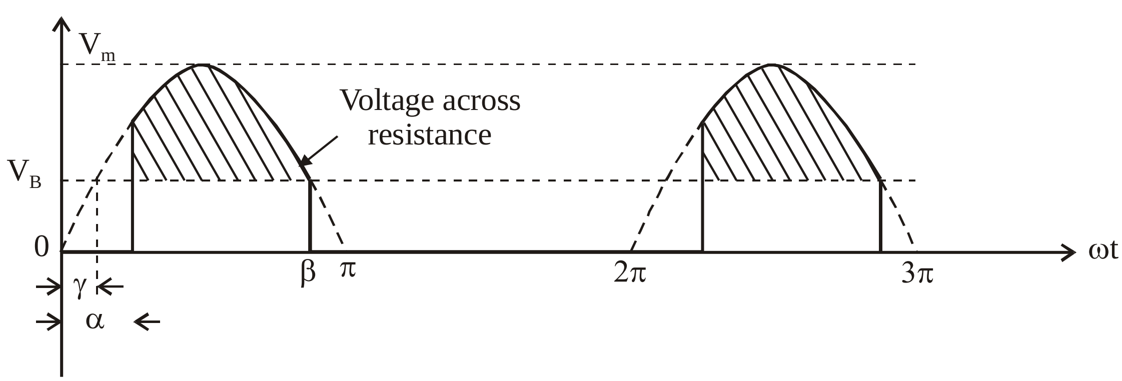
$$\alpha = \frac{\pi}{4}$$

TO FIND:

Battery Charging Current

SOLUTION:

It is obvious that the SCR cannot conduct when the instantaneous value of the supply voltage is less than 24 V, the battery voltage. The load voltage waveform is as shown (voltage across ion).



$$V_B = V_m \sin\gamma$$

$$24 = 200\sqrt{2}\sin\gamma$$

$$\gamma = \sin^{-1}\left(\frac{24}{200\times\sqrt{2}}\right) = 4.8675^{0} = 0.085 \text{ radians}$$

$$\beta = \pi - \gamma = 3.056 \text{ radians}$$

Average value of voltage across 10Ω

$$= \frac{1}{2\pi}\left[\int_{\alpha}^{\beta}\left(V_m \sin\omega t - V_B\right).d\left(\omega t\right)\right]$$

(The integral gives the shaded area)

$$= \frac{1}{2\pi}\left[\int_{\frac{\pi}{4}}^{3.056}\left(200\times\sqrt{2}\sin\omega t - 24\right).d\left(\omega t\right)\right]$$

$$= \frac{1}{2\pi}\left[200\sqrt{2}\left(\cos\frac{\pi}{4} - \cos 3.056\right) - 24\left(3.056 - \frac{\pi}{4}\right)\right]$$

$$= 68 \text{ Vots}$$

Therefore charging current

$$= \frac{\text{Average voltage across R}}{R}$$

$$= \frac{68}{10} = 6.8 \text{ Amps}$$

Note: If value of γ is more than α, then the SCR will trigger only at $\omega t = \gamma$, (assuming that the gate signal persists till then), when it becomes forward biased.

Therefore $$V_{dc} = \frac{1}{2\pi}\left[\int_{\gamma}^{\beta}\left(V_m \sin\omega t - V_B\right).d\left(\omega t\right)\right]$$

4. In a single phase full wave rectifier supply is 200 V AC. The load resistance is 10Ω, $\alpha = 60^0$. Find the average voltage across the load and the power consumed in the load.

GIVEN:

V=200 V, R=10Ω, $\alpha = 60^0$

TO FIND:

Average voltage across the load and the power consumed in the load

SOLUTION:

In a single phase full wave rectifier

$$V_{dc} = \frac{V_m}{\pi}\left(1+\cos\alpha\right)$$

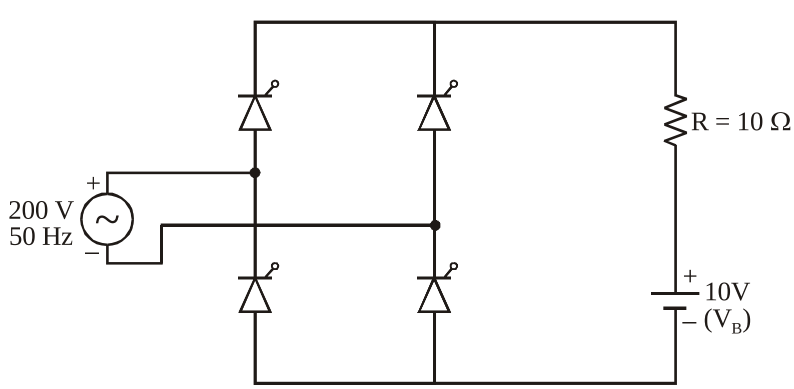
$$V_{dc} = \frac{200\times\sqrt{2}}{\pi}\left(1+\cos 60^0\right)$$

$$V_{dc} = 135 \text{ Volts}$$

Average Power

$$= \frac{V_{dc}^2}{R} = \frac{135^2}{10} = 1.823\ kW$$

2. In the circuit shown find the charging current if the trigger angle $\alpha = 90^0$.



GIVEN: $\alpha = 90^0$.

TO FIND: charging current

SOLUTION:

With the usual notation

$$V_B = V_m \sin\gamma$$

$$10 = 200\sqrt{2}\sin\gamma$$

Therefore $\gamma = \sin^{-1}\left(\frac{10}{200\times\sqrt{2}}\right) = 0.035 \text{ radians}$

$$\alpha = 90^0 = \frac{\pi}{2} \text{ radians} \quad ; \ \beta = (\pi - \gamma) = 3.10659$$

Average voltage across $10\Omega = \frac{2}{2\pi}\left[\int_\alpha^\beta (V_m \sin\omega t - V_B).d(\omega t)\right]$

$$= \frac{1}{\pi}\left[-V_m \cos\omega t - V_B(\omega t)\right]_\alpha^\beta$$

$$= \frac{1}{\pi}\left[V_m(\cos\alpha - \cos\beta) - V_B(\beta - \alpha)\right]$$

$$= \frac{1}{\pi}\left[200\times\sqrt{2}\left(\cos\frac{\pi}{2} - \cos 3.106\right) - 10\left(3.106 - \frac{\pi}{2}\right)\right]$$

$$= 85 \text{ V}$$

Note that the values of α & β are in radians.

Charging current $= \frac{\text{dc voltage across resistance}}{\text{resistance}}$

$$= \frac{85}{10} = 8.5 \text{ Amps}$$

3. A single phase full wave controlled rectifier is used to supply a resistive load of 10 Ω from a 230 V, 50 Hz, supply and firing angle of 90^0. What is its mean load voltage? If a large inductance is added in series with the load resistance, what will be the new output load voltage? NOV/DEC-13,15.

GIVEN:

R=10 Ω,V= 230 V, F=50 Hz, firing angle of 90^0

TO FIND:

V

SOLUTION:

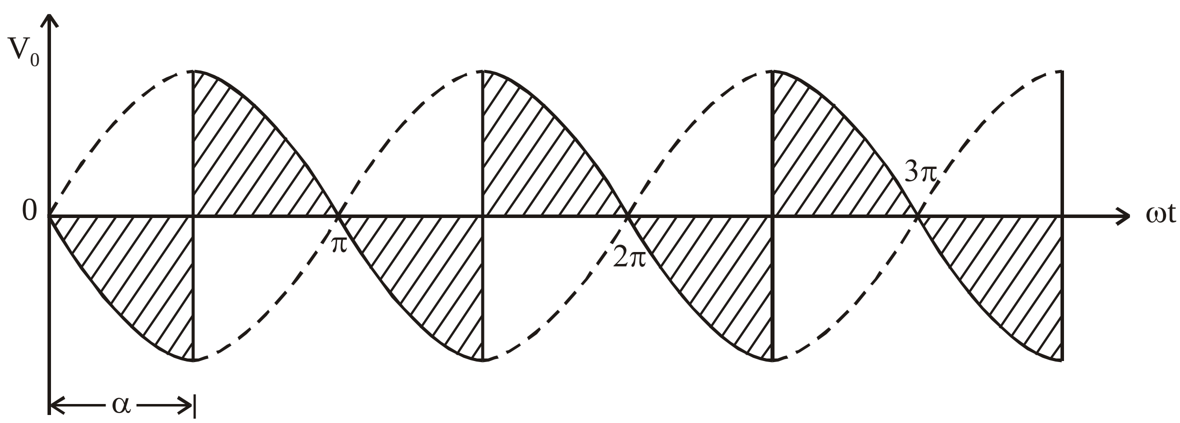
For a single phase full wave controlled rectifier with resistive load,

$$V_{dc} = \frac{V_m}{\pi}(1+\cos\alpha)$$

$$V_{dc} = \frac{230\times\sqrt{2}}{\pi}\left(1+\cos\frac{\pi}{2}\right)$$

$$V_{dc} = 103.5 \text{ Volts}$$

When a large inductance is added in series with the load, the output voltage wave form will be as shown below, for trigger angle $\alpha = 90^0$.



$$V_{dc} = \frac{2V_m}{\pi}\cos\alpha$$

Since $\alpha = \frac{\pi}{2}$; $\cos\alpha = \cos\left(\frac{\pi}{2}\right) = 0$

Therefore $V_{dc} = 0$ and this is evident from the waveform also.

4. The figure shows a battery charging circuit using SCRs. The input voltage to the circuit is 230 V RMS. Find the charging current for a firing angle of 45^0. If any one of the SCR is open circuited, what is the charging current?

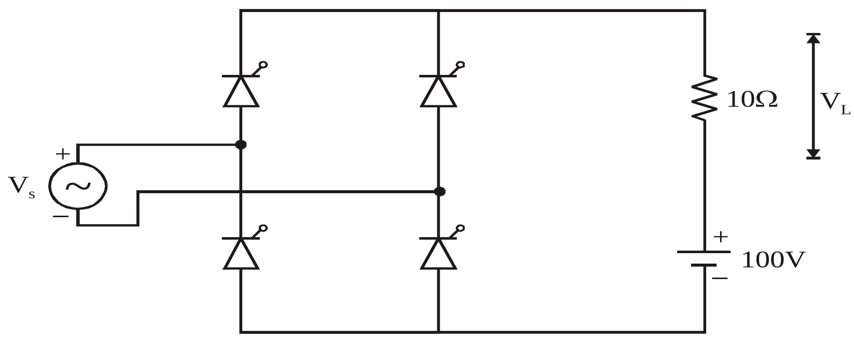
GIVEN:

230 V RMS, firing angle of 45^0

TO FIND:

charging current

SOLUTION:



With the usual notations

$$V_S = V_m \sin\omega t$$

$$V_S = \sqrt{2}\times 230\sin\omega t$$

$V_m \sin\gamma = V_B$, the battery voltage

$$\sqrt{2}\times 230\sin\gamma = 100$$

Therefore $\gamma = \sin^{-1}\left(\dfrac{100}{\sqrt{2}\times 230}\right)$

$$\gamma = 17.9^0 \text{ or } 0.312 \text{ radians}$$

$$\beta = (\pi - \gamma) = (\pi - 0.312)$$

$$\beta = 2.829 \text{ radians}$$

Average value of voltage across load resistance

$$= \frac{2}{2\pi}\left[\int_{\alpha}^{\beta}(V_m \sin\omega t - V_B)\, d(\omega t)\right]$$

$$= \frac{1}{\pi}\left[-V_m \cos\omega t - V_B(\omega t)\right]_{\alpha}^{\beta}$$

$$= \frac{1}{\pi}\left[V_m(\cos\alpha - \cos\beta) - V_B(\beta - \alpha)\right]$$

$$= \frac{1}{\pi}\left[230\times\sqrt{2}\left(\cos\frac{\pi}{4} - \cos 2.829\right) - 100\left(2.829 - \frac{\pi}{4}\right)\right]$$

$$= \frac{1}{\pi}\left[230\times\sqrt{2}(0.707 + 0.9517) - 204.36\right]$$

$$= 106.68 \text{ Volts}$$

Charging current $= \dfrac{\text{Voltage across resistance}}{R}$

$$= \frac{106.68}{10} = 10.668 \text{ Amps}$$

If one of the SCRs is open circuited, the circuit behaves like a half wave rectifier. The average voltage across the resistance and the charging current will be half of that of a full wave rectifier.

Therefore Charging Current $= \frac{10.668}{2} = 5.334$ Amps

5. A 230V, 50Hz, supply is connected to load resistance of 12ohm through half wave controlled rectifier. If the firing angle is 60degree, determine

1. Average output voltage
2. RMS output voltage
3. Ratio of rectification
4. Transformer Utilization Factor (TUF) *NOV/DEC-2014*

GIVEN:

V_S =230 V, F = 50 HZ , α=60°, R=12Ω

TO FIND:

1. Average output voltage
2. RMS output voltage
3. Ratio of rectification
4. Transformer Utilization Factor (TUF)

SOLUTION:

Single phase half wave controller V_S =230 V, F = 50 HZ , α=60°, R=12Ω

1) Average output voltage,

$$V_{DC} = \frac{V_m}{2\pi}(1+\cos\alpha)$$

$$V_{DC} = \frac{230\times\sqrt{2}}{2\pi}(1+\cos 60^\circ)$$

Vdc =77.65 V

2) RMS output voltage

$$V(RMS) = \frac{Vm}{2}[1/\pi(\pi-\alpha+\frac{\sin 2\alpha}{2})]^{1/2}$$

$$= \frac{230\sqrt{2}}{2}[1/\pi(\pi-\frac{\pi}{3})+\frac{\sin(120^\circ)}{2}]^{1/2}$$

$$= \frac{230\sqrt{2}}{2}[0.6667+0.4330]^{1/2}$$

$V(RMS) = 170.55$ V

3) Ratio of rectification = $(77.65)^2/(170.55)^2 = 0.2073$

Ratio of rectification efficiency = 20.73%

4) Transformer utilization factor (TUF)

$$TUF = \frac{(V_{dc})^2}{0.707V_m \times 0.3536V_m}$$

$$TUF = \frac{(77.65)^2}{115 \times 170.55V_m}$$

$$TUF = 0.3074$$

5) PIV (peak inverse voltage)

PIV=V_m

THREE PHASE CONTROLLED RECTIFIERS

INTRODUCTION TO 3-PHASE CONTROLLED RECTIFIERS

Single phase half controlled bridge converters & fully controlled bridge converters are used extensively in industrial applications up to about 15kW of output power. The single phase controlled rectifiers provide a maximum dc output of $V_{dc(\max)} = \frac{2V_m}{\pi}$.

The output ripple frequency is equal to the twice the ac supply frequency. The single phase full wave controlled rectifiers provide two output pulses during every input supply cycle and hence are referred to as two pulse converters.

Three phase converters are 3-phase controlled rectifiers which are used to convert ac input power supply into dc output power across the load.

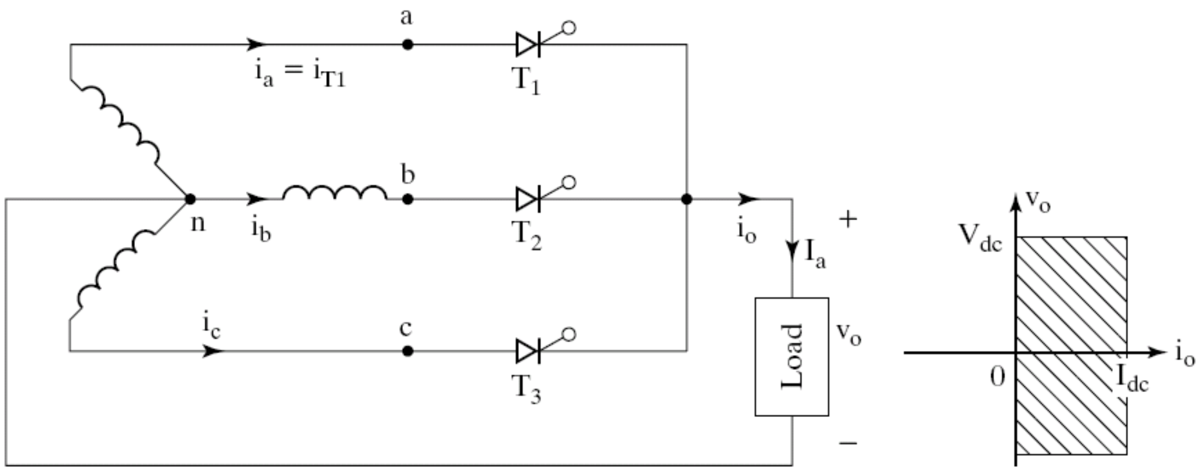
Features of 3-phase controlled rectifiers are

- Operate from 3 phase ac supply voltage.
- They provide higher dc output voltage and higher dc output power.
- Higher output voltage ripple frequency.
- Filtering requirements are simplified for smoothing out load voltage and load current

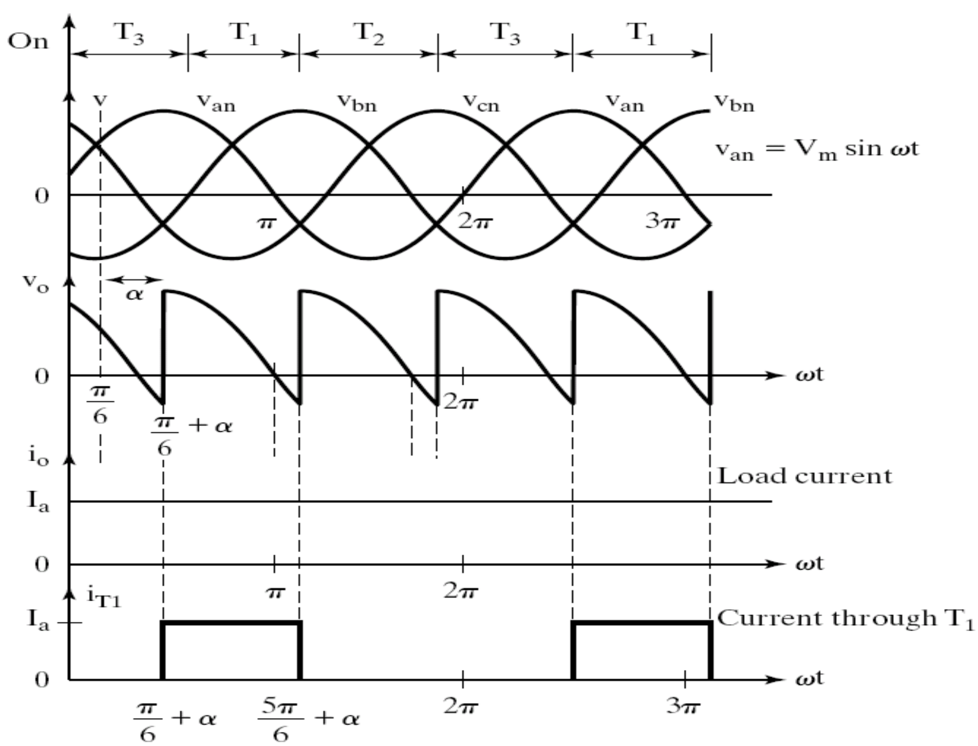
Three phase controlled rectifiers are extensively used in high power variable speed industrial dc drives.

3-PHASE HALF WAVE CONVERTER

Three single phase half-wave converters are connected together to form a three phase half-wave converter as shown in the figure.



(a) Circuit (b) Quadrant



(c) For inductive load

THEE PHASE SUPPLY VOLTAGE EQUATIONS

We define three line neutral voltages (3 phase voltages) as follows

$$v_{RN} = v_{an} = V_m \sin \omega t; \quad V_m = \text{ Max. Phase Voltage}$$

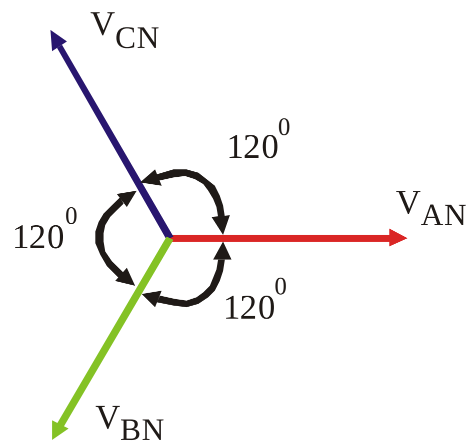
$$v_{YN} = v_{bn} = V_m \sin\left(\omega t - \frac{2\pi}{3}\right)$$

$$v_{YN} = v_{bn} = V_m \sin\left(\omega t - 120^0\right)$$

$$v_{BN} = v_{cn} = V_m \sin\left(\omega t + \frac{2\pi}{3}\right)$$

$$v_{BN} = v_{cn} = V_m \sin\left(\omega t + 120^0\right)$$

$$v_{BN} = v_{cn} = V_m \sin\left(\omega t - 240^0\right)$$



Vector diagram of 3-phase supply voltages

The 3-phase half wave converter combines three single phase half wave controlled rectifiers in one single circuit feeding a common load. The thyristor T_1 in series with one of the supply phase windings $'a-n'$ acts as one half wave controlled rectifier. The second thyristor T_2 in series with the supply phase winding $'b-n'$ acts as the second half wave controlled rectifier. The third thyristor T_3 in series with the supply phase winding $'c-n'$ acts as the third half wave controlled rectifier.

The 3-phase input supply is applied through the star connected supply transformer as shown in the figure. The common neutral point of the supply is connected to one end of the load while the other end of the load connected to the common cathode point.

When the thyristor T_1 is triggered at $\omega t = \left(\frac{\pi}{6} + \alpha\right) = \left(30^0 + \alpha\right)$, the phase voltage v_{an} appears across the load when T_1 conducts. The load current flows through the supply phase winding $'a-n'$ and through thyristor T_1 as long as T_1 conducts.

When thyristor T_2 is triggered at $\omega t = \left(\frac{5\pi}{6} + \alpha\right) = \left(150^0 + \alpha\right)$, T_1 becomes reverse biased and turns-off. The load current flows through the thyristor T_2 and through the supply phase winding

$'b-n'$. When T_2 conducts the phase voltage v_{bn} appears across the load until the thyristor T_3 is triggered .

When the thyristor T_3 is triggered at $\omega t = \left(\frac{3\pi}{2} + \alpha\right) = \left(270^0 + \alpha\right)$, T_2 is reversed biased and hence T_2 turns-off. The phase voltage v_{cn} appears across the load when T_3 conducts.

When T_1 is triggered again at the beginning of the next input cycle the thyristor T_3 turns off as it is reverse biased naturally as soon as T_1 is triggered. The figure shows the 3-phase input supply voltages, the output voltage which appears across the load, and the load current assuming a constant and ripple free load current for a highly inductive load and the current through the thyristor T_1.

For a purely resistive load where the load inductance 'L = 0' and the trigger angle $\alpha > \left(\frac{\pi}{6}\right)$, the load current appears as discontinuous load current and each thyristor is naturally commutated when the polarity of the corresponding phase supply voltage reverses. The frequency of output ripple frequency for a 3-phase half wave converter is $3f_S$, where f_S is the input supply frequency.

The 3-phase half wave converter is not normally used in practical converter systems because of the disadvantage that the supply current waveforms contain dc components (i.e., the supply current waveforms have an average or dc value).

TO DERIVE AN EXPRESSION FOR THE AVERAGE OUTPUT VOLTAGE OF A 3-PHASE HALF WAVE CONVERTER FOR CONTINUOUS LOAD CURRENT

The reference phase voltage is $v_{RN} = v_{an} = V_m \sin \omega t$. The trigger angle α is measured from the cross over points of the 3-phase supply voltage waveforms. When the phase supply voltage v_{an} begins its positive half cycle at $\omega t = 0$, the first cross over point appears at $\omega t = \left(\frac{\pi}{6}\right)\ radians = 30^0$.

The trigger angle α for the thyristor T_1 is measured from the cross over point at $\omega t = 30^0$. The thyristor T_1 is forward biased during the period $\omega t = 30^0$ to 150^0, when the phase supply voltage v_{an} has a higher amplitude than the other phase supply voltages. Hence T_1 can be triggered between 30^0 to 150^0. When the thyristor T_1 is triggered at a trigger angle α, the average or dc output voltage for continuous load current is calculated using the equation

$$V_{dc} = \frac{3}{2\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} v_O.d(\omega t)\right]$$

Output voltage $v_O = v_{an} = V_m \sin\omega t$ for $\omega t = (30^0 + \alpha)$ to $(150^0 + \alpha)$

$$V_{dc} = \frac{3}{2\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m \sin\omega t.d(\omega t)\right]$$

As the output load voltage waveform has three output pulses during the input cycle of 2π radians

$$V_{dc} = \frac{3V_m}{2\pi}\left[\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} \sin\omega t.d(\omega t)\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[(-\cos\omega t)\Big/_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha}\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[-\cos\left(\frac{5\pi}{6}+\alpha\right)+\cos\left(\frac{\pi}{6}+\alpha\right)\right]$$

Note from the trigonometric relationship

$$\cos(A+B) = (\cos A.\cos B - \sin A.\sin B)$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[-\cos\left(\frac{5\pi}{6}\right)\cos(\alpha)+\sin\left(\frac{5\pi}{6}\right)\sin(\alpha)+\cos\left(\frac{\pi}{6}\right).\cos(\alpha)-\sin\left(\frac{\pi}{6}\right)\sin(\alpha)\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[-\cos(150^0)\cos(\alpha)+\sin(150^0)\sin(\alpha)+\cos(30^0).\cos(\alpha)-\sin(30^0)\sin(\alpha)\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[-\cos(180^0-30^0)\cos(\alpha)+\sin(180^0-30^0)\sin(\alpha)+\cos(30^0).\cos(\alpha)-\sin(30^0)\sin(\alpha)\right]$$

Note: $\cos\left(180^0 - 30^0\right) = -\cos\left(30^0\right)$

$\sin\left(180^0 - 30^0\right) = \sin\left(30^0\right)$

Therefore

$$V_{dc} = \frac{3V_m}{2\pi}\left[+\cos\left(30^0\right)\cos\left(\alpha\right) + \sin\left(30^0\right)\sin\left(\alpha\right) + \cos\left(30^0\right).\cos\left(\alpha\right) - \sin\left(30^0\right)\sin\left(\alpha\right)\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[2\cos\left(30^0\right)\cos\left(\alpha\right)\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[2 \times \frac{\sqrt{3}}{2}\cos\left(\alpha\right)\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[\sqrt{3}\cos\left(\alpha\right)\right] = \frac{3\sqrt{3}V_m}{2\pi}\cos\left(\alpha\right)$$

$$V_{dc} = \frac{3V_{Lm}}{2\pi}\cos\left(\alpha\right)$$

Where

$V_{Lm} = \sqrt{3}V_m =$ Max. line to line supply voltage for a 3-phase star connected transformer.

The maximum average or dc output voltage is obtained at a delay angle $\alpha = 0$ and is given by

$$V_{dc(\max)} = V_{dm} = \frac{3\sqrt{3}\ V_m}{2\pi}$$

Where

V_m is the peak phase voltage.

And the normalized average output voltage is

$$V_{dcn} = V_n = \frac{V_{dc}}{V_{dm}} = \cos\alpha$$

TO DERIVE AN EXPRESSION FOR THE RMS VALUE OF THE OUTPUT VOLTAGE OF A 3-PHASE HALF WAVE CONVERTER FOR CONTINUOUS LOAD CURRENT

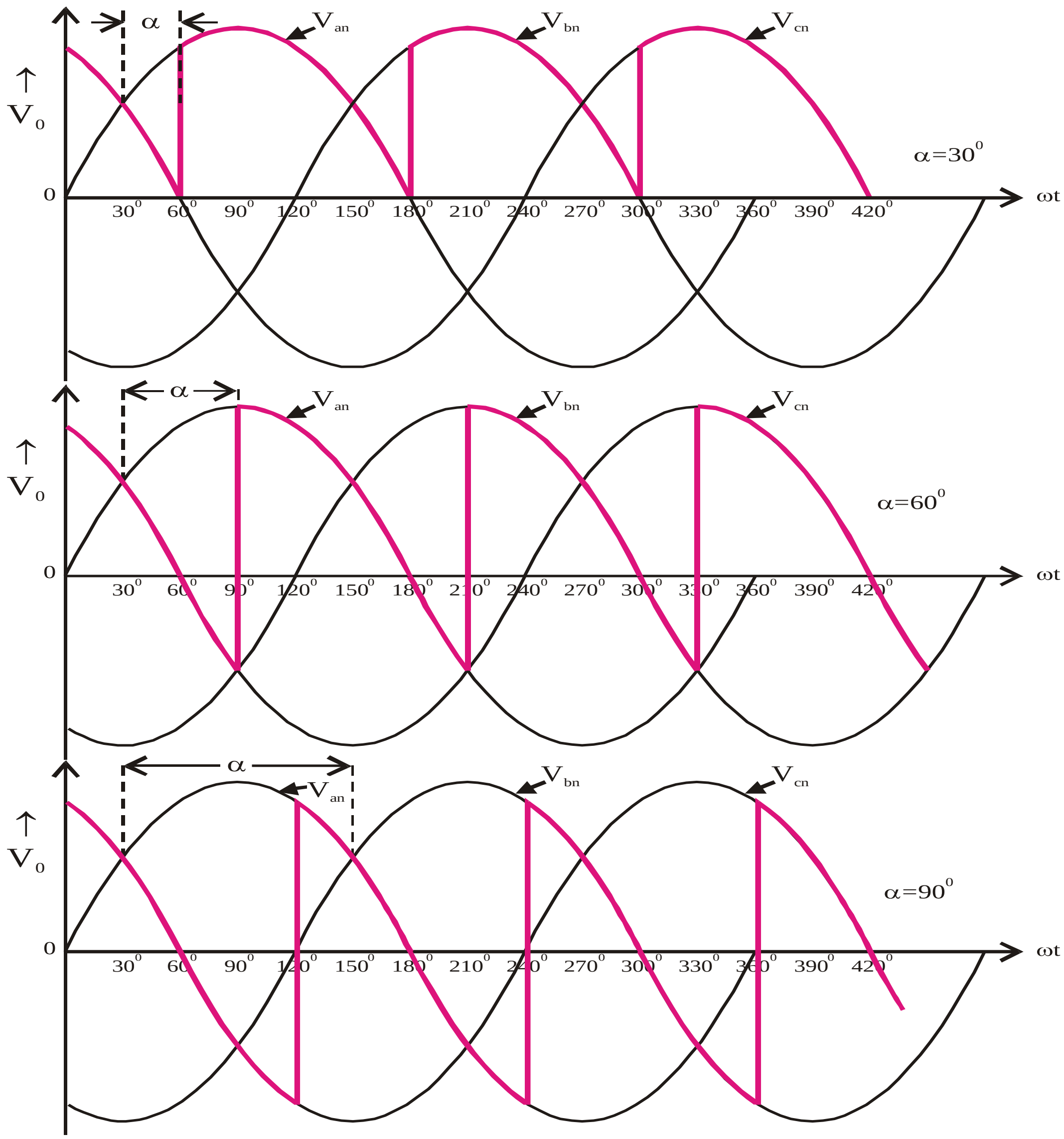
The rms value of output voltage is found by using the equation

$$V_{O(RMS)} = \left[\frac{3}{2\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} V_m^2 \sin^2 \omega t . d(\omega t) \right]^{\frac{1}{2}}$$

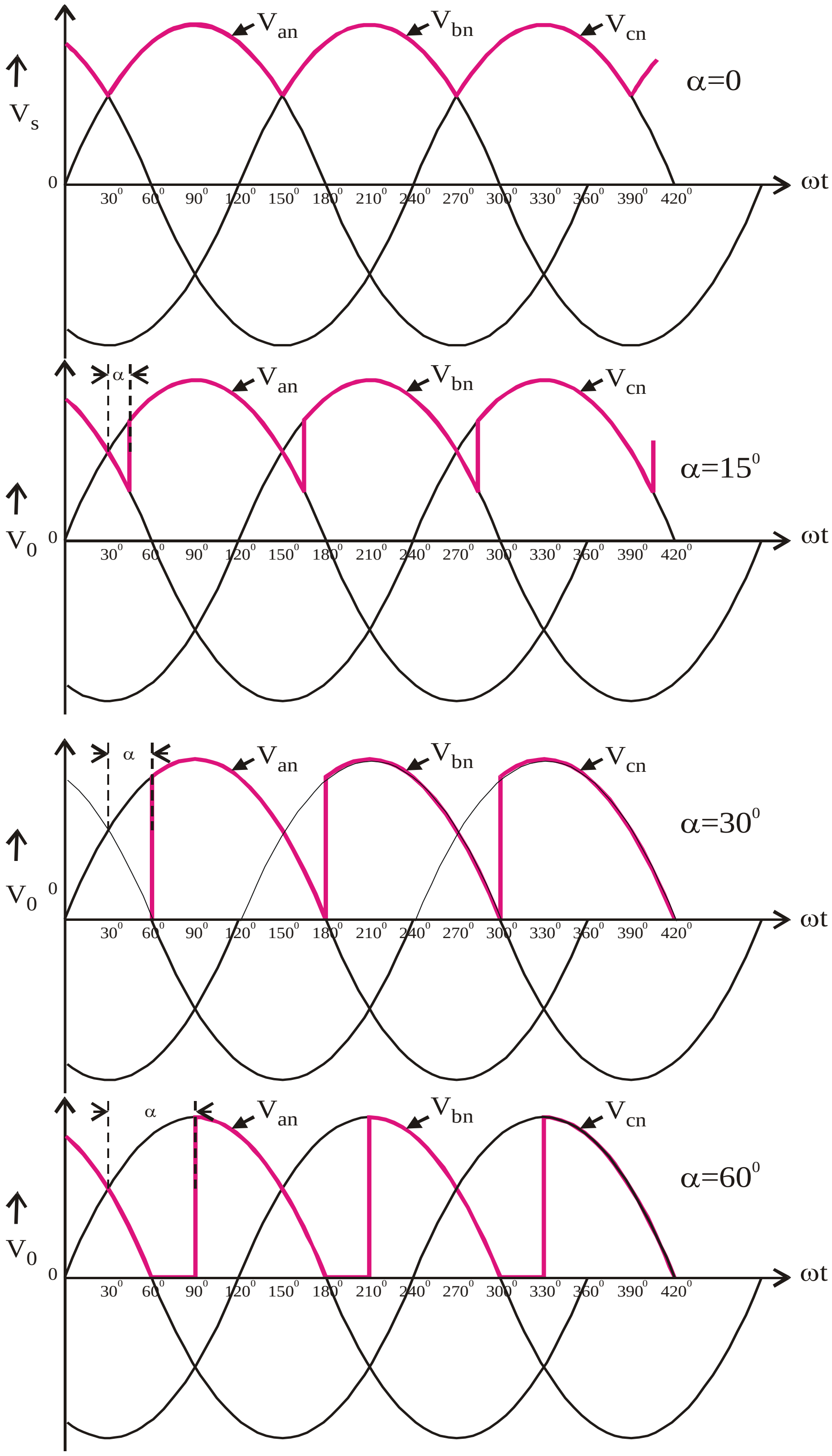
and we obtain

$$V_{O(RMS)} = \sqrt{3} V_m \left[\frac{1}{6} + \frac{\sqrt{3}}{8\pi} \cos 2\alpha \right]^{\frac{1}{2}}$$

3PHASE HALF WAVE CONTROLLED RECTIFIER OUTPUT VOLTAGE WAVEFORMS FOR DIFFERENT TRIGGER ANGLES WITH RL LOAD


α
V_{an}
V_{bn}
V_{cn}
V_0
0
$\alpha=30^0$
ωt
30^0 60^0 90^0 120^0 150^0 180^0 210^0 240^0 270^0 300^0 330^0 360^0 390^0 420^0
$\alpha=60^0$
$\alpha=90^0$

3 PHASE HALF WAVE CONTROLLED RECTIFIER OUTPUT VOLTAGE WAVEFORMS FOR DIFFERENT TRIGGER ANGLES WITH R LOAD



TO DERIVE AN EXPRESSION FOR THE AVERAGE OR DC OUTPUT VOLTAGE OF A 3 PHASE HALF WAVE CONVERTER WITH RESISTIVE LOAD OR RL LOAD WITH FWD.

In the case of a three-phase half wave controlled rectifier with resistive load, the thyristor T_1 is triggered at $\omega t = \left(30^0 + \alpha\right)$ and T_1 conducts up to $\omega t = 180^0 = \pi$ radians. When the phase supply voltage v_{an} decreases to zero at $\omega t = \pi$, the load current falls to zero and the thyristor T_1 turns off. Thus T_1 conducts from $\omega t = \left(30^0 + \alpha\right)$ to $\left(180^0\right)$.

Hence the average dc output voltage for a 3-pulse converter (3-phase half wave controlled rectifier) is calculated by using the equation

$$V_{dc} = \frac{3}{2\pi}\left[\int_{\alpha+30^0}^{180^0} v_O.d\left(\omega t\right)\right]$$

$$v_O = v_{an} = V_m \sin\omega t;\ \text{for } \omega t = \left(\alpha + 30^0\right) \text{ to } \left(180^0\right)$$

$$V_{dc} = \frac{3}{2\pi}\left[\int_{\alpha+30^0}^{180^0} V_m \sin\omega t.d\left(\omega t\right)\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[\int_{\alpha+30^0}^{180^0} \sin\omega t.d\left(\omega t\right)\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[-\cos\omega t \Big/_{\alpha+30^0}^{180^0}\right]$$

$$V_{dc} = \frac{3V_m}{2\pi}\left[-\cos 180^0 + \cos\left(\alpha + 30^0\right)\right]$$

Since $\cos 180^0 = -1,$

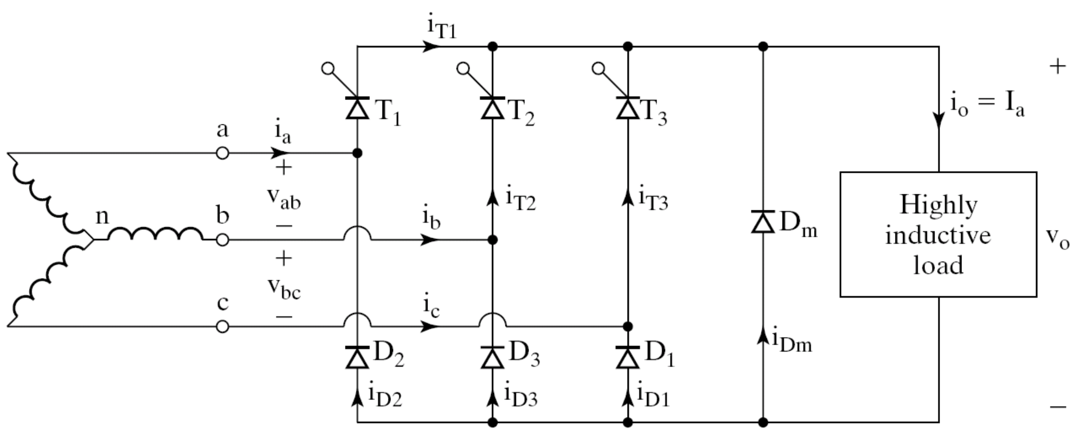
We get $V_{dc} = \frac{3V_m}{2\pi}\left[1 + \cos\left(\alpha + 30^0\right)\right]$

THREE PHASE SEMICONVERTERS

3-phase semi-converters are three phase half controlled bridge controlled rectifiers which employ three thyristors and three diodes connected in the form of a bridge configuration. Three thyristors are controlled switches which are turned on at appropriate times by applying appropriate gating signals. The three diodes conduct when they are forward biased by the corresponding phase supply voltages.

3-phase semi-converters are used in industrial power applications up to about 120kW output power level, where single quadrant operation is required. The power factor of 3-phase semi-converter decreases as the trigger angle α increases. The power factor of a 3-phase semi-converter is better than three phase half wave converter.

The figure shows a 3-phase semi-converter with a highly inductive load and the load current is assumed to be a constant and continuous load current with negligible ripple.

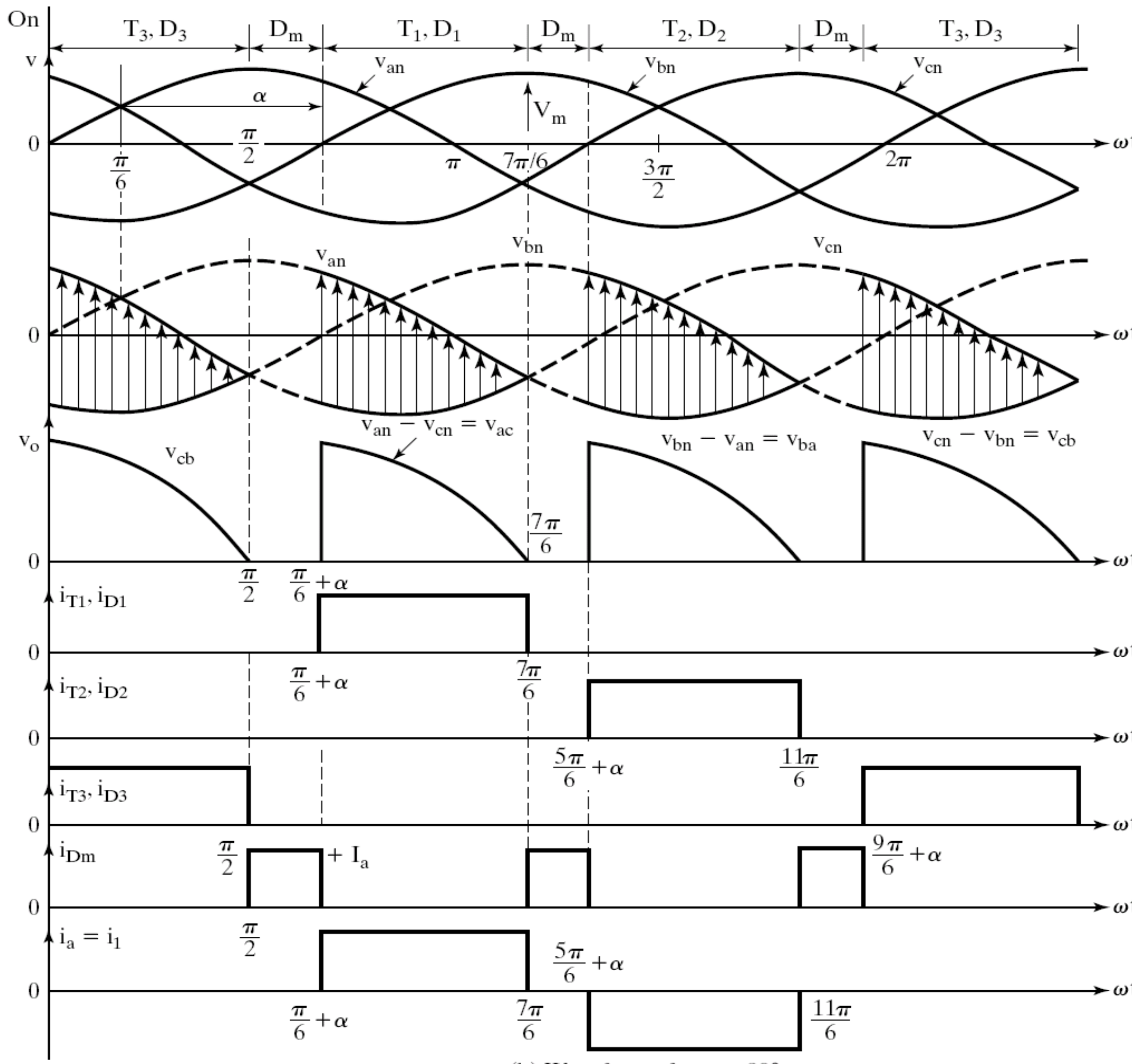


Thyristor T_1 is forward biased when the phase supply voltage v_{an} is positive and greater than the other phase voltages v_{bn} and v_{cn} . The diode D_1 is forward biased when the phase supply voltage v_{cn} is more negative than the other phase supply voltages.

Thyristor T_2 is forward biased when the phase supply voltage v_{bn} is positive and greater than the other phase voltages. Diode D_2 is forward biased when the phase supply voltage v_{an} is more negative than the other phase supply voltages.

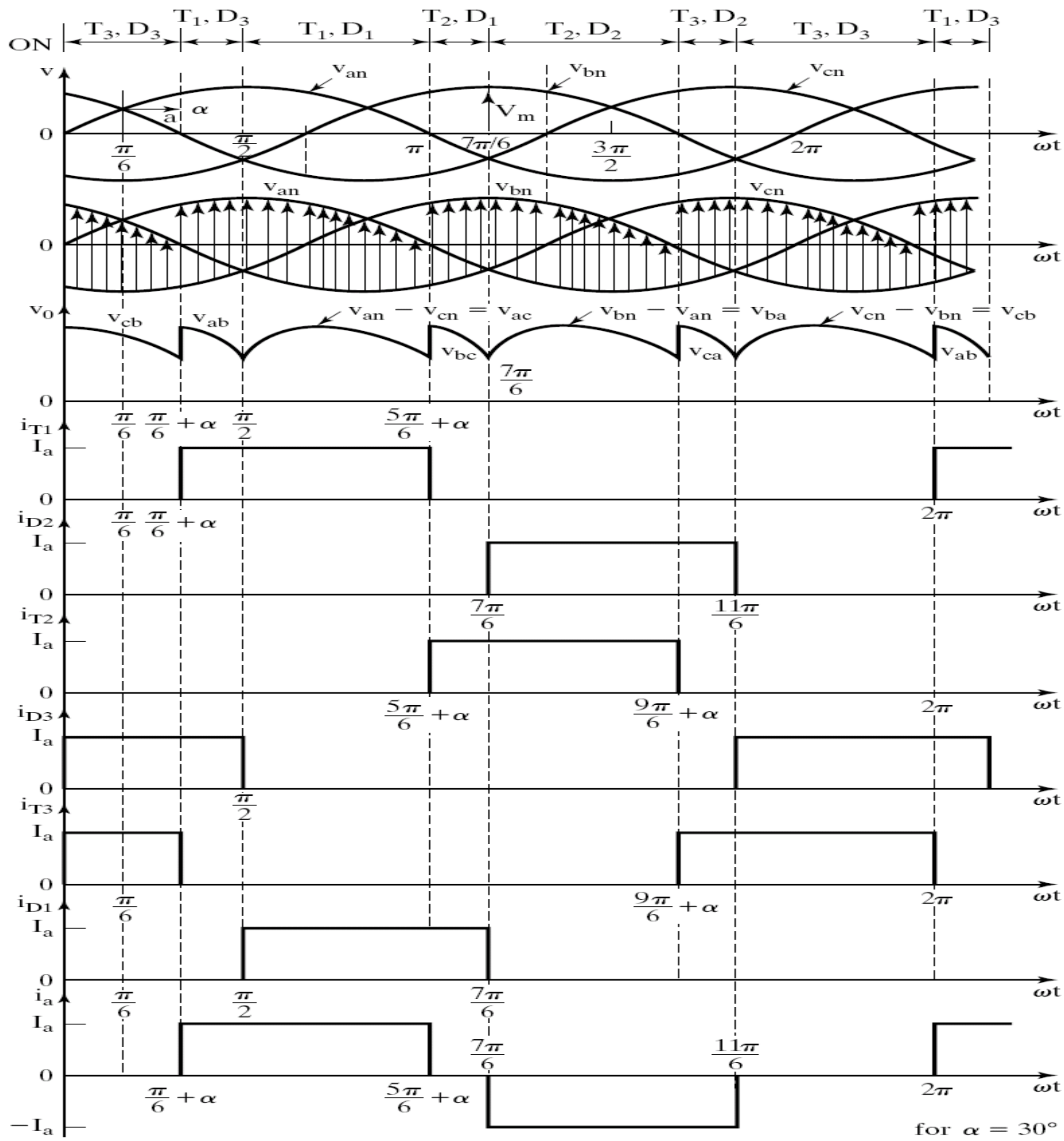
Thyristor T_3 is forward biased when the phase supply voltage v_{cn} is positive and greater than the other phase voltages. Diode D_3 is forward biased when the phase supply voltage v_{bn} is more negative than the other phase supply voltages.

The figure shows the waveforms for the three phase input supply voltages, the output voltage, the thyristor and diode current waveforms, the current through the free wheeling diode D_m and the supply current i_a . The frequency of the output supply waveform is $3f_S$, where f_S is the input ac supply frequency. The trigger angle α can be varied from 0^0 to 180^0. During the time period $\left(\frac{\pi}{6}\right) \le \omega t \le \left(\frac{7\pi}{6}\right)$ i.e., for $30^0 \le \omega t \le 210^0$, thyristor T_1 is forward biased. If T_1 is triggered at $\omega t = \left(\frac{\pi}{6}+\alpha\right)$, T_1 and D_1 conduct together and the line to line supply voltage v_{ac} appears across the load. At $\omega t = \left(\frac{7\pi}{6}\right)$, v_{ac} starts to become negative and the freewheeling diode D_m turns on and conducts. The load current continues to flow through the freewheeling diode D_m and thyristor T_1 and diode D_1 are turned off.



(b) Waveforms for $\alpha = 90°$

If the freewheeling diode D_m is not connected across the load, then T_1 would continue to conduct until the thyristor T_2 is triggered at $\omega t = \left(\frac{5\pi}{6} + \alpha \right)$ and the freewheeling action is accomplished through T_1 and D_2, when D_2 turns on as soon as v_{an} becomes more negative at $\omega t = \left(\frac{7\pi}{6} \right)$. If the trigger angle $\alpha \leq \left(\frac{\pi}{3} \right)$ each thyristor conducts for $\frac{2\pi}{3}$ radians $\left(120^0 \right)$ and the freewheeling diode D_m does not conduct. The waveforms for a 3-phase semi-converter with $\alpha \leq \left(\frac{\pi}{3} \right)$ is shown in figure



We define three line neutral voltages (3 phase voltages) as follows

$$v_{RN} = v_{an} = V_m \sin\omega t; \quad V_m = \text{ Max. Phase Voltage}$$

$$v_{YN} = v_{bn} = V_m \sin\left(\omega t - \frac{2\pi}{3}\right)$$

$$v_{YN} = v_{bn} = V_m \sin\left(\omega t - 120^0\right)$$

$$v_{BN} = v_{cn} = V_m \sin\left(\omega t + \frac{2\pi}{3}\right)$$

$$v_{BN} = v_{cn} = V_m \sin\left(\omega t + 120^0\right)$$

$$v_{BN} = v_{cn} = V_m \sin\left(\omega t - 240^0\right)$$

The corresponding line-to-line voltages are

$$v_{RB} = v_{ac} = \left(v_{an} - v_{cn}\right) = \sqrt{3}V_m \sin\left(\omega t - \frac{\pi}{6}\right)$$

$$v_{YR} = v_{ba} = \left(v_{bn} - v_{an}\right) = \sqrt{3}V_m \sin\left(\omega t - \frac{5\pi}{6}\right)$$

$$v_{BY} = v_{cb} = \left(v_{cn} - v_{bn}\right) = \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{2}\right)$$

$$v_{RY} = v_{ab} = \left(v_{an} - v_{bn}\right) = \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{6}\right)$$

Where V_m is the peak phase voltage of a star (Y) connected source.

TO DERIVE AN EXPRESSION FOR THE AVERAGE OUTPUT VOLTAGE OF THREE PHASE SEMICONVERTER FOR $\alpha > \left(\frac{\pi}{3}\right)$ AND DISCONTINUOUS OUTPUT VOLTAGE

For $\alpha \geq \frac{\pi}{3}$ and discontinuous output voltage: the average output voltage is found from

$$V_{dc} = \frac{3}{2\pi} \int_{\pi/6+\alpha}^{7\pi/6} v_{ac}.d(\omega t)$$

$$V_{dc} = \frac{3}{2\pi} \int_{\pi/6+\alpha}^{7\pi/6} \sqrt{3}\ V_m \sin\left(\omega t - \frac{\pi}{6}\right) d(\omega t)$$

$$V_{dc} = \frac{3\sqrt{3}V_m}{2\pi}(1+\cos\alpha)$$

$$V_{dc} = \frac{3V_{mL}}{2\pi}(1+\cos\alpha)$$

The maximum average output voltage that occurs at a delay angle of $\alpha = 0$ is

$$V_{dm} = \frac{3\sqrt{3}V_m}{\pi}$$

The normalized average output voltage is

$$V_n = \frac{V_{dc}}{V_{dm}} = 0.5(1+\cos\alpha)$$

The rms output voltage is found from

$$V_{O(RMS)} = \left[\frac{3}{2\pi} \int_{\pi/6+\alpha}^{7\pi/6} 3V_m^2 \sin^2\left(\omega t - \frac{\pi}{6}\right) d(\omega t)\right]^{\frac{1}{2}}$$

$$V_{O(RMS)} = \sqrt{3}V_m \left[\frac{3}{4\pi}\left(\pi - \alpha + \frac{1}{2}\sin 2\alpha\right)\right]^{\frac{1}{2}}$$

For $\alpha \le \frac{\pi}{3}$, and continuous output voltage

Output voltage $v_O = v_{ab} = \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{6}\right)$; for $\omega t = \left(\frac{\pi}{6} + \alpha\right)$ to $\left(\frac{\pi}{2}\right)$

Output voltage $v_O = v_{ac} = \sqrt{3}V_m \sin\left(\omega t - \frac{\pi}{6}\right)$; for $\omega t = \left(\frac{\pi}{2}\right)$ to $\left(\frac{5\pi}{6} + \alpha\right)$

The average or dc output voltage is calculated by using the equation

$$V_{dc} = \frac{3}{2\pi}\left[\int_{\pi/6+\alpha}^{\pi/2} v_{ab}.d\left(\omega t\right) + \int_{\pi/2}^{5\pi/6+\alpha} v_{ac}.d\left(\omega t\right)\right]$$

$$V_{dc} = \frac{3\sqrt{3}V_m}{2\pi}\left(1+\cos\alpha\right)$$

$$V_n = \frac{V_{dc}}{V_{dm}} = 0.5\left(1+\cos\alpha\right)$$

The RMS value of the output voltage is calculated by using the equation

$$V_{O(RMS)} = \left[\frac{3}{2\pi}\int_{\pi/6+\alpha}^{\pi/2} v_{ab}^2.d\left(\omega t\right) + \int_{\pi/2}^{5\pi/6+\alpha} v_{ac}^2.d\left(\omega t\right)\right]^{\frac{1}{2}}$$

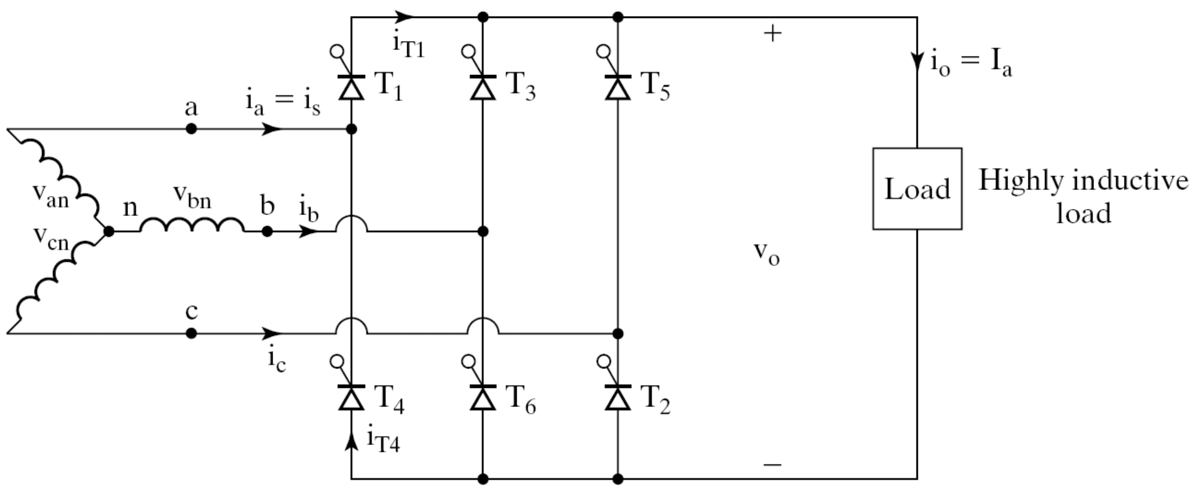
$$V_{O(RMS)} = \sqrt{3}V_m\left[\frac{3}{4\pi}\left(\frac{2\pi}{3} + \sqrt{3}\cos^2\alpha\right)\right]^{\frac{1}{2}}$$

THREE PHASE FULL CONVERTER

Three phase full converter is a fully controlled bridge controlled rectifier using six thyristors connected in the form of a full wave bridge configuration. All the six thyristors are controlled switches which are turned on at a appropriate times by applying suitable gate trigger signals.

The three phase full converter is extensively used in industrial power applications upto about 120kW output power level, where two quadrant operation is required. The figure shows a three phase full converter with highly inductive load. This circuit is also known as three phase full wave bridge or as a six pulse converter.

The thyristors are triggered at an interval of $\left(\frac{\pi}{3}\right)$ radians (i.e. at an interval of 60^0). The frequency of output ripple voltage is $6f_S$ and the filtering requirement is less than that of three phase semi and half wave converters.



At $\omega t=\left(\frac{\pi}{6}+\alpha\right)$, thyristor T_6 is already conducting when the thyristor T_1 is turned on by applying the gating signal to the gate of T_1. During the time period $\omega t=\left(\frac{\pi}{6}+\alpha\right)$ to $\left(\frac{\pi}{2}+\alpha\right)$, thyristors T_1 and T_6 conduct together and the line to line supply voltage v_{ab} appears across the load.

At $\omega t=\left(\frac{\pi}{2}+\alpha\right)$, the thyristor T_2 is triggered and T_6 is reverse biased immediately and T_6 turns off due to natural commutation. During the time period $\omega t=\left(\frac{\pi}{2}+\alpha\right)$ to $\left(\frac{5\pi}{6}+\alpha\right)$, thyristor T_1 and T_2 conduct together and the line to line supply voltage v_{ac} appears across the load.

The thyristors are numbered in the circuit diagram corresponding to the order in which they are triggered. The trigger sequence (firing sequence) of the thyristors is 12, 23, 34, 45, 56, 61, 12, 23, and so on. The figure shows the waveforms of three phase input supply voltages, output voltage, the thyristor current through T_1 and T_4 , the supply current through the line ‘a’.

We define three line neutral voltages (3 phase voltages) as follows

$$v_{RN} = v_{an} = V_m \sin \omega t \quad ; \qquad V_m = \text{ Max. Phase Voltage}$$

$$v_{YN} = v_{bn} = V_m \sin\left(\omega t - \frac{2\pi}{3}\right) = V_m \sin\left(\omega t - 120^0\right)$$

$$v_{BN} = v_{cn} = V_m \sin\left(\omega t + \frac{2\pi}{3}\right) = V_m \sin\left(\omega t + 120^0\right) == V_m \sin\left(\omega t - 240^0\right)$$

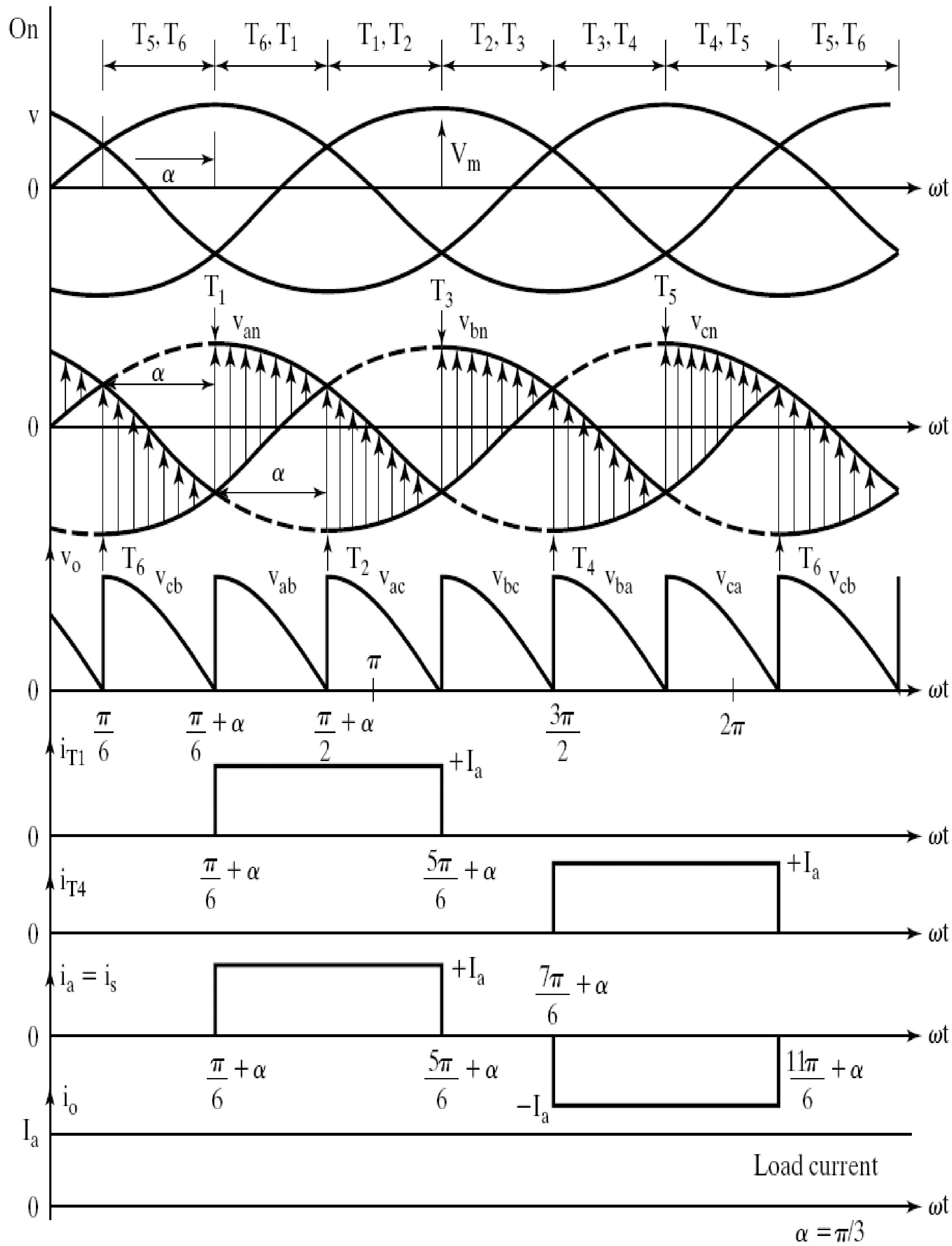
Where V_m is the peak phase voltage of a star (Y) connected source.

The corresponding line-to-line voltages are

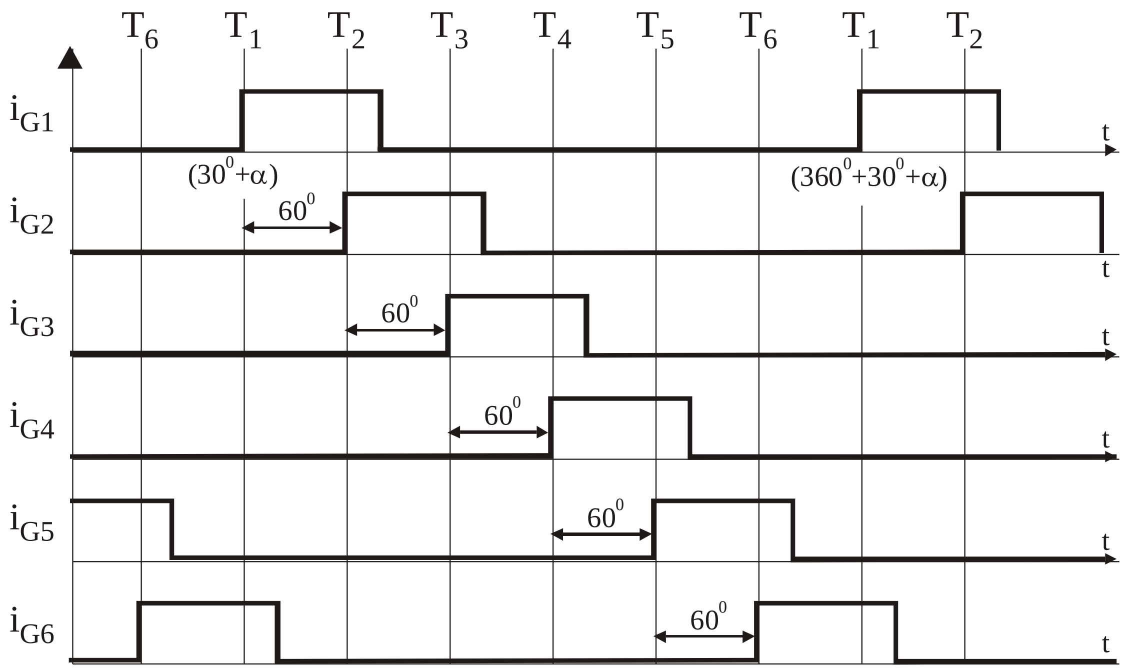
$$v_{RY} = v_{ab} = \left(v_{an} - v_{bn}\right) = \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{6}\right)$$

$$v_{YB} = v_{bc} = \left(v_{bn} - v_{cn}\right) = \sqrt{3}V_m \sin\left(\omega t - \frac{\pi}{2}\right)$$

$$v_{BR} = v_{ca} = \left(v_{cn} - v_{an}\right) = \sqrt{3}V_m \sin\left(\omega t + \frac{\pi}{2}\right)$$



On
T_5, T_6
T_6, T_1
T_1, T_2
T_2, T_3
T_3, T_4
T_4, T_5
T_5, T_6
v
V_m
α
0
ωt
T_1
T_3
T_5
v_{an}
v_{bn}
v_{cn}
v_o
T_6 v_{cb}
v_{ab}
T_2 v_{ac}
v_{bc}
T_4 v_{ba}
v_{ca}
T_6 v_{cb}
π
$\frac{\pi}{6}$
$\frac{\pi}{6}+\alpha$
$\frac{\pi}{2}+\alpha$
$\frac{3\pi}{2}$
2π
i_{T1}
$+I_a$
i_{T4}
$\frac{5\pi}{6}+\alpha$
$i_a = i_s$
$\frac{7\pi}{6}+\alpha$
$-I_a$
$\frac{11\pi}{6}+\alpha$
i_o
I_a
Load current
$\alpha = \pi/3$



Gating (Control) Signals of 3-phase full converter

TO DERIVE AN EXPRESSION FOR THE AVERAGE OUTPUT VOLTAGE OF THREE PHASE FULL CONVERTER WITH HIGHLY INDUCTIVE LOAD ASSUMING CONTINUOUS AND CONSTANT LOAD CURRENT

The output load voltage consists of 6 voltage pulses over a period of 2π radians, hence the average output voltage is calculated as

$$V_{O(dc)} = V_{dc} = \frac{6}{2\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_O . d\omega t \qquad ;$$

$$v_O = v_{ab} = \sqrt{3} V_m \sin\left(\omega t + \frac{\pi}{6}\right)$$

$$V_{dc} = \frac{3}{\pi} \int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3} V_m \sin\left(\omega t + \frac{\pi}{6}\right) . d\omega t$$

$$V_{dc} = \frac{3\sqrt{3} V_m}{\pi} \cos\alpha = \frac{3 V_{mL}}{\pi} \cos\alpha$$

Where $V_{mL} = \sqrt{3} V_m =$ Max. line-to-line supply voltage

The maximum average dc output voltage is obtained for a delay angle α = 0,

$$V_{dc(\max)} = V_{dm} = \frac{3\sqrt{3}V_m}{\pi} = \frac{3V_{mL}}{\pi}$$

The normalized average dc output voltage is

$$V_{dcn} = V_n = \frac{V_{dc}}{V_{dm}} = \cos\alpha$$

The rms value of the output voltage is found from

$$V_{O(rms)} = \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_O^2 .d(\omega t)\right]^{\frac{1}{2}}$$

$$V_{O(rms)} = \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} v_{ab}^2 .d(\omega t)\right]^{\frac{1}{2}}$$

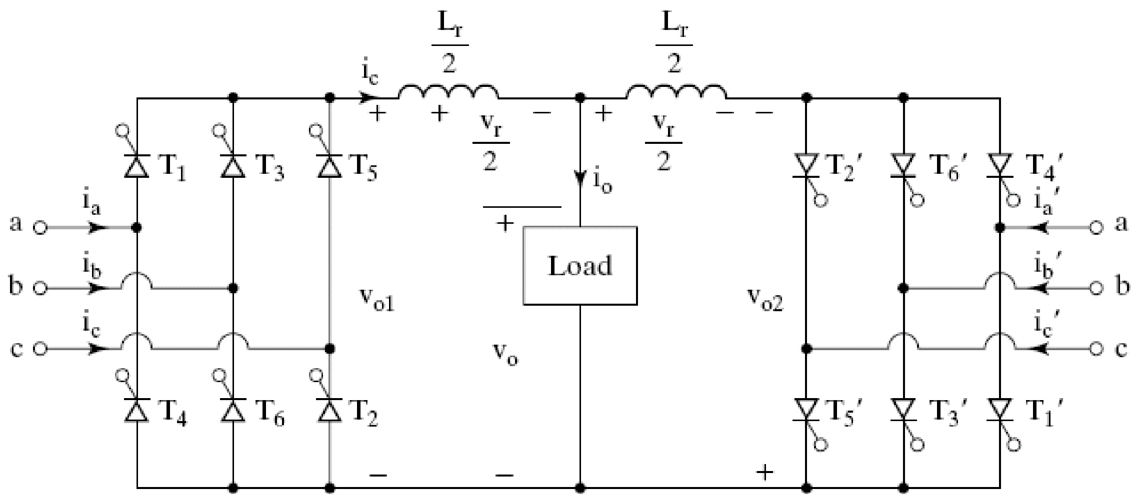
$$V_{O(rms)} = \left[\frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} 3V_m^2 \sin^2\left(\omega t + \frac{\pi}{6}\right).d(\omega t)\right]^{\frac{1}{2}}$$

$$V_{O(rms)} = \sqrt{3}V_m\left(\frac{1}{2} + \frac{3\sqrt{3}}{4\pi}\cos 2\alpha\right)^{\frac{1}{2}}$$

THREE PHASE DUAL CONVERTERS

In many variable speed drives, the four quadrant operation is generally required and three phase dual converters are extensively used in applications up to the 2000 kW level. Figure shows three phase dual converters where two three phase full converters are connected back to back across a common load. We have seen that due to the instantaneous voltage differences between the output voltages of converters, a circulating current flows through the converters. The circulating current is normally limited by circulating reactor, L_r. The two converters are controlled in such a way that if α_1 is the delay angle of converter 1, the delay angle of converter 2 is $\alpha_2 = (\pi - \alpha_1)$.

The operation of a three phase dual converter is similar that of a single phase dual converter system. The main difference being that a three phase dual converter gives much higher dc output voltage and higher dc output power than a single phase dual converter system. But the drawback is that the three phase dual converter is more expensive and the design of control circuit is more complex.



The figure below shows the waveforms for the input supply voltages, output voltages of converter1 and conveter2 , and the voltage across current limiting reactor (inductor) L_r. The operation of each converter is identical to that of a three phase full converter.

During the interval $\left(\frac{\pi}{6}+\alpha_1\right)$ to $\left(\frac{\pi}{2}+\alpha_1\right)$, the line to line voltage v_{ab} appears across the output of converter 1 and v_{bc} appears across the output of converter 2

We define three line neutral voltages (3 phase voltages) as follows

$$v_{RN} = v_{an} = V_m \sin \omega t \quad ; \quad V_m = \text{ Max. Phase Voltage}$$

$$v_{YN} = v_{bn} = V_m \sin\left(\omega t - \frac{2\pi}{3}\right) = V_m \sin\left(\omega t - 120^0\right)$$

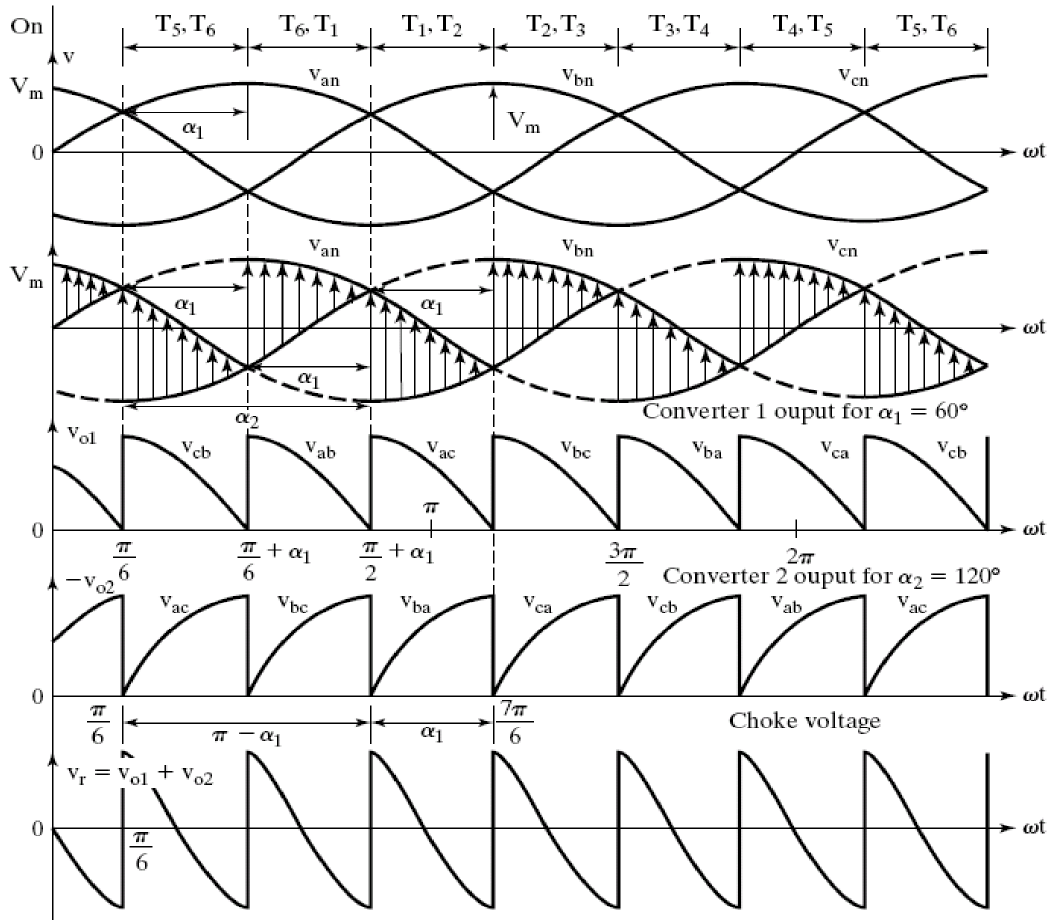
$$v_{BN} = v_{cn} = V_m \sin\left(\omega t + \frac{2\pi}{3}\right) = V_m \sin\left(\omega t + 120^0\right) = V_m \sin\left(\omega t - 240^0\right)$$

The corresponding line-to-line supply voltages are

$$v_{RY} = v_{ab} = \left(v_{an} - v_{bn}\right) = \sqrt{3} V_m \sin\left(\omega t + \frac{\pi}{6}\right)$$

$$v_{YB} = v_{bc} = \left(v_{bn} - v_{cn}\right) = \sqrt{3} V_m \sin\left(\omega t - \frac{\pi}{2}\right)$$

$$v_{BR} = v_{ca} = \left(v_{cn} - v_{an}\right) = \sqrt{3} V_m \sin\left(\omega t + \frac{\pi}{2}\right)$$



TO OBTAIN AN EXPRESSION FOR THE CIRCULATING CURRENT

If v_{O1} and v_{O2} are the output voltages of converters 1 and 2 respectively, the instantaneous voltage across the current limiting inductor during the interval $\left(\frac{\pi}{6}+\alpha_1\right)\leq \omega t \leq \left(\frac{\pi}{2}+\alpha_1\right)$ is

$$v_r = \left(v_{O1}+v_{O2}\right) = \left(v_{ab}-v_{bc}\right)$$

$$v_r = \sqrt{3}V_m\left[\sin\left(\omega t+\frac{\pi}{6}\right)-\sin\left(\omega t-\frac{\pi}{2}\right)\right]$$

$$v_r = 3V_m\cos\left(\omega t-\frac{\pi}{6}\right)$$

The circulating current can be calculated by using the equation

$$i_r(t) = \frac{1}{\omega L_r} \int_{\frac{\pi}{6}+\alpha_1}^{\omega t} v_r . d(\omega t)$$

$$i_r(t) = \frac{1}{\omega L_r} \int_{\frac{\pi}{6}+\alpha_1}^{\omega t} 3V_m \cos\left(\omega t - \frac{\pi}{6}\right) . d(\omega t)$$

$$i_r(t) = \frac{3V_m}{\omega L_r}\left[\sin\left(\omega t - \frac{\pi}{6}\right) - \sin\alpha_1\right]$$

$i_{r(\max)} = \frac{3V_m}{\omega L_r}$ = maximum value of the circulating current.

There are two different modes of operation of a three phase dual converter system.
Circulating current free (non circulating) mode of operation
Circulating current mode of operation

CIRCULATING CURRENT FREE (NON-CIRCULATING) MODE OF OPERATION

In this mode of operation only one converter is switched on at a time when the converter number 1 is switched on and the gate signals are applied to the thyristors the average output voltage and the average load current are controlled by adjusting the trigger angle α_1 and the gating signals of converter 1 thyristors.

The load current flows in the downward direction giving a positive average load current when the converter 1 is switched on. For $\alpha_1 < 90^0$ the converter 1 operates in the rectification mode V_{dc} is positive, I_{dc} is positive and hence the average load power P_{dc} is positive.

The converter 1 converts the input ac supply and feeds a dc power to the load. Power flows from the ac supply to the load during the rectification mode. When the trigger angle α_1 is increased above 90^0, V_{dc} becomes negative where as I_{dc} is positive because the thyristors of converter 1 conduct in only one direction and reversal of load current through thyristors of converter 1 is not possible.

For $\alpha_1 > 90^0$ converter 1 operates in the inversion mode & the load energy is supplied back to the ac supply. The thyristors are switched-off when the load current decreases to zero & after a short delay time of about 10 to 20 milliseconds, the converter 2 can be switched on by releasing the gate control signals to the thyristors of converter 2.

We obtain a reverse or negative load current when the converter 2 is switched ON. The average or dc output voltage and the average load current are controlled by adjusting the trigger angle α_2 of the gate trigger pulses supplied to the thyristors of converter 2. When α_2 is less than 90^0**,** converter 2 operates in the rectification mode and converts the input ac supply in to dc output power which is fed to the load.

When α_2 is less than 90^0 for converter 2, V_{dc} is negative & I_{dc} is negative, converter 2 operates as a controlled rectifier & power flows from the ac source to the load circuit. When α_2 is increased above 90^0, the converter 2 operates in the inversion mode with V_{dc} positive and I_{dc} negative and hence P_{dc} is negative, which means that power flows from the load circuit to the input ac supply.

The power flow from the load circuit to the input ac source is possible if the load circuit has a dc source of appropriate polarity.

When the load current falls to zero the thyristors of converter 2 turn-off and the converter 2 can be turned off.

CIRCULATING CURRENT MODE OF OPERATION

Both the converters are switched on at the same time in the mode of operation. One converter operates in the rectification mode while the other operates in the inversion mode. Trigger angles α_1 & α_2 are adjusted such that $(\alpha_1 + \alpha_2) = 180^0$

When $\alpha_1 < 90^0$, converter 1 operates as a controlled rectifier. When α_2 is made greater than 90^0, converter 2 operates in the inversion mode. V_{dc}, I_{dc}, P_{dc} are positive.

When $\alpha_2 < 90^0$, converter 2 operates as a controlled rectifier. When α_1 is made greater than 90^0, converter 1 operates as an Inverter. V_{dc} and I_{dc} are negative while P_{dc} is positive.

Problems

5. A 3 phase fully controlled bridge rectifier is operating from a 400 V, 50 Hz supply. The thyristors are fired at $\alpha = \frac{\pi}{4}$. There is a FWD across the load. Find the average output voltage for $\alpha = 45^0$ and $\alpha = 75^0$.NOV/DEC-13

GIVEN:

$$\alpha = \frac{\pi}{4}, 400 \text{ V}, 50 \text{ Hz}$$

TO FIND:

V_{dc}

SOLUTION:

For $\alpha = 45^0$, $V_{dc} = \frac{3V_m}{\pi}\cos\alpha$

$$V_{dc} = \frac{3\times\sqrt{2}\times 400}{\pi}\cos 45^0 = 382 \text{ Volts}$$

For $\alpha = 75^0$, $V_{dc} = \frac{6V_m}{2\pi}\left[1+\cos\left(60^0+\alpha\right)\right]$

$$V_{dc} = \frac{6\times\sqrt{2}\times 400}{2\pi}\left[1+\cos\left(60^0+75^0\right)\right]$$

$$V_{dc} = 158.4 \text{ Volts}$$

6. A 6 pulse converter connected to 415 V ac supply is controlling a 440 V dc motor. Find the angle at which the converter must be triggered so that the voltage drop in the circuit is 10% of the motor rated voltage.

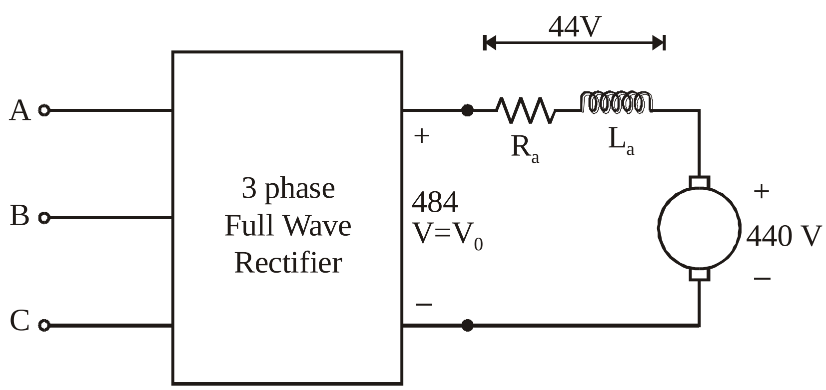
Given:

V=415 V

To find:

α

Solution:



R_a - Armature resistance of motor.

L_a - Armature Inductance.

If the voltage across the armature has to be the rated voltage i.e., 440 V, then the output voltage of the rectifier should be 440 + drop in the motor

That is $440 + 01 \times 440 = 484 \text{ Volts}$.

Therefore $$V_O = \frac{3V_m \cos\alpha}{\pi} = 484$$

That is $$\frac{3 \times \sqrt{2} \times 415 \times \cos\alpha}{\pi} = 484$$

Therefore $\alpha = 30.27^0$

7. A 3 phase half controlled bridge rectifier is feeding a RL load. If input voltage is 400 sin314t and SCR is fired at $\alpha = \frac{\pi}{4}$. Find average load voltage. If any one supply line is disconnected what is the average load voltage.

GIVEN:

V=400 sin314t ,SCR is fired at $\alpha = \frac{\pi}{4}$.

TO FIND:

V_{dc}

SOLUTION:

$\alpha = \frac{\pi}{4}$ radians which is less than $\frac{\pi}{3}$

Therefore $$V_{dc} = \frac{3V_m}{2\pi}\left[1 + \cos\alpha\right]$$

$$V_{dc} = \frac{3 \times 400}{2\pi}\left[1 + \cos 45^0\right]$$

$$V_{dc} = 326.18 \text{ Volts}$$

If any one supply line is disconnected, the circuit behaves like a single phase half controlled rectifies with RL load.

$$V_{dc} = \frac{V_m}{\pi}\left[1+\cos\alpha\right]$$

$$V_{dc} = \frac{400}{\pi}\left[1+\cos 45^0\right]$$

$$V_{dc} = 217.45 \text{ Volts}$$

EFFECT OF SOURCE INDUCTANCE ON THE PERFORMANCE OF SINGLE PHASE FULL CONVERTER.

Actually, in practice, inductance and resistance **must be present in** the supply source, and time is required for a current change to take place. The net result is that the current commutation is delayed, as it takes a finite time for the current to decay to zero in the outgoing thyristor, while the current will rise at the same rate in the incoming thyristor. Thus, in practice, the commutation process may occupy a quite significant period of time, during which both the "incoming" and "outgoing" thyristors are simultaneous in conduction. This period, during which both the outgoing and incoming thyristors are conducting, is known as the overlap period and the angle for which both devices share conduction is known as the overlap angle (μ) or commutation angle.

During this "commutation overlap" period, the waveforms of the voltage at the output terminals of the converter, as well as the current and voltage at the input terminal are different from those obtained with zero-source inductance. This has the modifying effect upon the external performance characteristics of the converter. At the output terminals, the effect of the input source inductance is to cause a loss of mean voltage, as well as modification to the harmonic distortion terms, while at the input terminals, a slight reduction of displacement factor, with respect to the a.c. source voltage, as well as the modification to the distortion-terms in the current waveform, takes place.

The inductive reactance of the a.c. supply is normally much greater than its resistance and, as it is the inductance which delays to current change, it is reasonable to neglect the supply resistance. However, if the source impedance is resistive, then there will be a drop across this resistance and the average output voltage of a converter gets reduced by an amount equivalent to the average drop. Since the source resistance is usually small, the commutation angle during which the load_current is transferred from thc_outgoing,to the incoming thvristors is generally neglected.the effect of source inductance is investigated in this section for both single-phase and three fully controlled converter.

Single-Phase Fully-Controlled Converters

- The commutation overlap is more predominant in full converters than semi converters.
- L_S – source inductance

- Load current assumed constant
- When the terminal L of the source voltage e_S, is positive, then the current flows through the path L-L_s-T_1-R-L-T_2-N
- Similarly when terminal N is positive the load current flows through N-T_3-Load-T_4-L_s-L

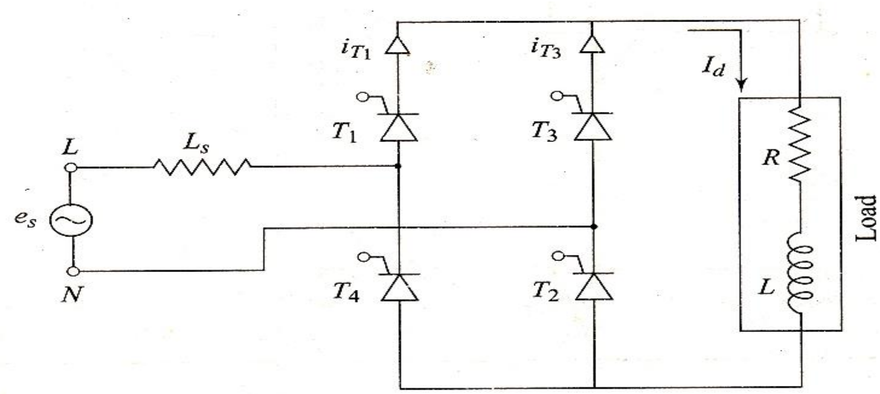
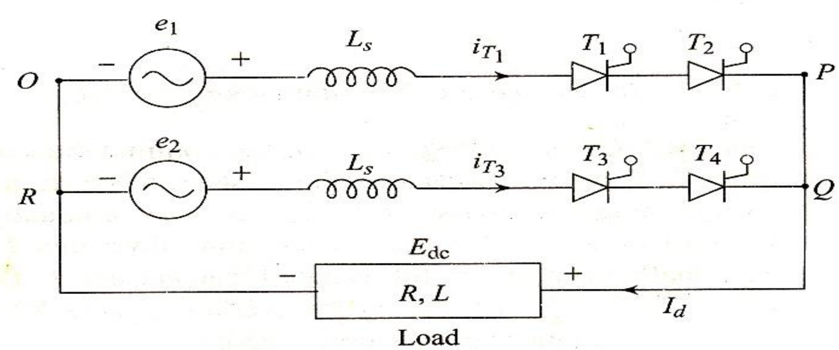


Fig. 6.51 ***(a)*** *Single-phase fully-controlled converter with source inductance* L_s



(b)Equivalent circuit

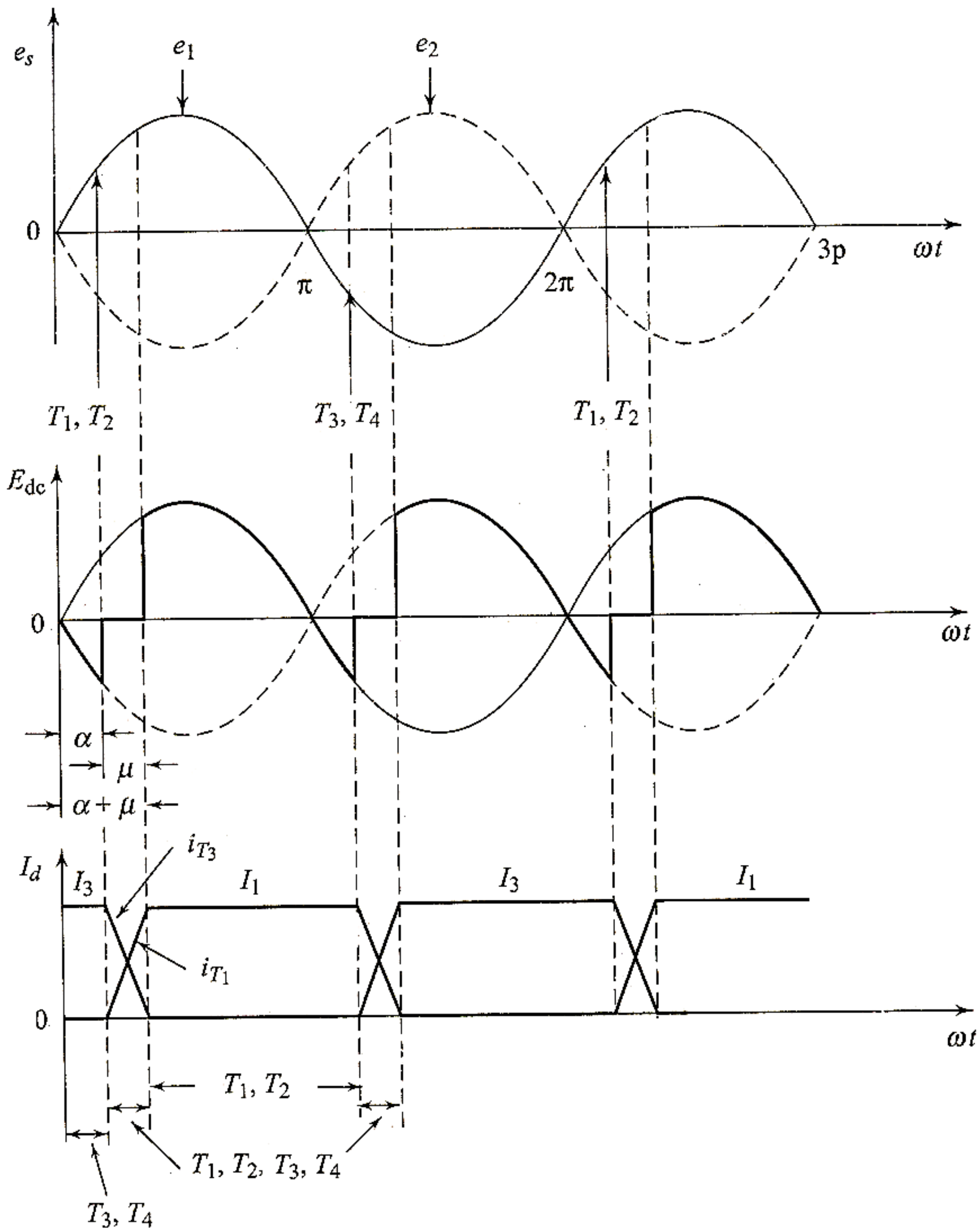


Fig. 6.51 ***(c)*** *Voltage and current-waveforms with* L_s

- When T_1,T_2 are triggered at a firing angle α, the commutation of already conducting thyristors T_3,T_4 begins.
- Because of the presence of source inductance L_s, the current through the outgoing thyristors T_3, T_4 gradually decreases to zero from initial value of I_d
- For T_1, T_2 current builds to full value of load current, I_d
- During the overlap angle μ, KVL for the loop OPQRO gives

$$e_1 - L_s \frac{d_{iT1}}{dt} = e_2 - L_s \frac{d_{i3}}{dt}$$

$$e_1 - e_2 = L_s \left(\frac{d_{iT1}}{dt} - \frac{d_{i3}}{dt} \right)$$

But from fig 6.51(c), we have the relation

$$e_1 = E_m \sin \omega t$$

$$e_2 = -E_m \sin \omega t$$

Sub e_1, e_2 in above eqn.

$$E_m \sin \omega t + E_m \sin \omega t = L_s \left(\frac{d_{iT1}}{dt} - \frac{d_{i3}}{dt} \right)$$

$$2E_m \sin \omega t = L_s \left(\frac{d_{iT1}}{dt} - \frac{d_{i3}}{dt} \right) - - - - - - -(1)$$

Since load current is assumed constant

$$i_{T1} + i_{T3} = I_d$$

Differentiating w.r.t t

$$\frac{d_{iT1}}{dt} = -\frac{d_{iT3}}{dt}$$

Sub above in (1)

$$2E_m \sin \omega t = L_s \left(\frac{d_{iT1}}{dt} + \frac{d_{iT1}}{dt} \right)$$

$$2E_m \sin \omega t = L_s \left(2\frac{d_{iT1}}{dt} \right)$$

$$\frac{2E_m}{2L_s} \sin \omega t = \left(\frac{d_{iT1}}{dt} \right)$$

$$\frac{E_m}{L_s} \sin \omega t = \left(\frac{d_{iT1}}{dt} \right) - - - - - (2)$$

If the overlap angle isμ then the current through the thyristor pair T1, T2 builds up from zerp to Id during this interval

Therefore, at $\omega t = \alpha, i_{T1} = 0 \; and \; at \; \omega t = (\alpha + \mu, i_{T1} = I_d)$

Integrating eqn. (2)

$$\int_0^{I_d} d_{iT1} = \frac{E_m}{L_s}\int_{\alpha/_\omega}^{(\alpha+\mu)/_\omega} sin\ \omega td(\omega t)$$

$$I_d = \frac{E_m}{\omega L_s}[cos\alpha - cos(\alpha+\mu)] - - - (3)$$

The avg. output voltage is given by

$$E_{dc} = \frac{E_m}{\pi}\int_{\alpha+\mu}^{\pi+\alpha} sin\ \omega td(\omega t)$$

$$E_{dc} = \frac{E_m}{\pi}[-cos\omega t]_{\alpha+\mu}^{\pi+\alpha}$$

$$E_{dc} = \frac{E_m}{\pi}[cos(\alpha+\mu) - cos\ (\alpha+\pi)] - - - -(4)$$

From eqn.(3)

$$cos(\alpha+\mu) = cos\alpha - \frac{\omega L_s}{E_m} I_d - - - -(5)$$

Sub the value $cos(\alpha+\mu)$ in eqn.(4) we get

$$E_{dc} = \frac{E_m}{\pi}\left[cos\alpha - \frac{\omega L_s}{E_m} I_d - cos\ (\alpha+\pi)\right]$$

$$E_{dc} = \frac{E_m}{\pi}\left[cos\alpha - \frac{\omega L_s}{E_m} I_d + cos\ \alpha\right]$$

$$E_{dc} = \frac{2E_m cos\alpha}{\pi} - \frac{\omega L_s}{E_m} I_d - - - -(6)$$

Also from eqn (5)

$$cos\alpha = cos(\alpha+\mu) + \frac{\omega L_s}{E_m} I_d - - - (7)$$

$Sub\ (7)in(6)$

$$E_{dc} = \frac{2E_m}{\pi}[cos(\alpha+\mu) + \frac{\omega L_s}{E_m} I_d] - \frac{\omega L_s}{E_m} I_d$$

$$E_{dc} = \frac{2E_m}{\pi} cos(\alpha+\mu) + \frac{2E_m}{\pi}\frac{\omega L_s}{E_m} I_d - \frac{\omega L_s}{E_m} I_d$$

$$E_{dc} = \frac{2E_m}{\pi} cos(\alpha+\mu) + \frac{\omega L_s}{E_m} I_d - - - (8)$$

With the help of above eqn we can draw waveform for 2 pulse single phase full y controlled converter

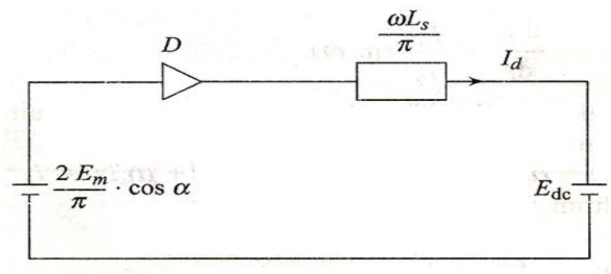
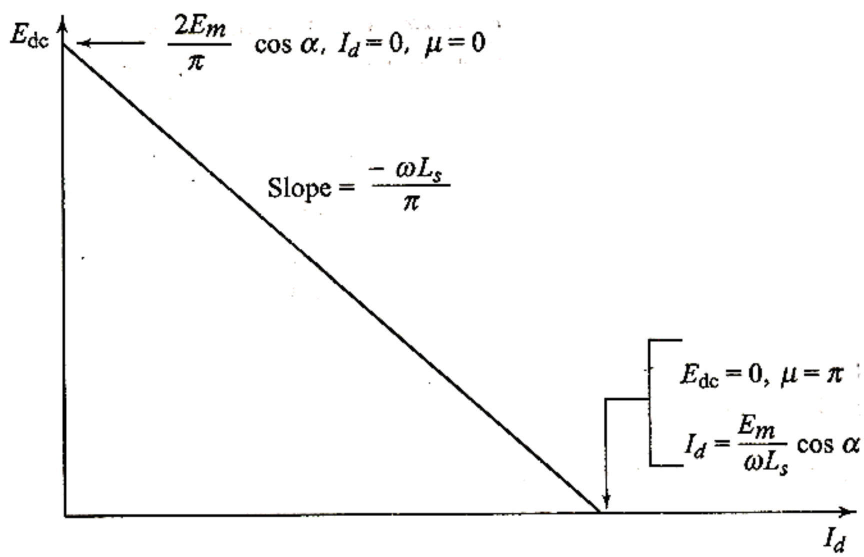


Fig. 6.51 ***(d)*** *D.C. equivalent circuit*



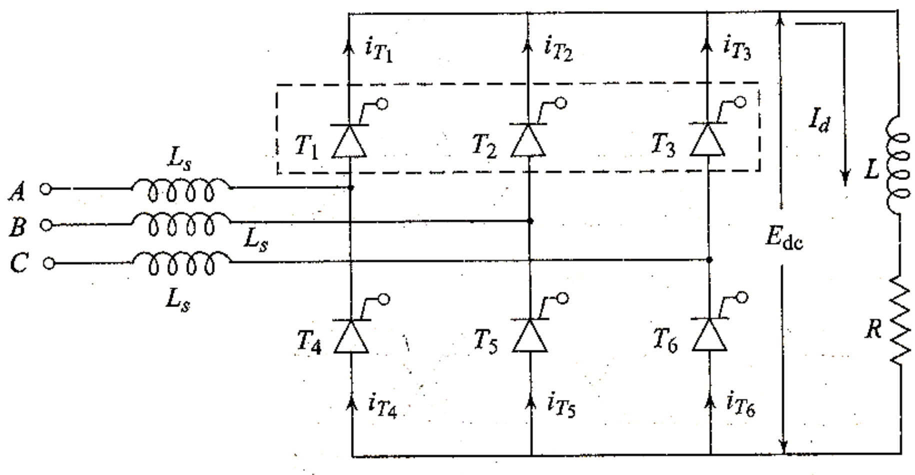
(e) *Variation of output voltage* E_{dc} *with* I_d

As long as the commutation angle μ is less than л, the output voltage is given by eqn(8)

When μ is equal to л, the load will be permanently short circuited by SCRs and the output voltage will be zero because during the overlap period, all SCRs will be conduction

THREE PHASE FULLY CONTROLLED BRIDGE CONVERTER (Six pulse bridge converter)

Three phase fully controlled bridge converter with a Source inductance Ls in each line is shown. In this case also the load current Id is assumed to be constant.

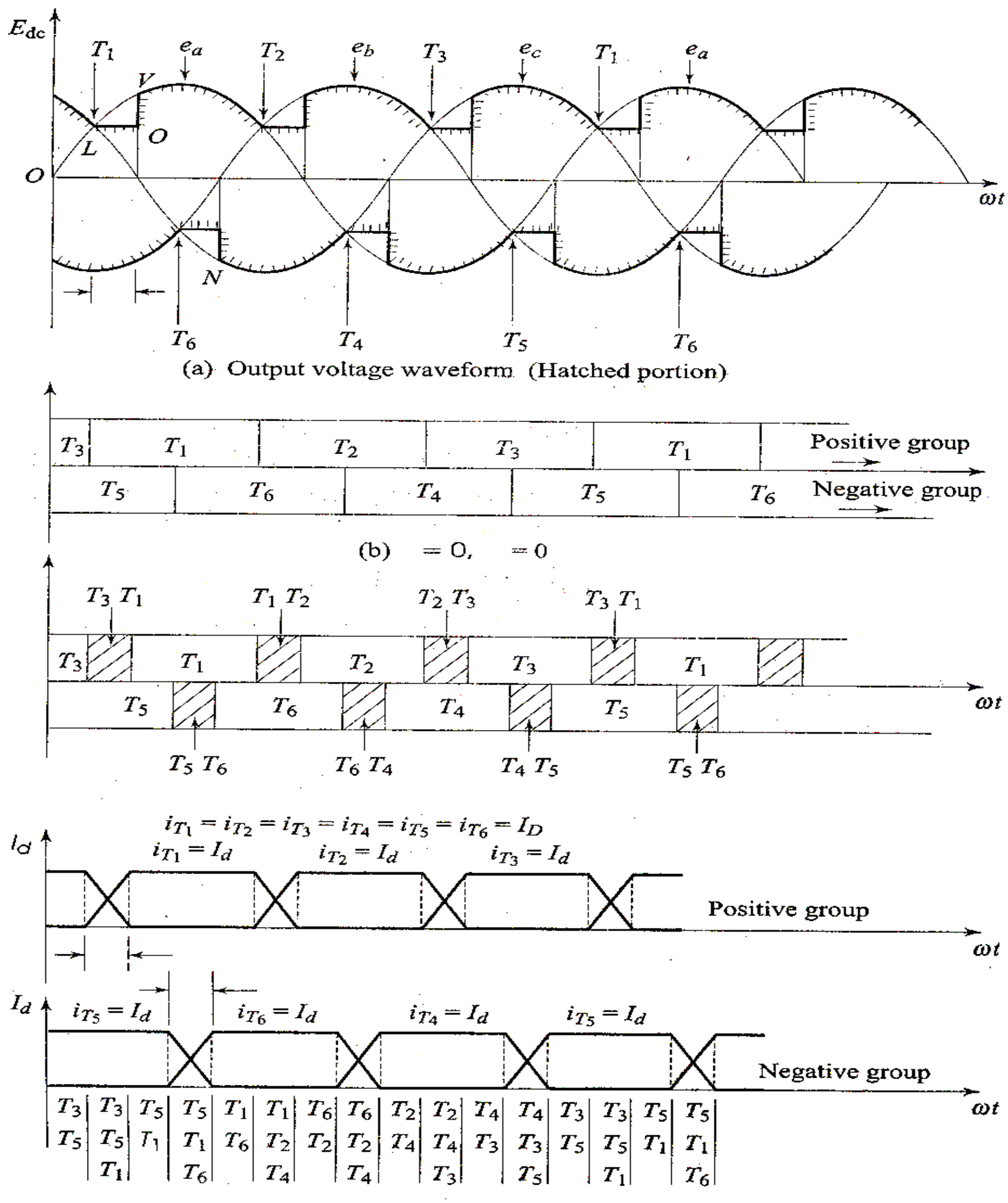


Three-phase fully-controlled bridge with source inductance L_s

- The conduction of various SCRs with firing angle α is shown in the waveform
- The effect of overlap is shown in waveform (c)
  - At ωt = 0 to 30° thyristor T3, T5 conducts
  - At ωt=30º to (30º+μ) T3, T5, T1 conducts
  - After ωt=(30º+μ) T5 and T1 conducts
  - At ωt=90° to (90º+μ) T5, T1, T6 conducts
  - After ωt=(90º+μ) T1 and T6 conducts
  - The above sequence is repeated

The sequence of conduction is as shown below

T_3–T_5, T_3–T_5–T_1, T_5–T_1, T_5–T_1–T_6, T_1–T_6, T_1–T_2–T_6, T_6–T_2, T_6–T_2–T_4, T_2–T_4, T_2–T_4–T_3, T_4–T_3, T_4–T_3–T_5, T_3–T_5 and so on.



(c)

VOLTAGE AND CURRENT WAVEFORM

- Hence it become clear that 3 Thyristor and 2 Thyristor conduct alternatively

- It is observed that for a six pulse converter , there are six shaded region which indicates sis commutation in each cycle of the supply voltage

UNIT – V
AC PHASE CONTROLLERS

CONSTRUCTION, V I & SWITCHING CHARACTERISTICS OF BI-POLAR JUNCTION TRANSISTOR.

A Bi-Polar Junction Transistor is a 3 layer, 3 terminals device. The 3 terminals are base, emitter and collector. It has 2 junctions' collector-base junction (CB) and emitter-base junction (EB). Transistors are of 2 types, NPN and PNP transistors.

The different configurations are common base, common collector and common emitter. Common emitter configuration is generally used in switching applications.

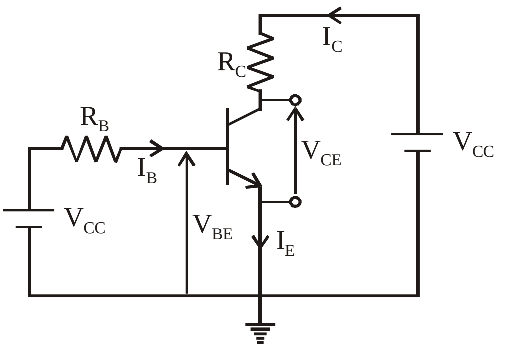


Fig: NPN Transistor

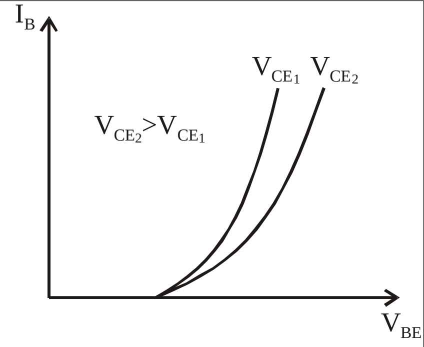


Fig: Input Characteristic

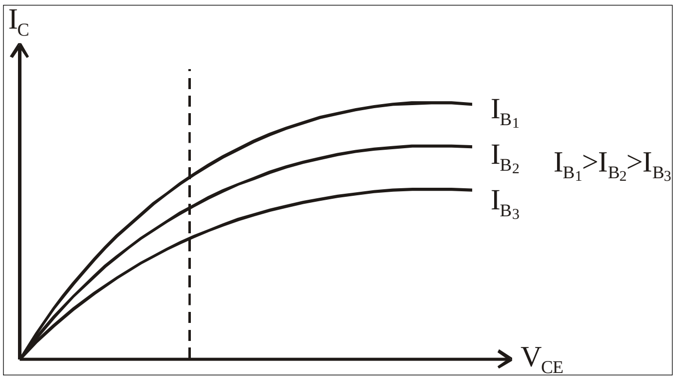


Fig: Output / Collector Characteristics

Transistors can be operated in 3 regions i.e., cut-off, active and saturation.

In the cut-of region transistor is OFF, both junctions (EB and CB) are reverse biased. In the cut-off state the transistor acts as an open switch between the collector and emitter.

In the active region, transistor acts as an amplifier (CB junction is reverse biased and EB junction is forward biased),

In saturation region the transistor acts as a closed switch and both the junctions CB and EB are forward biased.

SWITCHING CHARACTERISTICS

An important application of transistor is in switching circuits. When transistor is used as a switch it is operated either in cut-off state or in saturation state. When the transistor is driven into the cut-off state it operates in the non-conducting state. When the transistor is operated in saturation state it is in the conduction state.

Thus the non-conduction state is operation in the cut-off region while the conducting state is operation in the saturation region.

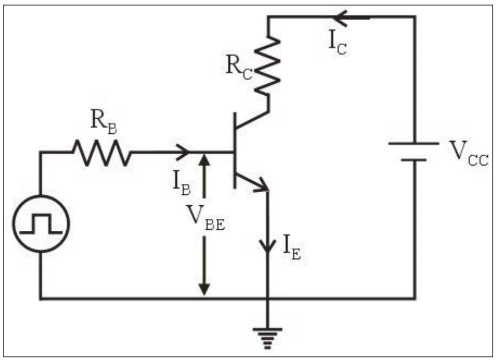


Fig: Switching Transistor in CE Configuration

As the base voltage V_B rises from 0 to V_B, the base current rises to I_B, but the collector current does not rise immediately. Collector current will begin to increase only when the base emitter junction is forward biased and $V_{BE} > 0.6V$. The collector current I_C will gradually increase towards saturation level $I_{C(sat)}$. The time required for the collector current to rise to 10% of its final value is called delay time t_d. The time taken by the collector current to rise from 10% to 90% of its final value is called rise time t_r. Turn on times is sum of t_d and t_r.

$$t_{on} = t_d + t_r$$

The turn-on time depends on

- Transistor junction capacitances which prevent the transistors voltages from changing instantaneously.
- Time required for emitter current to diffuse across the base region into the collector region once the base emitter junction is forward biased. The turn on time t_{on} ranges from 10 to 300 ns. Base current is normally more than the minimum required to saturate the transistor. As a result excess minority carrier charge is stored in the base region.

When the input voltage is reversed from V_{B1} to $-V_{B2}$ the base current also abruptly changes but the collector current remains constant for a short time interval t_S called the storage time.

The reverse base current helps to discharge the minority charge carries in the base region and to remove the excess stored charge form the base region. Once the excess stored charge is removed the baser region the base current begins to fall towards zero. The fall-time t_f is the time taken for the collector current to fall from 90% to 10% of $I_{C(sat)}$. The turn off time t_{off} is the sum of storage time and the fall time. $t_{off} = t_s + t_f$

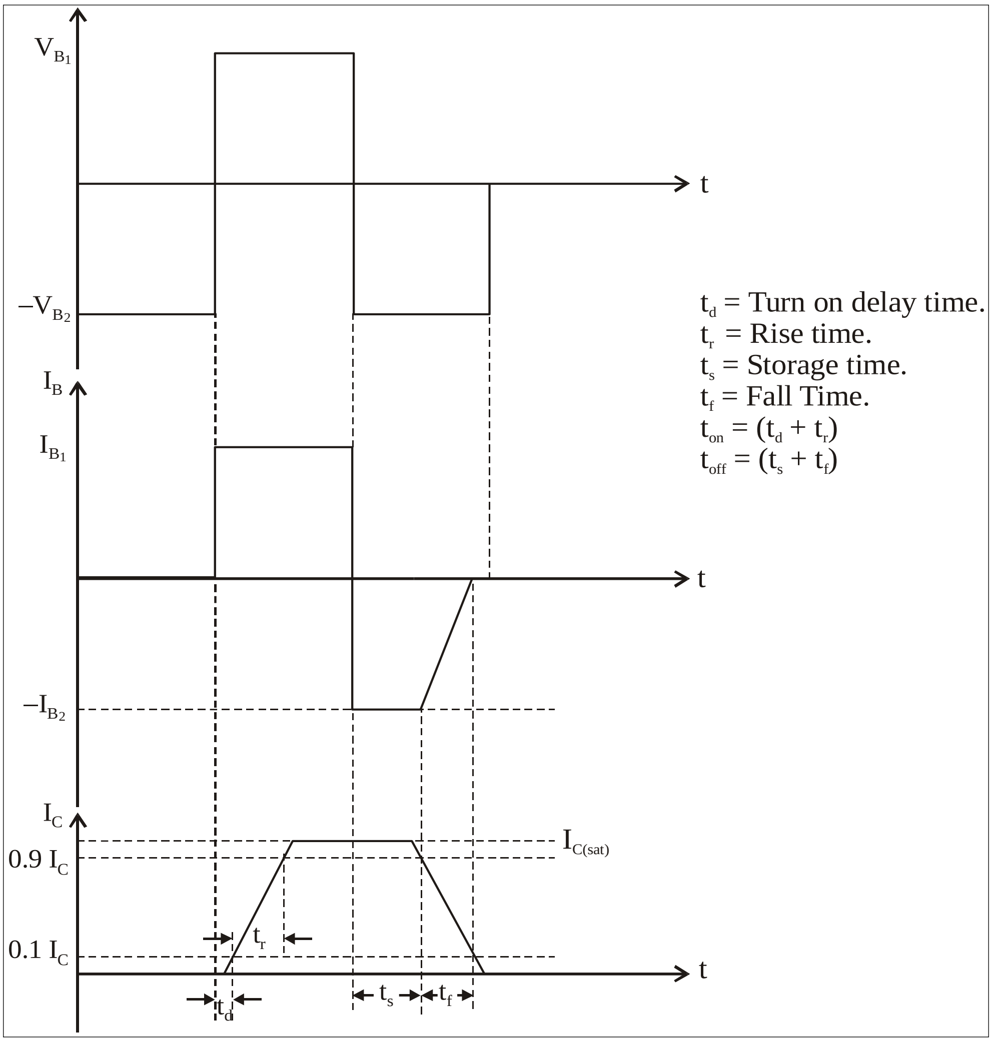
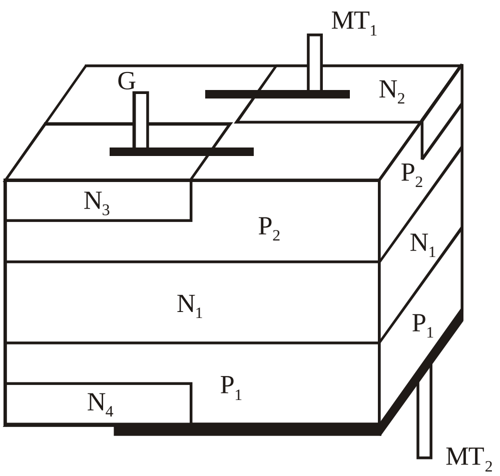


Fig: Switching Times of Bipolar Junction Transistor

CONSTRUCTION, OPERATION & STATIC CHARACTERISTICS OF TRIAC

A triac is a three terminal bi-directional switching thyristor device. It can conduct in both directions when it is triggered into the conduction state. The triac is equivalent to two SCRs connected in anti-parallel with a common gate. Figure below shows the triac structure. It consists of three terminals viz., MT_2 , MT_1 and gate G.



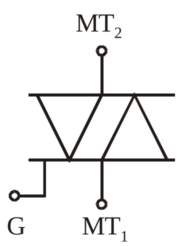


Fig. : Triac Structure

Fig. : Triac Symbol

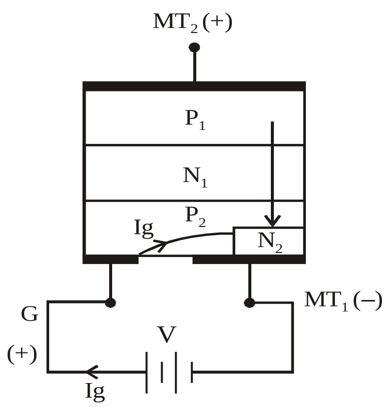
The gate terminal G is near the MT_1 terminal. Figure above shows the triac symbol. MT_1 is the reference terminal to obtain the characteristics of the triac. A triac can be operated in four different modes depending upon the polarity of the voltage on the terminal MT_2 with respect to MT_1 and based on the gate current polarity.

The characteristics of a triac is similar to that of an SCR, both in blocking and conducting states. A SCR can conduct in only one direction whereas triac can conduct in both directions.

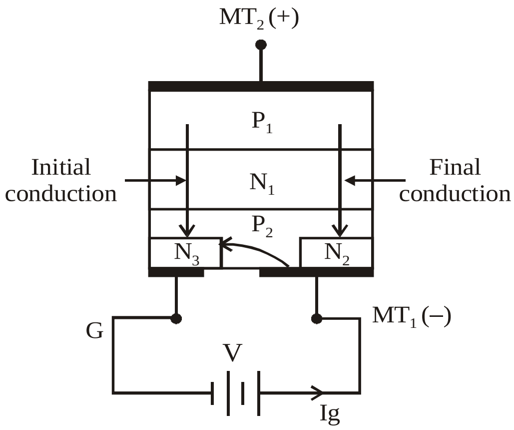
TRIGGERING MODES OF TRIAC

MODE 1 : MT_2 positive, Positive gate current (I^+ mode of operation)

When MT_2 and gate current are positive with respect to MT_1, the gate current flows through P_2-N_2 junction as shown in figure below. The junction P_1-N_1 and P_2-N_2 are forward biased but junction N_1-P_2 is reverse biased. When sufficient number of charge carriers are injected in P_2 layer by the gate current the junction N_1-P_2 breakdown and triac starts conducting through $P_1N_1P_2N_2$ layers. Once triac starts conducting the current increases and its V-I characteristics is similar to that of thyristor. Triac in this mode operates in the first-quadrant.



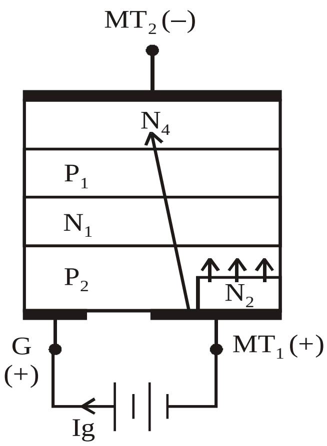
MODE 2 : MT_2 positive, Negative gate current (I^- mode of operation)



When MT_2 is positive and gate G is negative with respect to MT_1 the gate current flows through P_2-N_3 junction as shown in figure above. The junction P_1-N_1 and P_2-N_3 are forward biased but junction N_1-P_2 is reverse biased. Hence, the triac initially starts conducting through $P_1N_1P_2N_3$ layers. As a result the potential of layer between P_2-N_3 rises towards the potential of MT_2. Thus, a potential gradient exists across the layer P_2 with left hand region at a higher potential than the right hand region. This results in a current flow in P_2 layer from left to right, forward biasing the P_2N_2 junction. Now the right hand portion P_1-N_1 - P_2-N_2 starts conducting. The device operates in first quadrant. When compared to Mode 1, triac with MT_2 positive and negative gate current is less sensitive and therefore requires higher gate current for triggering.

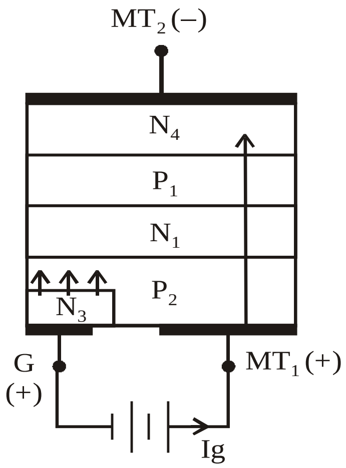
MODE 3 : MT_2 negative, Positive gate current (III^+ mode of operation)

When MT_2 is negative and gate is positive with respect to MT_1 junction P_2N_2 is forward biased and junction P_1-N_1 is reverse biased. N_2 layer injects electrons into P_2 layer as shown by arrows in figure below. This causes an increase in current flow through junction P_2-N_1. Resulting in breakdown of reverse biased junction N_1-P_1. Now the device conducts through layers $P_2N_1P_1N_4$ and the current starts increasing, which is limited by an external load.



The device operates in third quadrant in this mode. Triac in this mode is less sensitive and requires higher gate current for triggering.

MODE 4 : MT_2 negative, Negative gate current (III^- mode of operation)



In this mode both MT_2 and gate G are negative with respect to MT_1, the gate current flows through P_2N_3 junction as shown in figure above. Layer N_3 injects electrons as shown by arrows into P_2 layer. This results in increase in current flow across P_1N_1 and the device will turn ON due to increased current in layer N_1. The current flows through layers $P_2N_1P_1N_4$. Triac is more sensitive in this mode compared to turn ON with positive gate current. (Mode 3).

Triac sensitivity is greatest in the first quadrant when turned ON with positive gate current and also in third quadrant when turned ON with negative gate current. when MT_2 is positive with respect to MT_1 it is recommended to turn on the triac by a positive gate current. When MT_2 is negative with respect to MT_1 it is recommended to turn on the triac by negative gate current. Therefore Mode 1 and Mode 4 are the preferred modes of operation of a triac (I^+ mode and III^- mode of operation are normally used).

TRIAC CHARACTERISTICS

Figure below shows the circuit to obtain the characteristics of a triac. To obtain the characteristics in the third quadrant the supply to gate and between MT_2 and MT_1 are reversed.

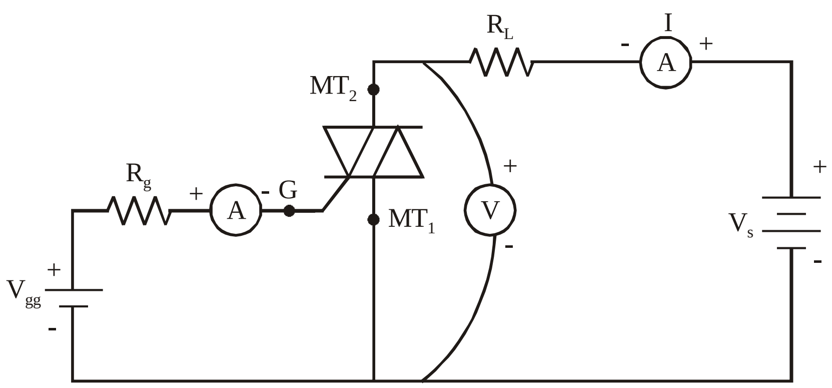


Figure below shows the V-I Characteristics of a triac. Triac is a bidirectional switching device. Hence its characteristics are identical in the first and third quadrant. When gate current is increased the break over voltage decreases.

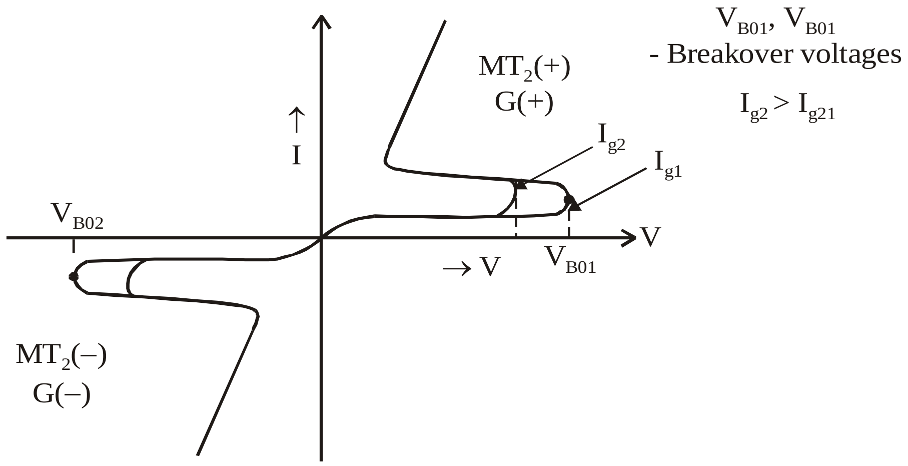


Fig.: Triac Characteristic

Triac is widely used to control the speed of single phase induction motors. It is also used in domestic lamp dimmers and heat control circuits, and full wave AC voltage controllers.

CONSTRUCTION & OPERATION OF POWER MOSFET

Power MOSFET is a metal oxide semiconductor field effect transistor. It is a voltage controlled device requiring a small input gate voltage. It has high input impedance. MOSFET is operated in two states viz., ON STATE and OFF STATE. Switching speed of MOSFET is very high. Switching time is of the order of nanoseconds.

MOSFETs are of two types

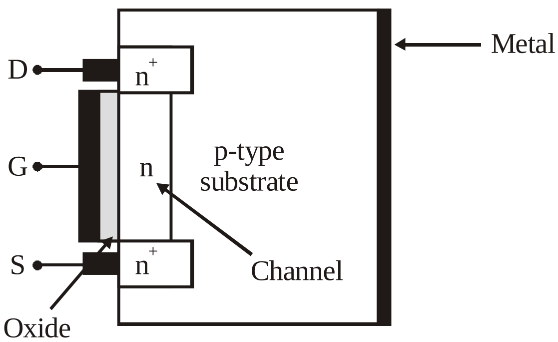
- Depletion MOSFETs
- Enhancement MOSFETs.

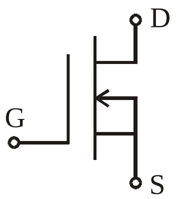
MOSFET is a three terminal device. The three terminals are gate (G), drain (D) and source (S).

DEPLETION MOSFET

Depletion type MOSFET can be either a n-channel or p-channel depletion type MOSFET.

A depletion type n-channel MOSFET consists of a p-type silicon substrate with two highly doped n^+ silicon for low resistance connections. A n-channel is diffused between drain and source. Figure below shows a n-channel depletion type MOSFET. Gate is isolated from the channel by a thin silicon dioxide layer.

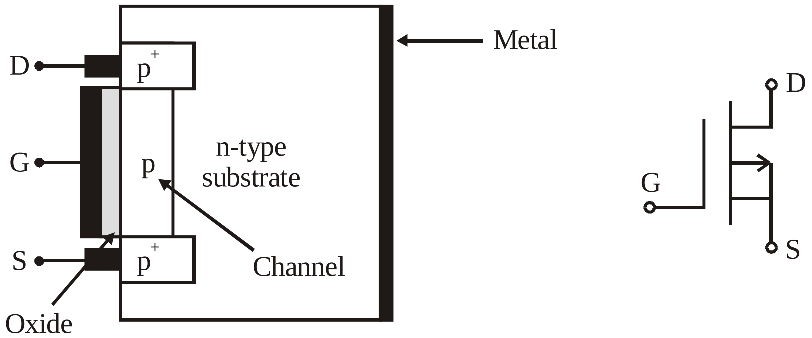




Structure **Symbol**

Fig. : n-channel depletion type MOSFET

Gate to source voltage (V_{GS}) can be either positive or negative. If V_{GS} is negative, electrons present in the n-channel are repelled leaving positive ions. This creates a depletion.



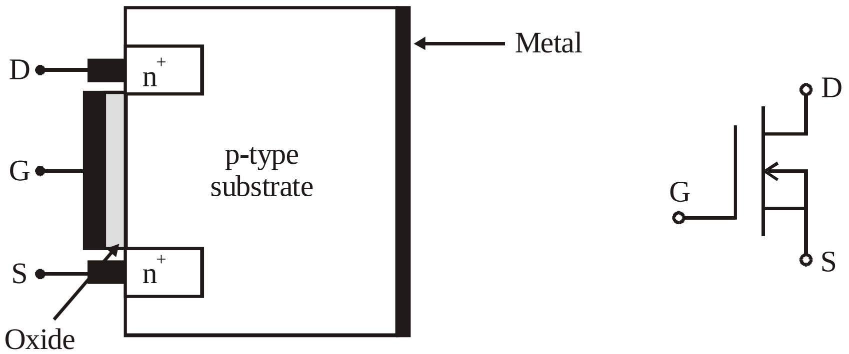
Structure Symbol

Fig. : P-channel depletion type MOSFET

Figure above shows a p-channel depletion type MOSFET. A P-channel depletion type MOSFET consists of a n-type substrate into which highly doped p-regions and a P-channel are diffused. The two P^{+} regions act as drain and source P-channel operation is same except that the polarities of voltages are opposite to that of n-channel.

ENHANCEMENT MOSFET

Enhancement type MOSFET has no physical channel. Enhancement type MOSFET can be either a n-channel or p-channel enhancement type MOSFET.



Structure Symbol

Fig. : n-channel enhancement type MOSFET

Figure above shows a n-channel enhancement type MOSFET. The P-substrate extends upto the silicon dioxide layer. The two highly doped n regions act as drain and source.

When gate is positive (V_{GS}) free electrons are attracted from P-substrate and they collect near the oxide layer. When gate to source voltage, V_{GS} becomes greater than or equal to a value called threshold voltage (V_T). Sufficient numbers of electrons are accumulated to form a virtual n-channel and current flows from drain to source.

Figure below shows a p-channel enhancement type of MOSFET. The n-substrate extends upto the silicon dioxide layer. The two highly doped P regions act as drain and source. For p-channel the polarities of voltages are opposite to that of n-channel.

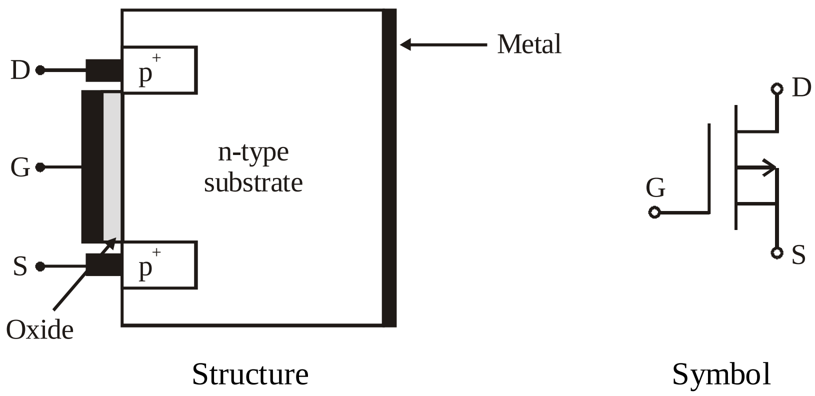


Fig. : P-channel enhancement type MOSFET.

VI CHARACTERISTICS OF MOSFET

Depletion MOSFET

Figure below shows n-channel depletion type MOSFET with gate positive with respect to source. I_D, V_{DS} and V_{GS} are drain current, drain source voltage and gate-source voltage. A plot of variation of I_D with V_{DS} for a given value of V_{GS} gives the Drain characteristics or Output characteristics.

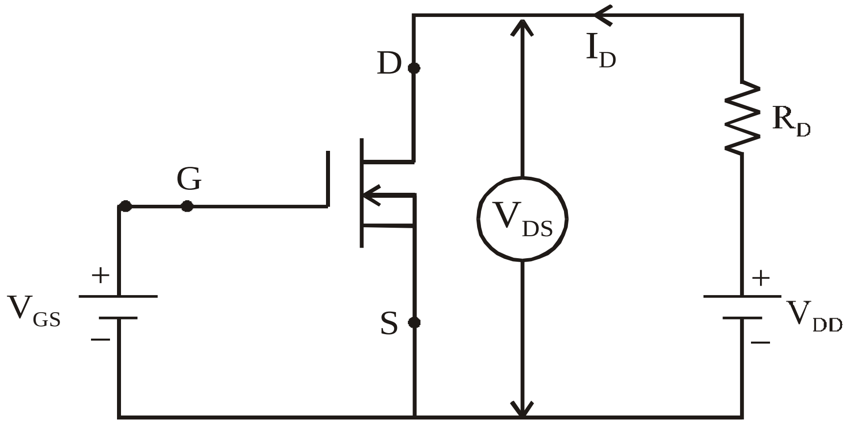


Fig: n-channel Depletion MOSFET

n-channel Depletion type MOSFET

V_{GS} & V_{DS} are positive. I_D is positive for n channel MOSFET . V_{GS} is negative for depletion mode. V_{GS} is positive for enhancement mode.

Figure below shows the drain characteristic. MOSFET can be operated in three regions

- Cut-off region,

- Saturation region (pinch-off region) and
- Linear region.

In the linear region I_D varies linearly with V_{DS}. i.e., increases with increase in V_{DS}. Power MOSFETs are operated in the linear region for switching actions. In saturation region I_D almost remains constant for any increase in V_{DS}.

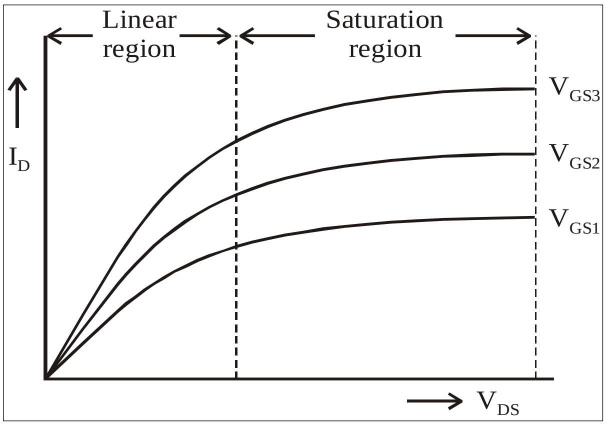


Fig.: Drain Characteristic

Figure below shows the transfer characteristic. Transfer characteristic gives the variation of I_D with V_{GS} for a given value of V_{DS}. I_{DSS} is the drain current with shorted gate. As curve extends on both sides V_{GS} can be negative as well as positive.

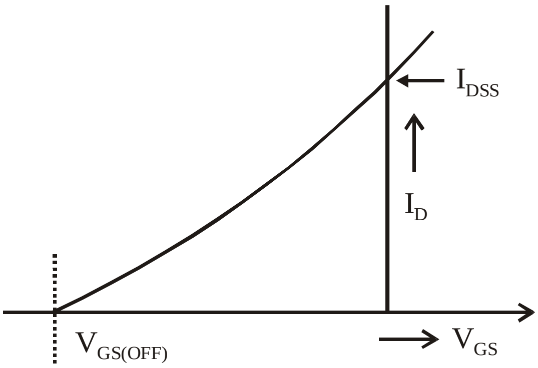


Fig.: Transfer characteristic

Enhancement MOSFET

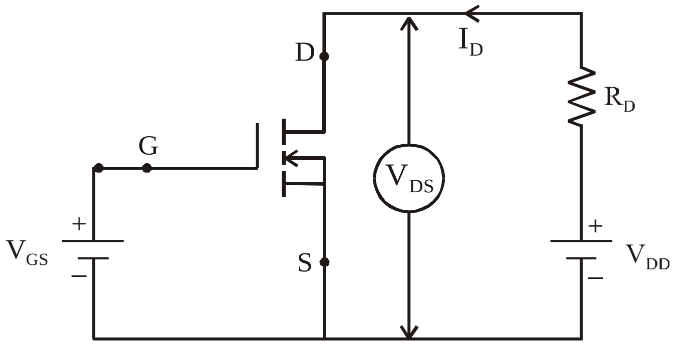
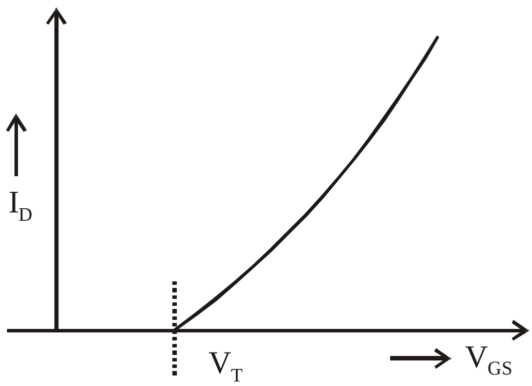


Fig: n-channel Enhancement MOSFET

Enhancement type MOSFET

V_{GS} is positive for a n-channel enhancement MOSFET. V_{DS} & I_D are also positive for n channel enhancement MOSFET

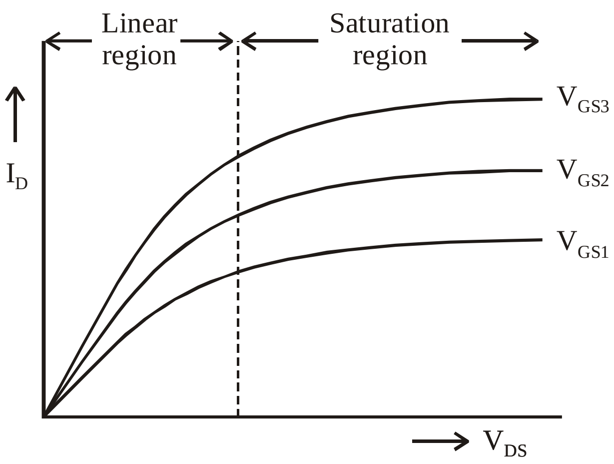
Figure above shows circuit to obtain characteristic of n channel enhancement type MOSFET. Figure below shows the drain characteristic. Drain characteristic gives the variation of I_D with V_{DS} for a given value of V_{GS} .



$V_T = V_{GS(TH)} =$ Gate Source Threshold Voltage

Fig.: Transfer Characteristic

Figure below shows the transfer characteristic which gives the variation of I_D with V_{GS} for a given value of V_{DS} .



$$V_{GS3} > V_{GS2} > V_{GS1}$$

Fig. : Drain Characteristic

MOSFET PARAMETERS

The parameters of MOSFET can be obtained from the graph as follows.

Mutual Transconductance $g_m = \dfrac{\Delta I_D}{\Delta V_{GS}} \Big/ V_{DS} = \text{Constant}$.

Output or Drain Resistance $R_{ds} = \dfrac{\Delta V_{DS}}{\Delta I_D} \Big/ V_{GS} = \text{Constant}$.

Amplification factor $\mu = R_{ds}$ x g_m

Power MOSFETs are generally of enhancement type. Power MOSFETs are used in switched mode power supplies.

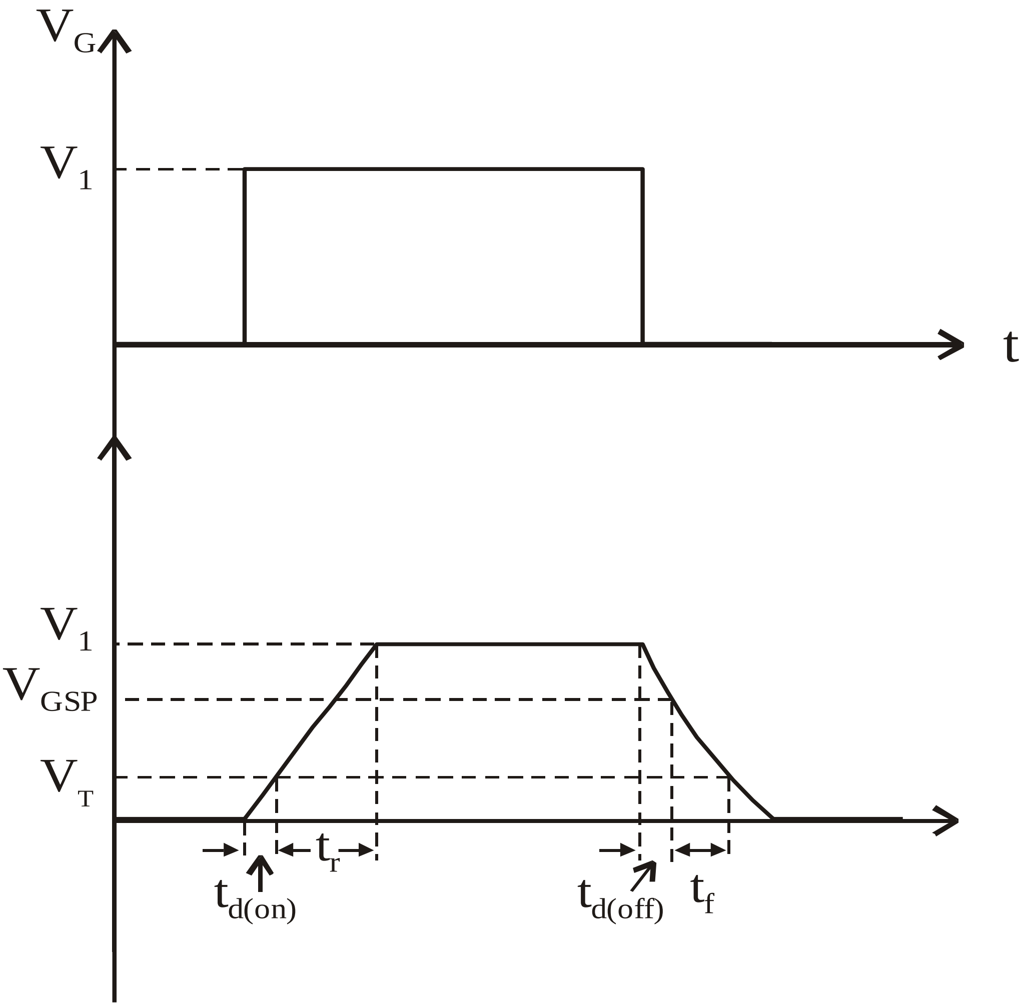
Power MOSFET's are used in high speed power converters and are available at a relatively low power rating in the range of 1000V, 50A at a frequency range of several tens of KHz $\left(f_{\max} = 100KHz\right)$.

SWITCHING CHARACTERISTICS OF MOSFET

Power MOSFETs are often used as switching devices. The switching characteristic of a power MOSFET depends on the capacitances between gate to source C_{GS}, gate to drain C_{GD} and drain to source C_{GS}. It also depends on the impedance of the gate drive circuit. During turn-on there is a turn-on delay $t_{d(on)}$, which is the time required for the input capacitance C_{GS} to charge to threshold voltage level V_T. During the rise time t_r, C_{GS} charges to full gate voltage V_{GSP} and the device operate in the linear region (ON state). During rise time t_r drain current I_D rises from zero to full on state current I_D.

- Total turn-on time, $t_{on} = t_{d(on)} + t_r$

MOSFET can be turned off by discharging capacitance C_{GS}. $t_{d(off)}$ is the turn-off delay time required for input capacitance C_{GS} to discharge from V_1 to V_{GSP}. Fall time t_f is the time required for input capacitance to discharge from V_{GSP} to threshold voltage V_T. During fall time t_f drain current falls from I_D to zero. Figure below shows the switching waveforms of power MOSFET.

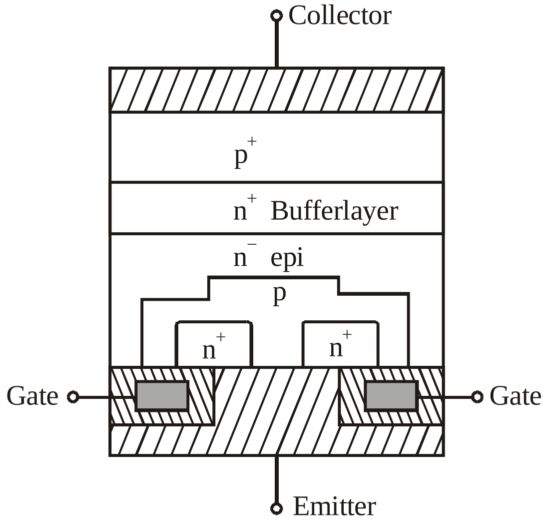


VG
V1
t
V1
VGSP
VT
tr
td(on)
td(off)
tf

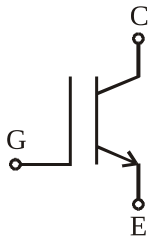
CONSTRUCTION, OPERATION & STATIC CHARACTERISTICS OF INSULATED GATE BIPOLAR TRANSISTOR (IGBT)

IGBT is a voltage controlled device. It has high input impedance like a MOSFET and low on-state conduction losses like a BJT.

Figure below shows the basic silicon cross-section of an IGBT. Its construction is same as power MOSFET except that n^+ layer at the drain in a power MOSFET is replaced by P^+ substrate called collector.



Structure



Symbol

Fig.: Insulated Gate Bipolar Transistor

IGBT has three terminals gate (G), collector (C) and emitter (E). With collector and gate voltage positive with respect to emitter the device is in forward blocking mode. When gate to emitter voltage becomes greater than the threshold voltage of IGBT, a n-channel is formed in the P-region. Now device is in forward conducting state. In this state p^+ substrate injects holes into the epitaxial n^- layer. Increase in collector to emitter voltage will result in increase of injected hole concentration and finally a forward current is established.

CHARACTERISTIC OF IGBT

Figure below shows circuit diagram to obtain the characteristic of an IGBT. An output characteristic is a plot of collector current I_C versus collector to emitter voltage V_{CE} for given values of gate to emitter voltage V_{GE}.

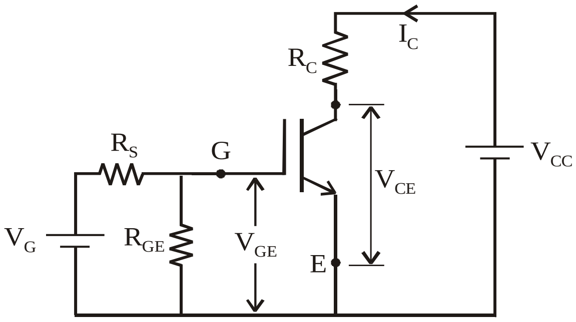


Fig.: Circuit Diagram to Obtain Characteristics

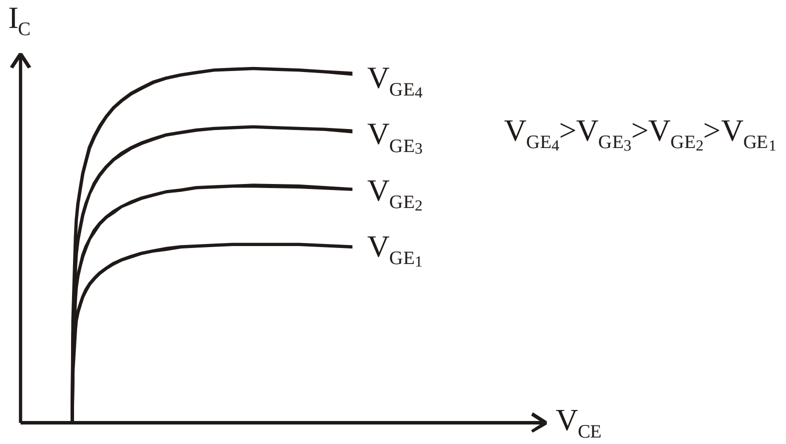


Fig. : Output Characteristics

A plot of collector current I_C versus gate-emitter voltage V_{GE} for a given value of V_{CE} gives the transfer characteristic. Figure below shows the transfer characteristic.

Note

Controlling parameter is the gate-emitter voltage V_{GE} in IGBT. If V_{GE} is less than the threshold voltage V_T then IGBT is in OFF state. If V_{GE} is greater than the threshold voltage V_T then the IGBT is in ON state.

IGBTs are used in medium power applications such as ac and dc motor drives, power supplies and solid state relays.

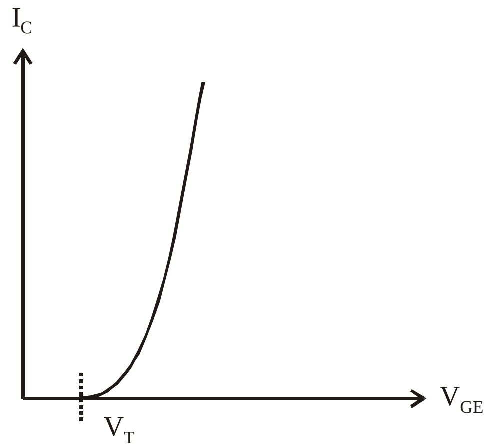


Fig. : Transfer Characteristic

SWITCHING CHARACTERISTIC OF IGBT

Figure below shows the switching characteristic of an IGBT. Turn-on time consists of delay time $t_{d(on)}$ and rise time t_r.

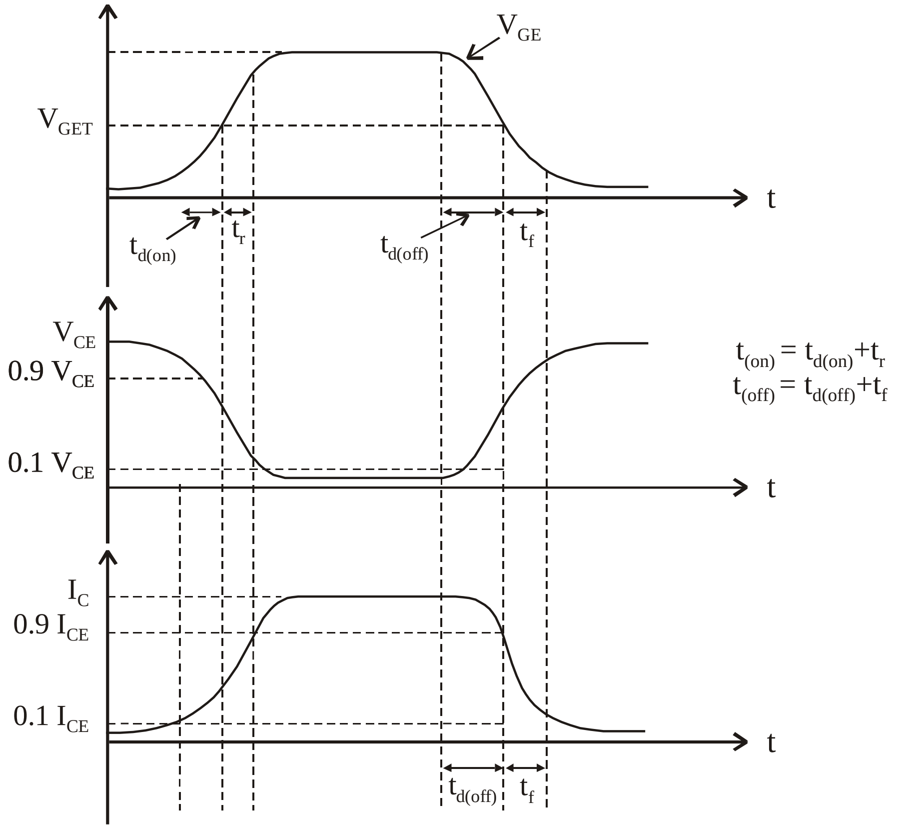


Fig. : Switching Characteristics

The turn on delay time is the time required by the leakage current I_{CE} to rise to 0.1 I_C, where I_C is the final value of collector current. Rise time is the time required for collector current to rise from 0.1 I_C to its final value I_C. After turn-on collector-emitter voltage V_{CE} will be very small during the steady state conduction of the device.

The turn-off time consists of delay off time $t_{d(off)}$ and fall time t_f. Off time delay is the time during which collector current falls from I_C to 0.9 I_C and V_{GE} falls to threshold voltage V_{GET}. During the fall time t_f the collector current falls from 0.90 I_C to 0.1 I_C. During the turn-off time interval collector-emitter voltage rises to its final value V_{CE}.

IGBT's are voltage controlled power transistor. They are faster than BJT's, but still not quite as fast as MOSFET's. the IGBT's offer for superior drive and output characteristics when compared to BJT's. IGBT's are suitable for high voltage, high current and frequencies upto 20KHz. IGBT's are available upto 1400V, 600A and 1200V, 1000A.

IGBT APPLICATIONS

Medium power applications like DC and AC motor drives, medium power supplies, solid state relays and contractors, general purpose inverters, UPS, welder equipments, servo controls, robotics, cutting tools, induction heating

TYPICAL RATINGS OF IGBT

Voltage rating = 1400V. Current rating = 600A. Maximum operating frequency = 20KHz. Switching time $\approx 2.3\mu s\ (t_{ON} \approx t_{OFF})$. ON state resistance = 600mΩ = $60x10^{-3}\Omega$.

POWER MOSFET RATINGS

Voltage rating = 500V. Current rating = 50A. Maximum operating frequency = 100KHz. Switching time $\approx 0.6\mu s$ to $1\mu s\ (t_{ON} \approx t_{OFF})$. ON state resistance $R_{D(ON)}$ = 0.4mΩ to $0.6m\Omega$.

t_f Turn off fall time = 350nsec.

$t_{OFF} = t_{d(OFF)} + t_f = 700n\sec$ (maximum)

t_{rr} Reverse recovery time 250nsec.

Q_{rr} Reverse recovery charge = 2.97μc (typical).

CONSTRUCTION & OPERATION OF THYRISTORS

A thyristor is the most important type of power semiconductor devices. They are extensively used in power electronic circuits. They are operated as bi-stable switches from non-conducting to conducting state.

A thyristor is a four layer, semiconductor of p-n-p-n structure with three p-n junctions. It has three terminals, the anode, cathode and the gate.

The word thyristor is coined from thyratron and transistor. It was invented in the year 1957 at Bell Labs. The Different types of Thyristors are

- Silicon Controlled Rectifier (SCR).
- TRIAC
- DIAC
- Gate Turn Off Thyristor (GTO)

SILICON CONTROLLED RECTIFIER (SCR)

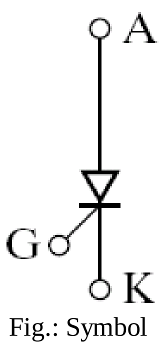


Fig.: Symbol

The SCR is a four layer three terminal device with junctions J_1, J_2, J_3 as shown. The construction of SCR shows that the gate terminal is kept nearer the cathode. The approximate thickness of each layer and doping densities are as indicated in the figure. In terms of their lateral dimensions Thyristors are the largest semiconductor devices made. A complete silicon wafer as large as ten centimeter in diameter may be used to make a single high power thyristor.

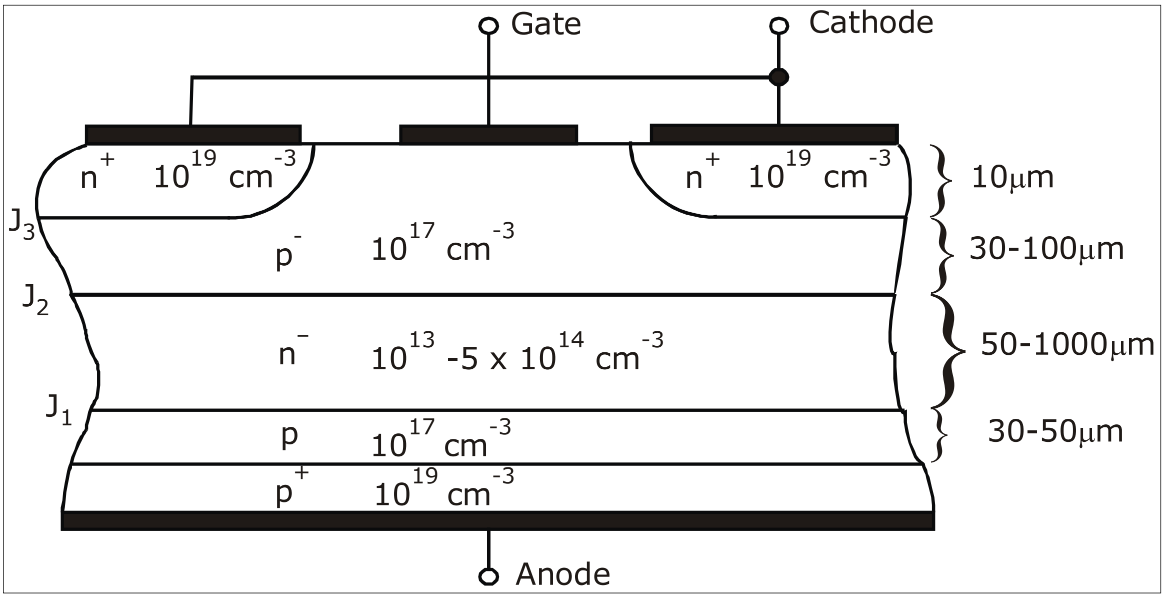


Fig.: Structure of a generic thyristor

QUALITATIVE ANALYSIS

When the anode is made positive with respect the cathode junctions $J_1 \& J_3$ are forward biased and junction J_2 is reverse biased. With anode to cathode voltage V_{AK} being small, only leakage current flows through the device. The SCR is then said to be in the forward blocking state. If V_{AK} is further increased to a large value, the reverse biased junction J_2 will breakdown due to avalanche effect resulting in a large current through the device. The voltage at which this phenomenon occurs is called the forward breakdown voltage V_{BO}. Since the other junctions $J_1 \& J_3$ are already forward biased, there will be free movement of carriers across all three junctions resulting in a large forward anode current. Once the SCR is switched on, the voltage drop across it is very small, typically 1 to 1.5V. The anode current is limited only by the external impedance present in the circuit.

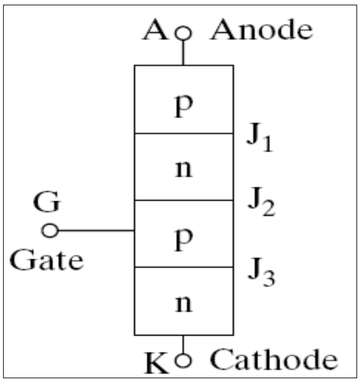
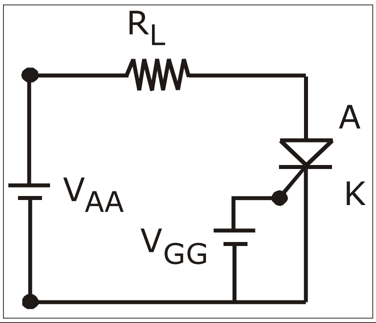


Fig.: Simplified model of a thyristor

Although an SCR can be turned on by increasing the forward voltage beyond V_{BO}, in practice, the forward voltage is maintained well below V_{BO} and the SCR is turned on by applying a positive voltage between gate and cathode. With the application of positive gate voltage, the leakage current through the junction J_2 is increased. This is because the resulting gate current consists mainly of electron flow from cathode to gate. Since the bottom end layer is heavily doped as compared to the p-layer, due to the applied voltage, some of these electrons reach junction J_2 and add to the minority carrier concentration in the p-layer. This raises the reverse leakage current and results in breakdown of junction J_2 even though the applied forward voltage is less than the breakdown voltage V_{BO}. With increase in gate current breakdown occurs earlier.

V-I CHARACTERISTICS OF THYRISTOR

Fig. Circuit



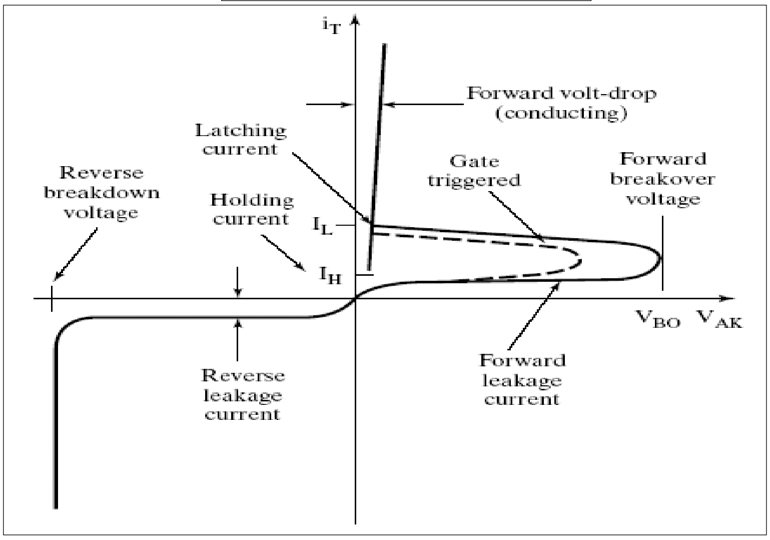


Fig: V-I Characteristics

A typical V-I characteristics of a thyristor is shown above. In the reverse direction the thyristor appears similar to a reverse biased diode which conducts very little current until avalanche breakdown occurs. In the forward direction the thyristor has two stable states or modes of operation that are connected together by an unstable mode that appears as a negative resistance on the V-I characteristics. The low current high voltage region is the forward blocking state or the off state and the low voltage high current mode is the on state. For the forward blocking state the quantity of interest is the forward blocking voltage V_{BO} which is defined for zero gate current. If a positive gate current is applied to a thyristor then the transition or break over to the on state will occur at smaller values of anode to cathode voltage as shown. Although not indicated the gate current does not have to be a dc current but instead can be a pulse of current having some minimum time duration. This ability to switch the thyristor by means of a current pulse is the reason for wide spread applications of the device.

However once the thyristor is in the on state the gate cannot be used to turn the device off. The only way to turn off the thyristor is for the external circuit to force the current through the device to be less than the holding current for a minimum specified time period.

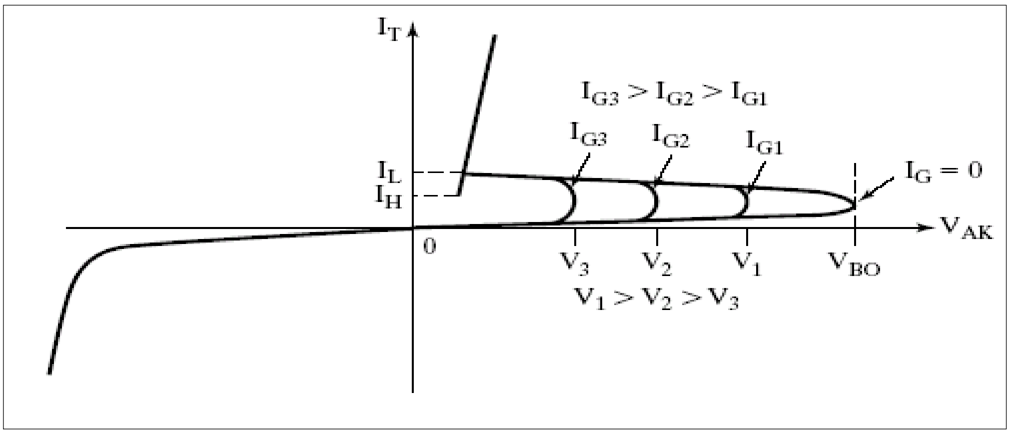


Fig.: Effects on gate current on forward blocking voltage

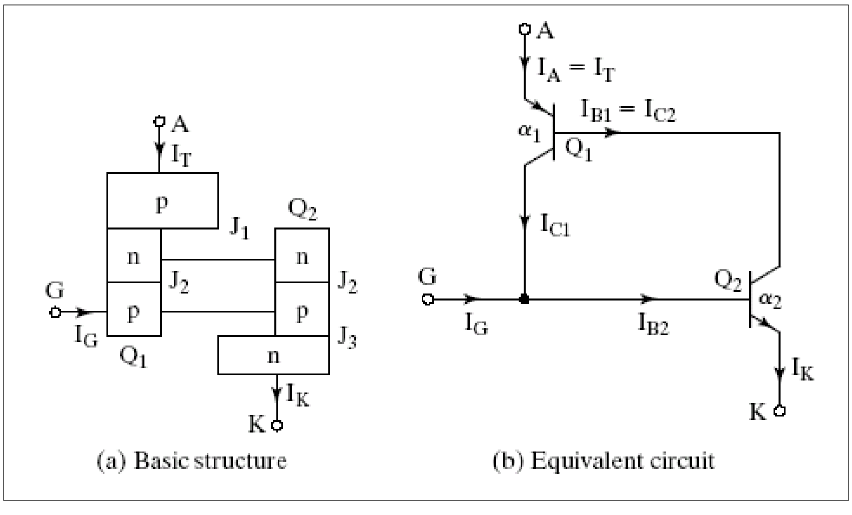
HOLDING CURRENT I_H

After an SCR has been switched to the on state a certain minimum value of anode current is required to maintain the thyristor in this low impedance state. If the anode current is reduced below the critical holding current value, the thyristor cannot maintain the current through it and reverts to its off state usually I_μ is associated with turn off the device.

LATCHING CURRENT I_L

After the SCR has switched on, there is a minimum current required to sustain conduction. This current is called the latching current. I_L associated with turn on and is usually greater than holding current.

TWO TRANSISTOR MODEL OF TRANSISTOR



The general transistor equations are,

$$I_C = \beta I_B + (1+\beta) I_{CBO}$$
$$I_C = \alpha I_E + I_{CBO}$$
$$I_E = I_C + I_B$$
$$I_B = I_E (1-\alpha) - I_{CBO}$$

The SCR can be considered to be made up of two transistors as shown in above figure.

Considering PNP transistor of the equivalent circuit,

$$I_{E_1} = I_A, I_C = I_{C_1}, \alpha = \alpha_1, I_{CBO} = I_{CBO_1}, I_B = I_{B_1}$$
$$\therefore \qquad I_{B_1} = I_A (1-\alpha_1) - I_{CBO_1} \qquad ---(1)$$

Considering NPN transistor of the equivalent circuit,

$$I_C = I_{C_2}, I_B = I_{B_2}, I_{E_2} = I_K = I_A + I_G$$
$$I_{C_2} = \alpha_2 I_k + I_{CBO_2}$$
$$I_{C_2} = \alpha_2 (I_A + I_G) + I_{CBO_2} \qquad ---(2)$$

From the equivalent circuit, we see that

$$\therefore \qquad I_{C_2} = I_{B_1}$$
$$\Rightarrow \qquad I_A = \frac{\alpha_2 I_g + I_{CBO1} + I_{CBO2}}{1-(\alpha_1 + \alpha_2)}$$

Two transistors analog is valid only till SCR reaches ON state

Case 1: When $I_g = 0$,

$$I_A = \frac{I_{CBO_1} + I_{CBO_2}}{1-(\alpha_1 + \alpha_2)}$$

The gain α_1 of transistor T_1 varies with its emitter current $I_E = I_A$. Similarly varies with $I_E = I_A + I_g = I_K$. In this case, with $I_g = 0$, α_2 varies only with I_A. Initially when the applied forward voltage is small, $(\alpha_1 + \alpha_2) < 1$.

If however the reverse leakage current is increased by increasing the applied forward voltage, the gains of the transistor increase, resulting in $(\alpha_1 + \alpha_2) \rightarrow 1$.

From the equation, it is seen that when $(\alpha_1 + \alpha_2) = 1$, the anode current I_A tends towards ∞. This explains the increase in anode current for the break over voltage V_{B0}.

Case 2: With gate current I_g applied.

When sufficient gate drive is applied, we see that $I_{B_2} = I_g$ is established. This in turn results in a current through transistor T_2, this increases α_2 of T_2. But with the existence of $I_{C_2} = \beta_2 I_{\beta_2} = \beta_2 I_g$, a current through T, is established. Therefore, $I_{C_1} = \beta_1 I_{B_1} = \beta_1 \beta_2 I_{B_2} = \beta_1 \beta_2 I_g$. This current in turn is connected to the base of T_2. Thus the base drive of T_2 is increased which in turn increases the base drive of T_1, therefore regenerative feedback or positive feedback is established between the two transistors. This causes $(\alpha_1 + \alpha_2)$ to tend to unity therefore the anode current begins to grow towards a large value. This regeneration continues even if I_g is removed this characteristic of SCR makes it suitable for pulse triggering; SCR is also called a Lathing Device.

SWITCHING CHARACTERISTICS (DYNAMIC CHARACTERISTICS) OF SCR

THYRISTOR TURN-ON CHARACTERISTICS

When the SCR is turned on with the application of the gate signal, the SCR does not conduct fully at the instant of application of the gate trigger pulse. In the beginning, there is no appreciable increase in the SCR anode current, which is because, only a small portion of the silicon pellet in the immediate vicinity of the gate electrode starts conducting. The duration between 90% of the peak gate trigger pulse and the instant the forward voltage has fallen to 90% of its initial value is called the gate controlled / trigger delay time t_{gd}. It is also defined as the duration between 90% of the gate trigger pulse and the instant at which the anode current rises to 10% of its peak value. t_{gd} is usually in the range of 1μsec.

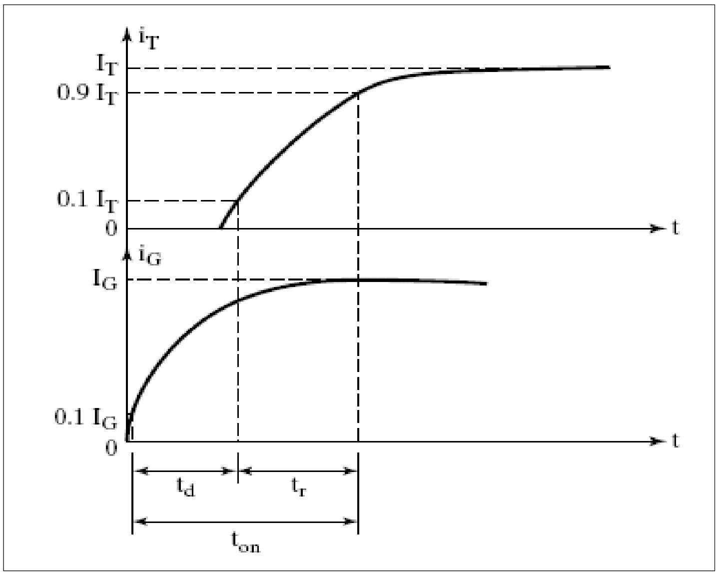
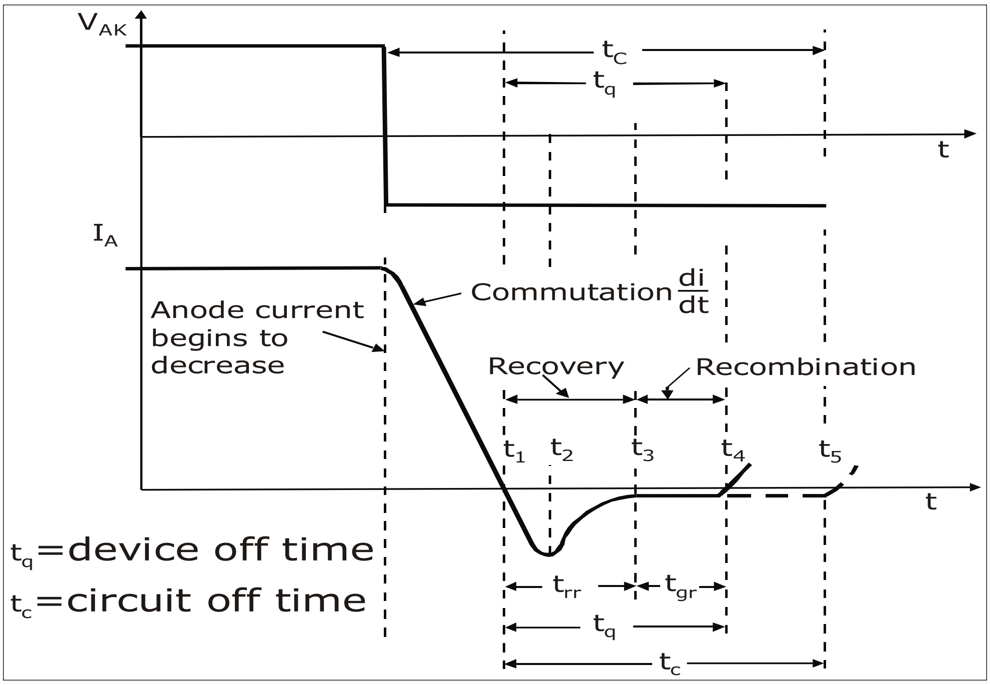


Fig.: Turn-on characteristics

Once t_{gd} has lapsed, the current starts rising towards the peak value. The period during which the anode current rises from 10% to 90% of its peak value is called the rise time. It is also defined as the time for which the anode voltage falls from 90% to 10% of its peak value. The summation of t_{gd} and t_r gives the turn on time t_{on} of the thyristor.

THYRISTOR TURN OFF CHARACTERISTICS



When an SCR is turned on by the gate signal, the gate loses control over the device and the device can be brought back to the blocking state only by reducing the forward current to a level below that of the holding current. In AC circuits, however, the current goes through a natural zero value and the device will automatically switch off. But in DC circuits, where no neutral zero value of current exists, the forward current is reduced by applying a reverse voltage across anode and cathode and thus forcing the current through the SCR to zero.

As in the case of diodes, the SCR has a reverse recovery time t_{rr} which is due to charge storage in the junctions of the SCR. These excess carriers take some time for recombination resulting in the gate recovery time or reverse recombination time t_{gr}. Thus, the turn-off time t_q is the sum of the durations for which reverse recovery current flows after the application of reverse voltage and the time required for the recombination of all excess carriers present. At the end of the turn off time, a depletion layer develops across J_2 and the junction can now withstand the forward voltage. The turn off time is dependent on the anode current, the magnitude of reverse V_g applied ad the magnitude and rate of application of the forward voltage. The turn off time for converte grade SCR’s is 50 to 100µsec and that for inverter grade SCR’s is 10 to 20µsec.

To ensure that SCR has successfully turned off , it is required that the circuit off time t_c be greater than SCR turn off time t_q.

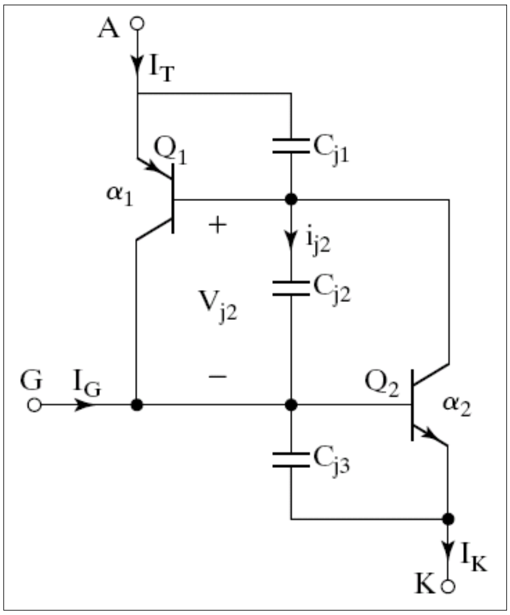
THYRISTOR TURN ON

- **Thermal Turn on:** If the temperature of the thyristor is high, there will be an increase in charge carriers which would increase the leakage current. This would cause an increase in α_1 & α_2 and the thyristor may turn on. This type of turn on many cause thermal run away and is usually avoided.
- **Light**: If light be allowed to fall on the junctions of a thyristor, charge carrier concentration would increase which may turn on the SCR.

- **LASCR:** Light activated SCRs are turned on by allowing light to strike the silicon wafer.
- **High Voltage Triggering:** This is triggering without application of gate voltage with only application of a large voltage across the anode-cathode such that it is greater than the forward breakdown voltage V_{BO}. This type of turn on is destructive and should be avoided.
- **Gate Triggering:** Gate triggering is the method practically employed to turn-on the thyristor. Gate triggering will be discussed in detail later.
- $\frac{dv}{dt}$ **Triggering:** Under transient conditions, the capacitances of the p-n junction will influence the characteristics of a thyristor. If the thyristor is in the blocking state, a rapidly rising voltage applied across the device would cause a high current to flow through the device resulting in turn-on. If i_{j_2} is the current throught the junction j_2 and C_{j_2} is the junction capacitance and V_{j_2} is the voltage across j_2, then

$$i_{j_2} = \frac{dq_2}{dt} = \frac{d}{dt}\left(C_{j_2} V_{j_2}\right) = \frac{C_{j_2} dV_{J2}}{dt} + V_{j_2} \frac{dC_{j_2}}{dt}$$

From the above equation, we see that if $\frac{dv}{dt}$ is large, 1_{j_2} will be large. A high value of charging current may damage the thyristor and the device must be protected against high $\frac{dv}{dt}$. The manufacturers specify the allowable $\frac{dv}{dt}$.



THYRISTOR RATINGS

First Subscript	Second Subscript	Third Subscript

D → off state	W → working	M → Peak Value
T → ON state	R → Repetitive	
F → Forward	S →Surge or non-repetitive	
R → Reverse		

VOLTAGE RATINGS

V_{DWM} : This specifies the peak off state working forward voltage of the device. This specifies the maximum forward off state voltage which the thyristor can withstand during its working.

V_{DRM} : This is the peak repetitive off state forward voltage that the thyristor can block repeatedly in the forward direction (transient).

V_{DSM} : This is the peak off state surge / non-repetitive forward voltage that will occur across the thyristor.

V_{RWM} : This the peak reverse working voltage that the thyristor can withstand in the reverse direction.

V_{RRM} : It is the peak repetitive reverse voltage. It is defined as the maximum permissible instantaneous value of repetitive applied reverse voltage that the thyristor can block in reverse direction.

V_{RSM} : Peak surge reverse voltage. This rating occurs for transient conditions for a specified time duration.

V_T : On state voltage drop and is dependent on junction temperature.

V_{TM} : Peak on state voltage. This is specified for a particular anode current and junction temperature.

$\frac{dv}{dt}$ rating: This is the maximum rate of rise of anode voltage that the SCR has to withstand and which will not trigger the device without gate signal (refer $\frac{dv}{dt}$ triggering).

CURRENT RATING

$I_{Taverage}$: This is the on state average current which is specified at a particular temperature.

I_{TRMS}: This is the on-state RMS current.

Latching current, I_L: After the SCR has switched on, there is a minimum current required to sustain conduction. This current is called the latching current. I_L associated with turn on and is usually greater than holding current

Holding current, I_H: After an SCR has been switched to the on state a certain minimum value of anode current is required to maintain the thyristor in this low impedance state. If the anode current is reduced below the critical holding current value, the thyristor cannot maintain the current through it and reverts to its off state usually I_μ is associated with turn off the device.

$\frac{di}{dt}$ rating: This is a non repetitive rate of rise of on-state current. This maximum value of rate of rise of current is which the thyristor can withstand without destruction. When thyristor is switched on, conduction starts at a place near the gate. This small area of conduction spreads rapidly and if rate of rise of anode current $\frac{di}{dt}$ is large compared to the spreading velocity of carriers, local hotspots will be formed near the gate due to high current density. This causes the junction temperature to rise above the safe limit and the SCR may be damaged permanently. The $\frac{di}{dt}$ rating is specified in $A/\mu\sec$.

GATE SPECIFICATIONS

I_{GT}: This is the required gate current to trigger the SCR. This is usually specified as a DC value.

V_{GT}: This is the specified value of gate voltage to turn on the SCR (dc value).

V_{GD}: This is the value of gate voltage, to switch from off state to on state. A value below this will keep the SCR in off state.

Q_{RR}: Amount of charge carriers which have to be recovered during the turn off process.

R_{thjc}: Thermal resistance between junction and outer case of the device.

VARIOUS GATE TRIGGERING METHODS OF SCR.

Types

The different methods of gate triggering are the following

- R-triggering.
- RC triggering.
- UJT triggering.

RESISTANCE TRIGGERING

A simple resistance triggering circuit is as shown. The resistor R_1 limits the current through the gate of the SCR. R_2 is the variable resistance added to the circuit to achieve control over the triggering angle of SCR. Resistor 'R' is a stabilizing resistor. The diode D is required to ensure that no negative voltage reaches the gate of the SCR.

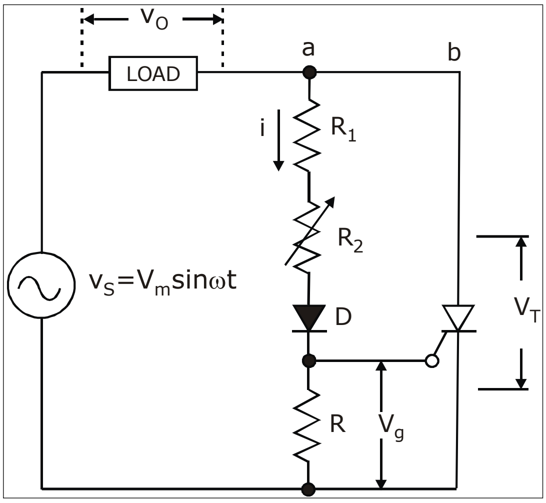


Fig.: Resistance firing circuit

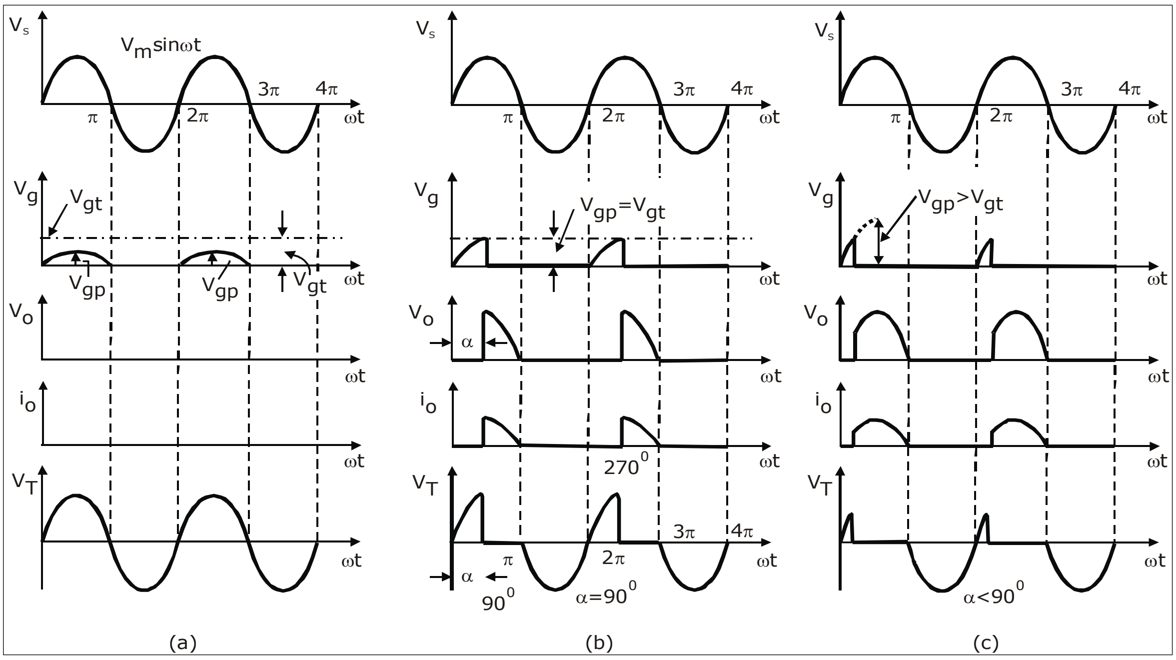


Fig.: Resistance firing of an SCR in half wave circuit with dc load

(a) No triggering of SCR (b) $\alpha = 90^0$ (c) $\alpha < 90^0$

Design

With $R_2 = 0$, we need to ensure that $\frac{V_m}{R_1} < I_{gm}$, where I_{gm} is the maximum or peak gate current of the SCR. Therefore $R_1 \geq \frac{V_m}{I_{gm}}$.

Also with $R_2 = 0$, we need to ensure that the voltage drop across resistor 'R' does not exceed V_{gm}, the maximum gate voltage

$$V_{gm} \geq \frac{V_m R}{R_1 + R}$$

$$\therefore \quad V_{gm}R_1 + V_{gm}R \geq V_m R$$

$$\therefore \quad V_{gm}R_1 \geq R\left(V_m - V_{gm}\right)$$

$$R \leq \frac{V_{gm}R_1}{V_m - V_{gm}}$$

OPERATION

Case 1: $V_{gp} < V_{gt}$

V_{gp}, the peak gate voltage is less then V_{gt} since R_2 is very large. Therefore, current 'I' flowing through the gate is very small. SCR will not turn on and therefore the load voltage is zero and v_{scr} is equal to V_s. This is because we are using only a resistive network. Therefore, output will be in phase with input.

Case 2: $V_{gp} = V_{gt}$, $R_2 \rightarrow$ optimum value.

When R_2 is set to an optimum value such that $V_{gp} = V_{gt}$, we see that the SCR is triggered at 90^0 (since V_{gp} reaches its peak at 90^0 only). The waveforms shows that the load voltage is zero till 90^0 and the voltage across the SCR is the same as input voltage till it is triggered at 90^0.

Case 3: $V_{gp} > V_{gt}$, $R_2 \rightarrow$ small value.

The triggering value V_{gt} is reached much earlier than 90^0. Hence the SCR turns on earlier than V_S reaches its peak value. The waveforms as shown with respect to $V_s = V_m \sin \omega t$.

At $\omega t = \alpha, V_S = V_{gt}, V_m = V_{gp} \left(\because V_{gt} = V_{gp} \sin \alpha \right)$

Therefore $\alpha = \sin^{-1}\left(\dfrac{V_{gt}}{V_{gp}} \right)$

But $V_{gp} = \dfrac{V_m R}{R_1 + R_2 + R}$

Therefore $\alpha = \sin^{-1}\left[\dfrac{V_{gt}\left(R_1 + R_2 + R\right)}{V_m R} \right]$

Since V_{gt}, R_1, R are constants $\alpha \alpha R_2$

RESISTANCE CAPACITANCE TRIGGERING

RC HALF WAVE

Capacitor 'C' in the circuit is connected to shift the phase of the gate voltage. D_1 is used to prevent negative voltage from reaching the gate cathode of SCR.

In the negative half cycle, the capacitor charges to the peak negative voltage of the supply $\left(-V_m\right)$ through the diode D_2. The capacitor maintains this voltage across it, till the supply voltage crosses zero. As the supply becomes positive, the capacitor charges through resistor 'R' from initial voltage of $-V_m$, to a positive value.

When the capacitor voltage is equal to the gate trigger voltage of the SCR, the SCR is fired and the capacitor voltage is clamped to a small positive value.

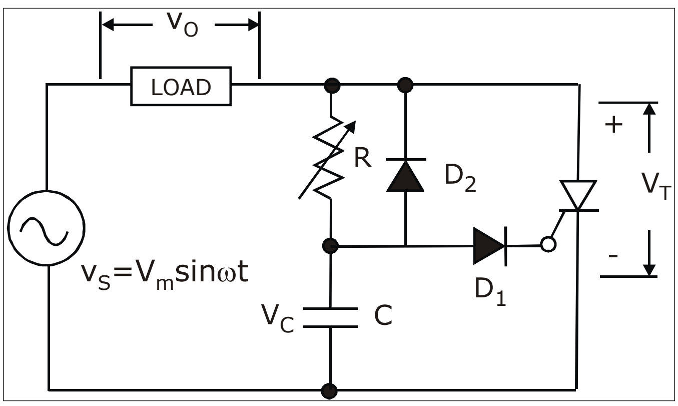


Fig.: RC half-wave trigger circuit

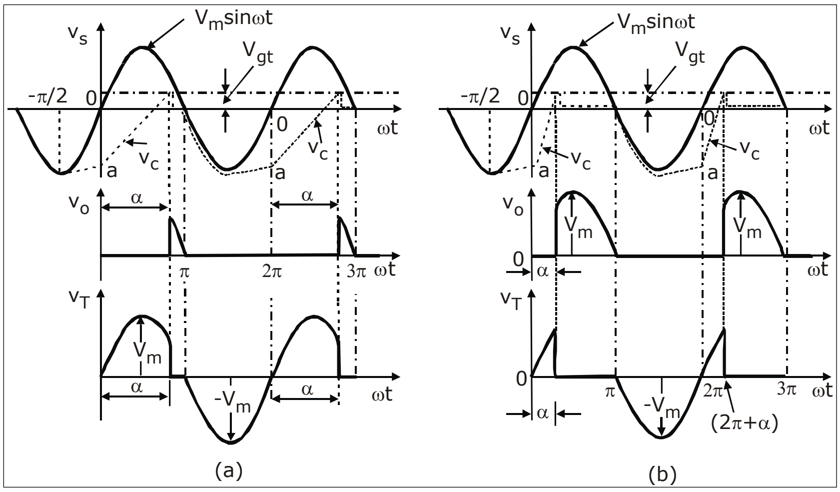


Fig.: Waveforms for RC half-wave trigger circuit

(a) High value of R (b) Low value of R

Case 1: R $\rightarrow$ Large.

When the resistor ‘R’ is large, the time taken for the capacitance to charge from $-V_m$ to V_{gt} is large, resulting in larger firing angle and lower load voltage.

Case 2: R $\rightarrow$ Small

When ‘R’ is set to a smaller value, the capacitor charges at a faster rate towards V_{gt} resulting in early triggering of SCR and hence V_L is more. When the SCR triggers, the voltage drop across it falls to 1 – 1.5V. This in turn lowers, the voltage across R & C. Low voltage across the SCR during conduction period keeps the capacitor discharge during the positive half cycle.

DESIGN EQUATION

From the circuit $V_C = V_{gt} + V_{d1}$. Considering the source voltage and the gate circuit, we can write $v_s = I_{gt}R + V_C$. SCR fires when $v_s \geq I_{gt}R + V_C$ that is $v_S \geq I_g R + V_{gt} + V_{d1}$. Therefore $R \leq \dfrac{v_s - V_{gt} - V_{d1}}{I_{gt}}$. The RC time constant for zero output voltage that is maximum firing angle for power frequencies is empirically gives as $RC \geq 1.3\left(\dfrac{T}{2}\right)$.

RC FULL WAVE

A simple circuit giving full wave output is shown in figure below. In this circuit the initial voltage from which the capacitor ‘C’ charges is essentially zero. The capacitor ‘C’ is reset to this voltage by the clamping action of the thyristor gate. For this reason the charging time constant RC must be chosen longer than for half wave RC circuit in order to delay the triggering. The RC value is empirically chosen as $RC \geq \frac{50T}{2}$. Also $R \leq \frac{v_s - V_{gt}}{I_{gt}}$.

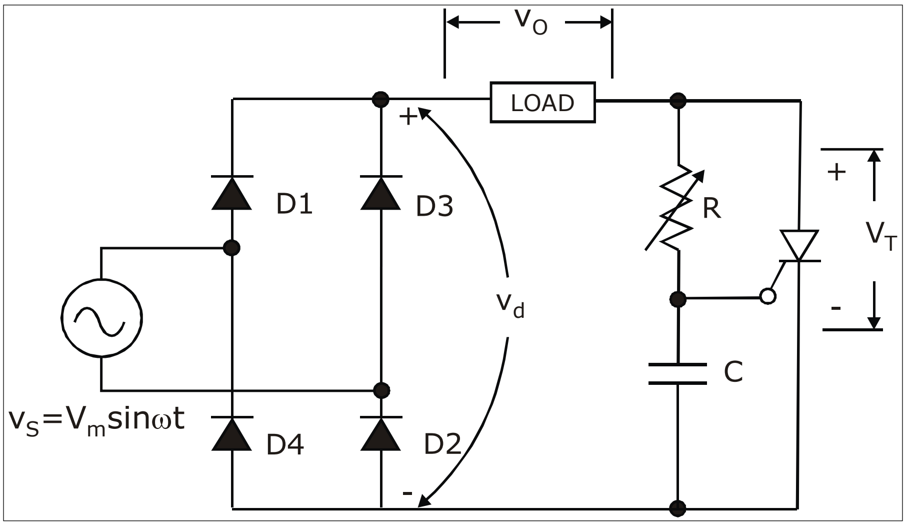


Fig: RC full-wave trigger circuit

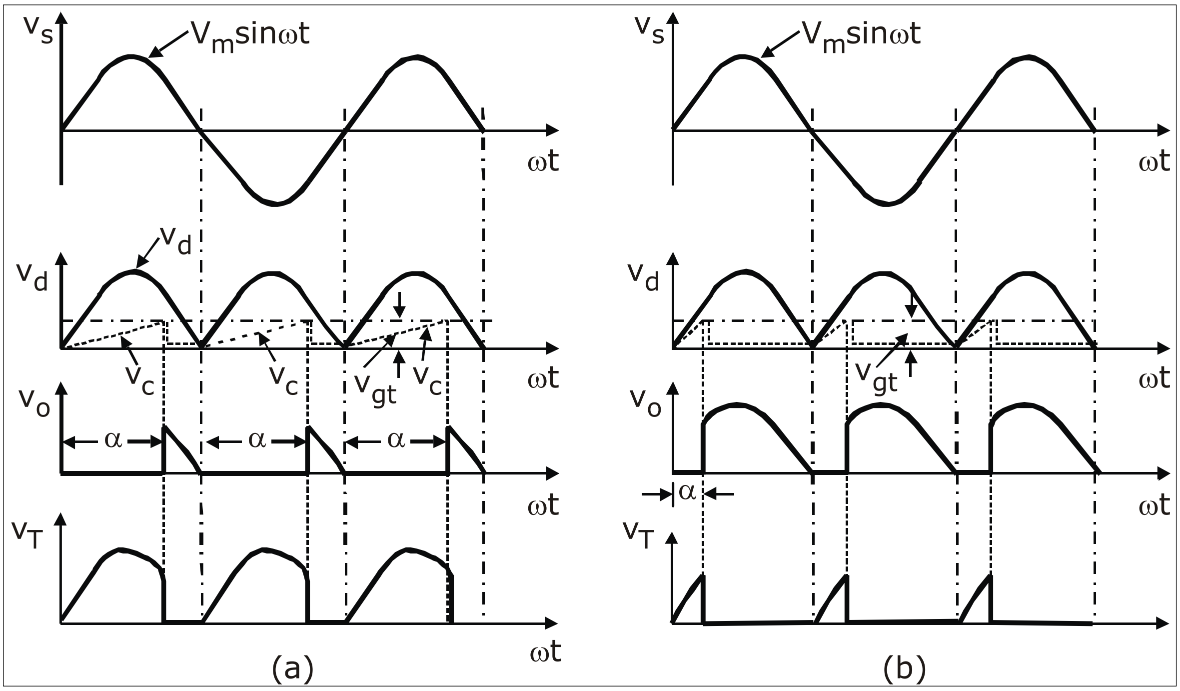


Fig: Wave-forms for RC full-wave trigger circuit

(a) High value of R **(b) Low value of R**

PROBLEM

1. Design a suitable RC triggering circuit for a thyristorised network operation on a 220V, 50Hz supply. The specifications of SCR are $V_{gt\min} = 5V$, $I_{gt\max} = 30mA$.

$$R = \frac{v_s - V_{gt} - V_D}{I_g} = 7143.3\Omega$$

Therefore $RC \geq 0.013$

$R \leq 7.143k\Omega$

$C \geq 1.8199\mu F$

UNI-JUNCTION TRANSISTOR (UJT)

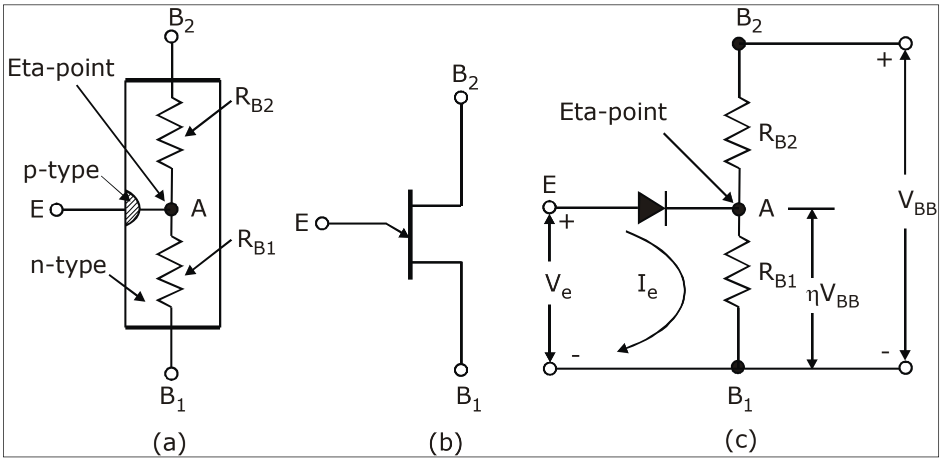


Fig.: (a) Basic structure of UJT (b) Symbolic representation (c) Equivalent circuit

UJT is an n-type silicon bar in which p-type emitter is embedded. It has three terminals base1, base2 and emitter 'E'. Between B_1 and B_2 UJT behaves like ordinary resistor and the internal resistances are given as R_{B1} and R_{B2} with emitter open $R_{BB} = R_{B1} + R_{B2}$. Usually the p-region is heavily doped and n-region is lightly doped. The equivalent circuit of UJT is as shown. When V_{BB} is applied across B_1 and B_2, we find that potential at A is

$$V_{AB1} = \frac{V_{BB} R_{B1}}{R_{B1} + R_{B2}} = \eta V_{BB} \left[\eta = \frac{R_{B1}}{R_{B1} + R_{B2}} \right]$$

η is intrinsic stand off ratio of UJT and ranges between 0.51 and 0.82. Resistor R_{B2} is between 5 to 10KΩ.

OPERATION

When voltage V_{BB} is applied between emitter 'E' with base 1 B_1 as reference and the emitter voltage V_E is less than $(V_D + \eta V_{BE})$ the UJT does not conduct. $(V_D + \eta V_{BB})$ is designated as V_P which is the value of voltage required to turn on the UJT. Once V_E is equal to $V_P \equiv \eta V_{BE} + V_D$, then UJT is forward biased and it conducts.

The peak point is the point at which peak current I_P flows and the peak voltage V_P is across the UJT. After peak point the current increases but voltage across device drops, this is due to the fact that emitter starts to inject holes into the lower doped n-region. Since p-region is heavily doped compared to n-region. Also holes have a longer life time, therefore number of carriers in the base region increases rapidly. Thus potential at 'A' falls but current I_E increases rapidly. R_{B1} acts as a decreasing resistance.

The negative resistance region of UJT is between peak point and valley point. After valley point, the device acts as a normal diode since the base region is saturated and R_{B1} does not decrease again.

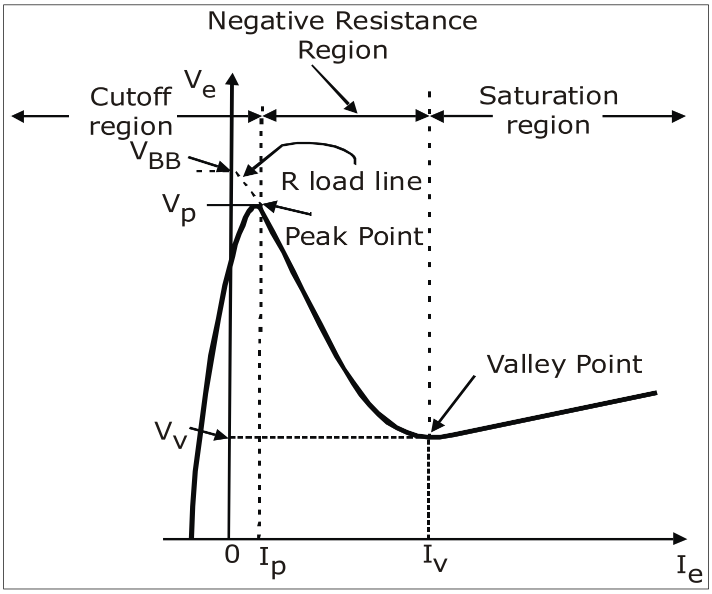


Fig.: V-I Characteristics of UJT

UJT RELAXATION OSCILLATOR

UJT is highly efficient switch. The switching times is in the range of nanoseconds. Since UJT exhibits negative resistance characteristics it can be used as relaxation oscillator. The circuit diagram is as shown with R_1 and R_2 being small compared to R_{B1} and R_{B2} of UJT.

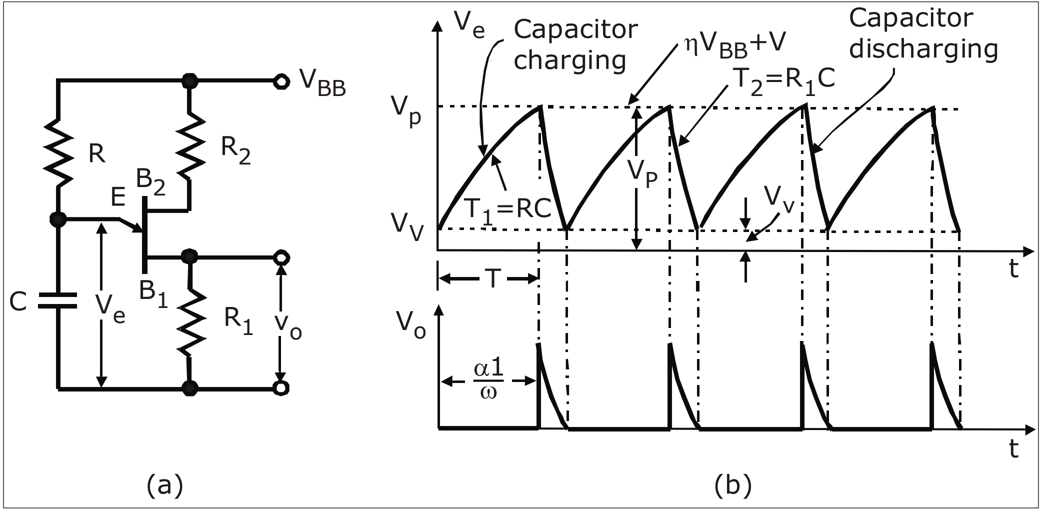


Fig.: UJT oscillator (a) Connection diagram and (b) Voltage waveforms

OPERATION

When V_{BB} is applied, capacitor 'C' begins to charge through resistor 'R' exponentially towards V_{BB}. During this charging emitter circuit of UJT is an open circuit. The rate of charging is $\tau_1 = RC$. When this capacitor voltage which is nothing but emitter voltage V_E reaches the peak point $V_P = \eta V_{BB} + V_D$, the emitter base junction is forward biased and UJT turns on. Capacitor 'C' rapidly discharges through load resistance R_1 with time constant $\tau_2 = R_1 C\left(\tau_2 \ll \tau_1\right)$. When emitter voltage decreases to valley point V_v, UJT turns off. Once again the capacitor will charge towards V_{BB} and the cycle continues. The rate of charging of the capacitor will be determined by the resistor R in the circuit. If R is small the capacitor charges faster towards V_{BB} and thus reaches V_P faster and the SCR is triggered at a smaller firing angle. If R is large the capacitor takes a longer time to charge towards V_P the firing angle is delayed. The waveform for both cases is as shown below.

EXPRESSION FOR PERIOD OF OSCILLATION 'T'

The period of oscillation of the UJT can be derived based on the voltage across the capacitor. Here we assume that the period of charging of the capacitor is lot larger than than the discharging time.

Using initial and final value theorem for voltage across a capacitor, we get

$$V_C = V_{final} + \left(V_{initial} - V_{final}\right) e^{-t/RC}$$

$$t = T, V_C = V_P, V_{initial} = V_V, V_{final} = V_{BB}$$

Therefore $$V_P = V_{BB} + \left(V_V - V_{BB}\right) e^{-T/RC}$$

$\Rightarrow$ $$T = RC \log_e\left(\frac{V_{BB} - V_V}{V_{BB} - V_P}\right)$$

If

$$V_V < V_{BB},$$

$$T = RC\ln\left(\frac{V_{BB}}{V_{BB} - V_P}\right)$$

$$= RC\ln\left[\frac{1}{1 - \frac{V_P}{V_{BB}}}\right]$$

But $\quad V_P = \eta V_{BB} + V_D$

If $\quad V_D \ll V_{BB} \qquad V_P = \eta V_{BB}$

Therefore $\quad T = RC\ln\left[\frac{1}{1-\eta}\right]$

DESIGN OF UJT OSCILLATOR

Resistor 'R' is limited to a value between 3 kilo ohms and 3 mega ohms. The upper limit on 'R' is set by the requirement that the load line formed by 'R' and V_{BB} intersects the device characteristics to the right of the peak point but to the left of valley point. If the load line fails to pass to the right of the peak point the UJT will not turn on, this condition will be satisfied if $V_{BB} - I_P R > V_P$, therefore $R < \frac{V_{BB} - V_P}{I_P}$.

At the valley point $I_E = I_V$ and $V_E = V_V$, so the condition for the lower limit on 'R' to ensure turn-off is $V_{BB} - I_V R < V_V$, therefore $R > \frac{V_{BB} - V_V}{I_V}$.

The recommended range of supply voltage is from 10 to 35V. the width of the triggering pulse $t_g = R_{B1}C$.

In general R_{B1} is limited to a value of 100 ohm and R_{B2} has a value of 100 ohm or greater and can be approximately determined as $R_{B2} = \frac{10^4}{\eta V_{BB}}$.

OPERATION OF $\frac{dv}{dt}$ PROTECTION

The $\frac{dv}{dt}$ across the thyristor is limited by using snubber circuit as shown in figure (a) below. If switch S_1 is closed at $t = 0$, the rate of rise of voltage across the thyristor is limited by the capacitor C_S. When thyristor T_1 is turned on, the discharge current of the capacitor is limited by the resistor R_S as shown in figure (b) below.

Fig. (a)

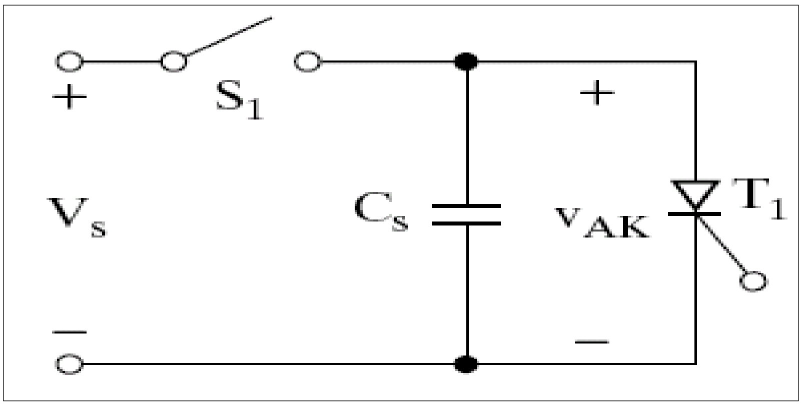


Fig. (b)

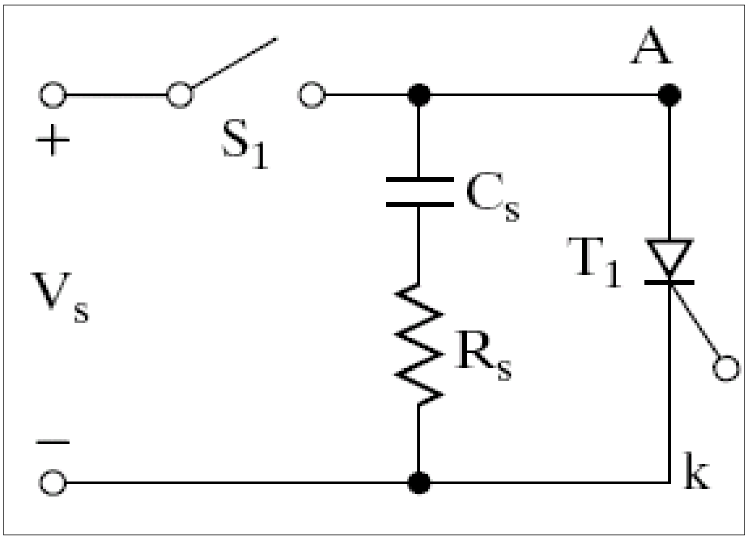
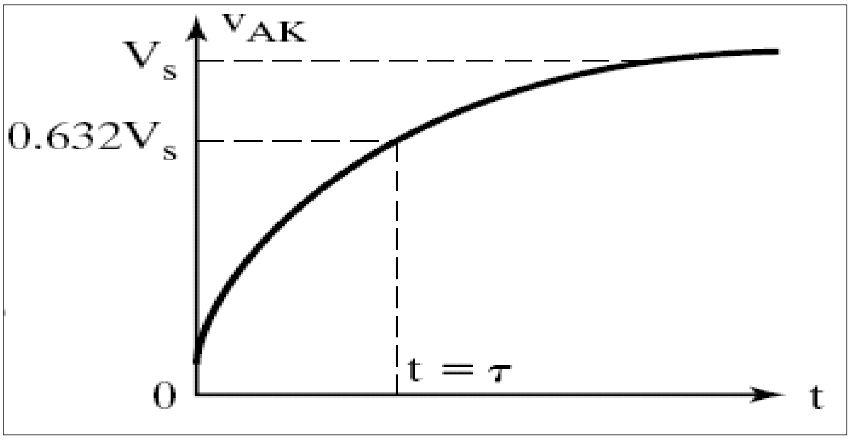


Fig. (c)



The voltage across the thyristor will rise exponentially as shown by fig (c) above.

From fig. (b) above, circuit we have (for SCR off)

$$V_S = i(t)R_S + \frac{1}{C}\int i(t)\,dt + V_c(0)_{[for\ t=0]}.$$

Therefore $\quad i(t) = \frac{V_S}{R_S} e^{-t/\tau_s}$, where $\tau_s = R_S C_S$

Also $\quad V_T(t) = V_S - i(t)R_S$

$$V_T(t) = V_S - \frac{V_S}{\cancel{R_S}} e^{-t/\tau_s} \cancel{R_S}$$

Therefore $\quad V_T(t) = V_S - V_S e^{-t/\tau_s} = V_S\left[1 - e^{-t/\tau_s}\right]$

At t = 0, $\quad V_T(0) = 0$

At $t = \tau_s$, $\quad V_T(\tau_s) = 0.632V_S$

Therefore $\quad \frac{dv}{dt} = \frac{V_T(\tau_s) - V_T(0)}{\tau_s} = \frac{0.632V_S}{R_S C_S}$

And $\quad R_S = \frac{V_S}{I_{TD}}$.

I_{TD} is the discharge current of the capacitor.

It is possible to use more than one resistor for $\frac{dv}{dt}$ and discharging as shown in the figure (d) below. The $\frac{dv}{dt}$ is limited by R_1 and C_S. $R_1 + R_2$ limits the discharging current such that $I_{TD} = \frac{V_S}{R_1 + R_2}$

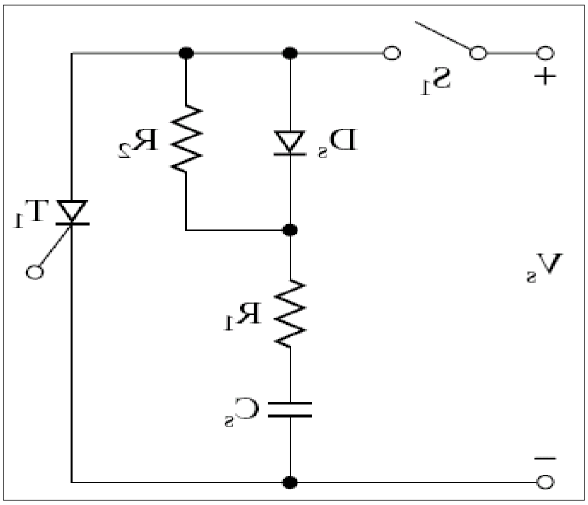


Fig. (d)

The load can form a series circuit with the snubber network as shown in figure (e) below. The damping ratio of this second order system consisting RLC network is given as,

$\delta = \dfrac{\alpha}{\omega_0} = \dfrac{R_S + R}{2}\sqrt{\dfrac{C_S}{L_S + L}}$, where L_S is stray inductance and L, R is load inductance and resistance respectively.

To limit the peak overshoot applied across the thyristor, the damping ratio should be in the range of 0.5 to 1. If the load inductance is high, R_S can be high and C_S can be small to retain the desired value of damping ratio. A high value of R_S will reduce discharge current and a low value of C_S reduces snubber loss. The damping ratio is calculated for a particular circuit R_S and C_S can be found.

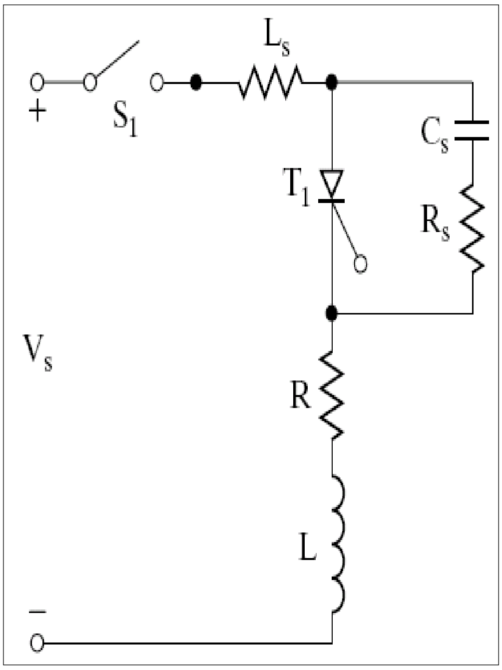
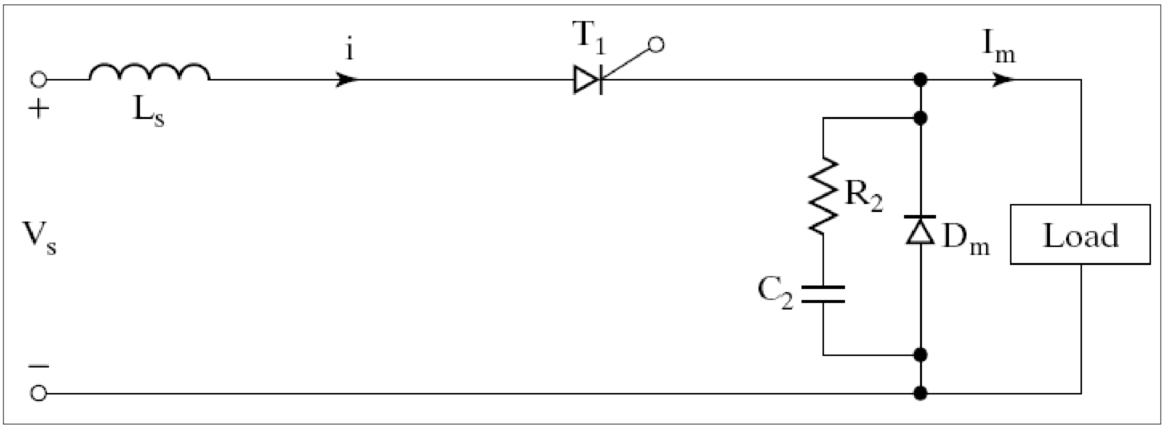


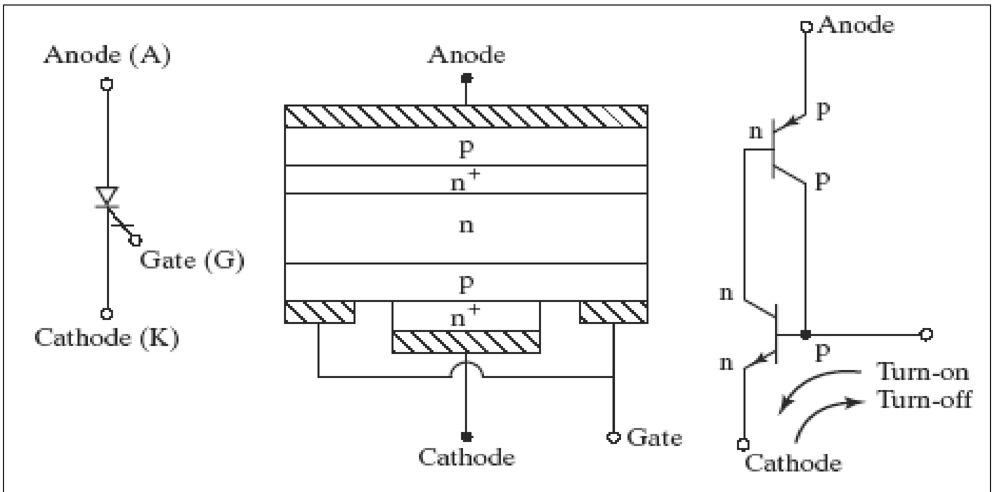
Fig. (e)

OPERATION OF $\frac{di}{dt}$ PROTECTION



Practical devices must be protected against high $\frac{di}{dt}$. As an example let us consider the circuit shown above, under steady state operation D_m conducts when thyristor T_1 is off. If T_1 is fired when D_m is still conducting $\frac{di}{dt}$ can be very high and limited only by the stray inductance of the circuit. In practice the $\frac{di}{dt}$ is limited by adding a series inductor L_S as shown in the circuit above. Then the forward $\frac{di}{dt} = \frac{V_S}{L_S}$.

GATE TURN-OFF THYRISTORS



(a) GTO symbol (b) Cross section (c) Equivalent circuit

A gate-turn-off thyristor (GTO) like an SCR can be turned on by applying a positive gate signal. However, it can be turned off by a negative gate signal. A GTO is a latching device and can be built with current and voltage ratings similar to those of an SCR. A GTO is turned on by applying a short positive pulse and turned off by a short negative pulse to its gate. The GTOs have advantages over SCRs.

Elimination of commutating components in forced commutation, resulting in reduction in cost, weight, and volume.

Reduction in acoustic and electro-magnetic noise due to the elimination of commutation chokes.

Faster turn-off permitting high switching frequencies and

Improved efficiency of converters.

In low power applications GTOs have the following advantages over bipolar transistors.

A higher blocking voltage capability.

A high ratio of peak controllable current to average current.

A high ratio of surge peak current to average current, typically 10:1.

A high on-state gain (anode current/gate current), typically 600; and

A pulsed gate signal of short duration.

Under surge conditions, a GTO goes into deeper saturation due to regenerative action. On the other hand, a bipolar transistor tends to come out of saturation.

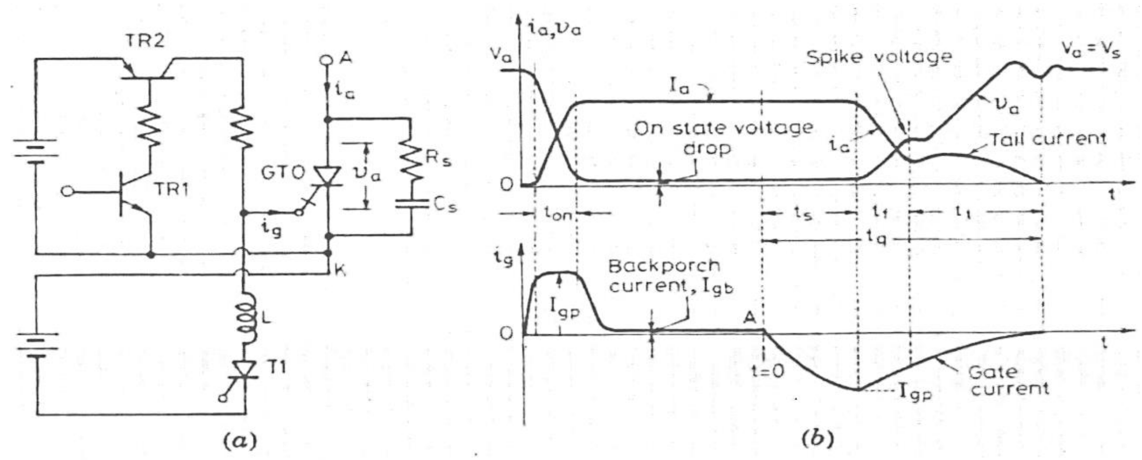
A GTO has low gain during turn-off, typically 6, and requires a relatively high negative current pulse to turn off. It has higher on-state voltage than that of SCRs. The on-state voltage of typical 550A, 1200V GTO is typically 3.4V.

Controllable peak on-state current I_{TGQ} is the peak value of on-state current which can be turned off by gate control. The off state voltage is reapplied immediately after turn-off and the reapplied dv/dt is only limited by the snubber capacitance. Once a GTO is turned off, the load current I_L, which is diverted through and charges the snubber capacitor, determines the reapplied dv/dt.

$$\frac{dv}{dt} = \frac{I_L}{C_s}$$

Where C_s is the snubber capacitance

SWITCHING CHARACTERISTICS OF GTO:



Gate turn-off thyristor (a) basic gate drive circuit and (b) switching characteristics.

$$t_q = t_s + t_f + t_t$$

Where,tq=Turn off time

t_s=storage time

t_f=fall time

t_t=tail time

During storage time t_s, the negative gate current rises to a particular value and prepares the GTO for turning off by flushing out the stored carriers. After t_s, anode current begins to fall rapidly and anode voltage starts rising.

As shown in the fig (b) the anode current falls to a certain value and then abruptly changes its rate of fall. This interval during which anode current falls rapidly is the fall time t_f and is of order 1µsec

At the time t= t_s+t_f, there is a spike in voltage due to abrupt change in anode current. After t_f , anode current ia and anode voltage va keep moving towards their turn off values for a time t_t called tail time.

NOTE:

- ✓ *For V-I Characteristics and Turn ON Switching Characteristics of GTO refer SCR Characteristics*
- ✓ *Turn ON Switching Characteristics of GTO is same as SCR Turn ON Characteristics, But TURN OFF Characteristics will be differ*

THYRISTOR COMMUTATION TECHNIQUES

In practice it becomes necessary to turn off a conducting thyristor. (Often thyristors are used as switches to turn on and off power to the load). The process of turning off a conducting thyristor is called commutation. The principle involved is that either the anode should be made negative with respect to cathode (voltage commutation) or the anode current should be reduced below the holding current value (current commutation).

The reverse voltage must be maintained for a time at least equal to the turn-off time of SCR otherwise a reapplication of a positive voltage will cause the thyristor to conduct even without a gate signal. On similar lines the anode current should be held at a value less than the holding current at least for a time equal to turn-off time otherwise the SCR will start conducting if the current in the circuit increases beyond the holding current level even without a gate signal. Commutation circuits have been developed to hasten the turn-off process of Thyristors. The study of commutation techniques helps in understanding the transient phenomena under switching conditions.

The reverse voltage or the small anode current condition must be maintained for a time at least equal to the TURN OFF time of SCR; Otherwise the SCR may again start conducting. The techniques to turn off a SCR can be broadly classified as

- Natural Commutation
- Forced Commutation.

NATURAL COMMUTATION (CLASS F)

This type of commutation takes place when supply voltage is AC, because a negative voltage will appear across the SCR in the negative half cycle of the supply voltage and the SCR turns off by itself. Hence no special circuits are required to turn off the SCR. That is the reason that this type of commutation is called Natural or Line Commutation. Figure 1.1 shows the circuit where natural commutation takes place and figure 1.2 shows the related waveforms. t_c is the time offered by the circuit within which the SCR should turn off completely. Thus t_c should be greater than t_q, the turn off time of the SCR. Otherwise, the SCR will become forward biased before it has turned off completely and will start conducting even without a gate signal.

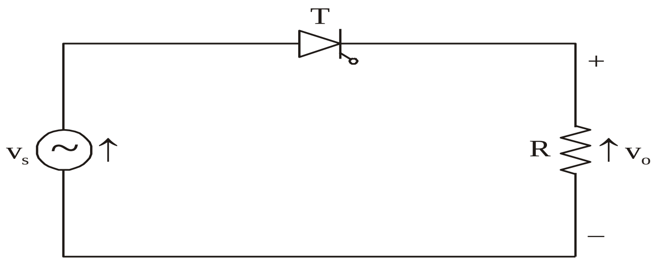


Fig. 1.1: Circuit for Natural Commutation

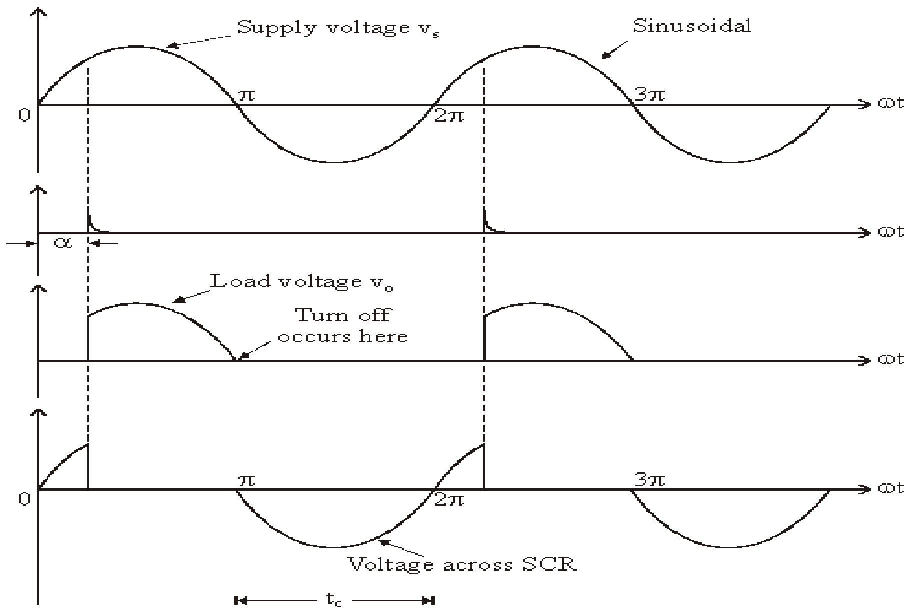


Fig. 1.2: Natural Commutation – Waveforms of Supply and Load Voltages (Resistive Load)

This type of commutation is applied in ac voltage controllers, phase controlled rectifiers and cyclo converters.

FORCED COMMUTATION

When supply is DC, natural commutation is not possible because the polarity of the supply remains unchanged. Hence special methods must be used to reduce the SCR current below the holding value or to apply a negative voltage across the SCR for a time interval greater than the turn off time of the SCR. This technique is called FORCED COMMUTATION and is applied in all circuits where the supply voltage is DC - namely, Choppers (fixed DC to variable DC), inverters (DC to AC). Forced commutation techniques are as follows:

- Self Commutation
- Resonant Pulse Commutation
- Complementary Commutation
- Impulse Commutation
- External Pulse Commutation.
- Load Side Commutation.
- Line Side Commutation.

SELF COMMUTATION OR LOAD COMMUTATION OR CLASS A COMMUTATION: (COMMUTATION BY RESONATING THE LOAD)

In this type of commutation the current through the SCR is reduced below the holding current value by resonating the load. i.e., the load circuit is so designed that even though the supply voltage is positive, an oscillating current tends to flow and when the current through the SCR reaches zero, the device turns off. This is done by including an inductance and a capacitor in series with the load and keeping the circuit under-damped. Figure 1.3 shows the circuit.

This type of commutation is used in *Series Inverter Circuit*.

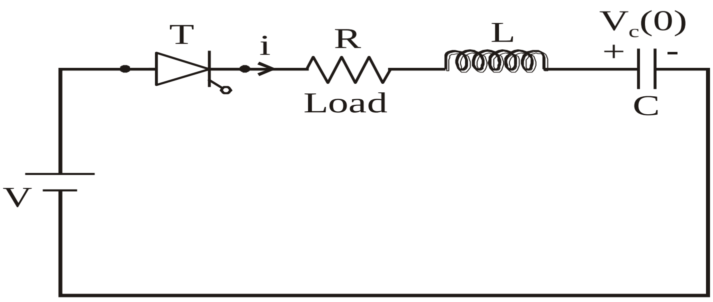


Fig. 1.3: Circuit for Self Commutation

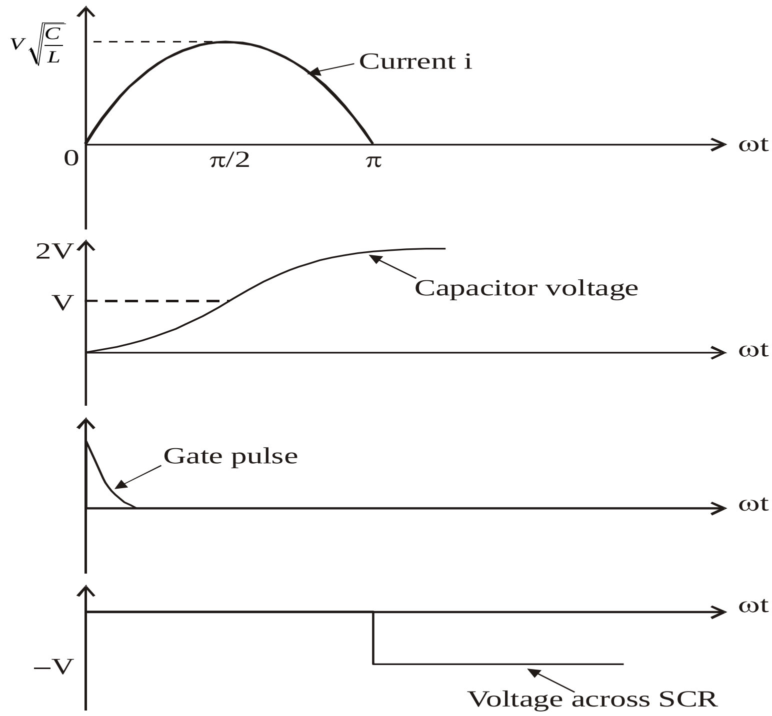


Fig. 1.5: Self Commutation – Wave forms of Current and Capacitors Voltage

RESONANT PULSE COMMUTATION (CLASS B COMMUTATION)

The circuit for resonant pulse commutation is shown in figure 1.12.

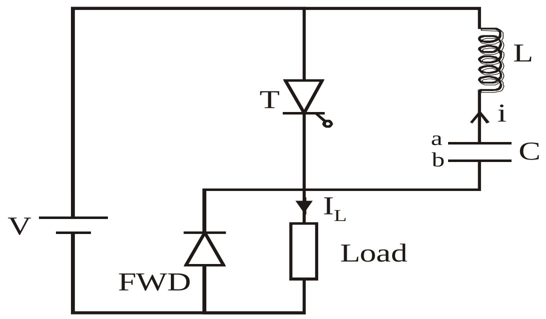


Fig. 1.12: Circuit for Resonant Pulse Commutation

This is a type of commutation in which a LC series circuit is connected across the SCR. Since the commutation circuit has negligible resistance it is always under-damped i.e., the current in LC circuit tends to oscillate whenever the SCR is on.

Initially the SCR is off and the capacitor is charged to V volts with plate 'a' being positive. Referring to figure 1.13 at $t = t_1$ the SCR is turned ON by giving a gate pulse. A current I_L flows through the load and this is assumed to be constant. At the same time SCR short circuits the LC combination which starts oscillating. A current 'i' starts flowing in the direction shown in figure. As 'i' reaches its maximum value, the capacitor voltage reduces to zero and then the polarity of the capacitor voltage reverses 'b' becomes positive). When 'i' falls to zero this reverse voltage becomes maximum, and then direction of 'i' reverses i.e., through SCR the load current I_L and 'i' flow in opposite direction. When the instantaneous value of 'i' becomes equal to I_L, the SCR current becomes zero and the SCR turns off. Now the capacitor starts charging and its voltage reaches the supply voltage with plate a being positive.

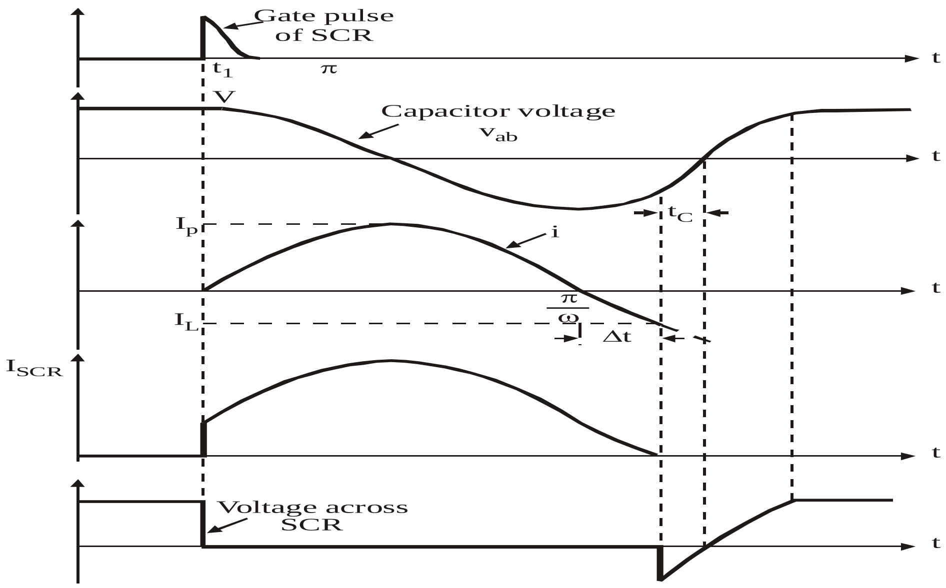


Fig. 1.13: Resonant Pulse Commutation – Various Waveforms

ALTERNATE CIRCUIT FOR RESONANT PULSE COMMUTATION

The working of the circuit can be explained as follows. The capacitor C is assumed to be charged to $V_C(0)$ with polarity as shown, T_1 is conducting and the load current I_L is a constant. To turn off T_1, T_2 is triggered. L, C, T_1 and T_2 forms a resonant circuit. A resonant current $i_c(t)$ flows in the direction shown, i.e., in a direction opposite to that of load current I_L.

$i_c(t) = I_p \sin\omega t$ (refer to the previous circuit description). Where $I_p = V_C(0)\sqrt{\frac{C}{L}}$ &

and the capacitor voltage is given by

$$v_c(t) = \frac{1}{C}\int i_C(t).dt$$

$$v_c(t) = \frac{1}{C}\int V_C(0)\sqrt{\frac{C}{L}}\sin\omega t.dt\,.$$

$$v_c(t) = -V_C(0)\cos\omega t$$

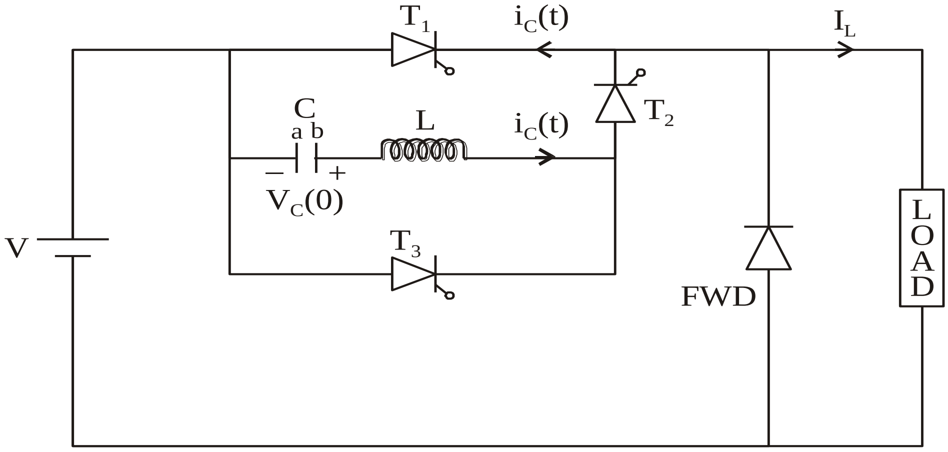


Fig. 1.16: Resonant Pulse Commutation – An Alternate Circuit

When $i_c(t)$ becomes equal to I_L (the load current), the current through T_1 becomes zero and T_1 turns off. This happens at time t_1 such that

$$I_L = I_p \sin\frac{t_1}{\sqrt{LC}}$$

$$I_p = V_C(0)\sqrt{\frac{C}{L}}$$

$$t_1 = \sqrt{LC}\sin^{-1}\left(\frac{I_L}{V_C(0)}\sqrt{\frac{L}{C}}\right)$$

and the corresponding capacitor voltage is

$$v_c(t_1) = -V_1 = -V_C(0)\cos\omega t_1$$

Once the thyristor T_1 turns off, the capacitor starts charging towards the supply voltage through T_2 and load. As the capacitor charges through the load capacitor current is same as load current I_L, which is constant. When the capacitor voltage reaches V, the supply voltage, the FWD starts conducting and the energy stored in L charges C to a still higher voltage. The triggering of T_3 reverses the polarity of the capacitor voltage and the circuit is ready for another triggering of T_1. The waveforms are shown in figure 1.17.

EXPRESSION FOR t_c

Assuming a constant load current I_L which charges the capacitor

$$t_c = \frac{CV_1}{I_L} \text{ seconds}$$

Normally $V_1 \approx V_C(0)$

For reliable commutation t_c should be greater than t_q, the turn off time of SCR T_1. It is to be noted that t_c depends upon I_L and becomes smaller for higher values of load current.

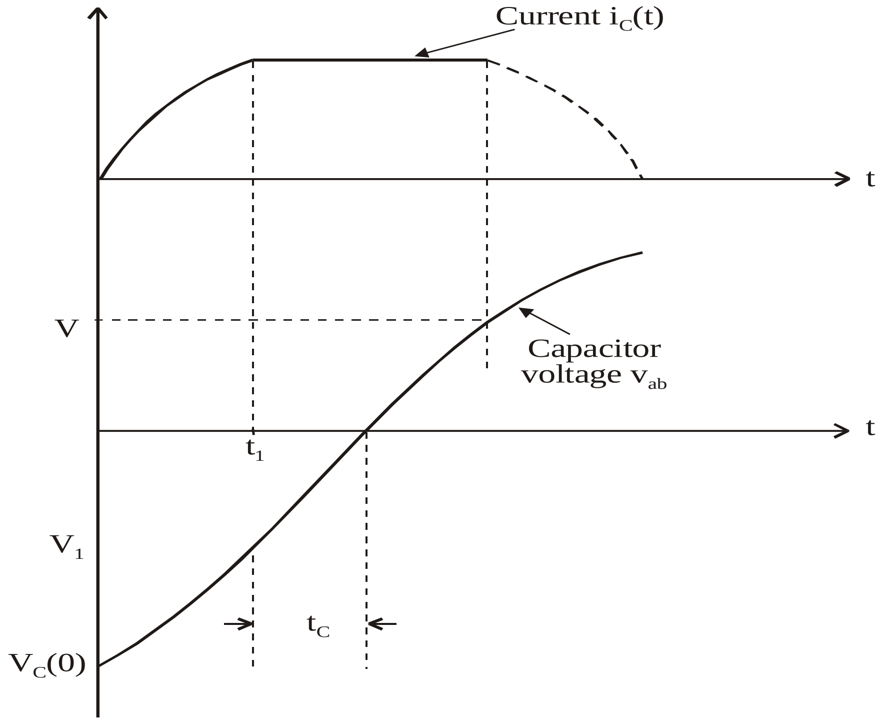


Fig. 1.17: Resonant Pulse Commutation – Alternate Circuit – Various Waveforms

RESONANT PULSE COMMUTATION WITH ACCELERATING DIODE

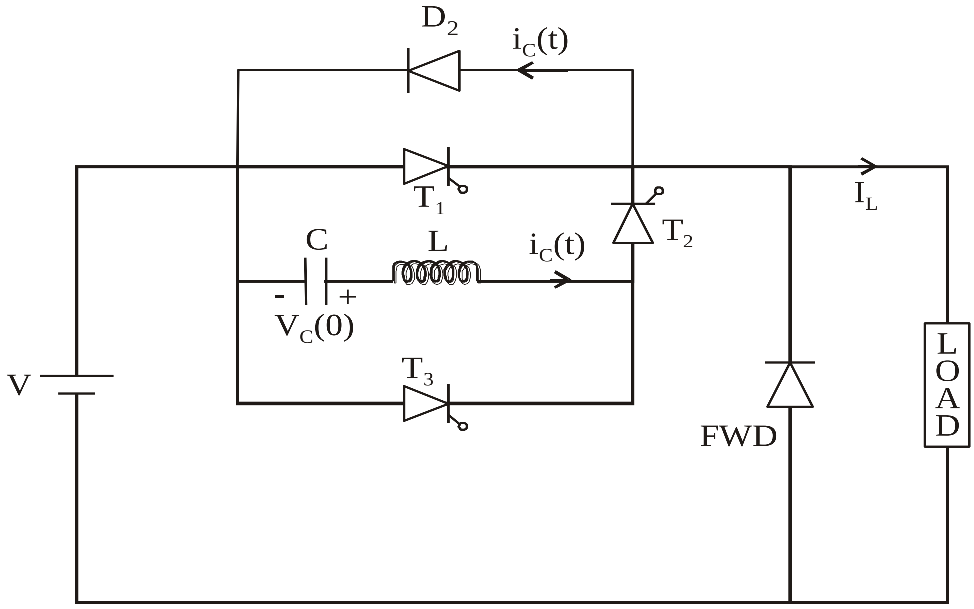


Fig. 1.17(a)

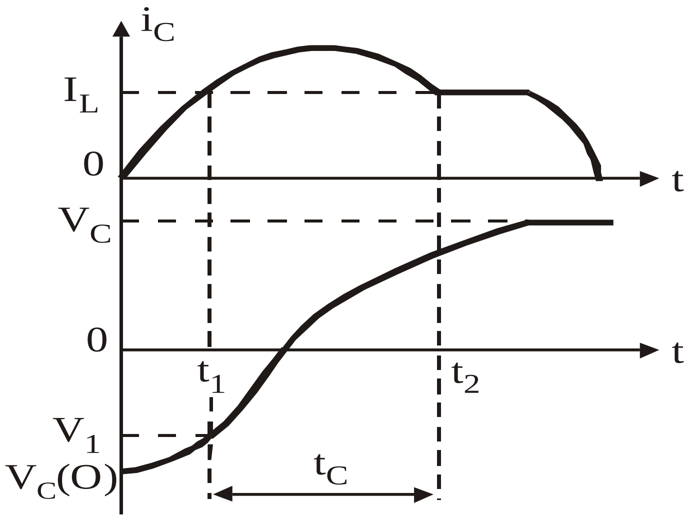


Fig. 1.17(b)

A diode D_2 is connected as shown in the figure 1.17(a) to accelerate the discharging of the capacitor 'C'. When thyristor T_2 is fired a resonant current $i_C(t)$ flows through the capacitor and thyristor T_1. At time $t = t_1$, the capacitor current $i_C(t)$ equals the load current I_L and hence current through T_1 is reduced to zero resulting in turning off of T_1. Now the capacitor current $i_C(t)$ continues to flow through the diode D_2 until it reduces to load current level I_L at time t_2. Thus the presence of D_2 has accelerated the discharge of capacitor 'C'. Now the capacitor gets charged through the load and the charging current is constant. Once capacitor is fully charged T_2 turns off by itself. But once current of thyristor T_1 reduces to zero the reverse voltage appearing across T_1 is the forward voltage drop of D_2 which is very small. This makes the thyristor recovery process very slow and it becomes necessary to provide longer reverse bias time.

From figure 1.17(b)

$$t_2 = \pi\sqrt{LC} - t_1$$

$$V_C(t_2) = -V_C(O)\cos\omega t_2$$

Circuit turn-off time $t_C = t_2 - t_1$

COMPLEMENTARY COMMUTATION (CLASS C COMMUTATION, PARALLEL CAPACITOR COMMUTATION)

In complementary commutation the current can be transferred between two loads. Two SCRs are used and firing of one SCR turns off the other. The circuit is shown in figure 1.21.

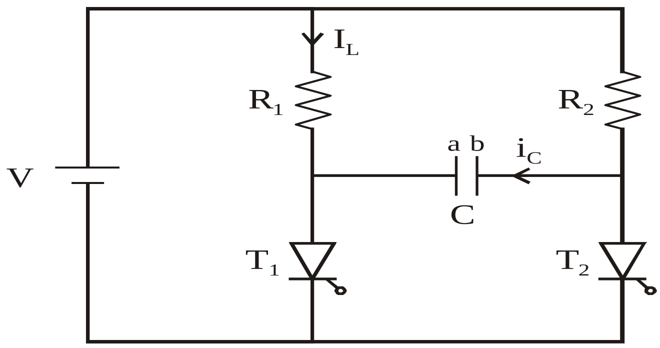
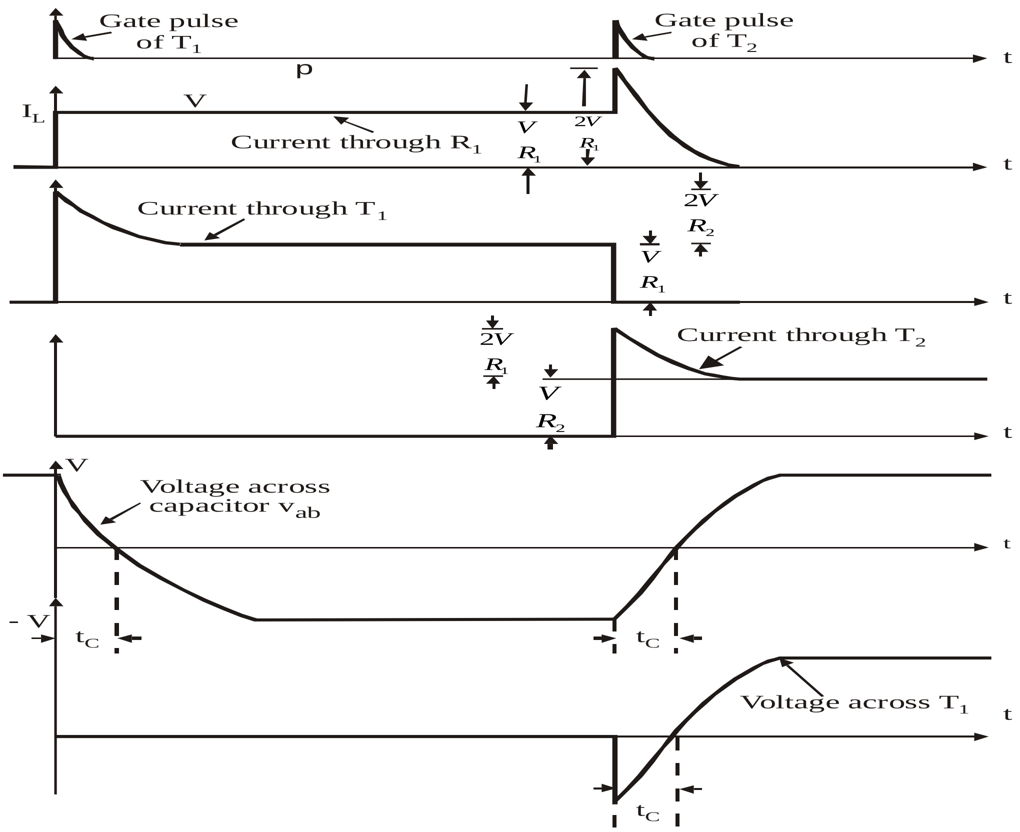


Fig. 1.21: Complementary Commutation

The working of the circuit can be explained as follows.

Initially both T_1 and T_2 are off; Now, T_1 is fired. Load current I_L flows through R_1. At the same time, the capacitor C gets charged to V volts through R_2 and T_1 ('b' becomes positive with respect to 'a'). When the capacitor gets fully charged, the capacitor current i_c becomes zero.

To turn off T_1, T_2 is fired; the voltage across C comes across T_1 and reverse biases it, hence T_1 turns off. At the same time, the load current flows through R_2 and T_2. The capacitor 'C' charges towards V through R_1 and T_2 and is finally charged to V volts with 'a' plate positive. When the capacitor is fully charged, the capacitor current becomes zero. To turn off T_2, T_1 is triggered, the capacitor voltage (with 'a' positive) comes across T_2 and T_2 turns off. The related waveforms are shown in figure



IMPULSE COMMUTATION (CLASS D COMMUTATION)

The circuit for impulse commutation is as shown in figure 1.25.

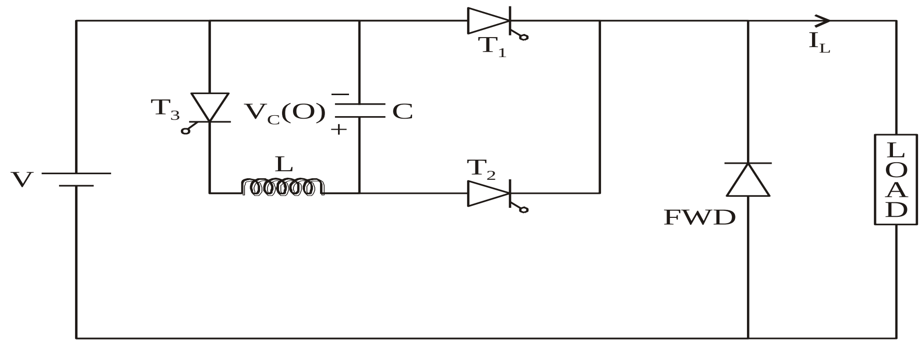


Fig. 1.25: Circuit for Impulse Commutation

The working of the circuit can be explained as follows. It is assumed that initially the capacitor C is charged to a voltage $V_C(O)$ with polarity as shown. Let the thyristor T_1 be conducting and carry a load current I_L. If the thyristor T_1 is to be turned off, T_2 is fired. The capacitor voltage comes across T_1, T_1 is reverse biased and it turns off. Now the capacitor starts charging through T_2 and the load. The capacitor voltage reaches V with top plate being positive. By this time the capacitor charging current (current through T_2) would have reduced to zero and T_2 automatically turns off. Now T_1 and T_2 are both off. Before firing T_1 again, the capacitor voltage should be reversed. This is done by turning on T_3, C discharges through T_3 and L and the capacitor voltage reverses. The waveforms are shown in figure

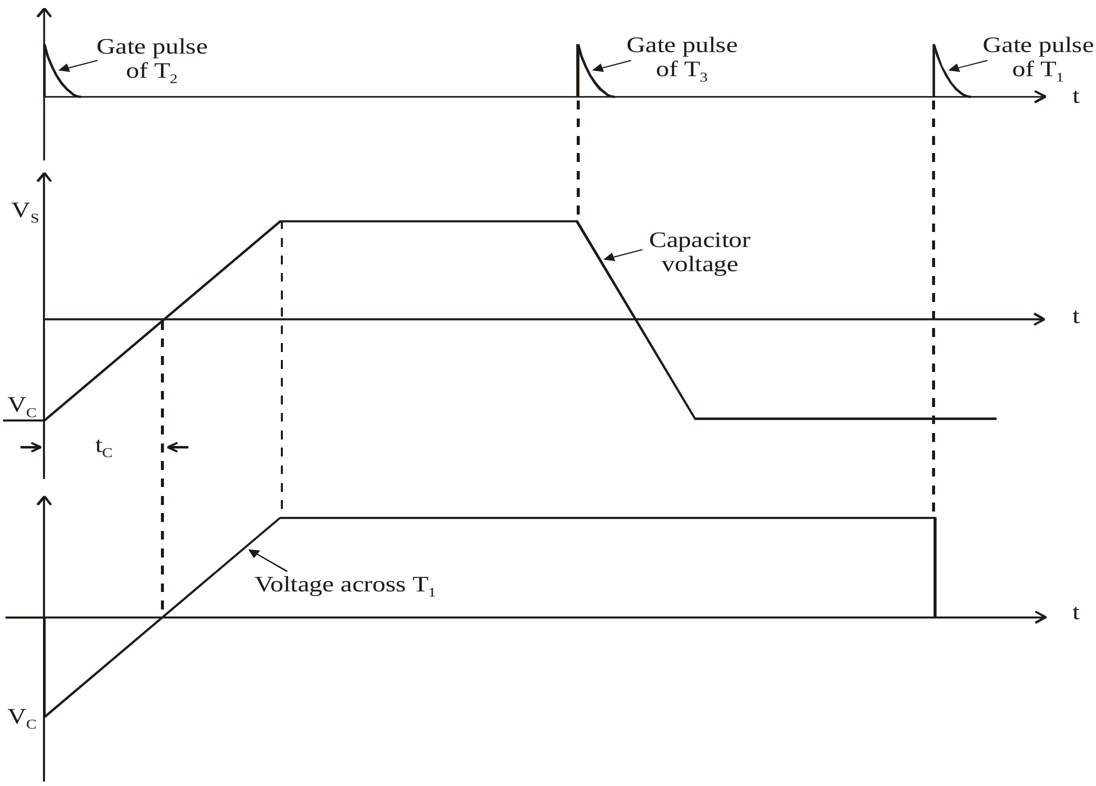


Fig. 1.26: Impulse Commutation – Waveforms of Capacitor Voltage, Voltage across T_1.

An alternative circuit for impulse commutation is shown in figure 1.27.

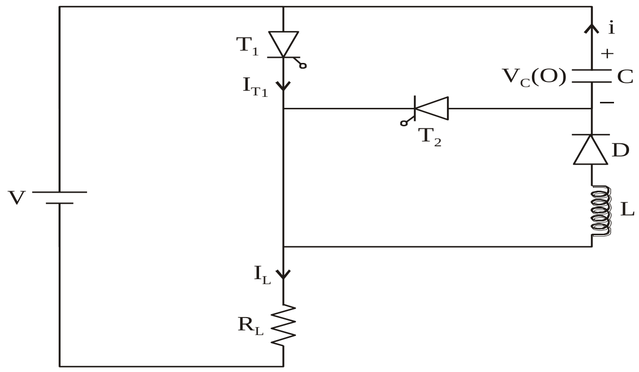


Fig. 1.27: Impulse Commutation – An Alternate Circuit

The working of the circuit can be explained as follows:

Initially let the voltage across the capacitor be $V_C(O)$ with the top plate positive. Now T_1 is triggered. Load current flows through T_1 and load. At the same time, C discharges through T_1, L and D (the current is 'i') and the voltage across C reverses i.e., the bottom plate becomes positive. The diode D ensures that the bottom plate of the capacitor remains positive.

To turn off T_1, T_2 is triggered; the voltage across the capacitor comes across T_1. T_1 is reverse biased and it turns off (voltage commutation). The capacitor now starts charging through T_2 and load. When it charges to V volts (with the top plate positive), the current through T_2 becomes zero and T_2 automatically turns off.

The related waveforms are shown in figure 1.28.

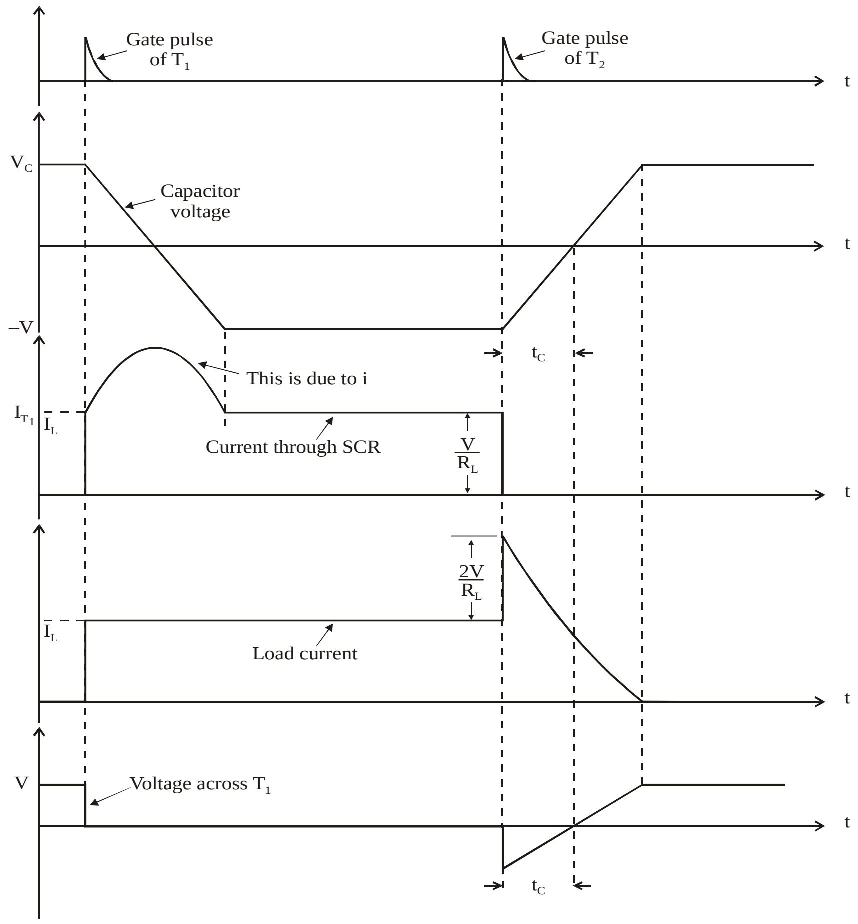


Fig. 1.28: Impulse Commutation – (Alternate Circuit) – Various Waveforms

EXTERNAL PULSE COMMUTATION (CLASS E COMMUTATION)

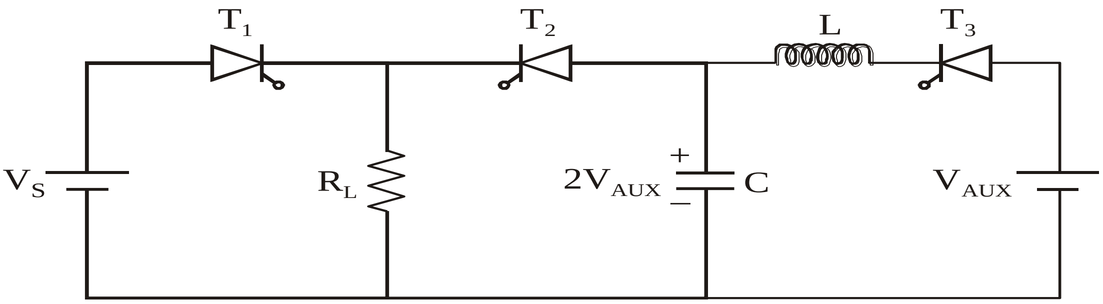


Fig. 1.34: External Pulse Commutation

In this type of commutation an additional source is required to turn-off the conducting thyristor. Figure 1.34 shows a circuit for external pulse commutation. V_S is the main voltage source and V_{AUX} is the auxiliary supply. Assume thyristor T_1 is conducting and load R_L is connected across supply V_S. When thyristor T_3 is turned ON at $t = 0$, V_{AUX}, T_3, L and C from an oscillatory circuit. Assuming capacitor is initially uncharged, capacitor C is now charged to a voltage $2V_{AUX}$ with upper plate positive at $t = \pi\sqrt{LC}$. When current through T_3 falls to zero, T_3 gets commutated. To turn-off the main thyristor T_1, thyristor T_2 is turned ON. Then T_1 is subjected to a reverse voltage equal to $V_S - 2V_{AUX}$. This results in thyristor T_1 being turned-off. Once T_1 is off capacitor 'C' discharges through the load R_L

LOAD SIDE COMMUTATION

In load side commutation the discharging and recharging of capacitor takes place through the load. Hence to test the commutation circuit the load has to be connected. Examples of load side commutation are Resonant Pulse Commutation and Impulse Commutation.

LINE SIDE COMMUTATION

In this type of commutation the discharging and recharging of capacitor takes place through the supply.

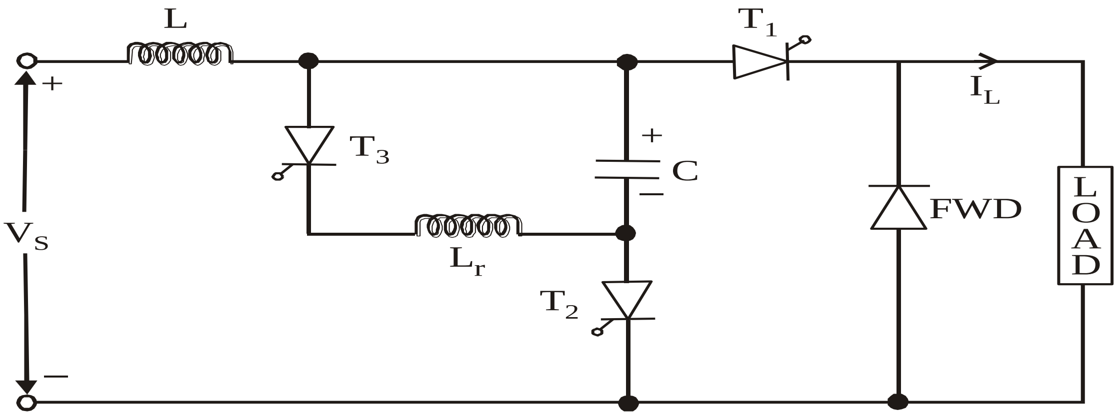


Fig.: 1.35 Line Side Commutation Circuit

Figure 1.35 shows line side commutation circuit. Thyristor T_2 is fired to charge the capacitor 'C'. When 'C' charges to a voltage of 2V, T_2 is self commutated. To reverse the voltage of capacitor to -2V, thyristor T_3 is fired and T_3 commutates by itself.

Assuming that T_1 is conducting and carries a load current I_L thyristor T_2 is fired to turn off T_1. The turning ON of T_2 will result in forward biasing the diode (FWD) and applying a reverse voltage of 2V across T_1. This turns off T_1, thus the discharging and recharging of capacitor is done through the supply and the commutation circuit can be tested without load.

PROBLEM

1. A UJT is used to trigger the thyristor whose minimum gate triggering voltage is 6.2V, The UJT ratings are: $\eta = 0.66$, $I_p = 0.5mA$, $I_v = 3mA$, $R_{B1} + R_{B2} = 5k\Omega$, leakage current = 3.2mA, $V_p = 14v$ and $V_v = 1V$. Oscillator frequency is 2kHz and capacitor C = 0.04μF. Design the complete circuit.

Solution

$$T = R_C C \ln\left[\frac{1}{1-\eta}\right]$$

Here,

$$T = \frac{1}{f} = \frac{1}{2\times10^3}$$, since $f = 2kHz$ and putting other values,

$$\frac{1}{2\times10^3} = R_C \times 0.04\times10^{-6} \ln\left(\frac{1}{1-0.66}\right) = 11.6k\Omega$$

The peak voltage is given as, $V_p = \eta V_{BB} + V_D$

Let $V_D = 0.8$, then putting other values,

$$14 = 0.66V_{BB} + 0.8$$

$$V_{BB} = 20V$$

The value of R_2 is given by

$$R_2 = \frac{0.7\left(R_{B2} + R_{B1}\right)}{\eta V_{BB}}$$

$$R_2 = \frac{0.7\left(5\times10^3\right)}{0.66\times20}$$

$$\therefore R_2 = 265\Omega$$

Value of R_1 can be calculated by the equation

$$V_{BB} = I_{leakage}\left(R_1 + R_2 + R_{B1} + R_{B2}\right)$$

$$20 = 3.2\times10^{-3}\left(R_1 + 265 + 5000\right)$$

$$R_1 = 985\Omega$$

The value of $R_{c(\max)}$ is given by equation

$$R_{c(\max)} = \frac{V_{BB} - V_p}{I_p}$$

$$R_{c(\max)} = \frac{20 - 14}{0.5 \times 10^{-3}}$$

$$R_{c(\max)} = 12 k\Omega$$

Similarly the value of $R_{c(\min)}$ is given by equation

$$R_{c(\min)} = \frac{V_{BB} - V_v}{I_v}$$

$$R_{c(\min)} = \frac{20 - 1}{3 \times 10^{-3}}$$

$$R_{c(\min)} = 6.33 k\Omega$$

2. Design the UJT triggering circuit for SCR. Given $-V_{BB} = 20V$, $\eta = 0.6$, $I_p = 10\mu A$, $V_v = 2V$, $I_v = 10mA$. The frequency of oscillation is 100Hz. The triggering pulse width should be $50\mu s$.

Solution

The frequency f = 100Hz, Therefore $T = \frac{1}{f} = \frac{1}{100}$

From equation $T = R_c C \ln\left(\frac{1}{1-\eta}\right)$

Putting values in above equation,

$$\frac{1}{100} = R_c C \ln\left(\frac{1}{1-0.6}\right)$$

$$\therefore R_c C = 0.0109135$$

Let us select $C = 1\mu F$. Then R_c will be,

$$R_{c(\min)} = \frac{0.0109135}{1 \times 10^{-6}}$$

$$R_{c(\min)} = 10.91 k\Omega.$$

The peak voltage is given as,

$$V_p = \eta V_{BB} + V_D$$

Let $V_D = 0.8$ and putting other values,

$$V_p = 0.6 \times 20 + 0.8 = 12.8V$$

The minimum value of R_c can be calculated from

$$R_{c(\min)} = \frac{V_{BB} - V_v}{I_v}$$

$$R_{c(\min)} = \frac{20 - 2}{10 \times 10^{-3}} = 1.8k\Omega$$

Value of R_2 can be calculated from

$$R_2 = \frac{10^4}{\eta V_{BB}}$$

$$R_2 = \frac{10^4}{0.6 \times 20} = 833.33\Omega$$

Here the pulse width is give, that is 50μs.

Hence, value of R_1 will be,

$$\tau_2 = R_1 C$$

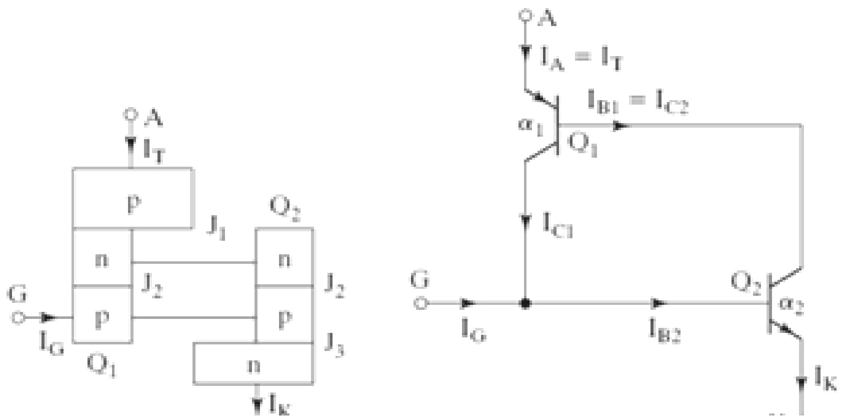
The width $\tau_2 = 50\mu\sec$ and $C = 1\mu F$, hence above equation becomes,

$$50 \times 10^{-6} = R_1 \times 1 \times 10^{-6}$$

$$\therefore R_1 = 50\Omega$$

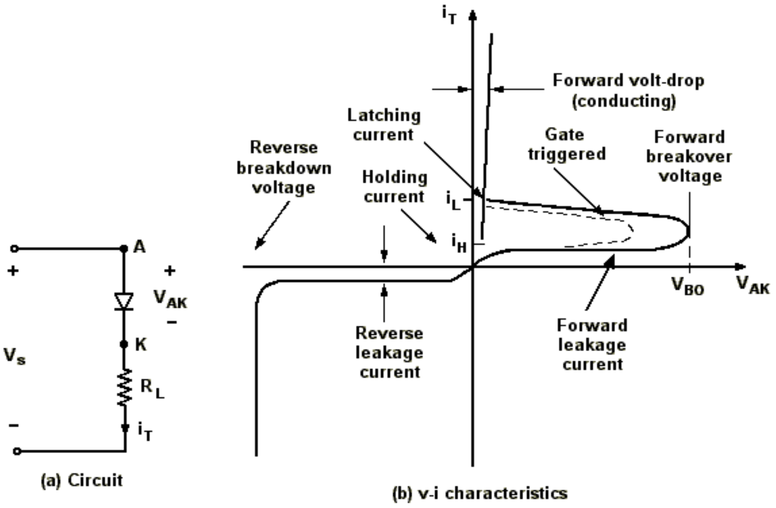
Thus we obtained the values of components in UJT triggering circuit as,

$R_1 = 50\Omega$, $R_2 = 833.33\Omega$, $R_c = 10.91k\Omega$, $C = 1\mu F$.

	UNIT I- SWITCHING POWER SUPPLIES PART - A	BL
1.	**What is a SCR?** A Silicon-Controlled Rectifier (SCR) is a three terminal, three-junction semiconductor device that acts as a true electronic switch. It is a unidirectional device. SCRs can be triggered normally only by currents going into the gate.	BL1
2.	**Define break over voltage of SCR.** Break over voltage is defined as the minimum forward voltage (gate being open) at which the SCR starts conducting heavily. Commercially available SCRs have breakover voltages from about 50 V to 500 V.	BL2
3.	**Draw the two-transistor model of a SCR. (MAY 2016)**  	BL1
4.	**List the applications of SCR.** (i) It can be used as a speed controller in DC and AC motors (ii)It can be used as switch in inverter. (iii) It can be used as switch in converter. (iv)It is used in battery charging. (v) It is used for phase control and heater control.(vi)It is used in light dimming control circuits.	BL1
5.	**What is meant by latching current & holding current? (Nov 2020)** The latching current is the minimum current, above which the SCR gets conducted into the forward conduction state. So current higher than the latching current is to be applied to the SCR to make it to conduct in the forward conducting region.	BL2
6.	**What is a TRIAC?** TRIAC is a three terminal bi-directional semiconductor-switching device. It can conduct in both the directions for any desired period. In operation it is	BL1

equivalent to two SCR's connected in antiparallel. Next to SCR it is the widely used device for power control.

7. Draw the VI characteristics of a SCR and mark important points. **BL1**



8. Distinguish between SCR and TRIAC. (Dec 2014) **BL4**

S.No	SCR	TRIAC
1	It is unidirectional device	It is a bidirectional device
2	It has fast turn off time	It has comparatively longer turn off time
3	It can be used to switch AC supply frequencies upto few KHz	It can be used to switch AC supply frequencies upto 40Hz only
4	It is triggered by positive voltage applied to the gate	It is triggered by either positive or negative voltage applied to the gate.

9. What are the advantages of IGBTs? (Nov 2016) (Nov 2017) (Nov 2022) **BL2**

The main advantages of using the Insulated Gate Bipolar Transistor over other types of transistor devices are its high voltage capability, low ON-resistance, ease of drive, relatively fast switching speeds and combined with zero gate drive current makes it a good choice for moderate speed, high voltage applications

10. Define pinch off voltage of MOSFET. (May 2012) **BL2**

In the drain characteristics as V_{ds} increases at one point I_d remains constant and this current is referred to as drain source saturation current I_{dss}. At this

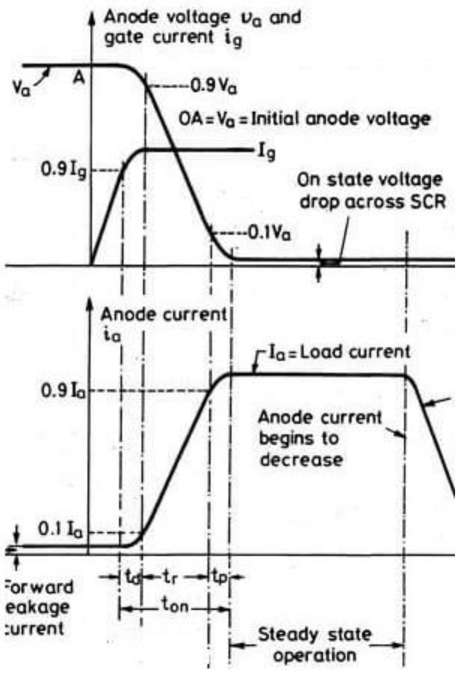
	point the channel appears as pinch off. The drain source voltage corresponding to this point is called pinch off voltage.	
11.	**What are the drawbacks of GTO? (Nov 2012)** In GTO, • ON state voltage drop and the associated loss is more. • Gate drive circuit losses are more. • Triggering gate current is higher as compared to the current required for a conventional SCR. • In GTO, magnitude of latching and holding current is more.	**BL4**
12.	**What is the use of snubber circuit? (June 2013) (Nov 2013)(DEC 2015) (Nov 2016)** Snubber circuit is used to prevent failure due to dv/dt. Snubber uses a small resistor (R) in series with a small capacitor (C). This combination can be used to suppress the rapid rise in voltage across a thyristor, preventing the erroneous turn-on of the thyristor.	**BL2**
13.	**List the various forced commutation techniques used to turn-off SCR.** The various forced commutation techniques used to turn-off SCR are: (i)Self-commutation (ii) Resonant pulse commutation (iii) Complementary commutation (iv)Impulse commutation (v)External commutation (vi)Load commutation.	**BL1**
14.	(i)	**BL2**
15.	**Mention the advantages of 'RC' triggering over 'R' triggering.** The limitation of resistance firing circuit can be overcome by the RC triggering circuit which provides the firing angle control from 0 to 180 degrees. By changing the phase and amplitude of the gate current, a large variation of firing angle is obtained using RC circuit.	**BL4**
16.	**How is di/dt and dv/dt protection provided in SCR? (Nov 2018)** **i. di/dt is the rate of change of anode current** Protection against rate change of anode current in a device is necessary because it may damage the device if the rise in current is faster. This change in current can be reduced by connecting inductor in series with the thyristor. The inductance L opposes the high di/dt variations and protect	**BL2**

	the device. **ii. dv/dt is the rate of change of voltage in SCR.** Protection against high rate of voltage rise is necessary because if SCR is not in conduction mode and is forward biased mode then high dV/dt may trigger the SCR, and SCR will not be able to serve its purpose. To protect the thyristor against false turn ON or against high dv/dt a "Snubber Circuit" is used. The snubber Circuit is a series combination of resistor 'R' and capacitor 'C' which is connected across the device.	
17.	**Mention the advantages of IGCT over IGBT.** Some Useful advantages of IGCT over IGBT are: • IGBT has high switching frequency compared to IGCT. • IGBT lifetime is ten times greater than IGCT. • IGCT has low ON state voltage drop. • IGCT are made like normal disk devices which has high electro-magnetic emission. They also have cooling problems.	**BL4**
18.	**Mention the merits and demerits of GTO. (Nov 2018)** **Merits:** o The gate turn OFF thyristor (GTO) has more di/dt ratings at turn ON. o It has faster turn OFF permitting high switching frequencies. o The commutation circuit is not required, hence it reduced size, weight and cost. o It has high efficiency. o It has high capability of blocking voltage. **Demerits:** o In a gate turn OFF thyristor (GTO), ON state voltage drop and the associated loss is more. o Gate drive circuit losses are more. o In a gate turn OFF thyristor (GTO), magnitude of latching and holding current is more. o Triggering gate current is higher as compared to the current required for a conventional SCR.	**BL4**

19.	**Mention the advantages of GTO over SCR. (April 2019) The gate turn OFF thyristor (GTO) has more di/dt ratings at turn ON.** • It has faster turn OFF, permitting high switching frequencies. • The commutation circuit is not required, hence it reduced size, weight, and cost. • It has high efficiency. • It has high capability of blocking voltage.	**BL4**
20.	**List the different methods to turn on SCR. (Nov 2019)** **Triggering (Turn on) Methods of Thyristor:** ▪ Forward Voltage Triggering. ▪ Thermal or Temperature Triggering. ▪ Radiation or Light triggering. ▪ dv/dt Triggering. ▪ Gate Triggering.	**BL1**
21.	**State the advantages of IGBT over MOSFET. (Nov 2021)** The main advantages of IGBT over a Power MOSFET are: a. Low driving power and a simple drive circuit due to the input MOS gate structure. b. It can be easily controlled as compared to current controlled devices (thyristor, BJT) in high voltage and high current applications with lower conduction losses. c. They have on-state voltage and current density comparable to a power BJT with higher switching frequency.	**BL2**
22.	**Define threshold voltage of power MOSFET. (Nov 2019)** Threshold voltage is the voltage applied between gate and source of a MOSFET that is needed to turn the device on for linear and saturation regions of operation. Threshold voltage, V_{gs}(th), is the minimum gate-source electrode bias required to form a conducting channel between the source and the drain regions. It is usually measured at a drain-source current of 250µA.	
23.	**What do you mean by second breakdown in power BJT? (Nov 2020)** Secondary Breakdown appears on the o/p characteristics of the BJT as a	**BL2**

precipitous drop in the collector emitter voltage at large collector currents. The collector voltage drop is often accompanied by significant rise in the collector current & a substantial increase in the power dissipation. Most importantly this dissipation is not uniformly spread over the entire volume of the device but is concentrated in highly localized regions. This localized heating is a combined effect of the intrinsic non uniformity of the collector current density distribution across the cross section of the device & the negative temperature. Coefficient of resistively of minority carrier devices which leads to the formation of "current filaments" by a positive feedback mechanism. Secondary breakdown can be avoided by using power transistor in safe operating area.

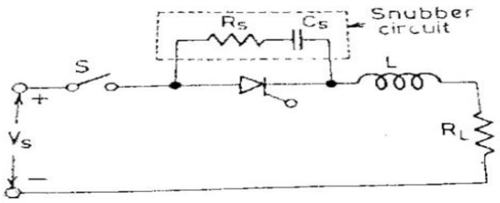
24. Draw the turn-on characteristics of SCR and mark the timings t_d, t_r and t_{on}. (Nov-Dec 2021) **BL2**



25. Mention the applications of GTO, IGCT, IGBT. **BL4**

GTO	IGCT	IGBT
• High power drives • Static compensators • Continuous supply sources • Induction heating sources	• High power drives • Supply inverter sources for DC transmissions • Big frequency	• Choppers • Continuous supply sources • Static compensators and active filters • Switching sources

	converters	
26.	**Justify why TRIAC is not popular as compared to SCR. (Nov 2022)** Triacs are not popular due to following reasons: 1. Commutation of Triac fails for inductive loads. Hence control of voltage is lost. 2. It has (dv/dt) rating lower than SCR. 3. Triac has low voltage and current ratings as compared to SCR. 4. Triac are not useful for DC applications, whereas SCR's are useful for both AC and DC applications. 5. We need to be careful about the triggering circuit as it can be triggered in either direction.	**BL4**
	PART-B	
1.	Explain the switching model, equivalent circuit and switching characteristics of power MOSFET.**(MAY 2015) (Nov-Dec 2016)**	**BL2**
2.	Explain the static and switching characteristics of IGBT and MOSFET? **(DEC-2012)(DEC 2014)(JUN 2014) (Nov 2017)(may 2019) (Nov 2022)**	**BL2**
3.	Explain why Triac is rarely used in I quadrant with negative pulse and in III quadrant with positive pulse. **(NOV / DEC 2018) (May 2016) (May 2019)**	**BL4**
4.	Explain various types of commutation circuit for SCR. **(DEC 2015) (NOV 2019)**	**BL4**
5.	Describe the basic structure of IGBT and explain its working. Give its equivalent circuit and explain the turn ON and turn OFF process. **(NOV 2013) (MAY 2015)**	**BL3**
6.	Explain the operation of SCR using two transistor analogy? **(JUN 2014)(DEC 2015)(May 2016)(Nov –Dec 2020)**	**BL3**
7.	Explain the turn OFF methods and turn OFF characteristics of SCR. **(DEC 2014)(Nov-Dec 2016)(Nov Dec 2021)**	**BL2**

8.	Explain the construction, static and switching characteristics of SCR.**(Nov 2022)**	**BL2**
9.	Explain the working of a current commutation technique. **(May 2018)**	**BL2**
10.	Describe the UJT triggering circuit with neat sketch. **(May 2018) (Nov 2020)**	**BL2**
11.	i. Explain the steady state and switching characteristics of MOSFET with diagrams.	**BL2**
12.	Explain the construction and switching characteristics of IGCT.	**BL2**
13.	Discuss the basic structure and working of power GTO. (6)	**BL2**
14.	With help of suitable diagram explain the dynamic characteristics of Power diode **(Nov 2020)**	**BL2**
15.	Explain the four modes of operation of a TRIAC. Compare their sensitivity. (**Nov 2021**)	**BL4**
	PART C	
1.	Figure shows a thyristor controlling the power in a load resistance RL. The supply voltage is 240V dc and the specified limits for di/dt and dv/dt for the SCR are 50A/μsec and 300V/μsec respectively. Determine the values of the di/dt inductance and the snubber circuit parameters Rs and Cs. **(Nov 2020)** 	**BL5**
2.	Design a snubber circuit to protect the SCR from overvoltage and overcurrent effect. **(May 2018) (NOV 2019)**	**BL6**

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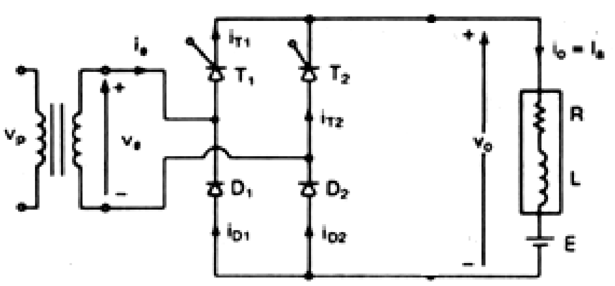
	UNIT II - INVERTERS **PART A**	**BL**
1.	**What is a controlled rectifier?** The output voltage of thyristor rectifier is varied by controlling the delay or firing angle of thyristors. Therefore thyristor rectifiers are called as controlled rectifiers.	**BL2**
2.	**Define delay angle or firing angle.** The delay angle is defined as the angle between the zero crossing of the input voltage and the instant the thyristor is fired. the angle measured from	**BL1**

	the angle that gives maximum average output voltage to the angle when the SCR is triggered or fired by gate pulse.	
3.	**Mention two functions of freewheeling diode.** (a)Reduction of ripple voltage in d.c terminals (b) Prevents reversal of load voltage except for small diode Voltage-drop(c) It transfers the load current away from the main rectifier, thereby allowing all its thyristors to regain their blocking states.	**BL2**
4.	**Explain about the two-quadrant operation?** A full converter is a two -quadrant converter and the polarity of its output voltage can be either positive or negative Current always positive. Many applications use three - phase converters, for two - quadrant operation in AC power supplies where the objective is to produce sinusoidal current waveforms on the AC side	**BL2**
5.	**Define form factor and ripple factor.** Form factor (FF) of a waveform is defined as the ratio of, rms value of waveform, to the average value of the waveform. Form factor ff = $\frac{E_{rms}}{E_{dc}}$ Ripple factor may be defined as the ratio of the root mean square (rms) value of the ripple voltage to the absolute value of the DC component of the output voltage, usually expressed as a percentage. Ripple factor = $(ff^2 - 1)^{1/2}$	**BL1**
6.	**Draw the power circuit diagram of half controlled thyristors-controlled rectifier.** 	**BL3**
7.	**What is the difference between symmetric and asymmetric**	**BL4**

	semiconductor configuration? (May 2017) (Nov 2022) In symmetric semiconductor, each leg contains one SCR and one diode. In asymmetric semi converter, one leg contains two SCRs and the other leg contains two diodes.	
8.	**What is Dual converter? Mention its functional mode of operation? (June 2014)** A dual converter can be of a single phase or a three phase. A dual converter consists of two bridges consisting of thyristors in which one for rectifying purpose where alternating current is converted to direct current which can be given to load. Other bridge of thyristors is used for converting D.C to A.C.	**BL2**
9.	**Explain the inversion mode of fully controlled bridge rectifier? (Nov-Dec 2012) (May-June 2012)** When firing angle α is greater than 90˚, then the voltage is maximum in negative is called inversion mode. Power is feedback from load to source in this mode.	**BL3**
10.	**Define the input power factor. (May 2017) (Nov 2022)** The input power factor is defined as the ratio of the total mean input power to the total RMS input volt-amperes. $PF = \frac{V_1 I_1 \cos\varphi 1}{V_{rms} I_{rms}} = \frac{I_1}{I_{rms}} * cos\varphi 1$ where, V_1 = phase voltage, I_1 = fundamental component of the supply current, φ_1 = input displacement angle, I_{rms} = supply rms current.	**BL1**
11.	**Mention the effect of source inductance in converters.** The source inductance causes the outgoing and incoming SCRs to conduct together. When the source inductor increases, the overlap angle increases and as a consequence the average output voltage decreases.	**BL2**
12.	**What is overlap angle? (Dec 2015)** When both incoming and outgoing thyristors conduct simultaneously causes short circuit of dc load. The period at which this occurs is referred as overlap period and angle corresponding to it is known as overlap angle.	**BL1**
13.	**Compare single phase converter and three phase converter.**	**BL4**

S.No	**Single phase converter**	**Three phase converter**

		1	Ripple content in output is more.	Ripple content in output is less.	
		2	Supply current waveform is square	Supply current waveform is quasi-square	
		3	Less complex and easy control	Complex control and implementation	
		4	Supply and load derating is higher	Supply and load derating is less.	
14.	**Compare half controlled (Semi converter) and fully controlled rectifier. (April May 2018)**				**BL4**

S .No	**Half controlled converter**	**Fully controlled converter**
1.	It uses one thyristor.	It uses four thyristor
2.	One quadrant converter	Two quadrant converter
3.	At time one thyristor is conducting	At a time two thyristor are conducting

15. **Classify the different types of controlled rectifier.(Nov-Dec 2016/ April 2019)** **BL1**

Classification of controlled rectifier are as follows:

i) Semi controlled or half controlled rectifier.

It can be further classified into symmetrical and asymmetrical configuration.

ii)Fully controlled rectifier

It can be further classified into midpoint and bridge type configuration.

16. **Write down the voltage equation for single phase semi converter.** **BL3**

Voltage equation of single-phase semi converter is expressed as

$$V_{dc} = \frac{2}{2\pi}\int_{\alpha}^{\pi} V_m sin\omega t.\, d(\omega t) = \frac{V_m}{\pi}(1 + cos\alpha)$$

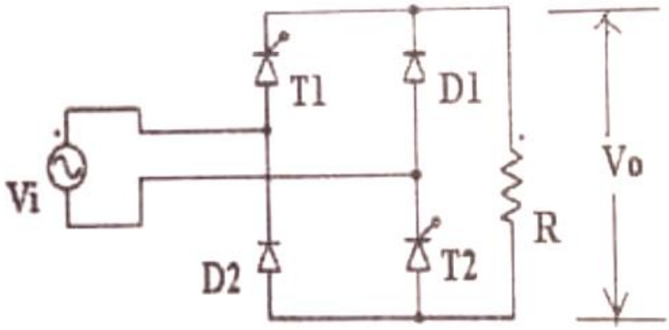
where V_{dc} – Output voltage, V_m – peak value of input voltage & α – firing angle.

17. **Write the relation between firing angle and extinction angle in single phase fully controlled rectifier when operating with RL load.(Nov 2019)** **BL2**

	The relation between firing angle 'α' and extinction angle 'β' in single phase fully controlled rectifier when operating with RL load can be expressed with the help of output dc voltage 'V_o' and peak ac voltage 'V_m' as, $$V_o = \frac{V_m}{\pi}(\cos\alpha - \cos\beta)$$ for discontinuous load current operation, $\pi < \beta < (\pi+\alpha)$.	
18.	**Define THD. (May-June 2012) (Nov 21)** The total harmonic distortion or THD, of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency $$THD = \frac{\sqrt{V_1^2 + V_2^2 + V_3^2 + \cdots V_n^2}}{V_1}$$ where, V_1 –fundamental voltage, V_n- voltage of nth harmonic component	**BL1**
19.	**Why is power factor of semi converter better than full converter? (Nov-Dec 2012)(Dec 2014)(DEC 2015/2018)** Semi converter has freewheeling diode in addition to 2 thyristors and 2 diodes. Hence the usage of freewheeling diode increases the power factor of semi converter by providing continuous load current.	**BL2**
20.	**Mention the output ripple frequency of 2, 3 and 6 - pulse converter. (Nov 19)** The ripple frequency is normally twice the supply frequency. The pulsed converter converts ac input voltage into dc voltage which consist of ripples. The ripple frequency of the output voltage is always equal to number of output pulses of the converter. Hence for 2 pulse converter the ripple frequency is 2, for 3 pulse it is 3 and for 6 pulse is 6.	**BL4**
21.	**Define Distortion factor. (Nov 21)** It is the ratio of the fundamental component to the r.m.s value of the waveform. $$DF = \frac{V_{01}}{V_{0r}}$$ Distortion factor and total harmonic distortion are related as	**BL1**

	THD = $\sqrt{\frac{1}{DF^2}} - 1$	
22.	**Mention the disadvantages of dual converter with circulating current mode of operation? (Nov 2013/ NOV 2018)** The disadvantages of the circulating current mode of operation is that a current flows continuously in the dual converter circuit even at times when the load current is zero. Hence, we should connect current limiting inductors (reactors) to limit the peak circulating current within specified value. The circulating current flowing through the series inductors gives rise to increased power losses, due to dc voltage drop across the series inductors which decreases the efficiency. Also, the power factor of operation is low. The current limiting series inductors are heavier and bulkier which increases the cost and weight of the dual converter.	**BL4**
23.	**Differentiate the device turn off time from the circuit turn-off time. (Nov 2020)** Device turn off time is the time required by the thyristor to regain its forward blocking capabilities from the time it is switched off, one of the conditions required for it to turn off is that it should have reverse biased voltage applied across it and the time duration for which it is done is called circuit turn off time.	**BL4**
24.	**Define pulse number (Nov 2020)** Pulse number is defined as the number of pulses in the dc output voltage within one time period of the ac source voltage. In high-power applications, ac–dc converters based on the concept of multi pulse, namely, 12, 18, 24, 30, 36, 48 pulses are used to reduce the harmonics in ac supply currents.	**BL1**
25.	**What is the function of freewheeling diode and state its advantages? (Nov 2016) (MAY 2016/2017/2018/2019)** i) Increase DC voltage for a given firing angle due to the elimination of negative portions of the instantaneous dc waveform in a SCR phase-controlled converter ii) Will reduce the generated ripple voltage on the DC side of a SCR phase-controlled converter, thereby reducing the filtering	**BL2**

	requirements. iii) Will improve the input PF in an SCR phase-controlled converter due to ending the input current waveform earlier by permitting internal free-wheeling.	
	PART-B	
1.	Explain the operation of 3 phase fully controlled bridge rectifier with relevant waveforms. **(JUN 2012) (Nov 2017) (APR 2019) (NOV 2019) (Nov 2022)**	**BL2**
2.	Explain the operation of 3 phase half-controlled bridge rectifier or semi converter **(DEC 2012)**	**BL2**
3.	Explain the functional modes of dual converter with necessary diagrams. **(Nov-Dec 2016) (May 2017) (Nov 2017) (Nov 2022)**	**BL2**
4.	A single-phase fully controlled bridge converter is connected to RLE load. The source voltage is 230 V, 50 Hz. The average load current of 10A continuous over the working range. For R= 0.4 Ω and L = 2mH, Compute (i) firing angle for E = 120V (ii) firing angle for E = -120V. **(Nov 21)**	**BL5**
5.	Explain the operation of single phase fully controlled rectifier with R load with neat waveforms in both rectification and inversion mode. **(May 2016/2017) (Nov 2020)**	**BL4**
6.	Explain the principle of operation of single-phase dual converter with neat power circuit diagram. **(Nov 21)**	**BL2**
7.	Discuss the effect of series inductance on the performance of single-phase full converter by clearly indicating the conduction of various thyristors during one cycle. **(June 2013) (Jun 2014) (NOV 2019)**	**BL3**
8.	Describe the working of a single-phase full converter in the rectifier mode with RL Load. Discuss how one pair of SCRs is commutated by an incoming pair of SCRs. Illustrate your answer with the waveforms of source voltage, load voltage and source current. Assume continuous conduction. Also derive the expressions for average and rms output voltage. **(June 2013) (Nov 2016/2018)**	**BL2**
9.	Explain the working of the following circuits. Draw and find out the expression for output voltage. **(May 2018)**	**BL3**

		
10.	With neat circuit diagram explain the working of Class E Resonant Rectifier. **(Nov 2020)**	**BL2**
11.	Explain the operation of a single-phase full converter with RLE load using relevant waveforms. Obtain the expressions for its average output voltage and RMS value of output voltage. **(May 2018)**	**BL2**
12.	A half-wave 3-phase rectifier is constructed using three individual diodes and a 120VAC 3-phase star connected transformer. If it is required to power a connected load with an impedance of 50Ω, Calculate, a) the average DC voltage output to the load. b) the load current, c) the average current per diode. Assume ideal diodes. **(NOV 2018)**	**BL5**
13.	Explain briefly with neat sketch how phase-controlled rectifier are used in the following applications. i. light dimmer ii. Excitation system iii. Solar PV systems. **(NOV 2019)**	**BL3**
14.	Show that the performance of a single – phase full converter as affected by source inductance is given by the relation **(Nov 2020)** $$\cos(\alpha+\mu) = \cos\alpha - \frac{\omega L_S I_0}{Vm}$$	**BL4**
15.	(i) A three phase fully controlled bridge converter operating from a 3 phase 220V, 50 Hz supply is used to charge a battery bank with nominal voltage of 240V. The battery bank has an internal resistance of 0.01D and the battery bank voltage varies by _10% around its nominal value between fully charged and uncharged condition. Assuming continuous conduction find out. (a). The range of firing angle of the converter (b). The range of ac input power factor. (c). The range of charging efficiency. When the battery bank is charged	**BL5**

	with a constant average charging current of 100 Amps through a 250 mH lossless inductor. (ii)The manufacturer of a selected diode gives the rate of fall of the diode current di/dt=20A/s, and its reverse recovery time trr=5;. What value of peak reverse current do you expect. **(Nov 2020)**	
	PART C	
1.	Design a converter to obtain a four-quadrant operation for renewable energy systems applications.	**BL6**
2.	Modify the working of single phase fully controlled converter to obtain the regeneration power. Also explain the same with suitable circuit diagram and relevant waveforms.	**BL6**

2

	UNIT III UNCONTROLLED RECTIFIERS **PART A**	**BL**
1.	**What is meant by time ratio/ duty cycle or PWM control (duty cycle) of a DC chopper? (Nov '19)** In chopper circuit, the ratio of on period to the total time period is known as time control ratio (or) duty ratio. It is given by T_{on}/T.	**BL2**
2.	**What is the effect of load inductance on the load current waveforms in the case of DC chopper??(Nov 2017) (April 2019) (Nov 2022)** The load current waveform is same as load voltage waveform in case of resistive load. In case of RL load, if load inductance is high, it will reduce the ripple in the output currents waveforms. Load current becomes continuous.	**BL2**
3.	**What is constant frequency control of chopper? (Nov-Dec 2012)** Constant frequency control (Pulse width modulation control): The chopping frequency is kept constant in this method therefore it is called as constant frequency control. The chopper ON time or chopper OFF time is adjusted in this method therefore it is also called as pulse width modulation control. By keeping the chopper frequency constant, the total period T remains constant. T_{on} and T_{off} both are varied to vary the duty cycle.	**BL1**
4.	**Differentiate between single quadrant and two quadrant DC chopper.**	**BL4**

S.No	**Single quadrant DC chopper**	**Two Quadrant DC chopper**

		1	Load current flows from source to load	Load current flows in either direction	
		2	Both voltage and current are positive	Voltage is positive, current is either positive or negative.	

5.	**What is the principle of step - up DC chopper?** A constant voltage is applied to the inductor. Hence the current through the inductor increases linearly during the period T_{on}. After the SCR is turned off, the energy in the inductor is transferred to the load along with supply voltage.	**BL2**
6.	**What is switching frequency in chopper?** The chopper is operated with a constant-frequency control law at switching frequencies from 50 Hz to 3000 Hz with input voltages ranging from 20V to 140V. Switching frequency is an important design and operating parameter.	**BL2**
7.	**What is the function of freewheeling diode in a chopper?** (i) It protects SCR from high voltage that may be induced when the inductive circuits is interrupted. (ii) It helps to maintain constant current though the load. (iii) It helps to commutate main SCR.	**BL2**
8.	**Which power electronic circuits is DC equivalent of transformer?** DC chopper which converts fixed DC to variable DC is a power electronic circuit which is DC equivalent of transformer. Using chopper, the input can be stepped up and stepped down as per the requirement of application.	**BL1**
9.	**What are the applications of DC Chopper? (Dec 2014)(DEC 2015)(May 2017)** DC chopper can be used for following applications like (i) Electric locomotives (ii) Battery operated cars. (iii) Power supplies etc.,	**BL1**
10.	**What are the advantages of DC choppers?** The advantages of DC choppers are: (i) Flexible, (ii) Easy to control & compact, (iii) Closed loop control can be implemented.	**BL1**
11.	**Distinguish between time ratio control and current limit control employed in a DC chopper. (Dec 2014) (DEC 2015)**	**BL4**

S.No	Time ratio control	Current Limit Control
1	Switch is controlled by varying time period.	Switch is controlled by varying amplitude limits
2	Pulse width modulation and frequency modulation are the types of TRC	Current is allowed to fluctuate between maximum and minimum value
3	PWM is the most widely used technique	CLC is rarely used because it requires sensors to sense current values.

12.	**What is meant by 'current limit control' of a chopper? (MAY 2015/2018)** In a DC-to-DC converter or chopper, the value of the current varies between the maximum as well as the minimum level for continuous voltage. In this technique, the chopper (switch in a DC-to-DC converter) is switched ON and then OFF to ensure that current is kept constant between the upper and lower limits. When the current goes beyond the maximum point, the chopper goes OFF. While the switch is at its OFF state, current freewheels via the diode and drops in an exponential manner. The chopper is switched ON when the current reaches the minimum level. This method can be used either when the ON time T is constant or when the frequency (f=1/T).	**BL2**
13.	**Write down the expression for average output voltage for step down chopper.** Average output voltage for step-down chopper $V_0 = \alpha$ Vs, where α is the duty cycle; V_0 - output voltage ;Vs - Supply voltage	**BL1**
14.	**What are the two types of control strategies available for dc chopper?** The two types of control strategies available for dc chopper are as follows, **a.** Time ratio control b. Current limit control	**BL1**
15.	**What is the different classification of chopper depending upon the direction of current and voltage?** (**Nov-Dec 2016)** Different types of choppers Class A chopper voltage positive and current positive Class B chopper voltage positive and current negative Class C chopper voltage positive or negative and current positive	**BL1**

	Class D chopper voltage positive and current positive or negative. Class E chopper four quadrant chopper.	
16.	**What is resonant converter? (May 2017/2018)** A resonant converter is a type of electric power converter that contains a network of inductors and capacitors called a "resonant tank", tuned to resonate at a specific frequency. They find applications in electronics, in integrated circuits. Resonant converter eliminates switching loss by using properties of resonant circuit to arrange either voltage (V) or current (I) to be zero at the instant of switching.	**BL2**
17.	**What are the advantages and disadvantages of a resonant pulse chopper?** Advantages: As a combination of switching device and LC network, the resonant switch offers advantages of quasi-sinusoidal current waveforms, zero switching stresses, zero switching losses, self-commutation, and reduced EMI. Disadvantages: In resonant pulse chopper, the peak resonant current should be greater than the expected load current which increases the size of the LC device used in chopper.	**BL2**
18.	**A step-up chopper is operated with a duty ratio of 0.6 for a dc input of 100 V. Determine the output voltage for a load resistance of R_L 5 ohm. (N** Given: Duty ratio, $\delta = 0.6$, V_{dc}= 100V, R_L =5 ohm Output voltage = $V_{av} = V_o = \delta V_{dc}$ = 0.6 x 100 = 60 V.	**BL5**
19.	**What is battery operated vehicle?** The vehicles which get powered through a self-controlled battery for converting fuel into electricity, such type of vehicles is called battery powered vehicles or electrical vehicles. It is a type of electric vehicle that exclusively uses chemical energy stored in rechargeable battery packs, with no secondary source of propulsion.	**BL1**
20.	**What type of battery is used in an electric car?** The various types of battery used in an electric car are Rechargeable batteries used in electric vehicles include lead–acid, NiCd, nickel–metal hydride, lithium-ion, Li-ion polymer, and, less commonly, zinc–air and molten-salt batteries.	**BL2**

21.	**What are the different types of motors used in electric vehicle?** Various types of Electric Motors used in Electric Vehicles are: 1. DC Series Motor 2. Brushless DC Motor 3. Permanent Magnet Synchronous Motor (PMSM) 4. Three Phase AC Induction Motors 5. Switched Reluctance Motors (SRM)	**BL1**
22.	**What are the disadvantages of frequency modulation scheme over the pulse-width modulation scheme? (Nov 21) (Nov 22)** The disadvantages of frequency modulation scheme are: • The chopping frequency must be varied over a wide range for control of output voltage in frequency modulation. • Filter design for such wide frequency variation is quite difficult. • A wide frequency variation is required for control of chopper duty cycle.	**BL4**
23.	**List the uses of class B chopper. (Nov 2020)** Class-B choppers are basically used for the regenerative braking of dc motor which operated in one quadrant of the system. These choppers are not capable of changing the direction of the output.	**BL2**
24.	**What are the effects of quick or fast charging (storage) or high –energy recovery (discharge) from a battery? (Nov 2020)** Fast discharging or charging is always occurring inside a battery at any given time. This causes the battery to discharge or produce electrical energy. Frequent fast charging may decrease battery capacity over time, but it depends on the EV model and the climate it is operating in.	**BL2**
25.	**Write any two salient features of Buck-Boost converter. (Nov 21)** The salient features of Buck-Boost converter are: • Polarity of the output voltage is opposite to that of the input voltage. • The output voltage can vary continuously from 0 to ∞ (for an ideal converter). • The output voltage ranges for a buck and a boost converter are respectively V_i to 0 and V_i to ∞.	**BL1**

	PART-B	
1.	Explain the working of boost converter with neat waveform also derive the expression of peak-to-peak voltage across the capacitor. (**May2017) (May 2018) (May 2019)**	**BL2**
2.	Explain the basic circuit and waveform and principle of operation of step-up converter **(June 2013) (Nov 2013) (Dec 2014) (MAY 2015)**	**BL2**
3.	Explain the Control strategies applied to dc chopper. **(DEC 2015) (May 2017)**	**BL2**
4.	A step-up chopper is used to deliver load voltage of 660V from 220V dc source if non conduction time of chopper is 100μs, Compute the pulse width. If pulse width is halved find new output voltage. **(May 2012)**	**BL5**
5.	Explain the working of buck-boost converter for continuous current mode of operation with neat waveform also derive the expression of peak-to-peak voltage across the capacitor. **(DEC 2015) (May 2016) (Nov 2020)**	**BL2**
6.	A type – A chopper has supply voltage Vs and duty cycle of 0.4 and 0.6 for these duty cycles calculate average and rms values of output voltage output power for R load ripple factor. **(June 2013)**	**BL5**
7.	Explain the working principle of voltage commutated chopper showing the current and voltage waveform across each device under different modes of operation. **(Nov 2016) (May 2018)** (**May2017) (May 2018) (May 2019)**	**BL2**
8.	For Type A step down chopper of dc source voltage 230 V, load resistance 10 ohm. Take a voltage drop of 2 V across chopper when it is on. For a duty cycle of 0.4, calculate (i) average and rms values of output voltage and (ii) chopper efficiency. **(Nov 2018)**	**BL5**
9.	Explain briefly with neat sketch how DC-DC converters are used in battery operated vehicle. Also explain the principle of operation of battery-operated vehicles.	**BL6**
10.	Explain the waveforms of type D chopper. Derive the expression for current ripple when it feeds RL load. **(Nov 19)**	**BL2**
11.	The buck regulator has an input range of 12 V. The regulated average output voltage is 5 V at R = 500 S and the peak-to-peak output ripple voltage is 20 mV. The switching frequency is 25 KHz if the peak to peak	**BL5**

	ripple current of inductor is limited to 0.8 A, determine: a) The duty cycle, K b) The filter inductance, L c) The filter capacitance, C and d) The critical value of L and C **(Nov 19) (Nov 2020)**	
12.	(i) Explain the control strategies of chopper. (ii)Derive the expression of the output voltage for a step-up chopper. **(Nov 2020)**	**BL2**
13.	Classify the basic topologies of switching regulators and explain the operation of buck regulator with continuous load current using suitable waveform. **(Nov 2020) (Nov 2021) (Nov 22)**	**BL2**
14.	Derive the expression of the output voltage for a step-up chopper. **(Nov 2021)**	**BL2**
15.	Explain the steady state analysis of step-down chopper. **(Nov 22)**	**BL2**
	PART C	
1.	Design a converter to obtain forward motoring and reverse braking application.	**BL6**
2.	Design a converter to obtain a four-quadrant operation for EV applications.	**BL6**

3

	UNIT IV – CONTROLLED RECTIFIERS **PART A**	**BL**
1.	**State the necessity of return current diodes in inverter. (Nov 2022)** If the load connected to the inverter is inductive, then high voltages occur across the thyristor when it is switched off. This will damage the thyristor if there is no path for diverting the current. Feedback diodes (or) return current diodes are connected across each thyristor in antiparallel. The feedback diode which is connected across the thyristors supply the reactive power to the source.	**BL2**
2.	**What is the necessity of isolation between power circuit and control circuit in power electronics applications?** In power electronic applications, usually isolation is provided between the drive and the power circuits. The triggering (drive or control) circuits work at low power levels as their job is only to trigger the device. On the other hand, the power circuits operate at high power levels. If the device	**BL2**

<table>
<tr><td></td><td>gets damaged, the trigger circuits are exposed to high power levels and hence, they get damaged. To avoid this, isolation is provided between the drive and power circuits.</td><td></td></tr>
<tr><td>3.</td><td>What is CSI? (Nov-Dec 2012)
The current source inverter converts the input direct current into an alternating current. In current source inverter, the input current remains constant but this input current is adjustable. The current source inverter is also called current fed inverter. The output voltage of the inverter is independent of the load. The magnitude and nature of the load current depends on the nature of load impedance.</td><td>BL1</td></tr>
<tr><td>4.</td><td>What are the methods of voltage control in Inverters?
i. External control of ac output voltage- AC voltage control, Series Inverter control
ii. External control of dc input voltage
iii. Internal Control of inverter – PWM Techniques –
1) Single pulse width modulation (PWM)
2) Sinusoidal pulse-width modulation (SPWM)
3) Trapezoidal pulse width modulation (TPWM)
4) Selective harmonic elimination pulse width modulation (SHE-PWM)
5) Modified sinusoidal pulse width modulation (MSPWM)
6) 60° Modulation (60°-PWM)
7) Harmonic injection pulse width modulation (HIPWM)
8) Space vector PWM (SVPWM)</td><td>BL1</td></tr>
<tr><td>5.</td><td>What is the difference between VSI and CSI? (MAY 2016/2018/2019)
<table><tr><th>VSI</th><th>CSI</th></tr><tr><td>Input voltage is maintained constant</td><td>Input current is constant but adjustable</td></tr><tr><td>The output voltage does not depend on the load</td><td>The output current does not depend on the load</td></tr><tr><td>The magnitude of the output current and its waveform depends on the nature of the load</td><td>The magnitude of the output voltage and its waveform depends on the nature of the load impedance</td></tr></table></td><td>BL4</td></tr>
</table>

		impedance		
		It requires feedback diodes	It does not requires feedback diodes	
		Commutation circuit is complicated i.e.it contains capacitors and inductors.	Commutation circuit is simple i.e. it contains only capacitors.	
		Can be operated in 120^0 and 180^0 mode.	Can be operated only in120^0 mode.	
6.	**What is the function of feedback diodes in bridge inverter? (Nov 2018) (Nov 2022)** Load current in delivered by the inverter may not reverse at the same instants as does the load voltage. Current may lead or lag the output voltage due to the presence of capacitance and/or inductance in the load circuit. Hence the feedback diodes connected in anti-parallel with each thyristor permit load current to flow back to the power circuit when thyristor is turned off.			**BL2**
7.	**What is harmonic elimination by PWM? (MAY 2015)** Pulse width modulation is used to eliminate harmonics by comparing reference signal and carrier signal and when reference signal is greater than carrier signal triggering pulses are generated for switches in the inverter.			**BL1**
8.	**In a CSI, if frequency of output voltage is 'f' Hz, what is the frequency of voltage input to CSI? (June 2013)** In CSI if the frequency of output voltage is f Hz, then the frequency of input voltage to CSI is 2f.			**BL3**
9.	**What is Space Vector modulation? (June 2013/May 2018)** Space vector modulation (SVM) is an algorithm for the control of pulse width modulation (PWM). It is used for the creation of alternating current (AC) waveforms; most commonly to drive 3 phase AC powered motors at varying speeds from fixed DC. The function of SVM is to use a steady state DC-voltage and by the means of six switches (e.g., transistors) emulate a three-phased sinusoidal waveform where the frequency and amplitude is adjustable.			**BL2**
10.	**What is meant by voltage source inverter? (Dec 2014) (DEC 2015)** Voltage source inverters (VSIs) are named so because it creates ac variable voltage from constant or stiff dc input voltage. VSI control the ac output			**BL2**

	voltage.	
11.	**Write the advantages or use of resonant converters in power electronic circuits? (Dec 2014/ April2019)** Resonant converters are used to reduce/eliminate the switching losses and the output waveform is more sinusoidal. There are three basic types of the resonant DC/DC converters: 1. Series resonant converter 2. Parallel resonant converter 3. Series-Parallel resonant converter.	**BL2**
12.	**What are the applications of inverter? (MAY 2016)** The inverter is an electrical device, which is used to convert the DC power to an AC power. The inverter for home is used for emergency backup power and used in some aircraft systems to convert a portion of the aircraft DC power to AC. Inverters are used to control the speed of AC motors.	**BL1**
13.	**What are the applications of CSI? (Nov-Dec 2016)** i) It can be used for the speed control of ac, especially induction, motors subject to variation in load torque. ii) used in induction heating.	**BL1**
14.	**Define modulation index. (Nov-Dec 2016)** Modulation index is the ratio of peak magnitudes of the modulating waveform and the carrier waveform. M= $\frac{Vm}{Vc}$. Modulation index used to control the output of inverter.	**BL2**
15.	**Why are thyristors not preferred for inverter? (May 2017)** Thyristors requires extra commutation circuits for turn off which results in increased complexity of the circuit. For these reasons thyristors are not preferred for inverters.	**BL2**
16.	**What are the disadvantages of the harmonics present in inverter system? (May2017)** i) The major effect of power system harmonics is to increase the current in the system. This is particularly the case for the third harmonic, which causes a sharp increase in the zero sequence current, and therefore increases the current in the neutral conductor. ii) Electric motors experience losses due to hysteresis and losses due to eddy currents set up in the iron core of the motor. These are proportional to the frequency of the current.	**BL2**

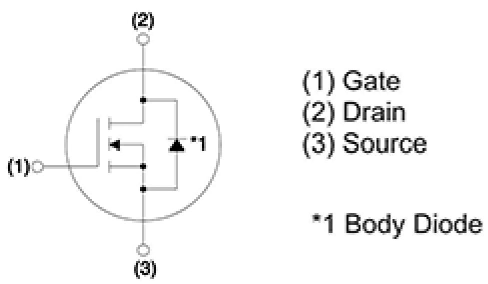
17.	**What is UPS?** An uninterruptible power supply or uninterruptible power source (UPS) is an electrical apparatus that provides emergency power to a load when the input power source or mains power fails. A UPS differs from an auxiliary or emergency power system or standby generator in that it will provide near-instantaneous protection from input power interruptions, by supplying energy stored in batteries, super capacitors, or flywheels.	**BL1**
18.	**What are the major functions of UPS?** The primary role of any UPS is to provide short-term power when the input power source fails. However, most UPS units are also capable in varying degrees of correcting common utility power problems: 1. Voltage spike or sustained overvoltage 2. Momentary or sustained reduction in input voltage 3. Voltage sag 4. Noise, defined as a high frequency transient or oscillation, usually injected into the line by nearby equipment 5. Instability of the mains frequency 6. Harmonic distortion, defined as a departure from the ideal sinusoidal waveform expected on the line.	**BL2**
19.	**What is the difference between Natural commutation and Forced commutation?**	**BL4**

Natural Commutation	Forced Commutation
Requires AC voltage at input	Requires DC voltage at input
External components like inductors, capacitors etc., are not required	External components are required
Used in controlled rectifiers, AC voltage controller	Used in choppers, inverters etc.,
SCR turns off due to negative supply voltage	SCR turns off due to reverse voltage or current
No power loss takes place during commutation	Power loss takes place during commutation
Zero cost	Significant cost

20.	**Compare freewheeling diode with feedback diode. (Nov 19)**	**BL4**

S.no	Freewheeling diode	Feedback diode
1.	Load energy is utilized by load itself through freewheeling diodes	Load energy is fed back to the supply through feedback diodes
2.	Freewheeling diodes must carry full load current	Feedback diode sometimes carry full load current
3.	Freewheeling diode response can be slower	Feedback diode response must be faster

21.	**Why THD must be mitigated? (Nov 19)** Total harmonic distortion (THD) is an important aspect in inverters and it should be kept as low as possible. Lower THD in inverters will have higher power factor, lower peak currents, and higher efficiency.	**BL2**
22.	**What are integral body diodes? (Nov-Dec 2020)** MOSFETs, whether SiC-MOSFETs or otherwise, have a body diode between the drain and the source, as indicated in the diagram. As a consequence of the MOSFET structure, the body diode is formed by the pn junction between the source and drain, and is also called a parasitic diode or an internal diode. The performance of the body diode is one important parameter of the MOSFET, and is important when using the MOSFET in an application.	**BL2**



23.	**Why PWM strategies are used in inverters? (Nov-Dec2020)** The main objective of the PWM is to control the inverter output voltage and to reduce the harmonic content in the output voltage. The pulse width modulation (PWM) techniques are mainly used for voltage control. They control the output voltage as well as reduce the harmonics.	**BL2**
24.	**A single-phase full bridge inverter has a resistive load of R = 10 Ω and the**	**BL4**

	input voltage V_{dc} of 100 V. Find the RMS output voltage at fundamental frequency. (Nov 21) Solution: The output voltage of a single-phase full bridge inverter is given by, Vo(rms) = $\frac{2\sqrt{2}}{n\pi}$ Vs Fundamental component of output voltage is V01 = $\frac{2\sqrt{2}}{\pi}$ Vs (for fundamental component, n= 1) For given input voltage, Vs = 100 V, the fundamental component of output voltage is V01 = $\frac{2\sqrt{2}}{\pi}$ 100 = 90.03 V	
25.	**Compare 180° and 120° mode inverter operation. (Nov 21)**	**BL4**

S.No	180 degree conduction	120 degree conduction
1	Each device conducts for 180 degree	Each device conducts for 120 degree
2	Three devices conduct in one interval	Two devices conduct in one interval
3	Cross conduction is possible	Cross conduction is not possible
4	Devices are better utilized	Devices are under utilized
5	Output power is higher because of higher voltage levels	Output power is less because of lower voltage levels

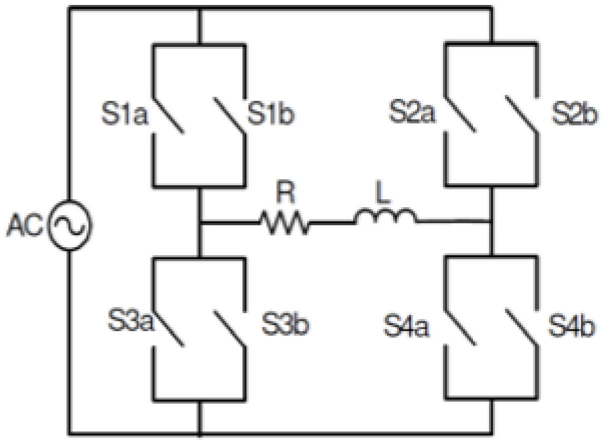
	PART-B	
1.	Explain the operation of series resonant Inverter. **(Nov 2022)**	**BL2**
2.	Explain the operation of 180° Conduction of three phase inverter. **(Nov 2020) (Nov 2022)** Or Explain the principle of operation of three-phase inverter with 180° conduction mode with necessary waveforms and circuits. **(Nov 2021).**	**BL2**
3.	Explain the operation of 120° Conduction of three phase inverter. Also obtain the expression for rms value of output voltage.**(Nov 18) (Nov 2022).** Or Describe the functioning of three-phase voltage source inverter supplying a balanced star connected load in 120° operating mode. **(Nov 2021)**	**BL2**
4.	State different methods of voltage control methods in inverters. Describe about	**BL2**

	PWM control in inverters. **(Nov 19)**	
5.	Explain with waveform multiple pulse width modulation inverter**(May 2015)**	**BL2**
6.	Explain the basic operation of single phase current source inverter. State the merits and demerits of them **(May 2012) (Nov 2013)(May 2016)(Nov 2020)**	**BL2**
7.	Explain multiple pulse width modulation and explain sinusoidal pulse width modulation. **(June 2013) (Nov 2013)**	**BL2**
8.	Explain in detail about the different methods of voltage control inverters.	**BL2**
9.	Explain the SPWM and modified SPWM techniques for inverter switching. **(May 2018) (Nov 2020)**	**BL2**
10.	Explain the principle of operation of 3-Φ auto sequentially commutated CSI with power circuit. Draw the equivalent circuits and relevant waveforms.	**BL2**
11.	Explain different types of UPS with neat diagram and the process of induction heating in detail.	**BL2**
12.	Provide the detailed working of single phase capacitor commutated CSI with R loads.Through a systematic analysis obtain the output current and voltage equations. Also mention the design considerations.**(Nov 19)**	**BL6**
13.	Write short notes on the principle of induction heating**(Nov 2020)**	**BL2**
	PART C	
1.	Explain the control techinque adopted in inverter to obtain the desired output for UPS application.	**BL5**
2.	Formulate the design procedure of inverter for renewable applications.	**BL6**

	UNIT V AC PHASE CONTROLLERS **PART A**	**BL**
1.	**What are the two types of control normally used in AC voltage controller?** (i) On-Off control (ii)Phase angle control are the two types of controllers normally used for AC voltage controller.	**BL2**
2.	**What is the difference between on-off control and phase angle control?** In On-Off control, thyristor switches connect the load to the AC source for a few cycles of input voltage and then disconnect it for another few cycles. In phase angle control, thyristor switches connect the load to the AC source for a portion of each cycle of input voltage.	**BL4**
3.	**Why is half wave AC voltage regulator not used? (Nov 2017) (Nov 2022)**	**BL2**

	Single-phase half wave voltage regulator consists of a Thyristors and a diode in anti parallel. Therefore, control is possible only in positive half cycle. The output waves are very much distorted. Therefore, half wave regulator is not used.	
4.	**Which method of commutation is used in AC voltage regulators?** Line commutation is used in AC voltage regulator. i.e. the thyristors will get turned off when the current through it falls below the holding current value because of the nature of the source itself.	**BL2**
5.	**Define duty cycle of AC voltage controller.** Duty cycle = n / n + m Where n = number of on-cycles m = number of off-cycles	**BL1**
6.	**Explain the term sequence control of ac voltage regulators. (Nov 2017) (Nov 2022)** Sequence control of a.c regulators means the use of two or more stages of voltage controllers in parallel for the regulation of output voltage. The voltage controllers in parallel are triggered in proper sequence one after the other to obtain a variable output with low harmonic content.	**BL2**
7.	**What are the advantages of sequence control of AC voltage regulators?** The advantages of sequence control are 1) the reduction of harmonics in the load voltages and line currents 2) Improvement of power factor.	**BL2**
8.	**Name some applications of AC regulator or AC voltage controller.** AC regulators are used in industries heating, illumination level controller on load transformer tap changing, speed control of induction motor etc.	**BL2**
9.	**What is Cycloconverter? (Nov-Dec 2016/2018)** A Cycloconverter is a direct-frequency changer that converts ac power at one frequency to ac power at another frequency by ac-ac conversion, without an intermediate conversion link.	**BL1**
10.	**List the applications of cycloconverter. (Nov-Dec 2012) (Nov 2013)** Cycloconverter are used in (i)Variable speed AC motors (ii)Induction heating (iii)Electric traction (iv)Static VAR systems etc.	**BL1**
11.	**List the advantages of Cycloconverter.**	**BL1**

	(i)Frequency conversion in single stage is possible (ii)Both frequency and voltage are controllable (iii)Natural commutation is used. Hence commutation circuits are not needed (iv)THD is lesser than d.c link converters (v)Isolation of a defective SCR does not require the Cycloconverter to be switched off (vi)The power transfer is bidirectional	
12.	**List the disadvantages or demerits of Cycloconverter.** (i)Cycloconverter operation is possible only for frequencies less than half of the input frequency (ii)Number of SCRs required is more than that for d.c link converters (iii)Complex control circuitry (iv)At smaller load currents, the Cycloconverters may create problem in firing delay control.	**BL1**
13.	**What are the factors affecting the harmonics in Cycloconverter?** (i) Number of pulses per cycle (ii)Circulating or non-circulating mode of operation (iii)Continuous or discontinuous conduction (iv)Effect of overlap (v)Effect of load power factor (vi)Control methods	**BL2**
14.	**Why the output frequency of a cycloconverter is significantly lower than the input frequency?** Since the cycloconverter is a phase-controlled AC-AC converter producing the desired output AC voltage by selecting segments of the input voltage utilizing natural commutation, the output frequency becomes significantly lower than the input frequency.	**BL3**
15.	**What is a matrix converter? (April '13, '14, 17) (Nov 13, 15,19)** The matrix converter is a single-stage converter. It uses bi-directional fully controlled switches for direct conversion from ac to ac. It is an alternative to the double sided PWM voltage rectifier-inverter. The matrix converter consist of 9 bi-directional switches that allows any output phase to be connected to any input phase.	**BL2**
16.	**What is the principle of on-off control of ac voltage controller?** Thyristor switch connects the AC supply to load for a time t_{on}, the switch is turned off by a gate pulse inhibiting for time t_{off}. In On-Off control technique Thyristors are used as switches to connect the load circuit to the ac supply (source) for a few cycles of the input ac supply and then to disconnect it for few input cycles. The Thyristors thus act as a high-speed contactor (or high-	**BL2**

	speed ac switch).	
17.	**Draw the matrix converter circuit.**  	**BL2**
18.	**What is meant by integral cycle control in AC voltage controllers?** In integral cycle control, thyristor switches connect the load to the AC source for a few cycles of input voltage and then disconnect it for another few cycles. Integral cycle controllers are converters with the ability to perform direct switching without losses. The process directly converts AC to AC without having to perform the intermediate processes of AC to DC then DC to AC. The basic integral control cycle is sinusoidal in nature.	**BL2**
19.	**What is the control range of firing angle in AC voltage controller with R-L load? (Dec 2014)** Single Phase AC Voltage Controller with R and RL Load is controlled by controlling the triggering angle of the thyristors in the circuits. The control range of ac voltage controller with RL load varies from $0\text{-}180^0$.	**BL2**
20.	**Mention the advantages of matrix converter over conventional converter.** The matrix converter has several advantages over traditional rectifier-inverter type power frequency converters. It provides sinusoidal input and output waveforms, with minimal higher order harmonics and no sub harmonics; it has inherent bi-directional energy flow capability; the input power factor can be fully controlled, it has minimal energy storage requirements, which allows to get rid of bulky and lifetime-limited energy-storing capacitors.	**BL2**
21.	**Mention merits and demerits of AC voltage controller. (Nov 2018)** **Merits**	**BL2**

	• They use line commutation; hence no extra commutation circuits are required. • They have high efficiencies since device losses are reduced. **Demerits** • large ripple and harmonics are present in the output. • Output waveforms are not sinusoidal.	
22.	**What is bidirectional switch? (Nov 2020)** A bidirectional power switch (BPS) is an active device built using MOSFETs or IGBTs, which allows a two-way bidirectional flow of current when powered ON and blocks a bidirectional flow of voltage when powered OFF. The action can be reversed by simply changing the voltage polarity.	**BL1**
23.	**What is the disadvantage of ON-OFF control? (Nov-Dec2020)** The disadvantage of ON – OFF control in ac voltage controllers is the introduction of harmonics in the supply current and load voltage waveforms particularly at low output voltage levels. It also has poor efficiency and input power factor.	**BL1**
24.	**List out the different types of cycloconverter. (Nov 21)** Types of Cycloconverters: a. Based on the output voltage magnitude: •Step-down cycloconverter and Step-up cycloconverter b. Based on the input supply: •Single-Phase to Single-Phase Cycloconverter •Three-Phase to Three-Phase Cycloconverter •Three-Phase to Single-Phase Cycloconverter	**BL1**
25.	**List the power factor control techniques in ac-ac converters. (Nov 21)** The various power factor control techniques are: • Extinction angle control • Symmetrical angle control • Pulse width modulation • Sinusoidal pulse width modulation.	**BL1**

	PART-B	
1.	Explain the operation of Single-phase full Wave ac – ac voltage regulator with R and RL load with neat waveforms and obtain expression for voltage and power factor. **(May 2015/16/19) (Dec 2015/2018).**	**BL2**
2.	Explain in detail the performance parameters of AC voltage controllers.	**BL2**
3.	Explain the operation of three phase to single phase cycloconverter with circuit diagram and waveforms **(May 2019)**	**BL2**
4.	Explain the operation of single phase to single phase cycloconverter with continuous and discontinuous load current with circuit and waveform. **(May 2015)(Nov 2013/2017/2018)**	**BL2**
5.	Explain the multistage sequence control of ac voltage regulators in single phase voltage controller. **(June 2012) (June 2013) (Dec 2016) (May 2017/2018)**	**BL2**
6.	Write a short note on the following: (i) Integral cycle control (ii) Multistage sequence control (iii) Step up cycloconverter (iv) Matrix converter **(Nov 2013 & Nov 2014)**	**BL2**
7.	Explain the principle of ON – OFF control technique (Integral cycle control) and derive an expression for the RMS value of output voltage for ON – OFF control method. **(June 2013/ Nov 19)**	**BL2**
8.	Explain the operation of matrix converter. **(Nov 2020) (Nov 2022)**	**BL2**
9.	Explain the operation of a three phase to three phase cycloconverter. **(May 2018)**	**BL2**
10.	A Single-phase full wave AC voltage controller has an input voltage of 230V, 50Hz, and it is feeding resistive load of 10 Ω. If the firing angle of thyristor is 110 degree. Find the output rms voltage, Input Power Factor and Average current of thyristor.	**BL5**
11.	A single-phase full wave ac voltage controller working on ON-OFF control technique has supply voltage of 230V, RMS 50Hz, load = 50Ω. The controller is ON for 30 cycles and off for 40 cycles. Calculate • ON & OFF time intervals. • RMS output voltage. • Input P.F. • Average and RMS thyristor currents. **(NOV ’19)**	**BL5**

12.	(i). Describe the operation of a 3-phase AC voltage controller with neat power diagram and waveforms. (ii). Explain in detail about multistage control in ac voltage controllers. **(Nov 2020)**	**BL2**
13.	Explain the principle of single phase to single phase step up cycloconverter with power circuit and waveforms**. (Nov 2021) (Nov 2022)**	**BL2**
14.	Derive the RMS voltage for a single-phase full wave ac voltage controller with RL load. **(Nov 2021)**	**BL2**
15.	A Single-phase full wave AC voltage controller has an input voltage of 220V, 50Hz, and it is feeding resistive load of 20 Ω. If firing angle of thyristor is 70 degrees. Find the output rms voltage, Input Power Factor and Average current of thyristor.	**BL5**
	PART C	
1.	Predict which type of converter is used for an application where both the amplitude and frequency of input ac signal must be modified. Also analyze its performance with three phase converters.	**BL6**
2.	Summarize the converter which uses single conversion stage for modification of both amplitude and frequency in ac signals.	**BL6**

BL - Bloom's Taxonomy Levels

1- Remembering, 2- Understanding, 3 - Applying, 4 - Analysing, 5 - Evaluating, 6 - Creating

CO - Course Outcomes

4

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ENGINEERING COLLEGE

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE3014- POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

SEMESTER V

REGULATIONS 2021

NOTES

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QUESTION BANK

EE3014 POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

UNIT I INTRODUCTION TO RENEWABLE ENERGY SYSTEMS 6

Classification of Energy Sources – Importance of Non-conventional energy sources – Advantages and disadvantages of conventional energy sources - Environmental aspects of energy - Impacts of renewable energy generation on the environment - Qualitative study of renewable energy resources: Ocean energy, Biomass energy, Hydrogen energy, - Solar Photovoltaic (PV), Fuel cells: Operating principles and characteristics, Wind Energy: Nature of wind, Types, control strategy, operating area.

UNIT II ELECTRICAL MACHINES FOR WIND ENERGY CONVERSION SYSTEMS (WECS) 6

Construction, Principle of operation and analysis: Squirrel Cage Induction Generator (SCIG), Doubly Fed Induction Generator (DFIG) - Permanent Magnet Synchronous Generator (PMSG).

UNIT III POWER CONVERTERS AND ANALYSIS OF SOLAR PV SYSTEMS 6

Power Converters: Line commutated converters (inversion-mode) - Boost and buck-boost converters- selection of inverter, battery sizing, array sizing. Simulation of line commutated converters, buck/boost converters. Analysis: Block diagram of the solar PV systems - Types of Solar PV systems: Stand-alone PV systems, Grid integrated solar PV Systems - Grid Connection Issues.

UNIT IV POWER CONVERTERS FOR WIND SYSTEMS 6

Power Converters: Three-phase AC voltage controllers- AC-DC-AC converters: uncontrolled rectifiers, PWM Inverters, Grid-Interactive Inverters - Matrix converter.

UNIT V HYBRID RENEWABLE ENERGY SYSTEMS 6

Need for Hybrid Systems- Range and type of Hybrid systems- Case studies of Diesel-PV, Wind-PV, Micro hydel-PV, Biomass-Diesel systems - Maximum Power Point Tracking (MPPT). 30 PERIODS LAB COMPONENT: 30 PERIODS 1. Simulation on modelling of Solar PV System- V I Characteristics 2. Simulation on Modelling of fuel cell- V I Characteristics 3. Simulation of self- excited Induction Generator. 4. Simulation of DFIG/ PMSG based Wind turbine. 5. Simulation on Grid integration of RES.

TOTAL: 30+30 = 60 PERIODS

COURSE OUTCOMES:

At the end of the course, students should be able to:

CO1: Examine the available renewable energy sources.

CO2: Demonstrate the working principles of electrical machines and power converters used for wind energy conversion system

CO3: Demonstrate the principles of power converters used for solar PV systems

CO4: Examine the available hybrid renewable energy systems.

CO5: Simulate AC-DC converters, buck/boost converters, AC-AC converters and

PWM inverters.

TEXT BOOKS:

1. S.N.Bhadra, D. Kastha, & S. Banerjee “Wind Electrical Systems”, Oxford University Press, 2009, 7th impression.
2. Rashid .M. H “Power electronics Hand book”, Academic press,2nd Edition, 2006 4th Edition, 2017
3. Rai. G.D, “Non-conventional energy sources”, Khanna publishers, 6th Edition, 2017.

UNIT I

INTRODUCTION

SYLLABUS: Environmental aspects of electric energy conversion: impacts of renewable energy generation on environment (Cost-GHG Emission) - Qualitative study of different renewable energy resources: Solar, wind, ocean, Biomass, Fuel cell, Hydrogen energy systems and hybrid renewable energy systems.

1. 1 ENVIRONMENTAL ASPECTS OF ELECTRIC ENERGY CONVERSION

1.1.1 Coal as thermal fuel

Coal is the raw fuel that provides 42% of the world's electricity. This distinguishes coal as the world's primary energy source for electricity generation. The name coal refers to a family of solid, organic fuels with different properties. Coal is mainly composed of elemental carbon and is formed by the conversion of deposited organic material. The lowest grade of coal formed is peat. Under the influence of high pressures and temperatures, the peat is transform into the coal. Using coal to generate power or heat is an old technique. The heat energy of these fuels is converted into mechanical energy by suitable prime movers such as steam engines, steam turbines, internal combustion engines etc.

1.1.2 Coal mining

There are two types of coal mining, strip mining and underground long wall mining. The environmental impacts from surface versus underground mining are not significantly different. The main difference between these two mining techniques is that the surface mining subsystem results in a higher amount of airborne ammonia emissions due to the production of ammonium nitrate explosives which are used at the mine. Another important difference is that underground mining requires limestone which emits a large amount of particulates during its production. The problematic pollutants in emission of coal based generating plants are Sulfur dioxide (SO_2), Nitrogen oxides (NOx), carbon monoxide (CO) and carbon dioxide (CO_2) and certain hydrocarbons.

1.1.3 Oxides of sulphur (SO_2)

Most of the sulphur present in the fossil is oxidized to SO_2 in the combustion chamber before being emitted by the chimney. In atmosphere it gets further oxidized to H_2SO_4 and metallic sulphates which are the major source of concern as these can cause acid rain, impaired visibility, damage to buildings and vegetation. Sulphate concentrations of 9-20 μg/m3 of air aggravate asthma, lung and heart disease.

1.1.4 Acidification

Acidification is one of the main problems arising from existing coal power. It takes place during many steps in the life cycle of electricity produced by coal combustion. Pumped mine water contains mud, dissolved sulphate and metal ions. It is also acidic and, therefore, needs to be neutralizing before being discharged. Drainage water from refuse piles with excavated and residual minerals can be very acidic, particularly if the rocks contain pyrite (ferric sulphide) that undergoes oxidation processes when exposed to the atmosphere. These oxidation processes take place in natural environments, but are greatly accelerated by mining activities, especially when no alkaline rocks are present to neutralize the acid formed.

1.1.5 Impact on biodiversity

The main environmental effect of electricity produced by coal combustion is probably related to the ubiquitous emission of greenhouse gases. The release to the atmosphere of such gases is larger from coal use than for any other fuel used for generating electricity. It is a general contention that any additional increase of greenhouse gases in the atmosphere will exacerbate global warming. This can lead to rapid changes in local weather conditions and can thus have many and profound influences on biodiversity. Organisms that cannot adapt or migrate successfully under changing climate conditions will be adversely affected.

1.2 ENVIRONMENT IMPACTS OF RENEWABLE ENERGY TECHNOLOGIES

Developing renewable energy technologies that exploit the sun, the wind, and geothermal energy is critical to addressing concerns about climate change and some environmental issues. However, using renewable energy sources will not eliminate all environmental concerns. Although renewable energy sources produce relatively low levels of Green House Gas emissions and conventional air pollution, manufacturing and transporting them will produce some emissions and pollutants. The production of some photovoltaic (PV) cells, for instance, generates toxic substances that may contaminate water resources. Renewable energy installations can also disrupt land use and wildlife habitat, and some technologies consume significant quantities of water.

To develop sound policies, policy makers must understand the relative environmental impacts of alternative energy sources, including how the impacts of renewable energy technologies compare to those of fossil-fuel technologies and to opportunities for improvements in energy efficiency. Understanding the potential environmental impacts of renewable energy technologies is also essential for identifying and pursuing designs, manufacturing methods, project siting, utility operations, and so on to mitigate or offset these effects.

1.2.1 Life cycle uses of energy

For renewable energy sources, net energy ratio (NER) is expected to be greater than one, indicating a positive return over the fossil-fuel energy investment. For fossil-fuel and nuclear technologies, NERs are smaller than one and essentially represent the overall life cycle efficiency of the project. NERs are strongly influenced by a number of underlying assumptions, such as plant capacity and life expectancy. For electricity generation from wind and solar energy, the strength of the resource (which will affect the capacity factor of the installed technology) is also a critical assumption. For silicon PV specifically, the NER is highly dependent upon the thickness of the wafer and the efficiency of the cell/module produced. NERs would be significantly higher for waste biomass.

1.2.2 Local and regional air pollution

Most renewable energy technologies have much lower life cycle emissions of conventional air pollutants than conventional coal and natural gas plants. One exception is electricity generation from biomass, which can produce significant NOx, particulate matter, and hazardous air pollutants, such as polycyclic aromatic hydrocarbons (PAHs). Although biomass has lower nitrogen content than fossil fuels, a substantial quantity of NOx is formed whenever high-temperature combustion occurs in air, through oxidation of atmospheric nitrogen (N_2) at high temperatures. Although direct emissions of NOx and SOx are expected to be low for geothermal power plants, flash and dry-steam geothermal facilities can produce significant quantities of hydrogen sulfide (H_2S) from geothermal reservoirs, unless steps are taken to decrease it.

1.2.3 Land and water use

The amount of land used is a rough substitute for other impacts of new development, including impacts on ecosystems, cultural and historical resources, scenery, and agricultural land. When the impacts on land use are measured simply by the surface area they occupy during their life cycle, some renewable energy technologies appear to have heavy land-use requirements. However, this approach does not take into account the intensity of land use or whether the technology allows for simultaneous use of land for other purposes. Whereas coal-fired power plants fully occupy the sites where they are constructed, small-scale PV installations may be placed on rooftops where they cause little or no interference with the primary use of the land for commercial or residential buildings. Thus, smaller scale or distributed solar technologies may have less of an impact on land use and habitat loss than large-scale, central station plants. Land-use concerns may also be addressed by deploying renewable energy systems on previously developed sites, rather than in undeveloped areas.

Water is a scarce resource in large portions. Recent global circulation model projections suggest that, if climate change proceeds as expected, under current business-as-usual scenarios, freshwater supplies will become even scarcer in some parts of the world. Electricity production using thermoelectric technologies requires vast amounts of water, primarily for cooling. In is about 43 percent of existing thermoelectric generating capacity uses once-through cooling, 42 percent uses re-circulating wet towers, 14 percent uses re-circulating cooling ponds, and 1 percent uses dry cooling. Water use by power plants is characterized by withdrawals and consumption. Although consumption is sometimes emphasized over withdrawals, the latter is important, because power plant operation may be constrained by the amount of water available for withdrawal and power plant uses may compete with other demands for water. Furthermore, water returns can be significant sources of thermal pollution and may include discharges of chemical pollutants, such as chlorine or other biocides used in cooling towers.

1.3 ENVIRONMENT IMPACTS OF DIFFERENT RENEWABLE ENERGY SOURCES

All energy sources have some impact on our environment. Fossil fuels—coal, oil, and natural gas—do substantially more harm than renewable energy sources by most measures, including air and water pollution, damage to public health, wildlife and habitat loss, water use, land use, and global warming emissions. However, renewable sources such as wind, solar, geothermal, biomass, and hydropower *also* have environmental impacts, some of which are significant. The exact type and intensity of environmental impacts varies depending on the specific technology used, the geographic location, and a number of other factors. By understanding the current and potential environmental issues associated with each renewable energy source, we can takes steps to effectively avoid or minimize these impacts as they become a larger portion of our electric supply.

1.3.1 Environmental impacts of wind energy

1.3.1.1 Land use

The land use impact of wind power facilities varies substantially depending on the site: wind turbines placed in flat areas typically use more land than those located in hilly areas. However, wind turbines do not occupy all of this land; they must be spaced approximately 5 to 10 rotor diameters apart (a rotor diameter is the diameter of the wind turbine blades). Thus, the turbines themselves and the surrounding infrastructure (including roads and transmission lines) occupy a small portion of the total area of a wind facility. Offshore wind facilities, require larger amounts of space because the turbines and blades are bigger than their land-based counterparts.

1.3.1.2 Wildlife and habitat

The impact of wind turbines on wildlife, most notably on birds and bats, has been widely document and studied. A recent survey founded evidence of bird and bat deaths from collisions with wind turbines and due to changes in air pressure caused by the spinning turbines, as well as from habitat disruption. Offshore wind turbines can have similar impacts on marine birds, but as with onshore wind turbines, the bird deaths associated with offshore wind are minimal. Wind farms located offshore will also impact fish and other marine wildlife.

1.3.1.3 Public health and community

Sound and visual impact are the two main public health and community concerns associated with operating wind turbines. Most of the sound generated by wind turbines is aerodynamic, caused by the movement of turbine blades through the air. There is also mechanical sound generated by the turbine itself. Overall sound levels depend on turbine design and wind speed. Some people living close to wind facilities have complained about sound and vibration issues. Under certain lighting conditions, wind turbines can create an effect known as shadow flicker. This annoyance can be minimized with careful siting, planting trees or installing window sunshades, or curtailing wind turbine operations when certain lighting conditions exist.

1.3.1.4 Water use

There is no water impact associated with the operation of wind turbines. As in all manufacturing processes, some water is used to manufacture steel and cement for wind turbines.

1.3.1.5 Life-cycle global warming emissions

While there are no global warming emissions associated with operating wind turbines, there are emissions associated with other stages of a wind turbine's life-cycle, including materials production, materials transportation, on-site construction and assembly, operation and maintenance, and decommissioning and dismantlement. Estimates of total global warming emissions depend on a number of factors, including wind speed, percent of time the wind is blowing, and the material composition of the wind turbine.

1.3.2 Environmental impacts of solar energy systems

1.3.2.1 Land use

Depending on their location, larger utility-scale solar facilities can raise concerns about land degradation and habitat loss. Total land area requirements vary depending on the technology, the topography of the site, and the intensity of the solar resource. Estimates for utility-scale PV systems range from 3.5 to 10 acres per megawatt, while estimates for concentrated solar power (CSP) facilities are between 4 and 16.5 acres per megawatt. Smaller scale solar PV arrays, which can be built on homes or commercial buildings, also have minimal land use impact.

1.3.2.2 Water use

Solar PV cells do not use water for generating electricity. However, as in all manufacturing processes, some water is used to manufacture solar PV components. Concentrating solar thermal plants (CSP), like all thermal electric plants, require water for cooling. Water use depends on the plant design, plant location, and the type of cooling system. CSP plants that use wet-recirculation technology with cooling towers withdraw between 600 and 650 gallons of water per megawatt-hour of electricity produced. CSP plants with once-through cooling technology have higher levels of water withdrawal, but lower total water consumption (because water is not lost as steam). Dry-cooling technology can reduce water use at CSP plants by approximately 90 percent. However, the exchanges to these water savings are higher costs and lower efficiencies.

1.3.2.3 Hazardous materials

The PV cell manufacturing process includes a number of hazardous materials, most of which are used to clean and purify the semiconductor surface. These chemicals, similar to those used in the general semiconductor industry, include hydrochloric acid, sulfuric acid, nitric acid, hydrogen fluoride, tri-chloroethane and acetone. The amount and type of chemicals used depends on the type of cell, the amount of cleaning that is needed, and the size of silicon wafer. Workers also face risks associated with inhaling silicon dust. Thus, PV manufactures must follow the rules to ensure that workers are not harmed by exposure to these chemicals and that manufacturing waste products are disposed of properly.

1.3.2.4 Life-cycle global warming emissions

While there are no global warming emissions associated with generating electricity from solar energy, there are emissions associated with other stages of the solar life-cycle, including manufacturing, materials transportation, installation, maintenance, and decommissioning and dismantlement. Most estimates of life-cycle emissions for photovoltaic systems are between 0.07 and 0.18 pounds of carbon dioxide equivalent per kilowatt-hour.

1.3.3 Environmental impacts of geothermal energy systems

1.3.3.1 Water quality and use

Geothermal power plants can have impacts on both water quality and consumption. Hot water pumped from underground reservoirs often contains high levels of sulfur, salt, and other minerals. Most geothermal facilities have closed-loop water systems, in which extracted water is pumped directly, back into the geothermal reservoir after it has been used for heat or electricity production. In such systems, the water is contained within steel well casings cemented to the surrounding rock. Water is also used by geothermal plants for cooling and re-injection. Depending on the cooling technology used, geothermal plants can require between 1,700 and 4,000 gallons of water per megawatt-hour. However, most geothermal plants can use either geothermal fluid or freshwater for cooling; the use of geothermal fluids rather than freshwater clearly reduces the plants overall water impact.

1.3.3.2 Air emissions

The distinction between open- and closed-loop systems is important with respect to air emissions. In closed-loop systems, gases removed from the well are not exposed to the atmosphere and are injected back into the ground after giving up their heat, so air emissions are minimal. In contrast, open-loop systems emit hydrogen sulfide, carbon dioxide, ammonia, methane, and boron. Hydrogen sulfide, which has a distinctive “rotten egg” smell, is the most common emission. Once in the atmosphere, hydrogen sulfide changes into sulfur dioxide (SO_2). This contributes to the formation of small acidic particulates that can be absorbed by the bloodstream and cause heart and lung disease. Sulfur dioxide also causes acid rain, which damages crops, forests, and soils, and acidifies lakes and streams. However, SO_2 emissions from geothermal plants are approximately 30 times lower per megawatt-hour than from coal plants.

Some geothermal plants also produce small amounts of mercury emissions, which must be mitigated using mercury filter technology. Scrubbers can reduce air emissions, but they produce a watery sludge composed of the captured materials, including sulfur, vanadium, silica compounds, chlorides, arsenic, mercury, nickel, and other heavy metals. This toxic sludge often must be disposed of at hazardous waste sites.

1.3.3.3 Land use

The amount of land required by a geothermal plant varies depending on the properties of the resource reservoir, the amount of power capacity, the type of energy conversion system, the type of cooling system, the arrangement of wells and piping systems, and the substation and auxiliary building needs. The Geysers, the largest geothermal plant in the world, has a capacity of approximately 1,517 megawatts and the area of the plant is approximately 78 square kilometers, which translates to approximately 13 acres per megawatt. Like the Geysers, many geothermal sites are located in remote and sensitive ecological areas, so project developers must take this into account in their planning processes.

1.3.3.4 Life-cycle global warming emissions

In open-loop geothermal systems, approximately 10 percent of the air emissions are carbon dioxide and a smaller amount of emissions are methane, a more potent global warming gas. Estimates of global warming emissions for open-loop systems are approximately 0.1 pounds of carbon dioxide equivalent per kilowatt-hour. In closed-loop systems, these gases are not released into the atmosphere, but there are a still some emissions associated with plant construction and surrounding infrastructure. Enhanced geothermal systems, which require energy to drill and pump water into hot rock reservoirs, have life-cycle global warming emission of approximately 0.2 pounds of carbon dioxide equivalent per kilowatt-hour. To put this into context, estimates of life-cycle global warming emissions for natural gas generated electricity are between 0.6 and 2 pounds of carbon dioxide equivalent per kilowatt-hour and estimates for coal-generated electricity are 1.4 and 3.6 pounds of carbon dioxide equivalent per kilowatt-hour.

1.3.4 Environmental impacts of hydroelectric energy systems

1.3.4.1 Land use

The size of the reservoir created by a hydroelectric project can vary widely, depending largely on the size of the hydroelectric generators and the topography of the land. Hydroelectric plants in flat areas tend to require much more land than those in hilly areas or canyons where deeper reservoirs can hold more volume of water in a smaller space. Flooding land for a hydroelectric reservoir has an extreme environmental impact: it destroys forest, wildlife habitat, agricultural land, and scenic lands.

1.3.4.2 Wildlife impacts

Dammed reservoirs are used for multiple purposes, such as agricultural irrigation, flood control, and recreation, so not all wildlife impacts associated with dams can be directly attributed to hydroelectric power. However, hydroelectric facilities can still have a major impact on aquatic ecosystems. For example, though there are a variety of methods to minimize the impact including fish ladders and in-take screens), fish and other organisms can be injured and killed by turbine blades. Apart from direct contact, there can also be wildlife impacts both within the dammed reservoirs and downstream from the facility. Reservoir water is usually more stagnant than normal river water. As a result, the reservoir will have higher than normal amounts of sediments and nutrients, which can cultivate an excess of algae and other aquatic weeds. These weeds can crowd out other river animal and plant-life, and they must be controlled through manual harvesting or by introducing fish that eat these plants. In addition, water is lost through evaporation in dammed reservoirs at a much higher rate than in flowing rivers.

1.3.4.3 Life-cycle global warming emissions

Global warming emissions are produced during the installation and dismantling of hydroelectric power plants, but recent research suggests that emissions during a facility's operation can also be significant. Such emissions vary greatly depending on the size of the reservoir and the nature of the land that was flooded by the reservoir. Small run-of-the-river plants emit between 0.01 and 0.03 pounds of carbon dioxide equivalent per kilowatt-hour. Life-cycle emissions from large-scale hydroelectric plants built in semi-arid regions are also modest: approximately 0.06 pounds of carbon dioxide equivalent per kilowatt-hour. However, estimates for life-cycle global warming emissions from hydroelectric plants built in tropical areas are much higher. After the area is flooded, the vegetation and soil in these areas decomposes and releases both carbon dioxide and methane. The exact amount of emissions depends greatly on site-specific characteristics. However, current estimates suggest that life-cycle emissions can be over 0.5 pounds of carbon dioxide equivalent per kilowatt-hour.

1.3.5 Environmental IMPACTS of Biomass energy systems

1.3.5.1 Deforestation and land degradation

Biomass comprising traditional fuels constitutes about 50% of energy consumption in developing countries. Deforestation leading to soil erosion, risks of floods, desertification on account of clearing of forests and woodlands for agriculture and livestock, and so on, are the common concerns of environmentalists at macro levels. At a micro level, the concerns range from non-suitability of forest soils for agricultural purposes, health problems due to smoke caused by burning of fuel-wood, loss in soil fertility due to use of agricultural residues and so on. Even a shift towards non-wood biomass fuels creates direct competition with animals that rely upon crop remains and the plants for food. Imbalance between the demand and production of fuel-wood is reported to be one of the primary factors responsible for forest depletion. The increasing use of fuel-wood for meeting the domestic and industrial needs of both rural and urban areas has contributed to forest decline. The environmental impacts of urban fuel-wood consumption have been severe due to commercial exploitation of fuel-wood for charcoal production. The demand for charcoal in urban areas has spread deforestation, which begins at the surrounding areas of urban centres and moving outwards.

1.3.5.2 Loss of soil nutrients

Agricultural residues constitute an important source of energy in rural areas of developing countries when left on fields improves the fertility of the soil. The use of agricultural residues for energy would thus be an issue if it reduces the fertility of the soil. It is important to note that all residues do not have the same effect on the soil. Some residues such as corncobs, rice husk, jute sticks, cotton stock, coffee pruning, and coconut shells do not decompose easily and have potential as energy sources. The choice of agricultural residues thus has an impact on the environment. Cattle dung, similarly, though it is a fertilizer, loses its value as fertilizer if burnt or left under the sun for a few days. The two categories of residues from agriculture sector are crop residue and cattle dung. Currently crop residue of cereals is largely used as food and woody residues are used as fuel. Burning of woody crop residue may not lead to any significant loss of nutrients to soil. Burning of cattle dung as fuel leads to loss of organic matter and other nutrients affecting crop production.

1.3.6 Environmental impacts of tidal energy systems

1.3.6.1 Understanding environmental impacts

In spite of the many benefits of exploiting tidal power, there are negative impacts, as well. For example, the risk to the marine environment and marine mammals is largely unknown. In order to operate tidal power stations appropriately and analyze the potential contribution tidal power can make in terms of renewable energy, we must better understand the environmental impacts of this technology. One important mention is the difference between environmental effects and environmental impacts. On one hand, environmental effects refer to the wide range of potential interactions between tidal energy equipment and the marine ecosystems. On the other hand, environmental impacts are those particular effects that we know for sure will cause deleterious ecological alterations.

1.3.6.2 Environmental impacts of Tidal energy

In many ways, the environmental impacts of harnessing tidal power are similar to those of offshore wind power generation. Several assessments over the past few years have identified the following potential environmental impacts. These indirect ecological impacts would result from lengthy installation of offshore renewable energy projects.

- Changing of substrates, sediment transit and deposition;
- Alteration of waves and sea currents;
- Noise pollution during installation and operation;
- Alteration of ecosystems for regional organisms;
- Emission of harmful electromagnetic fields;
- Intrusion upon animal migrations; and
- Potential strikes by any moving parts of the tidal system.

1.3.7 Environmental impacts of Hydrogen-based energy systems

There is increasing interest in the role that hydrogen-based energy systems may play in the future, especially in the transport sector. They appear to be an attractive alternative to current fossil fuel-based energy systems in the future, since these have been proven to affect climate due to greenhouse gasses emissions. However, any future hydrogen-based economy would need to assess the possible global environmental impacts of such alternative energy production. Emissions of hydrogen lead to increased burdens of methane and ozone and hence to an increase in global warming. Therefore, hydrogen can be considered as an indirect greenhouse gas with the potential to increase global warming. The scientists have estimated that the potential effects on climate from hydrogen-based energy systems would be much lower than those from fossil fuel-based energy systems. However, such impacts will depend on the rate of hydrogen leakage during its synthesis, storage and use. The researchers have calculated that a global hydrogen economy with a leakage rate of 1% of the produced hydrogen would produce a climate impact of 0.6% of the fossil fuel system it replaces. If the leakage rate was 10%, then the climate impact would be 6% of that of the fossil fuel system.

1.3.8 Environmental Impacts of Hydrokinetic Energy systems

Hydrokinetic energy, which includes wave and tidal power, encompasses an array of energy technologies, many of which are still in the experimental stages or in the early stages of deployment. While actual impacts of large-scale operations have not been observed, a range of potential impacts can be projected. For example, wave energy installations can require large expanses of ocean space, which could compete with other uses—such as fishing and shipping—and cause damage to marine life and habitats. Some tidal energy technologies are located at the mouths of ecologically-sensitive estuary systems, which could cause changes in hydrology and salinity that negatively impact animal and plant life.

1.3.9 Greenhouse gas emissions (GHG)

Compared to fossil-fuel-based electricity generation, renewable energy technologies offer a major advantage in lower emissions of CO_2 and other GHGs. In addition, all forms of renewable electricity production are expected to have significantly lower life cycle GHG emissions than electricity production from conventional coal and natural gas plants. Renewable energy would have less of an advantage if carbon capture and sequestration were included with fossil-fuel power plants, or if energy storage systems, such as battery energy storage, compressed air energy storage, or pumped hydro storage, were included as part of renewable energy systems. GHG emissions for some renewable technologies are difficult to estimate. For example, emissions from bio-power vary, depending on which feedstock is used and the assumptions about their production. Most CO_2 emission (CO_2e) values for bio-power range from 15 to 52 g CO_2e/kWh for biomass derived from cultivated feed-stocks, excluding emissions associated with initial land conversion. If carbon capture and storage were added to bio-power systems, there would also be large reductions in CO_2e values. Some studies have suggested that initial flooding of biomass when a hydroelectric reservoir is filled can release large quantities of CO_2 and methane. The amount of these emissions depends on the density of the biomass and the size of the reservoir.

1.4. QUALITATIVE STUDY OF DIFFERENT RENEWABLE ENERGY RESOURCES

1.4.1 Solar energy

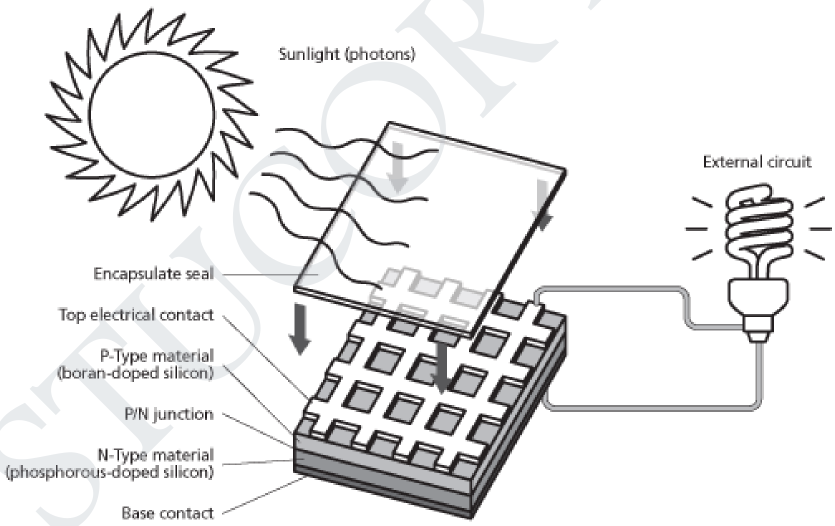
1.4.1.1 Concentrating solar power (CSP) technologies

Concentrating Solar Power (CSP) technologies use mirrors to concentrate (focus) the sun's light energy and convert it into heat to create steam to drive a turbine that generates electrical power. CSP technology utilizes focused sunlight. CSP plants generate electric power by using mirrors to concentrate (focus) the sun's energy and convert it into high-temperature heat. That heat is then channeled through a conventional generator. The plants consist of two parts: one that collects solar energy and converts it to heat, and another that converts the heat energy to electricity.

1.4.1.2 Solar photovoltaic technology basics

Solar cells, also called photovoltaic (PV) cells by scientists, convert sunlight directly into electricity. PV gets its name from the process of converting light (photons) to electricity (voltage), which is called the PV effect. Traditional solar cells are made from silicon, are usually flat-plate, and generally are the most efficient. Second-generation solar cells are called thin-film solar cells because they are made from amorphous silicon or non-silicon materials such as cadmium telluride. Thin film solar cells use layers of semiconductor materials only a few micrometers thick. Because of their flexibility, thin film solar cells can double as rooftop shingles and tiles, building facades, or the glazing for skylights. Third-generation solar cells are being made from a variety of new materials besides silicon, including solar inks using conventional printing press technologies, solar dyes, and conductive plastics. Some new solar cells use plastic lenses or mirrors to concentrate sunlight onto a very small piece of high efficiency PV material. The PV material is more expensive, but because so little is needed, these systems are becoming cost effective for use by utilities and industry.

1.4.1.3 Solar PV array module

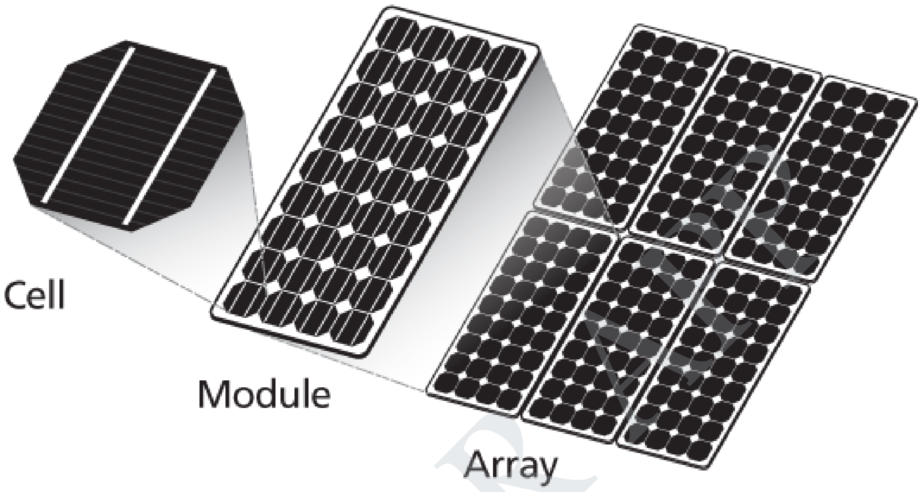


Construction and Working of PV / Solar Cell

The basic element of a PV System is the photovoltaic (PV) cell, also called a Solar Cell. An example of a PV / Solar Cell made of Mono-crystalline Silicon. This single PV / Solar Cell are like a square but with its four corners missing (it is made this way). A PV / Solar Cell is a semiconductor device that can convert solar energy into DC electricity through the Photovoltaic effect (Conversion of solar light energy into electrical energy). When light shines on a PV / Solar Cell, it may be reflected, absorbed, or passes right through. But only the absorbed light generates electricity.

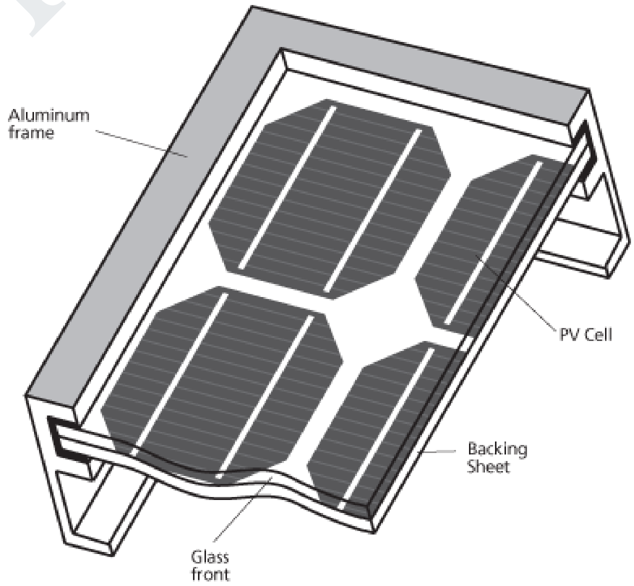
1.4.1.4 PV module / panel and PV array

To increase their utility, a number of individual PV cells are interconnected together in a sealed, weatherproof package called a Panel (Module). For example, a 12 V Panel (Module) will have 36 cells connected in series and a 24 V Panel (Module) will have 72 PV Cells connected in series To achieve the desired voltage and current, Modules are wired in series and parallel into what is called a PV Array. The flexibility of the modular PV system allows designers to create solar power systems that can meet a wide variety of electrical needs.



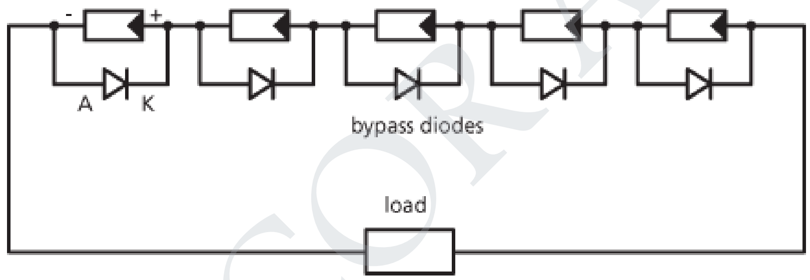
PV Cell, Module and Array

The cells are very thin and fragile so they are sandwiched between a transparent front sheet, usually glass, and a baking sheet, usually glass or a type of tough plastic. This protects them from breakage and from the weather. An aluminum frame is fitted around the module to enable easy fixing to a support structure.



1.4.1.5 Bypass diodes

As mentioned, PV / Solar cells are wired in series and in parallel to form a PV / Solar Panel (Module). The number of series cells indicates the voltage of the Panel (Module), whereas the number of parallel cells indicates the current. If many cells are connected in series, shading of individual cells can lead to the destruction of the shaded cell or of the lamination material, so the Panel (Module) may blister and burst. To avoid such an operational condition, Bypass Diodes are connected anti-parallel to the solar cells as in Figure. As a result, larger voltage differences cannot arise in the reverse-current direction of the solar cells. In practice, it is sufficient to connect one bypass diode for every 15-20 cells. Bypass diodes also allow current to flow through the PV module when it is partially shaded, even if at a reduced voltage and power. Bypass diodes do not cause any losses, because under normal operation, current does not flow through them.



Parallel PV cell with bypass diodes

1.4.1.6 Photovoltaic Power Systems

Photovoltaic (PV) technology converts one form of energy (sunlight) into another form of energy (electricity) using no moving parts, consuming no conventional fossil fuels, creating no pollution, and lasting for decades with very little maintenance. The use of a widely available and reasonably reliable fuel source—the sun—with no associated storage or transportation difficulties and no emissions makes this technology eminently practicable for powering remote scientific research platforms. The completely profitable nature of the technology also lends itself well to varying power requirements–from the smallest autonomous research platforms to infrastructure-based systems. Based on semiconductor technology, solar cells operate on the principle that electricity will flow between two semiconductors when they are put into contact with each other and exposed to light (photons). This phenomenon is known as the photovoltaic effect.

1.4.2 Wind energy

Wind energy is energy from moving air, caused by temperature (and therefore pressure) differences in the atmosphere. Irradiance from the sun heats up the air, forcing the air to rise. Conversely, where temperatures fall, a low pressure zone develops. Winds (i.e. air flows) balance out the differences. Hence, wind energy is solar energy converted into kinetic energy of moving air.

1.4.2.1 Characteristics

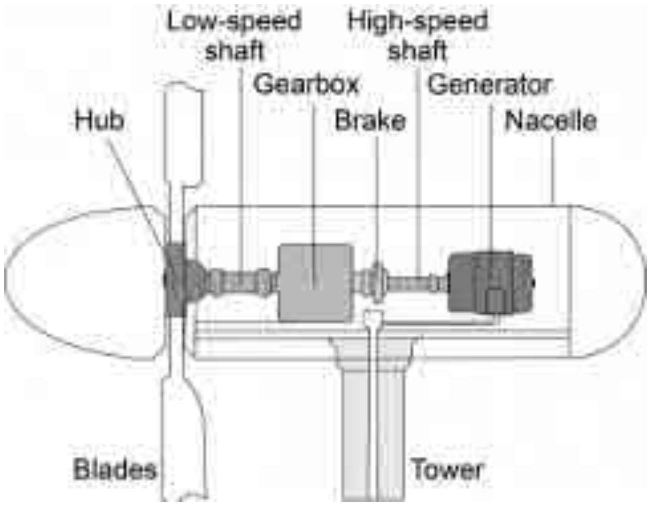
As the wind power is proportional to the cubic wind speed, it is crucial to have detailed knowledge of the site-specific wind characteristics. Even small errors in estimation of wind speed can have large effects on the energy yield, but also lead to poor choices for turbine and site. An average wind speed is not sufficient. Site-specific wind characteristics related to wind turbines include:

- Mean wind speed: Only interesting as a headline figure, but does not tell how often high wind speeds occur.
- Wind speed distribution : diurnal, seasonal, annual patterns
- Turbulence: short-term fluctuations
- Long-Term Fluctuations
- Distribution Of Wind Direction
- Wind Shear (Profile)

1.4.2.2 Wind turbine types

Horizontal Axis Wind Turbines (HAWT)

Horizontal axis wind turbines, also shortened to HAWT, are the common style that most of us think of when we think of a wind turbine. A HAWT has a similar design to a windmill; it has blades that look like a propeller that spin on the horizontal axis. Horizontal axis wind turbines have the main rotor shaft and electrical generator at the top of a tower, and they must be pointed into the wind. Small turbines are pointed by a simple wind vane placed square with the rotor (blades), while large turbines generally use a wind sensor coupled with a servo motor to turn the turbine into the wind. Most large wind turbines have a gearbox, which turns the slow rotation of the rotor into a faster rotation that is more suitable to drive an electrical generator.



Horizontal Axis Wind Turbine

Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Wind turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount.

Advantages

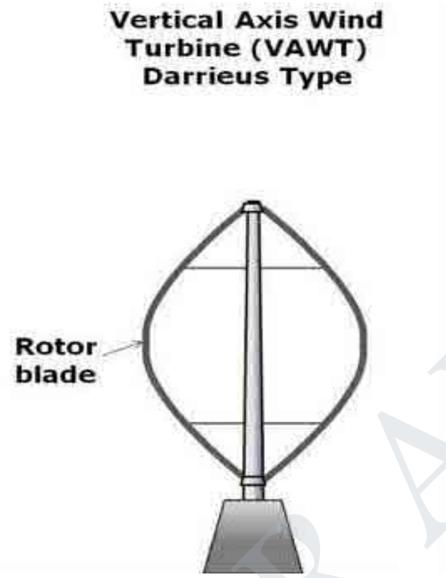
- The tall tower base allows access to stronger wind in sites with wind shear.
- High efficiency since the blades always moves perpendicularly to the wind, receiving power through the whole rotation.
- In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to backtrack against the wind for part of the cycle.
- Backtracking against the wind leads to inherently lower efficiency.

Disadvantages

- Massive tower construction is required to support the heavy blades, gearbox, and generator.
- Components of a horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) being lifted into position.
- Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
- HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

Vertical Axis Wind Turbines (VAWT)

Vertical axis wind turbines, as shortened to VAWTs, have the main rotor shaft arranged vertically. The main advantage of this arrangement is that the wind turbine does not need to be pointed into the wind. This is an advantage on sites where the wind direction is highly variable or has turbulent winds. With a vertical axis, the generator and other primary components can be placed near the ground, so the tower does not need to support it, also makes maintenance easier. The main drawback of a VAWT generally creates drag when rotating into the wind.



Vertical Axis Wind Turbine

It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten its service life. However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and these can double the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

Advantages

- No yaw mechanisms are needed.
- A VAWT can be located nearer the ground, making it easier to maintain the moving parts.
- VAWTs have lower wind startup speeds than the typical the HAWTs.
- VAWTs may be built at locations where taller structures are prohibited.

- VAWTs situated close to the ground can take advantage of locations where rooftops, mesas, hilltops, ridgelines, and passes funnel the wind and increase wind velocity.

Disadvantages

- Most VAWTs have an average decreased efficiency from a common HAWT, mainly because of the additional drag that they have as their blades rotate into the wind.
- Versions that reduce drag produce more energy, especially those that funnel wind into the collector area.
- Having rotors located close to the ground where wind speeds are lower and do not take advantage of higher wind speeds above.

1.4.3 Component of a wind turbine

1.4.3.1 Rotor

The part of the wind turbine that collects energy from the wind is called the rotor. The rotor usually consists of two or more wooden, fiberglass or metal blades which rotate about an axis (horizontal or vertical) at a rate determined by the wind speed and the shape of the blades. The blades are attached to the hub, which in turn is attached to the main shaft.

1.4.3.2 Drag Design

Blade designs operate on either the principle of drag or lift. For the drag design, the wind literally pushes the blades out of the way. Drag powered wind turbines are characterized by slower rotational speeds and high torque capabilities. They are useful for the pumping, sawing or grinding work. For example, a farm-type windmill must develop high torque at start-up in order to pump, or lift, water from a deep well.

1.4.3.3 Lift Design

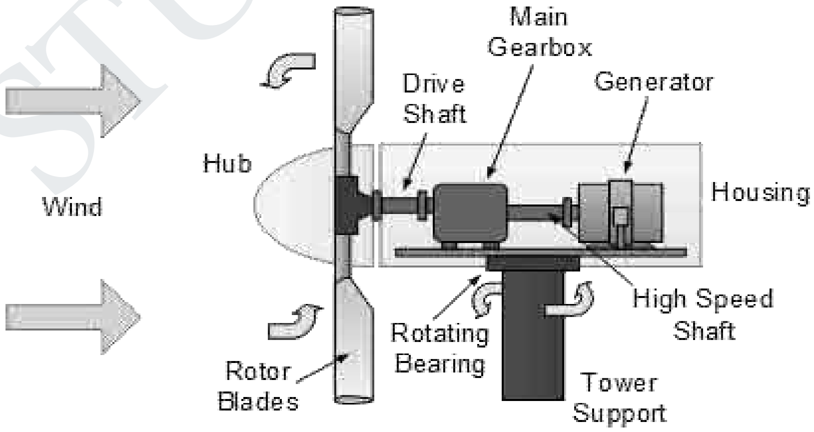
The lift blade design employs the same principle that enables airplanes, kites and birds to fly. The blade is essentially an airfoil, or wing. When air flows past the blade, a wind speed and pressure differential is created between the upper and lower blade surfaces. The pressure at the lower surface is greater and thus acts to "lift" the blade. When blades are attached to a central axis, like a wind turbine rotor, the lift is translated into rotational motion. Lift-powered wind turbines have much higher rotational speeds than drag types and therefore well suited for electricity generation.

1.4.3.4 Tip Speed Ratio

The tip-speed is the ratio of the rotational speed of the blade to the wind speed. The larger this ratio, the faster the rotation of the wind turbine rotor at a given wind speed. Electricity generation requires high rotational speeds. Lift-type wind turbines have maximum tip-speed ratios of around 10, while drag-type ratios are approximately 1. Given the high rotational speed requirements of electrical generators, it is clear that the lift-type wind turbine is most practical for this application.

1.4.3.5 Generator

The generator is what converts the turning motion of a wind turbine's blades into electricity. Inside this component, coils of wire are rotated in a magnetic field to produce electricity. Different generator designs produce either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings. The generator's rating, or size, is dependent on the length of the wind turbine's blades because more energy is captured by longer blades. It is important to select the right type of generator to match your intended use. Most home and office appliances operate on 120 volt (or 240 volt), 60 cycle AC. Some appliances can operate on either AC or DC, such as light bulbs and resistance heaters, and many others can be adapted to run on DC. Storage systems using batteries store DC and usually are configured at voltages of between 12 volts and 120 volts. Generators that produce AC are generally equipped with features to produce the correct voltage (120 or 240 V) and constant frequency (60 cycles) of electricity, even when the wind speed is fluctuating.



Components of a wind turbine

1.4.3.6 Transmission

The number of revolutions per minute (rpm) of a wind turbine rotor can range between 40 rpm and 400 rpm, depending on the model and the wind speed. Generators typically require rpm's of 1,200 to 1,800. As a result, most wind turbines require a gear-box transmission to increase the rotation of the generator to the speeds necessary for efficient electricity production. Some DC-type wind turbines do not use transmissions. Instead, they have a direct link between the rotor and generator. These are known as direct drive systems. Without a transmission, wind turbine complexity and maintenance requirements are reduced, but a much larger generator is required to deliver the same power output as the AC-type wind turbines.

1.4.3.7 Towers

The tower on which a wind turbine is mounted is not just a support structure. It also raises the wind turbine so that its blades safely clear the ground and so it can reach the stronger winds at higher elevations. Maximum tower height is optional in most cases, except where zoning restrictions apply. The decision of what height tower to use will be based on the cost of taller towers versus the value of the increase in energy production resulting from their use.

1.4.3.8 Advantages and disadvantages of wind power

Advantages

- The wind is free and with modern technology it can be captured efficiently.
- Once the wind turbine is built the energy it produces does not cause green house gases or other pollutants.
- Although wind turbines can be very tall each takes up only a small plot of land.
- Many people find wind farms an interesting feature of the landscape.
- Remote areas that are not connected to the electricity power grid can use wind turbines to produce their own supply.
- Wind turbines are available in a range of sizes which means a vast range of people and businesses can use them.

Disadvantages

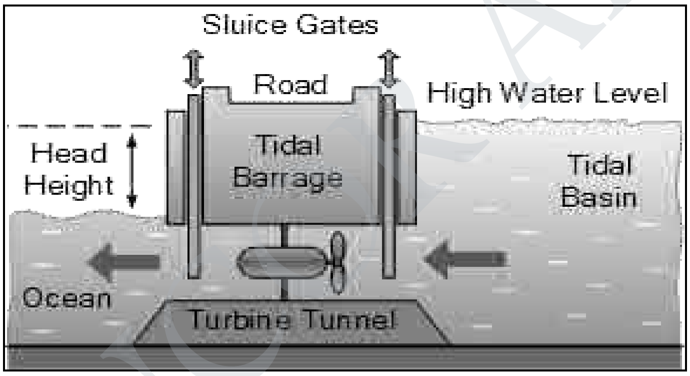
- More noise
- Threatening to Wildlife.
- Wind is Unpredictable.
- Limited Resource.
- Inefficient.
- Poor Television Reception.
- Installation Cost is high.

1.4.4 Ocean Power

1.4.4.1 Tidal Energy Generation

Tidal energy, just like hydro energy transforms water in motion into a clean energy. The motion of the tidal water, driven by the pull of gravity, contains large amounts of kinetic energy in the form of strong tidal currents called tidal streams. The daily ebbing and flowing, back and forth of the oceans tides along a coastline and into and out of small inlets, bays or coastal basins, is little different to the water flowing down a river or stream. The movement of the sea water is harnessed in a similar way using waterwheels and turbines to that used to generate hydro electricity. But because the sea water can flow in both directions in a tidal energy system, it can generate power when the water is flowing in and also when it is ebbing out. Therefore, tidal generators are designed to produce power when the rotor blades are turning in either direction. However, the costs of reversible electrical generators are more expensive than single direction generators.

1.4.4.2 Different Types of Tidal Energy Systems



Tidal Barrage

Tidal Barrage:

A *Tidal Barrage* is a type of tidal power generation that involves the construction of a fairly low dam wall, known as a “barrage” and hence its name, across the entrance of a tidal inlet or basin creating a tidal reservoir. This dam has a number of underwater tunnels cut into its width allowing sea water to flow through them in a controllable way using “sluice gates”. Fixed within the tunnels are huge water turbine generators that spin as the water rushes past them generating tidal electricity. Tidal barrages generate electricity using the difference in the vertical height between the incoming high tides and the outgoing low tides. As the tide ebbs and flows, sea water is allowed to flow in or out of the reservoir through a one way underwater tunnel system. This flow of tidal water back and forth causes the water turbine generators located within the tunnels to rotate producing tidal energy with special generators used to produce electricity on both the incoming and the outgoing tides.

Tidal Stream

Tidal Stream

A *Tidal Stream Generation* system reduces some of the environmental effects of tidal barrages by using turbine generators under the surface of the water. Major tidal flows and ocean currents, like the Gulf Stream, can be exploited to extract its tidal energy using underwater rotors and turbines. Tidal stream generation is very similar in principal to wind power generation, except this time water currents flow across turbines rotor blades which rotates the turbine, much like how wind currents turn the blades for wind power turbines. In fact, tidal stream generation areas on the sea bed can look just like underwater wind farms. Tidal streams are formed by the horizontal fast flowing volumes of water caused by the ebb and flow of the tide as the profile of the sea bed causes the water to speed up as it approaches the shoreline.

1.4.4.3 Advantages and disadvantages of Tidal Energy

Advantages

- Tidal energy is a renewable energy resource because the energy it produces is free and clean as no fuel is needed and no waste bi-products are produced.
- Tidal energy has the potential to produce a great deal of free and green energy.
- Tidal energy is not expensive to operate and maintain compared to other forms of renewable energies.
- Low visual impact as the tidal turbines are mainly if not totally submerged beneath the water.
- Low noise pollution as any sound generated is transmitted through the water.
- Tidal barrages provide protection against flooding and land damage.
- Large tidal reservoirs have multiple uses and can create recreational lakes and areas where before there were none.

Disadvantages of Tidal Energy

- Tidal energy is not always a constant energy source as it depends on the strength and flow of the tides which themselves are affected by the gravitational effects of the moon and the sun.
- Tidal Energy requires a suitable site, where the tides and tidal streams are consistently strong.
- Must be able to withstand forces of nature resulting in high capital, construction and maintenance costs.
- High power distribution costs to send the generated power from the submerged devices to the land using long underwater cables.
- Danger to fish and other sea-life as they get stuck in the barrage or sucked through the tidal turbine blades.

1.4.5 Wave energy

Waves are caused by the wind blowing over the surface of the ocean. In many areas of the world, the wind blows with enough consistency and force to provide continuous waves along the shoreline. Ocean waves contain tremendous energy potential. Wave power devices extract energy from the surface motion of ocean waves or from pressure fluctuations below the surface. Wave power varies considerably in different parts of the world. While an abundance of wave energy is available, it cannot be fully harnessed everywhere for a variety of reasons, such as other competing uses of the ocean (i.e. shipping, commercial fishing, naval operations) or environmental concerns in sensitive areas. Therefore, it is important to consider how much resource is recoverable in a given region.

1.4.6 Ocean thermal energy conversion (OTLC)

1.4.6.1 Closed-Cycle of OTLC

Closed-cycle systems use fluids with a low boiling point, such as ammonia, to rotate a turbine to generate electricity. Warm surface seawater is pumped through a heat exchanger, where the low-boiling-point fluid is vaporized. The expanding vapor turns the turbo-generator. Cold deep seawater—which is pumped through a second heat exchanger—then condenses the vapor back into a liquid that is then recycled through the system.

1.4.6.2 Open-Cycle of OTLC

Open-cycle systems use the tropical oceans' warm surface water to make electricity. When warm seawater is placed in a low-pressure container, it boils. The expanding steam drives a low-pressure turbine attached to an electrical generator. The steam, which has left its salt behind in the low-pressure container, is almost pure, fresh water. It is condensed back into a liquid by exposure to cold temperatures from deep-ocean water.

1.4.6.3 Hybrid OTLC

Hybrid systems combine the features of closed- and open-cycle systems. In a hybrid system, warm seawater enters a vacuum chamber, where it is flash-evaporated into steam, similar to the open-cycle evaporation process. The steam vaporizes a low-boiling-point fluid (in a closed-cycle loop) that drives a turbine to produce electricity.

1.4.6.4 Complementary Technologies

OTEC has potential benefits beyond power production. For example, spent cold seawater from an OTEC plant can chill fresh water in a heat exchanger or flow directly into a cooling system. OTEC technology also supports chilled-soil agriculture. When cold seawater flows through underground pipes, it chills the surrounding soil. The temperature difference between plant roots in the cool soil and plant leaves in the warm air allows many plants that evolved in temperate climates to be grown in the subtropics.

1.4.7 Biomass power plants

The most common types of boilers are hot water boilers and steam boilers. Wood chips, residues and other types of biomass are used in the boilers, in the same way as coal, natural gas and oil. Fuel is stored in a bunker for further transport to the boiler. In the boiler, water is heated to high temperature under pressure. Steam from the boiler powers the turbine, which is connected to the generator. Steam has passed through the turbine, heats area heating water, which is distributed through the area heating network's piping. Co-firing biomass with coal (replacing a portion of coal with biomass) is an effective method of using biomass for energy purposes and to reduce CO_2 emissions. Coal plants can be made suitable to replace part of the coal by biomass or even to convert fully to biomass – turning a coal plant into a 100% renewable energy plant.

1.4.7.1 Biomass used for electricity generation

Forest products: Woody biomass from multi-functional forests constitutes the majority of today's biomass. Pellets and briquettes are manufactured by compressing by-products from the forestry industry, such as sawdust, bark or small diameter wood. They are easy to transport and therefore suitable for export.

Waste, by-products and residues: Residues include manure, sewage, sludge and other degradable waste. Liquid biomass waste, such as manure, household waste and sewage plant residues, can be digested to biogas.

Energy crops: Energy crops are not used on a large scale for electricity or heat production today. As demand for sustainable biomass increases over time, such energy crops may play a more important role in the future. Examples include woody short rotation forestry/crops such as eucalyptus, poplar and willow. But also herbaceous (grassy) energy crops such as miscanthus can be used. Especially with the use of energy crops, it is important to ensure these plantations are established and managed in a sustainable manner.

1.4.8 Fuel cell

Fuel cell is a device that uses hydrogen (or hydrogen-rich fuel) and oxygen to create electricity by an electrochemical process. A single fuel cell consists of an electrolyte sandwiched between two thin electrodes (a porous anode and cathode). Hydrogen, or a hydrogen-rich fuel, is fed to the anode where a catalyst separates hydrogen's negatively charged electrons from positively charged ions (protons). At the cathode, oxygen combines with electrons and, in some cases, with species such as protons or water, resulting in water or hydroxide ions, respectively. The electrons from the anode side of the cell cannot pass through the membrane to the positively charged cathode; they must travel around it via an electrical circuit to reach the other side of the cell. This movement of electrons is an electrical current. The amount of power produced by a fuel cell depends upon several factors, such as fuel cell type, cell size, the temperature at which it operates, and the pressure at which the gases are supplied to the cell.

1.4.9 Hydrogen energy

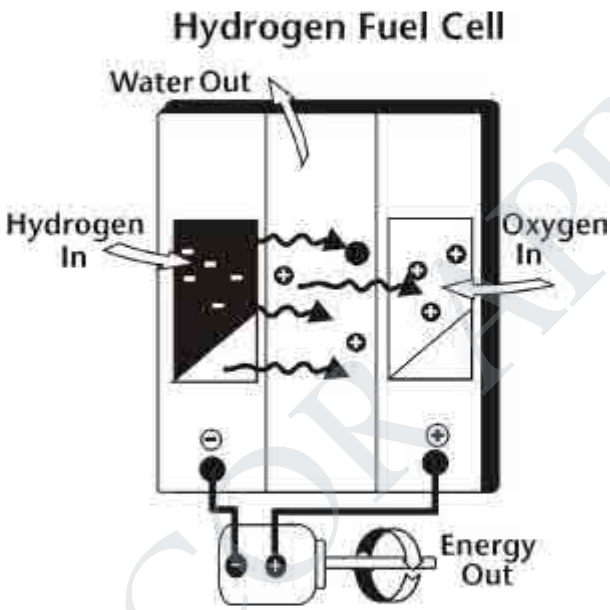
Hydrogen can be considered as a clean energy carrier similar to electricity. Hydrogen can be produced from various domestic resources such as renewable energy and nuclear energy. In the long-term, hydrogen will simultaneously reduce the dependence on foreign oil and the emission of greenhouse gases and other pollutants.

1.4.9.1 Hydrogen as an Energy Carrier

Hydrogen is considered as a secondary source of energy, commonly referred to as an energy carrier. Energy carriers are used to move, store and deliver energy in a form that can be easily used. Electricity is the most well-known example of an energy carrier. Hydrogen as an important energy carrier in the future has a number of advantages. For example, a large volume of hydrogen can be easily stored in a number of different ways. Hydrogen is also considered as a high efficiency, low polluting fuel that can be used for transportation, heating, and power generation in places where it is difficult to use electricity. In some instances, it is cheaper to ship hydrogen by pipeline than sending electricity over long distances by wire.

1.4.9.2 Hydrogen Fuel Cell

Fuel cells directly convert the chemical energy in hydrogen to electricity, with pure water and heat as the only byproducts. Hydrogen-powered fuel cells are not only pollution-free, but a two to three fold increase in the efficiency can be experienced when compared to traditional combustion technologies.



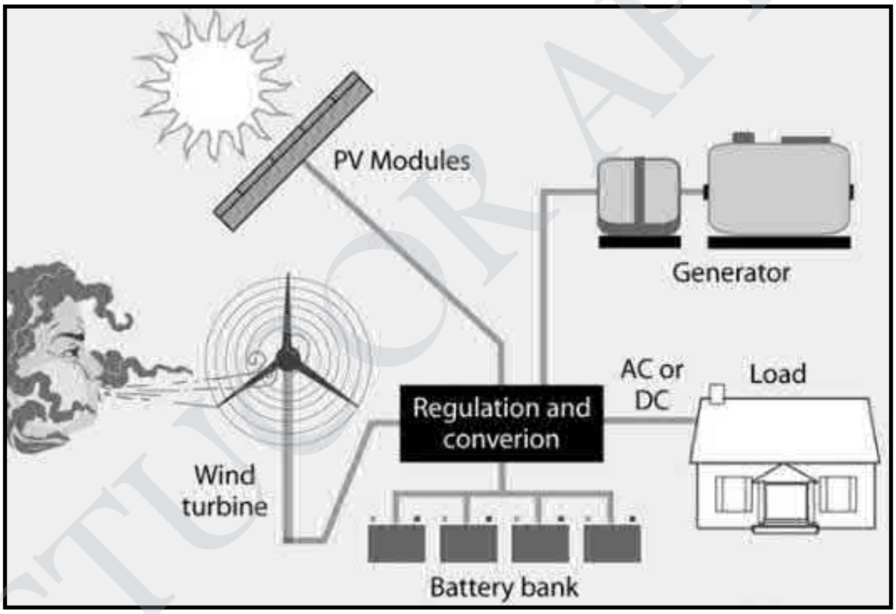
Hydrogen Fuel Cell

Fuel cells can power almost any portable devices that normally use batteries. Fuel cells can also power transportation such as vehicles, trucks, buses, and marine vessels, as well as provide auxiliary power to traditional transportation technologies. Hydrogen can play a particularly important role in the future by replacing the imported petroleum we currently use in our cars and trucks.

1.5. HYBRID RENEWABLE ENERGY SYSTEMS

Environmentally friendly power generation technologies will play an important role in future power supply. The renewable energy technologies include power generation from renewable energy sources, such as wind, PV(photovoltaic), MH(micro hydro), biomass, ocean wave, geothermal and tides. In general, the key reason for the deployment of the above energy systems are their benefits, such as supply security, reduced carbon emission, improved power quality, reliability and employment opportunity to the local people. Since the renewable energy resources are intermittent in nature therefore, hybrid combinations of two or more power generation technologies, along with storage can improve system performance. Hybrid Renewable Energy System (HRES) combines two or more renewable energy resources with some conventional source (diesel or petrol generator) along with storage, in order to fulfill the demand of an area. The intensity of the different energy sources into time is not the same. In general, when one of the sources is intensive, the other tends to be extensive, i.e. the sources complement one another. The distribution into time and the intensity of the energy sources depend on the meteorological conditions of the chosen area, on the season, on the relief, etc. The following definition of a hybrid system with renewable energy sources can be suggested. This is a power system, using one renewable and one conventional energy source or more than one renewable with or without conventional energy sources, that works in "stand alone" or "grid connected" mode.

1.5.1 Hybrid Wind and Solar Electric Systems



Hybrid Wind and Solar Electric Systems

A hybrid renewable energy system utilizes two or more energy production methods, usually solar and wind power. The major advantage of solar / wind hybrid system is that when solar and wind power production is used together, the reliability of the system is enhanced. Additionally, the size of battery storage can be reduced slightly as there is less reliance on one method of power production. Often, when there is no sun, there is plenty of wind. It is ideally suited to remote homes, schools and other off-grid applications. They can also be retrofitted to existing diesel-generator systems to save on high fuel costs and minimize noise.

Because the peak operating times for wind and solar systems occur at different times of the day and year, hybrid systems are more likely to produce power when need it. Many hybrid systems are stand-alone systems, which operate "off-grid" -- not connected to an electricity distribution system. For the times when neither the wind nor the solar system are producing, most hybrid systems provide power through batteries and/or an engine generator powered by conventional fuels, such as diesel. If the batteries run low, the engine generator can provide power and recharge the batteries. Adding an engine generator makes the system more complex, but modern electronic controllers can operate these systems automatically. An engine generator can also reduce the size of the other components needed for the system. Keep in mind that the storage capacity must be large enough to supply electrical needs during non-charging periods. Battery banks are typically sized to supply the electric load for one to three days. Since hybrid systems include both solar and wind power, they allow the power user to benefit from the advantages provided of both forms of energy.

1.5.2 Advantages of Hybrid Energy System

- Reductions in size of diesel engine and battery storage system, which can save the fuel and reduce pollution.
- Improves the load factors and help saving on maintenance and replacement costs.
- The cost of electricity can be reduced by integrating diesel systems with renewable power generation.
- Renewable hybrid energy systems can reduce the cost of high-availability renewable energy systems.

APPENDIX

Content beyond the Syllabus

A.1.1 Renewable energy sources in India

Renewable energy in India comes under the purview of the **Ministry of New and Renewable Energy** **(MNRE)**. Newer renewable electricity sources are targeted to grow massively by 2022, including a more than doubling of India's large wind power capacity and an almost 15 fold increase in solar power from April 2016 levels. Such ambitious targets would place India amongst the world leaders in renewable energy use and place India at the centre of its International Solar Alliance project promoting the growth and development of solar power internationally to over 120 countries.

India was the first country in the world to set up a ministry of non-conventional energy resources, in the early 1980s. India's overall installed capacity has reached **329.4 GW**, with renewable accounting for **57.472 GW** as of 14 June 2017. 61% of the renewable power came from wind, while solar contributed nearly **19%**. Large hydro installed capacity was **44.41 GW** as of 28 February 2017 and is administered separately by the Ministry of Power and not included in MNRE targets.

From 2015 onwards the MNRE began laying down actionable plans for the renewable energy sector under its ambit to make a quantum jump, building on strong foundations already established in the country. MNRE renewable electricity targets have been up scaled to grow from just under **43 GW** in April 2016 to **175 GW** by the year 2022, including **100 GW** from solar power, 60 GW from wind power, **10 GW** from bio power and **5 GW** from small hydro power. The Ministry of Power has announced that no new coal-based capacity addition is required for the 10 years to 2027 beyond the **50 GW** under different stages of construction and likely to come online between 2017 and 2022 The ambitious targets would see India quickly becoming one of the leading green energy producers in the world and surpassing numerous developed countries. The government intends to achieve 40% cumulative electric power capacity from non fossil fuel sources by 2030.

A.1.2 Wind power in India

The development of wind power in India began in the 1990s, and has significantly increased in the last few years. Although a relative newcomer to the wind industry compared with Denmark or the US, domestic policy support for wind power has led India to become the country with the fourth largest installed wind power capacity in the world.

As of 28 February 2017 the installed capacity of wind power in India was **29151.29 MW**, mainly spread across Tamil Nadu (**7,269.50 MW**), Maharashtra (**4,100.40 MW**), Gujarat (**3,454.30 MW**), Rajasthan (**2,784.90 MW**), Karnataka (**2,318.20 MW**), Andhra Pradesh (**746.20 MW**) and Madhya Pradesh (**423.40 MW**) Wind power accounts for 14% of India's total installed power capacity. India has set an ambitious target to generate 60,000 MW of electricity from wind power by 2022.

A.1.3 Solar power in India

India is densely populated and has high solar insolation, an ideal combination for using solar power in India. Much of the country does not have an electrical grid, so one of the first applications of solar power has been for water pumping; to begin replacing India's four to five million diesel powered water pumps, each consuming about 3.5 kilowatts, and off-grid lighting. Some large projects have been proposed, and a 35,000 km^2 (14,000 sq mi) area of the Thar Desert has been set aside for solar power projects, sufficient to generate **700 to 2,100 GW**.

The Indian Solar Loan Programme, supported by the United Nations Environment Programme has won the prestigious Energy Globe World award for Sustainability for helping to establish a consumer financing program for solar home power systems. Over the span of three years more than 16,000 solar home systems have been financed through 2,000 bank branches, particularly in rural areas of South India where the electricity grid does not yet extend. Launched in 2003, the Indian Solar Loan Programme was a four-year partnership between UNEP, The UNEP RISOE Centre, and two of India's largest banks, the Canara Bank and Syndicate Bank.

Announced in November 2009, the Government of India proposed to launch its Jawaharlal Nehru National Solar Mission under the National Action Plan on Climate Change with plans to generate **1,000 MW** of power by 2013 and up to **20,000 MW** grid-based solar power, **2,000 MW** of off-grid solar power and cover 20×10^6 m^2 (220×10^6 sq ft) with collectors by the end of the final phase of the mission in 2020. The Mission aims to achieve grid parity (electricity delivered at the same cost and quality as that delivered on the grid) by 2020. Achieving this target would establish India as a global leader in solar power generation. India is also the home to the world's first and only 100% solar powered airport, located at Cochin, Kerala.

EE6009 POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

UNIT II

ELECTRICAL MACHINES FOR RENEWABLE ENERGY CONVERSION

SYLLABUS: Reference theory fundamentals-principle of operation and analysis: IG, PMSG, SCIG and DFIG.

2.1 INTRODUCTION TO ELECTRO-MECHANICAL ENERGY CONVERSION

Energy exists in many forms, and we use numerous devices on a daily basis that convert one form of energy into another. When we speak of electromechanical energy conversion, however, we mean either the conversion of electric energy into mechanical energy or vice versa. For example, an electric motor converts electric energy into mechanical energy. On the other hand, an electric generator transforms mechanical energy to electric energy. Electromechanical energy conversion is a reversible process except for the losses in the system. The term "reversible" implies that the energy can be transferred back and forth between the electrical and the mechanical systems. However, each time we go through an energy conversion process, some of the energy is converted into heat and is lost from the system forever.

When a current-carrying conductor is placed in a magnetic field, it experiences a force that tends to move it. If the conductor is free to move in the direction of the magnetic force, the magnetic field aids in the conversion of electric energy into mechanical energy. This is essentially the principle of operation of all electric motors. On the other hand, if an externally applied force makes the conductor move in a direction opposite to the magnetic force, the mechanical energy is converted into electric energy. Generator action is based upon this principle.

Introduction For energy conversion between electrical and mechanical forms, electromechanical devices are developed. In general, electromechanical energy conversion devices can be divided into three categories:

Transducers (for measurement and control): These devices transform the signals of different forms. Examples are microphones, pickups, and speakers.

Force producing devices (linear motion devices): These type of devices produce forces mostly for linear motion drives, such as relays, solenoids (linear actuators), and electromagnets.

Continuous energy conversion equipment: These devices operate in rotating mode. A device would be known as a generator if it converts mechanical energy into electrical energy, or as a motor if it does the other way around (from electrical to mechanical). Since the permeability of ferromagnetic materials is much larger than the permittivity of dielectric materials, it is more advantageous to use electromagnetic field as the medium for electromechanical energy conversion.

2.2 REFERENCE THEORY FUNDAMENTALS

Transformation of three phase electrical quantities to two phase quantities is a usual practice to simplify analysis of three phase electrical circuits. Polyphase A.C machines can be represented by an equivalent two phase model provided the rotating polyphases winding in rotor and the stationary polyphase windings in stator can be expressed in a fictitious two axes coils. The process of replacing one set of variables to another related set of variable is called winding transformation or simply transformation or linear transformation. The term linear transformation means that the transformation from old to new set of variable and vice versa is governed by linear equations. The equations relating old variables and new variables are called transformation equation and the following general form:

[New Variable] = [Transformation matrix][Old variable]

[Old Variable] = [Transformation matrix][New variable]

Transformation matrix is a matrix containing the coefficients that relates new and old variables. Note that the second transformation matrix in the above-mentioned general form is inverse of first transformation matrix. The transformation matrix should account for power invariance in the two frames of reference. In case power invariance is not maintained, then torque calculation should be from original machine variables only.

2.3 INTRODUCTION TO REFERENCE FRAME THEORY

2.3.1 Overview

As the application of ac machines has continued to increase over this century, new techniques have been developed to aid in their analysis. Much of the analysis has been carried out for the treatment of the well-known induction machine. The significant breakthrough in the analysis of three-phase ac machines was the development of reference frame theory. Using these techniques, it is possible to transform the phase variable machine description to another reference frame. By judicious choice of the reference frame, it proves possible to simplify considerably the complexity of the mathematical machine model. While these techniques were initially developed for the analysis and simulation of ac machines, they are now invaluable tools in the digital control of such machines. As digital control techniques are extended to the control of the currents, torque and flux of such machines, the need for compact, accurate machine models is obvious.

Fortunately, the developed theory of reference frames is equally applicable to the synchronous machines, such as the Permanent Magnet Synchronous Machine (PMSM). This machine is sometimes known as the sinusoidal brushless machines or the brushless ac machine and is very popular as a high-performance servo drive due to its superior torque-to-weight ratio and its high dynamic capability. It is a three-phase synchronous ac machine with permanent-magnet rotor excitation and is designed to have a sinusoidal torque-position characteristic. The aim of this section is to introduce the essential concepts of reference frame theory and to introduce the space vector notation that is used to write compact mathematical descriptions of ac machines. Over the years, many different reference frames have been proposed for the analysis of ac machines. The most commonly used ones are the so-called stationary reference frame and the rotor reference frame.

2.3.2 Clarke's Transformation

The transformation of stationary circuits to a stationary reference frame was developed by E. Clarke. The stationary two-phase variables of Clarke's transformation are denoted as α and β. As shown in Figure 2.1, α-axis and β-axis are orthogonal.

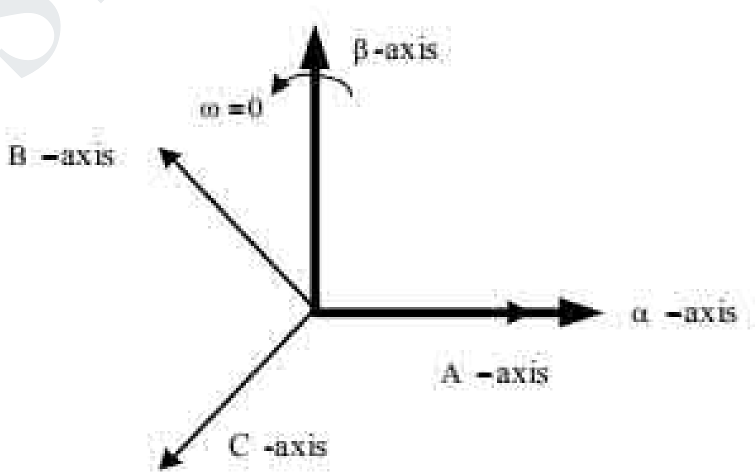


Figure 2.1: Clarke's transformation

In order for the transformation to be invertible, a third variable, known as the zero-sequence component, is added. The resulting transformation is

$$[f_{\alpha\beta 0}] = T_{\alpha\beta 0}[f_{abc}] \qquad (1)$$

where

$[f_{\alpha\beta 0}] = [f_{\alpha} \quad f_{\beta} \quad f_0]^T$

and

$[f_{abc}] = [f_a \quad f_b \quad f_c]^T$

Where f represents voltage, current, flux linkages, or electric charge and the transformation matrix, $T_{\alpha\beta 0}$ is given by

$$T_{\alpha\beta 0} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \qquad (2)$$

The inverse transformation is given by

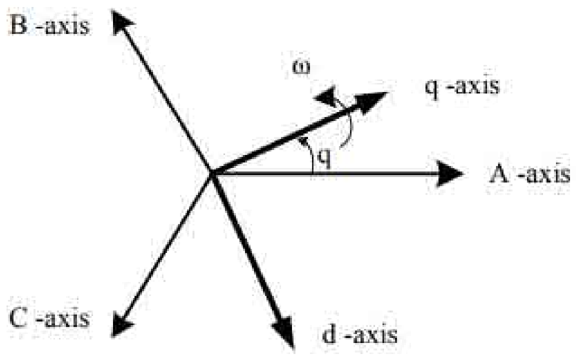
$$[f_{abc}] = T_{\alpha\beta 0}{}^{-1}[f_{\alpha\beta 0}] \qquad (3)$$

where the inverse transformation matrix is presented by

$$T_{\alpha\beta 0}{}^{-1} = \frac{2}{3}\begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \qquad (4)$$

2.3.3 Park's Transformation

Park's transformation, a revolution in machine analysis, has the unique property of eliminating all time varying inductances from the voltage equations of three-phase ac machines due to the rotor spinning. Although changes of variables are used in the analysis of ac machines to eliminate time-varying inductances, changes of variables are also employed in the analysis of various static and constant parameters in power system components. Fortunately, all known real transformations for these components are also contained in the transformation to the arbitrary reference frame. The same general transformation used for the stator variables of ac machines serves the rotor variables of induction machines. Park's transformation is a well-known three-phase to two-phase transformation in synchronous machine analysis.



Park's transformation

The transformation equation is of the form

$[f_{dq0s}] = T_{dq0}(\theta)[f_{abcs}]$ (1)

where

$[f_{dq0s}] = [f_{qs} \quad f_{ds} \quad f_{0s}]^T$

and

$[f_{abcs}] = [f_{as} \quad f_{bs} \quad f_{cs}]^T$

and the dq0 transformation matrix is defined as

$$T_{dq0}(\theta) = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (2)$$

θ is the angular displacement of Park's reference frame and can be calculated by

$$\theta = \int_0^t \omega(\zeta)\, d\zeta + \theta(0) \quad (3)$$

where ζ is the dummy variable of integration. It can be shown that for the inverse transformation we can write

$[f_{abcs}] = T_{dq0}(\theta)^{-1}.[f_{dq0s}]$ (4)

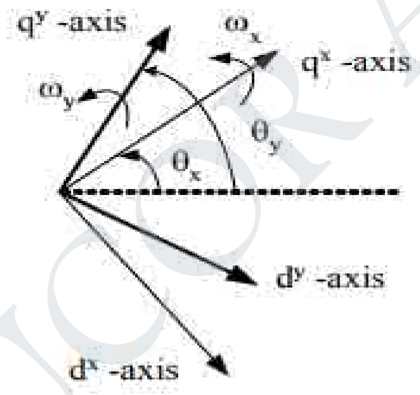
where the inverse of Park's transformation matrix is given by

$$T_{dq0}(\theta)^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \quad (5)$$

In the previous equations, the angular displacement θ must be continuous, but the angular velocity associated with the change of variables is unspecified. The frame of reference may rotate at any constant, varying angular velocity, or it may remain stationary. The angular velocity of the transformation can be chosen arbitrarily to best fit the system equation solution or to satisfy the system constraints. The change of variables may be applied to variables of any waveform and time sequence; however, we will find that the transformation given above is particularly appropriate for an a-b-c sequence.

2.3.4 Transformations between Reference Frames

In order to reduce the complexity of some derivations, it is necessary to transform the variables from one reference frame to another one. To establish this transformation between any two reference frames, we can denote y as the new reference frame and x as the old reference frame. Both new and old reference frames are shown in Figure.



Transformation between two reference frames

It is assumed that the reference frame x is rotating with angular velocity ωx and the reference frame y is spinning with the angular velocity ωy. θx and θy are angular displacements of reference frames x and y, respectively. In this regard, we can rewrite the transformation equation as

$$[f_{dq0s}^{y}] = T_{dq0s}^{x\to y}.[f_{dq0s}] \qquad (1)$$

But we have

$$[f_{dq0s}^{x}] = T_{dq0s}^{x}.[f_{abcs}] \qquad (2)$$

If we substitute (2) in (1) we get

$$[f_{dq0s}^{y}] = T_{dq0s}^{x\to y}.T_{dq0s}^{x}.[f_{abcs}] \qquad (3)$$

In another way, we can find out that

$$[f_{dq0s}^{y}] = T_{dq0s}^{y}.[f_{abcs}] \quad (4)$$

From (3) we obtain

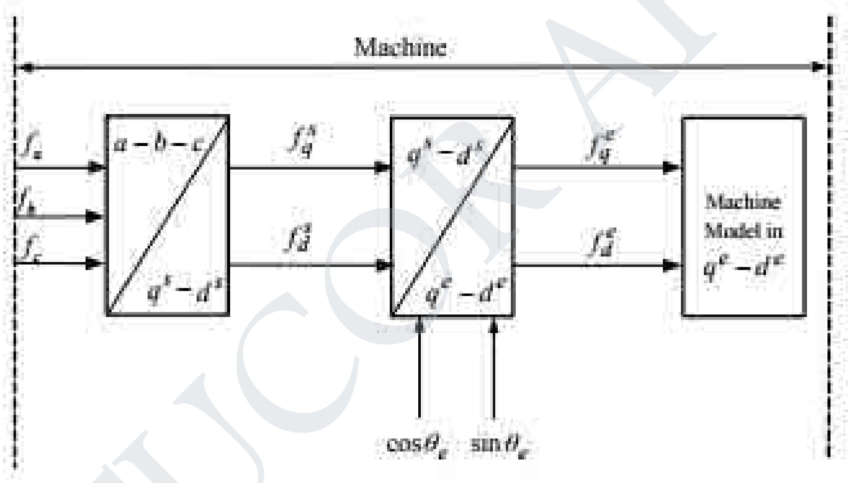
$$T_{dq0s}^{x\to y} = T_{dq0s}^{y}.{T_{dq0s}^{x}}^{-1} \quad (5)$$

Then, the desired transformation can be expressed by the following matrix:

$$T_{dq0s}^{x\to y} = \begin{bmatrix} \cos(\theta_y-\theta_x) & -\sin(\theta_y-\theta_x) & 0 \\ \sin(\theta_y-\theta_x) & \cos(\theta_y-\theta_x) & 0 \\ 1 & 1 & 1 \end{bmatrix} \quad (6)$$

2.3.5 Field Oriented Control (FOC) Transformations

2.3.5.1 Machine side transformation in field oriented control

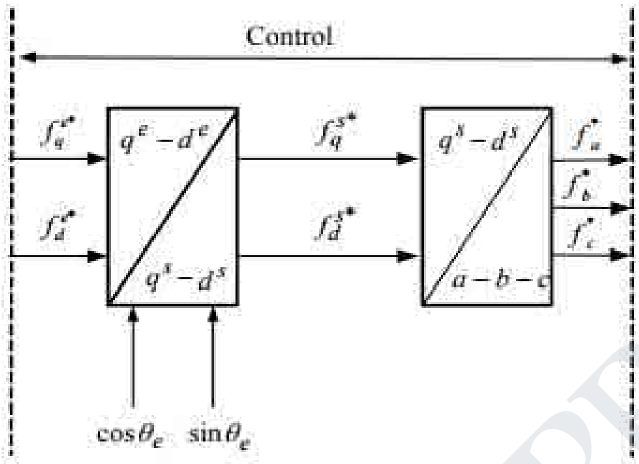


Machine side transformation in field oriented control

In the case of FOC of electric machines, control methods are performed in a two-phase reference frame fixed to the rotor (q^r -d^r) or fixed to the excitation reference frame (q^e -d^e). We want to transform all the variables from the three-phase a-b-c system to the two-phase stationary reference frame and then retransform these variables from the stationary reference frame to a rotary reference frame with arbitrary angular velocity of ω. These transformations are usually cascaded. The block diagram of this procedure is shown in Figure

2.3.5.2 Variable transformation in the field oriented control.

In this figure, f denotes the currents or voltages and q^e -d^e represents the arbitrary rotating reference frame with angular velocity θ_e and q^s -d^s represents the stationary reference frame. In the vector control method, after applying field oriented control it is necessary to transform variables to stationary a-b-c system. This can be achieved by taking the inverse transformation of variables from the arbitrary rotating reference frame to the stationary reference frame and then to the a-b-c system. In this block diagram, * is a representation of commanded or desired values of variables.



Variable transformation in the field oriented control

2.3.6 Commonly used reference frames

Based on speed of reference frame there are four major type of reference frames

1. **Arbitrary reference frame:** Reference frame speed is unspecified (ω), variables denoted by $\mathbf{f_{dqos}}$ or $\mathbf{f_{ds}}$, $\mathbf{f_{qs}}$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s}$.

2. **Stationary reference frame:** Reference frame speed is zero (**ω=0**), variables denoted by $\mathbf{f^s_{dqo}}$ or $\mathbf{f_d}^s$, $\mathbf{f_q}^s$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s}^s$.

3. **Rotor reference frame:** Reference frame speed is equal to rotor speed (**ω= ω$_r$**), variables denoted by $\mathbf{f^r_{dqo}}$ or $\mathbf{f_d}^r$, $\mathbf{f^{qr}}$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s}^s$.

4. **Synchronous reference frame:** Reference frame speed is equal to synchronous speed (**ω= ω$_e$**), variables denoted by $f^e_{\mathbf{dqo}}$ or $\mathbf{f_d}^e$, $\mathbf{f_q}^e$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s}^e$.

The choice of reference frame is not restricted but otherwise deeply influenced by the type of analysis that is to be performed so as to expedite the solution of the system equations or to satisfy system constraints. The best suited choice of reference frame for simulation of induction machine for various cases of analysis is listed here under:

- **Stationary reference frame** is best suited for studying stator variables only, for example variable speed stator fed IM drives, because stator d-axis variables are exactly identical to stator phase a-variable.

- **Rotor reference frame** is best suited when analysis is restricted to rotor variables as rotor d-axis variable is identical to phase-a rotor variable.

- **Synchronously rotating reference frame** is suitable when analog computer is employed because both stator and rotor d-q quantities becomes steady DC quantities. It is also best suited for studying multi-machine system.

It is worthwhile to note that all three types of reference frame can be obtained from arbitrary reference frame by simply changing ω. Modeling in arbitrary reference frame is therefore beneficial when a wide range of analysis is to be done.

2.3.7 Induction Machine Model in the Park Reference Frame

The induction machine was modeled using two separate frames. The first one is used to express stator quantities; the second one is used to express rotor quantities. Since these two frames are linked with angle θ, a model of the machine in a common frame named d, q can be obtained using the two rotation matrices. At a certain point, the position of the magnetic field rotating in the air gap is pinpointed by angle θ_s; in relation to stationary axis $\vec{O}_{sa}$: For the development of the machine model, a Park reference frame is assumed to be lined up with this magnetic field and to rotate at the same speed (ω_s): Angle θ_s corresponds to the angle of axes $\vec{O}_{sx}$ and θ_r; angle θ_r corresponds to the angle of axes $\vec{O}_{rx}$ and $\vec{O}_d$: Transforming angle θ_s is necessary to bring the stator quantities back to the Park rotating reference frame. Transforming angle θ_r is necessary to bring the rotor quantities back. The figure indicates that the angles are linked by a relation in order to express the rotor and stator quantities in the same Park reference frame ($\vec{O}$; $\vec{O}_d$; $\vec{O}_q$). This relation is:

$$\theta_s = \theta + \theta_r \qquad (1)$$

The same situation happens between the frame speeds in each frame and the mechanical speed, that is:

$$\omega_s = \omega + \omega_r \qquad (2)$$

With

$$\omega_s = \frac{d\theta_s}{dt}, = \omega_r = \frac{d\theta_r}{dt}, \omega = p\Omega = \frac{d\theta}{dt} \quad (3)$$

where Ω is mechanical speed and ω is very speed viewed in the electrical space.

The speed of the rotor quantities is ω_r in relation to rotor speed ω. In relation to the stator frame, the rotor quantities consequently rotate at the same speed xs as the stator quantities. Using the Park transform will allow the conception of an induction machine model independent from the rotor position. Two transformations are used. One [P(θ_s)]is applied to the stator quantities; the other [P(θ_r)]is applied to the rotor quantities.

$$[X_{s\_dqo}] = [\mathrm{P}(\theta_s)][X_{s_{abc}}][X_{r_{dqo}}] = [\mathrm{P}(\theta_r)][X_{r_{abc}}] \quad (4)$$

Direct and squared components x_d, x_q represent coordinates x_a, x_b,x_c in an orthogonal frame of reference rotating in the same plane. Term x_o represents the homopolar component, which is orthogonal to the plane constituted by the system x_a, x_b, x_c.

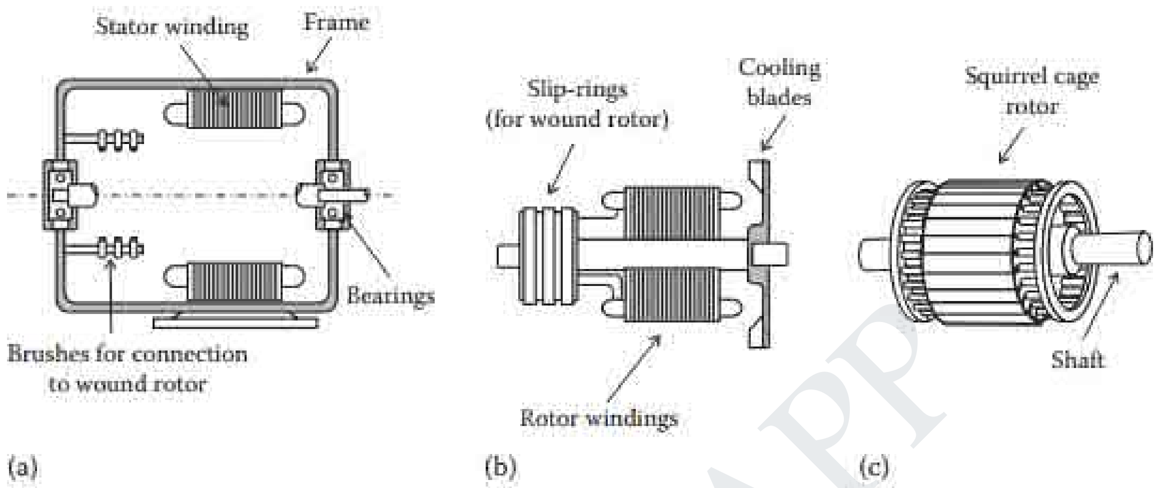
2.4 INDUCTION GENERATORS (IG)

2.4.1 Introduction

An induction generator or asynchronous generator is a type of alternating current (AC) electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotors faster than synchronous speed. A regular AC asynchronous motor usually can be used as a generator, without any internal modifications. Induction generators are useful in applications such as mini hydro power plants, wind turbines, or in reducing high-pressure gas streams to lower pressure, because they can recover energy with relatively simple controls. An induction generator usually draws its excitation power from an electrical grid; sometimes, however, they are self-excited by using phase-correcting capacitors. Because of this, induction generators cannot usually "black start" a de-energized distribution system. Induction Generator construction is based on the very common squirrel-cage induction motor type machine as they are cheap, reliable, and readily available in a wide range of electrical sizes from fractional horse power machines to multi-megawatt capacities making them ideal for use in both domestic and commercial renewable energy wind power applications.

Induction generator is not a self excited machine therefore in order to develop the rotating magnetic field, it requires magnetizing current and reactive power. The induction generator obtains its magnetizing current and reactive power from the various sources like the supply mains or it may be another synchronous generator. The induction generator can't work in isolation because it continuously requires reactive power from the supply system. However we can have a self excited or isolated induction generation in one case if we will use capacitor bank for reactive power supply instead of AC supply system.

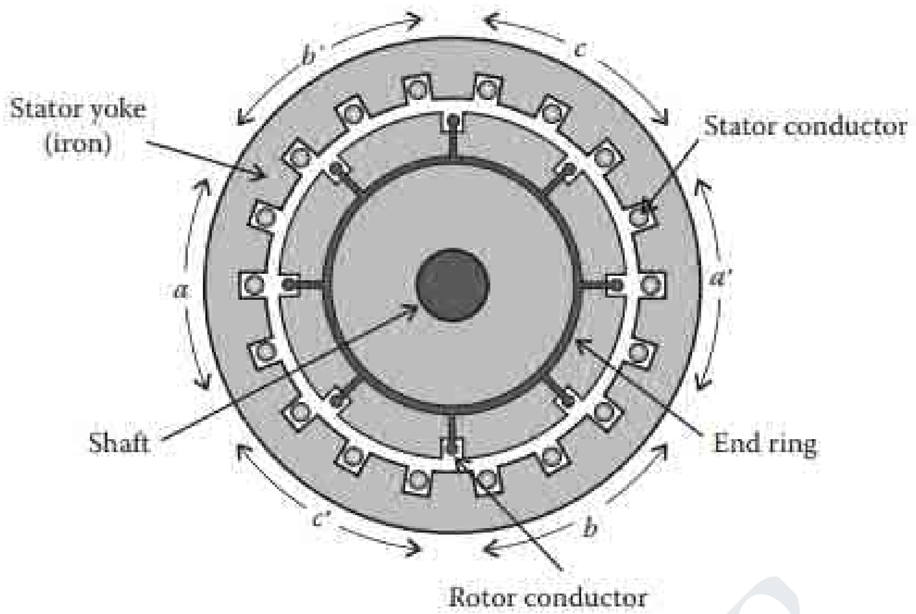
2.4.2 Construction



Induction machine longitudinal cut: (a) stator, (b) wound rotor, and (c) cage rotor

An induction generator is made up of two major components: the stator, which consists of steel laminations mounted on a frame so that slots are formed on the inside diameter of the assembly as in a synchronous machine, and the rotor, which consists of a structure of steel laminations mounted on a shaft with two possible configurations:

Wound rotor or cage rotor. Figure shows a schematic cut along the longitudinal axis of a typical wound-rotor induction machine. Figure (a) shows the external case with the stator yoke internally providing the magnetic path for the three-phase stator circuits. Bearings provide mechanical support for the shaft clearance (the air gap) between the rotor and stator cores. For a wound rotor, a group of brush holders and carbon brushes, indicated on the left side of Figure (a), allow for connection to the rotor windings. A schematic diagram of a wound rotor is shown in Figure (b). The winding of the wound rotor is of the three-phase type with the same number of poles as the stator, generally connected in Y.



Cross-sectional cut for an induction machine

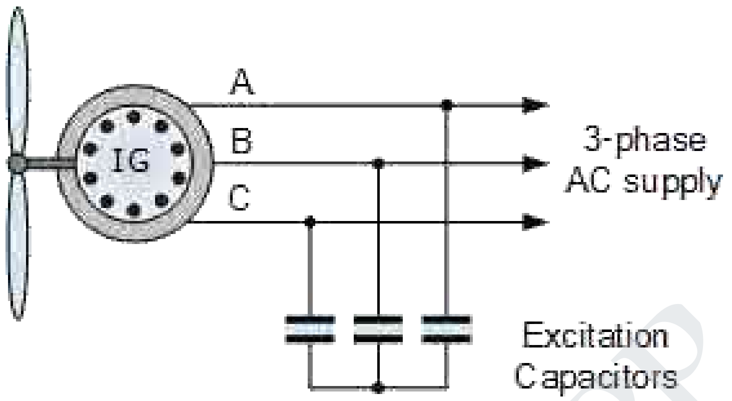
Three terminal leads are connected to the slip rings by means of carbon brushes. Wound rotors are usually available for very large power machines (>500 kW). External converters in the rotor circuit, rated with slip power, control the secondary currents providing the rated frequency at the stator. For most medium power applications, squirrel cage rotors, as in Figure (c), are used. Squirrel cage rotor windings consist of solid bars of conducting material embedded in the rotor slots and shorted at the two ends by conducting rings. In large machines, the rotor bars may be of copper alloy brazed to the end rings. Rotors sized up to about 20 inches in diameter are usually stacked in a mold made by aluminum casting, enabling a very economical structure combining the rotor bars, end rings, and cooling fan. Figure shows a cross-sectional cut indicating the distributed windings for three-phase stator excitation. Each winding (a, b, or c) occupies the contiguous slots within a 120° spatial distribution.

The stator: It is built up from silicon steel laminations punched and assembled so that it has a number of uniformly spaced identical slots, in integral multiples of six (such as 48 or 72 slots), roughly parallel to the machine shaft. Sometimes, the slots are slightly twisted or skewed in relation to the longitudinal axis, to reduce cogging torque, noise, and vibration, and to smooth up the generated voltage. Machines up to a few hundreds of KW rating and low voltage have semi closed slots, while larger machines with medium voltage have open slots.

2.4.3 Off-grid Induction Generator

We have seen above that an induction generator requires the stator to be magnetized from the utility grid before it can generate electricity. But you can also run an induction generator in a stand alone, off-grid system by supplying the necessary out-of-phase exciting or magnetizing current from excitation capacitors connected across the stator terminals of the machine. This also requires that there is some residual magnetism in the rotors iron laminations when you start the turbine. The excitation capacitors are shown in a star (wye) connection but can also be connected a delta (triangular) arrangement.

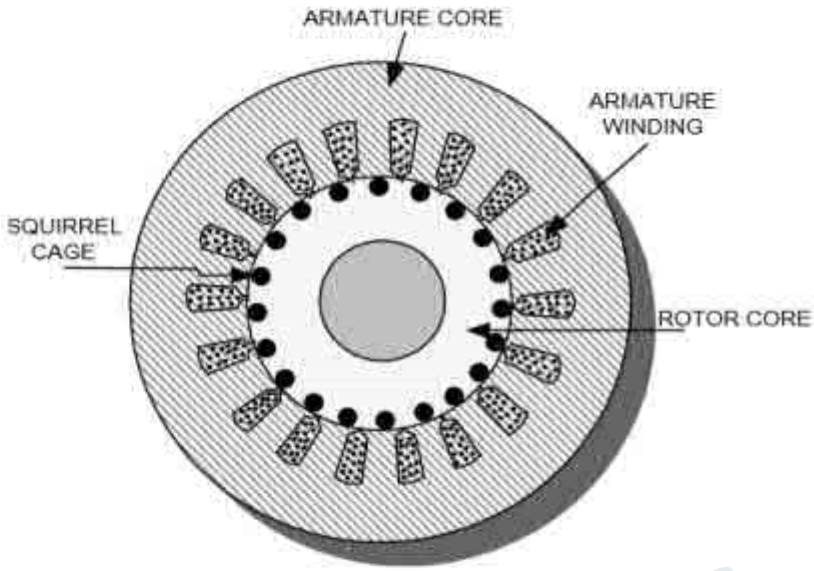
2.4.4 Capacitor Start Induction Generator



Capacitor Start Induction Generator

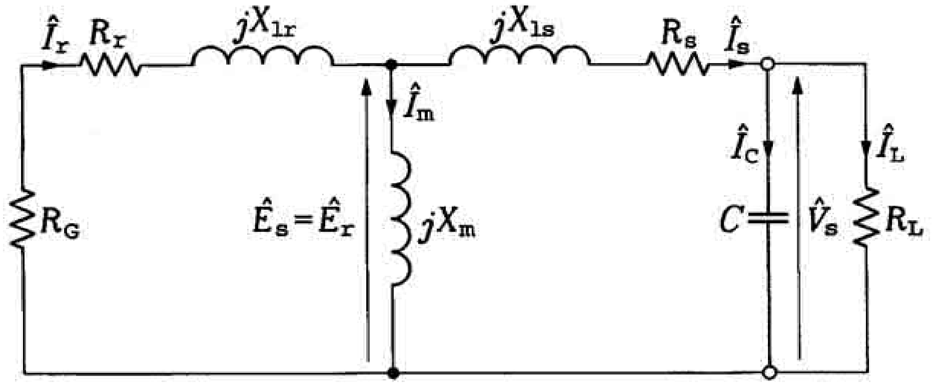
The excitation capacitors are standard motor-starting capacitors that are used to provide the required reactive power for excitation which would otherwise be supplied by the utility grid. The induction generator will self-excite using these external capacitors only if the rotor has sufficient residual magnetism. In the self-excited mode, the generator output frequency and voltage are affected by the rotational speed, the turbine load, and the capacitance value in farads of the capacitors. Then in order for self-excitation of the generator to occur, there needs to be a minimum rotational speed for the value of capacitance used across the stator windings. The "Self-excited induction generator", (SEIG) is a good candidate for wind powered electric generation applications especially in variable wind speed and remote areas, because they do not need external power supply to produce the magnetic field. A three-phase induction generator can be converted into a variable speed single-phase induction generator by connecting two excitation capacitors across the three-phase windings. One of value C amount of capacitance on one phase and the other of value 2C amount of capacitance across the other phase.

2.4.5 Principle of operation



An induction generator produces electrical power when its rotor is turned faster than the synchronous speed. For a typical four-pole motor (two pairs of poles on stator) operating on a 60 Hz electrical grid, the synchronous speed is 1800 rotations per minute (rpm). The same four-pole motor operating on a 50 Hz grid will have a synchronous speed of 1500 RPM. The motor normally turns slightly slower than the synchronous speed; the difference between synchronous and operating speed is called "slip" and is usually expressed as per cent of the synchronous speed. For example, a motor operating at 1450 RPM that has a synchronous speed of 1500 RPM is running at a slip of +3.3%. In normal motor operation, the stator flux rotation is faster than the rotor rotation. This causes the stator flux to induce rotor currents, which create a rotor flux with magnetic polarity opposite to stator. In this way, the rotor is dragged along behind stator flux, with the currents in the rotor induced at the slip frequency. In generator operation, a prime mover (turbine or engine) drives the rotor above the synchronous speed (negative slip). The stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, an active current is produced in stator coils and the motor now operates as a generator, sending power back to the electrical grid.

2.4.5.1 Excitation



Per-phase equivalent circuit of the stand-alone induction generator

An induction machine requires externally supplied armature current. Because the rotor field always lags behind the stator field, the induction machine always "consumes" reactive power, regardless of whether it is operating as a generator or a motor. A source of excitation current for magnetizing flux (reactive power) for the stator is still required, to induce rotor current. This can be supplied from the electrical grid or, once it starts producing power, from the generator itself. An induction machine can be started by charging the capacitors, with a DC source, while the generator is turning typically at or above generating speeds. Once the DC source is removed the capacitors will provide the magnetization current required beginning producing voltage. An induction machine that has recently been operating may also spontaneously produce voltage and current due to residual magnetism left in the core.

2.4.5.2 Active power

Active power delivered to the line is proportional to slip above the synchronous speed. Full rated power of the generator is reached at very small slip values (motor dependent, typically 3%). At synchronous speed of 1800 rpm, generator will produce no power. When the driving speed is increased to 1860 rpm (typical example), full output power is produced. If the prime mover is unable to produce enough power to fully drive the generator, speed will remain somewhere between 1800 and 1860 rpm range.

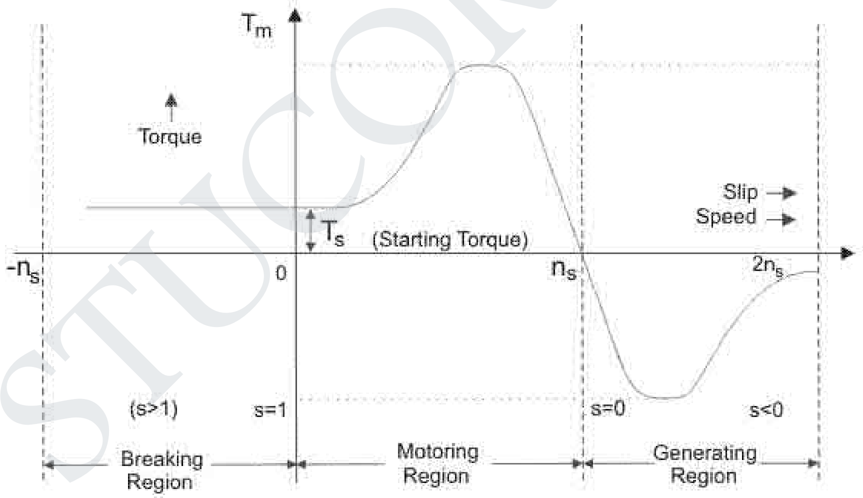
2.4.5.3 Required capacitance

A capacitor bank must supply reactive power to the motor when used in stand-alone mode. The reactive power supplied should be equal or greater than the reactive power that the machine normally draws when operating as a motor. Consider, an AC supply is connected to the stator terminals of an induction machine. Rotating magnetic field produced in the stator pulls the rotor to run behind it (the machine is acting as a motor). Now, if the rotor is accelerated to the synchronous speed by means of a prime mover, the slip will be zero and hence the net torque will be zero. The rotor current will become zero when the rotor is running at synchronous speed.

If the rotor is made to rotate at a speed more than the synchronous speed, the slip becomes negative. A rotor current is generated in the opposite direction, due to the rotor conductors cutting stator magnetic field. This generated rotor current produces a rotating magnetic field in the rotor which pushes (forces in opposite way) onto the stator field. This causes a stator voltage which pushes current flowing out of the stator winding against the applied voltage. Thus, the machine is now working as an induction generator (asynchronous generator).

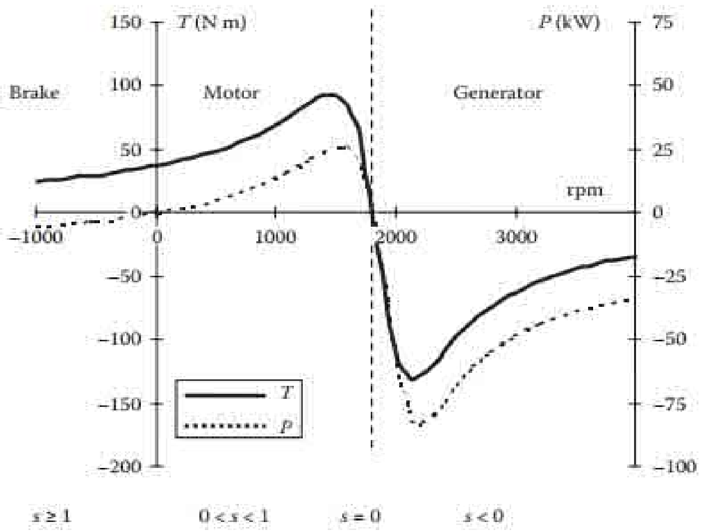
2.4.6 Torque-Slip characteristics

The basic fundamental of induction generators is the conversion between mechanical energy to electrical energy. This requires an external torque applied to the rotor to turn it faster than the synchronous speed. However, indefinitely increasing torque doesn't lead to an indefinite increase in power generation. The rotating magnetic field torque excited from the armature works to counter the motion of the rotor and prevent over speed because of induced motion in the opposite direction.



As the speed of the motor increases the counter torque reaches a max value of torque (breakdown torque) that it can operate until before the operating conditions become unstable. Ideally, induction generators work best in the stable region between the no-load condition and maximum torque region.

2.4.7 Torque–Speed characteristics



It can be observed that there is no torque at the synchronous speed. Both the torque–speed and the power–speed curves are almost linear since from no load to full load the machine's rotor resistance is much larger than its reactance. The resistance is predominant in this range, current and the rotor field as well as the induced torque increase almost linearly with the increase of the slip factors. The rotor torque varies as the square of the voltage across the terminals of the generator if the speed slows down close to the synchronous speed, the generator motorizes that is, it works as a motor; as we will show, the generated power has a maximum value for a given current drained from the generator in the same way, there is a maximum possible induced generator torque called pullout or breakdown torque, and from this torque value on, there will be over speed. The peak power supplied by the IG happens at a speed slightly different from the maximum torque, and, naturally, no electric power is converted into mechanical power when the rotor is at rest (zero speed). In the same way, in spite of the same rotation, the frequency of the IG varies with the load variation.

2.5 HIGH-EFFICIENCY INDUCTION GENERATOR

A high-efficiency induction generator is commercially available as a high-efficiency induction motor, except for some peculiarities. Therefore, the same care must be taken in design, materials selection, and manufacturing processes for building a high-efficiency generator. The main advantages of the high-efficiency induction generator compared with the conventional induction generator are better voltage regulation, less loss of efficiency. Steady-state model of Induction Generators with smaller loads, less over sizing when generators of lower power cannot be used, reduced internal losses, and, therefore, lower temperatures, less internal electric and mechanical stress, and, thus, increased useful life.

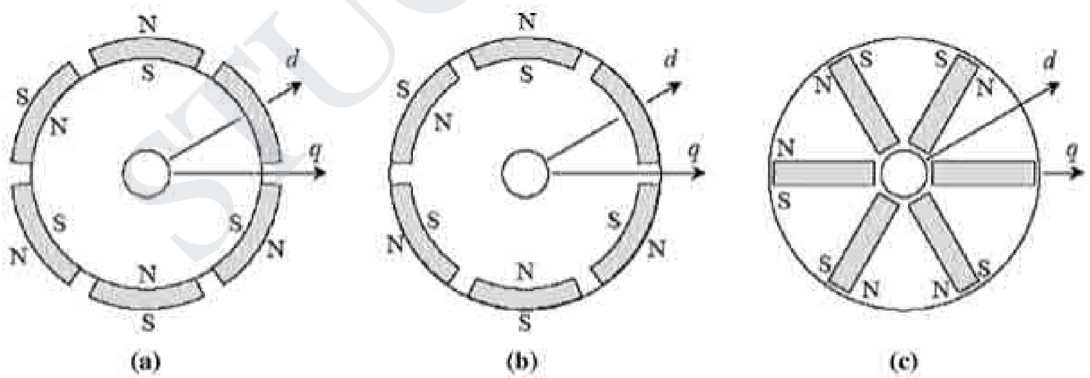
The constraints are the need for larger capacitors for self-excitation. High-efficiency induction generators should not be used for self-excited applications. The efficiency of the high-efficiency generator compared with the standard ones differs by more than about 10% for small power ratings (up to 50 kW) and about 2% for higher powers (above 100 kW). It is therefore highly recommended for micro power plants. Rated efficiencies are normalized, and they should have guaranteed minimum values stated by the manufacturer on the plate of the machine for each combination of power versus synchronous speed. High-efficiency generators are better suited to stand the harmful effects of the harmonic generated by nonlinear loads (power converters) because they have higher thermal margin and smaller losses.

2.6 PERMANENT MAGNET SYNCHRONOUS GENERATORS (PMSG)

2.6.1 Introduction

A permanent magnet synchronous generator is a generator where the excitation field is provided by a permanent magnet instead of a coil. The term synchronous refers here to the fact that the rotor and magnetic field rotate with the same speed, because the magnetic field is generated through a shaft mounted permanent magnet mechanism and current is induced into the stationary armature Synchronous generators are the majority source of commercial electrical energy. They are commonly used to convert the mechanical power output of steam turbines, gas turbines, reciprocating engines and hydro turbines into electrical power for the grid. Some designs of Wind turbines also use this generator type.

2.6.2 Construction

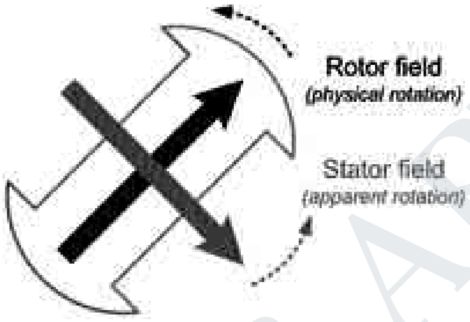


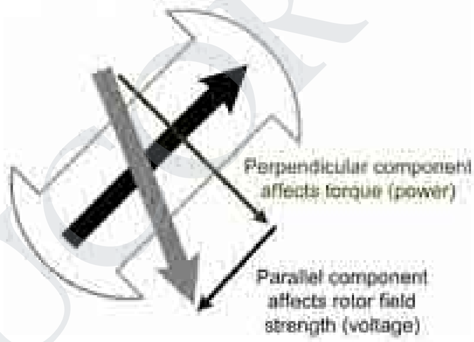
Types of PMSG rotor construction

(a) Surface mounted; (b) inset; (c) Interior PM motor

A Permanent Magnet Synchronous Generator is a generator where the excitation field is provided by a permanent magnet instead of a coil. The rotor contains the permanent magnet and the stator is the stationary armature that is electrically connected to a load. A set of 3 conductors make up the armature winding in standard utility equipment, placed 120^0 apart in space, this provides for a uniform force or torque on the generator rotor. The uniformity of the torque arises because the magnetic field resulting from the currents in the three conductors of the armature winding combine spatially in such a way as to resemble the magnetic field of a single rotating magnet. The stator magnetic field appears as a steady rotating field and spins at the same frequency as the rotor when the rotor contains a single dipole magnetic field. The two fields move in 'synchronicity' and maintain a fixed position with respect to each other as they rotate. The armature MMF combines vectorically with the persistent flux of the permanent magnets, which leads to higher air-gap flux density and eventually core saturation. In PMSG, the output voltage is proportional to the speed.

2.6.3 Operation





In the majority of designs the rotating assembly in the center of the generator called "rotor" contains the magnet, and the "stator" is the stationary armature that is electrically connected to a load. As shown in the diagram, the perpendicular component of the stator field affects the torque while the parallel component affects the voltage. The load supplied by the generator determines the voltage. If the load is inductive, then the angle between the rotor and stator fields will be greater than 90 degrees which corresponds to an increased generator voltage. This is known as an overexcited generator.

The opposite is true for a generator supplying a capacitive load which is known as an under excited generator. A set of three conductors make up the armature winding in standard utility equipment, constituting three phases of a power circuit that correspond to the three wires we are accustomed to see on transmission lines. The phases are wound such that they are 120 degrees apart spatially on the stator, providing for a uniform force or torque on the generator rotor. The uniformity of the torque arises because the magnetic fields resulting from the induced currents in the three conductors of the armature winding combine spatially in such a way as to resemble the magnetic field of a single, rotating magnet. This stator magnetic field or "stator field" appears as a steady rotating field and spins at the same frequency as the rotor when the rotor contains a single dipole magnetic field. The two fields move in "synchronicity" and maintain a fixed position relative to each other as they spin.

2.6.4 Advantages and disadvantages of PMSG

Advantages

- Light weight and small size in construction.
- Low losses and high efficiency
- No need of external excitation current.
- No need of gearbox.

Disadvantages

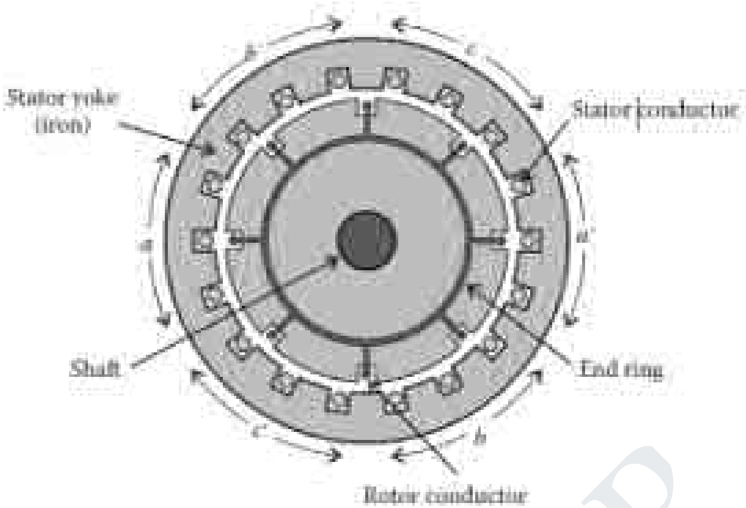
- It is useful for small wind turbines, but for large wind turbines the size of the magnet has to be increased.
- Demagnetization of permanent magnet due to atmospheric conditions is a big problem

2.7 SQUIRREL CAGE INDUCTION GENERATORS (SCIG)

2.7.1 Constructional features

Asynchronous Induction generators are widely used in wind mills due to the several advantages, such as robustness, mechanical simplicity and low price. Induction machines operate in the generating and motoring modes fundamentally in the same manner except for the reversal power flow. Therefore, the equivalent circuit and the associated performance are valid for different slip. If the rotor is driven by a prime mover above the synchronous speed, the mechanical power of the prime mover is converted into electrical power to the utility grid via stator winding. The SCIG is a self-excited induction generator where a three-phase capacitor bank is connected across the stator terminals to supply the reactive power requirement of a load. When such an induction machine is driven by an external mechanical power source, the residual magnetism in the rotor produces an Electromotive Force (EMF) in the stator windings. This

EMF is applied to the capacitor bank causing current flow in the stator winding and establishing a magnetizing flux in the machine.

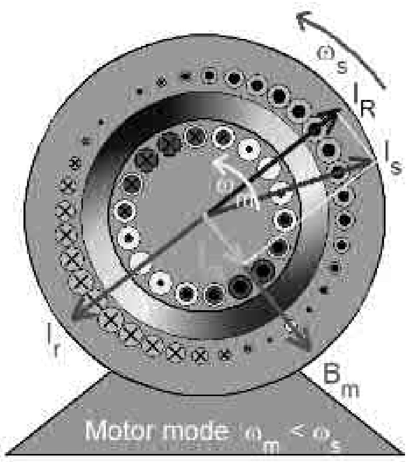


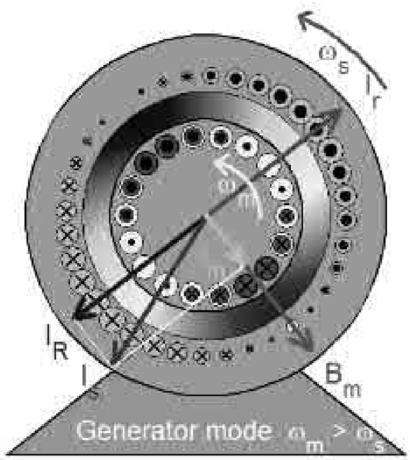
An induction generator connected and excited in this manner is capable of acting as a standalone generator supplying real and reactive power to a load. SCIG have a steep torque speed characteristic and therefore fluctuations in wind power are transmitted directly to the grid. SCIG feed only through the stator and generally operate at low negative slip, approximately 1 to 2 percent. The slip, and hence the rotor speed of a SCIG varies with the amount of power generated. The generator will always draw the reactive power from the grid. Reactive power consumption is partly or fully compensated by capacitors in order to achieve a power factor close to unity and make the induction machine to self-excite. The speed varies over a very small range above synchronous speed as it is coupled with the grid, hence commonly known as a fixed-speed generator. SCIG drives have bulky construction, low efficiency, low reliability and need of maintenance, also the existing of slip ring, brush and three-stage gearbox increases the system mass and cost, also electrical and mechanical loss. Recently, squirrel-cage induction generators are dropping in this application.

2.7.2 Principle of operation

Initially, the induction machine is connected in motoring command such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode. As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency.

Furthermore, the wind velocity variations will induce only small variations in the generator speed.





As the power varies proportionally with the wind speed cubed, the associated electromagnetic variations are important. SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. The rotating magnetizing field represented by the space vector $\mathbf{B_m}$ (or, equivalently by the magnetizing current $\mathbf{I_m}$) moves at the synchronous speed ω_s with respect to a stator (or stationary) observer and at the slip speed $\omega_{sl} = \omega_s - \omega_m$ with respect to a rotor observer. In the motor mode of operation where $\omega_m < \omega_s$, the rotor effectively moves backwards (clockwise) with respect to the field, inducing in each bar a voltage having the polarity indicated and a magnitude proportional to slip velocity u and to the field strength acting on the bar (in accordance with the flux-cutting rule $\mathbf{v} = \mathbf{Blu}$). Since the magnetic field is sinusoidally distributed in space, so will the induced voltages in the rotor bars. Ignoring the effects of rotor leakage, the resulting rotor currents are in phase with the induced voltages and are thus sinusoidally distributed in space varying sinusoidally in time at slip frequency; they may then be represented by the space vector $\mathbf{I_r}$ which rotate at the slip speed ω_{sl} with respect to the rotor and at synchronous speed ω_s with respect to the stator. Because $\mathbf{B_m}$ cannot change with a fixed stator input voltage (in accordance with Faraday's law), a stator space vector $\mathbf{I_R}$ is created in order to compensate for the rotor effects so that the resultant stator current becomes $\mathbf{I_s} = \mathbf{I_R} + \mathbf{I_m}$.

The electromagnetic force exerted on rotor bar acting in the positive or anticlockwise direction (same as rotor speed) in the present case of a motor. The resultant torque developed on the rotor also acts in the same direction. Follow the path taken by one rotor bar as it travels around, observing the polarity and magnitude (described by the size) of the bar current. In the case of a generator where $\omega_m > \omega_s$, all polarities and directions are reversed as can be observed in the right figure (except for the magnetizing component).

2.7.3 Modelling of Squirrel Cage Induction Generator (SCIG)

A three-phase voltage system may be expressed, with obvious meaning of the notation, as follows

$$V_a(t) = V\cos(\omega t + \varphi)$$

$$V_b(t) = V\cos\left(\omega t + \varphi - \left(\frac{2}{3}\right)\pi\right)$$

$$V_c(t) = V\cos\left(\omega t + \varphi - \left(\frac{4}{3}\right)\pi\right) \qquad (1)$$

The corresponding space-vector is calculated in (2). Notice that the amplitude of the defined voltage space-vector is equal to the peak amplitude of the instantaneous voltage:

$$V_s(t) = \frac{2}{3}(v_a(t) + av_b(t) + a^2 v_c(t)) = ve^{j\varphi}e^{j\omega t} \qquad (2)$$

where

$a = e^{j(2/3)\pi}$

$a^2 = e^{-j(2/3)\pi}$

$V = Ve^{j\omega}$

The phasor V is defined in such a way that its magnitude is equal to the peak-value of the voltage. The first part of (2) is valid also if the three-phase quantities do not form a balanced system. In this case, the space vector becomes:

$$V_s(t) = V_1 e^{j\varphi 1} e^{j\omega t} + V_2 v e^{-j\varphi 2} e^{-j\omega t} = V_1 e^{j\omega t} + V_2 e^{-j\omega t} \qquad (3)$$

Similar expressions can be obtained for currents and fluxes. The zero-sequence is not considered here, since commonly an induction generator is not grounded and therefore no zero-sequence current can flow. If no zero-sequence component is present, the instantaneous values of the currents in the three phases can be obtained from the corresponding space-vector as:

$$i_a(t) = Re(i_s)$$

$$i_b(t) = Re(a^2 i_s)$$

$$i_c(t) = Re(ai_s) \qquad (4)$$

Using the introduced space-vector notation and using a stationary reference frame, the equations describing the electrical dynamics of a squirrel-cage induction machine are given by :

$$v_s = R_s i_s + \frac{d\psi_s}{dt}$$

$$0 = R_r i_r + \frac{d\psi_r}{dt} - j\psi_r \psi_r \qquad (5)$$

$$\psi_s = L_s I_s + L_m I_r$$

$$\psi_r = L_m I_s + L_r I_r \qquad (6)$$

where

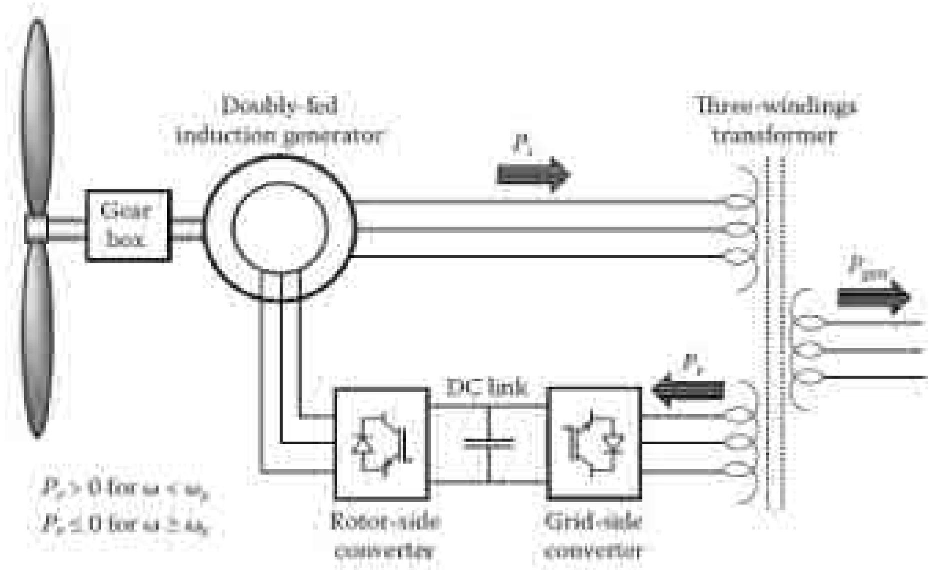
$$L_s = L_{sl} + L_m \text{ and } L_r + L_{rl} + L_m$$

2.8 DOUBLY FED INDUCTION GENERATORS (DFIG)

2.8.1 Constructional features

Doubly fed electrical generators are similar to AC electrical generators, but have additional features which allow them to run at speeds slightly above or below their natural synchronous speed. This is useful for large variable speed wind turbines, because wind speed can change suddenly. When a gust of wind hits a wind turbine, the blades try to speed up, but a synchronous generator is locked to the speed of the power grid and cannot speed up. Therefore large forces are developed in the hub, gearbox, and generator as the power grid pushes back. This causes wear and damage to the mechanism.

If the turbine is allowed to speed up immediately when hit by a wind gust, the stresses are lower and the power from the wind gust is converted to useful electricity. One approach to allowing wind turbine speed to vary is to accept whatever frequency the generator produces, convert it to DC, and then convert it to AC at the desired output frequency using an inverter. This is common for small house and farm wind turbines. But the inverters required for megawatt-scale wind turbines are large and expensive. Doubly fed generators are one solution to this problem. Instead of the usual field winding fed with DC, and an armature winding where the generated electricity comes out, there are two three-phase windings, one stationary and one rotating, both separately connected to equipment outside the generator. Thus the term "doubly fed". One winding is directly connected to the output, and produces 3-phase AC power at the desired grid frequency. The other winding (traditionally called the field, but here both windings can be outputs) is connected to 3-phase AC power at variable frequency. This input power is adjusted in frequency and phase to compensate for changes in speed of the turbine.



Wind turbine–powered DFIG with transformer-based utility connection

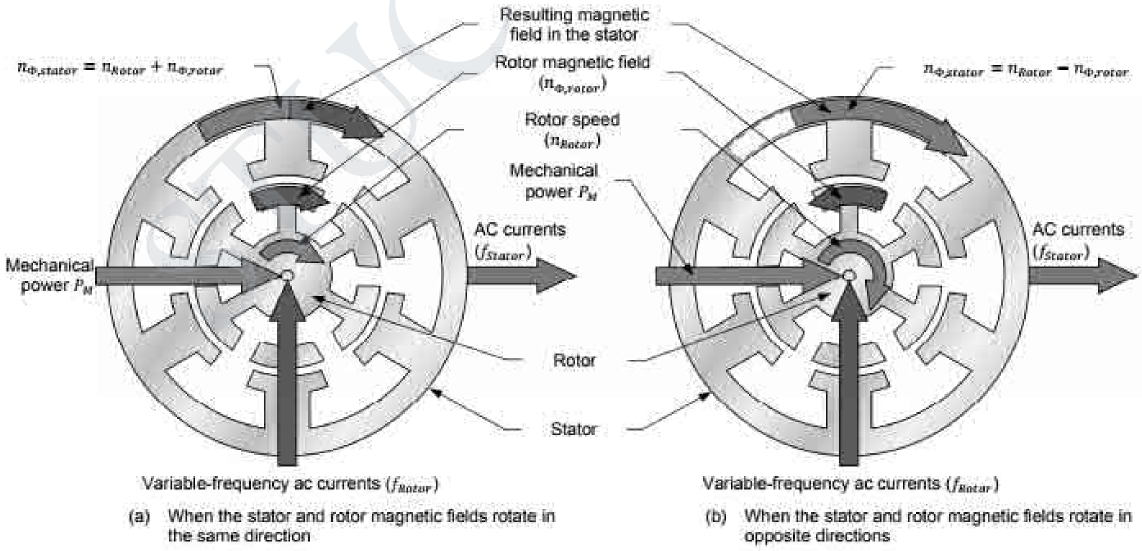
The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30% operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. Further, the voltage transients due to the grid disturbances (three- and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages - and high currents resulting from these voltages - from destroying the IGBTs and diodes of the converter, a protection circuit (called crowbar) is used.

The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected. In order to be able to continue the operation as quickly as possible an active crowbar has to be used. The active crowbar can remove the rotor short in a controlled way and thus the rotor side converter can be started only after 20-60 ms from the start of the grid disturbance when the remaining voltage stays above 15% of the nominal voltage. Thus it is possible to generate reactive current to the grid during the rest of the voltage dip and in this way help the grid to recover from the fault. For zero voltage ride through it is common to wait until the dip ends because with zero voltage it is not possible to know the phase angle where the reactive current should be injected.

2.8.2 Principle of operation

The principle of the Doubly-Fed Induction Generator (referred to as DFIG) is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converters that control both the rotor and the grid currents. Thus, rotor frequency can freely differ from the grid frequency (50 or 60 Hz). Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. It is possible to avoid the multiphase slip ring assembly but there are problems with efficiency, cost and size.

A doubly-fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications. First, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances. Second, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions. Third, the cost of the converter is low when compared with other variable speed solutions because only a fraction of the mechanical power, typically 25-30%, is fed to the grid through the converter, the rest being fed to grid directly from the stator. The efficiency of the DFIG is very good for the same reason. Doubly-fed electric machine is connected to a selection of resistors via multiphase slip rings for starting. However, the slip power was lost in the resistors. Thus means to increase the efficiency in variable speed operation by recovering the slip power were developed.



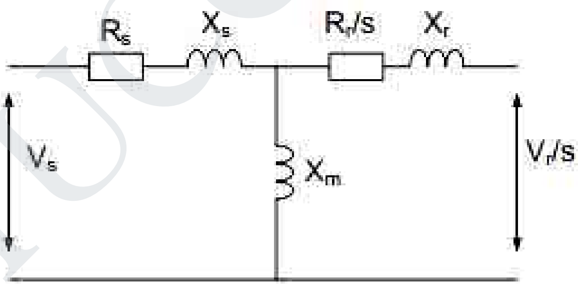
Interaction between the rotor speed and the frequency of the rotating magnetic field created in the rotor windings of a doubly-fed induction generator.

By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control. Direct torque control has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

2.8.3 Equivalent Circuit of DFIG

A doubly fed induction generator is basically a wound rotor induction generator fed by both stator and rotor, in which the stator winding is directly connected to the grid and the rotor winding is connected to the grid through AC/DC/AC converters. These converters are divided into two components: the rotor side converter and the grid side converter. A capacitor between the converters plays a role of a DC voltage source. A coupling inductor is used to link the grid side converter to the grid.

The operation principle of DFIG is fundamentally the same as that of a transformer. Thus, DFIG can be represented as a transformer's per phase equivalent circuit, where R_r and X_r represent rotor resistance and reactance referred to the stator side. But the equivalent circuit of induction machine differs from a transformer's primarily with respect to varying rotor frequency on the rotor voltage. In case of DFIG, there is a voltage injected to the rotor winding, so an equivalent circuit of classic induction machine needs to be modified by adding a rotor injected voltage as shown in Figure. In this figure, *s* is the rotor slip, *V* the voltage, *I* the current, *R* and *X* represent resistance and reactance, respectively. The subscripts *r*, *s* and *m* stand for rotor, stator and mutual, respectively.



The Equivalent Circuit of DFIG

Real and reactive power in the stator side like P_s and Q_s delivered to the connected grid can be derived from I_s and Vs as in (1):

$$P_s = 3Re(V_s I_s^*)$$

$$Q_s = 3Im(V_s I_s^*) \qquad (1)$$

Real and reactive power in the rotor side, P_r , Q_r , referred to stator side is derived from I_r and V_r/s, as in (2):

$$P_r = 3Re\left(\frac{V_r}{s} I_r^*\right)$$

$$Q_r = 3Im\left(\frac{V_r}{s} I_r^*\right) \quad (2)$$

It is possible to express the electromechanical torque, T_e , as in (3):

$$T_e = \frac{3}{2}\frac{p}{2} Re(j\Psi_s I_s^*) = \frac{3}{2}\frac{p}{2} Re(j\Psi_r I_r^*) \quad (3)$$

where

$$\Psi_s = \frac{X_s I_s + X_m I_r}{\omega_s}; \; \Psi_r = \frac{X_r I_r + X_m I_s}{\omega_S}$$

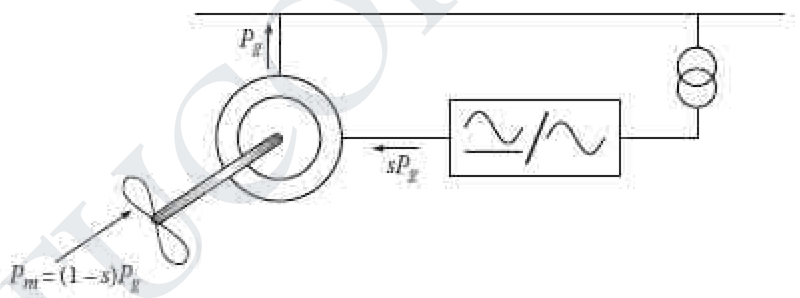
Ψ_s and Ψ_r : the stator and the rotor flux, respectively.

p: the number of poles per phase.

I_s^*, I_r^* : the complex conjugates of the stator and the rotor current, respectively.

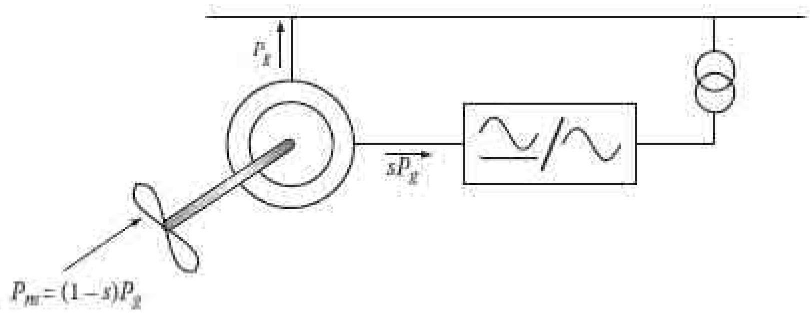
2.8.5 Sub- and Super-synchronous modes

Figure (a) shows the power balance in a DFIG at sub-synchronous generation where $s > 0$ and the power flow into the rotor by a current-controlled inverter. A step-up transformer is usually connected between the low-frequency low-voltage requirements and the grid in order to alleviate the rotor converter ratings.

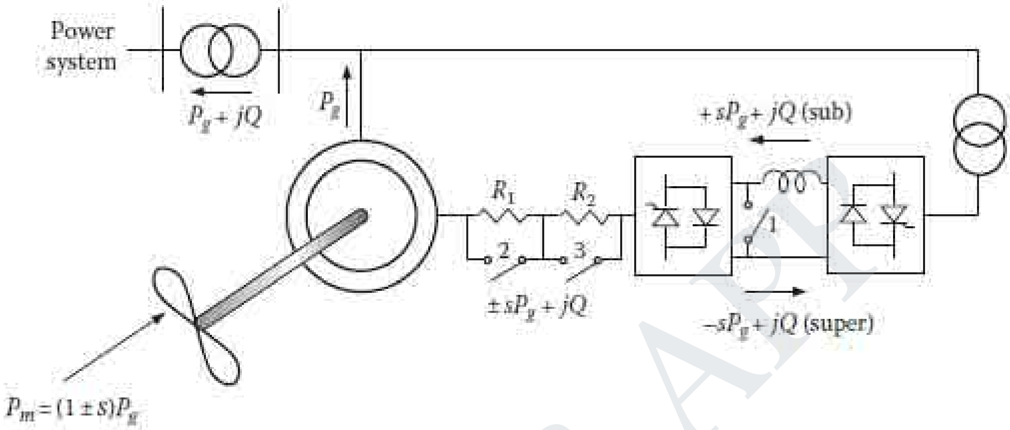


(a) Sub-synchronous generating mode (*s* > 0).

Figure (b) shows the super-synchronous generating mode where the mechanical speed is greater than the electrical synchronous speed, so the slip is negative ($s < 0$). The rotor voltages will have their phase sequence reversed; since $Pg < 0$ and $Pr < 0$, the rotor circuit contributes in generating power to the line with improved efficiency.



(b) Super-synchronous generating mode (*s* < 0).

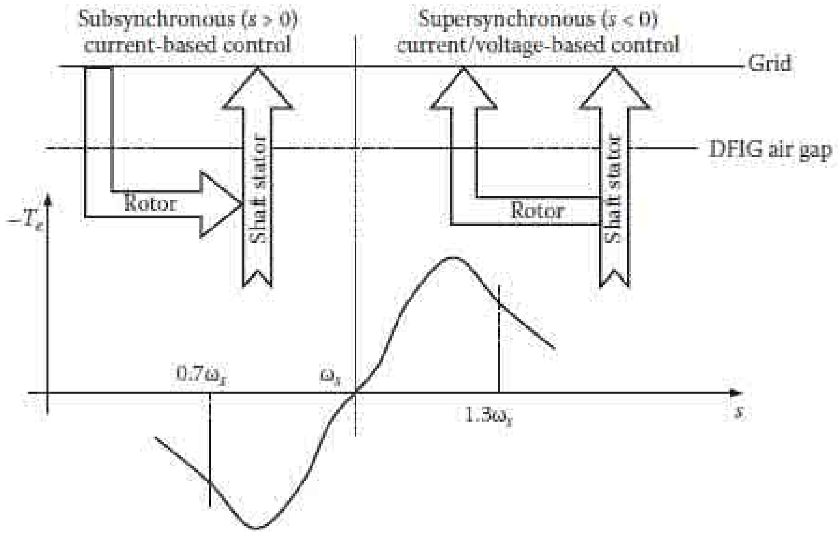


(c) Sub-synchronous mode back-to-back double converter.

It is important to note that the shaft incoming power indicates $Pm = (1 + s)Pg$ to show the extra capability of the power conversion, but the slip is actually negative. Thus, very efficient generating systems can be achieved using the super-synchronous region. Because the operating region is limited, the main drawback is the starting-up sequence of the system. One possible way around this is to use auxiliary resistors in the rotor circuit as indicated in Figure (c), then drive the machine in motoring mode, and, just after the cut-in speed, plug in the controller, which imposes regenerative operation.

2.8.6 Torque-slip curve for DFIG in sub- and super-synchronous modes.

For high-power machines, the stator resistance is neglected, and the stator terminal power is *Pg*. Considering that the power flowing out of the machine is negative (generating mode), the induction generator has a power balance in accordance with the torque-slip curve indicated in Figure. The power distribution for the generator operating at sub-synchronous and super-synchronous regions is indicated in the operating region from $0.7\omega s$ to $1.3\omega s$. For operation at the sub-synchronous region, the slip is positive, and therefore, the rotor circuit receives power from the line, whereas for the super-synchronous region, the slip is negative, and the rotor power supplements extra generating power to the grid.



2.8.7 Advantages and disadvantages of DFIG

Advantages

- DFIG is a variable speed generator and therefore has the variable speed advantages compared to fixed speed generators.
- It more fully converts the available wind power over a wider range of wind speeds with less mechanical complexity but more electrical and electronic complexity.
- DFIG provides variable speed with a smaller power converter compared to other variable-speed generators.
- Only the rotor power needs to be converted. That is typically about 30% of the total power.
- Reduced power conversion means reduced losses and increased efficiency. However the converter must be designed to transfer power in either direction, making it more complex than power converters for other types of variable-speed generators.
- The overall equipment, installation and maintenance cost is apparently lower for DFIG systems for some range of power levels.

Disadvantages

- A disadvantage of the DFIG compared to the permanent magnet synchronous generator is that the DFIG requires a speed increasing gearbox between the wind turbine and the generator whereas the PMSG can be constructed with a sufficient number of poles to allow direct drive.

APPENDIX

Content beyond the Syllabus

A.2.1 SCALAR CONTROL SCHEMES of INDUCTION GENERATOR

The fundamental objective behind the scalar method is to provide a controlled slip operation. The scheme depicted in Figure 1 with a grid-connected induction generator is a possible one. The static frequency converter in the figure can be a cyclo-converter, a matrix converter (bidirectional in nature), or a rectifier/inverter connection with a dc-link interfacing the 60 Hz grid with the generator stator. The simplified scheme requires a programmed slip, which will be dependent on machine parameter variation, temperature variation, and mechanical losses. Therefore, a closed-loop control will improve the drive performance. Since the slip frequency ωsl is proportional to torque, an outer speed control loop will generate a signal proportional to the required slip—for example, through a PI regulator.

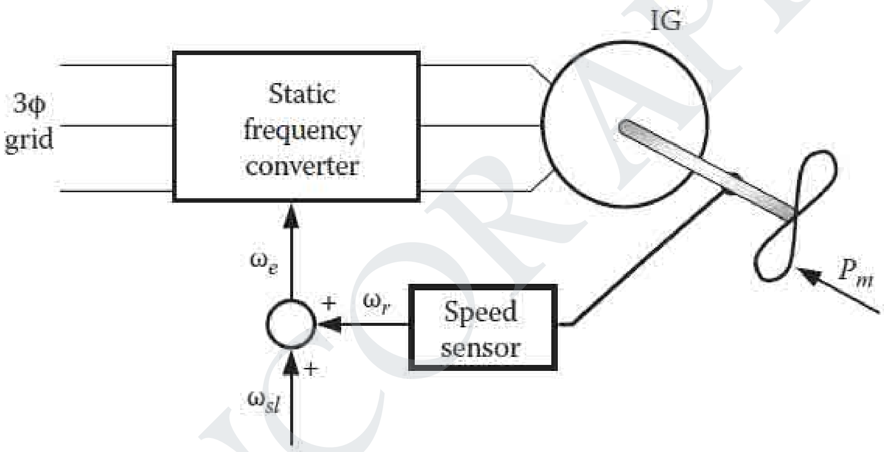


Figure 1: Principle of slip control for induction generators.

The system depicted in Figure 2 has an outer-loop speed control and a PI regulator that generates slip, which is added to the shaft speed to generate the stator frequency. The machine terminal voltage is also programmed through a look-up table. The converter receives both inputs ωe^* and Vs^*, which command a three-phase sinusoidal generator by PWM in the inverter. The scheme considers that external torque is applied on the generator shaft, and the shaft speed reference ωr^* is computed in order to seek a shaft operating speed that keeps the slip signal negative ωsl^*, maintaining the machine in generating mode. The three-phase inverter receives a negative phase sequence command, and the power delivered across the battery is indicated in the block diagram. Since most systems are grid connected, a dc-link is required to interface the machine converter to a grid inverter and pump energy back to the ac side.

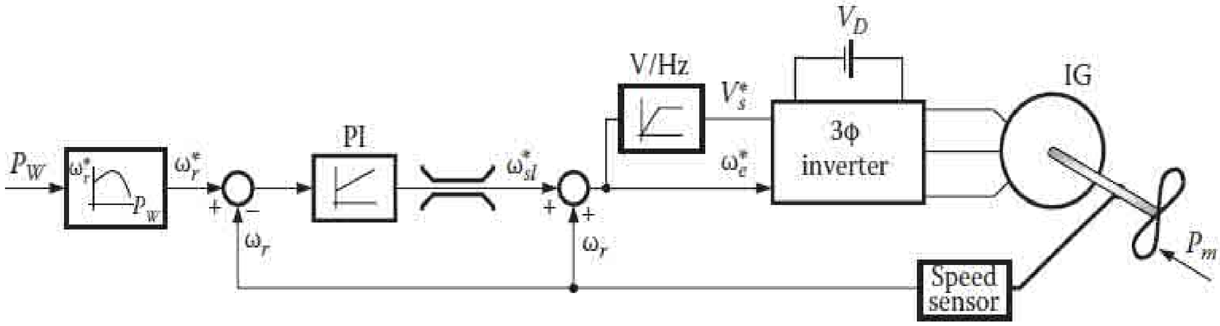


Figure 2: Closed-loop speed control of IG with V/Hz.

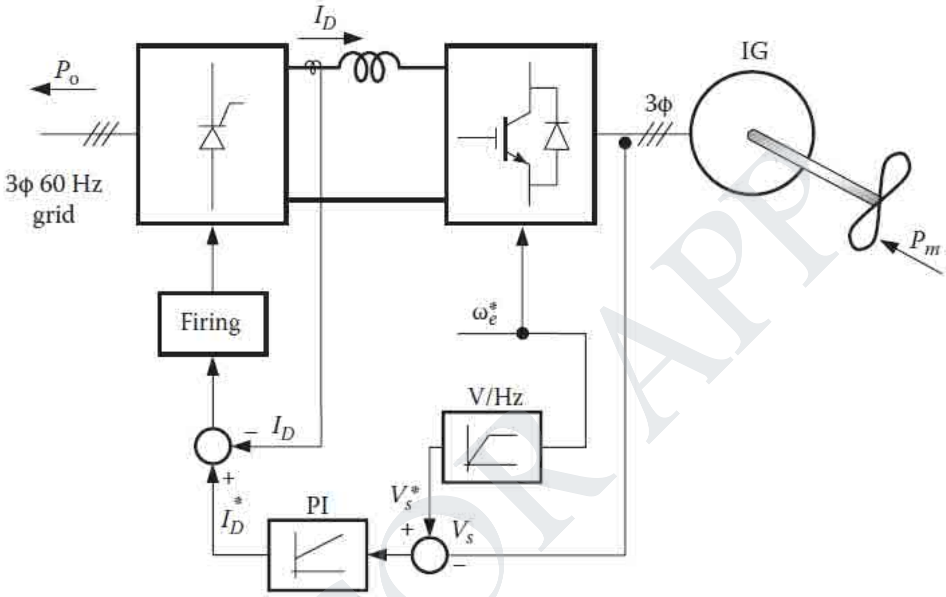


Figure 3: Current-fed link system for grid connection with V/Hz.

A current-fed link system for grid connection with V/Hz is depicted in Figure 3. The dc-link current allows easy bidirectional flow of power. Although the dc-link current is unidirectional, a power reversal is achieved by a change in polarity of the mean dc-link voltage, and symmetrical voltage-blocking switches are required. A thyristor-based controlled rectifier manages the three-phase utility side, and the machine-side inverter can use a transistor with a series diode. The system in Figure 3 is commanded by the machine stator frequency reference ω*e* *, and a look-up table for V/Hz sets a voltage reference, which is compared to the developed machine terminal voltage. A PI control produces the set point for the dc-link current, and firing for the thyristor bridge controls the power exchange (*Po*) with the grid. The stator frequency reference ω*e** can be varied in order to optimize the power tracking of the induction generator or may be programmed in accordance with the input power availability at the generator shaft (*PM*).

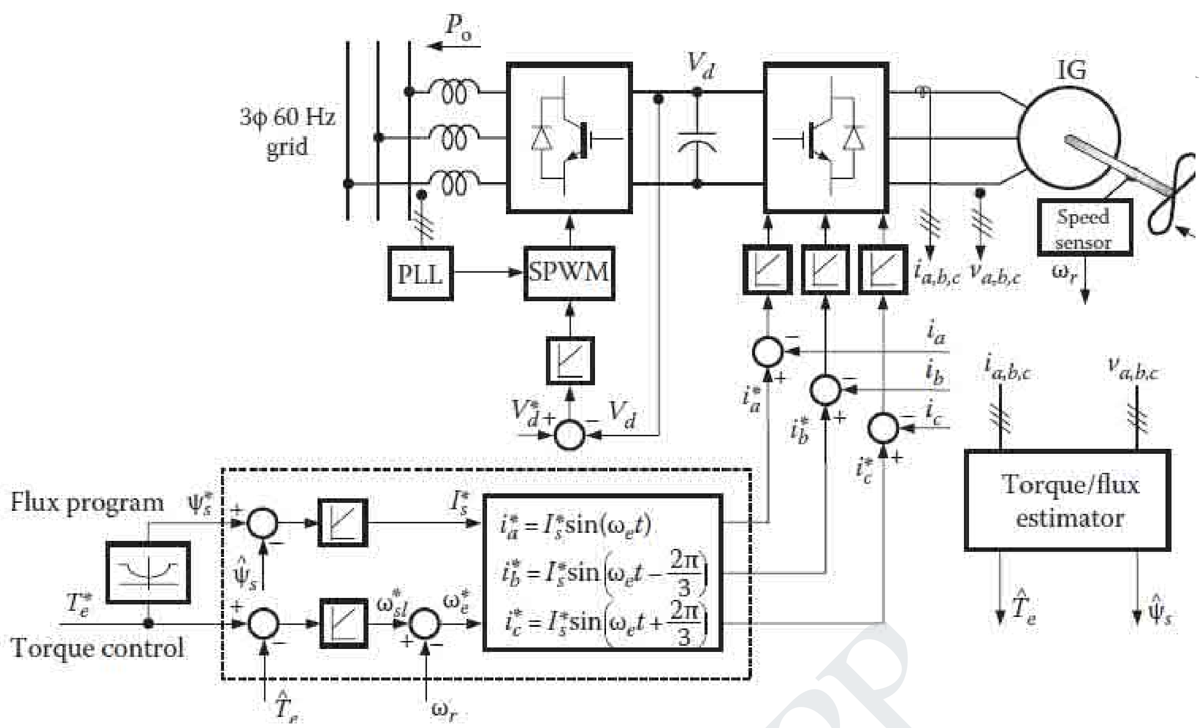


Figure 4: Voltage-fed link system for grid connection with current control for generator side.

An enhanced voltage-link double-PWM converter is depicted in Figure 4. The dc-link capacitor voltage is kept constant by the converter connected to the utility grid. The series inductances that connect the system to the grid keep the converter control within safe limits by inserting a current-source-like feature. When power is transferred from the induction generator, the dc-link voltage will increase slightly, and the feedback control of the grid-side converter will generate a sinusoidal pulse width modulation (SPWM) in order to pump this power to the grid. The generator side inverter is current controlled with either PI controllers on the stationary frame (with SPWM) or with hysteresis band controllers. Three-phase reference currents are generated through a programmed sine wave generator that receives the stator electrical angular speed reference ωe * and the current peak amplitude ΨIs* supplied by corresponding torque and flux loops. Those loops are closed with the estimation of actual torque flux in the generators by feeding back the generator current and voltage. In order to optimize the efficiency of the generator, a look-up table reads the torque command and programs the optimum flux reference for the system. A start-up sequence initially boosts the dc-link voltage to a higher voltage than the peak value of the grid, in order for the PWM to work properly. The overall system is very robust due to the current control in the inverters, the dc-link capacitor (with lower losses and faster response than dc-link inductors), the online estimation of generator torque and flux. The system may be implemented with the last generation of microcontrollers since internal computations are not so mathematically intensive. All these scalar based control schemes can also incorporate speed governor systems on the mechanical shaft in order to control the incoming power for hydropower applications.

EE6009 POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

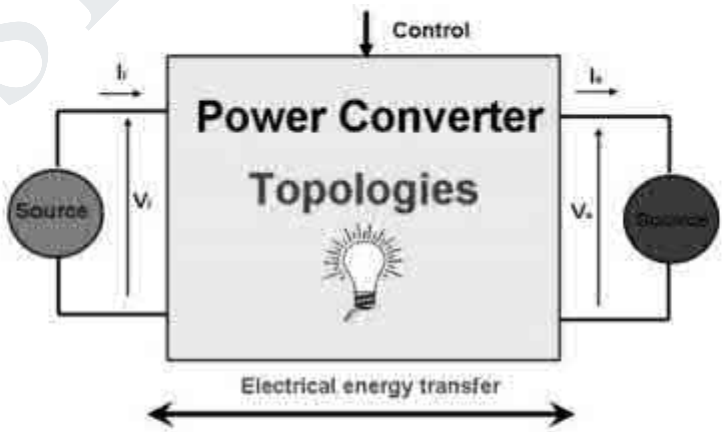
UNIT III

POWER CONVERTERS

SYLLABUS: Solar: Block diagram of solar photo voltaic system -Principle of operation: line commutated converters (inversion-mode) - Boost and buck-boost converters- selection of inverter, battery sizing, array sizing Wind: Three phase AC voltage controllers- AC-DC-AC converters: uncontrolled rectifiers, PWM Inverters, Grid Interactive Inverters-matrix converters.

3.1 INTRODUCTION TO POWER CONVERTERS

The task of a power converter is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for the user loads. Energy was initially converted in electromechanical converters (mostly rotating machines). Today, with the development and the mass production of power semiconductors, static power converters find applications in numerous domains and especially in particle accelerators. They are smaller and lighter and their static and dynamic performances are better. A static converter is a meshed network of electrical components that acts as a linking, adapting or transforming stage between two sources, generally between a generator and a load.



Power converter definition

An ideal static converter controls the flow of power between the two sources with 100% efficiency. Power converter design aims at improving the efficiency. But in a first approach and to define basic topologies, it is interesting to assume that no loss occurs in the converter process of a power converter.

3.2 SOLAR PHOTO-VOLTAIC SYSTEM

3.2.1 Introduction

A photovoltaic system, also PV system or solar power system is a power system designed to supply usable solar power by means of photo-voltaic. It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity, a solar inverter to change the electric current from DC to AC, as well as mounting, cabling and other electrical accessories to set up a working system. It may also use a solar tracking system to improve the system's overall performance and include an integrated battery solution, as prices for storage devices are expected to decline. Strictly speaking, a solar array only encompasses the ensemble of solar panels, the visible part of the PV system, and does not include all the other hardware, often summarized as balance of system . Moreover, PV systems convert light directly into electricity and shouldn't be confused with other technologies, such as concentrated solar power or solar thermal, used for heating and cooling.

PV systems range from small, rooftop-mounted or building-integrated systems with capacities from a few to several tens of kilowatts, to large utility-scale power stations of hundreds of megawatts. Nowadays, most PV systems are grid-connected, while off-grid or stand-alone systems only account for a small portion of the market. Operating silently and without any moving parts or environmental emissions, PV systems have developed from being niche market applications into a mature technology used for mainstream electricity generation.

3.2.2 Working and components of a PV system

The solar energy conversion into electricity takes place in a semiconductor device that is called a solar cell. A solar cell is a unit that delivers only a certain amount of electrical power. In order to use solar electricity for practical devices, which require a particular voltage or current for their operation, a number of solar cells have to be connected together to form a solar panel, also called a PV module. For large-scale generation of solar electricity the solar panels are connected together into a solar array. The solar panels are only a part of a complete PV solar system. Solar modules are the heart of the system and are usually called the power generators. One must have also mounting structures to which PV modules are fixed and directed towards the sun.

For PV systems that have to operate at night or during the period of bad weather the storage of energy are required, the batteries for electricity storage are needed. The output of a PV module depends on sunlight intensity and cell temperature; therefore components that condition the DC (direct current) output and deliver it to batteries, grid, and/or load are required for a smooth operation of the PV system. These components are referred to as charge regulators. For applications requiring AC (alternating current) the DC/AC inverters are implemented in PV systems. These additional components form that part of a PV system that is called balance of system. The elements of a PV system are schematically presented in Figure 1.

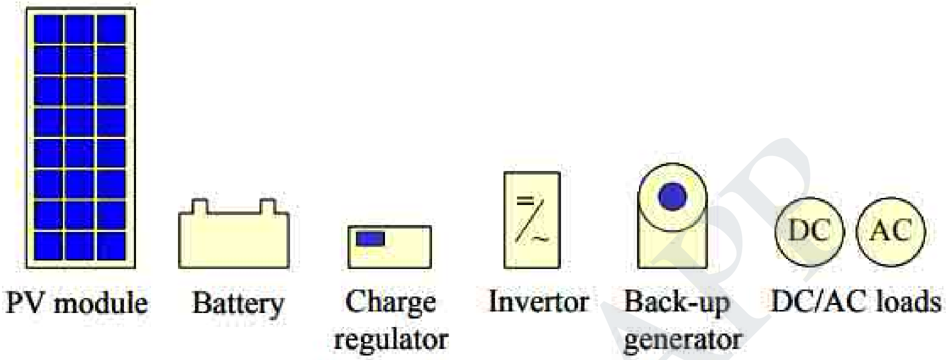


Figure 1: Components of a PV system

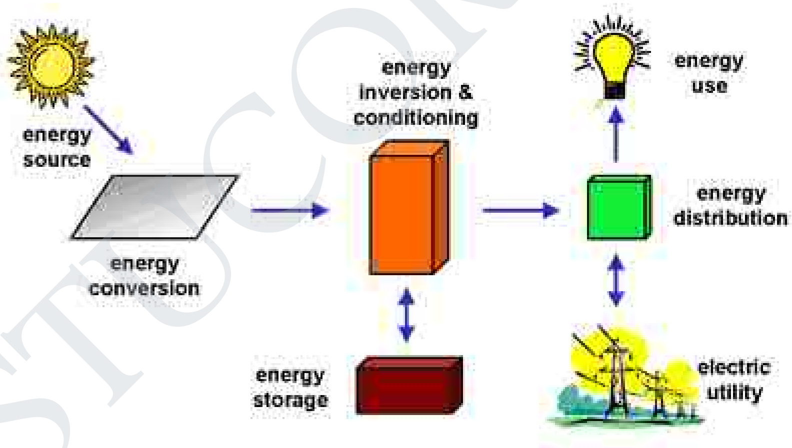
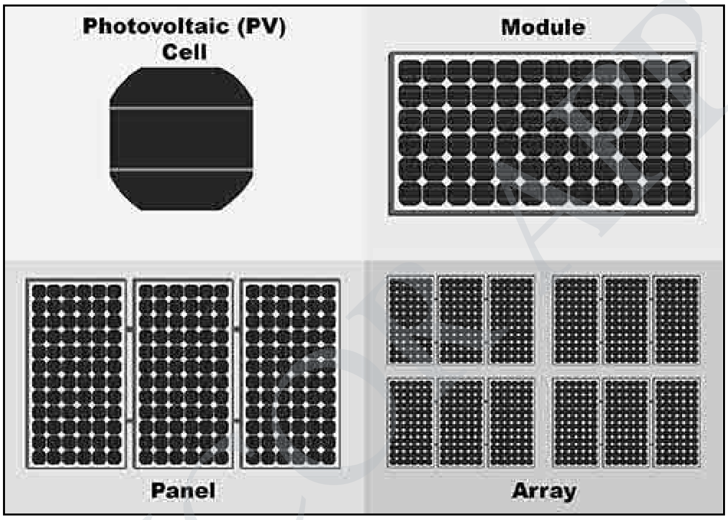


Figure 2: Major photovoltaic system components

Depending on the functional and operational requirements of the system, the specific components required may include major components such as a DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and sometimes the specified electrical load (appliances). In addition, an assortment of balance of system hardware, including wiring, over current, surge protection and disconnect devices, and other power processing equipment. Figure 2 show a basic diagram of a photovoltaic system and the relationship of individual components. Batteries are often used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed (during the night and periods of cloudy weather). Other reasons batteries are used in PV systems are to operate the PV array near its maximum power point, to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and over discharge.

3.2.3 PV module and Array

Photovoltaic cells are connected electrically in series and/or parallel circuits to produce higher voltages, currents and power levels. Photovoltaic modules consist of PV cell circuits sealed in an environmentally protective laminate, and are the fundamental building blocks of PV systems. Photovoltaic panels include one or more PV modules assembled as a pre-wired, field-installable unit. A photovoltaic array is the complete power-generating unit, consisting of any number of PV modules and panels.



Photovoltaic cells, modules, panels and arrays

3.2.4 Mounting structures

The principal aim of the mounting structures is to hold the PV modules securely in place, which usually means that they have to resist local wind forces. When placed in a public area the structures should prevent stealing the modules. The further common requirements are not to cause shading of the modules and to be arranged so that there is an easy access to the modules for the maintenance or repair. The cost of the structures should be low. For integration in buildings, special mounting structures are being developed that together with the modules serve as building elements.

3.2.5 Energy storage

The simplest means of electricity storage is to use the electric rechargeable batteries, especially when PV modules produce the DC current required for charging the batteries. Most of batteries used in PV systems are lead-acid batteries. In some applications, for example when used in locations with extreme climate conditions or where high reliability is essential, nickel-cadmium batteries are used. The major difficulty with this form of storage is the relative high cost of the batteries and a large amount required for large-scale application.

3.2.6 Charge regulators

Charge regulators are the link between the PV modules, battery and load. They protect the battery from overcharge or excessive discharge. Charge and discharge voltage limits should be carefully selected to suit the battery type and the operating temperature. These settings can significantly affect maximum operational life of a battery. High temperatures tend to reduce battery life because they accelerate corrosion and self-discharge. High temperatures may also increase out gassing during charging and therefore should be controlled. PV modules that are used to charge batteries usually operate at an approximately constant voltage, which is selected to suit the local temperature. However some PV systems regulators employ a maximum power point tracker (MPPT), which automatically permits the PV modules to operate at the voltage that produces maximum power output. Such regulators employ an electronic DC-DC converter to maintain their output at the required system voltage. The benefit of using an MPPT depends on the application and should be weighed against its additional cost and reliability risks. For many applications, it may be equally or more cost effective to operate the system at a fixed voltage.

3.2.7 Inverters

The inverter's main functions are: transformation of DC electricity into AC, wave shaping of the output AC electricity, and regulation of the effective value of the output voltage. The most important features of an inverter for PV applications are its reliability and its efficiency characteristics. They are designed to operate a PV system continuously near its maximum power point. The technology for high-switching-frequency inverters (typically 20 kHz or higher) is made possible by switch-mode semiconductor power devices. The efficiency of an inverter is normally quoted at its design operating power, but inverters in PV systems typically operate for much of their life at partial loads. For grid-connected operation, inverters must meet the requirements of the utilities concerning acceptable levels of harmonic distortion (quality of voltage and current output waveforms), and should not emit electrical noise, which could interfere with the reception of television or radio. They must also switch off when there is a grid failure for the safety of the engineers who have to repair the grid.

3.3 TYPES OF PV SYSTEMS

PV systems can be very simple, just a PV module and load, as in the direct powering of a water pump motor, or more complex, as in a system to power a house. Depending on the system configuration, we can distinguish three main types of PV systems: stand-alone, grid-connected, and hybrid.

3.3.1 Stand-alone systems

Stand-alone systems depend on PV power only. These systems can comprise only PV modules and a load or can include batteries for energy storage. When using batteries charge regulators are included, which switch off the PV modules when batteries are fully charged, and switch off the load in case batteries become discharged below a limit. The batteries must have enough capacity to store the energy produced during the day to be used at night and during periods of poor weather. Figure 1 shows schematically examples of stand-alone systems.

3.3.2 Grid-connected systems

Grid-connected PV systems have become increasingly popular as building integrated application. They are connected to the grid through inverters, and do not require batteries because the grid can accept all of the electricity that a PV generator can supply. Alternatively they are used as power stations. A grid-connected PV system is schematically presented in Figure 2.

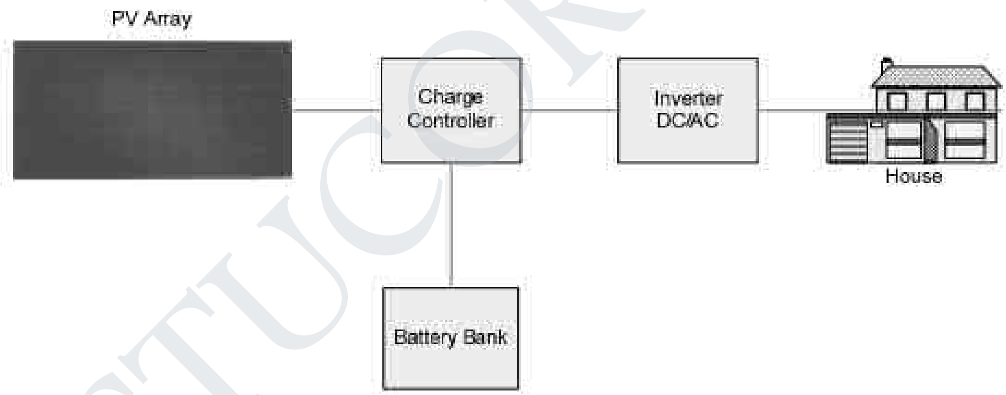


Figure 1: Stand-alone systems

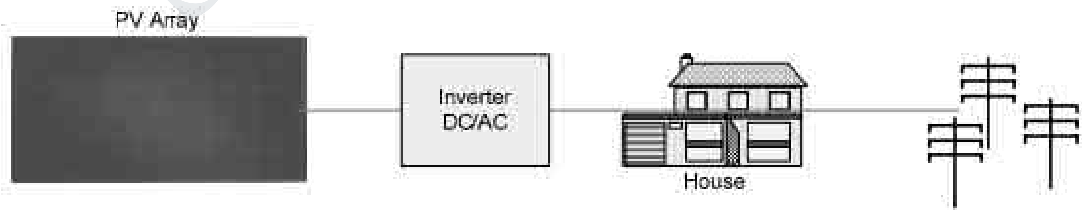


Figure 2: Grid-connected systems

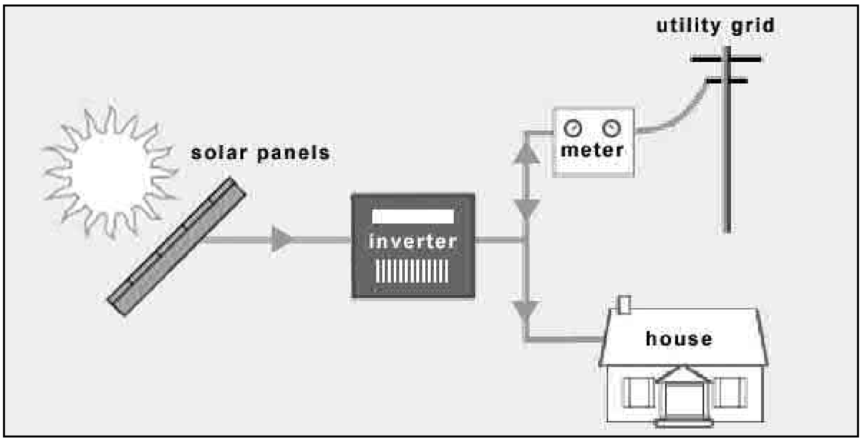


Figure 3: Hybrid PV-Diesel systems

3.3.3 Hybrid systems

Hybrid systems consist of combination of PV modules and a complementary means of electricity generation such as a diesel, gas or wind generator. In order to optimize the operations of the two generators, hybrid systems typically require more sophisticated controls than stand-alone PV systems. For example, in the case of PV/diesel systems, the diesel engine must be started when battery reaches a given discharge level and stopped again when battery reaches an adequate state of charge. The back-up generator can be used to recharge batteries only or to supply the load as well. A common problem with hybrid PV/diesel generators is inadequate control of the diesel generator. If the batteries are maintained at too high a state-of-charge by the diesel generator, then energy, which could be produced by the PV generator, is wasted. Conversely, if the batteries are inadequately charged, then their operational life will be reduced. Such problems must be expected if a PV generator is added to an existing diesel engine without installing an automatic system for starting the engine and controlling its output.

3.3.4 Equivalent circuit diagram of solar PV cell

Now a days, different semiconductor materials i.e. mono crystal polycrystalline and formless silicon are used. The single diode circuit configuration for PV cells is shown in Figure 1 and equation (1) shows the current expression. The double diode circuit configuration for PV cell is shown in Fig.2 and equation (2) shows the current expression.

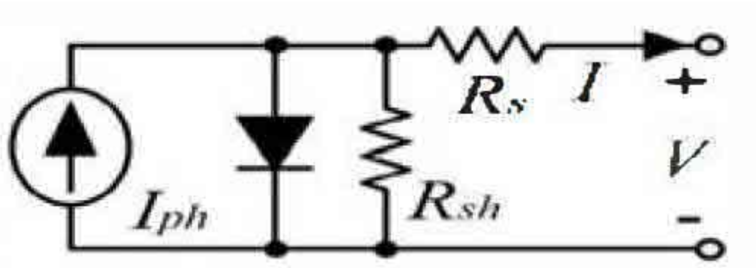


Figure 1: Single diode configuration for PV cell

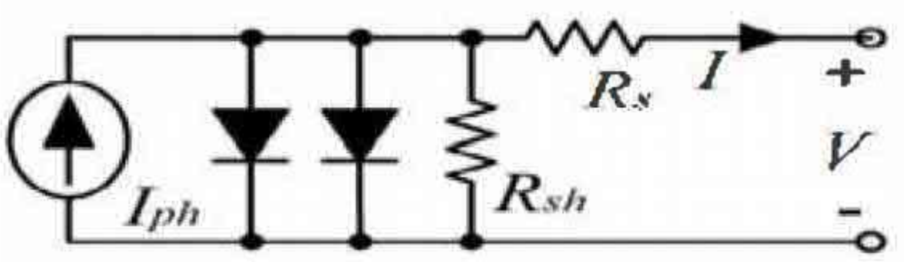


Figure 2: Double diode configuration for PV cell

For temperature dependence I_{ph} will be as shown in equation (3) for maximum power in case of single diode model.

$$I = I_{ph} - I_s\left[e^{\frac{q(V+IR_s)}{N_s K T_0 A}} - 1\right] - \frac{V + IR_s}{R_{sh}} \qquad (1)$$

$$I = I_{ph} - I_{s1}\left[e^{\frac{q(V+IR_s)}{A_1 KT}} - 1\right] - I_{s2}\left[e^{\frac{q(V+IR_s)}{A_2 KT}} - 1\right]\frac{V + IR_s}{R_{sh}} \qquad (2)$$

$$I_{ph} = I_{ph(T=298K)}\left[1 + \left(T - 298K(5 \times 10^{-4})\right)\right] \qquad (3)$$

$$I_{S1} = K_1 T^3 e^{\frac{-E_S}{KT}} \qquad (4a)$$

$$I_{S2} = K_2 T^{\frac{5}{2}} e^{\frac{E_S}{KT}} \qquad (4b)$$

Where

q	=	electron charge = 1.6×10^{-19} V
I_s	=	diode saturation current
I_{ph}	=	Photon Current
K_1	=	12000 A/m^2K^3
K_2	=	2.9×10^9 $A/m^2K^{5/2}$
R_s	=	Series Resistance
R_{sh}	=	Shunt Resistance
A	=	Diode ideality Factor
T_o	=	Operating temperature
N_s	=	No. of cells in series
K	=	Boltzmann constant = 1.38×10^{-23}J/K

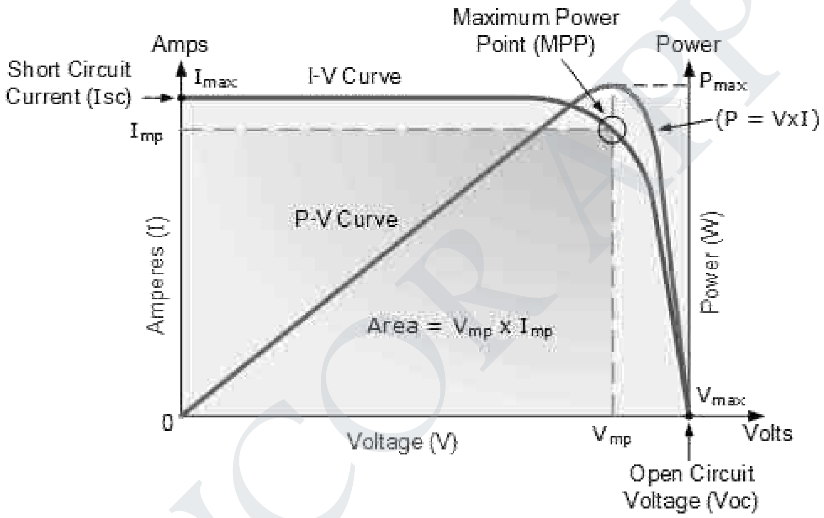
Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. Such a diversion reduces the amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. The effect of a shunt resistance is particularly more at low irradiance, since there will be less magnitude of current. The loss of this current to the shunt therefore has a larger impact. In addition, at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large. For the rise of series resistance the voltage and current density will be reduced and vice versa. For ideal solar plate R_s will be zero and the R_{sh} will be infinite. Therefore, for the maximum power from the solar PV cell Rs will be negligible value and the R_{sh} must have a higher value.

For maximum power in case of single diode model

$$\frac{dP_m}{dP_m} = \left[I_{ph} - I_{rs}\left[e^{\frac{q(V+qIR_s)}{N_s K T_0 A}} - 1 \right] - \left[\frac{V + IR_s}{R_{sh}} \right] + V_m \left[-\frac{q}{N_s K T_0 A} I_{rs} \left[e^{\frac{q(V+IR_s)}{N_s K T_0 A}} \right] - \frac{1}{R_{sh}} \right] \right] = 0 \quad (5)$$

3.3.5 Characteristics of PV array and MPP

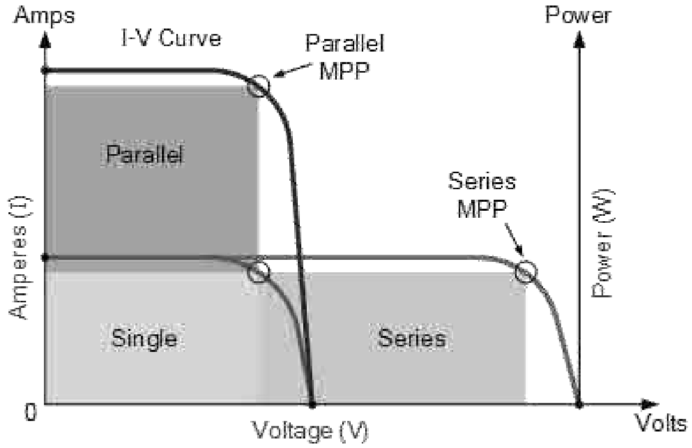
Solar Cell V-I Characteristics Curves are basically a graphical representation of the operation of a solar cell or module summarizing the relationship between the current and voltage at the existing conditions of irradiance and temperature. *V-I* curves provide the information required to configure a solar system so that it can operate as close to its optimal peak power point (MPP) as possible.



The above graph shows the *V-I* characteristics of a typical silicon PV cell operating under normal conditions. The power delivered by a solar cell is the product of current and voltage. If the multiplication is done, point for point, for all voltages from short-circuit to open-circuit conditions, the power curve above is obtained for a given radiation level. With the solar cell open-circuited that is not connected to any load the current will be at its minimum (zero) and the voltage across the cell is at its maximum, known as the solar cells **open circuit voltage**, or $\mathbf{V_{oc}}$. At the other extreme, when the solar cell is short circuited, that is the positive and negative leads connected together, the voltage across the cell is at its minimum (zero) but the current flowing out of the cell reaches its maximum, known as the solar cells **short circuit current**, or $\mathbf{I_{sc}}$.

<u>Solar Panel I-V Characteristic Curves</u>

Photovoltaic panels can be wired or connected together in either series or parallel combinations, or both to increase the voltage or current capacity of the solar array. If the array panels are connected together in a series combination, then the voltage increases and if connected together in parallels then the current increases.

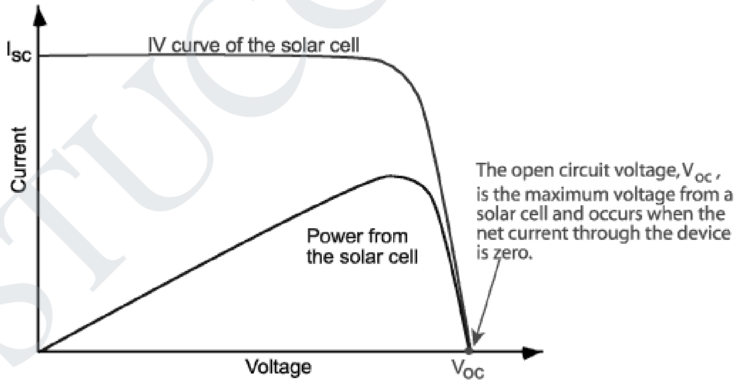


The electrical power in Watts, generated by these different photovoltaic combinations will still be the product of the voltage times the current, (P = V x I). However the solar panels are connected together, the upper right hand corner will always be the maximum power point (MPP) of the array.

3.3.6 Open circuit voltage and short circuit current of PV system

Open-Circuit Voltage

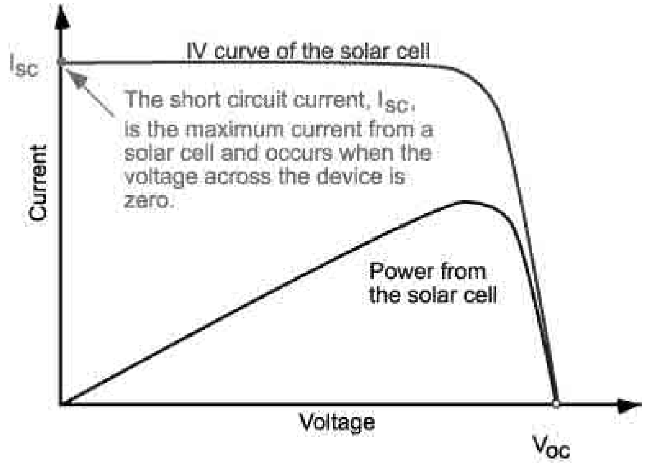
The open-circuit voltage, V_{OC}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. The open-circuit voltage is shown on the V-I curve below.



Open-Circuit Voltage

Short-Circuit Current

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as I_{SC}, the short-circuit current is shown on the V-I curve below.



Short-Circuit Current

The short-circuit current is due to the generation and collection of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell.

3.3.7 MPPT

Maximum power point tracking is often called as MPPT. This is an electronic system which commands a solar panel or a set of solar panels to generate the maximum amount of power. The MPPT is not a physical system strapped with solar trackers that position the panels so that they remain under the sun at all times. Although they can be used along with solar trackers, you must know that both are different systems. This fully electronic system varies the electrical operating point of the panels which enables them to deliver the maximum power. The Extra power generated by the panels is made available to the modules in the form of increased battery charging current.

3.4 PV POWER CONDITIONING SYSTEM

This is a power converter which interfaces the PV to utility grid and converts the DC supply from the PV plant to AC supply as requirement by the utility grid. Based on the galvanic connection between PV plant and grid, the power conditioning system (PCS) can be broadly classified into two types such as **isolated power conditioning system** and **non isolated power conditioning system**.

3.4.1 Isolated PV Power Conditioning System

In isolated type PV system the isolation between PV plant and grid is achieved by using a line frequency transformer at the output of the inverter (AC side) or by using high frequency transformer DC-DC converter at the input side of the inverter. In low frequency (power frequency) transformer system involves huge size, increasing magnetic loss and low efficiency than high frequency transformer based DC-DC converter system. This high frequency transformer involves complex control resonant problems and which increase the cost of the PV system.

3.4.2 Non Isolated PV Power Conditioning System

The non isolated grid connected PV system is again classified in to single-stage and multistage power conditioning systems. In single-stage, only one power processing stage is available to convert the PV power to AC supply. Nowadays, single stage power converters are most widely used in PV applications. The single- stage inverter can perform the buck, boost, and both buck- boost input voltage, inversion and maximum power point. The single-stage inverter has the advantages of improved efficiency, low cost, more reliability, modularity, and compact size than multistage power conversion systems.

Figure 1 shows a block diagram of conventional photovoltaic power conditioning systems. They consist of an inverter, LP-filter and line transformer. The filter eliminates/attenuates the harmonics on produced by the inverter, the filter output is stepped up at the grid level by a low frequency transformer.

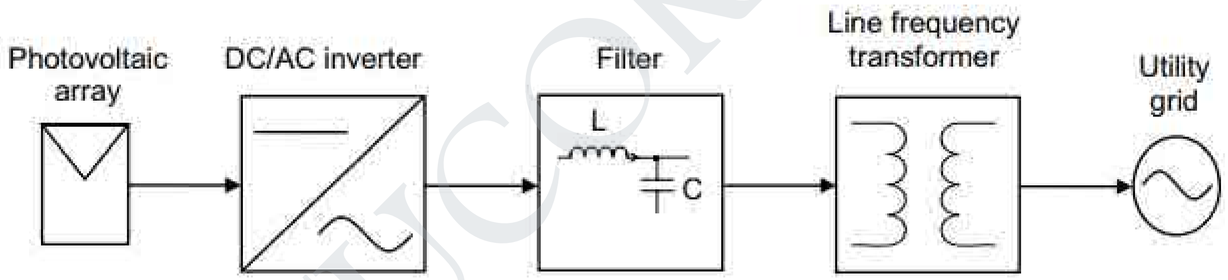


Figure 1: PV PCS with line frequency transformer

Figure 2 shows a block diagram of a conventional isolated type photovoltaic power conditioning system. In this system, a DC/DC converter using a high frequency transformer converts a DC voltage delivered by the PV into a controlled DC voltage suitable for the inverter.

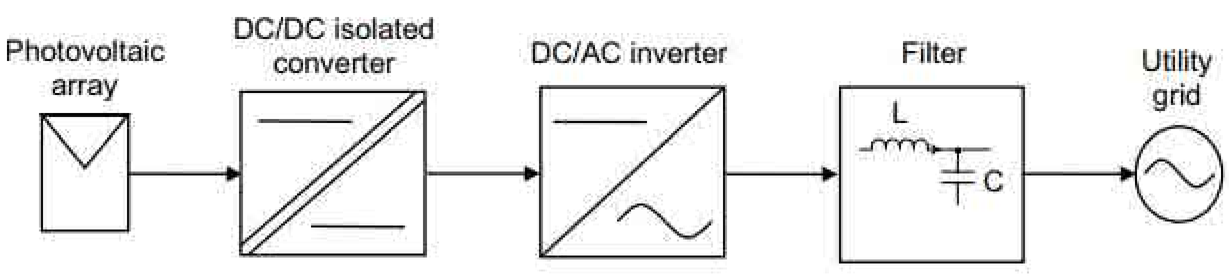


Figure 2: PV PCS with high frequency transformer

Figure 3 shows a block diagram of a conventional non-isolated type photovoltaic power conditioning system. In this system, a DC/DC non-isolated converter receives the fluctuating DC voltage delivered by the PV and converts it into DC voltage suitable for the inverter.

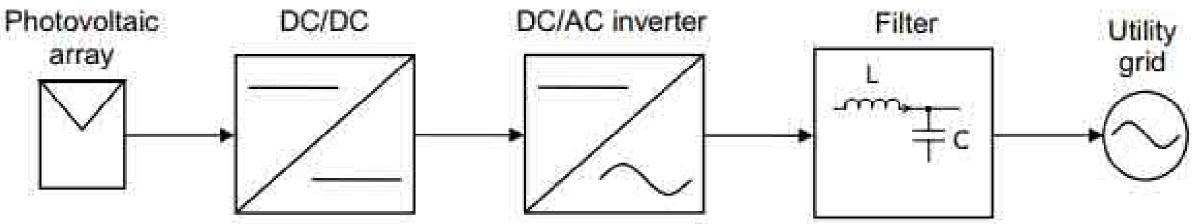
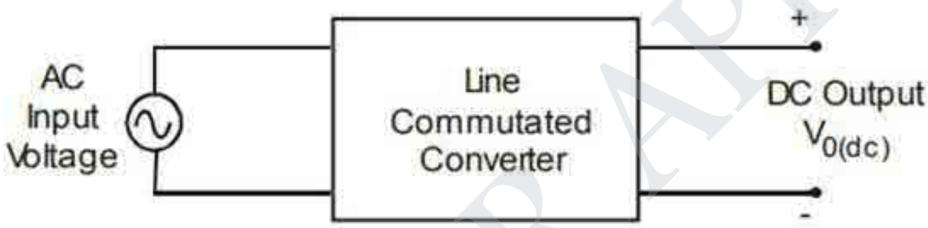


Figure 3: Conventional non-isolated type PV PCS

3.5 LINE COMMUTATED CONVERTERS

3.5.1 Introduction to Controlled Rectifiers

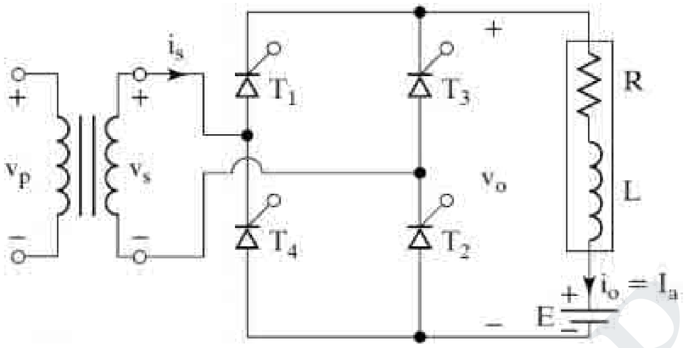


Controlled rectifiers are line commutated ac to dc power converters which are used to convert a fixed voltage, fixed frequency ac power supply into variable dc output voltage. Type of input: Fixed voltage, fixed frequency ac power supply. Type of output: Variable dc output voltage. The input supply fed to a controlled rectifier is ac supply at a fixed RMS voltage and at a fixed frequency. We can obtain variable dc output voltage by using controlled rectifiers. By employing phase controlled thyristors in the controlled rectifier circuits we can obtain variable dc output voltage and variable dc (average) output current by varying the trigger angle (phase angle) at which the thyristors are triggered. There are several types of power converters which use ac line commutation. These are referred to as line commutated converters.

3.5.2 Line commutated converters under inversion mode

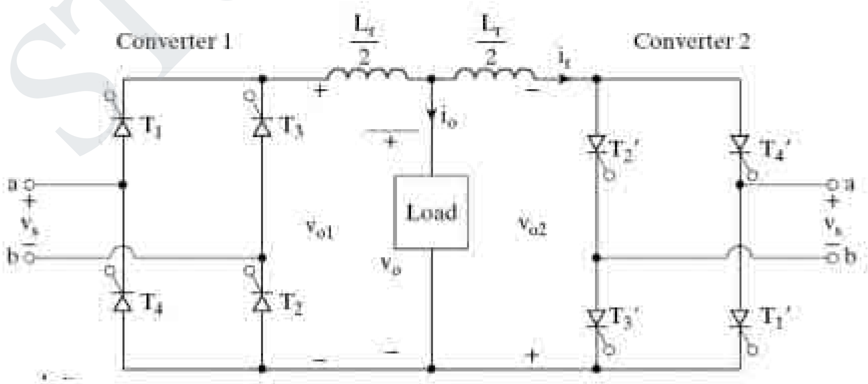
Single Phase Full Converter

The circuit diagram of a single phase fully controlled bridge converter is shown in the figure with a highly inductive load and a dc source in the load circuit so that the load current is continuous and ripple free (constant load current operation). The fully controlled bridge converter consists of four thyristors T_1, T_2, T_3 and T_4 connected in the form of full wave bridge configuration as shown in the figure. Each thyristor is controlled and turned on by its gating signal and naturally turns off when a reverse voltage appears across it. During the positive half cycle when the upper line of the transformer secondary winding is at a positive potential with respect to the lower end the thyristors T_1 and T_2 are forward biased during the time interval $\omega t = 0$ to π . As soon as the thyristors T_3 and T_4 are triggered a reverse voltage appears across the thyristors T_1 and T_2 and they naturally turn-off and the load current is transferred from T_1 and T_2 to the thyristors T_3 and T_4.



Single Phase Dual Converter

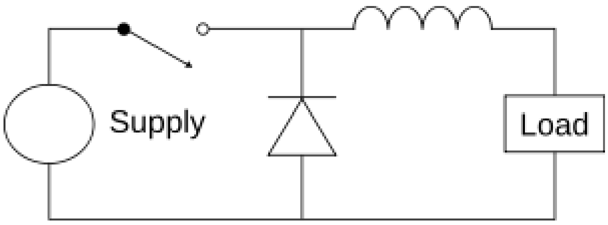
The dual converter system will provide four quadrant operation and is normally used in high power industrial variable speed drives. The converter number 1 provides a positive dc output voltage and a positive dc load current, when operated in the rectification mode. The converter number 2 provides a negative dc output voltage and a negative dc load current when operated in the rectification mode. We can thus have bidirectional load current and bi-directional dc output voltage. The magnitude of output dc load voltage and the dc load current can be controlled by varying the trigger angles of the converters 1 and 2 respectively. There are two modes of operations possible for a dual converter system like non circulating current mode of operation and circulating current mode of operation.



3.5.3 DC-DC Converters

DC-DC Buck Converter

A buck converter (step-down converter) is a DC-to-DC power converter which steps down voltage (while stepping up current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) typically containing at least two semi conductors and at least one energy storage element, a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

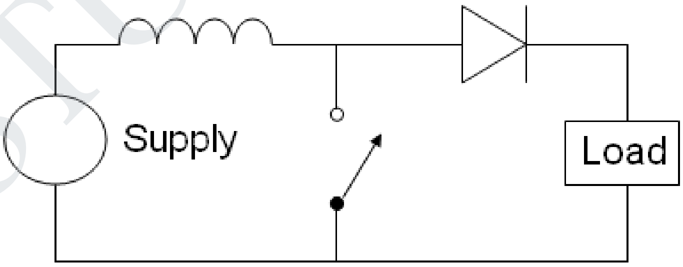


Buck converter circuit diagram.

The basic operation of the buck converter has the current in an inductor controlled by two switches. In the idealized converter, all the components are considered to be perfect. Specifically, the switch and the diode have zero voltage drop when on and zero current flow when off, and the inductor has zero series resistance.

DC-DC Boost Converters

A boost converter (step-up converter) is a DC-to-DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element: a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

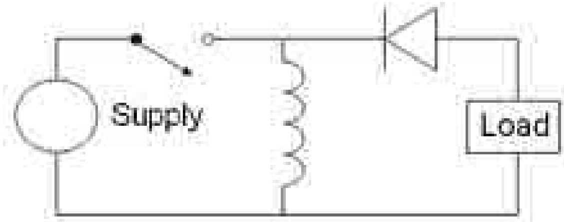


Basic schematic of a boost converter

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current by creating and destroying a magnetic field. In a boost converter, the output voltage is always higher than the input voltage. When the switch is closed, current flows through the inductor in clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive. When the switch is opened, current will be reduced as the impedance is higher. The magnetic field previously created will be destroyed to maintain the current towards the load. Thus the polarity will be reversed (means left side of inductor will be negative now). As a result, two sources will be in series causing a higher voltage to charge the capacitor through the diode D.

DC-DC Buck-Boost Converters

A Buck-Boost converter is a type of switched mode power supply that combines the principles of the Buck Converter and the Boost converter in a single circuit. Like other SMPS designs, it provides a regulated DC output voltage from either an AC or a DC input.



Buck-Boost Converters

It is equivalent to a fly-back using a single inductor instead of a transformer. Two different topologies are called buck–boost converter. Both of them can produce a range of output voltages, ranging from much larger (in absolute magnitude) than the input voltage, down to almost zero.

Modes of Buck Boost Converters

There are two different types of modes in the buck boost converter. The following are the two different types of buck boost converters.

- Continuous conduction mode.
- Discontinuous conduction mode.

Continuous Conduction Mode

In the continuous conduction mode the current from end to end of inductor never goes to zero. Hence the inductor partially discharges earlier than the switching cycle.

Discontinuous Conduction Mode

In this mode the current through the inductor goes to zero. Hence the inductor will totally discharge at the end of switching cycles.

Applications of Buck boost converter

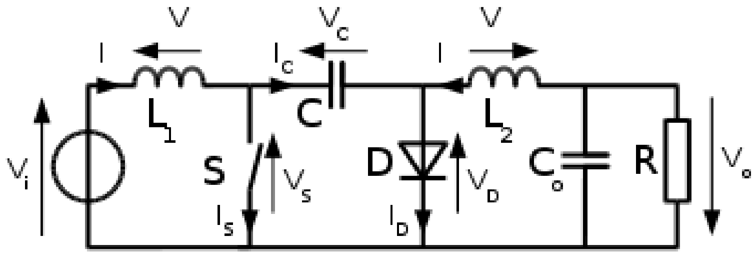
- It is used in the self regulating power supplies.
- It has consumer electronics.
- It is used in the Battery power systems.
- Adaptive control applications.
- Power amplifier applications.

Advantages of Buck Boost Converter

- It gives higher output voltage.

- Low operating duct cycle.
- Low voltage on MOSFETs

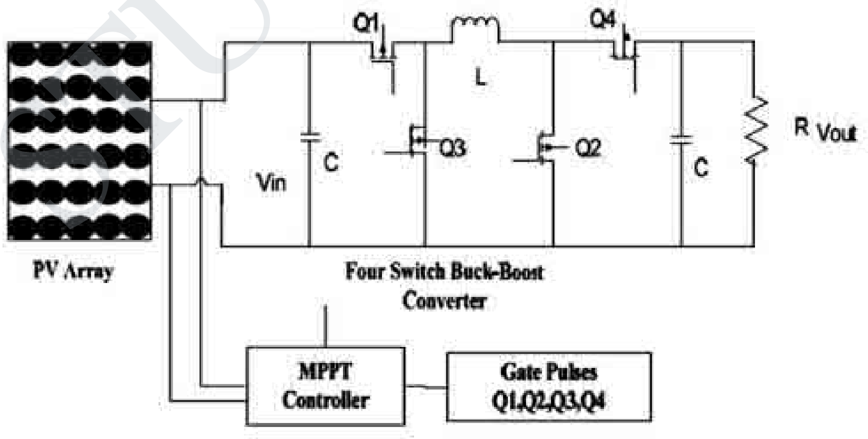
Cuk converter



Schematic of a non-isolated Cuk converter

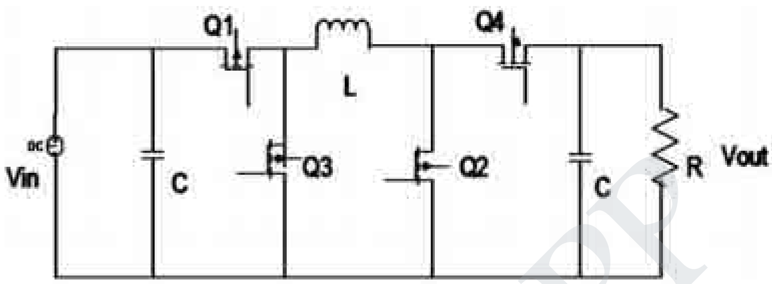
The Cuk converter is a type of DC/DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is essentially a boost converter followed by a buck converter with a capacitor to couple the energy. Similar to the buck–boost converter with inverting topology, the output voltage of non-isolated Cuk is typically also inverting, and can be lower or higher than the input. It uses a capacitor as its main energy-storage component, unlike most other types of converters which use an inductor. There are variations on the basic Cuk converter. For example, the coils may share single magnetic core, which drops the output ripple, and adds efficiency. Because the power transfer flows continuously via the capacitor, this type of switcher has minimized EMI radiation. The Cuk converter allows energy to flow bi-directionally by using a diode and a switch.

3.5.4 PV fed Buck Boost Converter (Four switched topology)

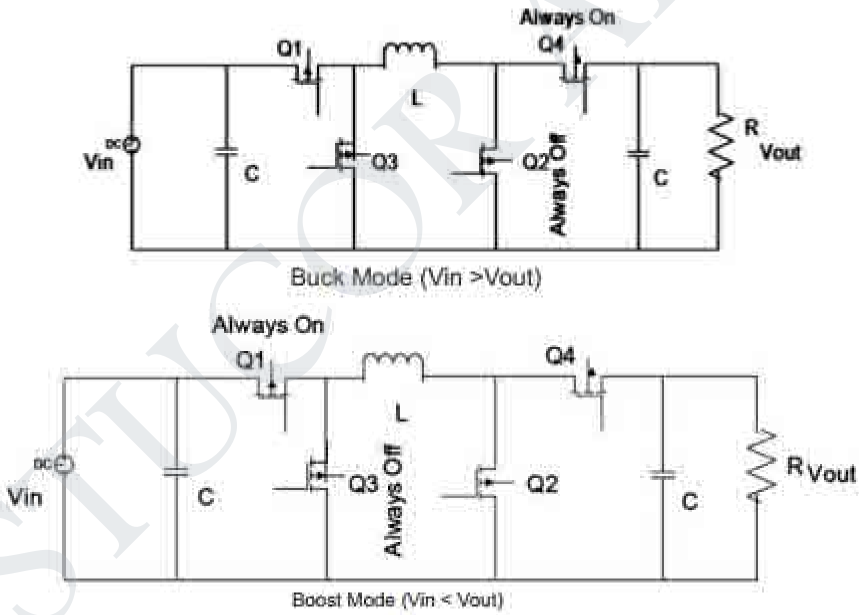


Four-switch power converter is cascaded combination of Buck converter followed by a Boost converter the converter is different from the other DC-DC converters why, because it has four switches to be controlled, that is, two gate pulses we need. This means for the same working point with different values both gate pulses can be used. Furthermore, due to its simple and cascaded combination of Buck-Boost structure, it presents high adaptability and high performance to system voltage changes.

The configuration of the system consists of the Solar PV array fed to FSBB Converter which feeds the Load. It is a combination of Buck converter followed by Boost converter; a four switch buck-boost converter can operate in buck mode or boost mode rather than conventional buck-boost converter. As such, its efficiency can be improved by synchronous rectification the power stage consist of four switches (Q_1, Q_2, Q_3, and Q_4), single inductor (L), and input and output Capacitors.



Four-switch buck-boost converter.



Equivalent circuit in Buck/Boost mode

Here the MOSFETs Q_3,Q_4 share the gate control signal, which is complementary to the gate control signal of MOSFETs Q_1 and Q_2, In the buck-boost mode the MOSFETs Q_1 and Q_2 share gate control signals and turn on and off simultaneously. When the MOSFETs Q_1 and Q_2 are turned on, the input voltage V_{in} is applied, the inductor L stores the energy, output capacitor supplies the load current entirely.

When Q_1 and Q_2 are turned off, MOSFETs Q_3, Q_4 are turned on in this stage the energy is transferred from the inductor to output load and capacitor. Here we are using a synchronous rectification scheme these means we are using MOSFETs instead of diodes to reduce the switching and power losses and to improve efficiency. The Figure shows the equivalent circuit of the converter in buck and boost mode. When Vin is higher than Vout, The MOSFET Q_2 is always OFF, Q_4 is always ON, Q_1 and Q_3 ON and OFF simultaneously thus it works like a buck converter ($V_{in} > V_{out}$) as shown in below figure. When Vin is lower than V_{out}, Q_1 is always ON and Q_3 is always OFF, Q_2 and Q_4 ON and OFF simultaneously it works as a boost converter ($V_{in} < V_{out}$) as shown in below figure.

3.5.5 Current regulated PWM inverters

Current regulation technique plays the most important role in Current Regulated PWM (CR-PWM) inverters which are widely applied in ac motor drives, ac power supply and active filters. The CR-PWM inverters, also known as current mode PWM inverters, implement an on line current feedback (closed loop) type of PWM. In comparison to a conventional feed forward (open loop) voltage controlled PWM inverters they show following advantages: - control of instantaneous peak current, - overload problem is avoided, - pulse drop problem does not occur, - extremely good dynamics, - nearly sinusoidal current waveforms, expect for the harmonics - compensation of the effect of load parameter changes (resistance and reactance). The basic problem involved in the implementation of CR-PWM inverters is the choice of suitable current regulation strategy, which affects both the parameters obtained. The main task of the control system in CR-PWM inverter is to force the current vector in the three phase load according to the reference trajectory.

3.6 SIZING BATTERIES AND INVERTERS FOR A SOLAR PV SYSTEM

3.6.1 Basics of sizing

The most important thing that one needs to know before sizing a PV system is the energy requirements of a setup. A few things that can help are:

1. Wattages and counts of all the appliances that need to be run on solar PV.
2. If you do not have wattages then you can look at the current requirement (in amperes) of the appliances and calculate wattage with this simple formula: Watts = Ampere x 240 (voltage)
3. Electricity bills of the setup. Used to check the monthly electricity units used in a setup. Daily units can be obtained by dividing month units by 28/29/30 or 31 (depending on the number of days in the month for which the bill is generated)

4. Daily usage of each appliance in hours. This is required if you do not have a sample electricity bill. This helps in calculating the number of units of electricity used in a day using the formula below: Units = (Watts x Hours) ÷1000

3.6.2 Sizing a PV panel

To size a PV panel, the most essential thing to know is the Total Units consumed in a day by the appliances in a setup. The size of PV system should not be less than the one that can generate total units consume in a day. Every PV panels has a peak wattage (W_p) mentioned on them. A 1 kW_p (or peak kilo watt) system would generate 5 to 7 units in a day. Thus the right size of PV system (in kW_p) should be estimated by dividing maximum daily usage units divided by 5. If you are going for a grid connected system where extra electricity produced will be sold back to the electricity provider. In such cases you can optimize the size of PV system based on the space that you have for installing PV panels.

3.6.3 Sizing Batteries for PV system

Along with sizing of the PV panel, it is important to size the batteries as well. Because if purchase more batteries then they will not get fully charged, if buy fewer batteries, may not be able to get the maximum benefit out of the solar panel. Most big PV systems use deep cycle (or deep discharge) batteries that are designed to discharge to low energy levels and also to recharge rapidly. These are typically lead acid batteries that may or may not require maintenance. Batteries have energy storage ratings mentioned in Amp-hour (Ah) or milli-Amp-hour (mAh). They also have a nominal voltage that they generate (typically deep discharge batteries are 12 V batteries, cell phone batteries are 5 V batteries, etc). To calculate the total energy a battery can store you can use following formula: Units = (Volt x Ah) ÷1000 or (Volt x mAh) ÷1000000. Batteries should be sized in a way that the units of energy generated by the PV system should be equal to the number we have calculated above. So assuming we have a 1 kWp system and we assume that on an average it generates 6 units a day and if we have to buy 12 V battery for it, the Ah (or storage) of battery required would be: (6 x1000) ÷12 = 500 Ah

3.6.4 Sizing Inverter for a Solar PV system

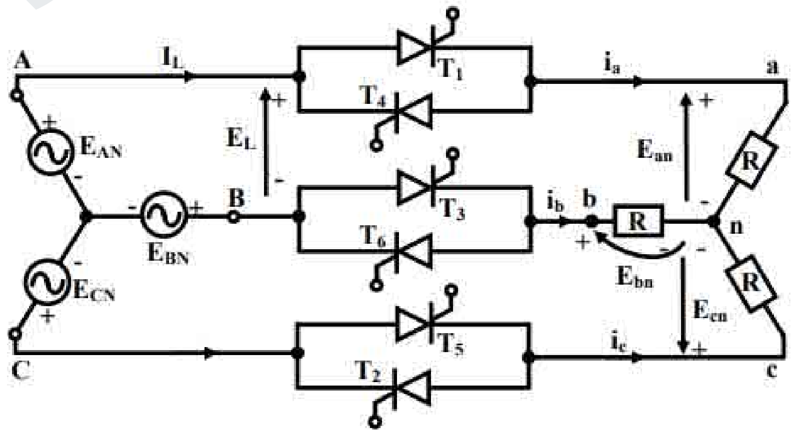
A power inverter or inverter is a system that converts Direct Current (or DC) to an alternating current (or AC). A solar panel produces DC current, batteries also generate DC current, but most systems we use in our daily lives use AC current. Inverters also have transformers to convert DC output voltage to any AC output voltage. Depending on the type of system (grid or off-grid) various types of inverters are available. Sizing of inverter depends on the wattage of appliances connected to it. The input rating of inverter should never be lower than the total wattages of the appliances. Also it should have the same nominal input voltage as that of the battery setup. It is always better to have inverter wattage about 20-25% more than that of the appliances connected. This is specifically essential if the appliances connected have compressors or motors (like AC, refrigerator, pumps, etc), which draw high starting current. Most inverters available in market are rated on KVA /VA or Kilo Volt Ampere/Volt Ampere. In ideal situations (power factor of 1) 1 VA = 1 Watt. But in real power factor varies from 0.85 to 0.99 (more about power factor on: What is Power Factor correction and how MDI (Maximum Demand Indicator) penalty can be avoided). So one can assume 1.18 VA = 1 Watt. So if you have a setup where the total wattage of the system is 1000 Watts, it means your inverter size required is more than 1180 VA or 1.18 KVA (add some extra to be on a safer side).

3.7 THREE-PHASE AC VOLTAGE REGULATORS

There are many types of circuits used for the three-phase ac regulators (ac to ac voltage converters), unlike single-phase ones. The three-phase loads (balanced) are connected in star or delta. Two thyristors connected back to back, or a triac, is used for each phase in most of the circuits as described. Two circuits are first taken up, both with balanced resistive (R) load

3.7.1 Three-phase, star connected AC Regulator with Balanced Resistive Load

The circuit of a three-phase, three-wire AC regulator (termed as ac to ac voltage converter) with balanced resistive (star-connected) load is shown in Figure. It may be noted that the resistance connected in all three phases are equal. Two thyristors connected back to back are used per phase, thus needing a total of six thyristors. The current flow is bidirectional, with the current in one direction in the positive half, and then, in other (opposite) direction in the negative half. So, two thyristors connected back to back are needed in each phase. The turning off of a thyristor occurs, if its current falls to zero. To turn the thyristor on, the anode voltage must be higher that the cathode voltage, and also, a triggering signal must be applied at its gate.



Three-phase, three-wire star connected AC voltage regulator

The expression of the RMS value of output voltage is obtained by per phase for balanced star-connected resistive load which depends on range of firing angle. If is the RMS value of the input voltage per phase, and assuming the voltage, as the reference, the instantaneous input voltages per phase are,

$e_{AN} = \sqrt{2}E_s sin\omega t$

$e_{BN} = \sqrt{2}E_s \sin\,(\omega t - 120^0)$

$e_{CN} = \sqrt{2}E_s sin\,(\omega t + 120^0)$

Then, the instantaneous input line voltages are,

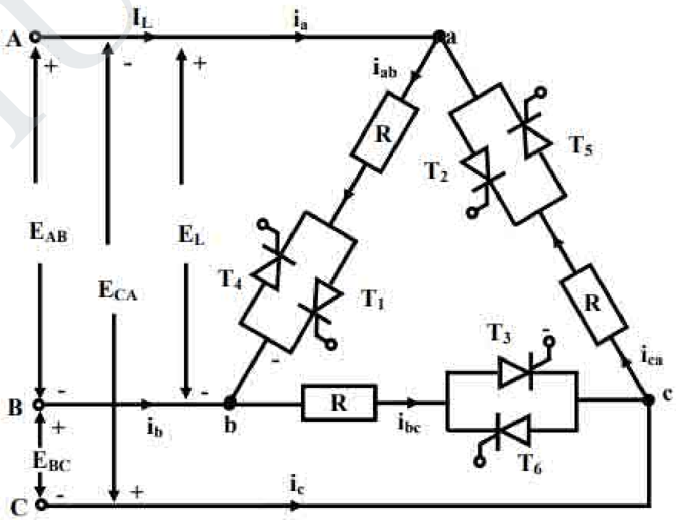
$e_{AB} = \sqrt{6}E_s sin(\omega t + 30^0)$

$e_{BC} = \sqrt{6}E_s \sin\,(\omega t - 90^0)$

$e_{CA} = \sqrt{6}E_s sin\,(\omega t + 150^0)$

3.7.2 Three-phase Delta-connected AC Regulator with Balanced Resistive Load

The circuit of a three-phase, delta-connected ac regulator (termed as ac to ac voltage converter) with balanced resistive load is shown in Figure. It may be noted that the resistance connected in all three phases are equal. Two thyristors connected back to back are used per phase, thus needing a total of six thyristors. As stated earlier, the numbering scheme may be noted. It may be observed that one phase of the balanced circuit is similar to that used for single phase ac regulator. Since the phase current in a balanced three-phase system is only (1/√3) of the line current, the current rating of the thyristors would be lower than that if the thyristors are placed in the line.



Assuming the line voltage as the reference, the instantaneous input line voltages are,

$e_{AB} = \sqrt{2}E_s sin\omega t$

$e_{BC} = \sqrt{2}E_s \sin\,(\omega t - 120^0)$

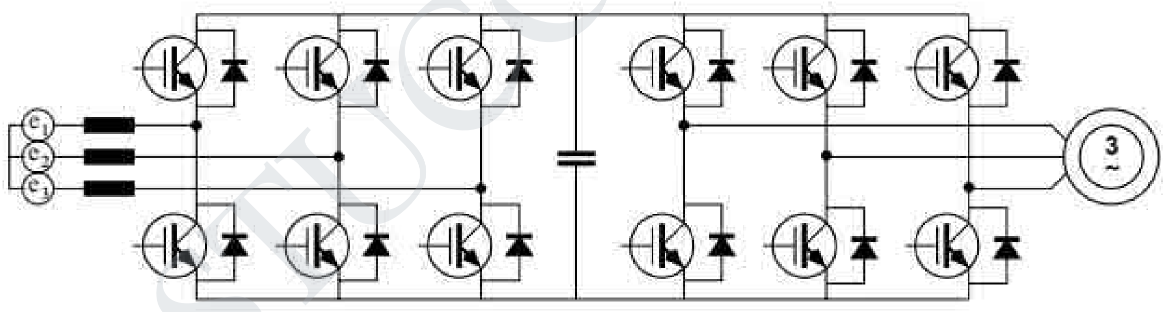
$e_{CA} = \sqrt{2}E_s sin\ (\omega t + 120^0)$

It may be noted that is the RMS value of the line voltage in this case.

3.8 THREE PHASE AC-DC-AC CONVERTERS (THE BACK-TO-BACK CONVERTER)

The back-to-back converter is consists simply of a force-commutated rectifier and a force-commutated inverter connected with a common dc-link shown in figure. The properties of this combination are well known; the line-side converter may be operated to give sinusoidal line currents, for sinusoidal currents, the dc-link voltage must be higher than the peak main voltage, the dc-link voltage is regulated by controlling the power flow to the ac grid and, finally, the inverter operates on the boosted dc-link, making it possible to increase the output power of a connected machine over its rated power. Another advantage in certain applications is that braking energy can be fed back to the power grid instead of just wasting it in a braking resistor.

An important property of the back-to-back converter is the possibility of fast control of the power flow. By controlling the power flow to the grid, the dc-link voltage can be held constant. The presence of a fast control loop for the dc-link voltage makes it possible to reduce the size of the dc-link capacitor, without affecting inverter performance. In fact, the capacitor can be made small enough to be implemented with plastic film capacitors.



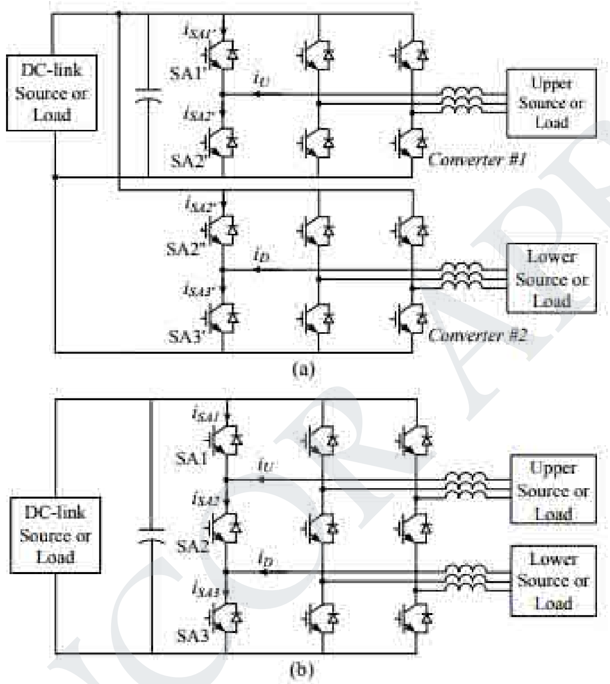
Back-to-back converter

3.8.1 Issues associated with a small DC-link capacitor

Smallest size of the dc-link capacitor is governed by the need to keep the switch-frequent ripple at acceptable (i.e. small) levels. Fluctuations in the load cannot be smoothed in the converter, but must be accommodated by other means. One alternative is to simply transfer such fluctuations to the power grid, but this may re-introduce the line-current harmonics the back to back converter is supposed to eliminate. However, load fluctuations will be random and thus relatively harmless compared to the in-phase harmonics generated by diode rectifiers. Another alternative is to use the load itself. In a typical drive, the mechanical energy stored in the drive is several orders of magnitude larger than the electrical energy stored in the DC-link capacitor in a back-to-back converter. If the application does not need servo-class performance, there is no reason why the rotational speed cannot be allowed to fluctuate slightly.

3.8.2 Application criteria for three-phase nine-switch converters

The nine-switch topology is derived from two converters connected back-to-back (BTB) shown in figure. Two phase legs from converter 1 and 2, respectively, are merged together to compose one phase leg of the nine switch converter, and meanwhile one switch is dismissed. Thus nine-switch converters have only three phase legs and each of them has only three switches.

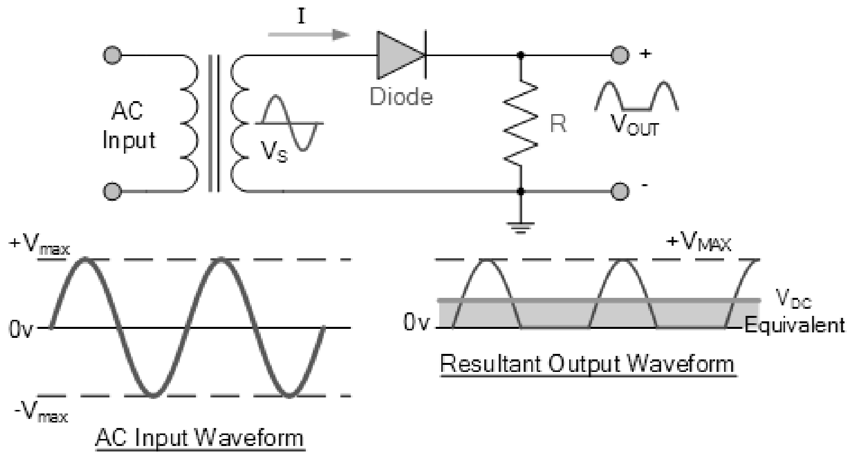


Nine-switch power converters

With such a topology, nine-switch converters retain the DC-link and can achieve all the functions of twelve-switch BTB even with three switches less.

3.9 UNCONTROLLED RECTIFIERS

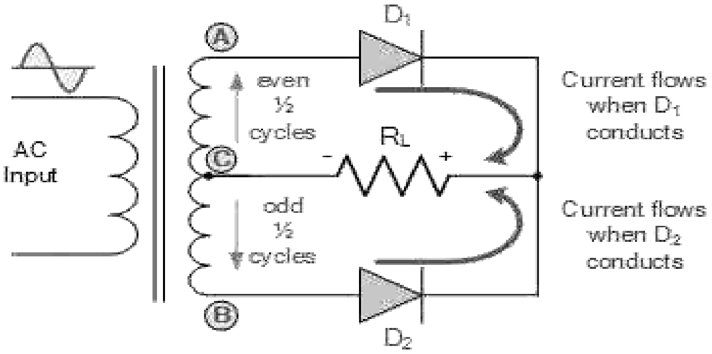
3.9.1 Half Wave Rectifier Circuit

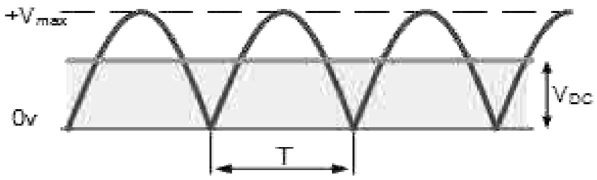


A rectifier is a circuit which converts the *Alternating Current* (AC) input power into a *Direct Current* (DC) output power. The input power supply may be either a single-phase or a multi-phase supply with the simplest of all the rectifier circuits being that of the **Half Wave Rectifier.** The power diode in a half wave rectifier circuit passes just one half of each complete sine wave of the AC supply in order to convert it into a DC supply. Then this type of circuit is called a "half-wave" rectifier because it passes only half of the incoming AC power supply as shown below. During each "positive" half cycle of the AC sine wave, the diode is *forward biased* as the anode is positive with respect to the cathode resulting in current flowing through the diode. During each "negative" half cycle of the AC sinusoidal input waveform, the diode is *reverse biased* as the anode is negative with respect to the cathode.

3.9.2 Full Wave Rectifier Circuit

Like the half wave circuit, a full wave rectifier circuit produces an output voltage or current which is purely DC or has some specified DC component. Full wave rectifiers have some fundamental advantages over their half wave rectifier counterparts. The average (DC) output voltage is higher than for half wave, the output of the full wave rectifier has much less ripple than that of the half wave rectifier producing a smoother output waveform. In a **Full Wave Rectifier** circuit two diodes are now used, one for each half of the cycle. A multiple winding transformer is used whose secondary winding is split equally into two halves with a common centre tapped connection.



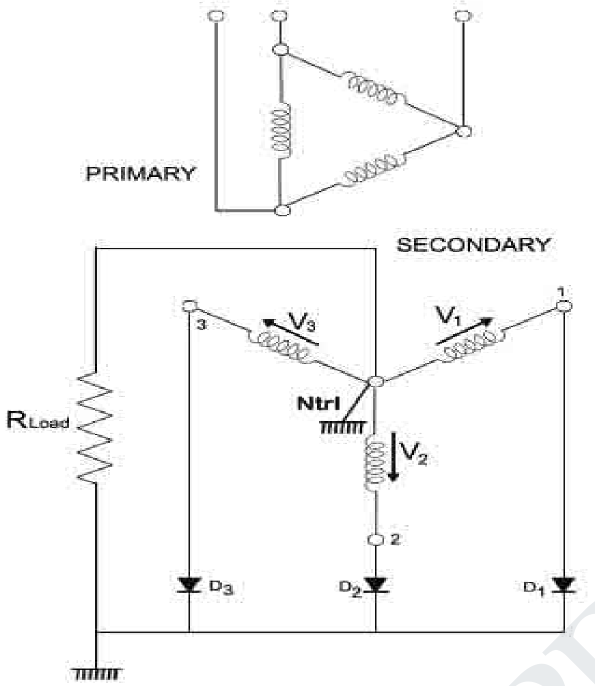


Resultant Output Waveform

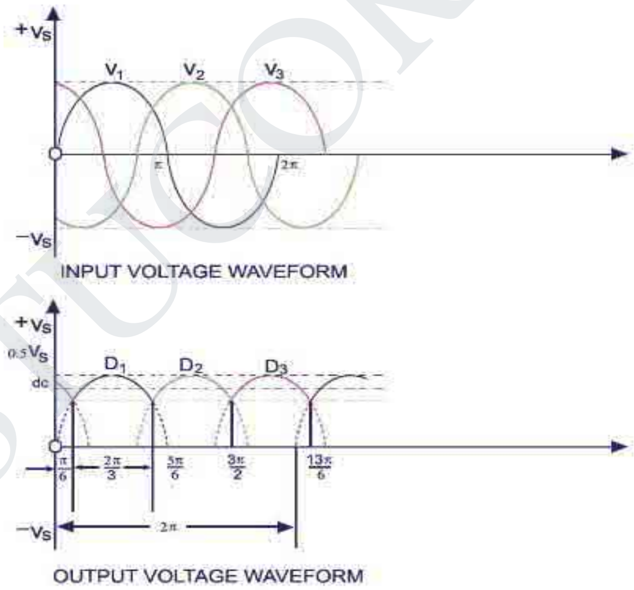
This configuration results in each diode conducting in turn when its anode terminal is positive with respect to the transformer centre point C producing an output during both half-cycles, twice that for the half wave rectifier so it is 100% efficient as shown below. The full wave rectifier circuit consists of two *power diodes* connected to a single load resistance (R_L) with each diode taking it in turn to supply current to the load. When point A of the transformer is positive with respect to point C, diode D_1 conducts in the forward direction as indicated by the arrows. When point B is positive (in the negative half of the cycle) with respect to point C, diode D_2 conducts in the forward direction and the current flowing through resistor R is in the same direction for both half-cycles. As the output voltage across the resistor R is the phasor sum of the two waveforms combined, this type of full wave rectifier circuit is also known as a “bi-phase” circuit.

3.9.3 Three phase Half Wave Rectifier

A three phase half wave rectifier, as the name implies, consists of a three phase transformer. Given below is a star connected secondary three phase transformer with three diodes connected to the three phases as shown in the figure. The neutral point ‘NTRL’ of the secondary is considered as the earth for the circuit and is given as the negative terminal for the load.

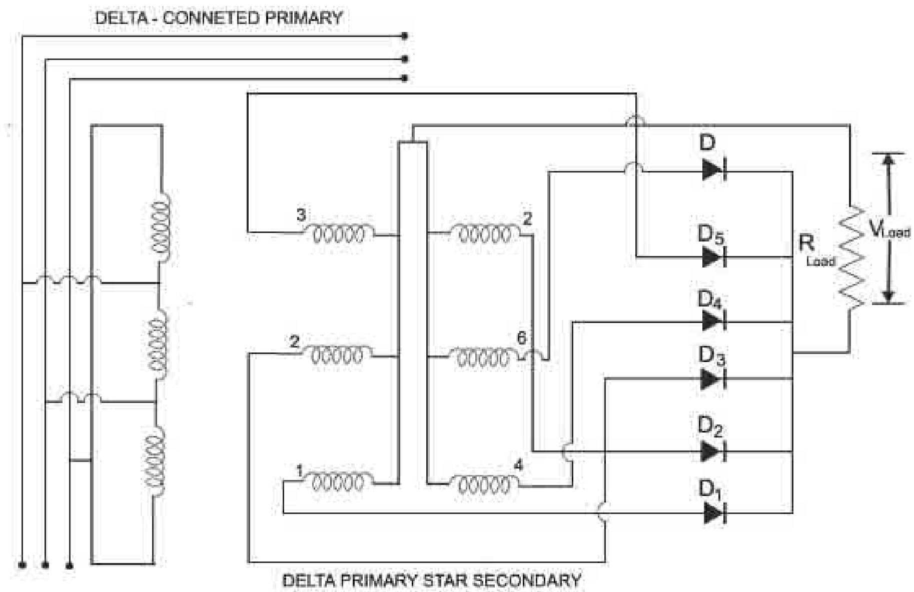


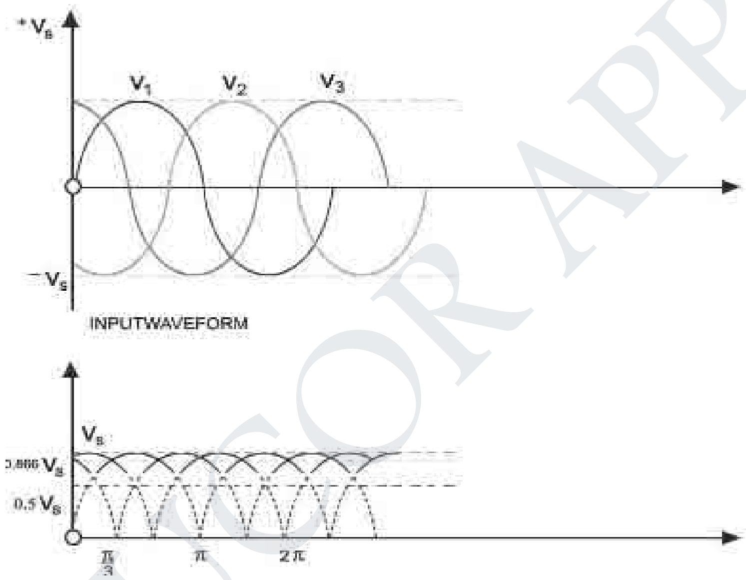
The input and the output wave forms for the circuit above is shown below. For each one-third of the cycle, each diode conducts. At the instant when one diode out of three is conducting, the other two are left inactive, at that instant their cathodes becomes positive with respect to the anodes. This process repeats for each of the three diodes.



3.9.4 Three Phase Full Wave Rectifier

A three phase full wave rectifier can also be called a six wave half wave rectifier as shown in the figure. The diodes D_1 to D_6 will conduct only for $1/6^{th}$ of the period, with a period of $\pi/3$. As shown in the output wave form, the fluctuation of dc voltage is less in a three phase circuit. The variation lies between the maximum alternation voltage and 86.6% of this, with the average value being 0.955 times the maximum value.



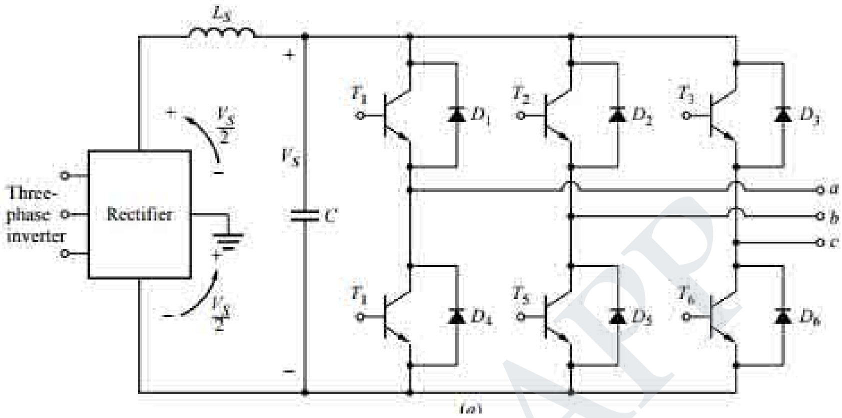


3.10 THREE PHASE PULSE WIDTH MODULATED (PWM) INVERTER

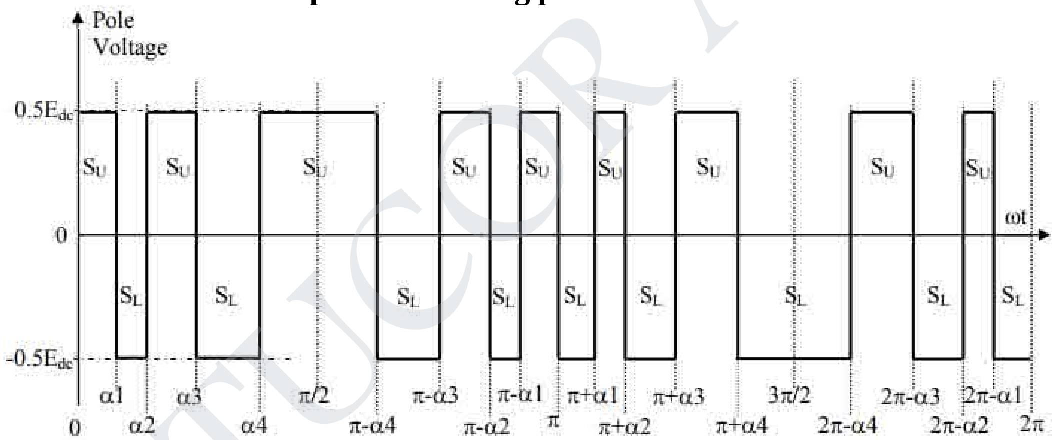
Pulse width modulated (PWM) inverters are among the most used power-electronic circuits in practical applications. These inverters are capable of producing ac voltages of variable magnitude as well as variable frequency. The PWM inverters are very commonly used in adjustable speed ac motor drive loads where one needs to feed the motor with variable voltage, variable frequency supply. For wide variation in drive speed, the frequency of the applied ac voltage needs to be varied over a wide range. The applied voltage also needs to vary almost linearly with the frequency. PWM inverters can be of single phase as well as three phase types. There are several different PWM techniques, differing in their methods of implementation. However in all these techniques the aim is to generate an output voltage, which after some filtering, would result in a good quality sinusoidal voltage waveform of desired fundamental frequency and magnitude. Nature of Pole Voltage Waveforms Output by PWM

Inverters Unlike in square wave inverters the switches of PWM inverters are turned on and off at significantly higher frequencies than the fundamental frequency of the output voltage waveform.

The time instances at which the voltage polarities reverse have been referred here as notch angles. It may be noted that the instantaneous magnitude of pole voltage waveform remains fixed at half the input dc voltage (E_{dc}). When upper switch (SU), connected to the positive dc bus is on, the pole voltage is + 0.5 E_{dc} and when the lower switch, connected to the negative dc bus, is on the instantaneous pole voltage is - 0.5 E^{dc}.



3 phase VSI using power transistors



A typical pole-voltage waveform of a PWM inverter

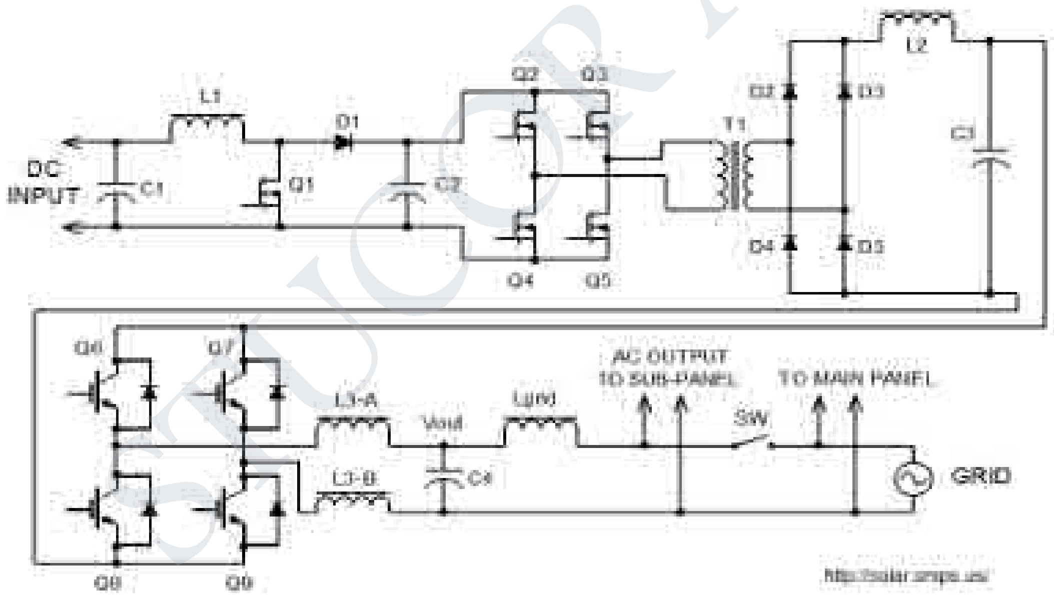
The switching transition time has been neglected in accordance with the assumption of ideal switches. It is to be remembered that in voltage source inverters, meant to feed an inductive type load, the upper and lower switches of the inverter pole conduct in a complementary manner. That is, when upper switch is on the lower is off and vice-versa. Both upper and lower switches should not remain on simultaneously as this will cause short circuit across the dc bus. On the other hand one of these two switches in each pole (leg) must always conduct to provide continuity of current through inductive loads. A sudden disruption in inductive load current will cause a large voltage spike that may damage the inverter circuit and the load.

3.11 GRID INTERACTIVE (GRID-TIE) INVERTERS

3.11.1 Introduction

A grid-tie inverter converts direct current (DC) into an alternating current (AC) suitable for injecting into an electrical power grid, normally 120V RMS at 60Hz or 240V RMS at 50 Hz. Grid-tie inverters are used between local electrical power generators: solar panel, wind turbine, hydro-electric, and the grid. In order to inject electrical power efficiently and safely into the grid, grid-tie inverters must accurately match the voltage and phase of the grid sine wave AC waveform. Some electricity companies will pay for electrical power that is injected into the grid. Payment is arranged in several ways. With net metering the electricity company pays for the net power injected into the grid, as recorded by a meter in the customer's premises. For example, a customer may consume 400 kilowatt-hours over a month and may return 500 kilowatt-hours to the grid in the same month. In this case the electricity company would pay for the 100 kilowatt hours balance of power fed back into the grid. Feed-in tariff, based on a contract with a distribution company or other power authority, is where the customer is paid for electrical power injected into the grid.

3.11.2 Operation



Grid-tie inverters convert DC electrical power into AC power suitable for injecting into the electric utility company grid. The grid tie inverter (GTI) must match the phase of the grid and maintain the output voltage slightly higher than the grid voltage at any instant. A high-quality modern grid-tie inverter has a fixed unity power factor, which means its output voltage and current are perfectly lined up, and its phase angle is within 1 degree of the AC power grid. The inverter has an on-board computer which senses the current AC grid waveform, and outputs a voltage to correspond with the grid. However, supplying reactive power to the grid might be necessary to keep the voltage in the local grid inside allowed limitations. Otherwise, in a grid segment with considerable power from renewable sources, voltage levels might rise too much at times of high production, i.e. around noon with solar panels.

Grid-tie inverters are also designed to quickly disconnect from the grid if the utility grid goes down. It ensures that in the event of a blackout, the grid tie inverter will shut down to prevent the energy it transfers from harming any line workers who are sent to fix the power grid.

Properly configured, a grid tie inverter enables a home owner to use an alternative power generation system like solar or wind power without extensive rewiring and without batteries. If the alternative power being produced is insufficient, the deficit will be sourced from the electricity grid.

3.11.3 Types

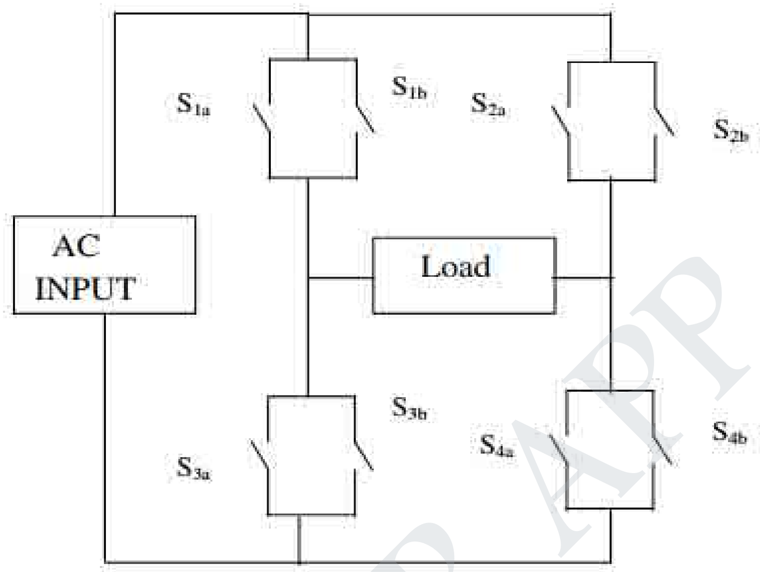
Grid-tie inverters include conventional low-frequency types with transformer coupling, newer high-frequency types, also with transformer coupling, and transformer-less types. Instead of converting direct current directly into AC suitable for the grid, high-frequency transformers types use a computer process to convert the power to a high-frequency and then back to DC and then to the final AC output voltage suitable for the grid. Transformer-less inverter are lighter, smaller, and more efficient than inverters with transformers. But transformer-less inverter have been slow to enter the market because of concerns that transformer-less inverters, which do not have galvanic isolation between the DC side and grid, could inject dangerous DC voltages and currents into the grid under fault conditions.

3.12 MATRIX CONVERTERS

3.12.1 Introduction

The main advantage of matrix converter is elimination of dc link filter. Zero switching loss devices can transfer input power to output power without any power loss. But practically it does not exist. The switching frequency of the device decides the THD of the converter. Maximum power transfer to the load is decided by nature of the control algorithm. Matrix converter has a maximum input output voltage transfer ratio limited to 87 % for sinusoidal input and output waveforms, which can be improved. Further, matrix converter requires more semiconductor devices than a conventional AC-AC indirect power frequency converter. Since monolithic bi-directional switches are available they are used for switching purpose. Matrix converter is particularly sensitive to the disturbances of the input voltage to the system. The instantaneous power flow does not have to equal power output. The difference between the input and output power must be absorbed or delivered by an energy storage element within the converter. The matrix converter replaces the multiple conversion stages and the intermediate energy storage element by a single power conversion stage, and uses a matrix of semiconductor bidirectional switches connecting input and output terminals. With this general arrangement of switches, the power flow through the converter can reverse. Because of the absence of any energy storage element, the instantaneous power input must be equal to the power output, assuming idealized zero-loss switches.

3.12.2 Single Phase Matrix Converter

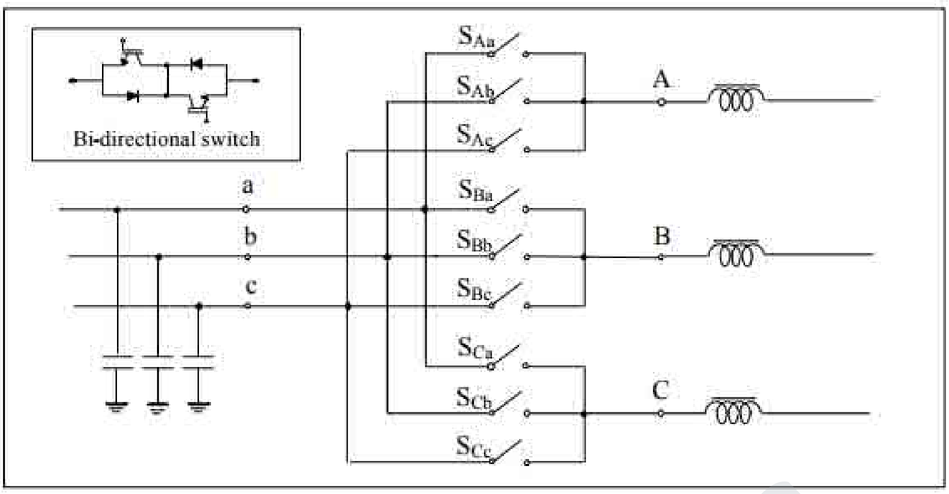


Single Phase Matrix Converter

The AC/AC converter is commonly classified as an indirect converter which utilizes a dc link between the two ac systems and converter that provides direct conversion. This converter consists of two converter stages and energy storage element, which convert input ac to dc and then reconverting dc back to output ac with variable amplitude and frequency. The operation of this converter stages is decoupled on an instantaneous basis by the energy storage elements and controlled independently, so long as the average energy flow is equal. Figure shows the single phase matrix converter switching arrangement.

3.12.3 Three Phase Matrix Converter

Three phase matrix converter consists of nine bidirectional switches. It has been arranged into three groups of three switches. Each group is connected to each phase of the output. These arrangements of switches can connect any input phase. These 3x3 arrangements can have 512 switching states. Among them only 27 switching states are permitted to operate this converter. Here A, B and C are input phase voltage connected to the output phase. Figure shows synchronous operating state vectors of three matrix converter. It shows that the converter switches are switched on rotational basis. In this case no two switches in a leg are switched on simultaneously. These states will not generate gate pulse when one phase of the supply is switched off.



Circuit scheme of a three phase to three phase matrix converter

The matrix converter consists of 9 bi-directional switches that allow any output phase to be connected to any input phase. The input terminals of the converter are connected to a three phase voltage-fed system, usually the grid, while the output terminal are connected to a three phase current-fed system, like an induction motor might be. The capacitive filter on the voltage-fed side and the inductive filter on the current-fed side represented in the scheme are intrinsically necessary. Their size is inversely proportional to the matrix converter switching frequency. It is worth noting that due to its inherent bi-directionality and symmetry a dual connection might be also feasible for the matrix converter: a current-fed system at the input and a voltage-fed system at the output. Taking into account that the converter is supplied by a voltage source and usually feeds an inductive load, the input phases should never be short-circuited and the output currents should not be interrupted. From a practical point of view these rules imply that one and only one bi-directional switch per output phase must be switched on at any instant. By this constraint, in a three phase to three phase matrix converter 27 are the permitted switching combinations.

APPENDIX

Content beyond the Syllabus

A.3.1 Role of Power Converters in Distributed Solar Power Generation

Solar Photovoltaic (SPV) technology is one of the most matured renewable energy (RE) technologies and there is an increasing demand of SPV installation both in grid-connected as well as off-grid stand-alone modes. Although in recent years, the penetration of solar PV installation has increased substantially due to several initiatives, it is yet to be considered as one of the mainstream renewable energy technologies. The main drawbacks of solar PV system is its high cost of installation for producing desired power level of electricity which is due to the high manufacturing cost of solar modules compounded with its low conversion efficiency. Most of the times, the power conversion system associated with the solar PV generating unit can cost up to 40% of the total cost. PV system, in general, is designed to deliver a specific amount of energy as per the requirement of the applications. Therefore, purchase and installation of all PV system will eventually be based on predicted or guaranteed energy production.

To make the solar PV system commercially viable, the cost of unit generation of electricity from solar PV system needs to be reduced which, in turn, calls for the development of a low cost, high efficient power conversion systems or schemes for delivering required electrical power. Hence it is always critical to design the most appropriate power converters and to assess their performance to ensure maximum power capture from solar modules along with impeccable power quality, reliability and efficiency. A major challenge that needs to be addressed by the DC-DC converters is to take the non-linear output characteristic of the solar PV sources which varies with solar insolation and temperature and convert it in to appropriate level of voltage. During recent years, different DC-DC converter topologies have been investigated for their applicability, safety and protection issues in SPV power generating system. Since there are several DC-DC converter and inverter topologies available, it is important to assess the performance of those topologies or system configuration under different operating conditions. Again the size of the distributed PV plant varies from few kW to several MW for which the type and configuration of the inverter also changes. Therefore the inverter has to be properly selected as the design and performance of the overall system depends mainly on the inverter. So there is a need of reviewing the type of inverter available mainly for off-grid application so that a judicious decision can be taken by the project developers and implementers for designing and developing efficient system.

A.3.2 Selection of Inverter Based On Control Scheme

There are various types of inverters available in the market. The self-commutated inverter can freely control the voltage and current waveform at the AC side, and adjust the power factor and suppress the harmonic current, and is highly resistant to local grid or utility grid disturbance. Line-commutated inverters are not suitable for use in standalone systems because AC voltage is required to turn off thyristors. Due to advances in switching devices, most Inverters for distributed power sources such as photovoltaic power generation now employ a Self-commutated inverter. Again, the self-commutated inverters can be a voltage source or a current source inverter In the case of photovoltaic power generation, the DC output of the photovoltaic array is the voltage source, thus, in general a voltage source inverter is employed rather than a current source inverter.

However, the voltage source inverter can be operated as both the voltage source and the current source when viewed from the AC side, only by changing the control scheme of the inverter. Therefore the control scheme (i.e voltage control scheme and current control scheme) of the inverter plays a very crucial role in the inverter and needs to be employed appropriately. In a case of the isolated power source without any grid interconnection, voltage control scheme should be provided. However, both voltage-control and current control schemes can be used for the grid interconnection inverter.

EE6009 POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

UNIT IV

ANALYSIS OF WIND AND PV SYSTEMS

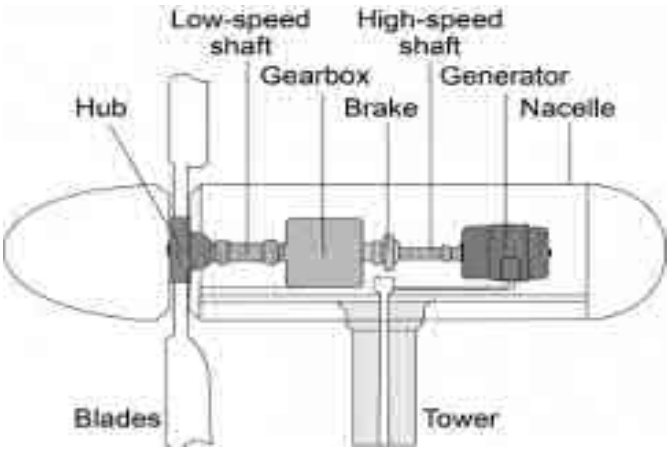
SYLLABUS: Stand alone operation of fixed and variable speed wind energy conversion systems and solar system-Grid connection Issues -Grid integrated PMSG, SCIG Based WECS, grid Integrated solar system

4.1. INTRODUCTION TO WIND TURBINE

Wind turbines are manufactured in a wide range of vertical and horizontal axis types. The smallest turbines are used for applications such as battery charging for auxiliary power for boats or caravans or to power traffic warning signs. Slightly larger turbines can be used for making contributions to a domestic power supply while selling unused power back to the utility supplier via the electrical grid. Arrays of large turbines, known as wind farms, are becoming an increasingly important source of intermittent renewable energy and are used by many countries as part of a strategy to reduce their reliance on fossil fuels.

4.2 TYPES OF WIND TURBINES

4.2.1 Horizontal Axis Wind Turbines (HAWT)



Horizontal Axis Wind Turbine

Horizontal axis wind turbines, also shortened to HAWT, are the common style that most of us think of when we think of a wind turbine. A HAWT has a similar design to a windmill; it has blades that look like a propeller that spin on the horizontal axis. Horizontal axis wind turbines have the main rotor shaft and electrical generator at the top of a tower, and they must be pointed into the wind. Small turbines are pointed by a simple wind vane placed square with the rotor (blades), while large turbines generally use a wind sensor coupled with a servo motor to turn the turbine into the wind. Most large wind turbines have a gearbox, which turns the slow rotation of the rotor into a faster rotation that is more suitable to drive an electrical generator. Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Wind turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount.

Advantages

- The tall tower base allows access to stronger wind in sites with wind shear.
- High efficiency since the blades always moves perpendicularly to the wind, receiving power through the whole rotation.
- In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to backtrack against the wind for part of the cycle.
- Backtracking against the wind leads to inherently lower efficiency.

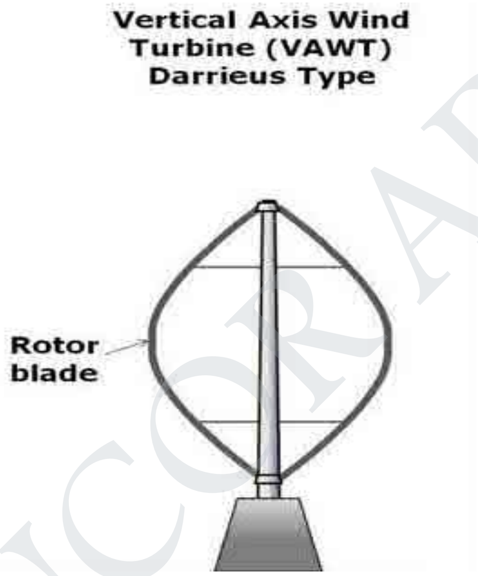
Disadvantages

- Massive tower construction is required to support the heavy blades, gearbox, and generator.
- Components of a horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) being lifted into position.

- Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
- HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

4.2.2 Vertical Axis Wind Turbines (VAWT)

Vertical axis wind turbines, as shortened to VAWTs, have the main rotor shaft arranged vertically. The main advantage of this arrangement is that the wind turbine does not need to be pointed into the wind. This is an advantage on sites where the wind direction is highly variable or has turbulent winds. With a vertical axis, the generator and other primary components can be placed near the ground, so the tower does not need to support it, also makes maintenance easier. The main drawback of a VAWT generally creates drag when rotating into the wind.



Vertical Axis Wind Turbine

It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten its service life. However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and these can double the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

Advantages

- No yaw mechanisms are needed.
- A VAWT can be located nearer the ground, making it easier to maintain the moving parts.

- VAWTs have lower wind startup speeds than the typical the HAWTs.
- VAWTs may be built at locations where taller structures are prohibited.
- VAWTs situated close to the ground can take advantage of locations where rooftops, mesas, hilltops, ridgelines, and passes funnel the wind and increase wind velocity.

Disadvantages

- Most VAWTs have an average decreased efficiency from a common HAWT, mainly because of the additional drag that they have as their blades rotate into the wind.
- Versions that reduce drag produce more energy, especially those that funnel wind into the collector area.
- Having rotors located close to the grounds where wind speeds are lower and do not take advantage of higher wind speeds above.

4.3 COMPONENTS OF A WIND TURBINE

4.3.1 Rotor

The part of the wind turbine that collects energy from the wind is called the rotor. The rotor usually consists of two or more wooden, fiberglass or metal blades which rotate about an axis (horizontal or vertical) at a rate determined by the wind speed and the shape of the blades. The blades are attached to the hub, which in turn is attached to the main shaft.

4.3.2 Drag Design

Blade designs operate on either the principle of drag or lift. For the drag design, the wind literally pushes the blades out of the way. Drag powered wind turbines are characterized by slower rotational speeds and high torque capabilities. They are useful for the pumping, sawing or grinding work. For example, a farm-type windmill must develop high torque at start-up in order to pump, or lift, water from a deep well.

4.3.3 Lift Design

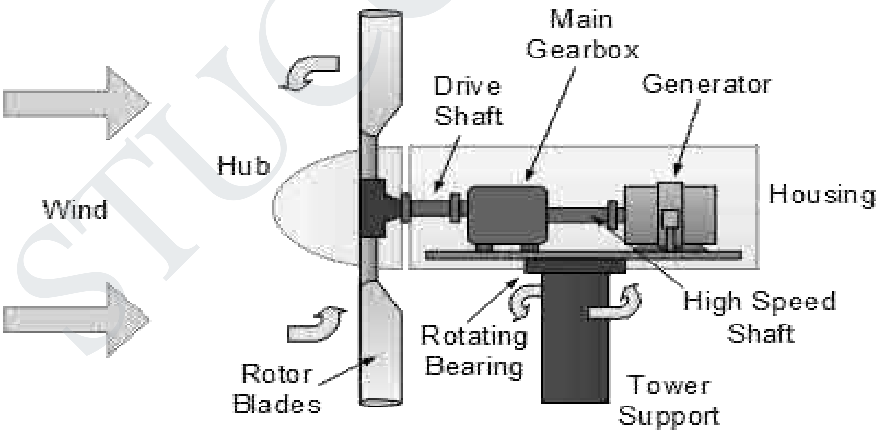
The lift blade design employs the same principle that enables airplanes, kites and birds to fly. The blade is essentially an airfoil, or wing. When air flows past the blade, a wind speed and pressure differential is created between the upper and lower blade surfaces. The pressure at the lower surface is greater and thus acts to "lift" the blade. When blades are attached to a central axis, like a wind turbine rotor, the lift is translated into rotational motion. Lift-powered wind turbines have much higher rotational speeds than drag types and therefore well suited for electricity generation.

4.3.4 Tip Speed Ratio

The tip-speed is the ratio of the rotational speed of the blade to the wind speed. The larger this ratio, the faster the rotation of the wind turbine rotor at a given wind speed. Electricity generation requires high rotational speeds. Lift-type wind turbines have maximum tip-speed ratios of around 10, while drag-type ratios are approximately 1. Given the high rotational speed requirements of electrical generators, it is clear that the lift-type wind turbine is most practical for this application.

4.3.5 Generator

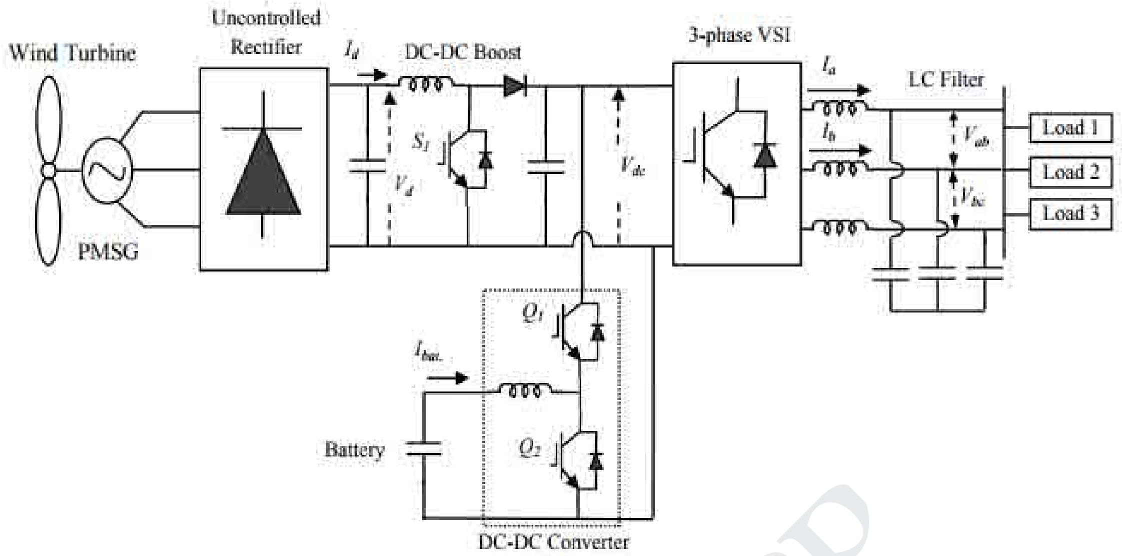
The generator is what converts the turning motion of a wind turbine's blades into electricity. Inside this component, coils of wire are rotated in a magnetic field to produce electricity. Different generator designs produce either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings. The generator's rating, or size, is dependent on the length of the wind turbine's blades because more energy is captured by longer blades. It is important to select the right type of generator to match your intended use. Most home and office appliances operate on 120 volt (or 240 volt), 60 cycle AC. Some appliances can operate on either AC or DC, such as light bulbs and resistance heaters, and many others can be adapted to run on DC. Storage systems using batteries store DC and usually are configured at voltages of between 12 volts and 120 volts. Generators that produce AC are generally equipped with features to produce the correct voltage (120 or 240 V) and constant frequency (60 cycles) of electricity, even when the wind speed is fluctuating.



Components of a wind turbine

4.4 PMSG BASED STAND-ALONE VARIABLE SPEED WIND ENERGY SUPPLY SYSTEM

The system consists of Wind turbine, Permanent magnet synchronous generator (PMSG) which is directly driven by the wind turbine without using a gearbox, a single switch three phase mode rectifiers which consist of a three phase diode bridge rectifier, a DC-DC boost converter, batteries bank which is connected to the DC-link voltage through DC-DC bidirectional buck-boost converter and a three phase voltage source inverter connected to the load through LC filter.



Power circuit topology of a variable speed stand-alone wind energy supply system

4.4.1 Generator Side Converter Control

The mechanical power captured from wind turbine is governed by the following equation:

$$P_m = 0.5\rho A C_p u_w^3 \qquad (1)$$

Where

P_m is the mechanical output power of the wind turbine (Watt),

ρ is the Air density (Kg/m^3)

A is the swept area (m^2),

C_p is the power coefficient of the wind turbine

υ_w is the wind speed (m/second).

Consequently, the output energy is determined by the power coefficient (C_p) of wind turbine if the swept area, air density, and wind speed are assumed to be constant. C_p is function in tip speed ratio (λ) and pitch angle (β) in degree. If β is equal zero, in this case C_p is only function in λ as shown in (2), and λ is function of rotor mechanical speed, rotor radius of blade and wind speed as indicated in (3).

$$C_p(\lambda) = \frac{60.04 - 4.69\lambda^{\left(\frac{-21+0.735\lambda}{\lambda}\right)}}{\lambda} + \frac{0.0068\lambda}{1 - 0.035\lambda} \qquad (2)$$

$$\lambda = \frac{\omega_r R}{v_w} \qquad (3)$$

Where

ω_r is the rotational speed (rad/second)

R is the radius of blade (m).

4.5. GRID CONNECTION OF WIND TURBINES

4.5.1. Overview of wind power generation and transmission

Wind energy conversion systems convert wind energy into electrical energy, which is then fed into electrical grid. The connection of wind turbines to the grid can be made at the low voltage, medium voltage and high voltage, as well as to the extra high voltage system even as most of the present turbines are connected to the medium voltage system (distribution system) of the grid, the future large offshore wind farms will have to be connected to the high and extra high voltage systems (transmission system).

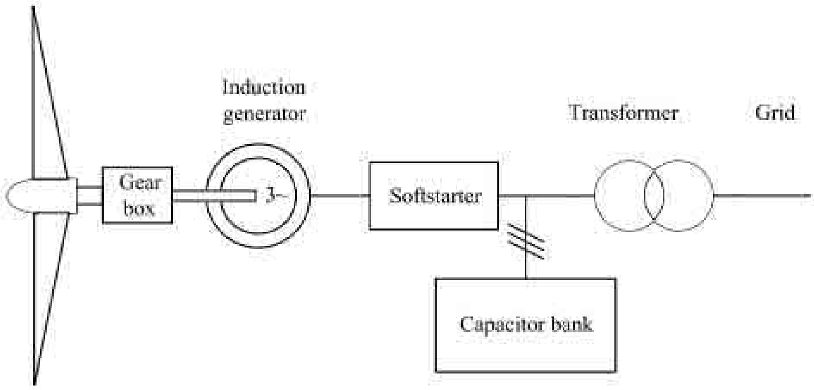
4.5.2. System components

The turbine rotor, gear box and generator are the main three components for energy conversion. The rotor, being the driving component in the conversion system, converts the wind energy into mechanical energy. An electronic inverter absorbs the mechanical power from the rotor, converting it into electrical energy, which is then fed into a supply grid. The gear box us used to adapt the rotor speed to the generator speed, if it is necessary. The main components of the grid for connection of the wind turbines are the transformer and the substation with safety equipment (circuit breaker) and the electricity meter inside. Due to relatively high losses in low voltage lines, each of the turbines in the wind farm has its own transformer, converting the voltage level of the turbine to the medium voltage line of the distribution system. To avoid long low voltage cabling the transformers are located directly beside the turbine. Only in case of small wind turbines it is possible to connect them directly to the low voltage level of the grid without using a transformer. For very large wind farms with high powers a separate substation is necessary for transformation from the medium voltage system to the high voltage system. Between a single wind turbine or a wind farm and the grid, at the point of common coupling (PCC), a circuit breaker has to be installed to provide disconnection possibility in case a fault. The circuit breaker is usually located at the medium voltage system side, inside a substation, together with the electricity meter. The meter has its own voltage and current transformers. Depending on the individual conditions of the existing supply system the connection to the grid can be performed as a radial feeder or as a ring feeder.

4.5.3 Grid connected Fixed-speed WECS

Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed

WECS are typically equipped with squirrel-cage induction generators (SCIG), soft starter and capacitor bank and they are connected directly to the grid, as shown in Figure.



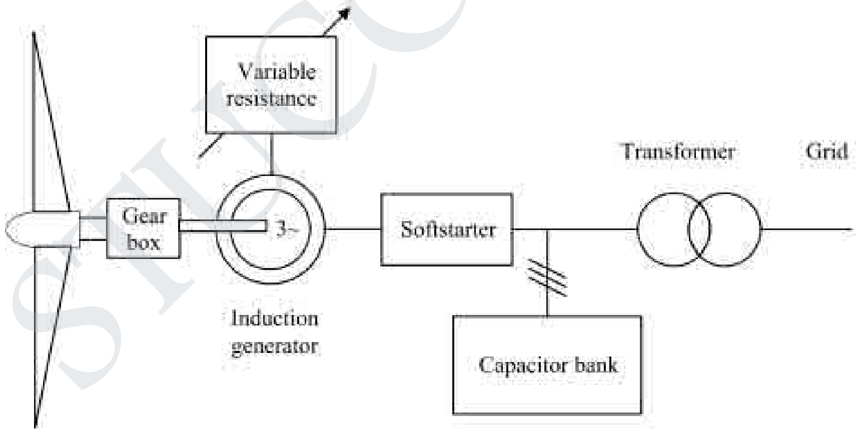
General structure of a fixed-speed WECS

Initially, the induction machine is connected in motoring regime such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode. As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency. Furthermore, the wind velocity variations will induce only small variations in the generator speed. As the power varies proportionally with the wind speed cubed, the associated electromagnetic variations are important.

SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. One of the major drawbacks of the SCIG is the fact that there is a unique relation between active power, reactive power, terminal voltage and rotor speed. That means that an increase in the active power production is possible only with an increase in the reactive power consumption, leading to a relatively low full-load power factor. In order to limit the reactive power absorption from the grid, SCIG based WECS are equipped with capacitor banks. In order to increase the power efficiency, the generator of some fixed-speed WECS has two winding sets, and thus two speeds. The first set is used at low wind speed (typically eight poles) and the other at medium and large wind speeds (typically four to six poles). Fixed-speed WECS have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed-speed operation, the mechanical stress is important. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant, stuck to the grid frequency. The unique feature of this WECS is that it has a variable additional rotor resistance, controlled by power electronic circuits.

4.5.4 Grid connected Variable-speed WECS

Variable-speed wind turbines are currently the most used WECS. The variable speed operation is possible due to the power electronic converters interface, allowing a full (or partial) decoupling from the grid. The doubly-fed-induction-generator (DFIG)-based WECS also known as improved variable-speed WECS, is presently the most used by the wind turbine industry. The DFIG having the stator windings connected directly to the three phase, constant-frequency grid and the rotor windings connected to a back-to-back (AC–AC) voltage source converter. Thus, the term "doubly-fed" comes from the fact that the stator voltage is applied from the grid and the rotor voltage is impressed by the power converter. This system allows variable-speed operation over a large, but still restricted, range, with the generator behavior being governed by the power electronics converter and its controllers. The power electronics converter comprises of two IGBT converters, namely the rotor side and the grid side converter, connected with a direct current (DC) link. Without going into details about the converters, the main idea is that the rotor side converter controls the generator in terms of active and reactive power, while the grid side converter controls the DC-link voltage and ensures operation at a large power factor.



General structure of a limited variable-speed WECS

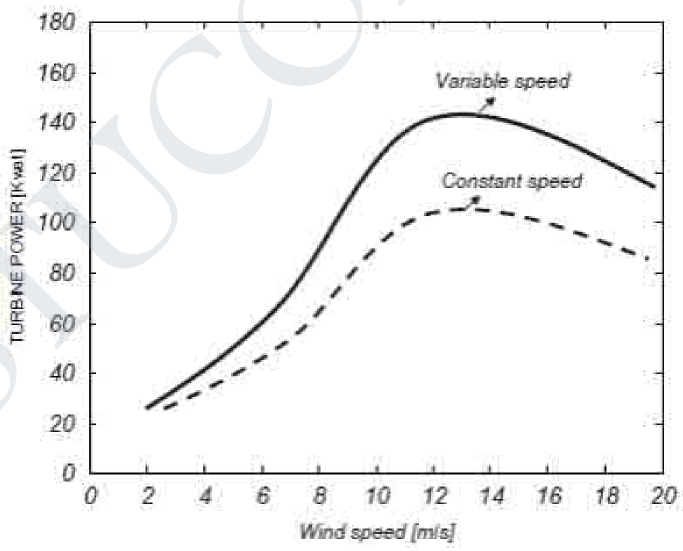
The stator outputs power into the grid all the time. The rotor, depending on the operation point, is feeding power into the grid when the slip is negative (over synchronous operation) and it absorbs power from the grid when the slip is positive (sub-synchronous operation. The size of the converter is not related to the total generator power but to the selected speed variation range. DFIG-based WECS are highly controllable, allowing maximum power extraction over a large range of wind speeds. Furthermore, the active and reactive power control is fully decoupled by independently controlling the rotor currents. Finally, the DFIG-based WECS can either inject or absorb power from the grid, hence actively participating at voltage control. Full variable-speed WECS are very flexible in terms of which type of generator is used.

4.5.5 Variable-speed turbine versus constant-speed turbine

In constant-speed turbines, there is no control on the turbine shaft speed. Constant speed control is an easy and low-cost method, but variable speed brings the following advantages:

- Maximum power tracking for harnessing the highest possible energy from the wind
- Lower mechanical stress
- Less variation in electrical power
- Reduced acoustical noise at lower wind speeds.

During turbine operation, there are some fluctuations related to mechanical or electrical components. The fluctuations related to the mechanical parts include current fluctuations caused by the blades passing the tower and various current amplitudes caused by variable wind speeds. The fluctuations related to the electrical parts, such as voltage harmonics, is caused by the electrical converter. The electrical harmonics can be conquered by choosing the proper electrical filter. However, because of the large time constant of the fluctuations in mechanical components, they cannot be canceled by electrical components. One solution that can largely reduce the disturbance related to mechanical parts is using a variable-speed wind turbine.

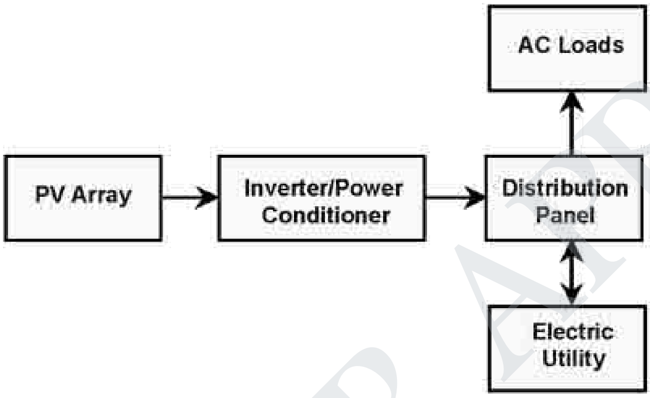


Comparison of power produced by a variable-speed wind turbine and a constant speed wind turbine at different wind speeds.

4.6 CLASSIFICATION OF PHOTOVOLTAIC POWER SYSTEMS

Photovoltaic (PV) systems are playing an increasingly significant role in electricity grids and there have been changes in system configurations in recent years. Classification of PV systems has become important in understanding the latest developments in improving system performance in energy harvesting. Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. The two principal classifications are grid-connected or utility-interactive systems and stand-alone systems. In general, grid-connected PV power systems can be categorized into two main groups: centralized MPPT (CMPPT) and distributed MPPT (DMPPT). Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems.

4.6.1 Diagram of grid-connected photovoltaic system.



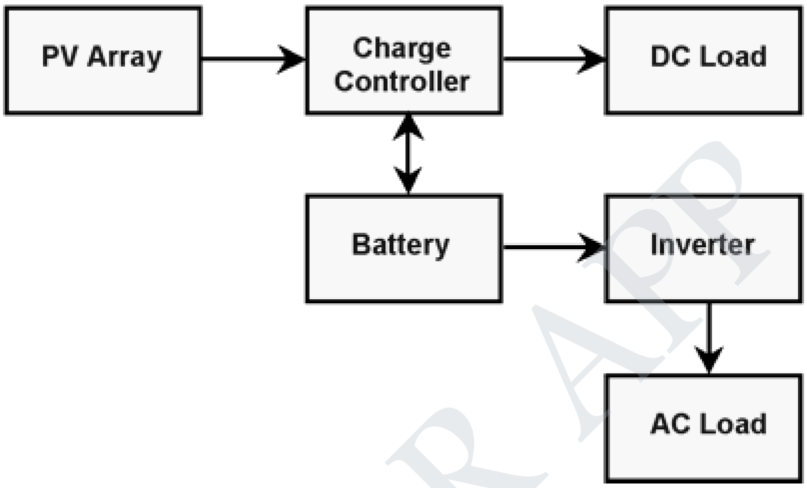
Grid-connected photovoltaic system

Grid-connected or utility-interactive PV systems are designed to operate in parallel with and interconnected with the electric utility grid. The primary component in grid-connected PV systems is the inverter, or power conditioning unit (PCU). The PCU converts the DC power produced by the PV array into AC power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energized. A bi-directional interface is made between the PV system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads or to back-feed the grid when the PV system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back into the utility grid when the grid is down for service or repair.

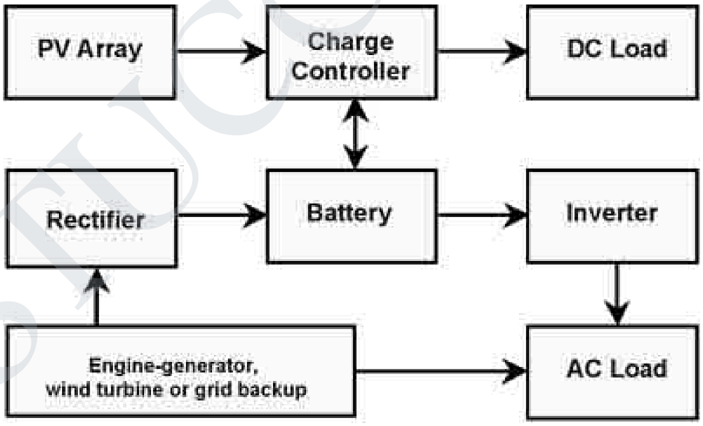
4.6.2 Stand-Alone Photovoltaic Systems

Stand-alone PV systems are designed to operate independent of the electric utility grid, and are generally designed and sized to supply certain DC and/or AC electrical loads. These types of systems may be powered by a PV array only, or may use wind, an engine-generator or utility power as an auxiliary power source in what is called a PV-hybrid system. The simplest type of stand-alone PV system is a direct-coupled system, where the DC output of a PV module or array is directly connected to a DC load.

Direct-coupled PV system



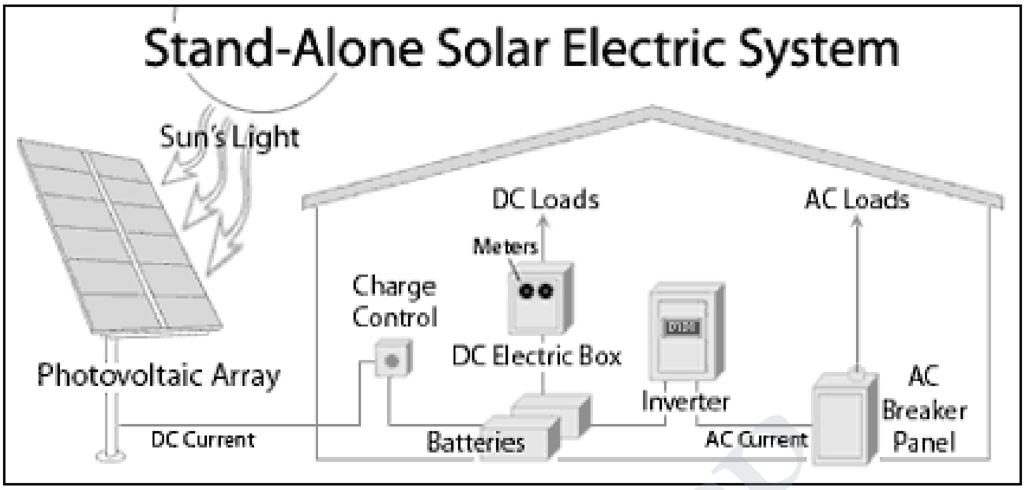
Stand-alone PV system with battery storage powering DC and AC loads



Photovoltaic hybrid system

Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours, making these designs suitable for common applications such as ventilation fans, water pumps, and small circulation pumps for solar thermal water heating systems. Matching the impedance of the electrical load to the maximum power output of the PV array is a critical part of designing well-performing direct-coupled system. For certain loads such as positive-displacement water pumps, a type of electronic DC-DC converter, called a maximum power point tracker (MPPT), is used between the array and load to help better utilize the available array maximum power output.

4.6.3 A Stand Alone Solar PV System



A free standing or **Stand Alone PV System** is made up of a number of individual photovoltaic modules (or panels) usually of 12 volts with power outputs of between 50 and 100+ watts each. These PV modules are then combined into a single array to give the desired power output. A simple *stand alone PV system* is an automatic solar system that produces electrical power to charge banks of batteries during the day for use at night when the suns energy is unavailable. A stand alone small scale PV system employs rechargeable batteries to store the electrical energy supplied by a PV panels or array. Stand alone PV systems are ideal for remote rural areas and applications where other power sources are either impractical or are unavailable to provide power for lighting, appliances and other uses. In these cases, it is more cost effective to install a single stand alone PV system than pay the costs of having the local electricity company extend their power lines and cables directly to the home.

4.6.3 A Stand Alone Solar PV System

While a major component and cost of a standalone PV system is the solar array, several other components are typically needed. These include:

Batteries:

Batteries are an important element in any stand alone PV system but can be optional depending upon the design. Batteries are used to store the solar-produced electricity for night time or emergency use during the day. Depending upon the solar array configuration, battery banks can be of 12V, 24V or 48V and many hundreds of amperes in total. Deep cycle lead acid batteries are generally used to store the solar power generated by the PV panels, and then discharge the power when energy is required. Deep cycle batteries are not only rechargeable, but they are designed to be repeatedly discharged almost all the way down to a very low charge.

Charge Controller:

A charge controller regulates and controls the output from the solar array to prevent the batteries from being over charged (or over discharged) by dissipating the excess power into a load resistance. Charge controllers within a standalone PV system are optional but it is a good idea to have one for safety reasons. The charge controller ensures that the maximum output of the solar panels or array is directed to charge the batteries without over charging or damaging them. They operate automatically, with most commercially available charge controllers having a digital display to show how much power has been created at any time, the state of charge of the batteries and programmable settings to discharge the batteries into a resistive dummy load to minimize the chances of sulphation of the battery cells extending the battery life.

Fuses and Isolation Switches:

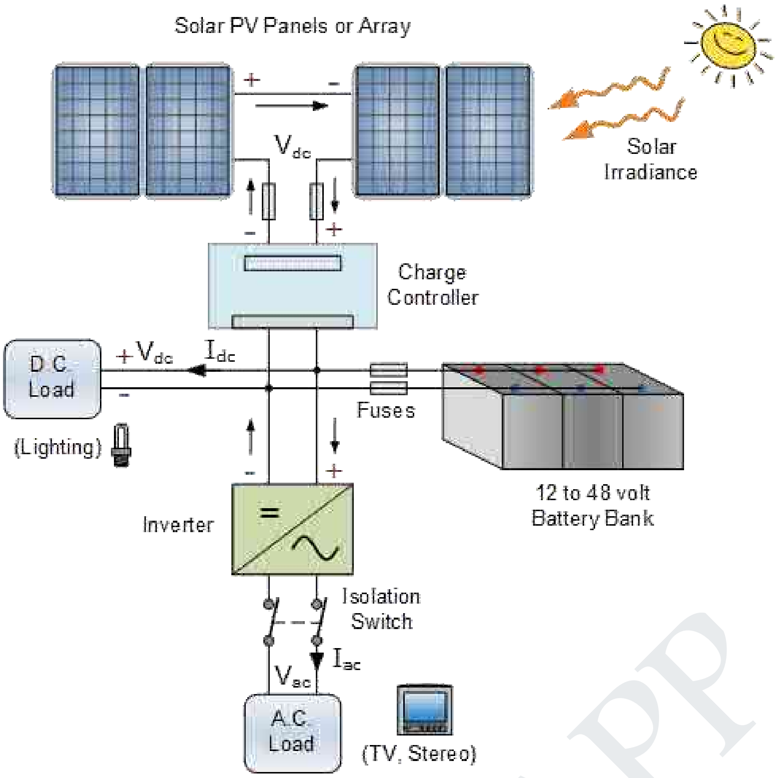
These allow PV installations to be protected from accidental shorting of wires allowing power from the PV modules and system to be turned "OFF" when not required saving energy and improving battery life.

Inverter:

Inverters are used to convert the 12V, 24V or 48 Volts direct current (DC) power from the solar array and batteries into an alternating current (AC) electricity and power of either 120 VAC or 240 VAC for use in the home to power AC mains appliances such as TV's, washing machines, freezers, etc.

Wiring:

The final component required in and PV solar system is the electrical wiring. The cables need to be correctly rated for the voltage and power requirements.



Newer low voltage solar technologies have been implemented in a wide variety of lighting applications. Street lights, security lights, solar garden lights and car park lamps can all be designed with small, built-in solar arrays producing a complete stand alone PV system. Exposed to the sun all day, these lights can retain their electrical charge to keep lit all night long. Electric road signs can take advantage of solar panels in the same way, although vital street and traffic signs on major roads and motorway's also have alternate sources of power as backup.

4.6.4 Important factors in having a standalone PV system

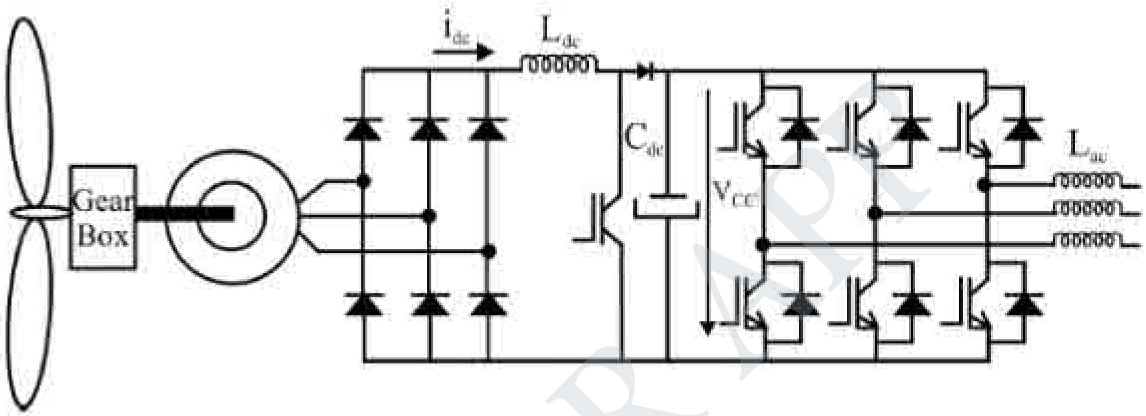
Solar panels only create electricity while the sun is shining on them so it may be necessary to store enough electricity to get through one or two days of cloudy weather. In this case solar electricity becomes a valuable resource, will not want to live without it, but will not want to waste it, either. Try reducing energy demand through energy efficient measures. Purchasing energy saving appliances and LED lights, for example, will reduce electrical demand and allow purchasing a smaller stand alone PV system to meet actual energy needs.

Energy efficiency allows starting small and then adding on as your energy needs increase. Secondly, while a standalone PV system is not a complicated system to install or run compared with other forms of off grid electrification devices, wind turbines, hydro-electric etc, solar PV systems still require regular maintenance that is not normally associated with standard grid connected mains power.

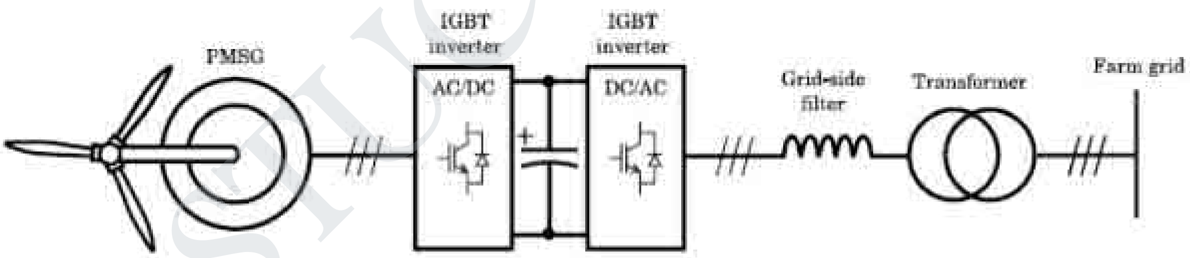
All the systems components have to be checked and cleaned on a regular basis to make sure that the system is running optimally and like many other off grid systems, PV systems require some basic electrical knowledge in order to be able to install and maintain them in an effective manner and to diagnose any problems so become an expert of system.

There are many advantages of a standalone PV system some include low maintenance, low upkeep cost, no waste or byproducts, and easy expansion by using multiple solar panels and batteries. The disadvantages include high initial investment, especially for the photovoltaic panels and deep cycle lead acid batteries, reliance on the sun, and the possible danger from battery acid and fumes associated with most forms of renewable energy.

4.7 GRID CONNECTED PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG) BASED WIND ENERGY CONVERSION SYSTEMS.



PM Synchronous generator with the rectifier, boost chopper, and the PWM line-side Converter



PM Synchronous generator with two back-to-back PWM converters

A typical power electronics topology that is used for a permanent magnet synchronous generator is shown in Figure. The three-phase variable voltage, variable frequency output from the wind turbine is rectified using a diode bridge. With the change in the speed of the synchronous generator, the voltage on the DC side of the diode rectifier changes. To maintain a constant DC-link voltage of the inverter, a step-up chopper is used to adapt the rectifier voltage. As viewed from the DC inputs to the inverter, the generator/rectifier system is then modeled as an ideal current source. This rectified output signal from the diode bride is filtered into a smooth DC waveform using a large capacitor. The DC signal is then inverted through the use of semiconductor switches into a three-phase, 50 Hz waveform. This waveform can then be scaled using a transformer to voltage levels required by the utility's AC system.

The generator is decoupled from the grid by a voltage-sourced DC-link; therefore, this PE interface provides excellent controllable characteristics for the wind energy system. The power converter to the grid enables a fast control of active and reactive power. However, the negative side is a more complex system where more sensitive power electronic parts are required. The diode rectifier is the most commonly used topology in power electronic applications. For a three-phase system it consists of six diodes. The diode rectifier can only be used in one quadrant, it is simple and it is not possible to control it. It can be used in some applications such as pre-charging.

The grid-side three-phase converter permits wind energy transfer into the grid and enables to control the amount of the active and reactive powers delivered to the grid. It also keeps the total-harmonic-distortion (THD) coefficient as low as possible, improving the quality of the energy injected into the public grid. The objective of the dc link is to act as energy storage, so that the captured energy from the wind is stored as a charge in the capacitors and may be instantaneously injected into the grid. The control signal is set to maintain a constant reference to the voltage of the dc link V_{dc}.

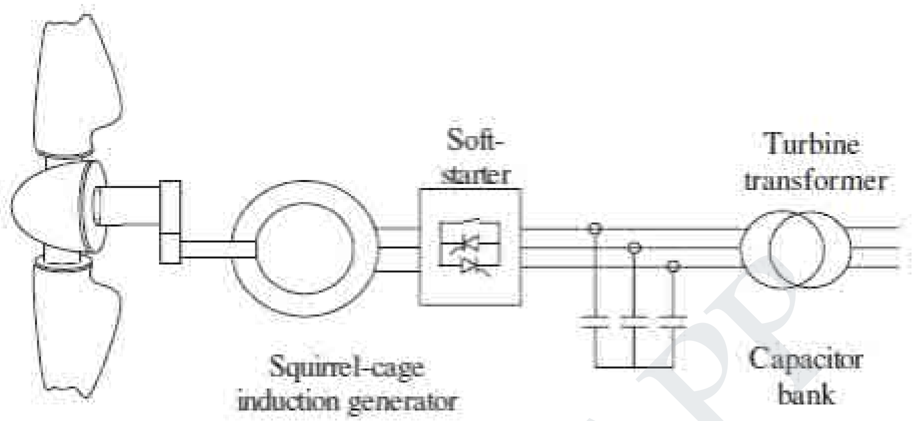
An alternative to the power-conditioning system of a wind turbine is to use a synchronous generator instead of an induction one and to replace a three-phase converter (connected to the generator) by a three phase diode rectifier and a chopper. Such choice is based on the low cost as compared to an induction generator connected to a VSI used as a rectifier. When the speed of the synchronous generator alters, the voltage on the dc side of the diode rectifier will change. A step-up chopper is used to adapt the rectifier voltage to the dc-link voltage of the inverter. When the inverter system is analyzed, the generator/rectifier system can be modeled as an ideal current source. The step-up chopper used as a rectifier utilizes a high switching frequency, so the bandwidth of these components is much higher than the bandwidth of the generator. Controlling the inductance current in the step-up converter can control the machine torque and, therefore, its speed. Based on the control design for the back-to-back PWM converter system, various advantages can be obtained such as:

- The line-side power factor is unity with no harmonic current injection
- Wind generator output current is sinusoidal
- There are no harmonic copper losses
- The rectifier can generate programmable excitation for the induction generator based system
- Continuous power generation from zero to the highest turbine speed is possible
- Power can flow in either direction, permitting the generator to run as a motor for start-up

- Similarly, regenerative braking can quickly stop the turbine; and islanded operation of the system is possible with a start-up capacitor charging the battery

4.8 GRID CONNECTED SQUIRREL CAGE INDUCTION GENERATOR (SCIG) BASED WIND ENERGY CONVERSION SYSTEMS.

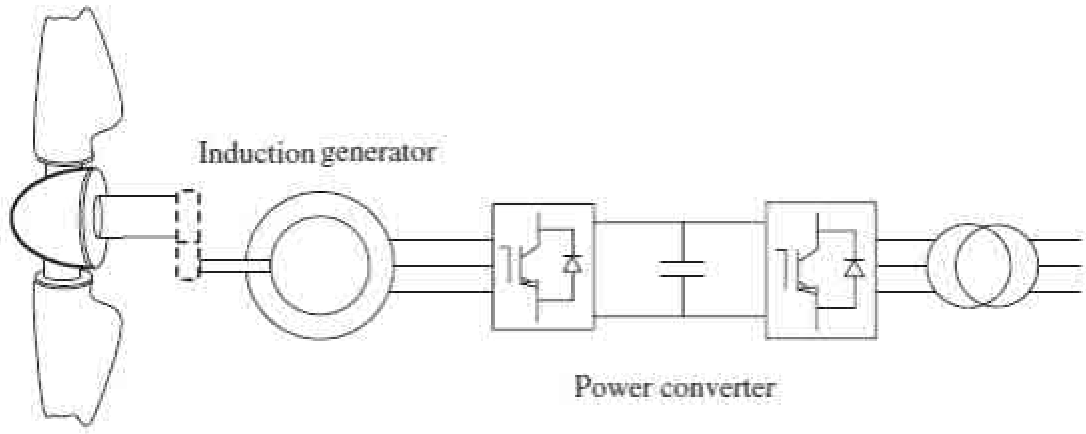
4.8.1 Fixed Speed System



SCIG Connected to Grid

Fixed-speed wind turbines are electrically fairly simple devices consisting of an aerodynamic rotor driving a low-speed shaft, a gearbox, a high-speed shaft and an induction (sometimes known as asynchronous) generator. From the electrical system viewpoint they are perhaps best considered as large fan drives with torque applied to the low-speed shaft from the wind flow. It consists of a squirrel-cage induction generator coupled to the power system through a turbine transformer. The generator operating slip changes slightly as the operating power level changes and the rotational speed is therefore not entirely constant. However, because the operating slip variation is generally less than 1%, this type of wind generation is normally referred to as fixed speed. Squirrel-cage induction machines consume reactive power and so it is conventional to provide power factor correction capacitors at each wind turbine. The function of the soft-starter unit is to build up the magnetic flux slowly and so minimize transient currents during energization of the generator.

4.8.2 Variable Speed System



Typical configuration of a fully rated converter-connected wind turbine

The typical configuration of a Variable Speed Grid Connected SCIG based fully rated converter wind turbine is shown in Figure. This type of turbine may or may not include a gearbox and a wide range of electrical generator types can be employed, for example, induction, wound-rotor synchronous or permanent magnet synchronous. As all of the power from the turbine goes through the power converters, the dynamic operation of the electrical generator is effectively isolated from the power grid. The electrical frequency of the generator may vary as the wind speed changes, while the grid frequency remains unchanged, thus allowing variable speed operation of the wind turbine. The power converters can be arranged in various ways. Whereas the generator-side converter (GSC) can be a diode rectifier or a PWM voltage source converter (VSC), the network side converter (NSC) is typically a PWM VSC. The strategy to control the operation of the generator and the power flows to the network depends very much on the type of power converter arrangement employed. The network-side converter can be arranged to maintain the DC bus voltage constant with torque applied to the generator controlled from the generator-side converter. Alternatively, the control philosophy can be reversed. Active power is transmitted through the converters with very little energy stored in the DC link capacitor. Hence the torque applied to the generator can be controlled by the network-side converter. Each converter is able to generate or absorb reactive power independently.

4.9 GRID INTEGRATED PV SYSTEM

4.9.1 Connecting Solar System to the Grid

Stand alone solar systems are self contained fixed or portable solar PV systems that are not connected to any local utility or mains electrical grid as they are generally used in remote and rural areas. This generally means that the electrical appliances are a long way from the nearest fixed electrical supply, or were the cost of extending a power line from the local grid may be very expensive. In recent years, however, the number of solar powered homes connected to the local electricity grid has increased dramatically. These **Grid Connected PV**

Systems have solar panels that provide some or even most of their power needs during the day time, while still being connected to the local electrical grid network during the night time. Solar powered PV systems can sometimes produce more electricity than is actually needed or consumed, especially during the long hot summer months. This extra or surplus electricity is either stored in batteries or as in most grid connected PV systems, fed directly back into the electrical grid network. The main advantage of a grid connected PV system is its simplicity, relatively low operating and maintenance costs as well as reduced electricity bills. The disadvantage however is that a sufficient number of solar panels need to be installed to generate the required amount of excess power. Since grid tied systems feed their solar energy directly back into the grid, expensive back-up batteries are not necessary and can be omitted from most grid connected designs. Also, as this type of PV system is permanently connected to the grid, solar energy consumption and solar panel sizing calculations are not required, giving a large range of options allowing for a system as small as 1.0 kWh on the roof to help reduce your electricity bills, or a much larger floor mounted array that is large enough to virtually eliminate your electricity bills completely.

4.9.2 Grid Connected Net Metering

If during a sunny day more electricity is produced by your solar PV system then use or consumes, this excess solar power is delivered back to the utility grid with the effect of rotating the electric meter backwards. When this happens you will normally be given credits by the local power company for the amounts of electricity produced by your grid connected PV system. If during the billing period use or consume more electrical energy than generate, are billed for the "net amount" of electricity consumed as would be normally. If, however, generate more solar energy than consume, are credited for the "net amount" of electricity generated which may be either a reduction in monthly electricity bill or a positive payment. When installing a PV system, if net metering is available by local electricity company, it may be required to install a new second electrical meter instead of using a single electricity meter that spins in both directions. This new meter allows for a measurement of net energy consumption, both entering and leaving the system and would be used to reduce your electricity bill. However, each electrical utility company has its own policy regarding the buying back of energy generated by your own small solar power station.

4.9.3 Simplified Grid Connected PV System

Grid connected PV systems always have a connection to the public electricity grid via a suitable inverter because a photovoltaic panel or array (multiple PV panels) only deliver DC power. As well as the solar panels, the additional components that make up a grid connected PV system compared to a standalone PV system are:

Inverter:

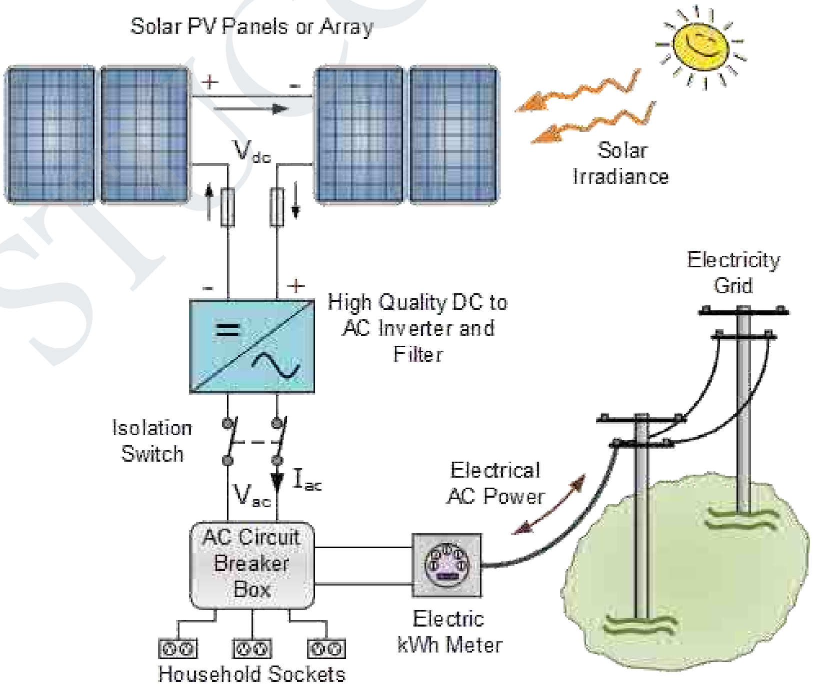
The inverter is the most important part of any grid connected system. The inverter extracts as much DC (direct current) electricity as possible from the PV array and converts it into clean mains AC (alternating current) electricity at the right voltage and frequency for feeding into the grid or for supplying domestic loads. It is important to choose the best quality inverter possible for the budget allowed as the main considerations in grid connected inverter choice are: *Power* – Maximum high and low voltage power the inverter can handle and *Efficiency* – How efficiently does the inverter convert solar power to AC power.

Electricity Meter:

The electricity meter also called a Kilowatt hour (kWh) meter is used to record the flow of electricity to and from the grid. Twin kWh meters can be used, one to indicate the electrical energy being consumed and the other to record the solar electricity being sent to the grid. A single bidirectional kWh meter can also be used to indicate the net amount of electricity taken from the grid.

AC Breaker Panel and Fuses:

The breaker panel or fuse box is the normal type of fuse box provided with a domestic electricity supply and installation with the exception of additional breakers for inverter and/or filter connections.



Safety Switches and Cabling:

A photovoltaic array will always produce a voltage output in sunlight so it must be possible to disconnect it from the inverter for maintenance or testing. Isolator switches rated for the maximum DC voltage and current of the array and inverter safety switches must be provided separately with easy access to disconnect the system. Other safety features demanded by the electrical company may include earthing and fuses. The electrical cables used to connect the various components must also be correctly rated and sized.

The Electricity Grid:

A grid connected system without batteries is the simplest and cheapest solar power setup available, and by not having to charge and maintain batteries they are also more efficient. It is important to note that a grid connected solar power system is not an independent power source unlike a standalone system. Should the mains supply from the electrical grid be interrupted, the lights may go out, even if the sun is shining. One way to overcome this is to have some form of short term energy storage built into the design.

4.9.4 Grid Connected System with Batteries

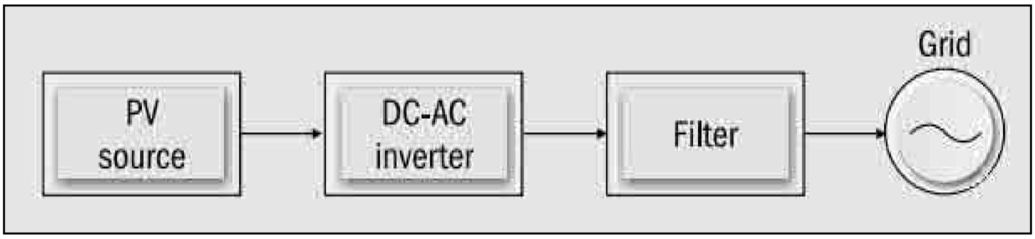
A small scale photovoltaic solar system that has storage batteries within its design also operates in conjunction with the local electricity company. The short-term peak demand is met by the battery without drawing from the grid and paying the extra charge. When used in grid connected PV systems, storage batteries can be classified into short term storage for a few hours or days to cover periods of bad weather and long term storage over several weeks to compensate for seasonal variations in the solar irradiation between the summer and winter months. Incorporating batteries into a grid connected system requires more components, is more expensive, and lowers the systems overall efficiency. But for many homeowners in remote areas who regularly experience a loss of their grid supply during bad weather conditions or have critical electrical loads that cannot be interrupted, having some form of backup energy storage within their grid connected system can be a great benefit.

4.10 CLASSIFICATION OF GRID INTEGRATED PV SYSTEM

Grid-connected PV systems basically have two different topologies. The conventionally used topology is a two stage configuration.

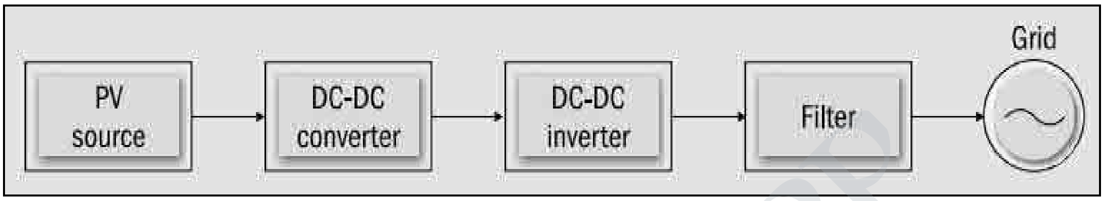
4.10.1 Single-stage configuration

As the conversion efficiency of the PV array is inherently very low (12%– 20%), the addition of more number of power processing stages further reduces the overall efficiency. Therefore, a PV system with higher efficiency can be realized by having single-stage power conversion scheme. A single-stage PV system eliminates intermediate DC–DC conversion stage as shown in Figure. It results in smaller physical volume, lower weight, and higher overall efficiency.



Single-stage PV energy conversion system

4.10.2 Two-stage configuration



The schematic diagram of a PV system, with a two-stage energy conversion system, is shown in Figure. It has two power converter stages between the PV source and the grid. Hence, it is called as two-stage configuration. In the first stage, the DC–DC converter is controlled so as to track the maximum power point of the PV array. The output of the DC–DC converter is fed to an inverter, which is a DC-AC converter, and is controlled to produce output current in phase with the utility voltage to obtain a UPF (unity power factor). The harmonics in the inverter output current are attenuated by using a low pass filter. As the DC–DC and DC–AC converters have independent control goals and architecture, the controllers are easy to design. Yet, the efficiency of the entire conversion system is compromised because of the large number of individual devices, like the passive elements of DC–DC converter and switching devices of both the converters. Moreover, excessive size, heavy weight, and high cost are amongst the major disadvantages of a two-stage energy conversion system.

4.10.3 Issues of Grid Connected Solar Photovoltaic system

Due to the random and intermittent nature of the renewable sources, integration of it into the grid causes technical challenges to be targeted and solved. The technical challenges cover the reduction in power quality, power fluctuation causing unreliability, storage, protection issues, optimal positioning of Distributed Generator (DG) and anti islanding.

4.10.4 Problems Concerned with Power Quality

As the renewable DG's are integrated through a power electronic converter to the grid they usually inject harmonics into the system. Harmonics are caused by the switching mechanism of the power electronic switches in the inverter which produce poor quality of power to be supplied to the customers. Hence soft switching control schemes of the inverter were introduced to overcome the harmonics. Active or passive filters can also be employed for the same change in the frequency and the operating voltage can also occur due to the varying nature of the DG which affects the power flow. The disconnection and reconnection of renewable energy source to the grid depending on the load demand causes voltage flicker. Appropriate tap settings for the transformer connecting the feeder to the grid should be made, which is more useful when two or more feeders are supplied by the same transformer, but the DG is concentrated on only one of the above feeder.

4.10.5 Storage

Due to the incorporation of renewable or PV source in the grid power path flow, the standard of the grid comes down. The grid may act as a source or sink of power in accordance to the power generated from the distributed generator (PV). If the PV power generation is surplus or in case of a weak grid battery can be made as a choice of storing the excess power. But introducing a battery to the grid connected PV systems invites issues of sizing and battery current and voltage control.

4.10.6 Protection Issues

Traditional power systems are protected by over current/over voltage relays and circuit breakers. But as energy conversion systems (solar) are introduced the protection of the network becomes more complex. The issues of alteration in the short circuit level, lack of sustained fault current and reverse power flow persists.

4.10.7 Short Circuit Level Change

The short circuit level is an important design parameter in the design of protective devices such as circuit breakers and relays. This is usually characterized by the equivalent system impedance at the fault point and indicates the amount of fault current for the relay to act upon the fault. The equivalent impedance does not vary with the grid powered network systems, but varies with the DG network systems as the input changes to it changes instantaneously. Since the SCC varies the forecast of the fault current magnitude changes which cannot be withstood by the designed circuit breaker rating right through the operation.

4.10.8 Reverse Power Flow

Conventional power systems possess unidirectional power flow. But as a renewable energy source is integrated to the conventional power system the power flow reversal takes place which alters the operation of protection circuits.

4.10.9 Lack of Sustained Fault Current

For the protection of the system from the fault current switch gear and circuit breakers are installed, which differentiates the fault current from the normal current. This differentiation is made with the significant increase in the fault current than the normal current. If the magnitude of the fault current varies from the DG then there is a tough task for the circuit breaker to identify the fault current amidst the normal current. Solar systems mainly employ power electronic switches which do not supply sustained fault currents.

4.10.10 Islanding

Islanding is a unique problem of the grid connected PV system. Islanding occurs on grid failure. Auto re-closure valve at the point of common coupling of the renewable generator to the grid is kept open offering the separation of the utility network with the grid. Else the voltage builds up on power generation without the energy absorption by the grid causing huge voltage unbalance resulting in system deterioration. Thus the anti islanding control technique came into picture for addressing the above problem. The standard anti islanding control techniques include over-voltage relay, under-voltage relay, over-frequency and under frequency relays.

4.11 INVERTER INTEGRATED REACTIVE POWER CONTROL STRATEGY IN THE GRID-CONNECTED PV SYSTEMS

4.11.1 Introduction

As a representative example of the rapid development of renewable energy sources, the installed capacity of photovoltaic (PV) systems is rapidly rising around the world. There are three different operation modes for PV systems: grid-forming, grid-feeding and grid-supporting. Grid-forming mode is mainly applied to off-grid PV systems. The main difference between grid-feeding and grid-supporting is that PV inverter performs like the ideal current source delivering power to the grid in grid-feeding mode, while it operates as the current source controlled by an active and reactive power reference value to adjust grid voltage in the other mode. It is well known that the magnitude of the power supplied by PV systems depends largely on the weather conditions of the outside world. At present, there are many studies on voltage/reactive power control strategies for PV inverters. The power factor control and the Reactive power-Voltage (Q-V) droop control method are two widely used PV inverter control strategies.

A multi-mode control strategy includes three kinds of operation modes—dynamic compensation mode, droop control mode and slope control mode—and each control mode was formulated according to the characteristics of specific conditions. In addition to the voltage deviations caused by voltage fluctuations, the power factor, the total harmonic distortion rate (THD) and other indicators are included in the power quality as well, which can also be optimized by the PV inverter under a certain control strategy. A power angle control method of the PV system, which not only reduced the THD in the grid, but also compensated the reactive power and improved the power factor.

4.11.2 Control Strategy

The integrated control strategy is divided into four parts, which are normal operation control mode, reverse power control mode, cloudy control mode and night control mode to deal with different weather or load conditions. The purpose of these four control methods is to mitigate voltage fluctuations in the PV systems, and to maintain the stability of the entire grid. In integrated control strategy, amount of reactive power injected or consumed at any time cannot exceed this upper limit Q_{max}. If the calculated value of reactive power by following parts of the control mode exceeds Q_{max} at a certain time, Q_{max} is considered to be the reference reactive power output in PV inverter.

APPENDIX

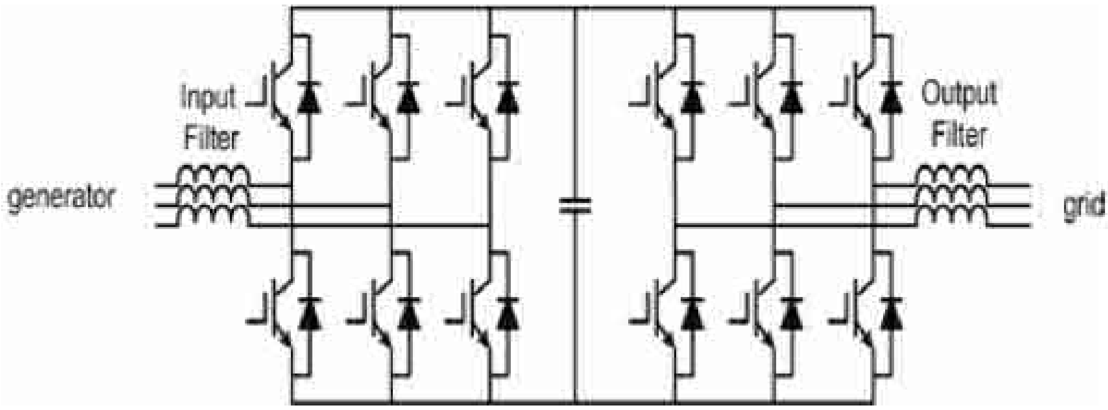
Content beyond the Syllabus

A.4 POWER CONVERTER TOPOLOGIES FOR WIND TURBINES

Basically two power converter topologies with full controllability of the generated power are currently used in the commercial wind turbine systems. These power converters are related to the partial-rating power converter wind turbine and the full-rating one. However, other topologies have been proposed in the last years.

A.4.1 Bi-directional back-to-back two-level power converter

The back-to-back Pulse Width Modulation-Voltage Source Converter (PWM-VSC) is a bi-directional power converter consisting of two conventional PWM-VSCs. This topology is shown in Figure.

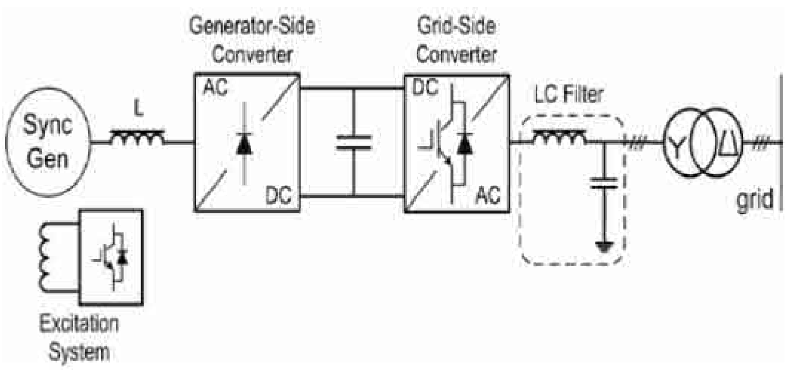


Structure of the back-to-back voltage source converter

The PWM-VSC is the most frequently used three phase frequency converter. As a consequence of this, the knowledge available in the field is extensive and very well established. Furthermore, many manufacturers produce components especially designed for use in this type of converter (e.g., a transistor-pack comprising six bridge coupled transistors and anti-paralleled diodes). Therefore, the component costs can be low compared to converters requiring components designed for a niche production. A technical advantage of the PWM-VSC is the capacitor decoupling between the grid inverter and the generator inverter. Besides affording some protection, this decoupling offers separate control of the two inverters, allowing compensation of asymmetry both on the generator side and on the grid side, independently. The inclusion of a boost inductance in the DC-link circuit increases the component count, but a positive effect is that the boost inductance reduces the demands on the performance of the grid side harmonic filter, and offers some protection of the converter against abnormal conditions on the grid.

A.4.2 Unidirectional power converter

A wound rotor synchronous generator requires only a simple diode bridge rectifier for the generator side converter as shown in Figure 7

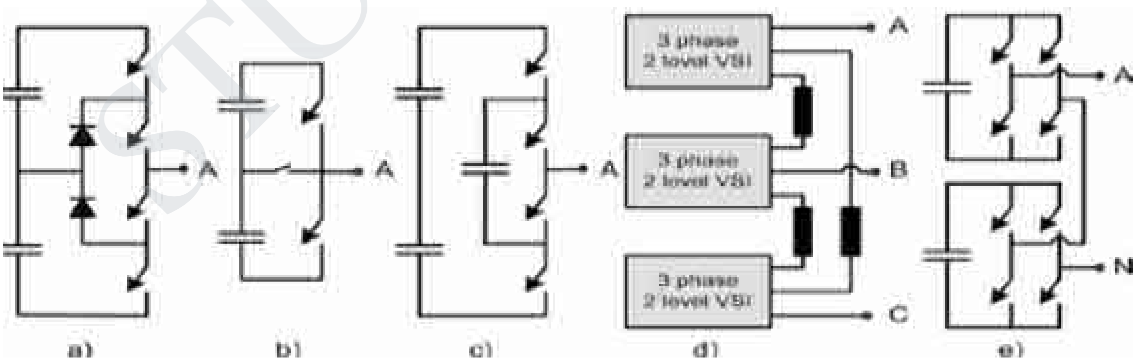


Variable speed wind turbine with synchronous generator and full rating power converter

The diode rectifier is the most common used topology in power electronic applications. For a three-phase system it consists of six diodes. The diode rectifier can only be used in one quadrant, it is simple and it is not possible to control it. It could be used in some applications with a DC-link. The variable speed operation of the wind turbine is achieved by using an extra power converter which feed the excitation winding. The grid side converter will offer a decoupled control of the active and reactive power delivered to the grid and also all the grid support features. These wind turbines can have a gearbox or they can be direct-driven. In order to achieve variable speed operation the wind turbines equipped with a permanent magnet synchronous generator (PMSG) will require a boost DC-DC converter inserted in the DC-link.

A.4.3 Multilevel power converter

Currently, there is an increasing interest in multilevel power converters especially for medium to high power, high-voltage wind turbine applications. The general idea behind the multilevel converter technology is to create a sinusoidal voltage from several levels of voltages, typically obtained from capacitor voltage sources. The different proposed multilevel converter topologies can be classified in the following five categories: multilevel configurations with diode clamps, multilevel configurations with bi-directional switch interconnection, multilevel configurations with flying capacitors, multilevel configurations with multiple three-phase inverters and multilevel configurations with cascaded single phase H-bridge inverters. These topologies are shown in Figure.



Multilevel power converter configuration

Initially, the main purpose of the multilevel converter was to achieve a higher voltage capability of the converters. As the ratings of the components increases and the switching- and conducting properties improve, the secondary effects of applying multilevel converters become more and more advantageous.

EE6009 POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

UNIT V

HYBRID RENEWABLE ENERGY SYSTEMS

SYLLABUS: Need for Hybrid Systems- Range and type of Hybrid systems- Case studies of Wind-PV Maximum Power Point Tracking (MPPT).

5.1 HYBRID RENEWABLE ENERGY SYSTEMS

5.1.1 Introduction

The renewable energy technologies include power generation from renewable energy sources, such as wind, PV(photovoltaic), MH (micro hydro), biomass, ocean wave, geothermal and tides. In general, the key reason for the deployment of the above energy systems are their benefits, such as supply security, reduced carbon emission, and improved power quality, reliability and employment opportunity to the local people. Since the RE resources are intermittent in nature therefore, hybrid combinations of two or more power generation technologies, along with storage can improve system performance. Hybrid Renewable Energy System (HRES) combines two or more renewable energy resources with some conventional source (diesel or petrol generator) along with storage, in order to fulfill the demand of an area.

5.1.2. Methodology

It is essential to have a well-defined and standardized frame work/steps taken for hybrid system based power generation for rural electrification. These steps are as follows:

Demand Assessment:

Using accurate load forecasting of remote villages, the load demand can be fetched. During load survey, following factors may be considered:

- Demand for street lighting
- Number of houses, schools, health centers, commercial establishment and their energy requirement
- Number of small scale industries and their energy demand
- Miscellaneous demand

Resource Assessment:

Resource assessment can be done by calculating potential available in wind, MHP, solar, Biomass, Biogas, and other renewable energy resources using meteorological data available.

Demand is fulfilled by Hybrid renewable energy system.

This can be done by combining one or more renewable energy sources with conventional energy sources. Some Hybrid renewable system configurations are as follows:

- PV/Wind/diesel generator HRES
- PV/wind/fuel cell HRES
- Wind/battery HRES
- Biomass/wind/diesel generator HRES
- PV/Wind/Biomass/fuel cell HRES

5.1.3 Need for Hybrid Systems

As convention fossil fuel energy sources diminish and the world's environmental concern about acid deposition and global warming increases, renewable energy sources (solar, wind, tidal, biomass and geothermal etc) are attracting more attention as alternative energy sources. These are all pollution free and one can say eco friendly. These are available at free of cost in India, there is severe power shortage and associated power quality problems. The quality of the grid supply in some places is characterized by large voltage and frequency fluctuations, scheduled and un-scheduled power cuts and load restrictions. Load shedding in many cities in India due to power shortage and faults is a major problem for which there is no immediate remedy in the near future since the gap between the power demand and supply is increasing every year.

In India wind and solar energy sources are available all over the year at free of cost whereas tidal and wave are coastal area. Geothermal is available at specific location. To meet the demand and for the sake of continuity of power supply, storing of energy is necessary. The term hybrid power system is used to describe any power system combine two or more energy conversion devices, or two or more fuels for the same device, that when integrated, overcome limitations inherent in either. Usually one of the energy sources is a conventional one (which necessarily does not depend on renewable energy resource) powered by a diesel engine, while the other(s) would be renewable viz. solar photovoltaic, wind or hydro. The design and structure of a hybrid energy system obviously take into account the types of renewable energy sources available locally, and the consumption the system supports. For example, the hybrid energy system presented here is a small-scale system and the consumption of power takes place during nights.

The wind energy component will make a more significant contribution in the hybrid system than solar energy. Although the energy produced by wind during night can be used directly without storage. Battery is needed to store solar and wind energy produced during the day. In addition to the technical considerations, cost benefit is a factor that has to be incorporated into the process of optimizing a hybrid energy system. In general, the use of wind energy is cheaper than that of solar energy. In areas where there is a limited wind source, a wind system has to be over-dimensioned in order to produce the required power, and these results in higher plant costs. It has been demonstrated that hybrid energy systems (renewable coupled with conventional energy source) can significantly reduce the total life cycle cost of a standalone power supplies in many off-grid situations. Numerous hybrid systems have been installed across the world, and expanding renewable energy industry has now developed reliable and cost competitive systems using a variety of technologies.

5.1.4 Benefits of Hybrid Systems

Improved reliability a robust power supply and downtime minimization during power outages could be achieved by virtue of varying the power sources, which is vital indeed due to its ability to provide backup power. System failure or disruption of diesel supply to the community are factors leading to utilizing an alternate generating system encompassing renewable energy / diesel hybrid system as to encourage continuous and reliability power supply. Photovoltaic and wind energy system attributive to fewer moving parts, requiring less maintenance than diesel, thus reduces downtime during repairs or routine maintenance. In fact, renewable energy sources being original and free, is more securing than diesel thus, beneficial to facilities.

The ability of renewable energy working in tandem with diesel, contributes to high quality and dynamic electricity services for 24 hours / day even as in a conventional system, the hours / day. The cost of photovoltaic or wind power generation lies in the form of upfront capital expenditures whereby the operation and maintenance expenses are low. Therefore, the generating cost via photovoltaic or wind is marginally more than a conventional system with respect to the additional generating capacity, nevertheless promises customer satisfaction of a continuous electricity supply. Reduced emissions and noise pollution Diesel generation emits air / water pollution agents as well as loud noise, proving the essentiality of renewable energy or diesel retrofits application in power generation which adopts an environmental-friendly technology. In fact, renewable energy system is also substantially quieter than diesel generators. Continuous power by incorporating diesel generator with renewable energy system, diesel generator is able to boost up the electricity supply during sudden increase in energy demand or when the batteries capacity decreases and thus, facilities face no supply interruption.

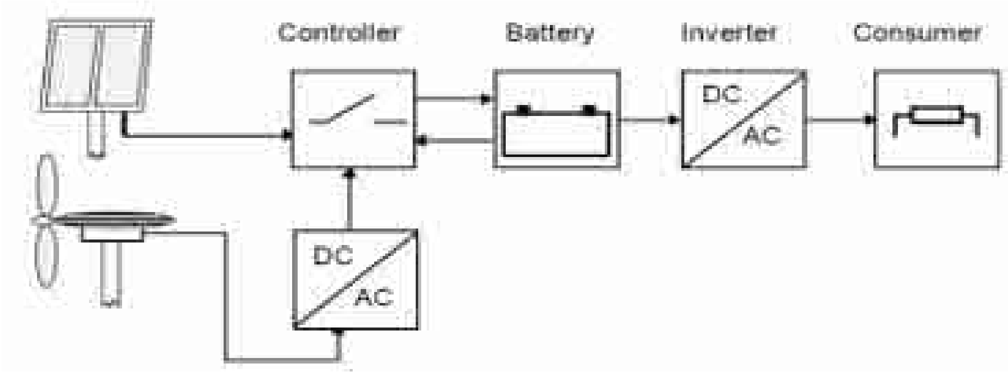
Reduced cost Renewable energy or diesel hybrid system act as the most cost-effective way of generating electricity with regards to savings on fuel consumption and lower maintenance cost. For a conventional diesel system at remote area, the fuel and transportation cost is typically very high, as well as the service and spare parts cost which grossly excessive to rural community. Efficient use of energy Hybrid system promotes efficient use of power since renewable energy system could be configured to cope with base load whilst the peak load could be met via diesel generator

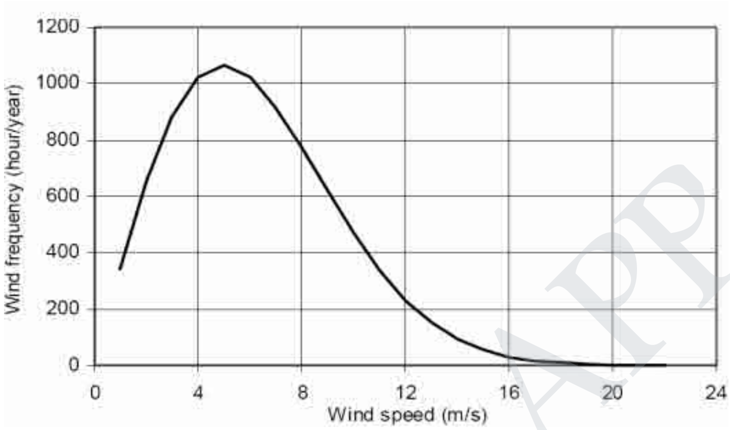
5.2 RANGE AND TYPE OF HYBRID SYSTEMS

5.2.1 Hybrid System Characteristics

Although hybrid energy systems are open, they can have the characteristics of a closed system if a subsystem with the function of "monitoring" is introduced as a feedback between output (consumer) and input (controller). As inputs of particular hybrid system cannot be changed. However, the load may be changed. With a backup system as another energy source the system can be designed as a partial closed-loop feedback system. There are various possibly to make combination of different energy sources. Selection of energy source for hybrid system is mainly depends upon availability at the place where it going to stabilized. In general in India solar energy is available almost all the places and infrastructure for power generation is rugged. Hence need low maintenance so it is smart to choose to have PV one of the energy sources in hybrid system. Wave and tidal energy available only at sea shore and need large capital investment and more maintenance, therefore not compatible for household hybrid system. But can be use in large power hybrid system. Corrosion because of seawater is a major drawback. Wind energy source is also a good choice but more preferable for open land hybrid system and status of wind throughout the year is also important. India has monsoon climate hence has enough potential of wind energy. Biomass energy is good option but it needs regular feeding to continuously operate. Biomass with grid hybrid system is broadly used in sugar mill in India. In residential applications, biomass can be used for space heating or for cooking. Businesses and industry use biomass for several purposes including space heating, hot water heating, and electricity generation.

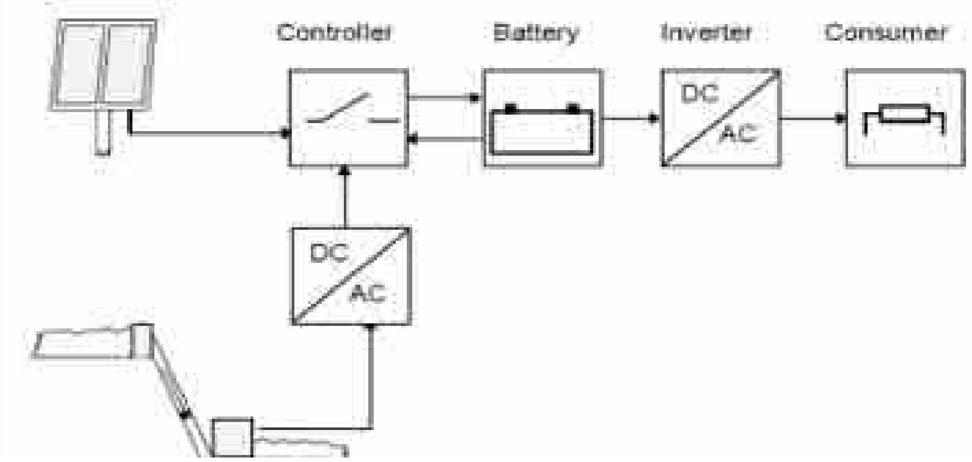
5.2.2 Wind/PV Hybrid System





A typical hybrid energy system consists of solar and wind energy sources. The principle of an open loop hybrid system of this type is shown in Figure. The power produced by the wind generators is an AC voltage but have variable amplitude and frequency that can then be transformed into DC to charge the battery. The controller protects the battery from overcharging or deep discharging. As high voltages can be used to reduce system losses, an inverter is normally in traduced to transform the low DC voltage to an AC voltage of 230V of frequency 50 Hz. The hybrid PV-wind generator system has been designed to supply continuous power of 1.5 kW and should have the following capabilities: Maximizes the electric power produced by the PV panels or by the wind generator by detecting and tracking the point of maximum power stores the electric energy in lead-acid batteries for a stable repeater operation. Control of the charge and discharge processes of the batteries protects wind generator from over speeding by connecting a dummy load to its output.

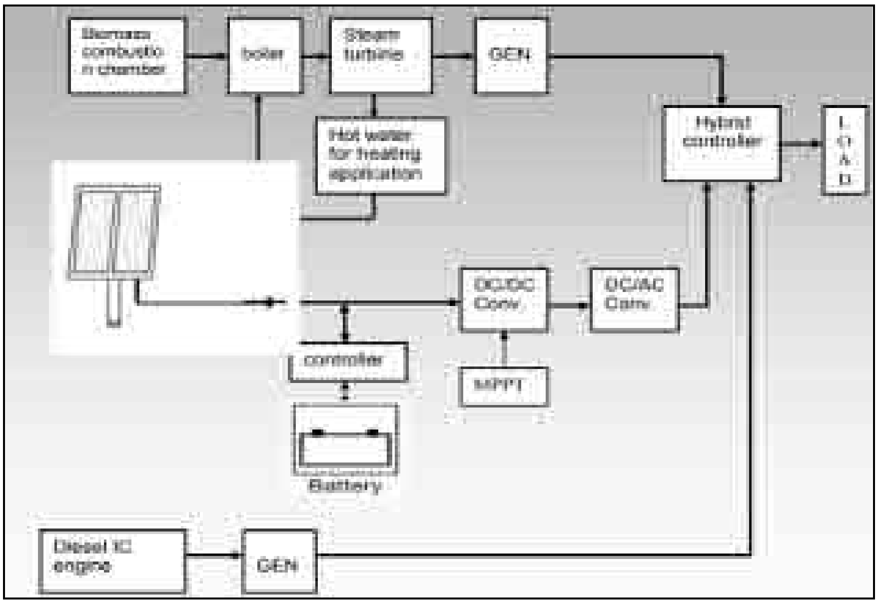
5.2.3 PV/Hydro Hybrid System



The block diagram of hybrid system, which combines PV with hydro system, is shown above. In this system there is a small reservoir to store the water. This type of hybrid system sometimes depends upon the geographical condition where the water at some height is available. System capacity is depends upon at the water quantity and solar radiation. The power supplied by falling water is the rate at which it delivers energy, and this depends on the flow rate and water head. The local water flow and head are limited at this project site, and a relatively simple hydro energy component is used in the project. Hydropower available is may be of runoff river type hence produces variable amplitude and frequency voltage. It can be use to charge the battery after converting it into DC.

5.2.4 Biomass-PV-Diesel Hybrid System

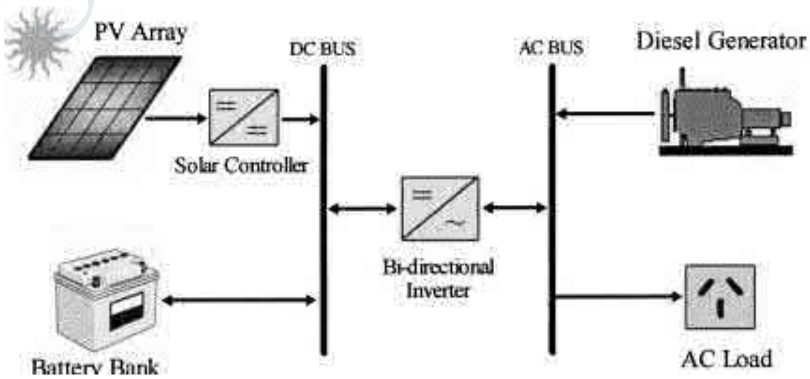
Biomass is matter usually thought of as garbage. Some of it is just substance lying around -- dead trees, tree branches, yard clippings, leftover crops, wood chips and bark and sawdust from lumber mills. It can even include used tires and livestock manure. The waste wood, tree branches and other scraps are gathered together in big trucks. The trucks bring the waste from factories and from farms to a biomass power plant. Here the biomass is dumped into huge hoppers. This is then fed into a furnace where it is burned. The heat is used to boil water in the boiler, and the energy in the steam is used to turn turbines and generators. Other application of Biomass is that it can also be tapped right at the landfill with burning waster products. When garbage decomposes, it gives off methane gas. Pipelines are put into the landfills and the methane gas can be collected. It is then used in power plants to make electricity.



In hybrid system diesel energy is only work as a backup source. When the demand on its peak, the available sources are insufficient for that then the diesel back is required. There is a controller, which maintains the energy balance during the load variation. It assigns the priority among the energy sources. It also maintains the synchronizing the voltage signal coming from the different sources. Suppose the instantaneous magnitude of voltage signal coming from PV sources is differ from that of coming from other source say biomass. Hence it causes the local circulating power flow.

5.2.5 Hybrid PV diesel system

A photovoltaic diesel hybrid system ordinarily consists of a PV system, diesel gensets and intelligent management to ensure that the amount of solar energy fed into the system exactly matches the demand at that time. Basically the PV system complements the diesel gensets. It can supply additional energy when loads are high or relieve the genset to minimize its fuel consumption.



In the future, excess energy could optionally be stored in batteries, making it possible for the hybrid system to use more solar power even at night. Intelligent management of various system components ensures optimal fuel economy and minimizes CO_2 emissions.

5.2.6 Advantages of a photovoltaic diesel hybrid system

In contrast to power supply systems using diesel gensets, and despite their higher initial cost, PV systems can be amortized in as little as four to five years, depending on the site and system size, and they have low operating costs. In addition, PV systems are flexible and can be expanded on a modular basis as the energy demand grows. Compared to pure gensets systems, a photovoltaic diesel hybrid system provides numerous advantages:

- Lower fuel costs
- Reduced risk of fuel price increases and supply shortages
- Minimal CO_2 .

5.2.7 Components of photovoltaic diesel hybrid system

PV inverters

PV inverters are the central components of the fuel Save Solution. Designed specifically to be used in weak utility grids, they are suitable for high voltage and frequency fluctuations. They also remain extremely productive in harsh ambient conditions such as heat, moisture, salty air, among others. A centralized PV system contains only one string into a central point where direct current is converted to alternating current. In a decentralized PV system, the PV power is divided into many strings, which are converted into alternating current by several inverters.

PV array

The solar power is generated in the PV modules, which can be mounted on the ground or on a roof, depending on local conditions. Inverters are compatible with all PV module types and technologies currently available on the market.

Fuel save Controller

The fuel save controller provides the perfect interface between the gensets, PV systems and loads, managing demand-based PV feed-in into the diesel-powered grid. As the central component of the fuel save solution, it ensures maximum security with reduced fuel costs and minimizes CO_2 emissions.

Diesel Genset

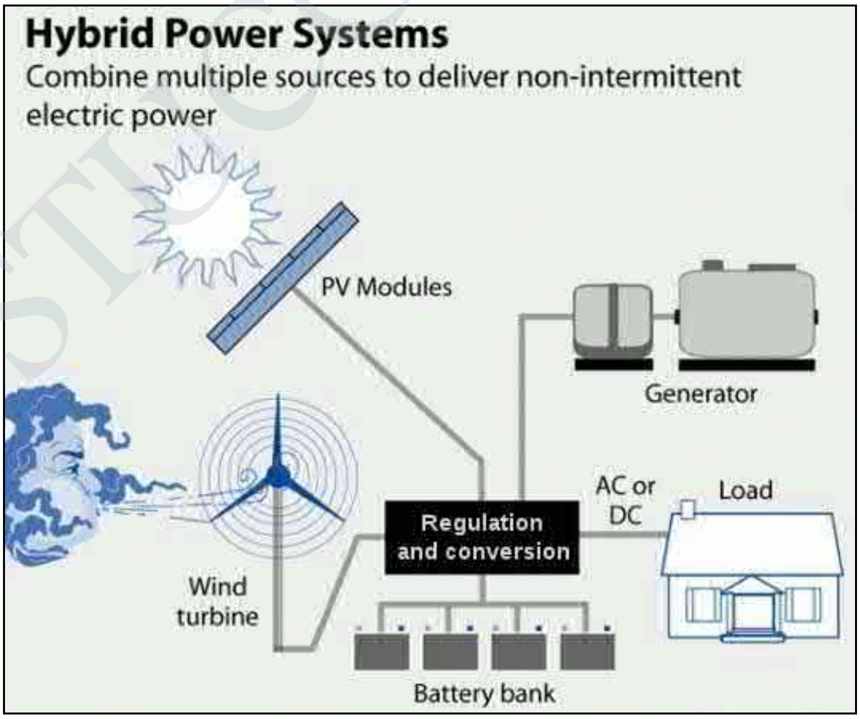
In grid-remote regions, pure diesel systems often provide the energy for industrial applications. They constitute the local grid, ensuring a constant power supply to all connected users. Because the gensets require a constant fuel supply, they are often the system's highest operating cost. In regions with weak utility grids, diesel gensets often serve as a backup during grid power outages.

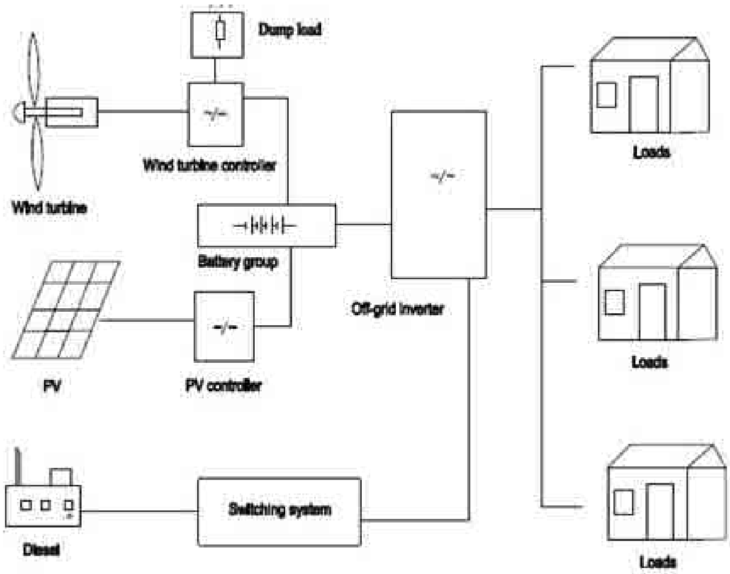
Optional storage batteries

To boost the efficiency of the entire energy supply system, it is advisable to include a storage battery. When solar irradiation is insufficient or energy is needed after dark, the storage battery supplies the required energy, ensuring optimal hybrid system operation.

5.3 PV/SOLAR THERMAL/GRID-CONNECTED HYBRID SYSTEM

The hybrid system that combines wind, solar, and diesel power generation system has become popular because of its advantages over either single system. The main advantages of hybrid systems are fuel saving lower atmospheric contamination, savings in maintenance, silent systems, and connection to other power supplies which enable higher service quality than traditional single-source generation systems. The main components of hybrid systems are: the power sources, the storage devices, the power management center, and monitor and control devices. There are two main advantages of the system compared to others. First, the energy of the proposed system is used wisely and efficiently by monitoring the load power and the available renewable energy to define the quantity of needed power and to select the best available source. Secondly, additional batteries are used as a dumped load in the system, which can be used if there is a shortage in the renewable energy source to minimize the usage of the diesel engine. In addition, a wireless monitoring system will be used to help in self-troubleshooting and a fast alarm system, which will minimize maintenance efforts.





Hybrid Solar Wind Diesel Power Generation system has different schematics that each has its own advantages and implementation. In the scheme illustrated in Figure, the battery is charged directly from the photovoltaic (PV) module and the wind turbine where each has its own charge controller. The load receives its required power from all energy sources via an inverted to convert the DC to AC. The battery is charged in similar way to the first scheme but the only difference is that the load receives its required power via the battery not others. Also, there is no dump load in this case.

The charge controller receives the power from the energy sources (PV module and the wind turbine) and delivers the power to the battery if it is not fully charged, to the dump load if the battery is fully charged. If the battery is not fully charged and the output power from the renewable energy sources is not satisfactory, the diesel engine is turned on to supply the load with the needed power until the battery is fully charged again. The sensors are used for controlling the power flow among the system devices and elements, and troubleshooting purposes. For wind turbine, if the wind sensor reading does not match the proper amount of energy produced by wind turbine, the controller will send a command to the generator housed in the wind turbine to shut off. For the PV module, if the light intensity sensor reading does not match the amount of power produced by the PV module, the controller will send a command to the disconnect the PV module from the charge controller. The system will take the power input from both the wind turbine and solar panel and send them to the charge controller. The charge controller will direct the power to the battery or the dump load battery based on battery voltage input.

When the battery voltage sensor inputs data that the battery is full, the charge controller will switch to dump load. However, when the battery is undercharged, the diesel engine will be switched on to supply the load with the power needed until the battery is charged again.

Moreover, the other sensors will be used for the troubleshooting purpose. For example, the system will be able to identify problem in the wind turbine or the solar panel. Such as when the wind speed and the light intensity sensors reading do not match with the input power given to the system that is read by the voltage and current sensors. Furthermore, the fuel level sensor will sense the diesel engine is running out of fuel.

5.3.1 Case studies of Wind-PV system

Many remote communities around the world cannot be physically or economically connected to an electric power grid. The electricity demand in these areas is conventionally supplied by small isolated diesel generators. The operating costs associated with these diesel generators may be unacceptably high due to discounted fossil fuel costs together with difficulties in fuel delivery and maintenance of generators. In such situations, renewable energy sources, such as solar photovoltaic (PV) and wind turbine generator provide a realistic alternative to supplement engine-driven generators for electricity generation in off-grid areas. It has been demonstrated that hybrid energy systems can significantly reduce the total life cycle cost of standalone power supplies in many off-grid situations, while at the same time providing a reliable supply of electricity using a combination of energy sources. Numerous hybrid systems have been installed across the world, and the expanding renewable energy industry has now developed reliable and cost competitive systems using a variety of technologies. In a report, India's gross renewable energy potential (up to 2032) is estimated at 220 GW.

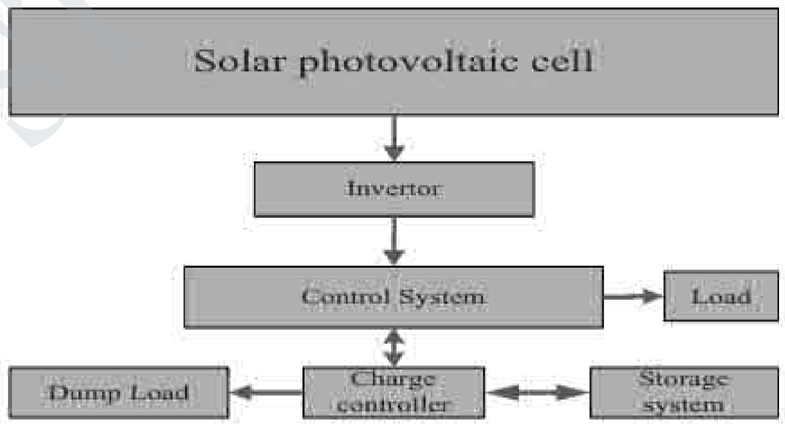
It is likewise noted in the report that, with a renewable energy capacity of 14.8 GW (i.e. 9.7% of the total installed generation capacities of 150 GW as on 30 June 2009), India has barely scratched the surface of a huge opportunity. However, in the last couple of years itself, the share of renewable energy in installed capacity has grown from 5 to 9.7%. This implies an enormous potential in energy generation, which can achieve several hundred GW with current renewable energy technologies. As the cost of building solar PV–wind capacity continues to fall over the next five to ten years; a significant scale-up of renewable generation is a very realistic possibility in the developing world. Thousands of villages across the globe are still being exiled from electricity and energizing these villages by extended grids or by diesel generators alone will be uneconomical. Moreover, with the current resource crunch with government, these villages receive low priority for grid extension because of lower economic return potential. Standalone solar PV–wind hybrid energy systems can provide economically viable and reliable electricity to such local needs.

Many countries with an average wind speed in the range of 5–10 m/s and average solar insolation level in the range of 3–6 KWh/m2 are pursuing the option of wind and PV system to minimize their dependence on fossil-based non-renewable fuels. Autonomous wind systems do not produce usable energy for a considerable portion of time during the year. This is primarily due to relatively high cut-in wind speeds which ranges from 3.5 to 4.5 m/s. In decree to overcome this downtime, the utilization of solar PV and wind hybrid system is advised. Such systems are usually equipped with diesel generators to meet the peak load during the short periods when there is a deficit of available energy to cover the load demand. Diesel generator sets, while being relatively inexpensive to purchase, are generally expensive to operate and maintain, especially at low load levels. In general, the variation of solar and wind energy does not match the time distribution of the demand.

5.4 DESCRIPTION OF HYBRID RENEWABLE ENERGY SCHEMES

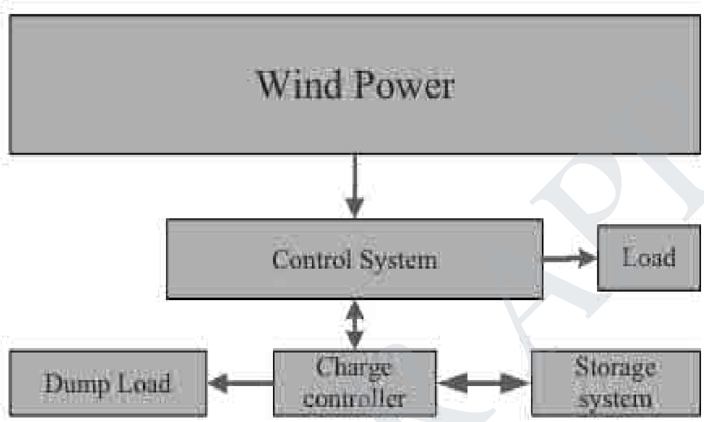
A hybrid renewable PV–wind energy system is a combination of solar PV, wind turbine, inverter, battery, and other addition components. A number of models are available for PV–wind combination as a PV hybrid system, wind hybrid system, and PV–wind hybrid system, which are employed to satisfy the load demand. Once the power resources (solar and wind flow energy) are sufficient excess generated power is fed to the battery until it is fully charged. Thus, the battery comes into play when the renewable energy sources (PV–wind) power is not able to satisfy the load demand until the storage is depleted. The operation of hybrid PV–wind system depends on the individual element. In order to evaluate the maximum output from each component, first the single component is modeled, thereafter which their combination can be evaluated to meet the require dependability. If the electric power production, though this type of individual element, is satisfactory the actual hybrid system will offer electrical power at the very least charge.

5.4.1 Hybrid photovoltaic system



Solar energy is one of the site-dependent, non-polluting energy sources, and is available in great quantity. It is a potential source of alternative/renewable energy and utilization of solar radiation for power generation reduces the dependence on fossil fuel. Solar PV power generation unit consists of PV generator, diesel generator, and inverter and battery system. For improved performance and better control, the role of battery storage is very important. The necessary condition for the design of the hybrid PV systems for maximum output power is hot climate. This type of system is cost effective and reliable, especially for those locations where the power supplies though the grid is not suitable and the cost of the transmission line is very high such as remote and isolated areas. Designed a system for computing production cost associated with hybrid PV battery method in which the size associated with PV method is calculated on such basis as electrical requirements not attained. For standalone hybrid PV system, analysis of reliability is determined in the term of loss of load (LOL) probability.

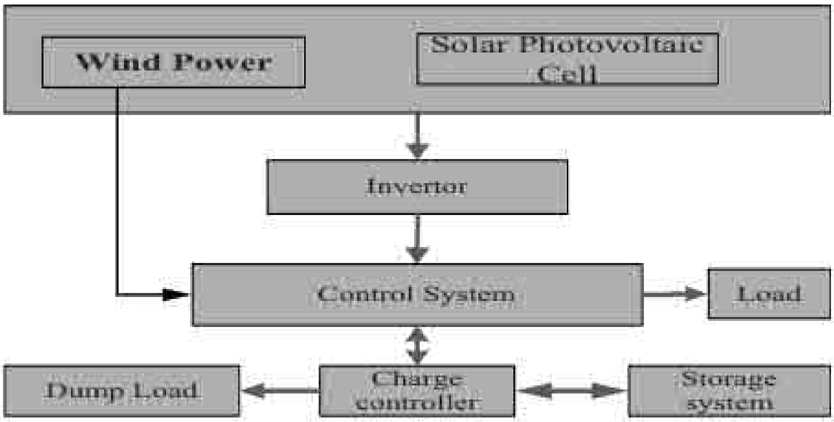
5.4.2 Hybrid wind energy system



For the design of a reliable and economical hybrid wind system a location with a better wind energy potential must be chosen. Optimal sizing of a hybrid wind system and forecasting of a hybrid system based on several optimization techniques are obtained based on the application. A methodology is obtained for identifying the wind turbine generator parameters as capacity factor which relates to identically rated available wind turbine and capacity factor calculated on the basis of wind speed data at different hours of the day of many years. Hybrid wind system performance, reliability, and reduction in the cost of energy (COE) can be obtained by using a battery backup system. When the hybrid system generated power is in surplus, this power is used for loading the batteries for backup security and this charge battery power is used when the load requirement is not supplied by design hybrid system. Figure shows the architecture of wind hybrid energy system.

5.4.3 Hybrid photovoltaic/wind energy system

PV and wind system, both depending on weather condition, individual hybrid PV and hybrid wind system does not produce usable energy throughout the year. For better performance of the standalone individual PV combination or wind combination need battery backup unit and diesel generator set results to increase the hybrid system cost.



The main objective of the design is to obtain a cost-effective solution. Different artificial techniques are available for the optimal size of the hybrid system to minimize total annual cost. A couple of renewable energy sources—PV panels and wind turbines—are viewed as, together with traditional diesel generators in order to optimally design ability as well as functioning, preparing of the hybrid system. An optimization is used to match hourly supply and demand problem had been resolved to have sparse matrices and also the linear programming algorithm.

5.5 POWER ELECTRONICS TOPOLOGIES AND CONTROL FOR HYBRID SOLAR PV-WIND SYSTEMS

5.5.1 Power electronics topologies and control for Grid-connected system

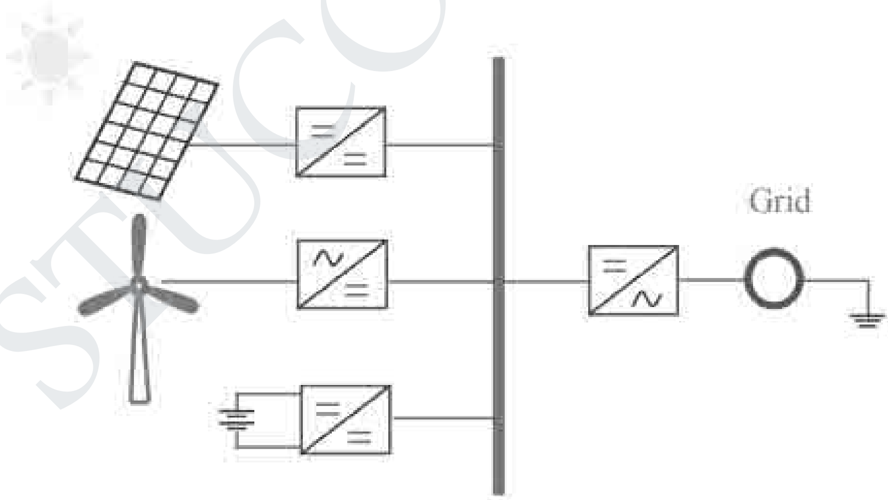


Figure 1: Grid-connected hybrid system at common DC bus

There are two topologies for grid-connected solar PV and wind hybrid system as can be seen from Figure 1 and 2. Figure 1 shows that the DC outputs' voltages from individual solar PV, wind and battery bank stream, through individual DC/DC and AC/DC units, are integrated on the DC side and go through one common DC/AC inverter which acts as an interface between the power sources and the grid to provide the desired power even with only one source available. Hence, the renewable energy sources act as current sources and can exchange power with the grid and the common DC/AC inverter controls the DC bus voltage. The individual units can be employed for maximum power point tracking (MPPT) systems to have the maximum power from the solar PV and wind systems and the common DC/AC inverter will control the DC bus voltage. The battery bank is charged when there is an extra power and discharged (by supplying power) when there is shortage of power from the renewable energy sources.

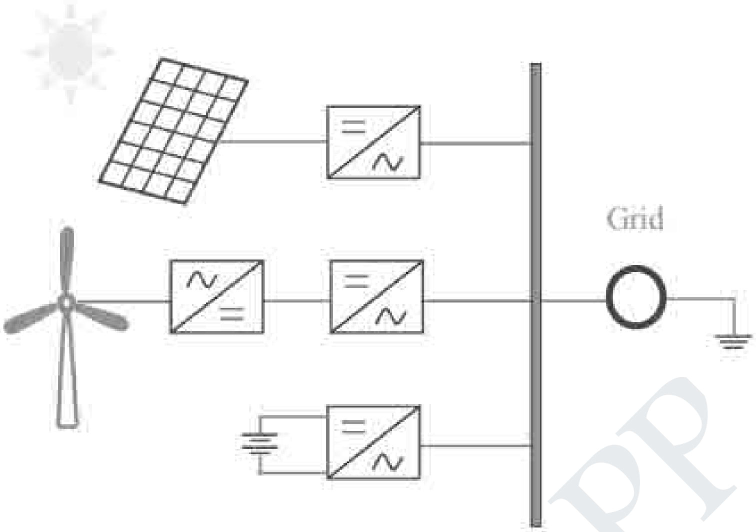


Figure 2: Grid-connected hybrid system at common AC bus

On the other hand, Figure 2 shows that renewable energy sources are injecting power directly to the grid through individual DC/AC and AC/DC-DC/AC units. Many modules have proposed and presented experimental results of PV-wind-battery hybrid systems along with power management schemes and control systems. Such systems were capable to operate in different modes of operation and able to transfer from one mode to another easily. The voltage converters play an important role in controlling the amount and the type of voltage whether AC or DC and the duty cycle of those converters can be used to improve the quality of power. The response of the duty cycle of a DC/DC converter is relatively fast in MPPT control process. Numerous intelligent techniques are used for grid-connected hybrid PV/FC/battery power system to control flow of power via DC/DC and DC/AC converters.

5.5.2 Power electronics topologies and control for standalone system

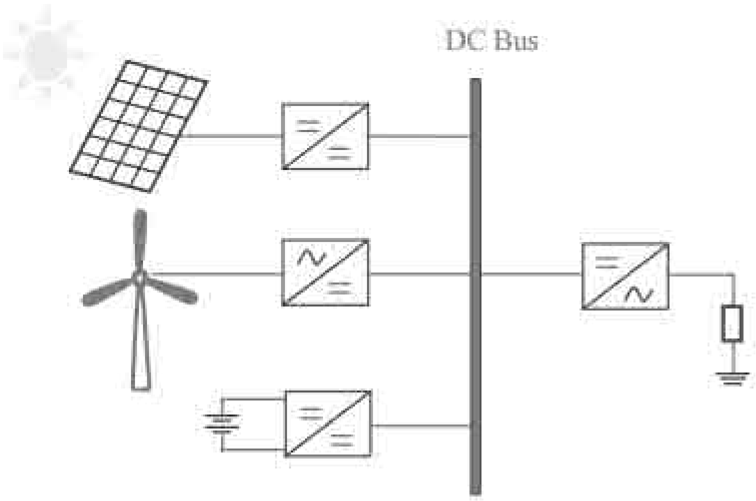


Figure 1: Stand-alone hybrid system at common DC bus

Figure 1 shows a stand-alone solar PV and wind hybrid system with DC common bus. One of its main advantages is to include DC interface bus for coupling different generation sources, which do not have to operate at a constant frequency and in synchronism. The DC bus line output voltage from all streams is set to be fixed and the output current from each source is controlled independently. The DC outputs' voltages from individual solar PV, wind and battery bank stream, through individual DC/DC and AC/DC units, are integrated on the DC side, combined in parallel and go through one common DC/AC inverter which acts as an interface between the power sources and the loads to provide the required power to the load by regulating the AC output voltage. The battery bank is interfaced by a DC/DC converter which regulates the DC-link bus voltage by charging (in case of extra power) or discharging the battery (in case of shortage of power). The renewable energy sources act as current sources and supply directly the loads. The interface common unit regulates the magnitude of the load's voltage. The individual AC/DC and DC/DC units can be employed for MPPT systems to have the maximum power from the solar PV and wind systems and the common DC/AC inverter will control magnitude of the load's voltage. The battery bank acts as a voltage source to control the common DC bus voltage by charging or discharging. In the conventional way for controlling the complete hybrid system, power electronics converters are used for maximum energy extract from solar and wind energy resources. In addition, advanced controlling techniques can remove the power fluctuations caused by the variability of the renewable energy sources.

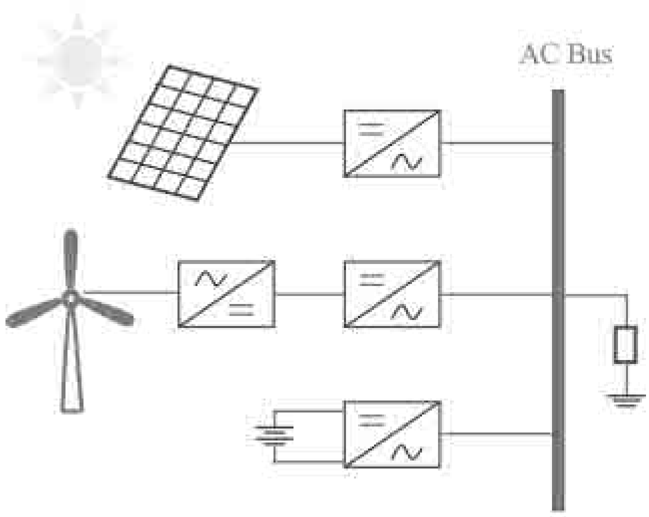


Figure 2: Stand-alone hybrid system at common AC bus

Figure 2 shows stand-alone solar PV and wind hybrid system with AC common bus. The form of pure AC bus bar system is widely used worldwide with lot of advantages, such as simple operation, plug and play scenario, low cost and easy extension according to the load's requirement. On the other hand, controlling AC voltage and frequency and energy management are some of the challenges for this type of topology. In this topology, the AC outputs' voltages from individual solar PV, wind and battery bank stream, through individual DC/AC and AC/DC-DC/AC units, are feeding the loads directly. The renewable energy sources can act as current sources provided that the battery bank exists as a voltage source to control the common AC bus voltage by charging or discharging. Hence, the individual units can be employed for MPPT systems to have the maximum power from the solar PV and wind systems provided that the battery bank exists as a voltage source to control the common AC bus voltage by charging or discharging. The battery bank is charged when there is an extra power and discharged and can supply power in case of shortage of power from the renewable energy sources. Droop control is normally applied to generators for frequency control and sometimes voltage control in order to have load sharing of parallel generators. It can also be used to perform proper current sharing in a micro-grid. With droop control, decentralized control for each interfacing converter is achieved. At the same time, no communication or only low bandwidth communication, such as power line communication, can be used in AC systems. Power flow was controlled using frequency and voltage drooping technique in order to ensure seamless transfer between grid connected and stand-alone parallel modes of operation.

5.6 MAXIMUM POWER POINT TRACKING (MPPT)

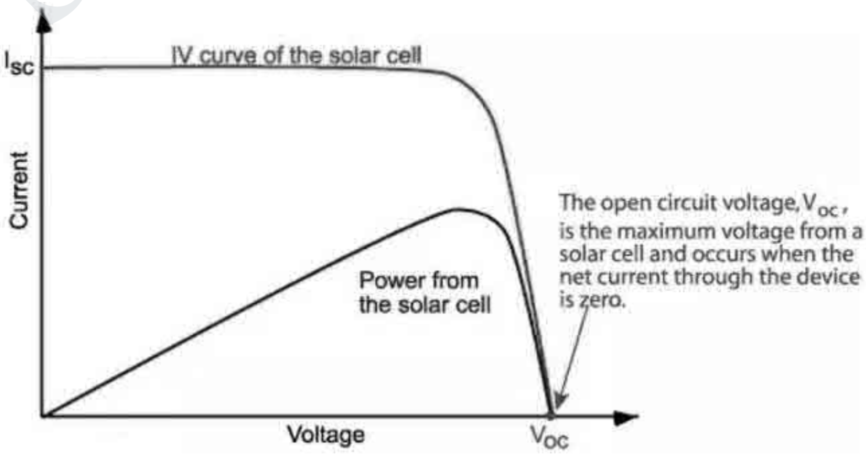
5.6.1 Maximum Power Point Tracking

MPPT is a technique used commonly with wind turbines and photovoltaic (PV) solar systems to maximize power extraction under all conditions. Although solar power is mainly covered, the principle applies generally to sources with variable power: for example, optical power transmission and thermo-photovoltaic. PV solar systems exist in many different configurations with regard to their relationship to inverter systems, external grids, battery banks, or other electrical loads. Regardless of the ultimate destination of the solar power, though, the central problem addressed by MPPT is that the efficiency of power transfer from the solar cell depends on both the amount of sunlight falling on the solar panels and the electrical characteristics of the load. As the amount of sunlight varies, the load characteristic that gives the highest power transfer efficiency changes, so that the efficiency of the system is optimized when the load characteristic changes to keep the power transfer at highest efficiency. This load characteristic is called the **maximum power point** and **MPPT** is the process of finding this point and keeping the load characteristic there. Electrical circuits can be designed to present arbitrary loads to the photovoltaic cells and then convert the voltage, current, or frequency to suit other devices or systems, and MPPT solves the problem of choosing the best load to be presented to the cells in order to get the most usable power out.

5.6.2 Working of MPPT

Maximum Power Point Tracking (MPPT) is a technology approach used in solar PV inverters to optimize power output in less-than-ideal sunlight conditions. Most modern inverters are equipped with at least one MPPT input.

An MPPT tracker is analogous to a thumb placed over a garden hose. If you put your thumb over part of the opening of the hose (adding resistance to the circuit), the pressure (voltage) goes up and the stream flies faster, but less water (current) is getting through. If you completely cover the opening, nothing gets through. If you remove your thumb entirely, the maximum flow rate gets through, but the stream falls limply at your feet.



That is the basic mechanism of the MPPT tracker which varies resistance in the circuit to modify current and voltage. Now imagine that there are hundreds of pumps (solar panels) upstream of the hose and they are delivering water (energy) to you. Further complicating things, some of these pumps go offline at certain parts of the day (partial shading of the array). So the force behind the delivery of water will be constantly varying.

5.7 MAXIMUM POWER POINT TRACKING ALGORITHMS

MPPT algorithms are necessary in PV applications because the MPP of a solar panel varies with the irradiation and temperature, so the use of MPPT algorithms is required in order to obtain the maximum power from a solar array. Over the past decades many methods to find the MPP have been developed and published. These techniques differ in many aspects such as required sensors, complexity, cost, range of effectiveness, convergence speed, correct tracking when irradiation and/or temperature change, hardware needed for the implementation or popularity, among others. The different MPPT algorithms are discussed below.

5.7.1 Hill-climbing techniques

Algorithms are based on the "hill-climbing" principle, which consists of moving the operation point of the PV array in the direction in which power increases. Hill-climbing techniques are the most popular MPPT methods due to their ease of implementation and good performance when the irradiation is constant. The advantages of these methods are the simplicity and low computational power they need.

5.7.2 Perturb and observe

The Perturb and observe (P&O) algorithm is also called "hill-climbing", but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves a perturbation on the duty cycle of the power converter and P&O a perturbation in the operating voltage of the DC link between the PV array and the power converter. In the case of the Hill-climbing, perturbing the duty cycle of the power converter implies modifying the voltage of the DC link between the PV array and the power converter, so both names refer to the same technique. In this method, the sign of the last perturbation and the sign of the last increment in the power are used to decide the next perturbation.

5.7.3 Incremental conductance

The incremental conductance algorithm is based on the fact that the slope of the curve power vs. voltage (current) of the PV module is zero at the MPP, positive (negative) on the left of it and negative (positive) on the right. It can be written as

$$\frac{\Delta V}{\Delta P} = 0 \left(\frac{\Delta I}{\Delta P} = 0\right) at\ the\ MPP$$
$$\frac{\Delta V}{\Delta P} > 0 \left(\frac{\Delta I}{\Delta P} < 0\right) on\ the\ left$$
$$\frac{\Delta V}{\Delta P} < 0 \left(\frac{\Delta I}{\Delta P} > 0\right) on\ the\ right$$

By comparing the increment of the power versus the increment of the voltage (current) between two consecutives samples, the change in the MPP voltage can be determined.

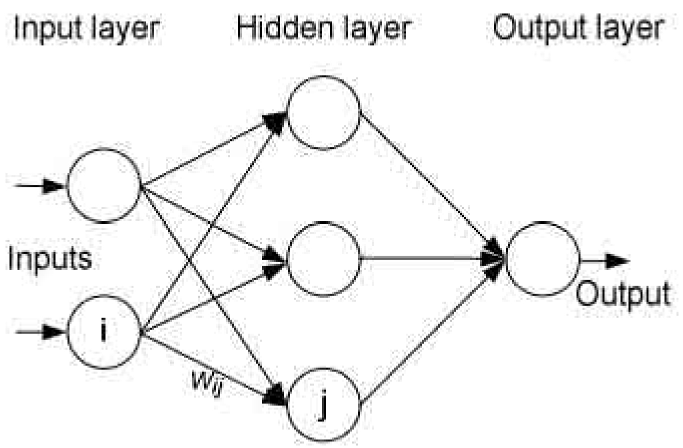
5.7.4 Fuzzy logic control

The use of fuzzy logic control has become popular over the last decade because it can deal with imprecise inputs, does not need an accurate mathematical model and can handle nonlinearity. The fuzzy logic consists of three stages: fuzzification, inference system and defuzzification. Fuzzification comprises the process of transforming numerical crisp inputs into linguistic variables based on the degree of membership to certain sets. The number of membership functions used depends on the accuracy of the controller, but it usually varies between 5 and 7. In some cases the membership functions are chosen less symmetric or even optimized for the application for better accuracy

The rule base, also known as rule base lookup table or fuzzy rule algorithm, associates the fuzzy output to the fuzzy inputs based on the power converter used and on the knowledge of the user. The last stage of the fuzzy logic control is the defuzzification. In this stage the output is converted from a linguistic variable to a numerical crisp one again using membership functions. There are different methods to transform the linguistic variables into crisp values.. The advantages of these controllers, besides dealing with imprecise inputs, not needing an accurate mathematical model and handling nonlinearity, are fast convergence and minimal oscillations around the MPP.

5.7.5 Neural networks

Another MPPT method well adapted to microcontrollers is Neural Networks [8]. They came along with Fuzzy Logic and both are part of the so called “Soft Computing”. The simplest example of a Neural Network (NN) has three layers called the input layer, hidden layer and output layer, as shown in Figure. More complicated NN’s are built adding more hidden layers. The number of layers and the number of nodes in each layer as well as the function used in each layer vary and depend on the user knowledge. The input variables can be parameters of the PV array such as V_{OC} and I_{SC}, atmospheric data as irradiation and temperature or a combination of these. The output is usually one or more reference signals like the duty cycle or the DC-link reference voltage



To execute this training process, data of the patterns between inputs and outputs of the neural network are recorded over a lengthy period of time, so that the MPP can be tracked accurately. The main disadvantage of this MPPT technique is the fact that the data needed for the training process has to be specifically acquired for every PV array and location, as the characteristics of the PV array vary depending on the model and the atmospheric conditions depend on the location.

5.7.6 Fractional open circuit voltage

This method uses the approximately linear relationship between the MPP voltage (V_{MPP}) and the open circuit voltage (V_{OC}), which varies with the irradiance and temperature.

$$V_{MPP} \approx K_1 V_{OC}$$

Where k_1 is a constant depending on the characteristics of the PV array and it has to be determined beforehand by determining the V_{MPP} and V_{OC} for different levels of irradiation and different temperatures. Once the constant of proportionality, k_1, is known, the MPP voltage V_{MPP} can be determined periodically by measuring V_{OC}. To measure V_{OC} the power converter has to be shut down momentarily so in each measurement a loss of power occurs. Another problem of this method is that it is incapable of tracking the MPP under irradiation slopes, because the determination of V_{MPP} is not continuous. One more disadvantage is that the MPP reached is not the real one because the relationship is only an approximation.

5.7.7 Fractional short circuit current

Just like in the fractional open circuit voltage method, there is a relationship, under varying atmospheric conditions, between the short circuit current I_{SC} and the MPP current, I_{MPP}, as is shown by

$$I_{MPP} \approx K_2 I_{SC}$$

The coefficient of proportionality k_2 has to be determined according to each PV array, as in the previous method happened with k_1. Measuring the short circuit current while the system is operating is a problem. It usually requires adding an additional switch to the power converter to periodically short the PV array and measure I_{SC}.

5.7.8 Current sweep

In this method the V-I characteristic curve is obtained using a sweep waveform for the PV array current. The sweep is repeated at fixed time intervals so the V-I curve is updated periodically and the MPP voltage (V_{MPP}) can be determined from it at these same intervals. On the other hand, the sweep takes certain time during which the operating point is not the MPP, which implies some loss of available power. Strictly speaking, it is not possible to track the MPP under irradiation slopes, because the MPP varies continuously. Only if the sweep is instantaneous the global MPP could be found, but that is impossible. Furthermore, the implementation complexity is high, the convergence speed is slow and both voltage and current measurements are required.

5.8. PARTICLE SWARM OPTIMIZATION BASED MPPT ALGORITHM FOR PV SYSTEM

This algorithm is used to reduce the steady state oscillation to practically zero once the maximum power point is located. Furthermore, it has ability to track the MPP for the extreme environmental conditions like large fluctuations of insolation and partial shading condition. The MPP tracker based on Particle Swarm Optimization for photovoltaic module arrays is capable of tracking global MPPs of multi-peak characteristic curves where the fixed values were adopted for weighing within the algorithm, the tracking performance lacked robustness, causing low success rates when tracking the global MPPs. Though the MPPs were tracked successfully, the dynamic response speed is low. The PSO based MPPT controller algorithm for various environmental conditions like fully shaded conditions and partially shaded conditions to find new global MPP with re-initialization of particles can be observed. The PSO has simple structure, easy implementation, and fast computation capability. It is able to locate the MPP for any type of P-V curve regardless of environmental variations and also to track the PV system as the search space of the PSO reduced and the time required for the convergence can be greatly reduced. The PSO based MPPT can be used to predict the I-V and P-V characteristics curves during partial shading condition also to evolve and ratify the photovoltaic system design encompassing the power converter and MPPT controller.

5.9 MAXIMUM POWER POINT TRACKING IN HYBRID PHOTO-VOLTAIC AND WIND ENERGY CONVERSION SYSTEM

5.9.1 Introduction

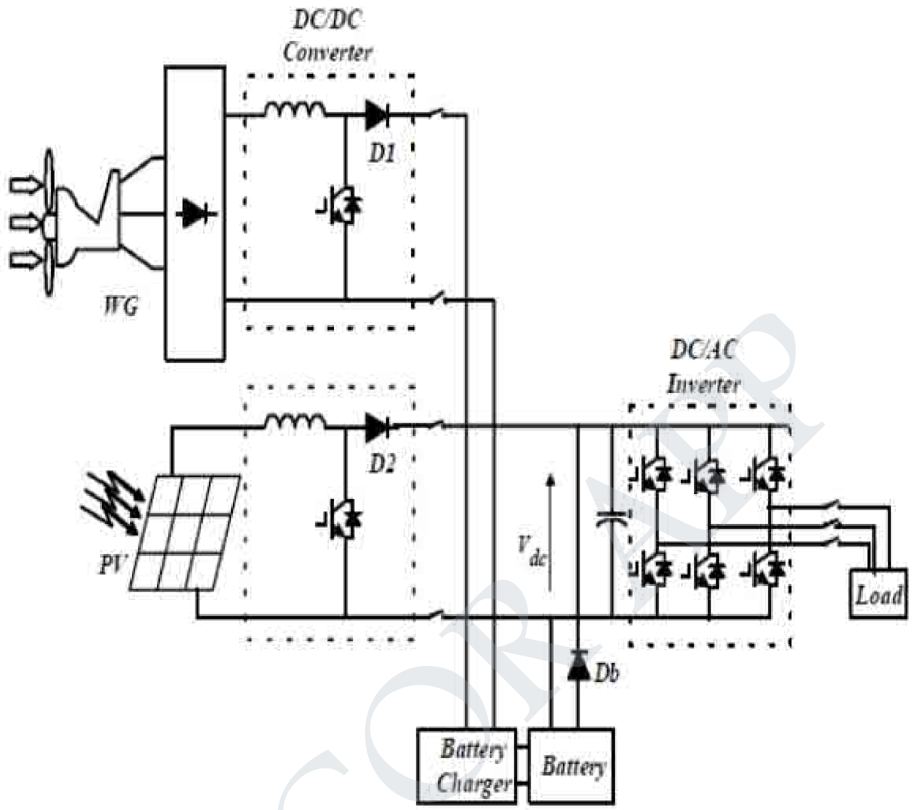
With exhausting of traditional energy resources and increasing concern of environment, renewable and clean energy is attracting more attention all over the world to overcome the increasing power demand. Out of all the renewable energy sources, Wind energy and solar energy are reliable energy sources. However, the renewable energy generation has a drawback that the change of the output characteristic becomes intense because the output greatly depends on climatic conditions, including solar irradiance, wind speed, temperature, and so forth. In this paper, combining the photovoltaic generation with wind power generation, the instability of an output characteristic each other was compensated. Photovoltaic generation and wind generation use Maximum Power Point Tracker (MPPT).

The Wind-solar complementary power supply system is a reasonable power supply which makes good use of wind and solar energy. This kind of power supply system can not only provide a bargain of low cost and high dependability for some inconvenient regions. In addition, the Wind/Solar complementary generation is more economical than a single PV or wind power generation in terms of both the cost and the protection of energy storage components. In stand-alone systems, sizing is extremely important since an adequate design lead to an efficient operation of the components with a minimum investment.

5.9.2 Modeling of Photo-Voltaic Hybrid Energy Conversion System

The construction of PV cell is very similar to that of the classical diode with a p-n junction formed by semiconductor material. When the junction absorbs light, the energy of absorbed photon is transferred to the electron-proton system of the material, creating charge carriers that are separated at the junction. The charge carriers in the junction region create a potential gradient, get accelerated under the electric field, and circulate as current through an external circuit. The solar cell is the basic building of the PV power system it produces about 1 W of power.

To obtain high power, numerous such cell are connected in series and parallel circuits on a panel (module), The solar array or panel is a group of a several modules electrically connected in series-parallel combination to generate the required current and voltage. The PV array must operate electrically at a certain voltage which corresponds to the maximum power point under the given operating conditions, i.e. temperature and irradiance. To do this, a maximum power point tracking (MPPT) technique should be applied. If the array is operating at voltage V and current I the operation point toward the maximum power point by periodically increasing or decreasing the array voltage, is often used in many PV systems. The configuration of hybrid wind and PV system is shown in Figure. This configuration is fit for stand-alone hybrid power system used in remote area. Wind and solar energy are converted into electricity and then sent to loads or stored in battery bank. The topology of hybrid energy system consisting of variable speed wind turbine coupled to a permanent magnet generator (PMG) and PV array. The two energy sources are connected in parallel to a common dc bus line through their individual dc-dc converters. The load may be dc connected to the dc bus line or may include a PWM voltage source inverter to convert the dc power into ac at 50 or 60 Hz. Each source has its individual control.



The output of the hybrid generating system goes to the dc bus line to feed the isolating dc load or to the inverter, which converts the dc into ac. A battery charger is used to keep the battery fully charged at a constant dc bus line voltage. When the output of the system is not available, the battery powers the dc load or discharged to the inverter to power ac loads, through a discharge diode. A battery discharge diode is to prevent the battery from being charged when the charger is opened after a full charge.

APPENDIX

Content beyond the Syllabus

A.5.1 MPPT SOLAR CHARGE CONTROLLERS

Maximum Power Point Tracking Solar Charge Controllers (MPPT) are different than the traditional PWM solar charge controllers in that they are more efficient and in many cases more feature rich. MPPT solar charge controllers allow solar panels to operate at their optimum power output voltage, improving their performance by as much as 30%. Traditional solar charge controllers reduce the efficiency of one part of your system in order to make it work with another. Read our MPPT charge controller blog to learn more about how you can maximize power output with MPPT Solar Charge Controllers! Several MPPT solar controllers can accept high input voltages (up to 600 DC) from your solar array and efficiently down convert the DC voltage to that of your system (e.g. 12, 24, 48VDC, etc) which means losing any generated power and you are able to use what you generate more efficiently.

Additionally, using a much higher DC voltage on the input side allows using thinner wire, decreasing wire cost and making installation easier. Choosing a well made charge controller is integral to the long life and efficiency of entire solar power system. By optimizing the power coming in from solar panels get that much closer to offsetting use of traditional on grid power sources and by protecting battery supply to protect from any unwanted and unneeded replacement costs. Solar charge controller is an item well worth investing in and researching as customize your solar panel electric system. Make sure to choose an option that is scalable and appropriate for power load and make sure that have sufficient battery storage space for the solar panels chosen to install.

A.5.2 SOLAR POWER MAXIMUM POWER POINT TRACKING WITH DIFFERENT BUCK-BOOST CONVERTER TOPOLOGIES

Solar energy is the most abundant resource on Earth, and is expected to become one of the primary energy supply resources in the future. Applications of solar energy are widespread in industrial, commercial, and military applications. However, effective use of solar energy depends on the technologies of solar power management systems. A power converter for maximal power point tracking (MPPT) and voltage or current regulation is inserted between the solar cell panel and the load to control power flow. This power converter directly affects the efficiency and performance of the solar power management system. To maximize the use of available solar power drawn from the solar panel and to widen the applications of solar energy, several studies have investigated the design and applications of buck-boost converters. The primary purpose is to establish a circuit simulation environment so that the performance of the buck-boost converters and MPPT systems can be evaluated quickly without the need of any hardware systems and instruments.

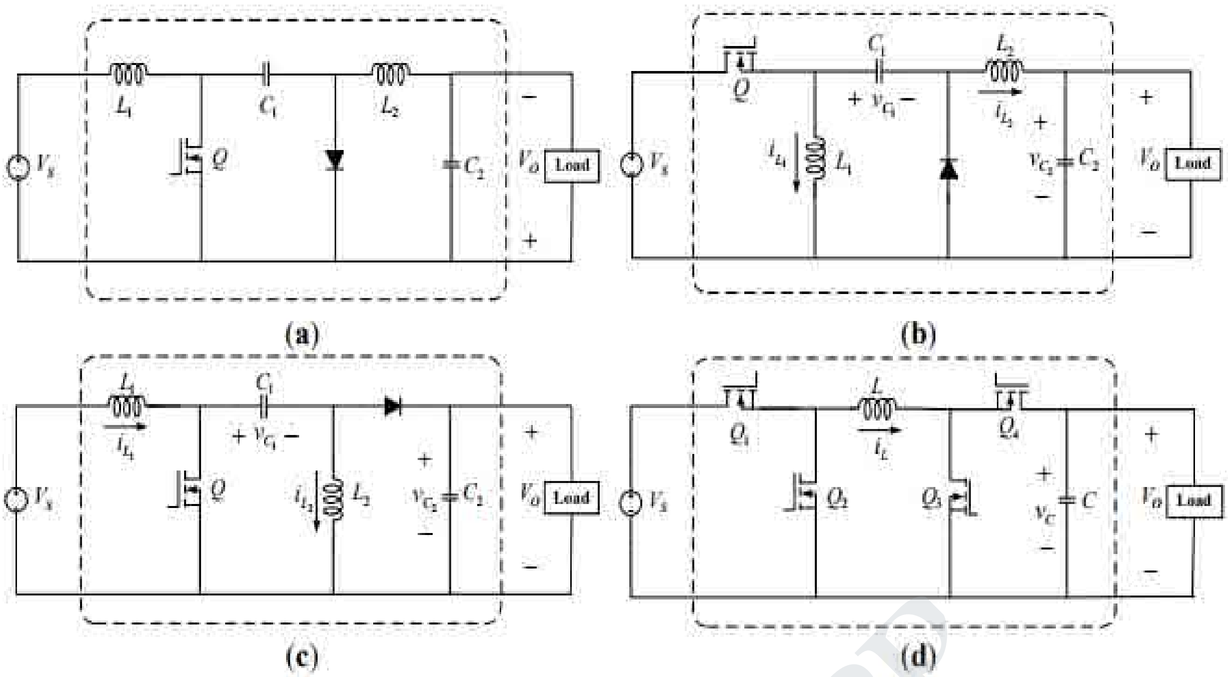


Figure: Buck-Boost Converters. (a) Cuk converter; (b) Zeta Converter; (c) SEPIC Converter; (d) Four-switch type converter.

The power converter is one of the essential elements for effective use of renewable power sources. This paper focuses on the development of a circuit simulation model for maximum power point tracking (MPPT) evaluation of solar power that involves using different buck-boost power converter topologies; including SEPIC, Zeta, and four-switch type buck-boost DC/DC converters. The circuit simulation model mainly includes three subsystems: a PV model; a buck-boost converter-based MPPT system; and a fuzzy logic MPPT controller. Dynamic analyses of the current-fed buck-boost converter systems are conducted and results are presented in the paper. The maximum power point tracking function is achieved through appropriate control of the power switches of the power converter.

Buck-Boost Converters

The buck-boost converter can convert the supply voltage source into higher and lower voltages at the load terminal. Several commonly used buck-boost converter topologies are shown in Figure. The Cuk converter is an inverting type power converter (output voltage polarity is reversed), and the Zeta, SEPIC, and four-switch type topologies represented in Figure are non-inverting buck-boost converters. The voltage at the load terminal is controlled by continuously adjusting the duty ratio of the power switch of the buck-boost converter. Zeta and SEPIC converters contain two inductors, two capacitors, a diode, and a metal-oxide-semiconductor field-effect transistor (MOSFET) power switch. In addition, the four-switch type converter is a synchronous buck-boost converter, containing an inductor, a capacitor, and four MOSFET power switches.

Buck-Boost Converter-Based MPPT System

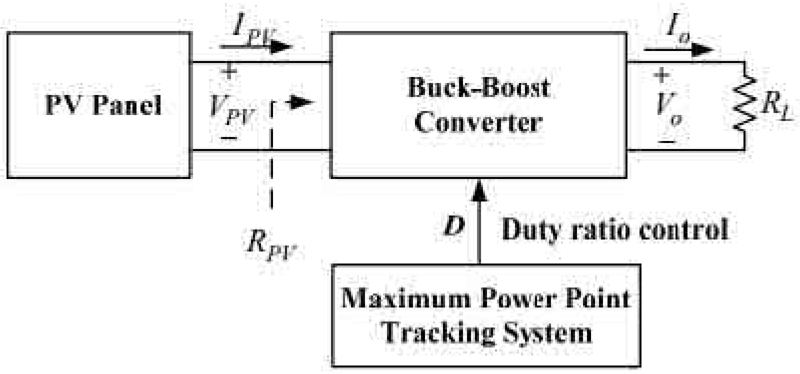


Figure: PV system with buck-boost converter incorporated

The operating point of the PV panel varies when the load condition varies. The maximum power point may be achieved through appropriate load selection. In most cases, the load is not likely to be optimal (regarding maximum power delivered from the PV panel). Maximum power from the PV panel may be attained by incorporating an intelligent mechanism to alter the load resistance observed from the PV panel. Power converters are widely used to adjust operating conditions to attain the maximum power point. Figure depicts the incorporation of a buck-boost converter into a PV system. The input voltage is controlled through appropriate adjustments of the duty ratio of the power switches of the converter.

EE3014 - POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS
UNIT-1

PART-A

1. List out the major factors influencing the amount of GHG emissions. (M.E-NOV/DEC2016)
   - Industrial revolutions
   - Deforestation
   - Fluorinated gases such as hydro fluorocarbon, per fluorocarbon, sulfur hexafluoride
   - Release of Carbon dioxide
   - Depletion of fossil fuels
2. Give any two environmental aspect of electric energy conversion. (APR/MAY2017) (M.E-NOV/DEC2013)
   - Increased atmospheric pollution
   - Depletion of fossil fuels
   - Reduction in sustainable development
3. What is SOFC? State its limitations. (M.E-NOV/DEC2016)
   A **solid oxide fuel cell** (or **SOFC**) is an electrochemical conversion device that produces electricity directly from oxidizing a fuel. Fuel cells are characterized by their electrolyte material; the SOFC has a solid oxide or ceramic electrolyte. Advantages of this class of fuel cells include high efficiency, long-term stability, fuel flexibility, low emissions, and relatively low cost. The largest disadvantage is the high operating temperature which results in longer start-up times and mechanical and chemical compatibility issues.
4. List the various renewable energy resources. (M.E-NOV/DEC2013)
   Biofuel, Biomass, Geothermal, Hydropower, Solar energy, Tidal power, Wave power, Wind power
5. List out the salient features of renewable energy resources. (M.E-NOV/DEC2010)
   - Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries.
   - Rapid deployment of renewable energy and energy efficiency is resulting in significant energy security, climate change mitigation, and economic benefits.
   - Renewable energy facilities generally require less maintenance than traditional generators.
   - Even more importantly, renewable energy produces little or no waste products such as carbon dioxide or other chemical pollutants, so has minimal impact on environment.
6. What is meant by spring and neap tides? (M.E-APR/MAY2013)

   During full or new moons which occur when the Earth, sun, and moon are nearly in alignment average tidal ranges are slightly larger. In this case, the gravitational pull of the sun is "added" to the gravitational pull of the moon on Earth, causing the oceans to bulge a bit more than usual. This means that high tides are a little higher and low tides are a little lower than average. These are called **spring tides**. Seven days after a spring tide, the sun and moon are at right angles to each other. When this happens, the bulge of the ocean caused by the sun partially cancels out the bulge of the ocean caused by the moon. This produces moderate tides known as **neap tides**, meaning that high tides are a little lower and low tides are a little higher than average. Neap tides occur during the first and third quarter moon, when the moon appears "half full."

7. How is a fuel cell characterized? (M.E-APR/MAY2013)

The fuel cell characterization is of particular importance to the fuel cell developers, scientists and researchers. Therefore, it is one of the most important topics of the fuel cell technology. Once the fuel cell is fabricated, it is required to access whether a fuel cell is good or bad from the pool of the developed cells. It is required to know whether the fuel cell is comparatively inferior or superior to the competitive cell either prepared by others or the improvement from the previous cells. In order to distinguish between inferior or superior fuel cell, the characterization techniques are very straight forward by using i-v characteristics of the fuel cell. The fuel cell characterization can be divided into two broad categories,

In-situ characterization: In–situ characterization means the fuel cell is fabricated and now you would like to performance of the fuel cell. You may also be interested to know how much losses are occurring in the fuel cell, quantity of the losses, location of the losses etc. Thus we have to characterize the fuel cell in the ready form. A few major in-situ characterization techniques are

1. Current voltage measurements
2. Current interruption technique
3. Cyclic voltammetry
4. Electrochemical impedance spectroscopy

Ex-situ characterization: Once we know that the performance of the fuel cell is not upto the desired standards then we have to find out the route cause. We need to identify the problematic component(s) as well as the reasons of ill-performance. Thus we need to characterize the component for its properties. Various characterization techniques may be followed depending upon the individual components of the fuel cell. A some of them are shown below,

Electrolyte: Proton conductivity; cross-over etc.

Bipolar plate: Mechanical and chemical strength; flow field design; electrical conductivity etc.

Catalyst: Surface area; selectivity etc.

Gas diffusion layer: Porosity; hydropholicity; hydrophilicity; strength etc.

8. What are fuel cells? (M.E-NOV/DEC2010)

A fuel cell is an electrochemical cell that converts the chemical energy from a fuel into electricity through an electrochemical reaction of hydrogen fuel with oxygen or another oxidizing agent. Fuel cells are different from batteries in requiring a continuous source of fuel and oxygen (usually from air) to sustain the chemical reaction, whereas in a battery the chemical energy comes from chemicals already present in the battery. Fuel cells can produce electricity continuously for as long as fuel and oxygen are supplied.

9. Justify how fuel cell becomes renewable energy source. (APR/MAY2017)

Fuel cells have the potential to be used for cogeneration of electricity and heat, covering thus the heat and power needs for domestic and other larger scale industrial applications, which is very interesting under the perspective of the steadily increased tendency for decentralized power production. Fuel cell systems are flexible regarding the power output and they can be used for the power production of electrical power in the region from 50 W to 100 MW. Specifically, the power output of small portable systems can be as low as a few watts, whereas in the case of biological fuel cells for medical applications the power output can be lower. They produce zero or very low emissions, especially Green House Gases (GHGs) depending on the fuel used.

10. Mention the use of a fuel cell. (ME-Nov/Dec17)
    - They produce zero or very low emissions, especially Green House Gases (GHGs) depending on the fuel used.
    - Modular in design, offering flexibility in size and efficiencies in manufacturing
    - Can be utilized for combined heat and power purposes, further increasing the efficiency of energy production
11. What are the contributions of GHG Emissions in renewable energy generation?
    The acceleration of GHG emissions indicates a mounting threat of runaway climate change, with potentially disastrous human consequences. The utilization of Renewable energy sources together with improvement of the energy end use efficiency can contribute to the reduction of primary energy consumption, to the mitigation of GHG emissions and thereby to the prevention of dangerous climate change.
12. What is hydrogen energy?
    Hydrogen has been identified as a potential zero emission energy carrier for the future, primarily transport sector. Hydrogen is an energy carrier but not an energy resource, and thus hydrogen must be produced. Hydrogen can be produced from coal, natural gas, propane gas, biomass and water. Some organic substances can be used for hydrogen production and they includes methanol synthesized via synthesis gas from natural gas and coal.
13. Define solar insolation.
    Solar insolation is a measure of solar radiation energy received on a given surface area in a given time. It is commonly expressed as average irradiance in watts per square meter or kilowatt-hours per square meter per day. In the case of photovoltaics it is commonly measured as kilowatt hours per year per kilowatt peak rating.

UNIT-2

PART-A

1. Define reference theory. (M.E-NOV/DEC2013)
   The reference frame theory is a powerful tool for the analysis of electrical machines and it helps in the design of sophisticated control techniques. By using the reference frame theory, it is possible to transform the phase variable machine description to another reference frame. Moreover, this theory reduces the complexity involved in the modeling of electrical machines.
2. Write the significance of reference theory. (APR/MAY2017)

The voltage equations that describe the performance of induction and synchronous machines are functions of the rotor speed, whereupon the coefficients of the differential equations that describe the behavior of these machines are time varying except when the rotor is stalled. A change of variables is often used to reduce the complexity of these differential equations. This general transformation refers machine variables to a frame of reference that rotates at an arbitrary angular velocity. This transformation is set forth because many of its properties can be studied without the complexities of machine equations. By this approach, many of basic concepts and interpretations of this general transformation are readily and concisely established.

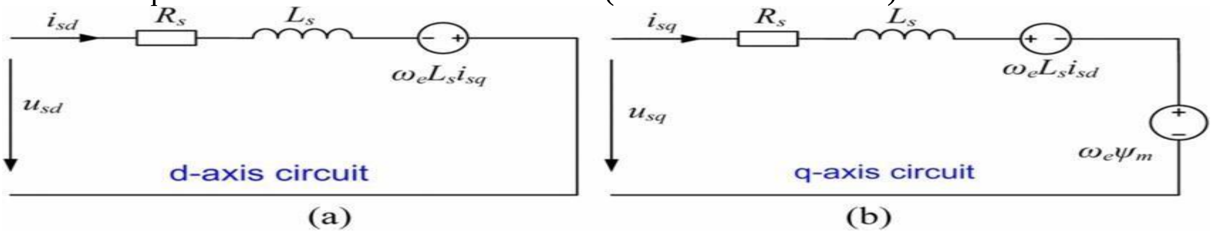
3. Why are induction generators preferred over DC generators in WECS?
   (M.E-NOV/DEC2016) (M.E-APR/MAY2013)
   - Simple and robust construction.
   - Can run independently.
   - Inexpensive.
   - Minimal maintenance.
   - Inherent overload protection.
   - At high speed, reduces size and weight of machine and filter components.
4. What is the principle of operation of induction generator? (M.E-NOV/DEC2010)

   An induction generator or asynchronous generator is a type of alternating current (AC) electrical generator that uses the principles of induction motors to produce power. Induction generators operate by mechanically turning their rotors faster than synchronous speed. A regular AC asynchronous motor usually can be used as a generator, without any internal modifications. Induction generators are useful in applications such as mini hydro power plants, wind turbines, or in reducing high-pressure gas streams to lower pressure, because they can recover energy with relatively simple controls. An induction generator usually draws its excitation power from an electrical grid; sometimes, however, they are self-excited by using phase-correcting capacitors. Because of this, induction generators cannot usually "black start" a de-energized distribution system.

5. Name any four types of generators used in wind energy conversion systems.
   (APR/MAY2017)

Induction generator, Permanent Magnet synchronous generator, Squirrel cage induction generator, doubly fed induction generator

6. Draw the equivalent circuit model of a PMSG. (M.E-NOV/DEC2016)



7. What are the merits of squirrel cage induction generator for wind energy conversion? (M.E-NOV/DEC2010)
   - The low cost and low maintenance requirements of induction generators.
   - Another advantage is that it can be on the ground, completely separate from the wind machine. If there is a problem in the converter, it could be switched out of the circuit for repair and the wind machine could continue to run at constant speed.
8. What is meant by DFIG? (M.E-NOV/DEC2013)
   DFIG for Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. It is possible to avoid the multiphase slip ring assembly. The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed.
9. What are the constructional differences between SCIG and DFIG? (M.E-APR/MAY2013)

SCIG	DFIG
Only stator is connected to electrical source	Both rotor and stator are connected to electrical sources
Rotor is made up of solid conducting bars embedded in the slots of a magnetic core	The rotor has three phase windings which are energized with three phase currents

10. Define tip-speed ratio.
    The tip-speed ratio, X, or TSR for wind turbines is the ratio between the tangential speed of the tip of a blade and the actual speed of the wind. The tip-speed ratio is related to efficiency, with the optimum varying with blade design. Higher tip speeds result in higher noise levels and require stronger blades due to large centrifugal forces.

$$\lambda = \frac{\text{Tip speed of blade}}{\text{wind speed}}$$

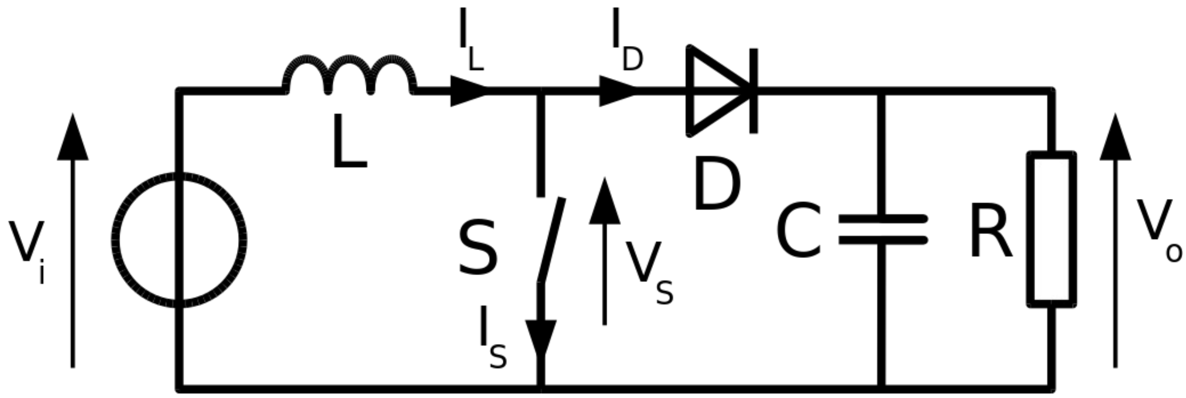
11. What is meant by pitch angle control?
Blade pitch control is a feature of nearly all large modern horizontal-axis wind turbines. While operating, a wind turbine's control system adjusts the blade pitch to keep the rotor speed within operating limits as the wind speed changes. Feathering the blades stops the rotor during emergency shutdowns, or whenever the wind speed exceeds the maximum rated speed. During construction and maintenance of wind turbines, the blades are usually feathered to reduce unwanted rotational torque in the event of wind gusts.

UNIT-3

PART-A

1. What are the advantages of boost and buck converters? (M.E-NOV/DEC2013)
Advantages of buck converter:
   - It has high efficiency
   - di/dt of the load current is reduced by inductor L
   - This circuit requires only one transistor.

   Advantages of boost converter:
   - Input current is continuous
   - This regulator can step up the output voltage
2. Draw the schematic of boost converter. (M.E-NOV/DEC2010)



3. What is the function of boost converter in solar photovoltaic system? (APR/MAY2017)
It is connected between PV panel and DC load. The main function of boost converter is to boost (step up) the output voltage of PV panel so that it can drive the load.
4. What are the factors to be considered for the selection of batteries for solar energy conversion system? (M.E-NOV/DEC2016)
   - Battery voltage
   - Battery capacity
   - Battery life cycle
   - State of charge (SOC)
   - Depth of discharge (DOD) (70-80% of DOD)
   - Discharge rate
   - Self discharge
5. What are the advantages of dc link inverters? (M.E-APR/MAY2013)
   - Lossless turn-on and turn-off of all devices

- Switching loss is less
- High efficiency up to 95%

6. What is a grid interactive inverter? State its significance. (M.E-NOV/DEC2016)
    - It acts as an interface that converts dc current produced by the solar cells into utility grade ac current.
    - The inverters must produce good quality sine wave output, must follow the frequency and voltage of the grid, and must extract maximum power from the solar cells with the help of MPPT.
    - The inverter input stage varies the input voltage until the maximum power point on the I-V curve is found.
    - The inverter must monitor all the phases of the grid, and inverter output must be controlled in terms of voltage and frequency variation.
7. What is meant by matrix converters? (APR/MAY2017) (M.E-NOV/DEC2013) (M.E-NOV/DEC2010)
    Matrix converter is capable of direct conversion from AC to AC by using bidirectional fully controlled switches. The matrix converter arranges semiconductor switches into a matrix configuration and controls them to convert an input AC voltage directly into the desired AC voltage.
8. Where is matrix converters used? (M.E-APR/MAY2013)
    - m phase to n phase conversion
    - All silicon motor drives with capability of regeneration
    - Grid interface for non conventional energy sources
    - Variable voltage, variable frequency power supplies
9. What is line commutated inverter?
    The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. The controlled rectifier can provide controllable output dc voltage in a single unit. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output dc voltage is obtained by controlling the conduction interval of each thyristor. This method is known as phase control and converters are also called “phase controlled converters”. Since thyristors can block voltage in both directions it is possible to reverse the polarity of the output dc voltage and hence feed power back to the ac supply from the dc side. Under such condition the converter is said to be operating in the “inverting mode”. The thyristors in the converter circuit are commutated with the help of the supply voltage in the inverter mode of operation and are known as “Line commutated inverter”.
10. Define the photo conversion efficiency of the PV cell.
    The photo conversion efficiency of the PV cell is defined as the following:

    $$\eta = \frac{electrical\ \ power\ \ output}{solar\ power\ impinging the\ cell}$$

    Obviously, the higher the efficiency, the higher the output power we get under a given illumination.
11. What is the inversion mode operation of line commutated inverter?
    The driver circuit has to be changed to shift the firing angle from rectifier operation ($0<\alpha<90^0$) to inverter operation ($90^0<\alpha<180^0$).
12. What is the basic requirement of PV array sizing?

Maintain the energy balance over the specified period. The energy drained during lean times must be made up by the positive balance during the remaining time of the period.

UNIT-4

PART-A

1. Differentiate between fixed and variable speed wind energy conversion systems. (APR/MAY2017) (M.E-NOV/DEC2016) (M.E-NOV/DEC2010)

- For a fixed speed wind turbine, the generator is connected to the grid directly operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency.
- For a variable speed wind turbine the generator is connected to the grid through power electronics equipments. The rotor speed has the possibility to be controlled by those equipments.

2. What is meant by energy payback period? (M.E-APR/MAY2013)

The Energy Pay Back Time is defined by EPBT = E_{input}/E_{saved}, where E_{input} is the energy input during the module life cycle (which includes the energy requirement for manufacturing, installation, energy use during operation, and energy needed for decommissioning) and E_{saved} the annual energy savings due to electricity generated by the solar PV module.

3. What are the issues in connecting the renewable energy systems to the grid? (M.E-NOV/DEC2016)
   - Local issues: capacity, voltage control and stability, harmonics.
   - Large area issues: balance of power, transmission capacity.
4. List out the grid connection issues. (M.E-NOV/DEC2013)
   - Harmonics
   - Frequency and voltage fluctuations
   - Islanding issues
5. What are the major problems associated with grid integration of wind energy system? (APR/MAY2017)

   If the penetration of wind power into the grid is continuously increased, it might reach to a level where economics of the total power production is affected in a negative way. This will limit the penetration of wind power into the grid. The optimum penetration depends on specific circumstances and characteristics of the utility system. For higher power penetration, total electricity production system is to be re-optimized. This may require integration of some more peak load units or storage capacity plants. Also the distance of wind resource from the grid poses another limiting factor as it influences the economics of wind power.
6. Define grid integrated solar system. (M.E-NOV/DEC2013)

A grid-connected photovoltaic power system or grid-connected PV power system is an electricity generating solar PV power system that is connected to the utility grid. A grid-connected PV system consists of solar panels, one or several inverters, a power conditioning unit and grid connection equipment. They range from small residential and commercial rooftop systems to large utility-scale solar power stations. Unlike stand-alone power systems, a grid-connected system rarely includes an integrated battery solution, as they are still very expensive. When conditions are right, the grid-connected PV system supplies the excess power, beyond consumption by the connected load, to the utility grid.

7. What will happen if no load is connected to a solar PV system?
   (M.E-APR/MAY2013)
   At no load the solar cell will be operating in open circuit condition. If there is internal shunting resistance it will slightly load the solar cell. This shunt resistance must be high enough such that it will not cause an appreciable loss of the photo voltaic power. The terminal open circuit voltage given in data sheet is measured with the shunt is present. Open circuit condition means that the there is no load connected to the cell. Under this condition the photo generated electrical power will be dissipated in the cell causing some temperature rise compared to the maximum operating power condition.
8. List out the issues to be addressed while integrating the solar PV systems with grid.
   (M.E-NOV/DEC2010)
   - Islanding
   - Variations in frequency
   - Harmonics
9. What is islanding?
   Islanding is the condition in which a distributed generator continues to power a location even though power from the electric utility grid is no longer present. Islanding can be dangerous to utility workers, who may not realize that a circuit is still powered, even though there is no power from the electrical grid. For that reason, distributed generators must detect islanding and immediately stop producing power; this is referred to as anti-islanding.
10. Define Fill Factor
    The Fill Factor (FF) which indicates the quality of PV cell is defined as the ratio of peak power to the product of open circuit voltage and short circuit current.
    $FF = (V_m I_m) / (V_{OC} I_{SC})$
11. What is the role of back to back converter in wind energy conversion system?
    It is an AC/DC/AC converter which is widely used in renewable energy systems. For example, in a variable speed wind energy conversion system the general function of AC/DC/AC converter is to transmit the power generated from wind turbines to the grid. The converter should provide good abilities to transmit power effectively, respond quickly and accurately, and operate stably in potential extreme conditions.
12. What is inrush current?
    The small unavoidable difference between the site and the grid voltages will result in an inrush current to flow between the site and the grid. The inrush current eventually decays to zero at an exponential rate that depends on the internal resistance and inductance.
13. What is the main objective of MPPT converter in grid system?

- Capture the maximum available power from the solar panel whatever the condition of the climate.
- Step up the PV panel voltage to the required level of DC voltage in order to transfer

the captured power from the solar to the grid through inverter.

UNIT-5

PART-A

1. What is need of hybrid systems? (M.E-NOV/DEC2016) (M.E-NOV/DEC2013) (M.E-APR/MAY2013)
    - Rapid depletion of fossil fuels has necessitated an urgent need for alternative sources of energy to cater the continuously increasing energy demand.
    - Another key reason to reduce our consumption of fossil fuels is the growing global warming phenomena. Environmentally friendly power generation technologies will play an important role in future power supply.
    - The renewable energy technologies include power generation from renewable energy sources, such as wind, PV(photovoltaic), MH(micro hydro), biomass, ocean wave, geothermal and tides. In general, the key reason for the deployment of the above energy systems are their benefits, such as supply security, reduced carbon emission, and improved power quality, reliability and employment opportunity to the local people.
    - Since the RE resources are intermittent in nature therefore, hybrid combinations of two or more power generation technologies, along with storage can improve system performance.
    - Hybrid Renewable Energy System (HRES) combines two or more renewable energy resources with some conventional source (diesel or petrol generator) along with storage, in order to fulfil the demand of an area.
    - Hybrid energy systems oftentimes yield greater economic and environmental returns than wind, solar, geothermal or tri-generation stand-alone systems by themselves.
2. What are the advantages of hybrid renewable energy systems? (APR/MAY2017)
    - Higher total energy efficiency
    - More reliable
    - Operational flexibility
    - Lower emission
3. What are the advantages of PV-Diesel hybrid system? (M.E-NOV/DEC2016)
    The diesel generator can supply the load directly, therefore improving the system efficiency and reducing the fuel consumption.
    No switching of ac power between different energy sources is required, which simplifies the electrical output interface.

The system load can be met in an optimal way.
Efficiency is high.
Fuel consumption is reduced.

4. Give the range of hybrid systems. (M.E-NOV/DEC2013)
    - Control methods are complex.
    - Power conditioning system design is quite difficult.
5. Name the various types of hybrid energy systems. (M.E-APR/MAY2013)
    - PV-wind hybrid system
    - PV-diesel hybrid system
    - Wind-PV hybrid with diesel
    - Biomass-wind-fuel cell hybrid system.
6. What is the importance of Maximum Power Point Tracking (MPPT) in the operation of a photovoltaic system? (APR/MAY2017)
    The daily solar irradiation diagram has abrupt variations during the day. Under these conditions, the MPP of the PV array changes continuously; consequently the PV system's operation point must change to maximize the energy produced. An MPPT technique is therefore used to maintain the PV array's operating point at its maximum power point.
7. What are Hybrid Renewable Energy Systems? (M.E-NOV/DEC2010)
    Hybrid Renewable Energy System (HRES) combines two or more renewable energy resources with some conventional source (diesel or petrol generator) along with storage, in order to fulfil the demand of an area. Hybrid energy systems oftentimes yield greater economic and environmental returns than wind, solar, geothermal or tri-generation stand-alone systems by themselves.
8. What are the types of PV-diesel hybrid systems?
    - Series hybrid energy systems
    - Switched hybrid energy systems
    - Parallel hybrid energy systems
9. List the various MPPT techniques
    - Constant voltage method
    - Hill climbing
    - Perturb and observe methods
    - Incremental conductance method
    - Neural network
    - Fuzzy logic control
10. What are the various stages adopted in fuzzy logic control?
    - Fuzzification
    - Rule based table lookup
    - Defuzzificztion

QUESTION BANK - PARTB

UNIT-1

PART-B

1. What are the different types of fuel cells? Explain them with neat diagrams. (M.E-NOV/DEC2016)

Basically fuel cell in common language is a device which converts chemical energy from a fuel into electrical energy. It happens by undergoing a chemical reaction where positively charged hydrogen ions react with oxygen or any other oxidizing agent by an electrochemical process. The fuel cell consists of two electrodes where the reaction takes place; one is positively charged called anode and the negatively charged called cathode.

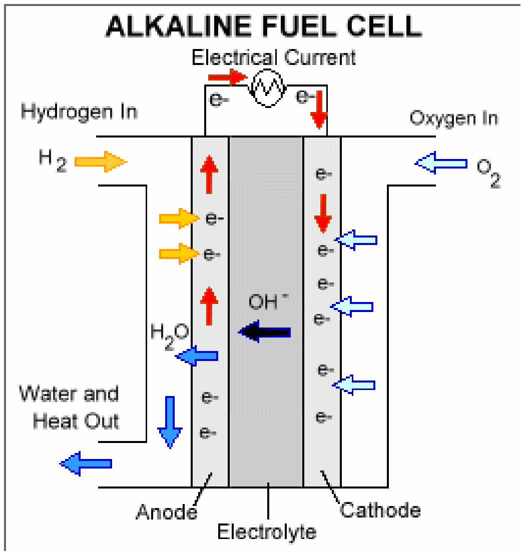
A single fuel cell consists of an electrolyte sandwiched between those two thin electrodes anode and cathode. This electrolyte and a catalyst are needed to fasten the reaction rate and to mobilise the ions to one electrode to the other. The electrons from the anode side of the cell cannot pass through the membrane to the positively charged cathode; they must travel around it via an electrical circuit to reach the other side of the cell. This movement of electrons is an electrical current. The amount of power produced by a fuel cell depends upon several factors, such as fuel cell type, cell size, the temperature at which it operates, and the pressure at which the gases are supplied to the cell A single fuel cell generates a tiny amount of direct current (DC) Electricity. Many fuel cells are usually assembled into a stack. Cell or stack, the principles are the same.

On the basis of the electrolyte used the fuels cell can be classified as Follows:-

1. Alkaline Fuel Cell-alkaline solution electrolyte such as KOH.
2. Phosphoric Acid Fuel Cells (PAFC)-electrolyte is phosphoric acid.
3. Solid Proton Exchange Membrane Fuel Cell-electrolyte is polymer electrolyte membrane fuel cells and their electrolyte consists of the proton exchange membrane.
4. Molten Carbonate Fuel Cells-electrolyte as molten carbonate.
5. Solid Oxide Fuel Cells (SOFC)-electrolyte is ceramic ion conducting electrolyte in solid oxide form.
6. Regenerative Fuel Cell

Alkaline Fuel Cells (AFC)

The alkaline fuel cell uses an alkaline electrolyte such as 40% aqueous **potassium hydroxide**. In alkaline fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons. It was originally used by NASA on space missions. NASA space shuttles use Alkaline Fuel Cells. Alkaline fuel cells (AFCs) were one of the first fuel cell technologies developed, and they were the first type widely used in the U.S. space program to produce electrical energy and water onboard spacecraft. These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. AFCs are high-performance fuel cells due to the rate at which chemical reactions take place in the cell. They are also very efficient, reaching efficiencies of 60 percent in space applications. The disadvantage of this fuel cell type is that it is easily poisoned by carbon dioxide (CO2). In fact, even the small amount of CO2 in the air can affect the cell's operation, making it necessary to purify both the hydrogen and oxygen used in the cell. CO2 can combine with KOH to form potassium carbonate which will increase the resistance. The purification process is costly.



Anode Reaction: $2H_2 + 4OH^-$ → $4H_2O + 4e^-$
Cathode Reaction: $O_2 + 2H_2O + 4e^-$ → $4OH^-$

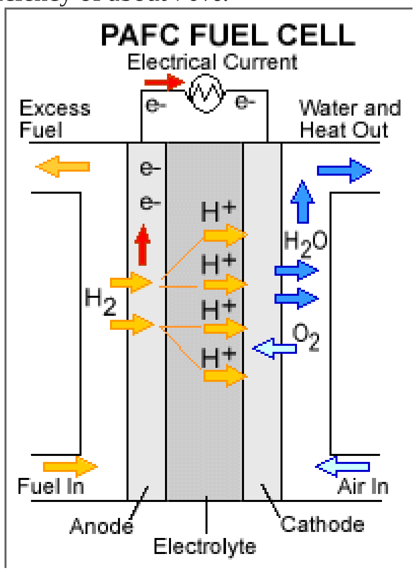
Phosphoric Acid Fuel Cells (PAFC)

A phosphoric acid fuel cell (PAFC) consists of an anode and a cathode made of a finely dispersed platinum catalyst on carbon and a silicon carbide structure that holds the phosphoric acid electrolyte. In phosphoric acid fuel cells, protons move through the electrolyte to the cathode to combine with oxygen and electrons, producing water and heat.

The phosphoric acid fuel cell (PAFC) is considered the "first generation" of modern fuel cells. It is one of the most mature cell types and the first to be used commercially, with over 200 units currently in use. This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses.

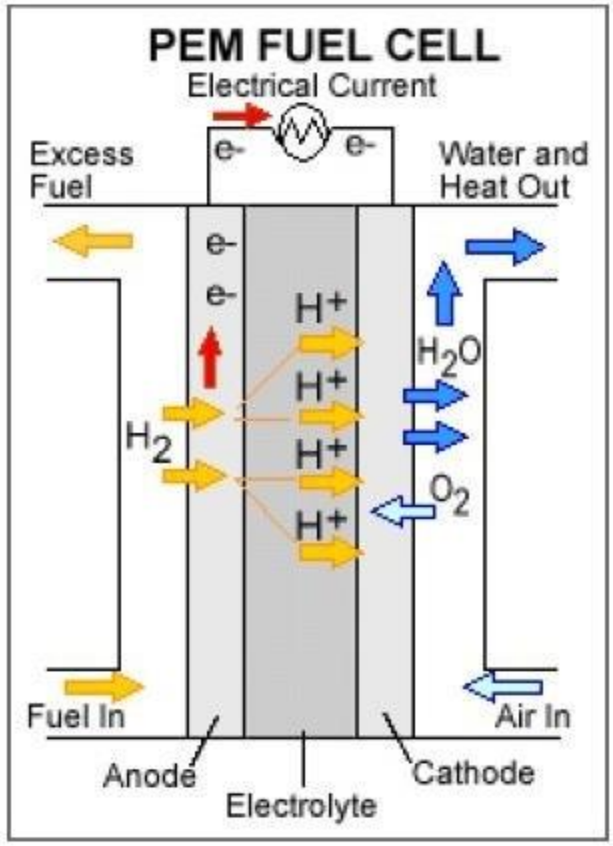
Anode reaction: $2H_2 \rightarrow 4H^+ + 4e^-$
Cathode reaction: $O_2\,(g) + 4H^+ + 4e^- \rightarrow 2H_2O$
Overall cell reaction: $2\,H_2 + O_2 \rightarrow 2H_2O$

PAFCs are CO2-tolerant and even can tolerate a CO concentration of about 1.5 percent, which broadens the choice of fuels they can use. They have an efficiency of about 70%.



Solid Proton Exchange Membrane Fuel Cell

In polymer electrolyte membrane (PEM) fuel cells, protons move through the electrolyte to the cathode to combine with oxygen and electrons, producing water and heat. Polymer electrolyte membrane (PEM) fuel cell uses a polymeric membrane as the electrolyte, with platinum electrodes. These cells operate at relatively low temperatures. These cells are the best candidates for cars, for buildings and smaller applications. Polymer electrolyte membrane (PEM) fuel cells—also called proton exchange membrane fuel cells—deliver high power density and offer the advantages of low weight and volume, compared to other fuel cells. PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst.



Anode: $H_2 = 2H^+ + 2e^-$

Cathode: $\frac{1}{2} O_2 + 2H^+ + 2e^- = H_2O$

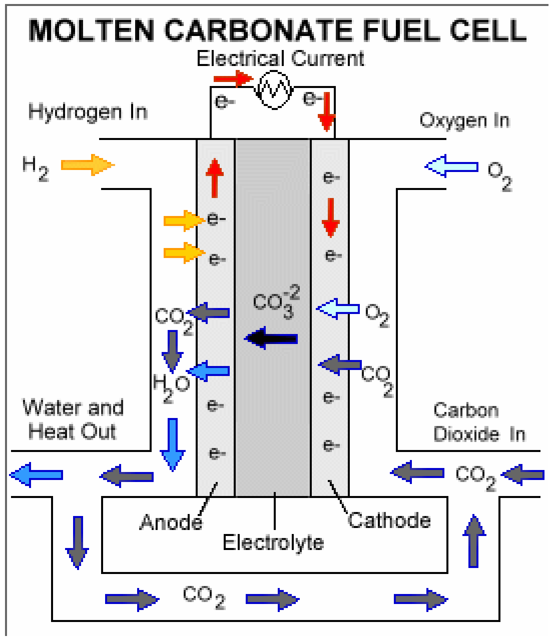
<u>**Molten Carbonate Fuel Cells (MCFC):**</u>

The molten carbonate fuel cell uses a **molten carbonate salt as the electrolyte.** It has the potential to be fuelled with coal- derived fuel gases, methane or natural gas. These fuel cells can work at up to 60% efficiency In molten carbonate fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons. Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications.

Anode Reaction: $CO_3^{2-} + H_2 \rightarrow H_2O + CO_2 + 2e^-$

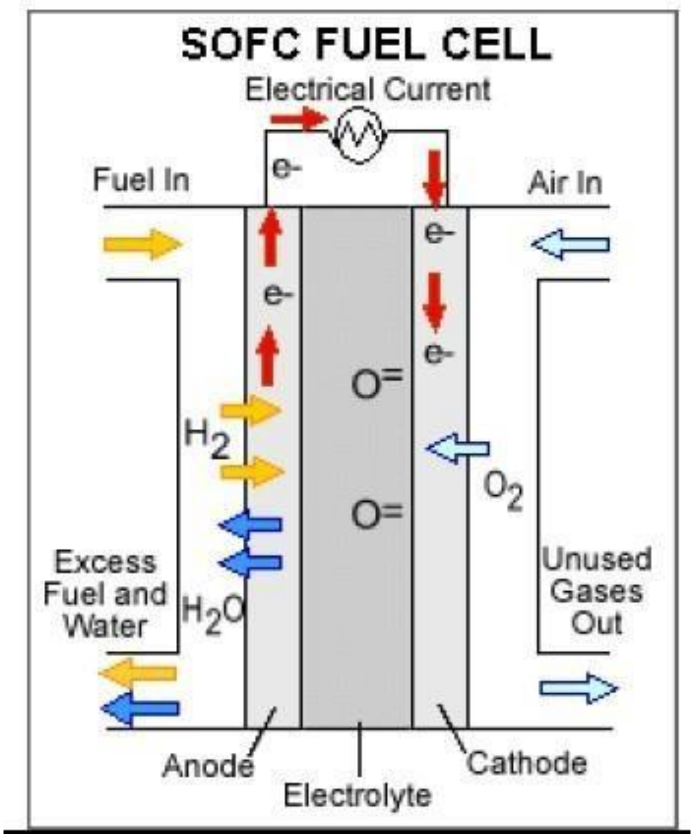
Cathode Reaction: $CO_2 + \frac{1}{2}O_2 + 2e^- \rightarrow CO_3^{2-}$

Overall Cell Reaction: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$



Solid Oxide Fuel Cells (SOFC)

They use a solid ceramic electrolyte, such as zirconium oxide stabilised with yttrium oxide, instead of a liquid and operate at 800 to 1,000°C. In solid oxide fuel cells, negative ions travel through the electrolyte to the anode where they combine with hydrogen to generate water and electrons. Efficiencies of around 60 per cent and are expected to be used for generating electricity and heat in industry and potentially for providing auxiliary power in vehicles. Since the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical of other fuel cell types.



REGENERATIVE FUEL CELL

If a fuel cell is a device that takes a chemical fuel and consumes it to produce electricity and a waste product, an RFC can be thought of as a device that takes that waste product and electricity to return the original chemical fuel. Indeed any fuel cell chemistry can be run in reverse, as is the nature of oxidation reduction reactions.

When you run a fuel cell in reverse, the anode becomes the cathode and the cathode becomes the anode. The mechanics of an electrolyser are best understood using the hydrogen fuel cell as an example. In a hydrogen fuel cell, the goal is to consume hydrogen and oxygen to generate water and an electric current that can be used to perform work. The oxidation reaction occurs at the anode, breaking down hydrogen H2 gas into positive hydrogen ions and negative electrons. The reduction reaction occurs at the cathode combining hydrogen and oxygen and electrons into water. An external wire between the anode and the cathode completes the circuit, allowing electrons to flow from the anode to the cathode. This current can be used to supply useful work. By contrast, supplying a current and reversing the polarities of the electrodes in the hydrogen fuel cell results in a regenerative hydrogen fuel cell. The electrode that was once the cathode is now the anode; it oxidizes water decomposing it into oxygen gas O2, hydrogen ions and electrons. The electrode that was once the anode is now the cathode; it reduces hydrogen and electrons into hydrogen gas. The external current will have to be supplied from a power source, like a solar cell.

$$H2 + ½O_2 \rightarrow H_2O$$

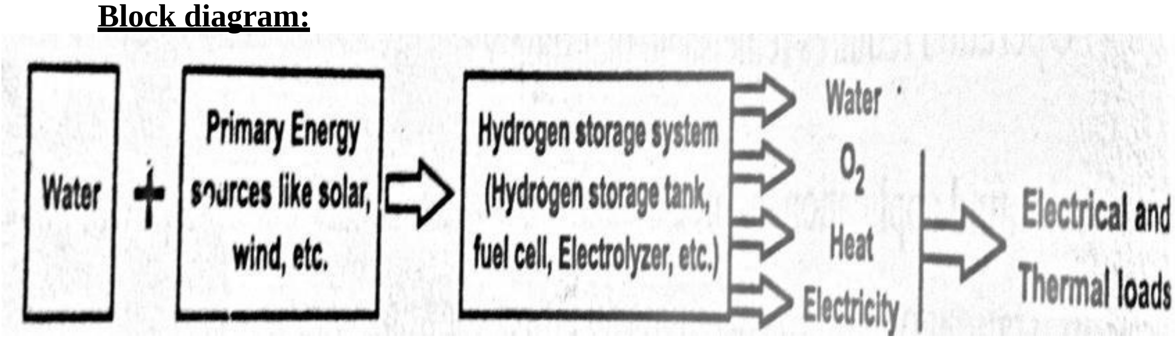
Fuel Cell Efficiency

Since fuel cells use materials that are typically burnt to release their energy, the fuel cell efficiency is described as the ratio of the electrical energy produced to the heat that is produced by burning the fuel. From the basic definition of efficiency: $\eta = W / Q_{in}$

2. What is Hydrogen energy? Explain the operation of hydrogen energy system with a neat schematic. (APR/MAY 2017) (M.E-NOV/DEC 2010)

   Hydrogen has been identified as a potential zero-emission energy carrier for the future, primarily for the transport sector. Hydrogen is a very efficient and clean fuel. Its combustion will produce no greenhouse gases, no ozone layer depleting chemicals, little or no acid rain ingredients and pollution. Hydrogen is an energy carrier but not an energy resource, and thus hydrogen must be produced. It can be produced from coal, natural gas, propane gas, biomass and water. Some organic substances can be used for hydrogen production and they includes methanol synthesized via synthesis gas from natural gas and coal, ethanol made from biological fermentation of crops and biomass etc. For some special applications, hydrogen containing inorganic compounds such as ammonia and hydrogen sulphide have also been considered as source compounds for hydrogen production. The cost of hydrogen production is an important issue. Hydrogen produced by steam reformation costs approximately three times the cost of natural gas per unit of energy produced. Hydrogen storage is an obstacle for the introduction of hydrogen in the transportation sector. There are three options- compressed gas, liquefied gas and hydrogen stored inside pores in solid, porous materials. None of these are satisfactory.

Block diagram:



Conversion of Hydrogen Energy into Electricity:

Hydrogen gas is an expensive and complex fuel to make because it has to be separated from whatever element it is joined to. It often takes a lot of energy to make hydrogen gas, making it a costly power source. There are a number of ways to separate hydrogen from its companion elements.

Before we look at how hydrogen is converted into electricity, it would be beneficial to know how hydrogen is produced. Hydrogen is produced using two main methods; steam reforming and electrolysis (commonly referred to as water splitting).

Steam reforming

This method produces hydrogen from hydrocarbon fuels such as methane, oil, renewable liquid fuels, gasified biomass, gasified coal and natural gas. A processing device called a reformer is used in this hydrogen production process. The reformer react steam with the hydrocarbon fuels at extremely high temperatures to generate hydrogen. Today, over 90% of hydrogen gas is produced using the steam reforming technique.

Electrolysis

Electrolysis is a method that utilizes direct current (DC) to instigate a chemical reaction. In the production of hydrogen, electrolysis decomposes water and splits it into its main elements, which are hydrogen and oxygen by use of an electric current. The electricity used in the electrolysis process can be derived from fossil fuels such as oil, natural gas, and coal or hydrocarbons.

Fuel Cells:

The most effective way to convert hydrogen into oxygen is using a fuel cell. A fuel cell converts chemical energy into electrical energy. A fuel cell enables hydrogen and oxygen to blend in an electrochemical reaction. The result is production of electricity, water, and heat. Fuel cells mimic batteries since they both convert the energy generated by the electrochemical reaction into useful electric power. Nonetheless, the fuel cell will generate electric power as long as fuel, mainly hydrogen, is available.

Fuel cells represent a potential technology for use a source of electricity and heat for buildings. It's also a promising source of power for electric and hybrid vehicles. Fuel cells function best on pure hydrogen. However, other fuels such as gasoline, methanol, or natural gas can be reformed to generate the needed hydrogen for fuel cells.

With technology moving fast, hydrogen could come on par with electricity as a vital energy carrier. An energy carrier transmits energy to the customer in a ready to use form. Some renewable energy sources such as wind and sun may not be able to generate energy around the clock, but are able to produce hydrogen and electric power and stored for later use.

Issues regarding storage include

- Operating pressure and temperature
- Life span of storage material
- Requirements of hydrogen purity imposed by fuel cell
- Reversibility of hydrogen uptake and release
- Refuelling conditions of rate and time
- Hydrogen delivery pressure
- Overall safety, toxicity and cost

Advantages:

- High energy yield
- Most abundant element
- Produced from many primary energy sources
- Most versatile fuel

Disadvantages:

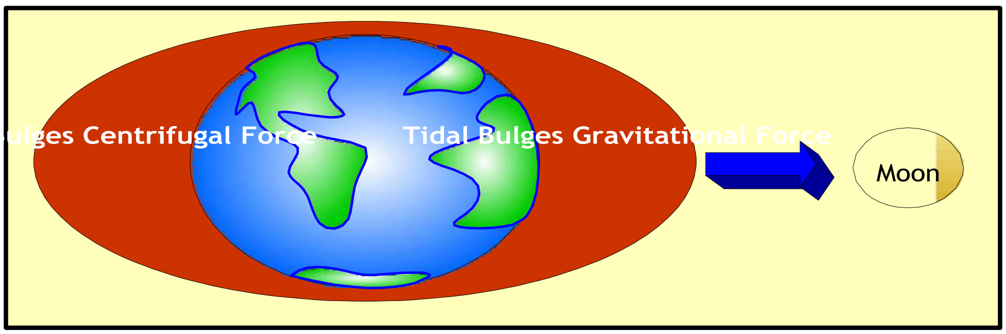
- Low density (large storage area)
- Not found free in nature
- Low ignition energy
- Currently expensive

3. Enumerate the prospects of ocean energy. (M.E-APR/MAY 2013) (M.E-NOV/DEC 2010)

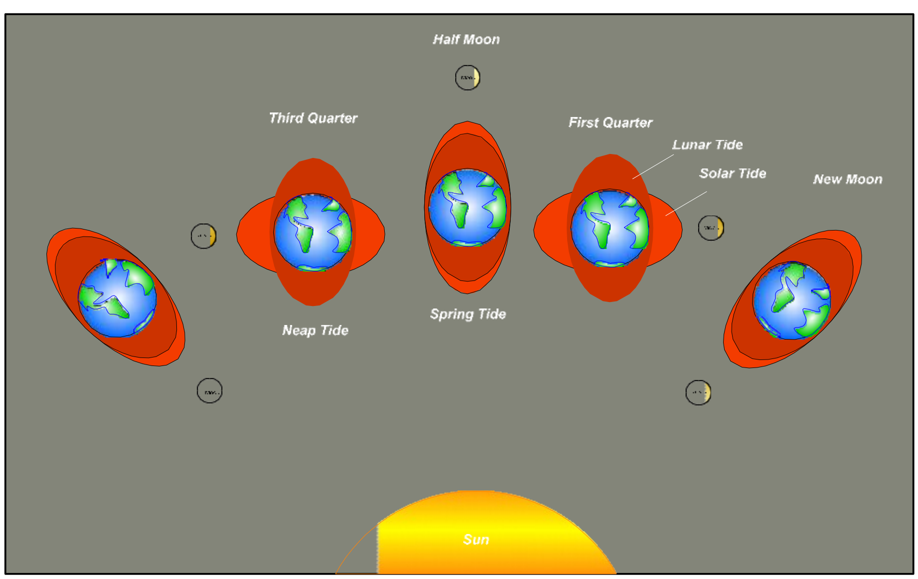
From the oceans we can harvest: thermal energy, from the temperature difference of the warm surface waters and the cool deeper waters, as well as potential and kinetic energy, usually lumped as mechanical energy, from the tides, waves and currents. The technological concept to harvest the thermal energy in the ocean is universally called Ocean Thermal Energy Conversion (OTEC). The basic electric generation systems are: *closed-cycle, open-cycle*, and *hybrid.* Oceans mechanical energy is very different from the oceans thermal energy. Tides are driven primarily by the gravitational pull of the moon, waves are driven primarily by the winds and ocean currents are even more complex driven by solar heating and wind in the waters near the equator, also by tides, salinity and density of the water. For these reasons tides, waves and currents are intermittent sources of energy, while ocean thermal energy is quite constant. The electricity conversion of all three usually involves mechanical devices. This Ocean Energy Resource section is organized in terms of the energy resource. We will discuss in order; tides, currents, thermal and waves.

Tides

The interaction of the sun-moon-earth system causes ones of the strangest phenomena: *tides*. Tides rise and fall is the product of the gravitational and centrifugal forces, of primarily the moon with the earth. The gravitational forces maintain the moon on its positions with respect to the earth, forcing to pull the earth and the moon together see Figure. The centrifugal force acts on the opposite direction pulling the moon away from the earth. These two forces act together to maintain the equilibrium between these two masses. The influence of the sun can be included on the balance of the entire system. The distance plays an important role on the development of the tides. Based on the Newton's laws, the gravitational force is proportional to the square of the distance of two bodies, but the tidal force is proportional to the cube of the distance. For this reason although the moon has a much smaller mass than the sun it is much closer to the earth. The moon effect is 2¼ greater than that of the sun on the generation of tides.



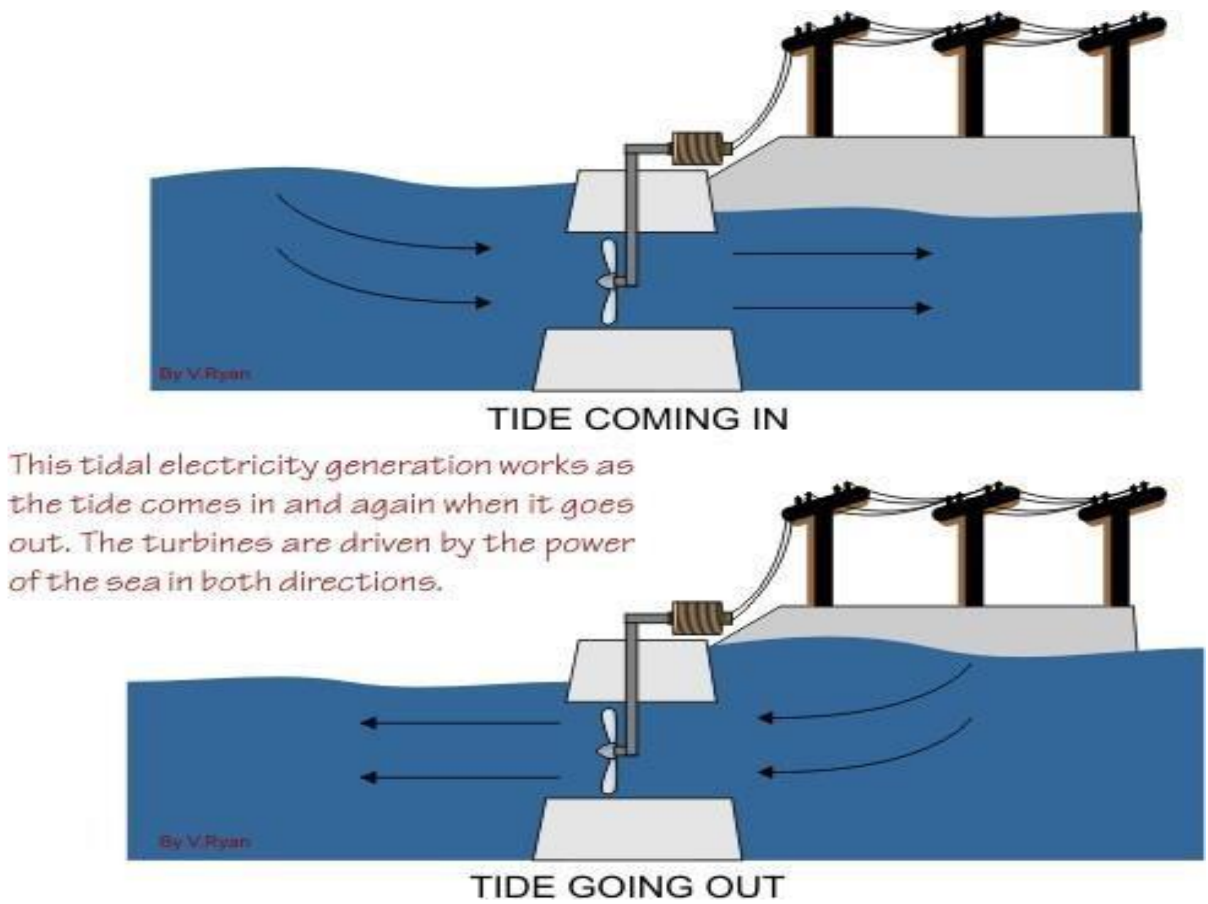
The gravitational force of attraction of the moon causes that the oceans waters bulge on the side of the earth that faces the moon. The centrifugal force produce the same effect but in the opposite side of the earth. On these two sides it can be observe the maximum amplitudes of the tides (high tides) and on the midways of it occur the minimum amplitudes of the tides (low tides). As the earth rotates these two bulges travel at the same rate as the earth's rotation. The moon rotates around the earth with respect to the sun approximately 29.5 days (lunar month) in the same direction that the earth rotates every 24 hours. The rotation of the earth with respect to the moon is approximately 24.84 hours (24 hours and 50 minutes) and is called lunar day. This is the reason of why the tides advance approximately 50 minutes each day. In the same manner that the ocean waters bulges towards the moon, the gravitational force of the sun causes that the ocean waters bulges too but in a lesser degree. Twice a month, when the earth, the moon and the sun are aligned (full and new moon) the tide generating forces of the sun and the moon are combined to produce tide ranges that are greater than average knowing as the *spring tides.* At half moon (first and third quarters) the sun and the moon are 90º with respect to the earth and the tide generating forces tend to produce tidal ranges that are less than the averages knowing as the *neap tides*, see Figure below. Typically the spring tides ranges tend to be twice of the neap tides ranges.



The tidal movements can be reflect and restrict by the interruption of masses of land, the bottom friction can reduce its velocity and the depth, size and shape of the ocean basins, bays and estuaries altered the movements of the tidal bulges and generate different types of tides. There are three types of tides: diurnal, semidiurnal and mixed.

Tidal Energy to Electric Energy Conversion

The technology that is use to produce electricity using the difference between the low and high tides is very similar to the one use on the generation of electricity on the traditional hydroelectric power plants. The use of the tidal energy requires a dam or barrage across a shallow area preferably an estuary, bay or gulf of high tidal range where the difference on the low and high tide have to be at least 5 meters. The tide basins are filled and empty every day with the flood tides when the water level rises and with the ebb tides when the water level falls. On the barrage there are low-head turbines and sluices gates that allow the water to flow from one side of the barrage to inside the tidal basin. This difference on elevation of the water level creates a hydrostatic head that generates electricity. There are different modes to generate electricity using the barrage systems:



Ebb generation - Incoming water (flood tide) is allowed to flow freely to fill the basin until high tide, then the sluices are close and water are retained on one side of the barrage. When the level of the water outside of the barrage decreased (ebb tide) sufficiently to create a hydrostatic head between the open waters and the tide basin, the sluices are open and water flows through the turbines and generate electricity. Once the head is low the sluices gates are open and the basin is filled again.

Flood generation - During the flood tide the sluices gates and low-head turbines are kept closed to allow the water level outside of the barrage to increase. Once a hydrostatic head is created the sluices gates are opened and the water flows through the turbines into the basin. This mode is less efficient than the ebb mode.

Two way generation - This mode permits to generate electricity using both the ebb and the flood tide. The main problem with this type of mode is that the turbines must work both ways, when water enters or exits the basin. This requires more expensive turbines and at this time computer simulations do not indicate that this mode increases significantly the energy production.

Pumping- On the ebb generation the hydrostatic head can be increased reversing the power and turning the turbine-generator into a pump-motor. During the generation the energy that was use is returned.

Double basin- All of the modes discuss above use one tide basin. Using two basins, the turbines are placed between the basins. The main basin will going to use the ebb generation mode to operate and pump water with part of the energy that is generated to and from the second basin to generated electricity continuously. This mode has the disadvantage that is very expensive.

Ocean Currents

Ocean currents are driven by solar heating and wind in the waters near the equator, also by tides, salinity and density of the water. Current can be divided in two types: marine currents and tidal currents. Marine currents are relatively constant and flow in one direction. Tidal currents occurred close to the shore due to gravitational forces. Currents are flowing bodies like wind. Current energy can be calculated using the formula of kinetic energy of flowing bodies, K_E=0.5*p*v^2. The kinetic energy of flowing bodies is proportional to the cube of their velocities and their density. Ocean energy can be compared with wind energy because these two types of resources are two forms of flowing bodies. The speed of ocean currents is lower when compared to wind speeds but the water is 832 times denser than air. Also ocean currents can be predicted with years in advanced as these depend of the movements of the sun and moon. Through the world there can be found ocean currents of more than five knots or 2.5m/s
(1 knot=0.50 m/s) and current energy has been estimated greater than 5,000 GW, with power densities of up to 15 kW/m^2.

Currents Energy to Electric Energy Conversion

Technologies to convert ocean currents energy into electricity are under development. Several devices are being tested and are very similar to wind energy technologies, consisting in turbines of horizontal and vertical axis of rotation used underwater. The purpose of these technologies is to capture the ocean currents generated by the flow created by the motion of tides. In the horizontal axis turbines the rotational axis is parallel to the directional of the water flow. In vertical axis systems the rotational axis turbines rotate perpendicular to the water flow.

Ocean Thermal Energy

The large difference between the temperatures of the ocean surface waters, especially on the tropics and the deep seawaters stimulate the presence of thermal gradients. Based on this concept, the Ocean Thermal Energy Conversion (OTEC) has been proposed and is currently under development. OTEC converts the difference between warm surface waters and cold deeper waters (approximately 1000 m below the surface) into energy.

Ocean Thermal Energy Conversion (OTEC)

OTEC offers the advantage of a resource which is available almost equally during the day and night with slightly variations on winter and summer. This renewable source can be combined with other applications that are deriving from it like: mar culture, potable water production and air conditioning refrigerant among others.

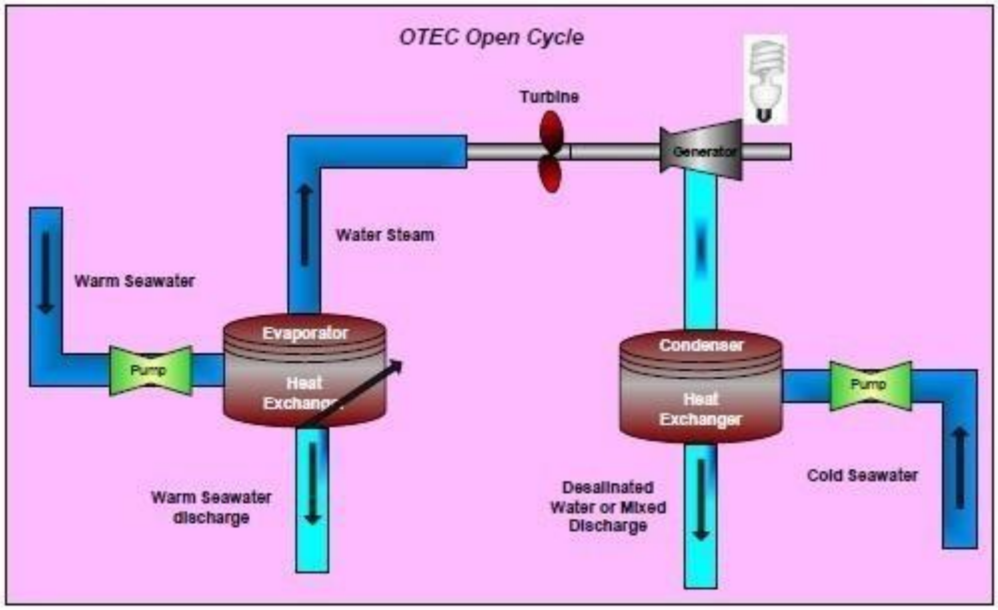
OTEC power plants must be located on areas where the ocean water temperature difference of at least 20º C can be accomplished. But other factors have to taking into account before considered a particular location suitable for an OTEC development. Some of these factors are

- Distance from the thermal resource to the shore (grid interconnection),
- Depth of the cold water location and sea bottom,
- Type of OTEC facility (Shoreline or near-shoreline, platforms or free-floating), Oceans conditions (waves, currents),
- Sea bottom conditions (mooring, floating power conductors installations), Environmental Impacts
- Deep Ocean Water Applications (DOWA) potential, Government's incentives, and others.

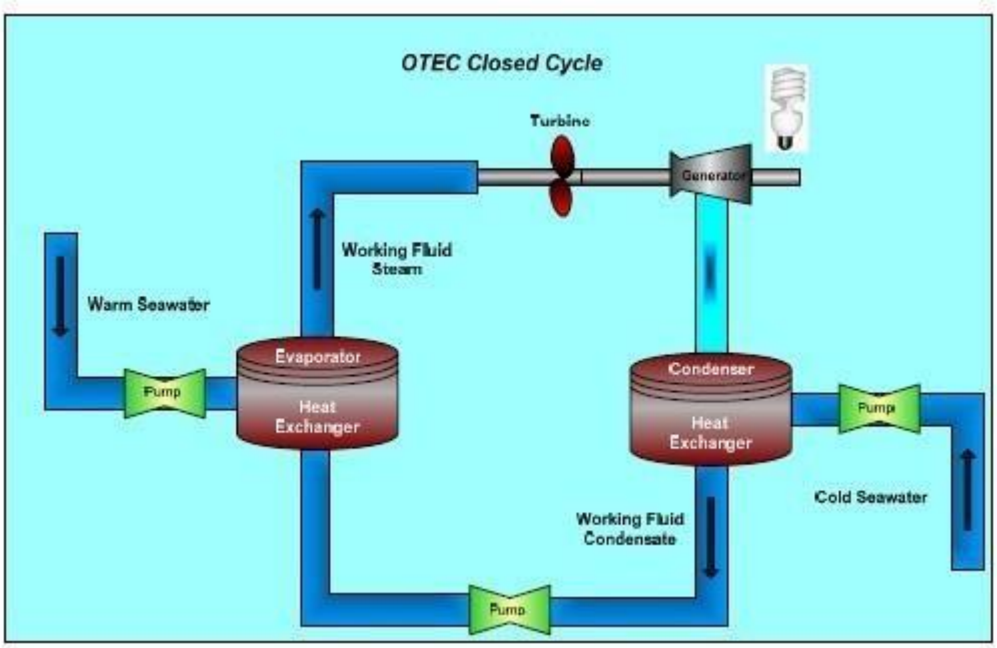
To operate an OTEC plant to generate electricity two working cycles can be used: the OTEC closed cycle proposed by Arsene d'Arsonval and the OTEC open cycle proposed by Georges Claude.

OTEC working cycles

Open Cycle - In the open cycle warm seawater can be use as the working fluid. When the surface seawater is flashed evaporated it is pumped into a vacuum chamber to produce a spray of the liquid. Making the pressure of the chamber less than the saturation pressure of the spray of the water, it starts to boil. The steam that is produce passes through the turbine to generate electricity. The steam later condensates using the cold seawater and is not returned to the evaporator. This condensation process can be done using two methods: spray cold seawater over the steam or in a surface condenser in which the steam and the coldwater do not enter in contact with each other, producing desalinated water. If the condensation is done using the spray method the mixed of steam and cold water is discharged back to the ocean, see Figure below.

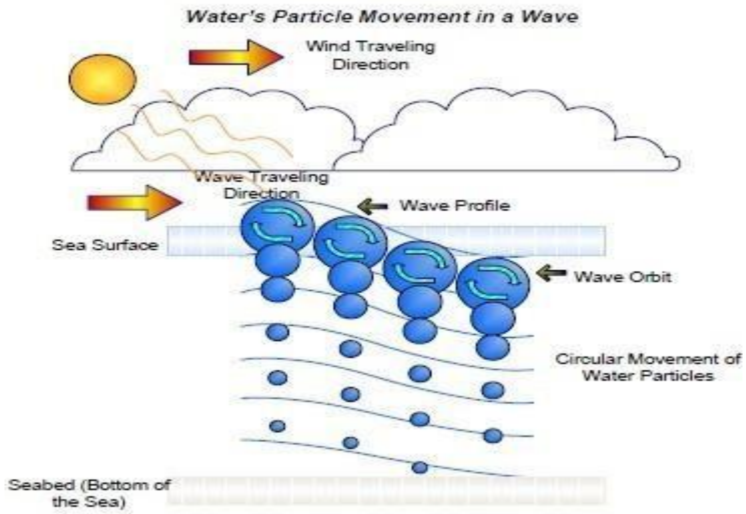


Closed Cycle - In the OTEC closed cycle two working fluids work to complete the cycle. First, it is necessary to use warm seawater to vaporize a second working fluid such as ammonia, propane or a Freon-type refrigerant. This second working fluid will flow through an evaporator (heat exchanger). The high pressure steam that is produced moves a turbine that is connected to a generator that produces electricity. After the steam moves the turbine, it is condensate using the cold seawater that is pumped from the depths and is pumped back to the evaporator to start the cycle. The turbines that are use in the closed cycle are usually smaller than the ones use in the open cycle because the density and operating pressure of the second working fluid are higher, see Figure below

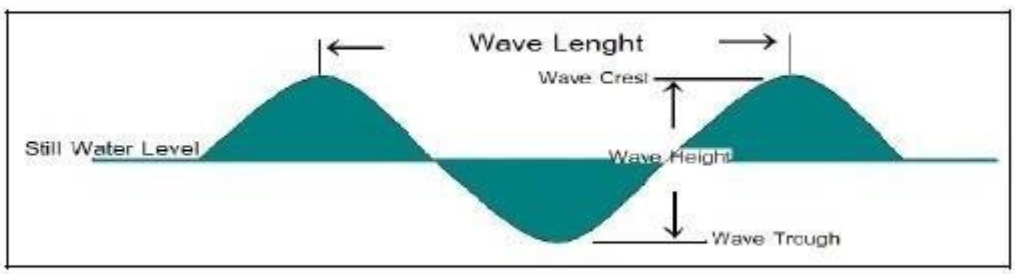


Ocean Waves Energy

Waves can be formed through the presence of many forces that acts on the ocean surface. The gravitational forces like the one that acts between the Earth, the Moon and the Sun and the geological forces that produce subsea earthquakes that can generate tsunamis are some of the forces that act on the formation of ocean waves. But the most common and known form of waves are the ones that are derivative of the solar energy. When the sun heats the earth surface it generates zones with different pressures that produce winds. As those winds blows over the ocean surface the friction that is created between the wind and the water forms the waves, see Figure below. The increase on the speed of the winds cause that the waves increase on height and mass much faster that in depth. The size of the waves will depend on three (3) factors: Strength of the winds, Amount of time that the winds blow, the distance (fetch) over which it blows.



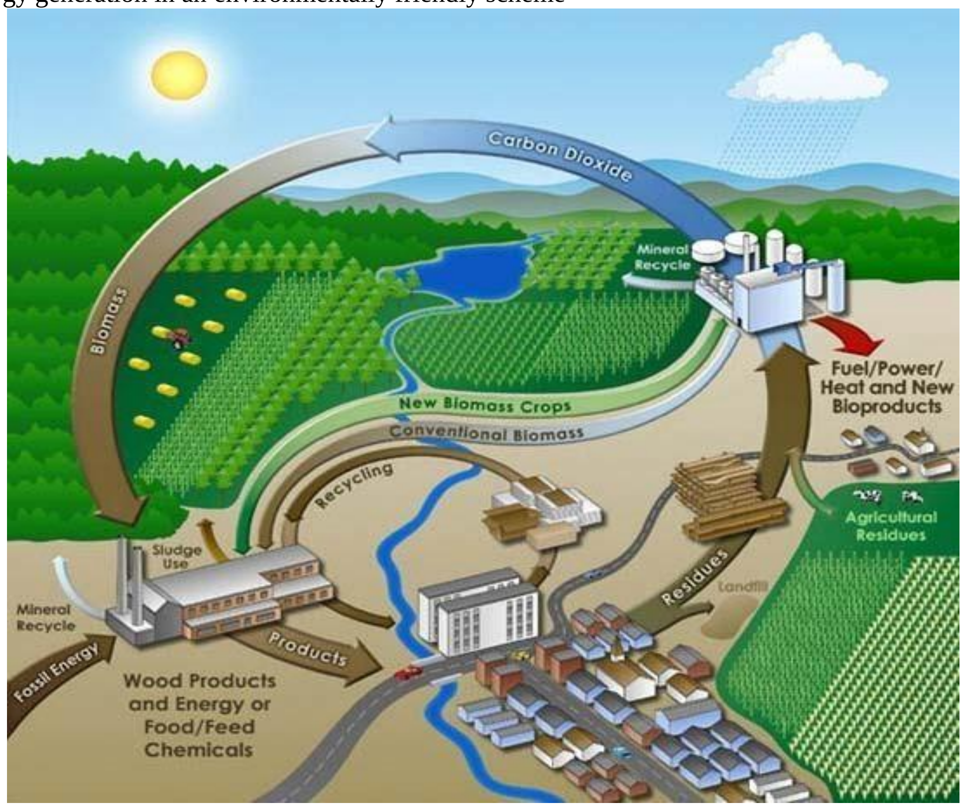
Waves can be characterized by its height (H), its period (T) and its wave length (λ). The wave height is the vertical elevation of the wave crest above the trough; normally it is less than 1/7 of its length. The wave period is the interval of time that it takes for two wave crests to pass a fixed point and the wave length is the horizontal distance between two crests, see below Figure.



Ocean waves vary from location because steady wind causes longer wave duration and with the seasons of the year, because the waves are larger on winter than in summer. Ocean waves can be classified in two types: the *local seas* and the *swells. Local seas* are ocean waves generated by the action of the winds on the location that they blow; their length is ten to twenty times their height. The *swells* are a group of long and short waves that can travel thousands of miles from their point of origin, which normally is a storm in the middle of the ocean. These types of waves suffer little attenuation and arrive at distant coasts with fury.

4. Enumerate the prospects of biomass energy. (M.E-APR/MAY 2013)
   Biomass is a term used to describe all organic matter produced by photosynthesis, existing on the earth's surface. They include all water- and land-based vegetation and trees, and all waste biomass such as municipal solid waste (MSW), municipal bio solids (sewage), and animal wastes (manures), forestry and agricultural residues, and certain types of industrial wastes. The world's energy markets have relied heavily on the fossil fuels. Biomass is the only other naturally occurring energy-containing carbon resource that is large enough in quantity to be used as a substitute for fossil fuels. Through the process of photosynthesis, chlorophyll in plants captures the sun's energy by converting carbon dioxide from the air and water from the ground into carbohydrates, i.e., complex compounds composed of carbon, hydrogen, and oxygen. When these carbohydrates are burned, they turn back into carbon dioxide and water and release the sun's energy they contain. In this way, biomass functions as a sort of natural battery for storing solar energy. The exploitation of energy from biomass has played a key role in the evolution of mankind. Until relatively

recently it was the only form of energy which was usefully exploited by humans and is still the main source of energy for more than half the world's population for domestic energy needs. One of the simplest forms of biomass is a basic open fire used to provide heat for cooking, warming water or warming the air in our home. More sophisticated technologies exist for extracting this energy and converting it into useful heat or Power in an efficient way. In the mid-1800s, biomass, principally wood biomass, supplied over 90% of U.S. energy and fuel needs, after which biomass energy usage began to decrease as fossil fuels became the preferred energy resources. This eventuality of fossil fuel and the adverse impact of fossil fuel usage on the environment are expected to be the driving forces that stimulate the transformation of biomass into one of the dominant energy resources. Unlike fossil fuels, biomass is renewable in the sense that only a short period of time is needed to replace what is used as an energy resource. Biomass also is the only renewable energy source that releases carbon dioxide in use. However the release is compensated by the fact that the biomass grown uses the carbon dioxide from the atmosphere to store energy during photosynthesis. If the biomass resource is being used sustainably, there are no net carbon emissions over the time frame of a cycle of biomass production. Below Figure shows a biomass energy cycle and the way biomass is utilized for energy generation in an environmentally friendly scheme



METHODS OF EXTRACTING BIOMASS ENERGY

Biomass can be converted to thermal energy, liquid, solidor gaseous fuels and other chemical products through a variety of conversion processes. All of today's capacity is based on mature, direct-combustion technology. Future efficiency improvements will include co-firing of biomass in existing coal-fired boilers and the introduction of high-efficiency gasification, combined-cycle systems, fuel cell systems, and modular systems. Generally, the prominent bio power technologies are comprised of direct combustion, co-firing, gasification, pyrolysis, anaerobic digestion, and fermentation.

1. Direct Combustion

This is perhaps the simplest method of extracting energy from biomass. Industrial biomass combustion facilities can burn many types of biomass fuel, including wood, agricultural residues, wood pulping liquor, municipal solid waste (MSW) and refuse-derived fuel. Biomass is burned to produce steam, the steam turns a turbine and the turbine drives a generator, producing electricity. Because of potential ash build-up (which fouls boilers, reduces efficiency and increases costs), only certain types of biomass materials are used for direct combustion.

2. Gasification

Gasification is a process that exposes a solid fuel to high temperatures and limited oxygen, to produce a gaseous fuel. The gas produced by the process as shown in below Figure is a mix of gases such as carbon monoxide, carbon dioxide, nitrogen, hydrogen, and methane. The gas is then used to drive a high efficiency, combined-cycle gas turbine. Gasification has several advantages over burning solid fuel. One is convenience – one of the resultant gases, methane, can be treated in a similar way as natural gas, and used for the same purposes. Another advantage of gasification is that it produces a fuel that has had many impurities removed and could therefore cause fewer pollution problems when burnt. Under suitable circumstances, it can also produce synthesis gas, a mixture of carbon monoxide and hydrogen which can be used to make hydrocarbon (e.g., methane and methanol) for replacing fossil fuels. Hydrogen itself is a potential fuel without much pollution which can conceivably substitute oil and petroleum in a foreseeable future.

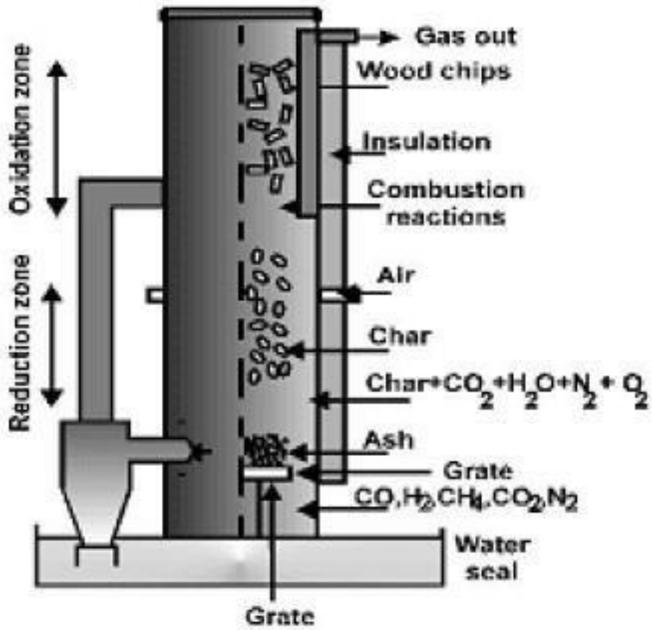


Figure. Gasification Process

3. Pyrolysis

In its simplest form, pyrolysis represents heating the biomass to drive off the volatile matter and leaving behind the Charcoal. This process has doubled the energy density of the original material because charcoal, which is half the weight of the original biomass, contains the same amount of energy, making the fuel more transportable. The charcoal also burns at a much higher temperature than the original biomass, making it more useful for manufacturing processes. More sophisticated pyrolysis techniques are developed recently to collect volatiles that are otherwise lost to the system. The collected volatiles produce a gas which is rich in hydrogen (a potential fuel) and carbon monoxide. These compounds are synthesized into methane, methanol, and other hydrocarbons. The steps involved in this process are illustrated in below Figure. Flash pyrolysis is used to produce bio-crude, a combustible fuel. Heat is used to chemically convert biomass into pyrolysis oil. The oil, which is easier to store and transport than solid biomass material, is then burned like petroleum to generate electricity. Pyrolysis can also convert biomass into phenol oil, a chemical used to make wood adhesives, moulded plastics, and foam insulation.

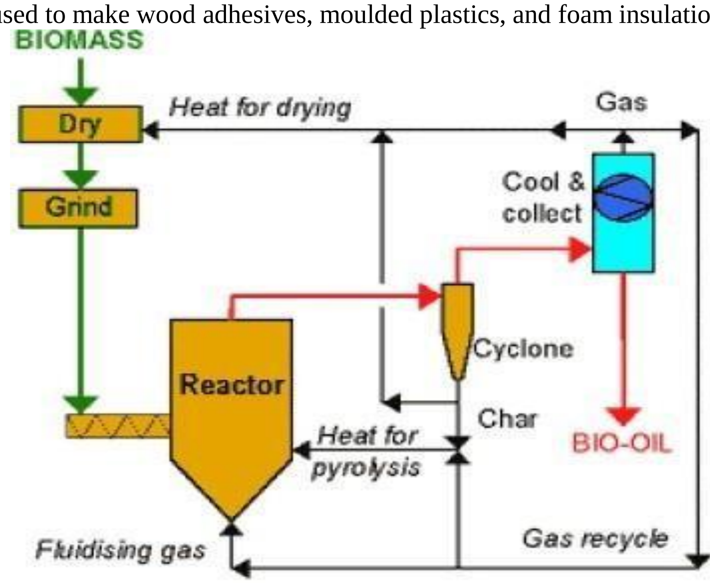


Figure. Pyrolysis process

4. Digestion

Biomass digestion works by utilizing anaerobic bacteria. These microorganisms usually live at the bottom of swamps or in other places where there is no air, consuming dead organic matter to produce methane and hydrogen. We put these bacteria to work for us. By feeding organic matter such as animal dung or human sewage into tanks, called digesters, and adding bacteria, we collect the emitted gas to use as an energy source. This process is a very efficient means of extracting usable energy from such biomass. Usually, up to two thirds of the fuel energy of the animal dung could be recovered. Another related technique is to collect methane gas from landfill sites. A large proportion of household biomass waste, such as kitchen scraps, lawn clipping and pruning, ends up at the local tip. Over a period of several decades, anaerobic bacteria at the bottom of such tips could steadily decompose the organic matter and emit methane. The gas can be extracted and used by capping a landfill site with an impervious layer of Clay and then inserting perforated pipes that would collect the gas and bring it to the surface.

5. Fermentation

For centuries, people have used yeasts and other microorganisms to ferment the sugar of various plants into ethanol. Producing fuel from biomass by fermentation is just an extension of this process, although a wider range of plant material from sugar cane to wood fibre can be used. For instance, the waste from a wheat mill in New South Wales is used to produce ethanol through fermentation. Ethanol is then mixed with diesel to produce diesehol, a product used by trucks and buses in Australia. Technological advances will inevitably improve the method. For example, scientists in Australia and the U.S. have substituted a genetically engineered bacterium for yeast in the fermentation process. The process has vastly increased the efficiency by which waste paper and other forms of wood fiber is fermented into ethanol.

Bio fuels: Biomass is converted into transportation fuels such as ethanol, methanol, biodiesel and additives for reformulated gasoline. Bio fuels are used in pure form or blended with gasoline.

Ethanol: Ethanol, the most widely used bio fuel, is made by fermenting biomass in a process similar to brewing beer. Currently, most of the 1.5 billion gallons of ethanol used in the U.S. each year is made from corn and blended with gasoline to improve vehicle performance and reduce air pollution.

Methanol: Biomass-derived methanol is produced through gasification. The biomass is converted into a synthesis gas (syngas) that is processed into methanol. Most of the 1.2 billion gallons of methanol annually produced in the U.S. are made from natural gas and used as solvent, antifreeze, or to synthesize other chemicals. About 38 percent is used for transportation as a blend or in reformulated gasoline.

Biodiesel: Biodiesel fuel, made from oils and fats found in micro-algae and other plants is substituted for or blended with diesel fuel.

BENEFITS OF BIOMASS ENERGY:

Some of the advantages of using biomass as a source of energy are illustrated below.

1. Biomass energy is an abundant, secure, environmental friendly and renewable source of energy. Biomass does not add carbon dioxide to the atmosphere as it absorbs the same amount of carbon in growing as it releases when consumed as a fuel.
2. One of the major advantages of biomass is that it can be used to generate electricity with the same equipment or in the same power plants that are now burning fossil fuels.
3. Biomass energy is not associated with environmental impacts such as acid rain, mine spoils, open pits, oil spills, radioactive waste disposal or the damming of rivers.
4. Biomass fuels are sustainable. The green plants from which biomass fuels are derived fix carbon dioxide as they grow, so their use does not add to the levels of atmospheric carbon. In addition, using refuse as a fuel avoids polluting landfill disposal.
5. Alcohols and other fuels produced by biomass are efficient, viable, and relatively clean burning.
6. Biomass is easily available and can be grown with relative ease in all parts of the world.

CONSTRAINTS TO BIOMASS ENERGY USE:

1. Biomass is still an expensive source of energy, both in terms of producing biomass and converting it into Alcohols, as a very large quantity of biomass are needed.
2. On a small scale there is most likely a net loss of energy as a lot of energy must be used for growing the plant mass; biomass is difficult to store in the raw form.
3. One of the disadvantages of biomass is that direct combustion of biomass can be harmful to the environment as burning biomass releases carbon dioxide, which contributes to the warming of the atmosphere and possible climatic change. Burning also creates soot and other air pollutants.
4. Over-collecting wood can destroy forests. Soils bared of trees erode easily and do not hold rainfall. Increased runoff can cause flooding downstream.
5. When plant and animal wastes are used as fuel, they cannot be added to the soil as fertilizer. Soil without fertilizer is depleted of nutrients and produces fewer crops.
6. Biomass has less energy than a similar volume of fossil fuels.

5. List out the available renewable energy sources. Explain how solar energy sources plays significant role of electric power generation. (APR/MAY 2017)
Bio fuel, Biomass, Geothermal, Hydropower, Solar energy, Tidal power, Wave power, Wind power.

Solar energy

Solar energy is an important, clean, cheap and abundantly available renewable energy. It is received on Earth in cyclic, intermittent and dilute form with very low power density 0 to 1 kW/m^2.Solar energy received on the ground level is affected by atmospheric clarity, degree of latitude, etc. For design purpose, the variation of available solar power, the optimum tilt angle of solar flat plate collectors, the location and orientation of the heliostats should be calculated.

Units of solar power and solar energy:

In SI units, energy is expressed in Joule. Other units are angley and Calorie where
1 angley = 1 Cal/cm^2.day
1 Cal = 4.186 J
For solar energy calculations, the energy is measured as an hourly or monthly or yearly average and is expressed in terms of kJ/m^2/day or kJ/m^2/hour. Solar power is expressed in terms of W/m^2 or kW/m^2.

Essential subsystems in a solar energy plant:

1. **Solar collector or concentrator**: It receives solar rays and collects the energy. It may be of following types:
a) Flat plate type without focusing
b) Parabolic trough type with line focusing
c) Paraboloid dish with central focusing
d) Fresnel lens with centre focusing
e) Heliostats with centre receiver focusing
2. **Energy transport medium**: Substances such as water/ steam, liquid metal or gas are used to transport the thermal energy from the collector to the heat exchanger or thermal storage. In solar PV systems energy transport occurs in electrical form.
3. **Energy storage**: Solar energy is not available continuously. So we need an energy storage medium for maintaining power supply during nights or cloudy periods. There are three major types of energy storage:
a) Thermal energy storage; b) Battery storage; c) Pumped storage hydro-electric plant.
4. **Energy conversion plant**: Thermal energy collected by solar collectors is used for producing steam, hot water, etc. Solar energy converted to thermal energy is fed to steam thermal or gas-thermal power plant.
5. **Power conditioning, control and protection system**: Load requirements of electrical energy vary with time. The energy supply has certain specifications like voltage, current, frequency, power etc. The power conditioning unit performs several functions such as control, regulation, conditioning, protection, automation, etc.

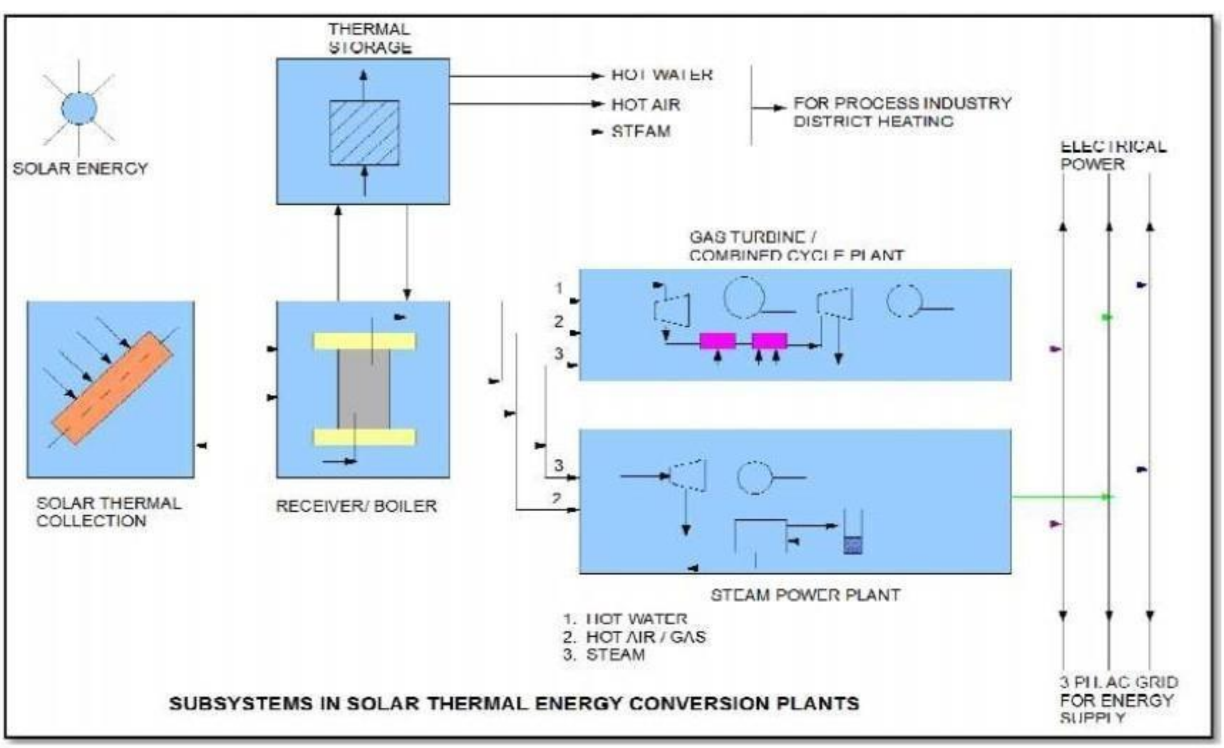


Fig Subsystems in solar thermal energy conversion plants

6. **Alternative or standby power supply**: The backup may be obtained as power from electrical network or standby diesel generator.

Energy from the sun:

The sun radiates about 3.8 x 10^{26} W of power in all the directions. Out of this about 1.7 x10^{17} W is received by earth. The average solar radiation outside the earth's atmosphere is 1.35 kW/m^2 varying from 1.43 kW/m^2 (in January) to 1.33 kW/m^2 (in July).

Solar thermal energy (STE) is a form of energy and a technology for harnessing solar energy to generate thermal energy or electrical energy for use in industry, and in the residential and commercial sectors. The first installation of solar thermal energy equipment occurred in the Sahara Desert approximately in 1910. When a steam engine was run on steam produced by sunlight. Because liquid fuel engines were developed and found more convenient, the Sahara project was abandoned, only to be revisited several decades late.

Solar thermal collectors are classified by the United States Energy Information Administration as low-, medium-, or high-temperature collectors. Low-temperature collectors are flat plates generally used to heat swimming pools. Medium-temperature collectors are also usually flat plates but are used for heating water or air for residential and commercial use. High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for fulfilling heat requirements up to 300 deg C / 20 bar pressure in industries, and for electric power production. However, there is a term that used for both the applications. Concentrated Solar Thermal (CST) for fulfilling heat requirements in industries and Concentrated Solar Power (CSP) when the heat collected is used for power generation. CST and CSP are not replaceable in terms of application. A solar thermal collector system gathers the heat from the solar radiation and gives it to the heat transport fluid. The heat-transport fluid receives the heat from the collector and delivers it to the thermal storage tank, boiler steam generator, heat exchanger etc. Thermal storage system stores heat for a few hours. The heat is released during cloudy hours and at night. Thermal-electric conversion system receives thermal energy and drives steam turbine generator or gas turbine generator. The electrical energy is supplied to the electrical load or to the AC grid. Applications of solar thermal energy systems range from simple solar cooker of 1 kW rating to complex solar central receiver thermal power plant of 200 MW rating.

For producing grid-connected electric power, following two major types of solar energy technologies are commercially viable.

- Concentrated Solar Power (CSP) technology
- Solar Photo Voltaic (PV) technology

Concentrated Solar Power (CSP) technology

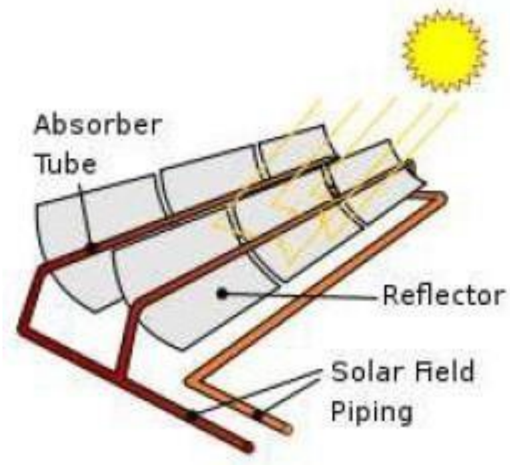
Concentrated solar power plants produce electric power by converting the sun's energy into high temperature heat using various minor configurations. The working fluid in the heat engine that is heated by the concentrated sunlight can be a liquid (water, oil) salts or a gas (air, nitrogen, helium). The amount of power generated by a CSP plant depends on the quality of the reflector design and material and the amount of direct sunlight impinging on the reflector.

Following are the most commonly accepted CSP technologies for solar energy collection

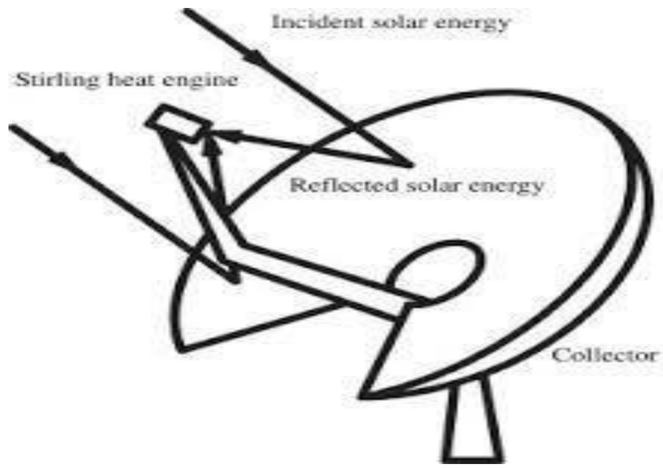
- Parabolic trough
- Parabolic dish
- Power tower
- Fresnel reflector

Parabolic trough

Parabolic trough power plants use a curved, mirrored trough which reflects the direct solar radiation onto a glass tube containing a fluid (also called a receiver, absorber or collector) running the length of the trough, positioned at the focal point of the reflectors. The trough is parabolic along one axis and linear in the orthogonal axis. For change of the daily position of the sun perpendicular to the receiver, the trough tilts east to west so that the direct radiation remains focused on the receiver. However, seasonal changes in the in angle of sunlight parallel to the trough does not require adjustment of the mirrors, since the light is simply concentrated elsewhere on the receiver. Thus the trough design does not require tracking on a second axis. The receiver may be enclosed in a glass vacuum chamber. The vacuum significantly reduces convective heat loss. A fluid (also called heat transfer fluid) passes through the receiver and becomes very hot. Common fluids are synthetic oil, molten salt and pressurized steam. The fluid containing the heat is transported to a heat engine where about a third of the heat is converted to electricity. Full-scale parabolic trough systems consist of many such troughs laid out in parallel over a large area of land. Since 1985 a solar thermal system using this principle has been in full operation in California in the United States. It is called the Solar Energy Generating Systems (SEGS) system. Other CSP designs lack this kind of long experience and therefore it can currently be said that the parabolic trough design is the most thoroughly proven CSP technology.



Parabolic dish



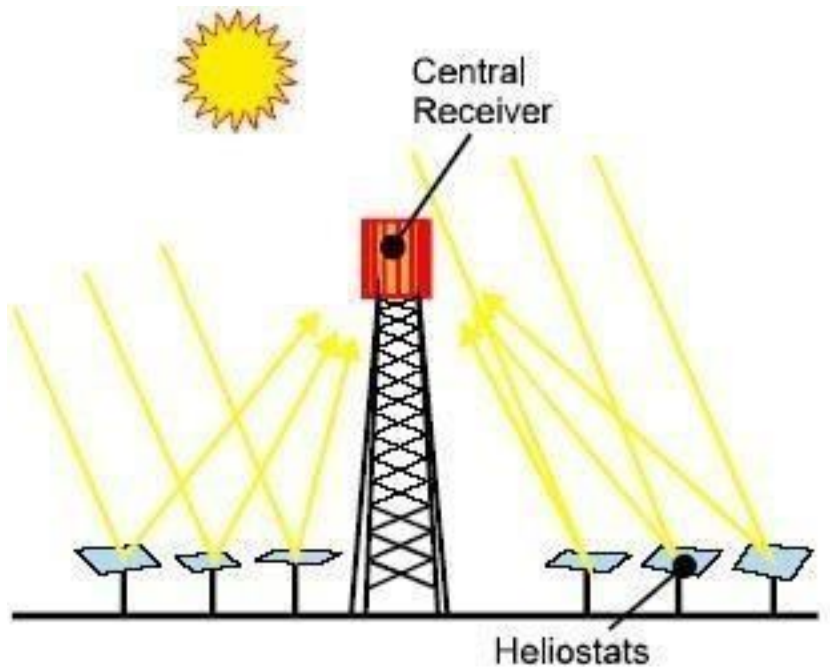
Solar Parabolic dish

With a parabolic dish collector, one or more parabolic dishes concentrate solar energy at a single focal point, similar to the way a reflecting telescope focuses starlight, or a dish antenna focuses radio waves. This geometry may be used in solar furnaces and solar power plants. The shape of a parabola means that incoming light rays which are parallel to the dish's axis will be reflected toward the focus, no matter where on the dish they arrive. Light from the sun arrives at the Earth's surface almost completely parallel, and the dish is aligned with its axis pointing at the sun, allowing almost all incoming radiation to be reflected towards the focal point of the dish. Most losses in such collectors are due to imperfections in the parabolic shape and imperfect reflection. Losses due to atmospheric scattering are generally minimal. However, on a hazy or foggy day, light is diffused in all directions through the atmosphere, which significantly reduces the efficiency of a parabolic dish. In dish stirling power plant designs, a stirling engine coupled to a dynamo, is placed at the focus of the dish. This absorbs the energy focused onto it and converts it into electricity.

Power tower

A power tower is a large tower surrounded by tracking mirrors called heliostats. These mirrors align themselves and focus sunlight on the receiver at the top of tower, collected heat is transferred to a power station below. This design reaches very high temperatures. High temperatures are suitable for electricity generation using conventional methods like steam turbine or a direct high temperature chemical reaction such as liquid salt. By concentrating sunlight, current systems can get better efficiency than simple solar cells. A larger area can be covered by using relatively inexpensive mirrors rather than using expensive solar cells. Concentrated light can be redirected to a suitable location via optical fiber cable for such uses as illuminating buildings. Heat storage for power production during cloudy and overnight conditions can be accomplished, often by underground tank storage of heated fluids. Molten salts have been used to good effect. Other working fluids, such as liquid metals, have also been proposed due to their superior thermal properties.

However, concentrating systems require sun tracking to maintain sunlight focus at the collector. They are unable to provide significant power in diffused light conditions. Solar cells are able to provide some output even if the sky becomes cloudy, but power output from concentrating systems drops drastically in cloudy conditions as diffused light cannot be concentrated.



Fresnel Reflector

A linear Fresnel reflector power plant uses a series of long, narrow, shallow-curvature (or even flat) mirrors to focus light onto one or more linear receivers positioned above the mirrors. On top of the receiver a small parabolic mirror can be attached for further focusing the light. These systems aim to offer lower overall costs by sharing a receiver between several mirrors (as compared with trough and dish concepts), while still using the simple line-focus geometry with one axis for tracking. This is similar to the trough design (and different from central towers and dishes with dual-axis). The receiver is stationary and so fluid couplings are not required (as in troughs and dishes). The mirrors also do not need to support the receiver, so they are structurally simpler. When suitable aiming strategies are used (mirrors aimed at different receivers at different times of day), this can allow a denser packing of mirrors on available land area.

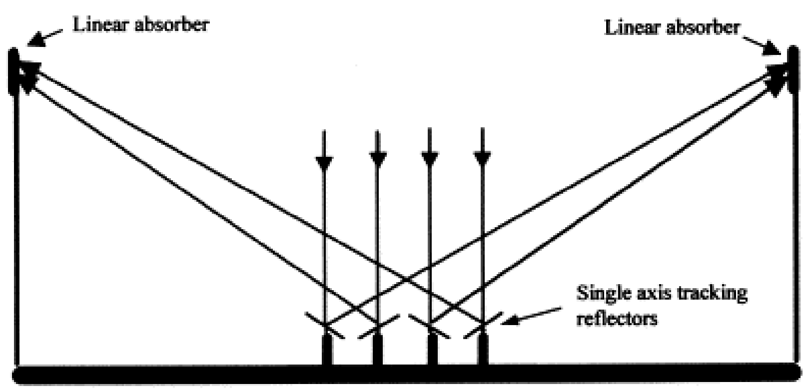
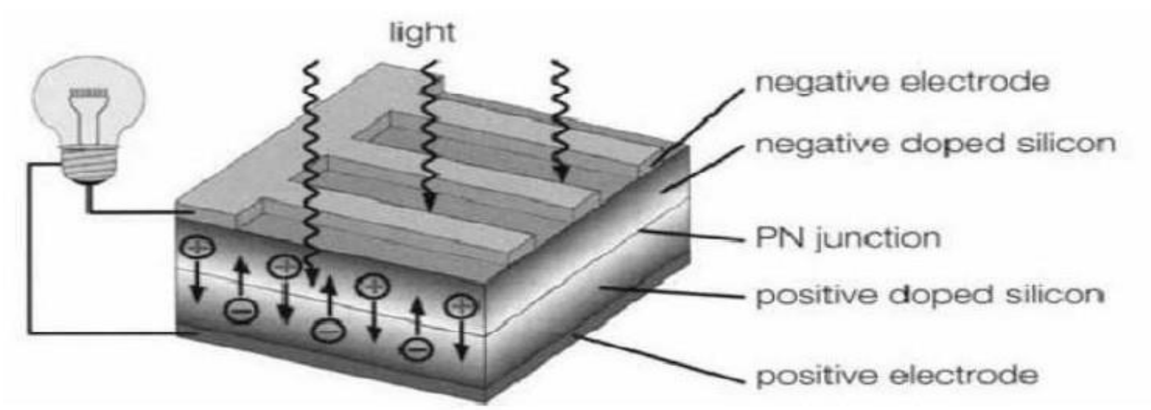


PHOTO VOLTAIC TECHNOLOGY:

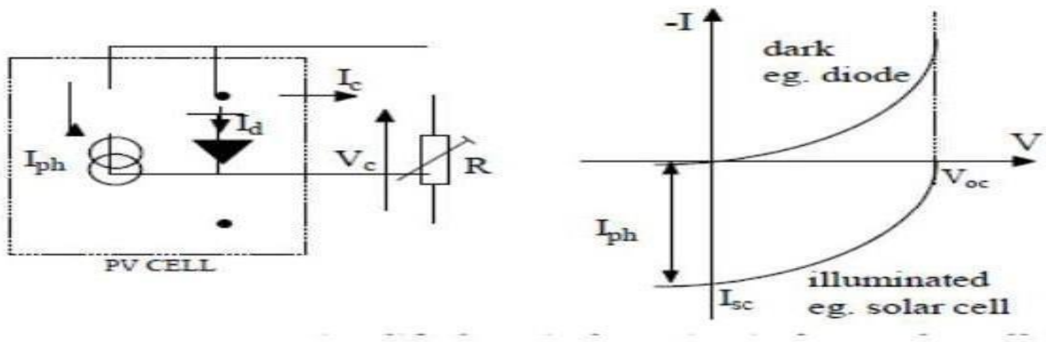
The density of power radiated from the sun (referred to as the ‘‘solar energy constant’’) at the outer atmosphere is 1.373kW/m^2. Part of this energy is absorbed and scattered by the earth’s atmosphere. The final incident sunlight on earth’s surface has a peak density of 1kW/m2 at noon in the tropics. The technology of photovoltaic (PV) is essentially concerned with the conversion of this energy into usable electrical form. The basic element of a PV system is the solar cell. Solar cells can convert the energy of sunlight directly into electricity. Consumer appliances used to provide services such as lighting, water pumping, refrigeration, telecommunications, and television can be run from photovoltaic electricity. Solar cells rely on a quantum-mechanical process known as the ‘‘photovoltaic effect’’ to produce electricity. A typical solar cell consists of a p n junction formed in a semiconductor material similar to a diode. Below Figure shows a schematic diagram of the cross section through a crystalline solar cell. It consists of a 0.2–0.3mm thick mono crystalline or polycrystalline silicon wafer having two layers with different electrical properties formed by ‘‘doping’’ it with other impurities (e.g., boron and phosphorus). An electric field is established at the junction between the negatively doped (using phosphorus atoms) and the positively doped (using boron atoms) silicon layers. If light is incident on the solar cell, the energy from the light (photons) creates free charge carriers, which are separated by the electrical field. An electrical voltage is generated at the external contacts, so that current can flow when a load is connected. The photocurrent (Iph), which is internally generated in the solar cell, is proportional to the radiation intensity.



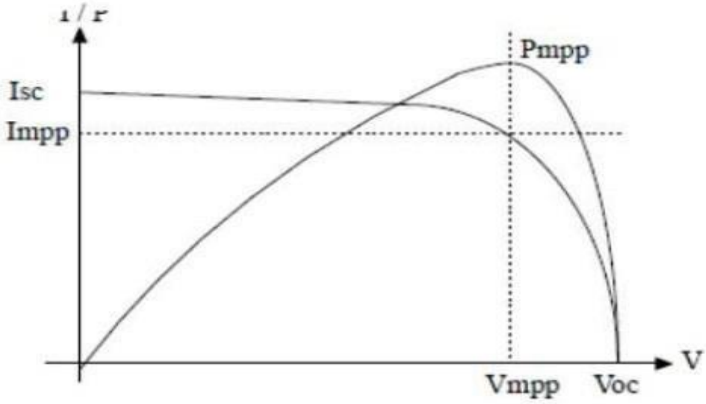
A simplified equivalent circuit of a solar cell consists of a current source in parallel with a diode as shown in Figure below. A variable resistor is connected to the solar cell generator as a load. When the terminals are short-circuited, the output voltage and also the voltage across the diode are both zero. The entire photocurrent (Iph) generated by the solar radiation then flows to the output. The solar cell current has its maximum (Isc). If the load resistance is increased, this results in an increasing voltage across the p n junction of the diode, a portion of the current flows through the diode and the output current decreases by the same amount. When the load resistor is open circuited, the output current is zero and the entire photocurrent flows through the diode. The relationship between current and voltage may be determined from the diode characteristic equation:

$$I = I_{ph} - I_0 \left(e^{\frac{kt}{qv}} - 1 \right) = I_{ph} - I_d$$

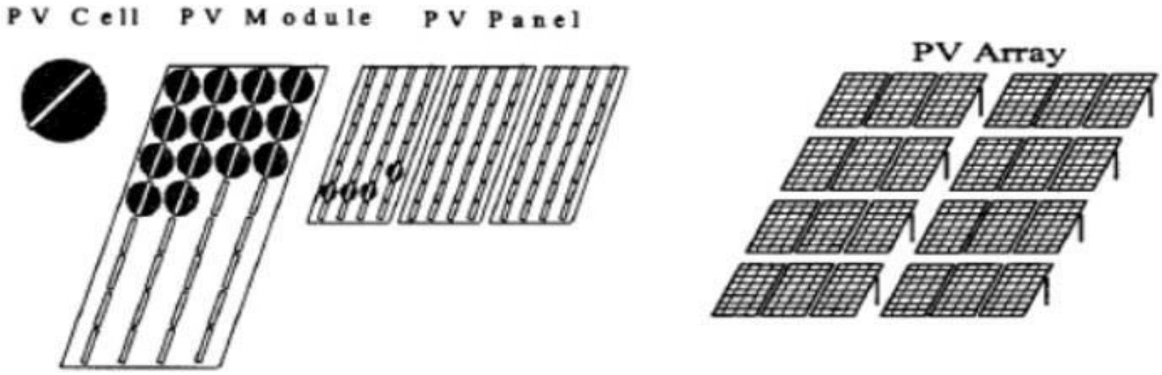
Where q is the electron charge, k is the Boltzmann constant, Iph is photocurrent, I0 is the reverse saturation current, Id is diode current, and T is the solar cell operating temperature (K). The current versus voltage (I-V) of a solar cell is thus equivalent to an ‘‘inverted’’ diode.



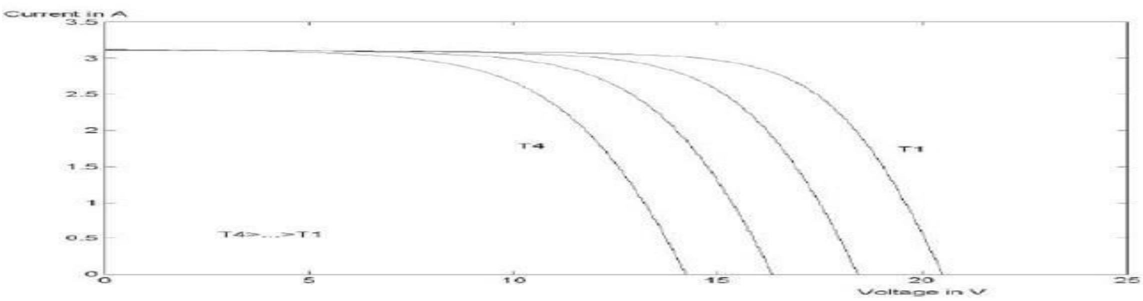
A solar cell can be operated at any point along its characteristic current–voltage curve, as shown in Figure below. Two important points on this curve are the open circuit voltage (Voc) and short-circuit current (Isc). The open-circuit voltage is the maximum voltage at zero current, whereas the short circuit current is the maximum current at zero voltage. For a silicon solar cell under standard test conditions, Voc is typically 0.6–0.7 V, and Isc is typically 20–40mA for every square centimetre of the cell area. To a good approximation, Isc is proportional to the illumination level, whereas Voc is proportional to the logarithm of the illumination level.



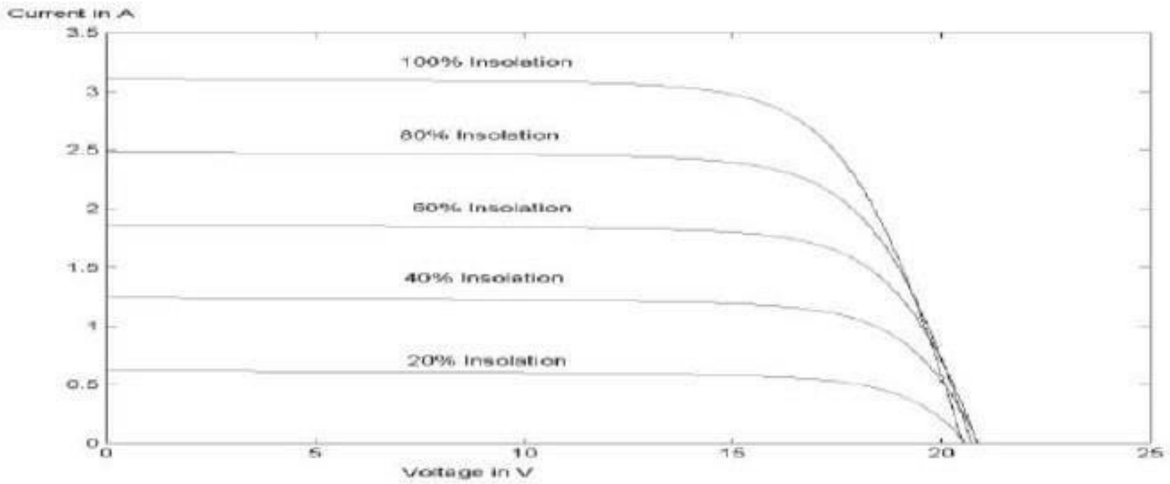
A plot of power (P) against voltage (V) for this device (Fig. 3) shows that there is a unique point on the I-V curve at which the solar cell will generate maximum power. This is known as the maximum power point (Vmp, Imp). Silicon solar cells typically produce only about 0.5 V, a number of cells are connected in series in a PV module. A panel is a collection of modules physically and electrically grouped together on a support structure. An array is a collection of panels (see Figure below).



The effect of temperature on the performance of a silicon solar module is illustrated in Figure below. Note that Isc slightly increases linearly with temperature, but Voc and the maximum power Pm decrease with temperature.



Below Figure shows the variation of PV current and voltages at different insolation levels. From Figs. 5 and 6, it can be seen that the I V characteristics of solar cells at a given insolation and temperature consist of a constant voltage segment and a constant-current segment. The current is limited, as the cell is short-circuited. The maximum power condition occurs at the knee of the characteristic where the two segments meet.



ARRAY DESIGN

The major factors influencing the electrical design of the solar array are as follows:

- The sun intensity
- The sun angle
- The load matching for maximum power
- The operating temperature

SUN TRACKING:

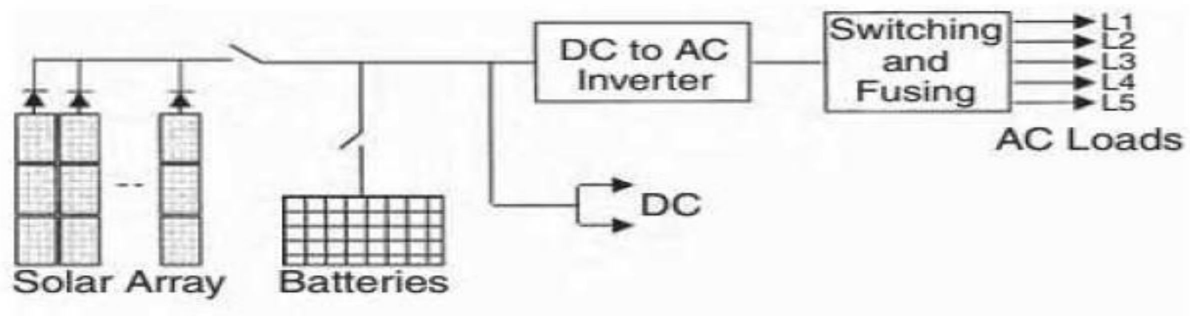
More energy is collected by the end of the day if the PV module is installed on a tracker with an actuator that follows the sun. There are two types of sun trackers:

• One-axis tracker, which follows the sun from east to west during the day.

• Two-axis tracker, which follows the sun from east to west during the day, and from north to south during the seasons of the year.

TYPICAL PV STAND-ALONE SYSTEM

The typical PV stand-alone system consists of a solar array and a battery connected as shown in Figure. The PV array supplies power to the load and charges the battery when there is sunlight. The battery powers the load otherwise. An inverter converts the DC power of the array and the battery into 60 or 50 Hz power. Inverters are available in a wide range of power ratings with efficiencies ranging from 85 to 95%. The array is segmented with isolation diodes for improving reliability. In such a design, if one string of the solar array fails, it does not load or short the remaining strings. Multiple inverters are preferred for reliability. For example, three inverters, each with a 35% rating, are preferred to one with a 105% rating. If one such inverter fails, the remaining two can continue supplying most loads until the failed one is repaired or replaced. The same design approach also extends to using multiple batteries.



PV stand-alone power system with battery.

6. Explain how wind energy sources plays significant role of electric power generation. (APR/MAY 2017)

Wind energy

The wind is a clean, free, and readily available renewable energy source. Each day, around the world, wind turbines are capturing the wind's power and converting it to electricity. This source of power generation plays an increasingly important role in the way we power our world. Wind energy is a commercially available renewable energy source, with state-of-the-art wind plants producing electricity at about $0.05 per kWh. However, even at that production cost, wind-generated electricity is not yet fully cost-competitive with coal-or natural-gas-produced electricity for the bulk electricity market. The wind is a by-product of solar energy. Approximately

2% of the sun's energy reaching the earth is converted into wind energy. The surface of the earth heats and cools unevenly, creating atmospheric pressure zones that make air flow from high-to low-pressure areas. The wind has played an important role in the history of human civilization. The first known use of wind dates back 5,000 years to Egypt, where boats used sails to travel from shore to shore.

SPEED AND POWER RELATIONS

The kinetic energy in air of mass m moving with speed V is given by the following in joules:

$$\text{kinetic energy} = \frac{1}{2} m V^2$$

The power in moving air is the flow rate of kinetic energy per second in watts:

$$\text{power} = \frac{1}{2}(\text{mass flow per second}) V^2$$

If

P= mechanical power in the moving air (watts),

ρ = air density (kg/m3),

A= area swept by the rotor blades (m2), and

V= velocity of the air (m/sec),

then the volumetric flow rate is AV, the mass flow rate of the air in kilograms per second is ρAV, and the mechanical power coming in the upstream wind is given by the following in watts:

$$P = \frac{1}{2}(\rho A V) V^2 = \frac{1}{2}\rho A V^3$$

Two potential wind sites are compared in terms of the specific wind power expressed in watts per square meter of area swept by the rotating blades. It is also referred to as the power density of the site, and is given by the following expression in watts per square meter of the rotor-swept area:

$$\text{specific power of the site} = \frac{1}{2}\rho V^3$$

This is the power in the upstream wind. It varies linearly with the density of the air sweeping the blades and with the cube of the wind speed. The blades cannot extract all of the upstream wind power, as some power is left in the downstream air that continues to move with reduced speed.

POWER EXTRACTED FROM THE WIND

The actual power extracted by the rotor blades is the difference between the upstream and downstream wind powers. Using Equation 3.2, this is given by the following equation in units of watts:

$$P_o = \frac{1}{2}(\text{mass flow per second})\left\{V^2 - V_o^{\,2}\right\}$$

where

Po= mechanical power extracted by the rotor, i.e., the turbine output power,

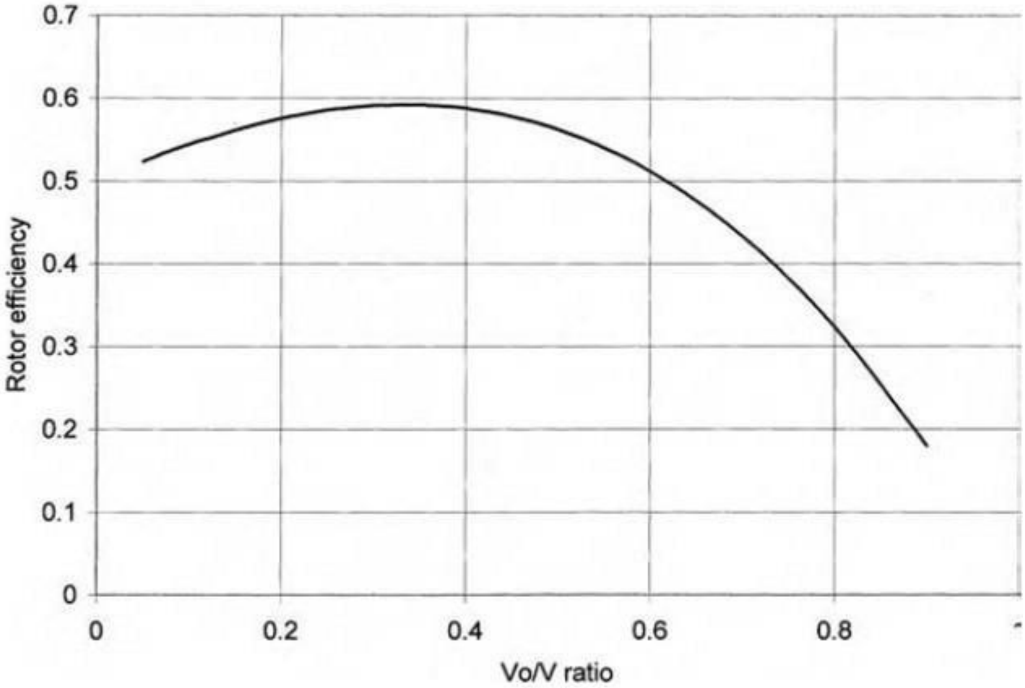
V= upstream wind velocity at the entrance of the rotor blades, and

Vo= downstream wind velocity at the exit of the rotor blades.

$$\text{mass flow rate} = \rho A \frac{V + V_o}{2}$$

The mechanical power extracted by the rotor, which drives the electrical generator, is therefore:

$$P_o = \frac{1}{2}\left[\rho A \frac{(V + V_o)}{2}\right](V^2 - V_o^2)$$



Rotor efficiency vs. V_o/V ratio has a single maximum.

The preceding expression is algebraically rearranged in the following form:

$$P_o = \frac{1}{2}\rho A V^3 \frac{\left(1+\frac{V_o}{V}\right)\left[1-\left(\frac{V_o}{V}\right)^2\right]}{2}$$

The power extracted by the blades is customarily expressed as a fraction of the upstream wind power in watts as follows:

$$P_o = \frac{1}{2}\rho A V^3 C_p$$

Where

$$C_p = \frac{\left(1+\frac{V_o}{V}\right)\left[1-\left(\frac{V_o}{V}\right)^2\right]}{2}$$

Comparing Equations, we can say that Cp is the fraction of the upstream wind power that is extracted by the rotor blades and fed to the electrical generator. The remaining power is dissipated in the downstream wind. The factor Cp is called the power coefficient of the rotor or the rotor efficiency.

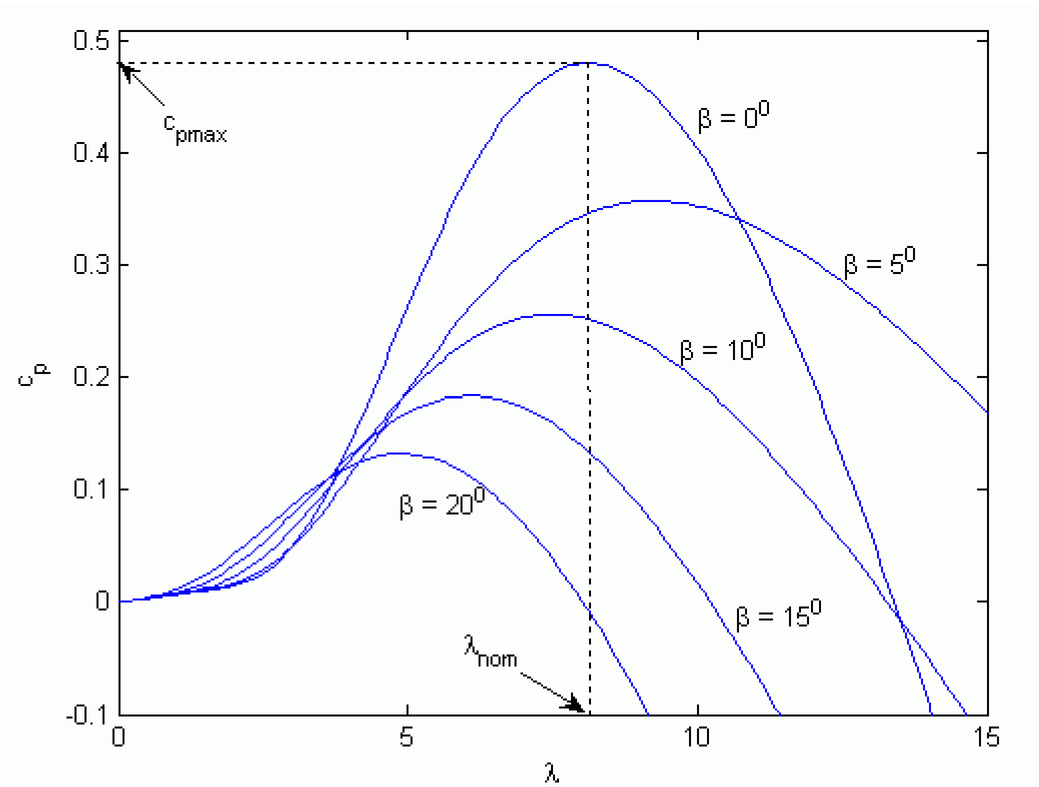


Figure: typical characteristics of wind energy conversion system

Advantages of Wind Energy

- It is a free source of energy
- Produces no water or air pollution
- Wind farms are relatively inexpensive to build
- Land around wind farms can have other uses

Disadvantages of Wind Energy

- Requires constant and significant amounts of wind
- Wind farms require significant amounts of land
- Can have a significant visual impact on landscapes

Wind Turbine Types:

The wind turbine captures the wind's kinetic energy in a rotor consisting of two or more blades mechanically coupled to an electrical generator. The turbine is mounted on a tall tower to enhance the energy capture. Numerous wind turbines are installed at one site to build a wind farm of the desired power generation capacity. Obviously, sites with steady high wind produce more energy over the year. Two distinctly different configurations are available for turbine design, the horizontal axis configuration and the vertical-axis configuration. The horizontal-axis machine has been the standard in Denmark from the beginning of the wind power industry. Therefore, it is often called the Danish wind turbine. The vertical-axis machine has the shape of an egg beater and is often called the Darrieus rotor after its inventor. It has been used in the past because of its specific structural advantage. However, most modern wind turbines use a horizontal axis design. Except for the rotor, most other components are the same in both designs, with some differences in their placements.

Vertical-axis wind turbines

Vertical-axis wind turbines (VAWTs) are a type of wind turbine where the main rotor shaft is set transverse to the wind (but not necessarily vertically) while the main components are located at the base of the turbine. This arrangement allows the generator and gearbox to be located close to the ground, facilitating service and repair. VAWTs do not need to be pointed into the wind,[1][2] which removes the need for wind-sensing and orientation mechanisms. Major drawbacks for the early designs (Savonius, Darrieus and giromill) included the significant torque variation or "ripple" during each revolution, and the large bending moments on the blades. Later designs addressed the torque ripple issue by sweeping the blades helically. A VAWT tipped sideways, with the axis perpendicular to the wind streamlines, functions similarly. A more general term that includes this option is "transverse axis wind turbine" or "cross-flow wind turbine." For example, the original Darrieus patent, US Patent 1835018, includes both options. Drag-type VAWTs such as the Savonius rotor typically operate at lower tipspeed ratios than lift-based VAWTs such as Darrieus rotors and cyclo turbines.

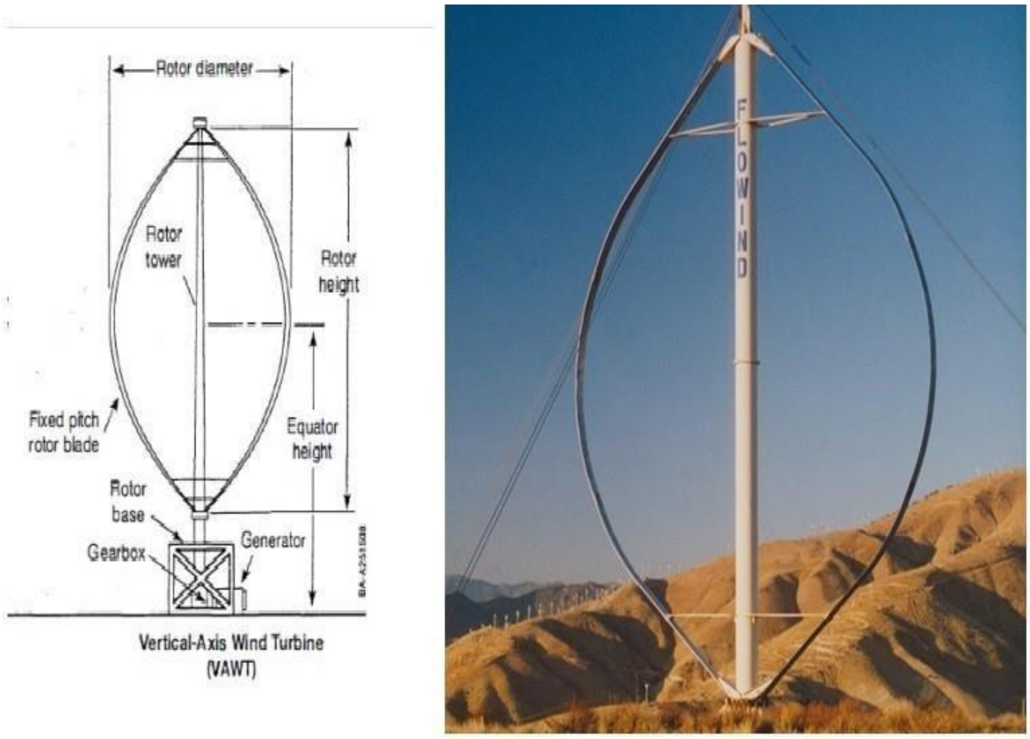


Figure Vertical-axis wind turbines

Advantages

VAWTs offer a number of advantages over traditional horizontal-axis wind turbines (HAWTs):

- They are omni-directional and do not need to track the wind. This means they don't require a complex mechanism and motors to yaw the rotor and pitch the blades.
- Ability to take advantage of turbulent and gusty winds. Such winds are not harvested by HAWTs, and in fact cause accelerated fatigue for HAWTs.
- Wings of the Darrieus type have a constant chord and so are easier to manufacture than the blades of a HAWT, which have a much more complex shape and structure.
- Can be grouped more closely in wind farms, increasing the generated power per unit of land area.
- Can be installed on a wind farm below the existing HAWTs; this will improve the efficiency (power output) of the existing farm.

Disadvantages

One of the major outstanding challenges facing vertical axis wind turbine technology is dynamic stall of the blades as the angle of attack varies rapidly. The blades of a VAWT are fatigue-prone due to the wide variation in applied forces during each rotation. This can be overcome by the use of modern composite materials and improvements in design - including the use of aerodynamic wing tips that cause the spreader wing connections to have a static load. The vertically oriented blades can twist and bend during each turn, causing them to break apart. VAWTs have proven less reliable than HAWTs, although modern designs of VAWTs have overcome many of the issues associated with early designs.

Horizontal-axis wind turbines

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servomotor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator. Any solid object produces a wake behind it, leading to fatigue failures, so the turbine is usually positioned upwind of its supporting tower. Downwind machines have been built, because they don't need an additional mechanism for keeping them in line with the wind. In high winds, the blades can also be allowed to bend which reduces their swept area and thus their wind resistance. In upwind designs, turbine blades must be made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.

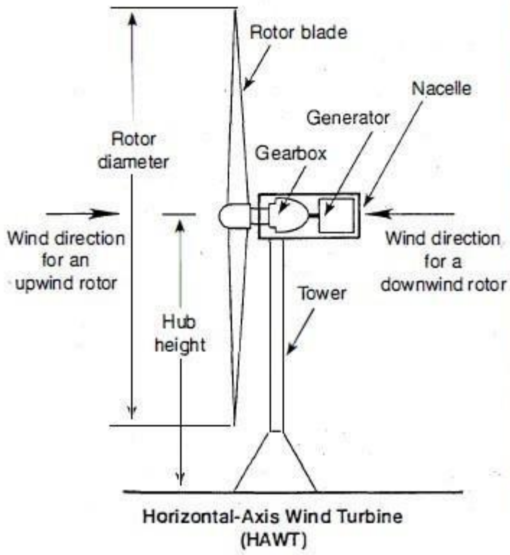


Figure Horizontal-axis wind turbines

Advantages

- Variable blade pitch, which gives the turbine blades the optimum angle of attack. Allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.
- The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up, the wind speed can increase by 20% and the power output by 34%.

Disadvantages

- Taller masts and blades are more difficult to transport and install. Transportation and installation can now cost 20% of equipment costs.
- Stronger tower construction is required to support the heavy blades, gearbox, and generator.
- Reflections from tall HAWTs may affect side lobes of radar installations creating signal clutter, although filtering can suppress it.
- Mast height can make them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.

Components of wind turbine:

- **Rotor:**

The portion of the wind turbine that collects energy from the wind is called the rotor. The rotor usually consists of two or more wooden, fiber glass or metal blades which rotate about an axis (horizontal or vertical) at a rate determined by the wind speed and the shape of the blades. The blades are attached to the hub, which in turn is attached to the main shaft.

- **Gearbox**

The gearbox alters the rotational velocity of the shaft to suit the generator

- **Generator**

The generator is a device that produces electricity when mechanical work is given to the system.

- **Control and protection system**

The protection system is like a safety feature that makes sure that the turbine will not be working under dangerous condition. This includes a brake system triggered by the single of higher wind speeds to stop the rotor from movement under excessive wind gusts.

- **Tower**

The tower is the main shaft that connects the rotor to the foundation. It also raises the rotor high in the air where we can find stronger winds.

- **Foundation**

The foundation or the base supports the entire wind turbine and make sure that it is well fixed onto the ground or the roof for small household wind turbines. This is usually consists of a solid concrete assembly around the tower to maintain its structural integrity.

- **Tip Speed Ratio:**

The tip-speed is the ratio of the rotational speed of the blade to the wind speed. The larger this ratio, the faster the rotation of the wind turbine rotor at a given wind speed.

7. Explain the impacts of renewable energy generation on environment.(APR/MAY 2017) (M.E-NOV/DEC2013)

Introduction

Today, renewable energy provides only a tiny fraction of its potential electricity output worldwide. But numerous studies have repeatedly shown that renewable energy can be rapidly deployed to provide a significant share of future electricity needs, even after accounting for potential constraints In accordance with REN21 Renewable 2010 Global Status Report renewable energy replaces conventional fuels in four distinct areas: electricity generation, hot water/space heating, motor fuels, and rural (off-grid) energy services:

1. **Power generation**

Renewable energy provides 19% of electricity generation worldwide. Renewable power generators are spread across many countries, and wind power alone already provides a significant share of electricity in some areas: for example, 14% in the U.S. state of Iowa, 40% in the northern German state of Schleswig-Holstein, and 49% in Denmark. Some countries get most of their power from renewable, including Iceland (100%), Norway (98%), Brazil (86%), Austria (62%), New Zealand (65%), and Sweden (54%).

2. Heating

Solar hot water makes an important contribution to renewable heat in many countries, most notably in China, which now has 70% of the global total (180 GWh). Most of these systems are installed on multi-family apartment buildings and meet a portion of the hot water needs of an estimated 50– 60 million households in China. Worldwide, total installed solar water heating systems meet a portion of the water heating needs of over 70 million households. The use of biomass for heating continues to grow as well. In Sweden, national use of biomass energy has surpassed that of oil. Direct geothermal for heating is also growing rapidly.

3. Transport fuels

Renewable bio fuels have contributed to a significant decline in oil consumption in the United States since 2006. The 93 billion litres of bio fuels produced worldwide in 2009 displaced the equivalent of an estimated 68 billion litres of gasoline, equal to about 5% of world gasoline production.

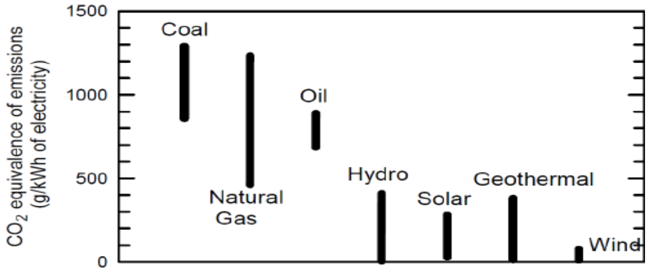
Types of Environmental Impacts

It is important to understand the environmental impacts associated with producing power from renewable sources such as wind, solar, geothermal, biomass, and hydropower. The exact type and intensity of environmental impacts varies depending on the specific technology used, the geographic location, and a number of other factors. Various aspects of the impact of renewable energy sources can be analyzed, including, among others: air and water emissions, waste generations, specially hazardous materials, noise generation, land use, global warming emissions. By understanding the current and potential environmental issues associated with each renewable energy source, we can takes steps to effectively avoid or minimize these impacts as they become a larger portion of our electric supply. A whole series of determinants are favouring the development of the energy sector based on renewable resources: increasing social awareness of the need to limit emissions of harmful substances, legislation, pro-environmental policies of governments, by-laws, support in the form of programmes and financial mechanisms, not to mention the rising costs of energy from conventional sources and the need to ensure energy security. Because the environmental performance of renewable energy systems is greatly improved by: increased efficiency and longer lifetimes, both should be stimulated for the devices and whole systems.

What does it mean: environment?

The Oxford dictionary (Brown, 1993) defines environment as “ the set of circumstances or conditions ... in which a person or community lives, works, develops, etc, or a thing exists or operates; the external conditions affecting the life of a plant or animal”.

In most countries, industrial development is contingent on the developer obtaining a permit from a regulatory authority which involves assessing the impact the development may have on the environment. Preservation of the environment is not merely a local issue but an international concern. The brief comparison between environmental benefits and costs of the use of different types of RES is presented in the Figure and Table .



Environmental benefits	Environmental costs
1. Energy produced by the renewable energy systems 2. Greenhouse gas savings	1. Production of devices and BOS • Greenhouse gas emissions • Heavy metals emissions • Energy used (Energy pay-back time[1]) 2. Wastes generated by different RES industry

Environmental Impacts of Different Technologies

Environmental Impacts of Wind Power

A wind farm, when installed on agricultural land, has one of the lowest environmental impacts of all energy sources: it occupies less land area per kilowatt-hour (kWh) of electricity generated than any other energy conversion system, apart from rooftop solar energy, and is compatible with grazing and crops; it generates the energy used in its construction in just 3 months of operation, yet its operational lifetime is 20–25 years; greenhouse gas emissions and air pollution produced by its construction are very tiny and declining. There are no emissions or pollution produced by its operation; in substituting for base-load (mostly coal power) wind power produces a net decrease in greenhouse gas emissions and air pollution, and a net increase in biodiversity; modern wind turbines are almost silent and rotate so slowly (in terms of revolutions per minute) that they are rarely a hazard to birds. Modern wind turbine designs have significantly reduced the noise from turbines. Turbine designers are working to minimise noise, as noise reflects lost energy and output. Noise levels at nearby residences are managed through the siting of turbines, the approvals process for wind farms and operational management of the wind farm. The noise limit for wind farms is 35 A-weighted decibels, which is usually around 5 A weighted decibels above a quiet countryside. Alternatively, the limit is 5 A-weighted decibels above the level of background noise (i.e. without wind farm noise), if that is greater than 35 A-weighted decibels. Low frequency sound and infrasound (ie usually beneath the threshold of human hearing) are everywhere in the environment. They are emitted from natural sources such as wind and rivers and artificial sources such as traffic and air conditioning. Modern turbine designs which locate the blades upwind instead of downwind have significantly reduced the level of infrasound. Scientific and health authorities have found the low level of infrasound emitted by wind turbines pose no health risks. Wind turbines may create shadow flicker on nearby residences when the sun passes behind the turbine. However, this can easily be avoided by locating the wind farm to avoid unacceptable shadow flicker, or turning the turbine off for the few minutes of the day when the sun is at the angle that causes flicker. Shadow flicker is considered in the NSW development assessment process to ensure potential impacts are addressed. Many energy policy studies have noted how wind turbines present direct and indirect hazards to birds, other avian species, and bats [5], [6]. Birds can directly smash into moving or even stationary turbine blades, crash into towers and nacelles, and collide with local distribution lines. These risks are exacerbated when turbines are placed on ridges and upwind slopes or built close to migration routes. Some species, such as bats, face additional risks from the rapid reduction in air pressure near turbine blades, which can cause internal haemorrhaging. For fossil-fuelled power stations, the most significant fatalities come from climate change, which is altering weather patterns and destroying habitats that birds depend on. For nuclear power plants, the risk is almost equally spread across hazardous pollution at uranium mine sites and collisions with draft cooling structures.

Environmental Impacts of Solar Power

Photovoltaic's is now a proven technology which is inherently safe, as opposed to some dangerous electricity generating technologies. Over its estimated life a photovoltaic module will produce much more electricity than was used in its production. A 100 W module will prevent the emission of over two tonnes of CO2. Photovoltaic systems make no noise and cause no pollution while in operation. PV cell technologies that have relatively lower environmental risks compared to other types of electric sources. However, chemicals used in PV cells could be released to air, surface water, and groundwater in the manufacturing facility, the installation site, and the disposal or recycling facility. The production of photovoltaic devices involves the use of a variety of chemicals and materials. The amounts and types of chemicals used will vary depending upon the type of cell being produced. Based on a review of the chemical information reported, it appears that most of the chemicals used by the manufacturing companies are not released in reportable quantities. The releases of chemicals to the air from the photovoltaic facilities were reported as both air stack emissions and fugitive air emissions. The chemicals released in the largest quantities in air stack emissions included 1, 1, 1-trichloroethane, acetone, ammonia, isopropyl alcohol, and methanol. The scale of the system plays a significant role in the level of environmental impact. Depending on their location, larger utility-scale solar facilities can raise concerns about land degradation and habitat loss and impacts from utility-scale solar systems can be minimized by siting them at lower-quality locations such as abandoned mining land, or existing transportation and transmission corridors. Solar PV cells do not use water for generating electricity. However, as in all manufacturing processes, some water is used to manufacture solar PV components. Concentrating solar thermal plants (CSP), like all thermal electric plants, require water for cooling. Water use depends on the plant design, plant location, and the type of cooling system.

Environmental Impacts of Geothermal Energy

Geothermal power is a relatively benign source of energy. For the most part, the impacts of development are positive. Worldwide geothermal energy utilization increases yearly because it is an attractive alternative to burning imported and domestic fossil fuels. Electricity generation from geothermal resources involves much lower greenhouse gas (GHG) emission rates than that from fossil fuels. According to the International Atomic Energy Agency (IAEA), replacing one kilowatt-hour (kWh) of fossil power with a kilowatt-hour of geothermal power reduces the estimated global warming impact by approximately 95%. However, geothermal development could have certain negative impacts if appropriate mitigation actions and monitoring plants are not in place. Any large-scale construction and drilling operation will produce visual impacts on the landscape, create noise and wastes and affect local economies. Some countries have strict environmental regulations regarding some of the impacts associated with geothermal development, and others do not. Environmental issues usually addressed during the development of geothermal fields include air quality, water quality, waste disposal, geologic hazards, noise, biological resources and land use issues. The protection of groundwater is important during the drilling phase. The groundwater is to be managed sustainably. It is part of the ecosystem, is a habitat for animals and plants, and has a role in the livelihood of local residents. The main visual impact during the construction phase is the presence of a drilling rig, but once a project is in the production phase the rig is not required and the energy centre footprint is very small. Because of low emissions, the geothermal power plants also meet the most stringent clean air standards. It should be noted that all geothermal plants have to meet various national and local environmental standards and regulations, although emissions are not routinely measured below a certain threshold, and emissions from geothermal plants typically fall below this threshold. The list of barriers resulting from environmental regulations can be rather long. Environmental regulations should include groundwater protection incl. pressure issues, soil protection but also protocol on micro-seismicity, and surface issues. For work safety, construction and traffic, any legislation applicable for similar activities in mining, drilling, construction, etc. should be applied.

Environmental Impacts of Biomass

Biomass power plants share some similarities with fossil fuel power plants: both involve the combustion of a feedstock to generate electricity. Thus, biomass plants raise similar, but not identical, concerns about air emissions and water use as fossil fuel plants. Biomass power plants, like coal- and natural gas-fired power plants, require water for cooling. Land use impacts from biomass power production are driven primarily by the type of feedstock: either a waste stream or an energy crop that is grown specifically for generating electricity. There are global warming emissions associated with growing and harvesting biomass feedstock, transporting feedstock to the power plant, and burning or gasifying the feedstock. Transportation and combustion emissions are roughly equivalent for all types of biomass. However, global warming emissions from the sourcing of biomass feedstock vary widely. It was once commonly thought that biomass had net zero global warming emissions, because the growing biomass absorbed an equal amount of carbon as the amount released through combustion, but now it is understood that some biomass feedstock sources are associated with substantial global warming emissions. Beneficial biomass resources include energy crops that do not compete with food crops for land, portions of crop residues such as wheat straw or corn Stover, sustainably-harvested wood and forest residues, and clean municipal and industrial wastes.

Environmental Impacts of Hydroelectric Power

Although hydropower has no air quality impacts, construction and operation of hydropower dams can significantly affect natural river systems as well as fish and wildlife populations. Assessment of the environmental impacts of a specific hydropower facility requires case-by-case review. Negative impact of dams are as follows: in flat basins large dams cause flooding of large tracts of land, destroying local animals and habitats; people have to be displaced causing change in life style and customs - about 40 to 80 million people have been displaced physically by dams worldwide; large amounts of plant life are submerged and decay an aerobically; the migratory pattern of river animals like salmon and trout are affected; dams restrict sediments that are responsible for the fertile lands downstream; salt water intrusion into the deltas means that the saline water cannot be used for irrigation; large dams are breeding grounds for mosquitoes and cause the spread of disease; dams serve as a heat sink, and the water is hotter than the normal river water - this warm water when released into the river downstream can affect animal life.

8. Describe the consequences of green house effect. (M.E-APR/MAY 2013)

Life on earth is made possible by energy from the sun, which arrives mainly in the form of visible light. About 30 percent of the sunlight is scattered back into space by outer atmosphere and the balance 70 percent reaches the earth's surface, which reflects it in form of infrared radiation. The escape of slow moving infrared radiation is delayed by the green house gases. A thicker blanket of greenhouse gases traps more infrared radiation and increase the earth's temperature.

Greenhouse gases makeup only 1 percent of the atmosphere, but they act as a blanket around the earth, or like a glass roof of a greenhouse and keep the earth 30 degrees warmer than it would be otherwise - without greenhouse gases, earth would be too cold to live. Human activities that are responsible for making the greenhouse layer thicker are emissions of carbon dioxide from the combustion of coal, oil and natural gas; by additional methane and nitrous oxide from farming activities and changes in land use; and by several man made gases that have a long life in the atmosphere.

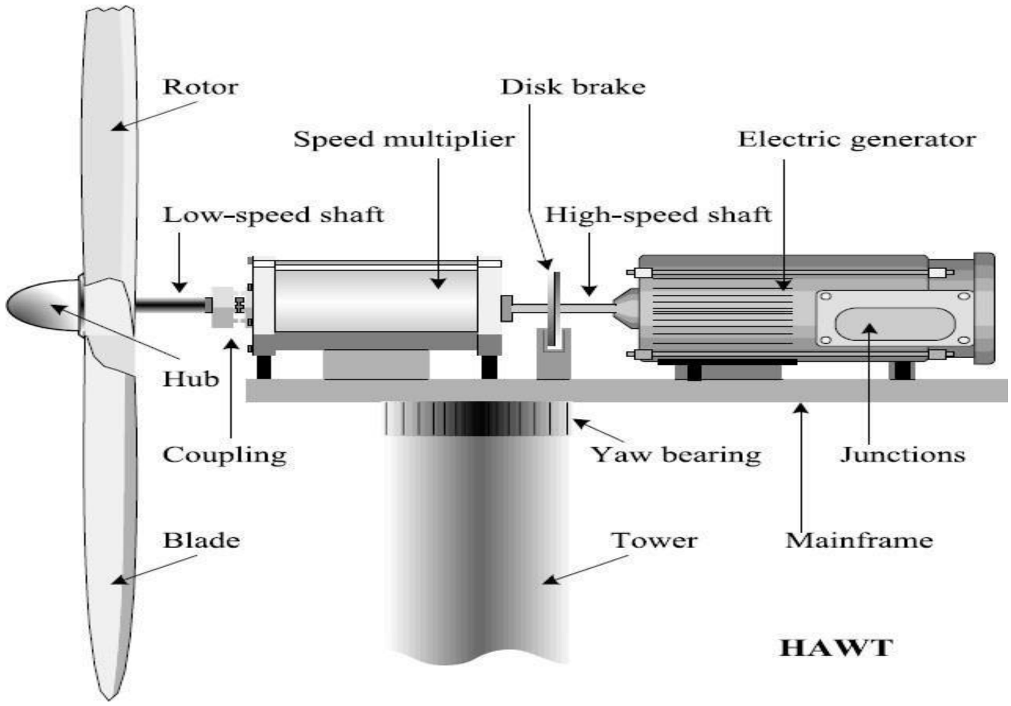
The increase in greenhouse gases is happening at an alarming rate. If greenhouse gases emissions continue to grow at current rates, it is almost certain that the atmospheric levels of carbon dioxide will increase twice or thrice from pre-industrial levels during the 21st century.

Even a small increase in earth's temperature will be accompanied by changes in climate such as cloud cover, precipitation, wind patterns and duration of seasons. In an already highly crowded and stressed earth, millions of people depend on weather patterns, such as monsoon rains, to continue as they have in the past. Even minimum changes will be disruptive and difficult. Carbon dioxide is responsible for 60 percent of the "enhanced greenhouse effect". Humans are burning coal, oil and natural gas at a rate that is much faster than the rate at which these fossil fuels were created. This is releasing the carbon stored in the fuels into the atmosphere and upsetting the carbon cycle (a precise balanced system by which carbon is exchanged between the air, the oceans and land vegetation taking place over millions of years). Currently, carbon dioxide levels in the atmospheric are rising by over 10 percent every 20 years.

9. Explain wind energy conversion system with neat schematic. (M.E-NOV/DEC 2010)

WECS Technology

A WECS is a structure that transforms the kinetic energy of the incoming air stream into electrical energy. This conversion takes place in two steps, as follows. The extraction device, named *wind turbine rotor* turns under the wind stream action, thus harvesting a mechanical power. The rotor drives a rotating electrical machine, the generator, which outputs electrical power. Several wind turbine concepts have been proposed over the years. A historical survey of wind turbine technology is beyond the scope here, but someone interested can find that in Ackermann (2005). There are two basic configurations, namely *vertical axis wind turbines* (VAWT) and, *horizontal axis wind turbines* (HAWT). Today, the vast majority of manufactured wind turbines are horizontal axis, with either two or three blades. HAWT is comprised of the tower and the nacelle, mounted on the top of the tower (Figure). Except for the energy conversion chain elements, the nacelle contains some control subsystems and some auxiliary elements (*e.g.*, cooling and braking systems, *etc.*).



The energy conversion chain is organised into four subsystems:

- aerodynamic subsystem, consisting mainly of the turbine rotor, which is composed of blades, and turbine hub, which is the support for blades;
- drive train, generally composed of: low-speed shaft – coupled with the turbine
- hub, speed multiplier and high-speed shaft – driving the electrical generator;
- electromagnetic subsystem, consisting mainly of the electric generator;
- Electric subsystem, including the elements for grid connection and local grid.

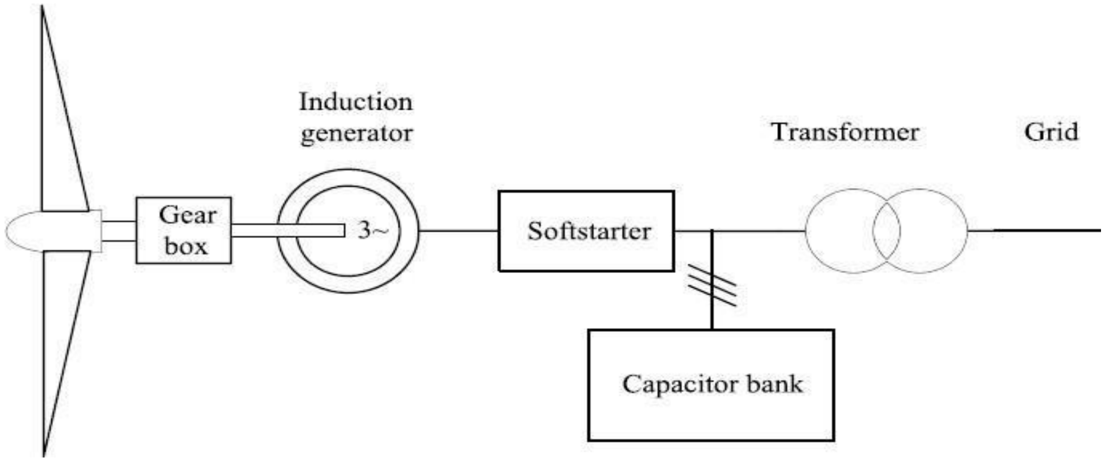
All wind turbines have a mechanism that moves the nacelle such that the blades mare perpendicular to the wind direction. This mechanism could be a tail vane (small wind turbines) or an electric yaw device (medium and large wind turbines). Concerning the power conversion chain, it involves naturally some loss of power. Because of the nonzero wind velocity behind the wind turbine rotor one can easily understand that its efficiency is less than unity. Also, depending on the operating regime, both the motion transmission and the electrical power generation involve losses by friction and by Joule effect respectively. Being directly coupled one with the other, the energy conversion chain elements dynamically interact, mutually influencing their operation.

Power Generation System

The electrical power generation structure contains both electromagnetic and electrical subsystems. Besides the electrical generator and power electronics converter it generally contains an electrical transformer to ensure the grid voltage compatibility. However, its configuration depends on the electrical machine type and on its grid interface.

Fixed-speed WECS

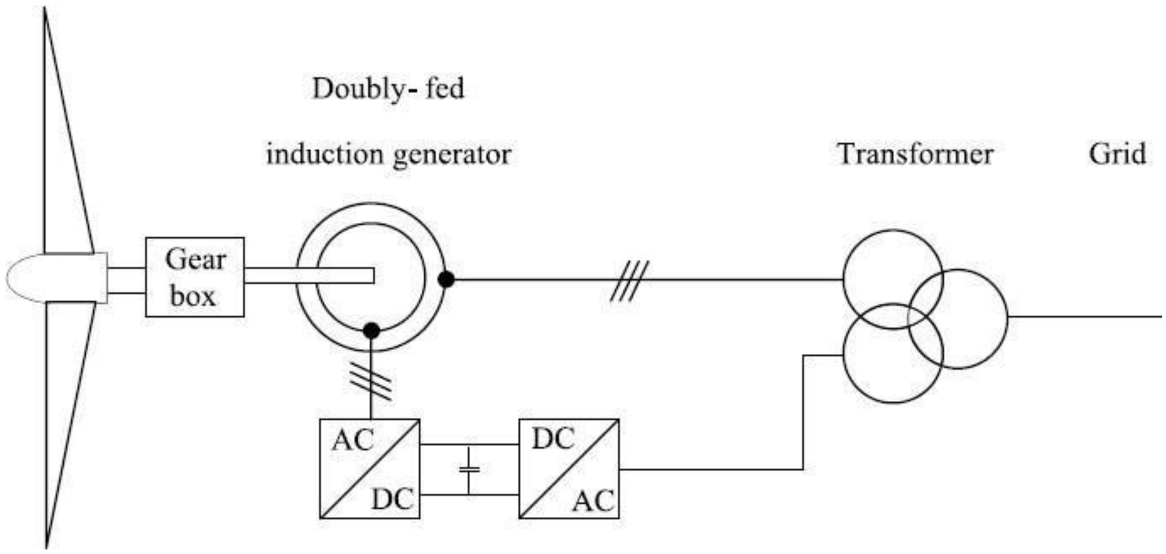
Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed WECS are typically equipped with squirrel-cage induction generators (SCIG), soft starter and capacitor bank and they are connected directly to the grid, as shown in Figure below . This WECS configuration is also known as the " *Danish concept*" because it was developed and widely used in Denmark.



Initially, the induction machine is connected in motoring regime such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode. As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency. Furthermore, the wind velocity variations will induce only small variations in the generator speed. As the power varies proportionally with the wind speed cubed, the associated electromagnetic variations are important. SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. One of the major drawbacks of the SCIG is the fact that there is a unique relation between active power, reactive power, terminal voltage and rotor speed. That means that an increase in the active power production is possible only with an increase in the reactive power consumption, leading to a relatively low full-load power factor. In order to limit the reactive power absorption from the grid, SCIG based WECS are equipped with capacitor banks. The soft starter's role is to smooth the inrush currents during the grid connection. SCIG-based WECS are designed to achieve maximum power efficiency at a unique wind speed. In order to increase the power efficiency, the generator of some fixed-speed WECS has two winding sets, and thus two speeds. The first set is used at low wind speed (typically eight poles) and the other at medium and large wind speeds (typically four to six poles). Fixed-speed WECS have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed-speed operation, the mechanical stress is important. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant, stuck to the grid frequency.

Variable-speed WECS

Variable-speed wind turbines are currently the most used WECS. The variable speed operation is possible due to the power electronic converters interface, allowing a full (or partial) decoupling from the grid. The doubly-fed-induction-generator (DFIG)-based WECS (Figure below), also known as improved variable-speed WECS, is presently the most used by the wind turbine industry.

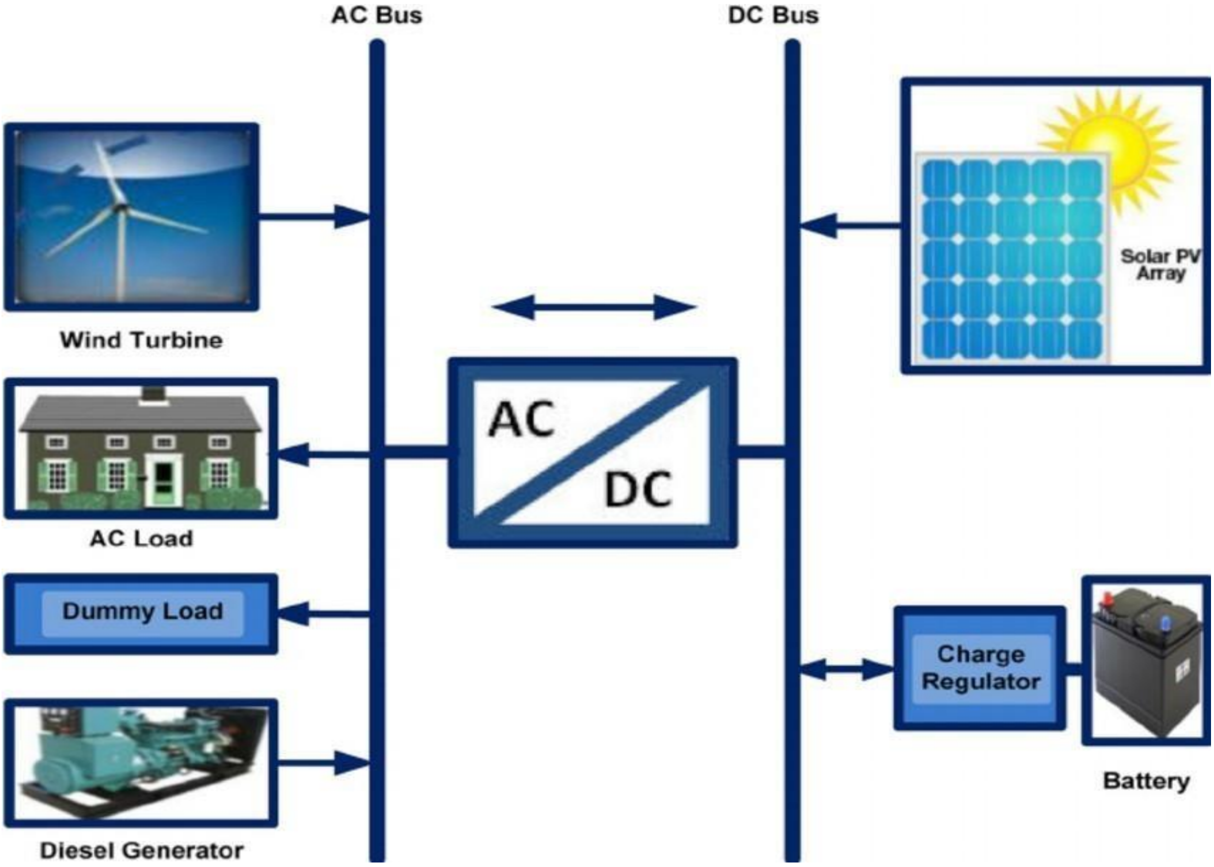


The DFIG is a WRIG with the stator windings connected directly to the three phases, constant-frequency grid and the rotor windings connected to a back-to-back (AC–AC) voltage source converter. Thus, the term “doubly-fed” comes from the fact that the stator voltage is applied from the grid and the rotor voltage is impressed by the power converter. This system allows variable-speed operation over a large, but still restricted, range, with the generator behaviour being governed by the power electronics converter and its controllers. The power electronics converter comprises of two IGBT converters, namely the rotor side and the grid side converter, connected with a direct current (DC) link. Without going into details about the converters, the main idea is that the rotor side converter controls the generator in terms of active and reactive power, while the grid side converter controls the DC-link voltage and ensures operation at a large power factor. The stator outputs power into the grid all the time. The rotor, depending on the operation point, is feeding power into the grid when the slip is negative (over synchronous operation) and it absorbs power from the grid when the slip is positive (sub-synchronous operation). In both cases, the power flow in the rotor is approximately proportional to the slip (Lu. The size of the converter is not related to the total generator power but to the selected speed variation range. Typically a range of 40% around the synchronous speed is used. DFIG-based WECS are highly controllable, allowing maximum power extraction over a large range of wind speeds. Furthermore, the active and reactive power control is fully decoupled by independently controlling the rotor currents. Finally, the DFIG-based WECS can either inject or absorb power from the grid, hence actively participating at voltage control.

10. Explain in detail about Hybrid Renewable Energy Systems.

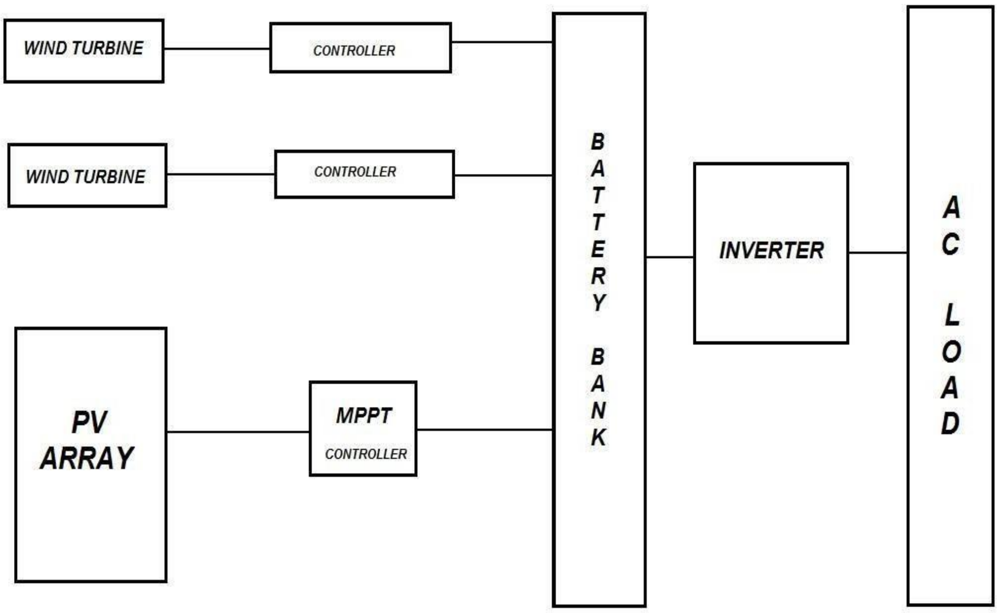
Introduction

Rapid depletion of fossil fuels has necessitated an urgent need for alternative sources of energy to cater the continuously increasing energy demand. Another key reason to reduce our consumption of fossil fuels is the growing global warming phenomena. Environmentally friendly power generation technologies will play an important role in future power supply. The renewable energy technologies include power generation from renewable energy sources, such as wind, PV(photovoltaic), MH(micro hydro), biomass, ocean wave, geothermal and tides. In general, the key reason for the deployment of the above energy systems are their benefits, such as supply security, reduced carbon emission, and improved power quality, reliability and employment opportunity to the local people. Since the RE resources are intermittent in nature therefore, hybrid combinations of two or more power generation technologies, along with storage can improve system performance. Hybrid Renewable Energy System (HRES) combines two or more renewable energy resources with some conventional source (diesel or petrol generator) along with storage, in order to fulfil the demand of an area. An example of PV-wind diesel generator HRES is shown in figure below.



Wind- solar Hybrid Renewable energy system

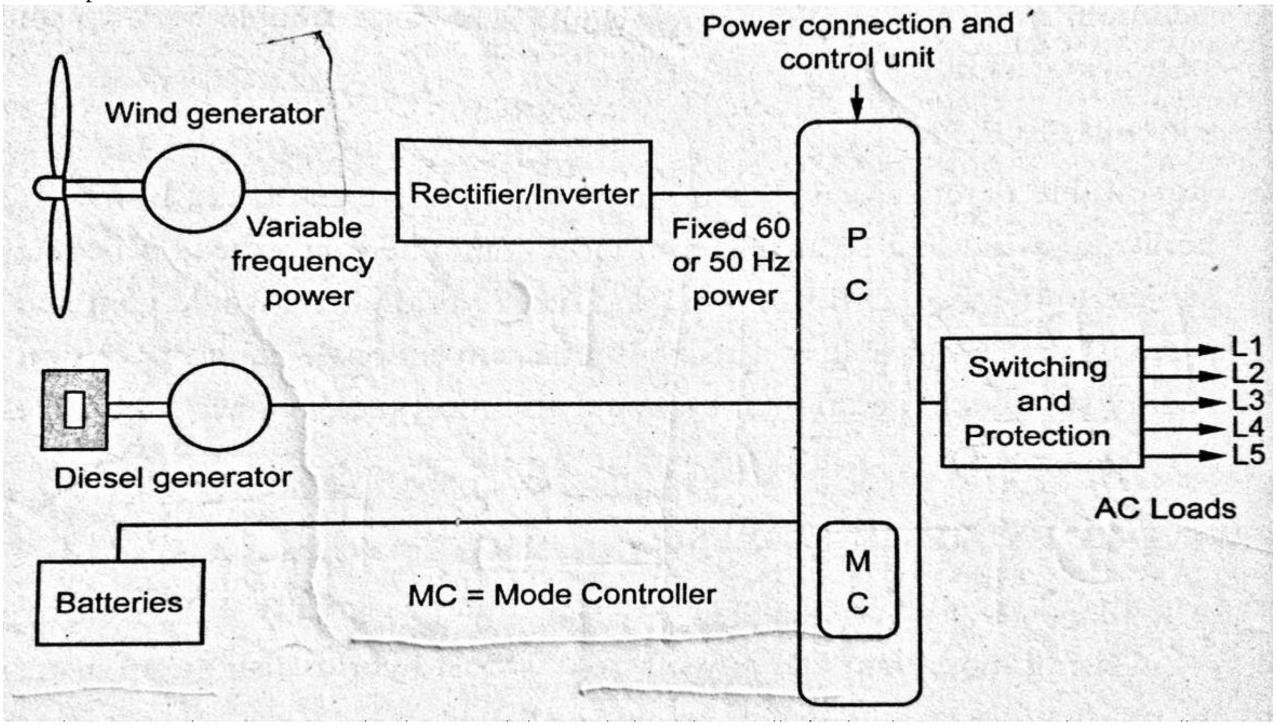
Another example of a hybrid energy system is a photovoltaic array coupled with a wind turbine. This would create more output from the wind turbine during the winter, whereas during the summer, the solar panels would produce their peak output. Hybrid energy systems often yield greater economic and environmental returns than wind, solar, geothermal or trigeneration stand-alone systems by themselves.



Wind-PV hybrid with Diesel

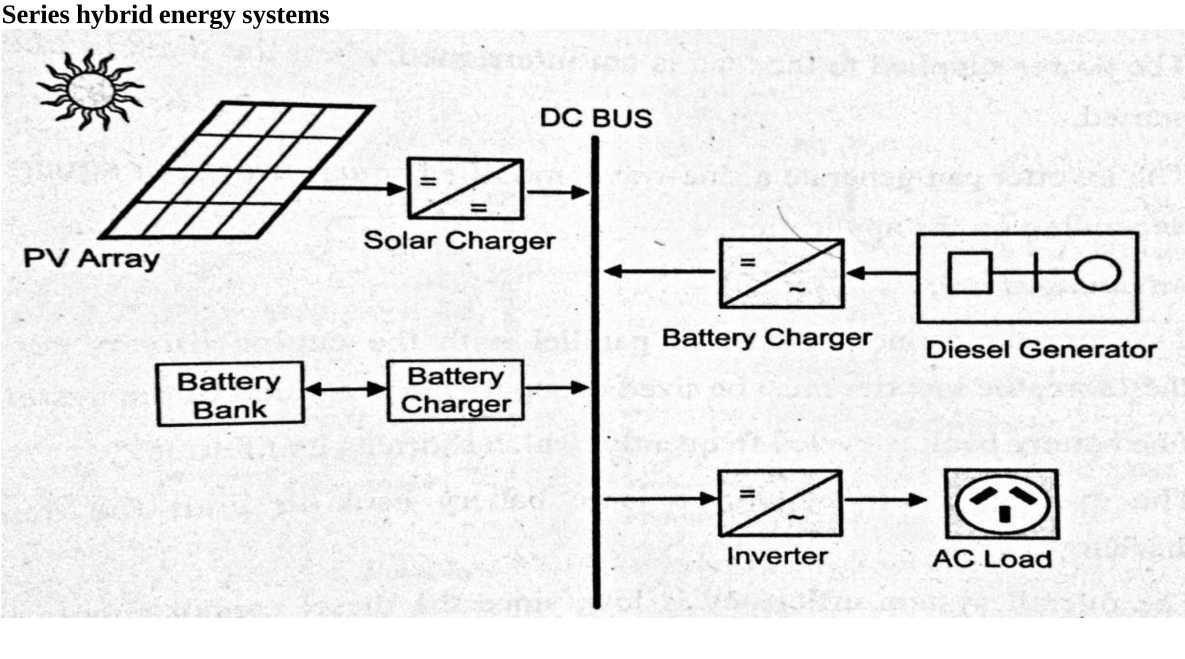
The certainty of meeting load demands at all times is greatly enhanced by the hybrid system using more than one power source. Most hybrids use diesel generator with PV or wind, since diesel provides more predictable power on demand. In some hybrids, batteries are used in addition to the diesel generator. The batteries meet the daily load fluctuation, and the diesel generator takes care of long term fluctuations. Below figure is a schematic layout of wind/diesel/battery hybrid system. The power connection and control unit (PCCU) provides a central place to make organised connections of most system components.

In addition, the PCCU houses the following components
Battery charge and discharge regulators
Transfer switches and protection circuit breakers
Power flow meters
Mode controller
The below figure is a commercially available PCCU for hybrid power system. The transient analysis of integrated wind-PV-diesel requires an extensive model that takes the necessary input data and event definitions for computer simulation.



TYPES OF PV-DIESEL HYBRID SYSTEMS
Series hybrid energy systems
Switched hybrid energy systems
Parallel hybrid energy systems

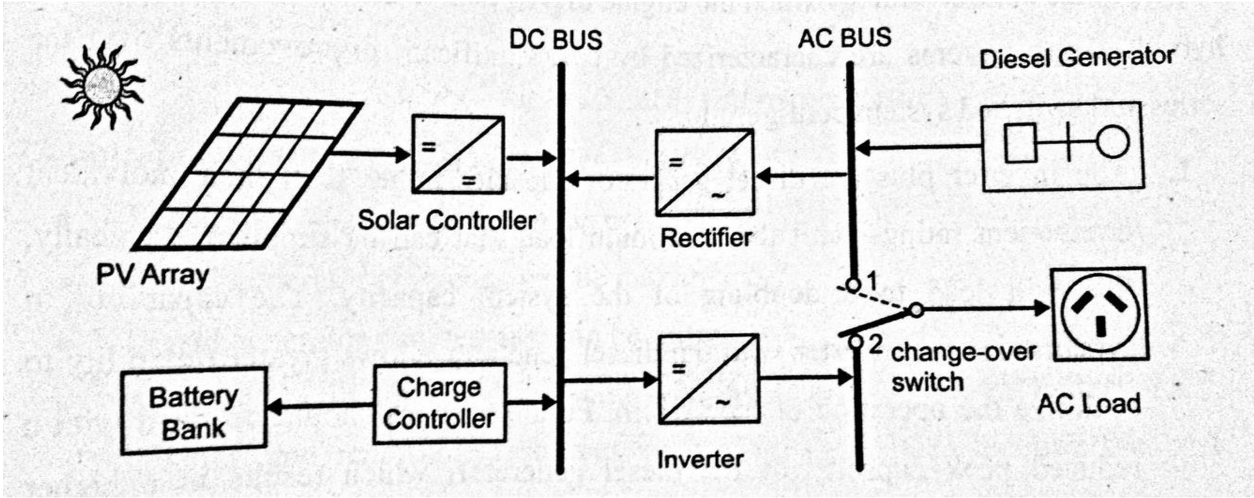
Series hybrid energy systems



The above figure shows a series PV-diesel hybrid system. to ensure reliable operation of series hybrid energy systems, both the diesel generator and inverter have to be sized to meet peak loads. AC power delivered to the load is converted from dc to regulated ac by an inverter or a motor generator unit. The power generated by the diesel generator is first rectified and subsequently converted back to ac before being supplied to the load, which leads to significant conversion losses. The solar controller prevents overcharging of the battery bank from PV generator when PV power exceeds the load demand and batteries are fully charged. The system can be operated in manual or automatic mode, with the addition of appropriate battery voltage sensing and start/stop control of engine-driven generator.

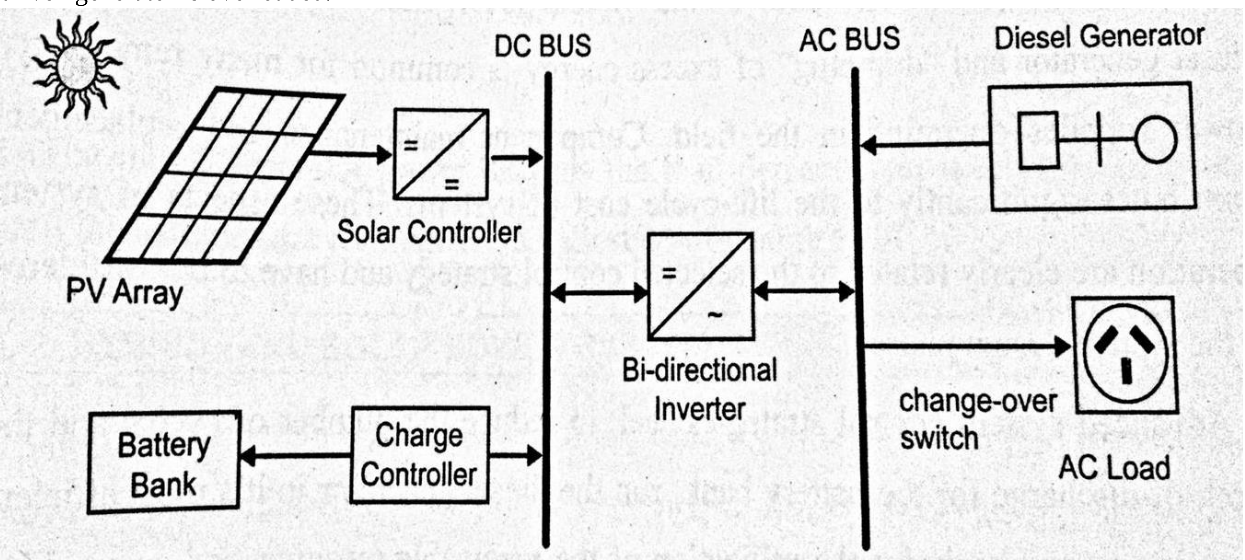
Switched hybrid energy systems

It allows operation with either engine driven generator or the inverter as the ac source, yet no parallel operation of the main generation sources is possible. The diesel generator and renewable energy source can charge the battery bank. The main advantage is that the load can be supplied directly by the engine driven generator, which results in a high overall conversion efficiency. Typically, the diesel generator power will exceed the load demand, with excess energy being used to recharge the battery bank. During periods of low electricity demand the diesel generator is switched off and the load is supplied from the PV array together with stored energy.



Parallel hybrid energy systems

The another configuration called parallel one allows all energy sources to supply the load separately at low or medium load demand, as well as supplying peak loads from combined sources by synchronizing the inverter with alternator output waveform. Such a configuration is represented in the below figure. The bidirectional inverter can charge the battery bank when excess energy is available from engine driven generator, as well as a DC-AC converter. The bidirectional inverter may provide peak saving as part of control strategy when engine driven generator is overloaded.



Advantages of Hybrid Renewable Energy Systems:

- Higher total energy efficiency
- More reliable
- Operational flexibility
- Lower emission

Disadvantages of Hybrid Renewable Energy Systems:

Most of us already know how a solar/wind/biomass power generating system works, all these generating systems have some or the other drawbacks, like Solar panels are too costly and the production cost of power by using them is generally higher than the conventional process, it is not available in the night or cloudy days. Similarly Wind turbines can’t operate in high or low wind speeds and Biomass plant collapses at low temperatures.

UNIT-2

PART-B

1. Draw the schematic of double fed induction generator and explain its construction and principle of operation in detail. (M.E-NOV/DEC2016)

Double Fed Induction Generator (DFIG)

Wound rotor induction generators (WRIGs) are provided with three phase windings on the rotor and on the stator. They may be supplied with energy at both rotor and stator terminals. This is why they are called doubly fed induction generators (DFIGs) or double output induction generators (DOIGs). Both motoring and generating operation modes are feasible, provided the power electronics converter that supplies the rotor circuits via slip-rings and brushes is capable of handling power in both directions. As a generator, the WRIG provides constant (or controlled) voltage *Vs* and frequency *f*1 power through the stator, while the rotor is supplied through a static power converter at variable voltage *Vr* and frequency *f*2. The rotor circuit may absorb or deliver electric power. As the number of poles of both stator and rotor windings is the same, at steady state, according to the frequency theorem, the speed ω_m is as follows:

$$\omega_m = \omega_1 \pm \omega_2; \quad \omega_m = \Omega_R \cdot p_1$$

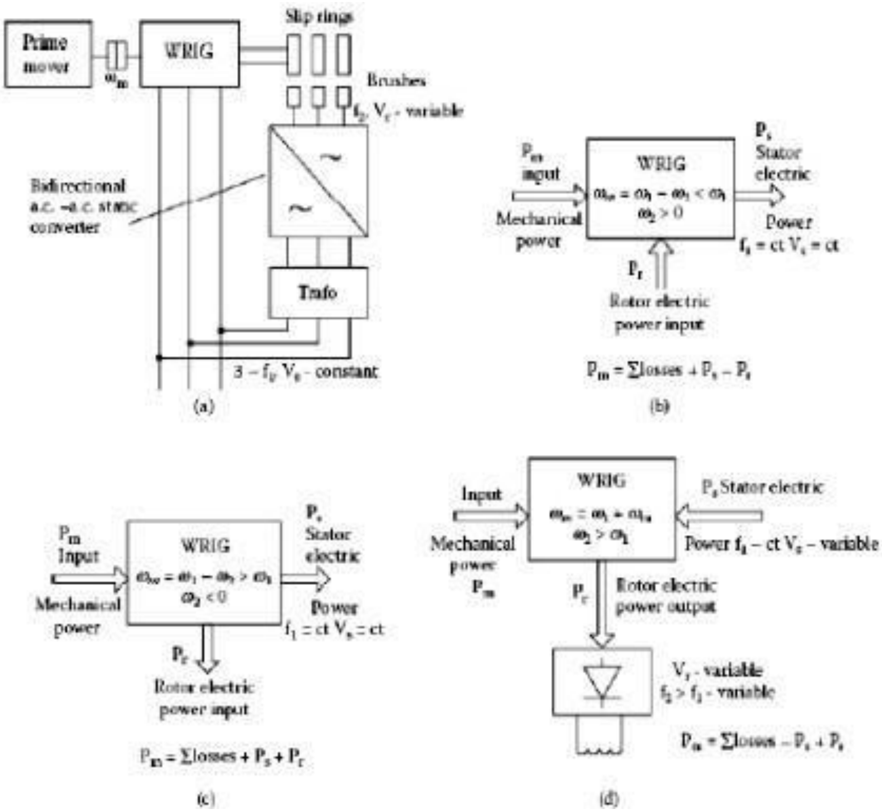
where

p_1 is the number of pole pairs

Ω_R is the mechanical rotor speed

The sign is positive (+) in above Equation when the phase sequence in the rotor is the same as in the stator and $\omega_m<\omega_1$, that is sub synchronous operation. The negative (-) sign in the above equation corresponds to an inverse phase sequence in the rotor when $\omega_m>\omega_1$ that is, super synchronous operation. For constant frequency output, the rotor frequency ω_2 has to be modified in step with the speed variation. This way, variable speed at constant frequency (and voltage) may be maintained by controlling the voltage, frequency, and phase sequence in the rotor circuit. It may be argued that the WRIG works as a synchronous generator (SG) with three-phase alternating current (AC) excitation at slip frequency $\omega_2=\omega_1-\omega_m$. However as ω_1 not equal to ω_m, the stator induces voltages in the rotor circuits even at steady state, which is not the case in conventional SGs. Additional power components thus occur. The main operational modes of WRIG are depicted in Figure a through Figure d (basic configuration shown in Figure a). The first two modes (Figure b and Figure) refer to the already defined sub synchronous and super synchronous generations. For motoring, the reverse is true for the rotor circuit; also, the stator absorbs active power for motoring. The slip *S* is defined as follows:

$$S = \frac{\omega_2}{\omega_1} \quad \begin{matrix} > 0; \text{ subsynchronous operation} \\ < 0; \text{ supersynchronous operation} \end{matrix}$$



The main output active power is delivered through the stator, but in super synchronous operation, a good part, about slip stator powers (SPs), is delivered through the rotor circuit. With limited speed variation range, say from *Smax* to *-Smax*, the rotor-side static converter rating — for zero reactive power capability on the rotor side — would be $P_{conv} = |S_{max}| P_{max}$ With *Smax* typically equal to ±0.2 to 0.25, the static power converter ratings and costs would correspond to 20 to 25% of the stator delivered output power. At maximum speed, the WRIG will deliver increased electric power, *Pmax*

$$P_{max} = P_s + P_{rmax} = P_s + |S_{max}| P_s$$

With the WRIG designed at *Ps* for ω*m*=*ω* 1 speed. The increased power is delivered at higher than rated speed:

$$\omega_{max} = \omega_1 (1 + |S_{max}|)$$

Consequently, the WRIG is designed electrically for *Ps at ωm* = *ω*1, but mechanically at *wm max* and *Pmax*. The capability of a WRIG to deliver power at variable speed but at constant voltage and frequency represents an asset in providing more flexibility in power onversion and also better stability in frequency and voltage control in the power systems to which such generators are connected. The reactive power delivery by WRIG depends heavily on the capacity of the rotor-side converter to provide it. When the converter works at unity power delivered on the source side, the reactive power in the machine has to come from the rotor-side converter. However, such a capability is paid for by the increased ratings of the rotor-side converter. As this means increased converter costs, in general, the WRIG is adequate for working at unity power factor at full load on the stator side. Large reactive power releases to the power system are still to be provided by existing SGs or from WRIGs working at synchronism (*S* = 0, ω2 = 0) with the back-toback pulse-width modulated (PWM) voltage converters connected to the rotor controlled adequately for the scope. Wind and small hydro energy conversion in units of 1 megawatt (MW) and more per unit require variable speed to tap the maximum of energy reserves and to improve efficiency and stability limits. High-power units in pump-storage hydro- (400 MW) and even thermo power plants with WRIGs provide for extra flexibility for the ever-more stressed distributed power systems of the near future. Even existing (old) SGs may be retrofitted into WRIGs by changing the rotor and its static power converter control. The WRIGs may also be used to generate power solely on the rotor side for rectifier loads (Figured). To control the direct voltage (or direct current [DC]) in the load, the stator voltage is controlled, at constant frequency ω_1 by a low-cost alternating current (AC) three-phase voltage changer. As the speed increases, the stator voltage has to be reduced to keep constant the current in the DC load connected to the rotor. If the machine has a large number of poles ($2p1$ = 6, 8, 12), the stator AC excitation input power becomes rather low, as most of the output electric power comes from the shaft (through motion). Such a configuration is adequate for brushless exciters needed for synchronous motors (SMs) or for generators, where field current is needed from zero speed, that is, when full-power converters are used in the stator of the respective SMs or SGs. With $2p1 = 8$, $n = 1500$ rpm, and $f1 = 50$ Hz, the frequency of the rotor output $f2 = f1 + np1 = 50 + (1500/60)* 4 = 150$ Hz. Such a frequency is practical with standard iron core laminations and reduces the contents in harmonics of the output rectified load current.

Steady state Equations

The emf self induced by stator winding with rotor winding open is as follows:

$$E_1 = \pi\sqrt{2} f_1 W_1 K_{W1} \phi_{10}; \quad (RMS)$$

$$K_{W1} = K_{d1} \cdot K_{y1}$$

The flux per pole ϕ_{10} is

$$\phi_{10} = \frac{2}{\pi} B_{g10} \tau l_i$$

where

l_i is the stack length

τ is the pole pitch

D_{is} is the stator bore diameter

B_{g10} is the airgap fundamental flux density peak value:

$$B_{g10} = \frac{\mu_0 F_{10}}{K_C g (1 + K_s)}$$

F_{10} is the amplitude of stator mmf fundamental per pole

From Equation 1.17, with $\nu = 1$,

$$F_{10} = \frac{3 W_1 K_{W1} I_0 \sqrt{2}}{\pi p_1}$$

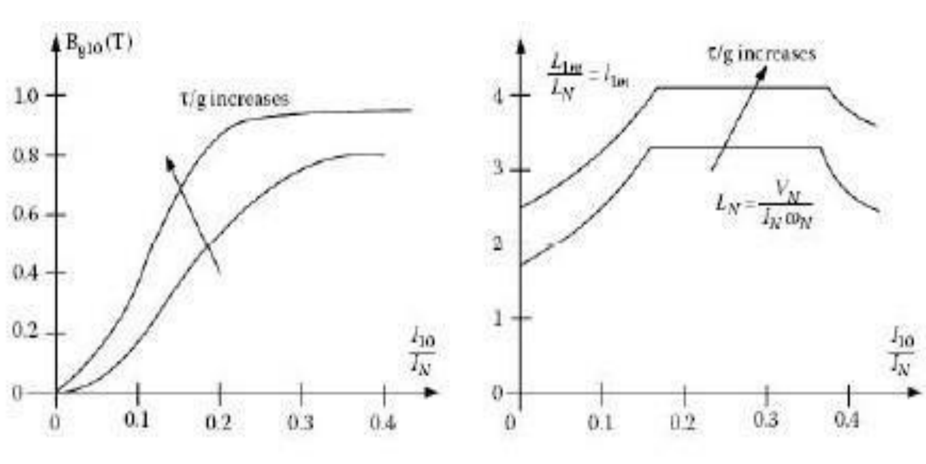


FIGURE Typical airgap flux density (B_{g10}) and magnetization inductance (in per unit [P.U.]) vs. P.U. stator current.

But the same emf E_1 may be expressed as

$$E_1 = \omega_1 L_{1m} \cdot I_{10}$$

So, the main flux, magnetization (cyclic) inductance of the stator — with all three phases active and symmetric — L_{1m} is as follows

$$L_{1m} = \frac{6\mu_0 (W_1 K_{W1})^2 \tau l_i}{\pi^2 p_1 K_C g(1+K_s)}$$

The Carter coefficient $K_C > 1$ accounts for both stator and rotor slot openings ($K_C \approx K_{C1} K_{C2}$). The saturation factor K_S, which accounts for the iron core magnetic reluctance, varies with stator mmf (or current for a given machine), and so does magnetic inductance L_{1m} (Figure).

Besides L_{1m}, the stator is characterized by the phase resistance R_s and leakage inductance L_{sl} [2]. The same stator current induces an emf E_{2s} in the rotor open-circuit windings. With the rotor at speed ω_r — slip $S = (\omega_1 - \omega_r)/\omega_1$ — E_{2s} has the frequency $f_2 = Sf_1$:

$$E_{2s}(t) = E_{2s}\sqrt{2}\cos\omega_2 t$$

$$E_{2s} = \pi\sqrt{2} S f_1 W_2 K_{W2} \phi_{10}$$

Consequently,

$$\frac{E_{2s}}{E_1} = S\frac{W_2 K_{W2}}{W_1 K_{W1}} = S \cdot K_n$$

This rotor emf at frequency Sf_1 in the rotor circuit is characterized by phase resistance $R_r{}^r$ and leakage inductance $L^r{}_{rl}$. Also, the rotor is supplied by a system of phase voltages at the same frequency ω_2 and at a prescribed phase.

The stator and rotor equations for steady-state/phase may be written in complex numbers at frequency ω_1 in the stator and ω_2 in the rotor:

$$(R_s + j\omega_1 L_{sl})\underline{I}_s - \underline{V}_s = \underline{E}_1 \quad at \quad \omega_1$$

$$(R_r^r + jS\omega_1 L_{rl})\underline{I}_r^r - \underline{V}_r^r = \underline{E}_{2s} \quad at \quad \omega_2$$

$$(R_r + jS\omega_1 L_{rl})\underline{I}_r - \underline{V}_r = \frac{\underline{E}_{2s}}{K_{rs}}; \quad E_{2s} = SE_1K_{rs}$$

$$R_r = R_r'/K_{rs}^2 \quad L_{rl} = L_{rl}'/K_{rs}^2$$

$$\underline{V}_r = \underline{V}_r'/K_{rs} \quad \underline{I}_r = \underline{I}_r' \cdot K_{rs}$$

The division of Equation 1.31 by slip S yields the following:

$$\left(\frac{R_r}{S} + j\omega_1 L_{rl}\right)\underline{I}_r - \frac{\underline{V}_r}{S} = \frac{S\underline{E}_1}{S}$$

But, Equation 1.31 may also be interpreted as being "converted" to frequency ω_1, as E_1 is at ω_1 ($E_{2s}/S - E_1$):

$$\left(\frac{R_r}{S} + j\omega_1 L_{rl}\right)\underline{I}_r - \frac{\underline{V}_r}{S} = \underline{E}_1; \quad at\ \omega_1$$

In Equation 1.33, the rotor voltage V_r and current I_r vary with the frequency ω_1 and, thus, are written (in fact) in stator coordinates. A "rotation transformation" has been operated this way. Also, all variables are reduced to the stator. Physically, this would mean that Equation 1.33 refers to a rotor at standstill, which may produce or absorb active power to cover the losses and delivers in motoring the mechanical power of the actual machine it represents.

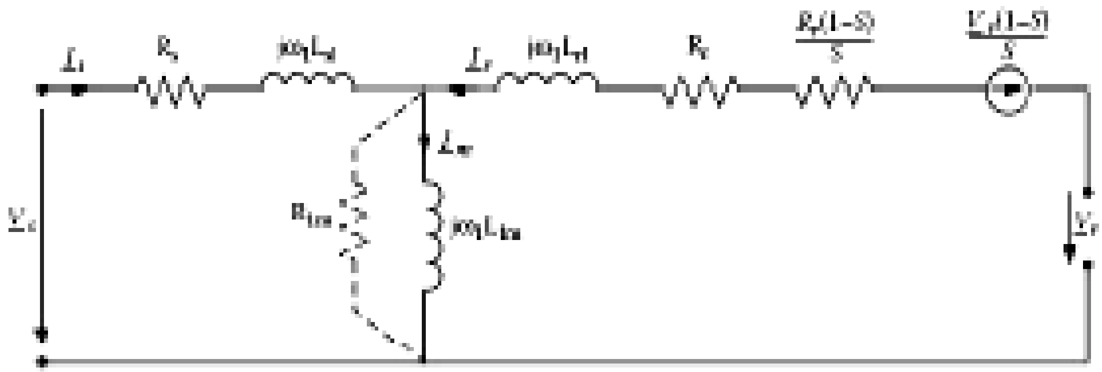
Finally, the emf E_1 may now be conceived to be produced by both I_s and I_r (at the same frequency ω_1), both acting upon the magnetization inductance L_{1m} as the rotor circuit is reduced to the stator:

$$\underline{E}_1 = -j\omega_1 L_{1m}(\underline{I}_s + \underline{I}_r) = -j\omega_1 L_{1m}\underline{I}_m$$

Equivalent circuit:

The equivalent circuit is shown in the below figure

$$p_{cos} = 3R_sI_s^2; \quad p_{cor} = 3R_rI_r^2; \quad p_{Fe} = 3R_{1m}(S\omega_1)I_m^2$$



- The resistance R_{1m} that represents the core losses depends slightly on slip frequency $\omega_2 = S\omega_1$, as non-negligible core losses also occur in the rotor core for $Sf_1 > 5$ Hz.
- The active power balance equations are straightforward, from Figure , as the difference between input electrical powers P_s and P_r and the losses represents the mechanical power P_m:

$$P_m = \left[3\frac{R_r I_r^2}{S} - 3\frac{\text{Re}(I_r^* V_r)}{S}\right](1-S) = T_e \frac{\omega_1}{p_1}(1-S) = P_{elm}(1-S)$$

$$\Sigma_p = p_{con} + p_{cor} + p_{mec} + P_{Fe}$$

P_{elm} is the electromagnetic (through airgap) power.

$$P_s + P_r' = 3\text{Re}(\underline{V}_s \underline{I}_s^*) + 3\text{Re}(\underline{V}_r \underline{I}_r^*) = P_m + \Sigma p$$

T_e is the electromagnetic torque. The sign of mechanical power for given motion direction is used to discriminate between motoring and generating. The positive sign (+) of P_m is considered here for motoring

The motor/generator operation mode is determined by two factors: the sign of slip S and the sign and relative value of the active power input (or extracted) electrically from the rotor P_r (Table 1.1). So, the WRIG may operate as a generator or a motor both subsynchronously ($\omega_r < \omega_1$) and supersynchronously ($\omega_r > \omega_1$). The power signs in Table 1.1 may be portrayed as in Figure

If all the losses are neglected,

$$P_m = -P_r\frac{(1-S)}{S} = P_s + P_r$$

Consequently,

$$P_r = -SP_s$$

The higher the slip, the larger the electric power absorption or delivery through the rotor. Also, it should be noted that in supersynchronous operation, both stator and rotor electric powers add up to convert the mechanical power. This way, up to a point, oversizing, in terms of torque capability, is not required when operation at $S = -S_{max}$ occurs with the machine delivering $P_s(1 + |S_{max}|)$ total electric power.

Reactive power flow is similar. From the equivalent circuit,

$$Q_s + Q_r = 3Imag(\underline{V}_s \underline{I}_s^*) + 3Imag\left(\frac{\underline{V}_r \underline{I}_r^*}{S}\right) = 3\omega_1(L_{sl} I_s^2 + L_{rl} I_r^2 + L_m I_m^2)$$

TABLE 1.1 Operation Modes

S	$0 < S < 1$ Subsynchronous ($\omega_r < \omega_1$)		$S < 0$ Supersynchronous ($\omega_r > \omega_1$)	
Operation Mode	Motoring	Generating	Motoring	Generating
P_m	>0	<0	>0	<0
P_s	>0	<0	>0	<0
P_r	<0	>0	>0	<0

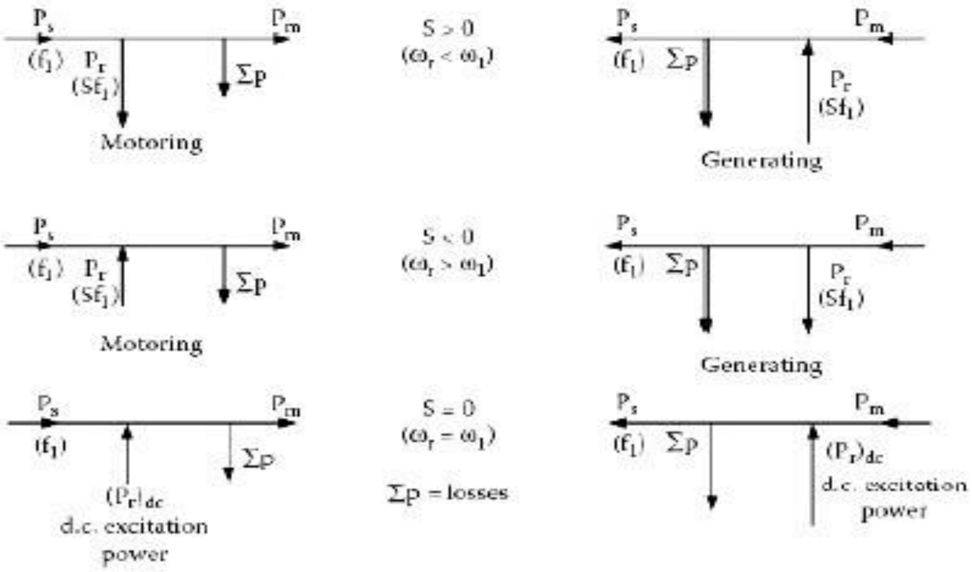


FIGURE Operation modes of wound rotor induction generator (WRIG) at $S > 0$, $S < 0$, and $S = 0$.

So, the reactive power required to magnetize the machine may be delivered by the rotor or by the stator or by both. The presence of *S* in Equation is justified by the fact that machine magnetization is perceived in the stator at stator frequency ω1. As the static power converter rating depends on its rated apparent power rather than active power, it seems to be practical to magnetize the machine from the stator. In this case, however, the WRIG absorbs reactive power through the stator from the power grids or from a capacitive-resistive load. In stand-alone operation mode, however, the WRIG has to provide for the reactive power required by the load up to the rated lagging power factor conditions. If the stator operates at unity power factor, the rotor-side static power Converter has to deliver reactive power extracted either from inside itself (from the capacitor in the DC link) or from the power grid that supplies it. As magnetization is achieved with lowest kVAR in DC, when active power is not needed, the machine may be operated at synchronism to fully contribute to the voltage stability and control in the power system. To further understand the active and reactive power flows in the WRIG, phasor diagrams are used.

2. Explain the operation of SCIG in detail with proper analysis.(APR/MAY2017)(M.E-NOV/DEC2013) (M.E-NOV/DEC2010)

Squirrel Cage Induction Generator

Three-phase induction machines have three windings in the stator and three windings more in the rotor, although, these can be real or imaginary. As it is known, all electrical machines can be described as motor and generator as well, consequently, they can be described with the same set of equations. It is appropriate to remember that these equations govern the operation of the electrical machines. These equations are divided in two groups, Voltage equations and Torque equations in machine variables and other which are expressed in the axes of the reference variables. With the goal of simplifying these equations, to consider the following hypothesis:

Symmetric and balanced three-phase induction machine, with a single winding rotor

- (Squirrel cage simple) and constant gap.
- Material is assumed to be linear, that is to say, the iron saturation is discarded.
- The iron magnetic permeability is assumed to be infinite in front of the air permeability, which means that the magnetic flux density is radial to the gap.
- All kind of losses in the iron are neglected.
- Both the stator windings as the rotor windings represent distributed windings which always generate a sinusoidal magnetic field distribution in the gap.

All hypothesis that we have explained before, using the induction motor's illustration, guide us to the following system of equations which describe the dynamic behaviour of the induction machine.

$$\left\{ \begin{array}{c} v_s^{abc} \\ v_r^{abc} \end{array} \right\} = \left[\begin{array}{cc} r_s^{abc} & 0 \\ 0 & r_r^{abc} \end{array} \right] \left\{ \begin{array}{c} i_s^{abc} \\ i_r^{abc} \end{array} \right\} + \frac{d}{dt} \left\{ \begin{array}{c} \lambda_s^{abc} \\ \lambda_r^{abc} \end{array} \right\}$$

with

v_s^{abc}	stator winding's voltage vector
v_r^{abc}	rotor winding's voltage vector
i_s^{abc}	stator winding's current vector
i_r^{abc}	rotor winding's current vector
λ_s^{abc}	stator winding's concatenated flows vector
λ_r^{abc}	rotor winding's concatenated flows vector

The relationship between concatenated flows, rotor and stator's current is given by

$$\left\{ \begin{array}{c} \lambda_s^{abc} \\ \lambda_r^{abc} \end{array} \right\} = \left[\begin{array}{cc} L_{ss}^{abc} & L_{sr}^{abc} \\ L_{rs}^{abc} & L_{rr} \end{array} \right] \left\{ \begin{array}{c} i_s^{abc} \\ i_r^{abc} \end{array} \right\}$$

where each term represents a 3-dimensional matrix or a three-dimensional vector. Then, the

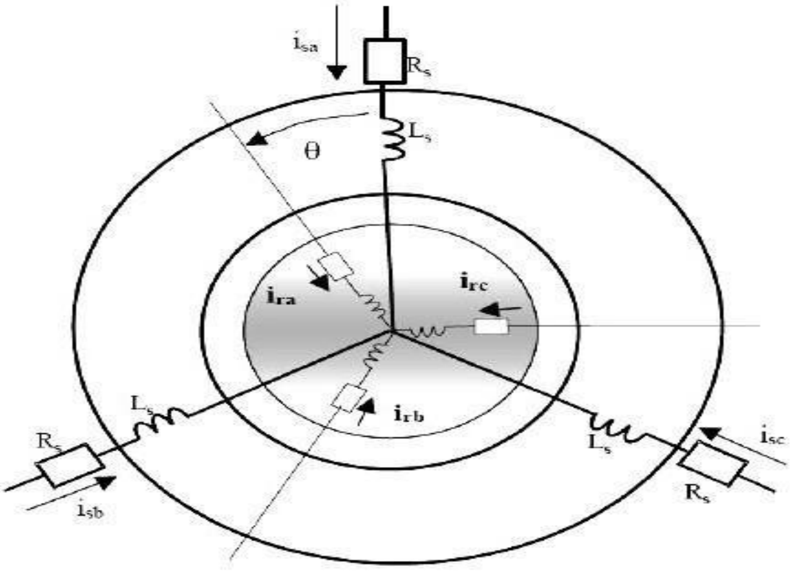


Figure : Induction machine's schematic illustration

vectors can be written as

$$v_s = \begin{pmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{pmatrix}, v_r = \begin{pmatrix} v_{ra} \\ v_{rb} \\ v_{rc} \end{pmatrix}, i_s = \begin{pmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{pmatrix}, i_r = \begin{pmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{pmatrix}$$

and impedance matrices as

$$r_s^{abc} = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix}$$

$$r_r^{abc} = \begin{bmatrix} r_r & 0 & 0 \\ 0 & r_r & 0 \\ 0 & 0 & r_r \end{bmatrix}$$

$$L_{ss}^{abc} = \begin{bmatrix} L_{ls} + L_{ss} & L_{sm} & L_{sm} \\ L_{sm} & L_{ls} + L_{ss} & L_{sm} \\ L_{sm} & L_{sm} & L_{ls} + L_{ss} \end{bmatrix}$$

$$L_{sr}^{abc} = \{L_{rs}^{abc}\}^t = L_{sr} \begin{bmatrix} cos(\theta_r) & cos(\theta_r + \frac{2\pi}{3}) & cos(\theta_r - \frac{2\pi}{3}) \\ cos(\theta_r - \frac{2\pi}{3}) & cos(\theta_r) & cos(\theta_r + \frac{2\pi}{3}) \\ cos(\theta_r + \frac{2\pi}{3}) & cos(\theta_r - \frac{2\pi}{3}) & cos(\theta_r) \end{bmatrix}$$

$$L_{rr}^{abc} = \begin{bmatrix} L_{lr} + L_{rr} & L_{rm} & L_{rm} \\ L_{rm} & L_{lr} + L_{rr} & L_{rm} \\ L_{rm} & L_{rm} & L_{lr} + L_{rr} \end{bmatrix}$$

with:

ω_r	generator's shaft's orientation angle from electric system
r_s	resistance of the stator windings
r_r	resistance of the rotor windings
L_{ss}	self-inductance of the stator windings without the winding owing the dispersion flow
L_{rr}	self-inductance of the rotor windings without the winding owing the dispersion flow
L_{sm}	coupling inductances between stator windings
L_{rm}	coupling inductances between rotor windings
L_{sr}	maximum value reached by coupling inductances between stator and rotor windings
L_{ls}	dispersion inductance of the stator windings
L_{lr}	dispersion inductance of the rotor windings

The electromechanical conversion theory provides the following equation:

$$\Gamma_r = \frac{1}{2}[i]^t \frac{\delta[L(\theta_r)]}{\delta(\theta_r)}[i]$$

where

Γ_r	Torque on the rotor shaft
$L(\theta_r)$	Induction machine's coupling inductance matrix. $L(\theta_r) = \begin{bmatrix} L_{ss} & L_{sr} \\ L_{rs} & L_{rr} \end{bmatrix}$

Usually the induction machines are designed with number of poles over 1. Theoretically, this could be understood as a ideal multiplier with a transmission ratio P between shaft's mechanical angle (θm) and electrical system's angle.

$$\Gamma_m = \frac{P}{2}[i]^t \frac{\delta[L(\theta_r)]}{\delta(\theta_r)}[i]$$

Without the loss of generality we may suppose the number of poles is exactly one. However, we want to remark the results obtained generalize to the situation of multiple poles. The equation expresses the torque developed by the induction machine at any time, depending on the instantaneous currents circulating by each one of the six windings, and the separation angle between the stator winding 1 and the rotor winding 1. This equation is obtained by the electrical system energy balance.Developing the equation it is easily simplified due to Lss and Lrr are not θr dependent. Then the derivative of this constant vanishes. So the new equation can be written as

$$\Gamma_r = \frac{1}{2} \left\{ \begin{array}{c} i_s^{abc} \\ i_r^{abc} \end{array} \right\}^t \begin{bmatrix} 0 & N_{sr} \\ N_{rs} & 0 \end{bmatrix} \left\{ \begin{array}{c} i_s^{abc} \\ i_r^{abc} \end{array} \right\}$$

where

$$N_{sr}^{abc} = \{N_{rs}^{abc}\}^t = -L_{sr} \begin{bmatrix} sin(\theta_r) & sin(\theta_r + \frac{2\pi}{3}) & sin(\theta_r - \frac{2\pi}{3}) \\ sin(\theta_r - \frac{2\pi}{3}) & sin(\theta_r) & sin(\theta_r + \frac{2\pi}{3}) \\ sin(\theta_r + \frac{2\pi}{3}) & sin(\theta_r - \frac{2\pi}{3}) & sin(\theta_r) \end{bmatrix}$$

The generator which we will be the studied object is a SCIG (Squirrel Cage Induction Generator), this type of generator is known also as Short-Circuit Induction Generator, owing to rotor windings are then connected in short circuit. So, the only part of the generator connected to the grid will be the stator. Because of this connection to the rotor windings, we are able to get the next simplification $Vr^{abc} = 0$. Then, the equation described before could be written as follows:

$$\left\{ \begin{array}{c} v_s^{abc} \\ 0^{abc} \end{array} \right\} = \left[\begin{array}{cc} r_s^{abc} & 0 \\ 0 & r_r^{abc} \end{array} \right] \left\{ \begin{array}{c} i_s^{abc} \\ i_r^{abc} \end{array} \right\} + \frac{d}{dt} \left\{ \begin{array}{c} \lambda_s^{abc} \\ \lambda_r^{abc} \end{array} \right\}$$

State space of SCIG generator

The dynamic behavior of the machine can be studied by means of a dynamic linear system. Although, most adequate mathematical expression to realize the system simulation is the state space, we are able to obtain our goal with just the few next steps:

First, it is necessary to put on the different side of the equal sign derivative variables and non-derivative.

$$\begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix} \frac{d}{dt} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\} = \left\{ \begin{array}{c} v_{sq} \\ v_{sd} \\ 0 \\ 0 \end{array} \right\} - \begin{bmatrix} r_s & L_s\dot{\theta} & 0 & M\dot{\theta} \\ -L_s\dot{\theta} & r_s & -M\dot{\theta} & 0 \\ 0 & M(\dot{\theta}-\dot{\theta}_r) & r_r & L_r(\dot{\theta}-\dot{\theta}_r) \\ -M(\dot{\theta}-\dot{\theta}_r) & 0 & -L_r(\dot{\theta}-\dot{\theta}_r) & r_r \end{bmatrix} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\}$$

Second, we have to determine the inverse of the matrix which is with the derivative. It is needed because of $A^{-1} * A = I$.

$$\begin{bmatrix} L_s & 0 & M & 0 \\ 0 & L_s & 0 & M \\ M & 0 & L_r & 0 \\ 0 & M & 0 & L_r \end{bmatrix}^{-1} = \frac{1}{L_s L_r - M^2} \begin{bmatrix} L_r & 0 & -M & 0 \\ 0 & L_r & 0 & -M \\ -M & 0 & L_s & 0 \\ 0 & -M & 0 & L_s \end{bmatrix}$$

Third, to leave only the derivative variables without multiplying constants, we should multiply the inverse in both sides.

$$\frac{d}{dt} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\} = -\frac{1}{L_s L_r - M^2} \begin{bmatrix} L_r & 0 & -M & 0 \\ 0 & L_r & 0 & -M \\ -M & 0 & L_s & 0 \\ 0 & -M & 0 & L_s \end{bmatrix} \begin{bmatrix} r_s & L_s\dot{\theta} & 0 & M\dot{\theta} \\ -L_s\dot{\theta} & r_s & -M\dot{\theta} & 0 \\ 0 & M(\dot{\theta}-\dot{\theta}_r) & r_r & L_r(\dot{\theta}-\dot{\theta}_r) \\ -M(\dot{\theta}-\dot{\theta}_r) & 0 & -L_r(\dot{\theta}-\dot{\theta}_r) & r_r \end{bmatrix} \left\{ \begin{array}{c} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{array} \right\} + \frac{1}{L_s L_r - M^2} \begin{bmatrix} L_r & 0 & -M & 0 \\ 0 & L_r & 0 & -M \\ -M & 0 & L_s & 0 \\ 0 & -M & 0 & L_s \end{bmatrix} \left\{ \begin{array}{c} v_{sq} \\ v_{sd} \\ 0 \\ 0 \end{array} \right\}$$

Finally, we have to multiply the matrices and discard unnecessary elements of the system. Then, we get the following equation:

$$
\underbrace{\frac{d}{dt}\begin{Bmatrix} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{Bmatrix}}_{X} =
$$

$$
\underbrace{-\frac{1}{L_s L_r - M^2}\begin{bmatrix} L_r r_s & M^2\dot{\theta}_r + (L_s L_r - M^2)\dot{\theta} & -M r_r & M L_r \dot{\theta}_r \\ -M^2\dot{\theta}_r - (L_s L_r - M^2)\dot{\theta} & L_r r_s & -M L_r \dot{\theta}_r & -M r_r \\ -M r_s & -M L_s \dot{\theta}_r & L_s r_r & (L_s L_r - M^2)\dot{\theta} - L_s L_r \dot{\theta}_r \\ M L_s \dot{\theta}_r & -M r_s & -(L_s L_r - M^2)\dot{\theta} - L_s L_r \dot{\theta}_r & L_s r_r \end{bmatrix}}_{A} \underbrace{\begin{Bmatrix} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{Bmatrix}}_{X}
$$

$$
+\underbrace{\frac{1}{L_s L_r - M^2}\begin{bmatrix} L_r & 0 \\ 0 & L_r \\ -M & 0 \\ 0 & -M \end{bmatrix}}_{B} \underbrace{\begin{Bmatrix} v_{sq} \\ v_{sd} \\ 0 \\ 0 \end{Bmatrix}}_{U}
$$

$$
\frac{di_{s0}}{dt} = \frac{r_s}{L_{ss} + 2L_{sm} + L_{ls}} i_{s0} - \frac{1}{L_{ss} + 2L_{sm} + L_{ls}} v_{s0}
$$

$$
\frac{di_{r0}}{dt} = \frac{r_r}{L_{rr} + 2L_{rm} + L_{lr}} i_{r0} - \frac{1}{L_{rr} + 2L_{rm} + L_{lr}} v_{r0}
$$

3. Draw the equivalent circuit and show the steady state analysis of permanent magnet synchronous generator (PMSG). Explain the merits and demerits of PMSG for wind energy conversion system. (APR/MAY2017)(M.E-NOV/DEC2013)(M.E-APR/MAY2013)(M.E-NOV/DEC2010)

Permanent magnet synchronous generator (PMSG)

By permanent magnet (PM) synchronous generators (SGs), we mean here radial or axial airgap PM brushless generators with distributed ($q > 1$) or concentrated ($q \leq 1$) windings and rectangular or sinusoidal current control with surface PM or interior PM (IPM) rotors. A PMSG's output voltage amplitude and frequency are proportional to speed. In constant speed prime mover applications, PMSGs might perform voltage self-regulation by proper design; that is, inset or interior PM pole rotors. Small speed variation (10 to 15%) may be acceptable for diode rectified loads with series capacitors and voltage self-regulation. However, most applications require operation at variable speed, and, in this case, constant output voltage vs. load, be it direct current (DC) or alternating current (AC), requires full static power conversion and close-loop control.

Classification of PMSG

PMSGs are classified as

- Radial or axial flux machines
- Longitudinal or transversal flux machines
- Inner rotor or outer rotor machines
- Interior (inset) magnet or exterior (surface mounted) magnet machines

<u>Longitudinal or transversal flux machines:</u>

In transversal flux machines, the plane of flux path is perpendicular to the direction of rotor motion. One attractive property of transversal flux machines is that the current loading and magnetic loading can be adjusted independently.

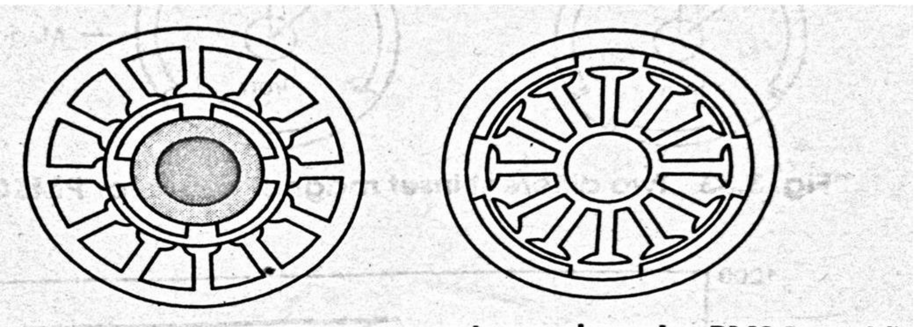
<u>Inner rotor or outer rotor machines:</u>

<u>outer rotor machines:</u>

The rotor surrounds the stator in outer rotor machines. In these machines, the magnets are usually located on the inner circumference of the rotor. The rotor has higher radius compared with the stator and it can be equipped with higher number of poles for the same pole pitch.

<u>Inner rotor machines:</u>

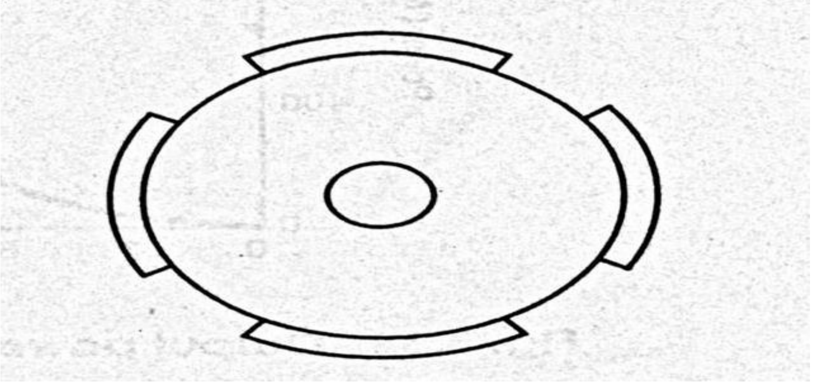
In small machines, the main contributions to the losses are copper losses and therefore the stator winding has the highest temperature rise in the active material of the machine. Hence it is more beneficial to put the stator winding, rather than the magnets, closer to the housing, where the cooling properties are good. This causes less temperature rise for same amount of losses.



1 Inner rotor PMSG (left) and an outer rotor PMSG (right)

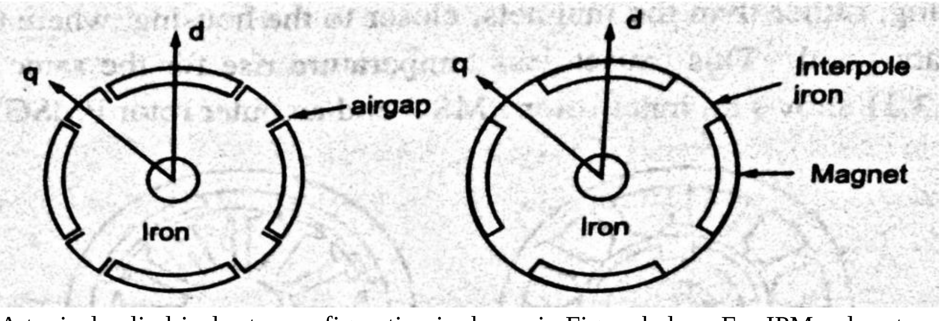
Exterior (surface mounted) magnet machines:

Here the magnets are mounted on the surface of rotor. The magnets are glued and/or bandaged to the rotor surface in order to withstand centrifugal force. Usually, the magnets are oriented or magnetized in radial direction and the direct and quadrature axis reactances are almost equal.



Interior (inset) magnet machines:

In this, the rotor core is modified with iron inter poles. Inter poles cause saliency and the inductances in direct and quadrature directions are different. The magnets are radially magnetised but flux leakage is high which results in low power factor. So, this topology is not common in use.



A typical cylindrical rotor configuration is shown in Figure below. For IPM pole rotors, the magnetic reluctance along the direct (d) axis is larger than for the transverse (q) axis; thus, $L_d < L_q$ — that is, inverse saliency, in contrast to electromagnetically excited pole rotors for standard synchronous machines. The d axis falls along PM field axis in the airgap. The rotor may be internal or external to the stator, in cylindrical rotor configurations. Interior rotors require a carbon fiber mechanical shield (retainer) against centrifugal forces for high-speed applications (above 50 to 80 m/sec peripheral speed). In contrast, external rotors do not need such a retainer, but the yoke has to withstand high centrifugal forces in high-speed rotors.

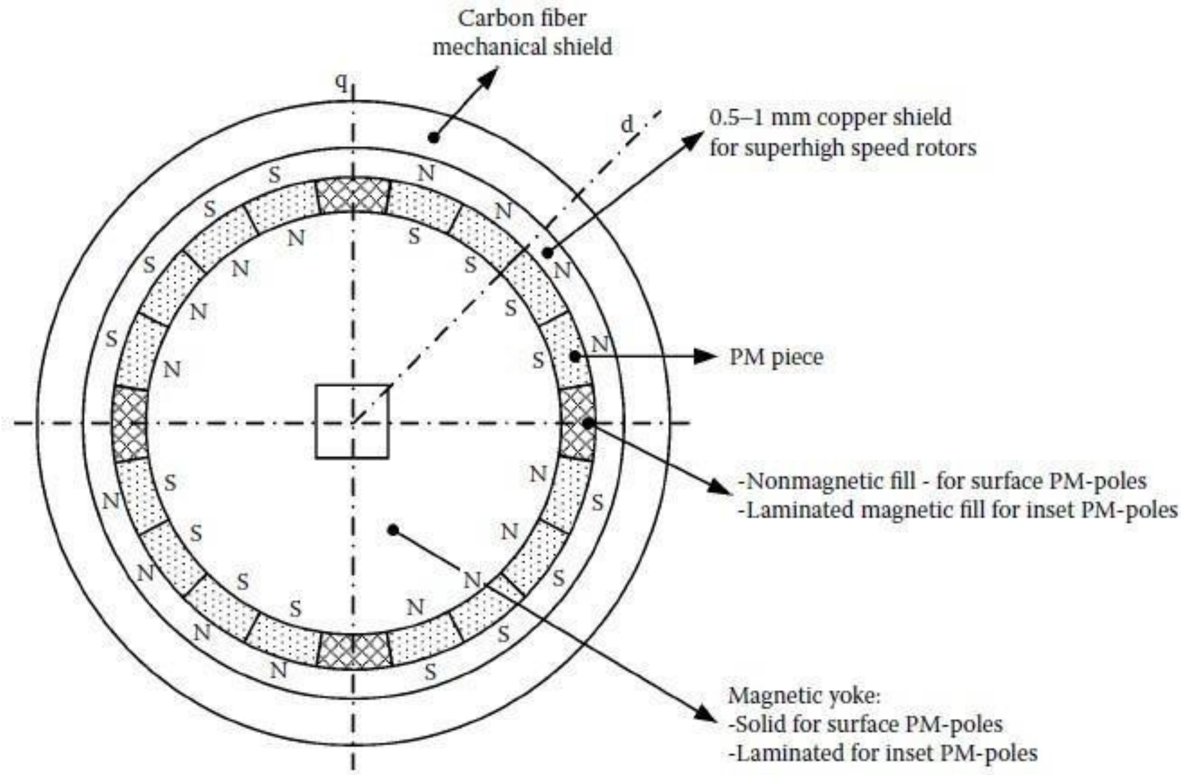


FIGURE Four-pole surface permanent magnet (PM) and inset PM pole rotor configurations.

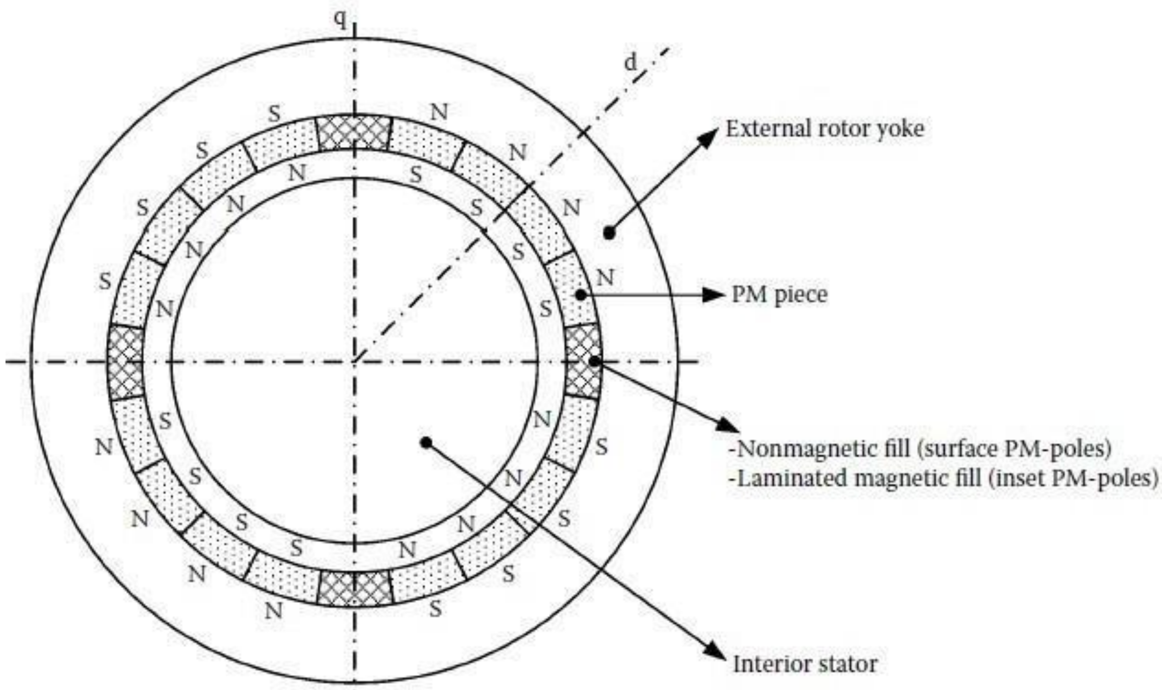


FIGURE Four-pole cylindrical external rotor.

Operating modes of PMSG:

Three operating modes:

- Silent mode
- Variable speed operation mode
- Constant speed mode

<u>Silent mode:</u>

A turbine is silent in two cases: wind speed is below a cut-in level or above the cut-off speed. If the speed is below its cut-in level it produces insufficient torque to move the turbine. At the same time winds above cut-off level may damage the turbine, which must be stopped in such conditions.

<u>Variable speed operation mode:</u>

A turbine operates at variable speed in the wind velocity range from cut-in to rated wind speed. Rated wind speed differs by turbine types, but often has the value of 12m/s.

<u>Constant speed mode:</u>

It takes place above rated wind speed. Turbine output power remains constant at this mode.

The Circuit Model

The Phase Coordinate Model

In essence, the circuit model of a PMSG starts with the phase voltage equations in stator coordinates:

$$i_a R_s - V_a = -\frac{d\Psi_a}{dt}$$

$$i_b R_s - V_b = -\frac{d\Psi_b}{dt}$$

$$i_c R_s - V_c = -\frac{d\Psi_c}{dt}$$

$$\begin{vmatrix} \Psi_a \\ \Psi_b \\ \Psi_c \end{vmatrix} = \begin{vmatrix} L_{sl} + L_{aa}(\theta_{er}) & L_{ab}(\theta_{er}) & L_{ac}(\theta_{er}) \\ L_{ab}(\theta_{er}) & L_{sl} + L_{bb}(\theta_{er}) & L_{bc}(\theta_{er}) \\ L_{ac}(\theta_{er}) & L_{bc}(\theta_{er}) & L_{sl} + L_{cc}(\theta_{er}) \end{vmatrix} \begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix} + \begin{vmatrix} \Psi_{PMa}(\theta_{er}) \\ \Psi_{PMb}(\theta_{er}) \\ \Psi_{PMc}(\theta_{er}) \end{vmatrix}$$

where θ_{er} is the rotor PM axis angle to stator phase a axis/electrical angle.

The self-inductance and mutual inductance of the stator depend sinusoidally on θ_{er} only for IPM rotors, in distributed winding IPM rotor machines. For surface PM pole rotors, stator inductances are independent of θ_{er}. However, the presence of slot openings introduces an additional dependence of stator inductances on N_s θ_{er} for IPM rotors. For concentrated windings, the stator self-inductance and mutual inductance perform in a similar way, with respect to rotor pole configurations, but their values tend to be larger than for distributed windings and equivalent machine geometries. However, the end-turn leakage inductances are notably smaller for concentrated windings.

The trapezoidal distribution may be considered this way:

$$\Psi_{PMa}(\theta_{er}) = \Psi_{PM1}(\theta_{er}) + \Psi_{PM2}(2\theta_{er} - \gamma_2) + \Psi_{PM3}(3\theta_{er} - \gamma_3) + \ldots\ldots$$

The even harmonics occur only with PM pole shifting, adopted to reduce cogging torque. Also, space subharmonics may occur. They have to be avoided for practical designs.

For surface PM pole rotors, the general expressions of E_{aa}, E_{ab}, E_{ac}, and Ψ_{PMa} developed earlier may be used to calculate L_{aah}, L_{abh}, L_{ach}, Ψ_{PMa}, $(i_b = i_c = 0)$:

$$L_{aah} = \frac{E_{aa}}{\omega_1 i_a};\; L_{abh} = \frac{E_{ab}}{\omega_1 i_a};\quad L_{ach} = \frac{E_{ac}}{\omega_1 i_a};\;\; \Psi_{PMa} = \frac{|E_{PMa}|}{\omega_1}$$

The instantaneous interaction torque expression, in the absence of magnetic saturation, is as follows:

$$T_e = -\frac{\partial W_m}{\partial \theta_{er}}$$

$$W_m = \frac{1}{2}L_{aah}i_a^2 + \frac{1}{2}L_{bbh}i_b^2 + \frac{1}{2}L_{cch}i_c^2 + L_{abh}i_a i_b + L_{bch}i_b i_c + L_{cah}i_c i_a$$
$$+ \Psi_{PMa}(\theta_{er})i_a + \Psi_{PMb}(\theta_{er})i_b + \Psi_{PMc}(\theta_{er})i_c$$

The d-q model of PMSG:

The *d–q* model is based on the assumption that the stator self-inductance and mutual inductance are either constant or vary sinusoidally with the rotor position. In general, the PM flux linkages in the stator phases also vary sinusoidally, but with Eventual harmonics in may be treated in the *d–q* model also, and they are expected to create time pulsations in the torque with sinusoidal currents at speed and frequency.

$$|L_{abc}(\theta_{er})| = \begin{vmatrix} L_{sl} + L_0 + L_2\cos 2\theta_{er} & M_0 + L_2\cos\left(2\theta_{er} + \frac{2\pi}{3}\right) & M_0 + L_2\cos\left(2\theta_{er} - \frac{2\pi}{3}\right) \\ M_0 + L_2\cos\left(2\theta_{er} + \frac{2\pi}{3}\right) & L_{sl} + L_0 + L_2\cos\left(2\theta_{er} - \frac{2\pi}{3}\right) & M_0 + L_2\cos 2\theta_{er} \\ M_0 + L_2\cos\left(2\theta_{er} - \frac{2\pi}{3}\right) & M_0 + L_2\cos 2\theta_{er} & L_{sl} + L_0 + L_2\cos\left(2\theta_{er} + \frac{2\pi}{3}\right) \end{vmatrix}$$

$$M = -\frac{L_0}{2} \text{ for distributed windings}$$

For PM machines, $L_2 < 0$, as they have the PMs placed along axis *d* and exhibit "inverse saliency," in contrast to standard synchronous machine excitation:

$$\begin{vmatrix} \Psi_{PMa}(\theta_{er}) \\ \Psi_{PMb}(\theta_{er}) \\ \Psi_{PMc}(\theta_{er}) \end{vmatrix} = \begin{vmatrix} \Psi_{PM1}\cos\theta_{er} + \cdots\cdots \\ \Psi_{PM1}\cos\left(\theta_{er} - \frac{2\pi}{3}\right) + \cdots\cdots \\ \Psi_{PM1}\cos\left(\theta_{er} + \frac{2\pi}{3}\right) + \cdots\cdots \end{vmatrix}$$

The matrix form of the phase coordinates model is as follows:

$$|i_{a,b,c}||R_s| - |V_{a,b,c}| = -\frac{d|\Psi_{a,b,c}|}{dt}$$

$$\Psi_{a,b,c} = |L_{a,b,c}(\theta_{er})||i_{a,b,c}| + \Psi_{PMa,b,c}(\theta_{er})$$

The Park transformation $P(\theta_{er})$ is used to derive the d–q model:

$$|P(\theta_{er})| = \frac{2}{3}\begin{vmatrix} \cos(-\theta_{er}) & \cos\left(-\theta_{er}+\frac{2\pi}{3}\right) & \cos\left(-\theta_{er}-\frac{2\pi}{3}\right) \\ \sin(-\theta_{er}) & \sin\left(-\theta_{er}+\frac{2\pi}{3}\right) & \sin\left(-\theta_{er}-\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{vmatrix}$$

The Park transformation from stator to rotor coordinates is, in Equation 10.38, valid for the trigonometric motion direction and axis q in front of axis d by 90° (electrical degrees) (Figure 10.23):

$$\begin{vmatrix} i_d \\ i_q \\ i_0 \end{vmatrix} = |P(\theta_{er})|\begin{vmatrix} i_a \\ i_b \\ i_c \end{vmatrix}$$

The same transformation is valid for Ψ_{dq0}, V_{dq0}.

Finally, for sinusoidal $\Psi_{PMa,b,c}(\theta_{er})$ distributions,

$$i_d R_s - V_d = -L_d\frac{di_d}{dt} + \omega_r L_q i_q$$

$$i_q R_s - V_q = -L_q\frac{di_q}{dt} - \omega_r(L_d i_d + \Psi_{PM1})$$

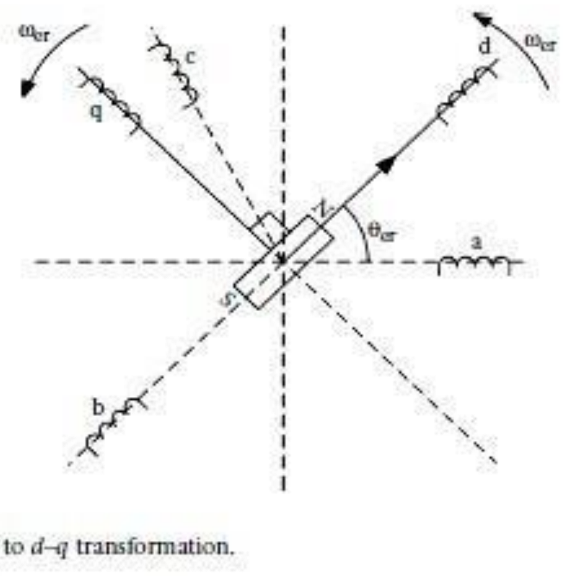


FIGURE Three-phase to d–q transformation.

with

$$\overline{\Psi}_s = \Psi_d + j\Psi_q \qquad \Psi_d = \Psi_{PM1} + L_d i_d \qquad \Psi_q = L_q i_q$$

$$\overline{V}_s = V_d + jV_q \qquad \bar{i}_s = i_d + ji_q$$

The so-called space-vector (or complex variable) model of a PMSG is obtained:

$$\bar{i}_s R_s - \overline{V}_s = -\frac{d\overline{\Psi}_s}{dt} - j\omega_r \overline{\Psi}_s$$

The torque is obtained from power balance in Equation 10.37:

$$T_e = p_1 \frac{P_e}{\omega_r} = \frac{3}{2} p_1 \mathrm{Re}(j\overline{\Psi}_s \vec{i}_s) = \frac{3}{2} p_1 (\Psi_d i_q - \Psi_q i_d) = \frac{3}{2} p_1 (\Psi_{PM1} + (L_d - L_q) i_d) i_q$$

Also,

$$L_d = L_{1s} + \frac{3}{2}(L_0 - |L_2|) \qquad L_q = L_{1s} + \frac{3}{2}(L_0 + |L_2|)$$

The winding losses P_{copper} are as follows:

$$P_{copper} = \frac{3}{2} R_s \left(i_d^2 + i_q^2\right)$$

4. Explain with a neat diagram the operation of an induction generator.(M.E-APR/MAY2013)

INDUCTION GENERATOR

The electric power in industry is consumed primarily by induction machines working as motors driving mechanical loads. For this reason, the induction machine, invented by Nikola Tesla and financed by George Westinghouse in the late 1880s, represents a well-established technology. The primary advantage of the induction machine is the rugged brushless construction that does not need a separate DC field power. The disadvantages of both the DC machine and the synchronous machine are eliminated in the induction machine, resulting in low capital cost, low maintenance, and better transient performance. For these reasons, the induction generator is extensively used in small and large wind farms and small hydroelectric power plants. The machine is available in numerous power ratings up to several megawatts capacity, and even larger. For economy and reliability, many wind power systems use induction machines as electrical generators.

CONSTRUCTION OF INDUCTION GENERATOR

In the electromagnetic structure of the induction generator, the stator is made of numerous coils wound in three groups (phases), and is supplied with three-phase current. The three coils are physically spread around the stator periphery and carry currents, which are out of time phase. This combination produces a rotating magnetic field, which is a key feature in the working of the induction machine. The angular speed of the rotating magnetic field is called the *synchronous speed*. It is denoted by Ns and is given by the following in rpm

$$N_s = \frac{120f}{p}$$

Where f = frequency of the stator excitation
p= Number of magnetic poles.
The stator coils are embedded in slots in a high-permeability magnetic core to produce the required magnetic field intensity with a small exciting current. The rotor, however, has a completely different structure. It is made of solid conducting bars, also embedded in slots in a magnetic core. The bars are connected together at both ends by two conducting end rings (see Figure). Because of its resemblance, the rotor is called a *squirrel cage rotor*, or the *cage rotor*, for short, and the motor is called the *squirrel cage induction motor*.

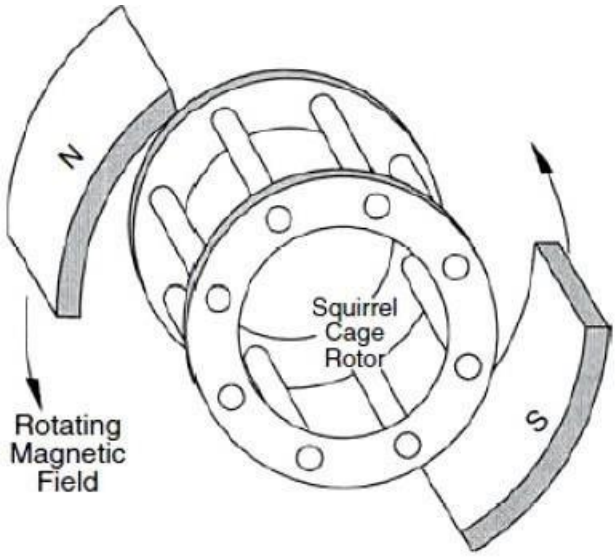


FIGURE Squirrel cage rotor of the induction machine under rotating magnetic field.

WORKING PRINCIPLE

The stator magnetic field is rotating at the synchronous speed determined by Equation below. This field is conceptually represented by the rotating magnets in figure above. The relative speed between the rotating field and the rotor induces the voltage in each closed loop of the rotor conductors linking the stator flux. The magnitude of the induced voltage is given by Faraday's law of electromagnetic induction, namely:

$$e = -\frac{d\phi}{dt}$$

Where φ=the magnetic flux of the stator linking the rotor loop.

This voltage in turn sets up the circulating current in the rotor. The electromagnetic interaction of the rotor current and stator flux produces the torque. The magnitude of this torque is given by the following:

$$T = k\Phi I_2 \cos \phi_2$$

where

k = constant of proportionality

Φ = magnitude of the stator flux wave

I_2 = magnitude of induced current in the rotor loops

ϕ_2 = phase angle by which the rotor current lags the rotor voltage

The rotor accelerates under this torque. If the rotor were on frictionless bearings in a vacuum with no mechanical load attached, it would be completely free to rotate with zero resistance. Under this condition, the rotor would attain the same speed as the stator field, namely, the synchronous speed. At this speed, the current induced in the rotor is zero, no torque is produced, and none is required. Under these conditions, the rotor finds Equilibrium and will continue to run at the synchronous speed. If the rotor is now attached to a mechanical load such as a fan, it will slow down. The stator flux, which always rotates at a constant synchronous speed, will have a relative speed with respect to the rotor. As a result, electromagnetically induced voltage, current, and torque are produced in the rotor. The torque produced must equal that needed to drive the load at this speed. The machine works as a motor in this condition. If we attach the rotor to a wind turbine and drive it faster than its synchronous speed via a step-up gear, the induced current and the torque in the rotor reverse the direction. The machine now works as the generator, converting the mechanical power of the turbine into electric power, which is delivered to the load connected to the stator terminals. If the machine were connected to a grid, it would feed power into the grid. Thus, the induction machine can work as an electrical generator only at speeds higher than the synchronous speed. The generator operation, for this reason, is often called the *super synchronous operation* of the induction machine. As described in the preceding text, an induction machine needs no electrical connection between the stator and the rotor. Its operation is entirely based on electromagnetic induction; hence, the name. The absence of rubbing electrical contacts and simplicity of its construction make the induction generator a very robust, reliable, and low-cost machine. For this reason, it is widely used in numerous industrial applications. Engineers familiar with the theory and operation of the electrical transformer would see the working principle of the induction machine can be seen as the transformer with shorted secondary coil. The high-voltage coil on the stator is excited, and the low voltage coil on the rotor is shorted on itself. The electrical or mechanical power from one to the other can flow in either direction. The theory and operation of the transformer, therefore, holds true when modified to account for the relative motion between the stator and the rotor. This motion is expressed in terms of the slip of the rotor relative to the synchronously rotating magnetic field.

ROTOR SPEED AND SLIP

The slip of the rotor is defined as the ratio of the speed of rotating magnetic field sweeping past the rotor and the synchronous speed of the stator magnetic field as follows:

$$s = \frac{N_s - N_r}{N_s}$$

where

s = slip of the rotor in a fraction of the synchronous speed

N_s = synchronous speed = 60 f/p

N_r = rotor speed

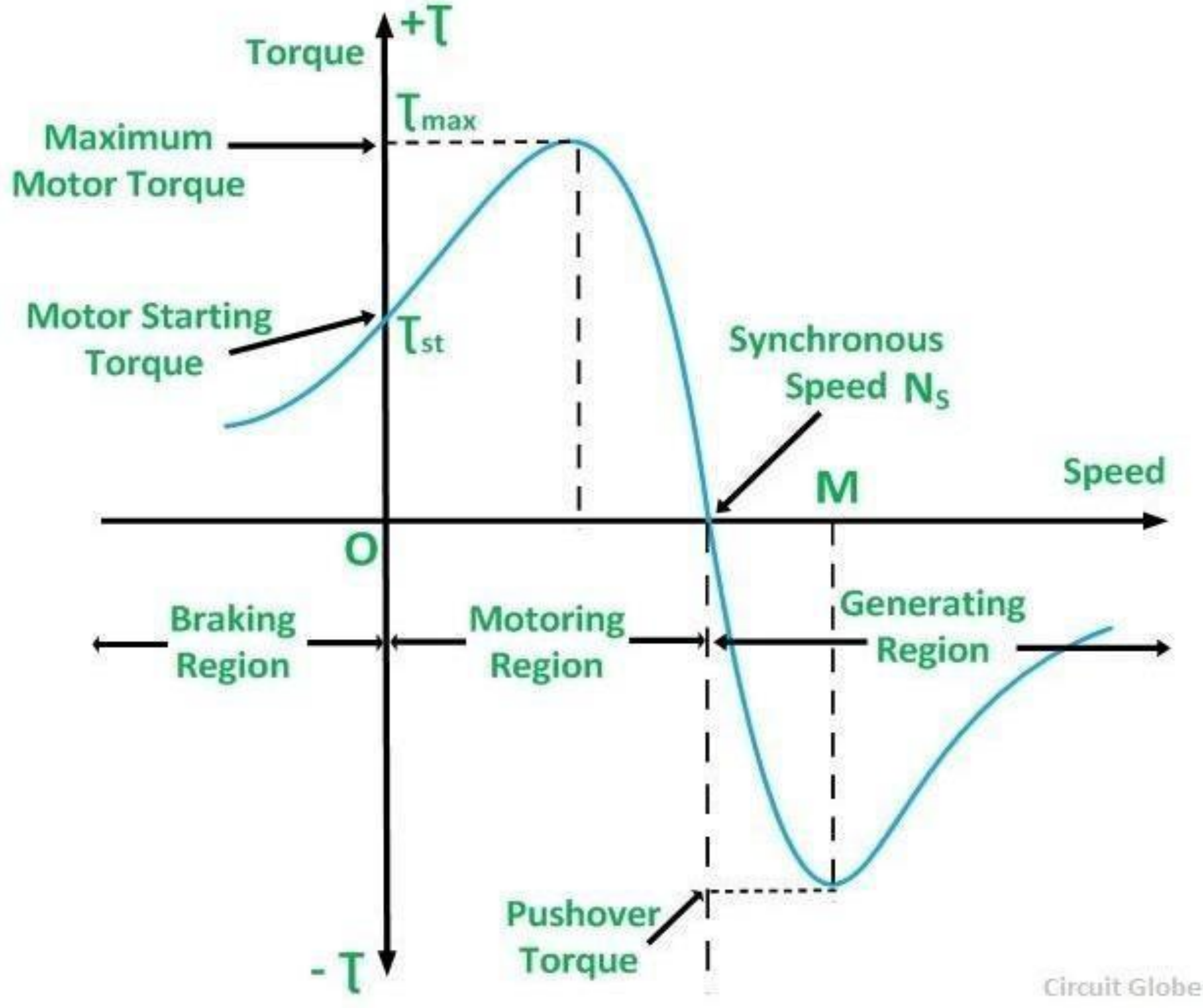
The slip is positive in the motoring mode and negative in the generating mode. In both modes, a higher rotor slip induces a proportionally higher current in the rotor, which results in greater electromechanical power conversion. In both modes, the value of slip is generally a few to several percent. Higher slips, however, result in greater electrical loss, which must be effectively dissipated from the rotor to keep the operating temperature within the allowable limit. The heat is removed from the machine by the fan blades attached to one end ring of the rotor. The fan is enclosed in a shroud at the end. The forced air travels axially along the machine exterior, which has fins to increase the dissipation area. The induction generator feeding a 60-Hz grid must run at a speed higher than 3600 rpm in a 2-pole design, 1800 rpm in a 4-pole design, and 1200 rpm in a 6- pole design. The wind turbine speed, on the other hand, varies from a few hundred rpm in kW range machines to a few tens of rpm in MW-range machines. The wind turbine, therefore, must interface the generator via a mechanical gear. As this somewhat degrades efficiency and reliability, many small stand-alone plants operate with custom-designed generators operating at lower speeds without any mechanical gear. Under the steady-state operation at slip " *s*," the induction generator has the following operating speeds in rpm:

Stator flux wave speed	N_s
Rotor mechanical speed	$N_r = (1 - s)N_s$
Stator flux speed with respect to rotor	sN_s
Rotor flux speed with respect to stator	$N_r + sN_s = N_s$

Thus, the squirrel cage induction machine is essentially a constant-speed machine, which runs slightly slipping behind the rotating magnetic field of the three phase stator current. The rotor slip varies with the power converted, and the rotor speed variations are within a few percent. It always consumes reactive power — undesirable when connected to a weak grid — which is often compensated by capacitors to achieve the systems power factor closed to one. Changing the machine speed is difficult. It can be designed to run at two different but fixed speeds by changing the number of poles of the stator winding. The voltage usually generated in the induction generator is 690-V AC. It is not economical to transfer power at such a low voltage over a long distance. Therefore, the machine voltage is stepped up to a higher value between 10,000 V and 30,000 V via a step-up transformer to reduce the power losses in the lines.

CHARACTERISTICS OF INDUCTION GENERATOR:

The characteristics of induction generator is shown in the below figure.



5. Explain the operating principle of squirrel cage induction generator coupled with wind turbine. (APR/MAY2017)

Fixed Speed Wind Energy Conversion Systems

Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed WECS are typically equipped with squirrel-cage induction generators (SCIG), soft starter and capacitor bank and they are connected directly to the grid, as shown in Figure below. This WECS configuration is also known as the “Danish concept” because it was developed and widely used in Denmark.

Initially, the induction machine is connected in motoring regime such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode. As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency. Furthermore, the wind velocity variations will induce only small variations in the generator speed. As the power varies proportionally with the Wind speed cubed, the associated electromagnetic variations are important.

SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. One of the major drawbacks of the SCIG is the fact that there is a unique relation between active power, reactive power, terminal voltage and rotor speed. That means that an increase in the active power production is possible only with an increase in the reactive power consumption, leading to a relatively low full-load power factor. In order to limit the reactive power absorption from the grid, SCIG based WECS are equipped with capacitor banks. The soft starter’s role is to smooth the inrush currents during the grid connection.

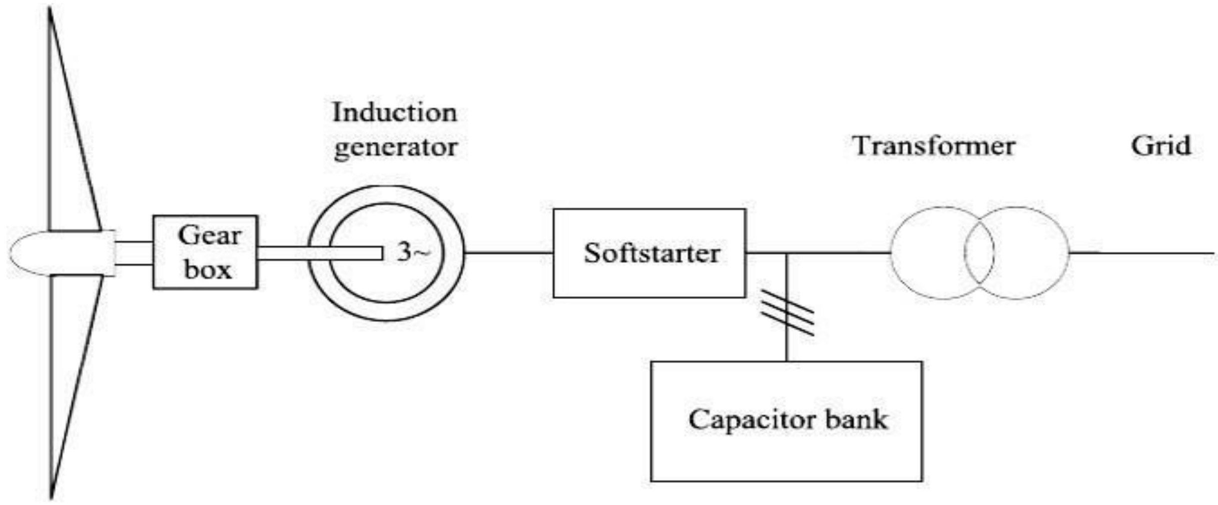


Fig General structure of a fixed-speed WECS

SCIG-based WECS are designed to achieve maximum power efficiency at a unique wind speed. In order to increase the power efficiency, the generator of some fixed-speed WECS has two winding sets, and thus two speeds. The first set is used at low wind speed (typically eight poles) and the other at medium and large wind speeds (typically four to six poles).

Fixed-speed WECS have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed-speed operation, the mechanical stress is important. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant, stuck to the grid frequency.

UNIT-3

PART-B

1. Draw the schematic diagram of standalone solar photovoltaic system. What are the main components used in it? Explain their functions.(APR/MAY2017)(M.E-NOV/DEC2010)

Photovoltaic (PV) Systems

Photovoltaic (PV) systems convert sunlight to electric current. You are already familiar with some simple PV applications in today's society, such as calculators and wrist watches. More complicated systems provide power for communications satellites, water pumps, and the lights, appliances, and machines in homes and workplaces. Many road and traffic signs along highways are now powered by PV.

PV systems produce some electric current any time the sun is shining, but more power is produced when the sunlight is more intense and strikes the PV modules directly. While solar thermal systems use heat from the sun to heat water or air, PV does not use the sun's heat to make electricity. Instead, electrons freed by the interaction of sunlight with semiconductor materials in PV cells create an electric current. PV modules are much less tolerant of shading than are solar water-heating panels. When siting a PV system, it is most important to minimize any shading of the PV modules.

PV allows you to produce electricity—without noise or air pollution—from a clean, renewable resource. A PV system never runs out of fuel, and it won‘t increase oil imports.

Block Diagram of Solar Photovoltaic System

Generally there are two types of Solar Photovoltaic System they are

1. Autonomous Solar Photovoltaic system or Stand alone Solar Photovoltaic system.
2. Grid Connected PV system.

a) Without Battery.

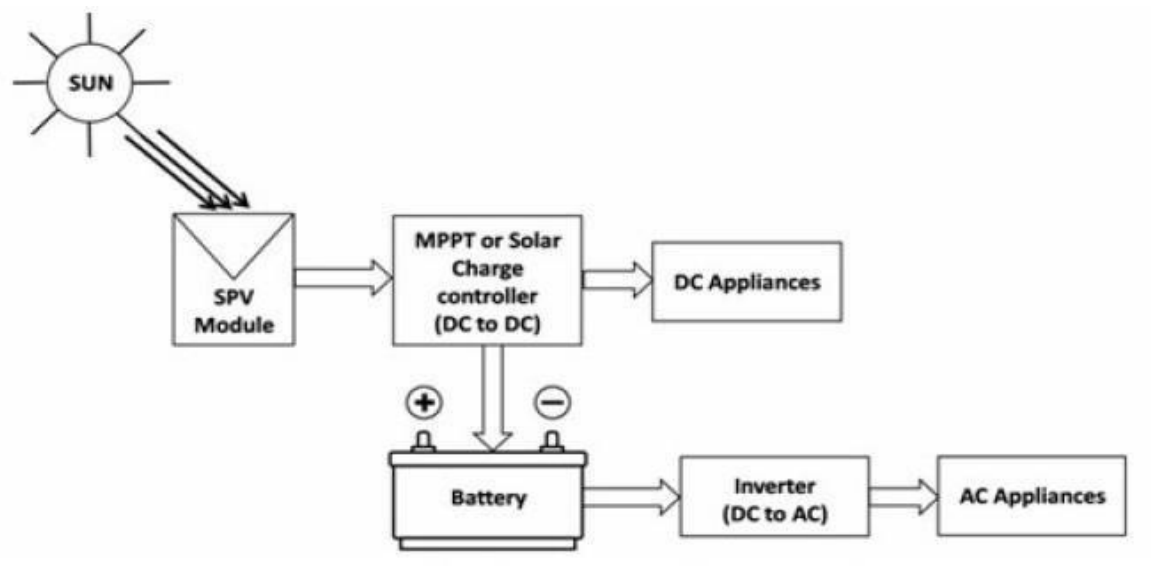
b) With Battery.

Autonomous PV system (or) Stand alone Solar Photovoltaic System (SPV)

A Standalone SPV system is the one which is not connected to the power grid. Standalone PV systems usually have a provision for energy storage. This system has battery support to supply the load requirements during the night hours or even when sunshine is not adequate (Cloudy conditions) during the day.

Block Diagram

Figure shows the block diagram of Standalone SPV system. Power is generated when sun light falls on the SPV module. This power is given to the MPPT or Charge controller block. The function of this block is to control the variation in the output of the SPV module and make it suitable for use at the output according to the supply required by a load. There are two types of the loads: AC and DC. DC components are directly connected to the MPPT or Charge controller block, where as the AC appliances are connected through the Battery and inverter.

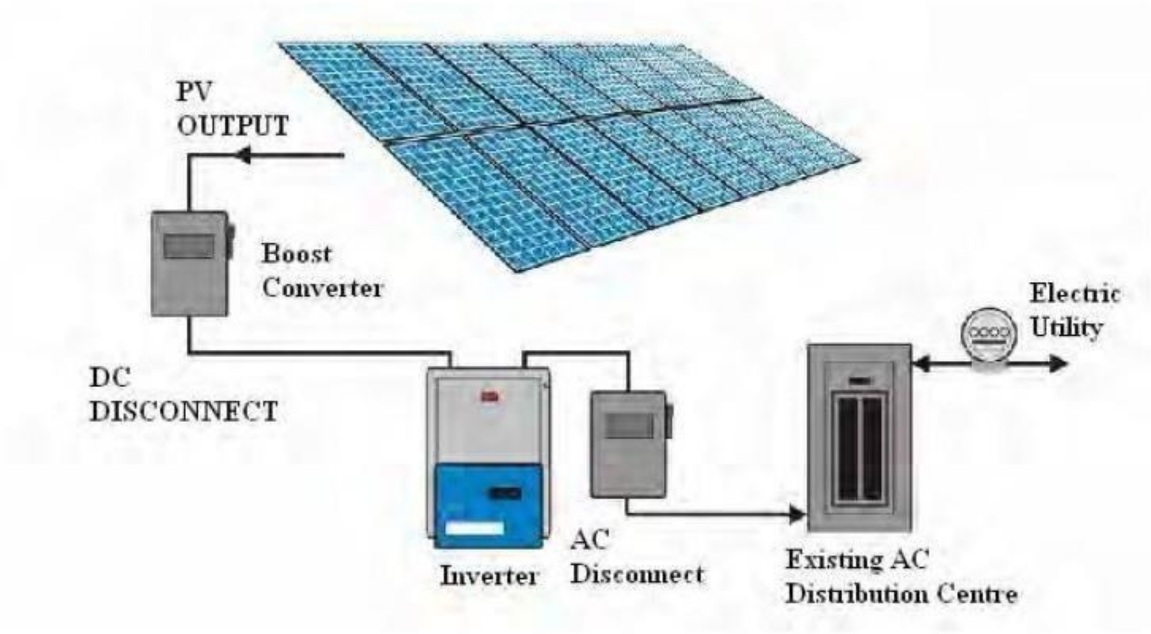


Simple Block Diagram of Standalone SPV system

In this way, a Standalone system is connected depending upon whether only AC load is present or both AC and DC load are present.

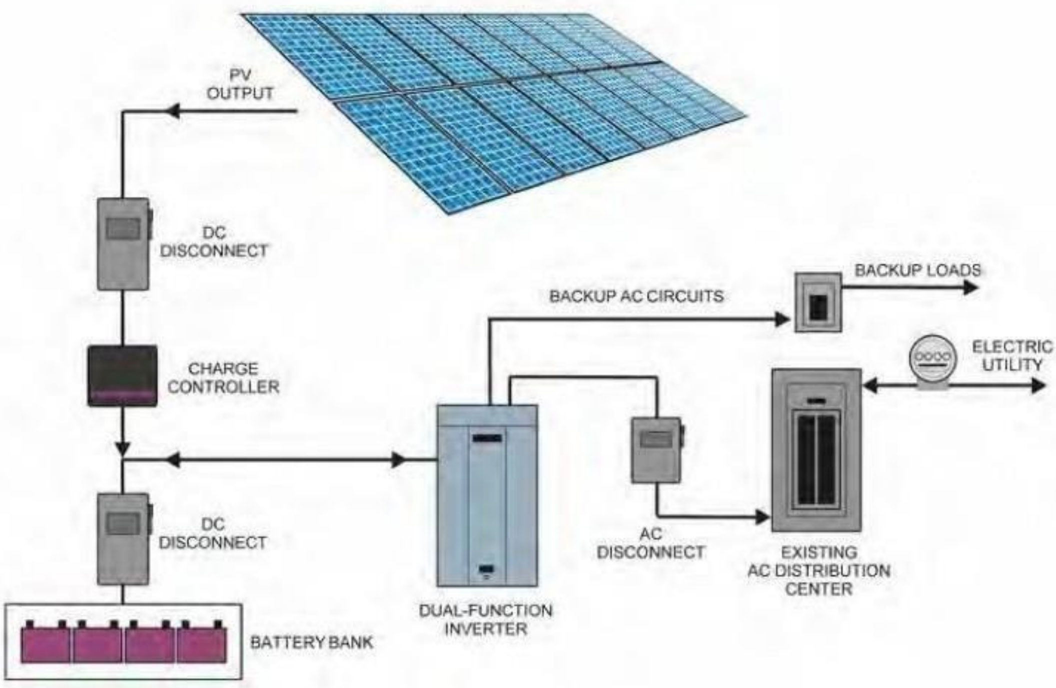
Typical Grid Tied System (Battery less)

There are no batteries to store excess power generated-the electric utility essentially stores it for you through a system called "net-metering." DC (direct current) generated by the PV panels is converted into AC (alternating current) power by the inverter (exactly the same high quality AC current delivered to your site by the utility-provided power grid). Output from the inverter is connected to your existing distribution panel (breaker panel) which feeds the rest of your site. While the system is generating electricity, power needs are provided by the PV system (up to its capacity), reducing or eliminating the power you would have drawn from the utility grid at that time. During periods when your grid-tie system is generating even more energy than your site requires, any excess is fed back into the grid for others to use and the electric utility company "buys" it from you at the retail rate. They provide credits to your account for all the power that is pushed back into the grid through the meter. And your meter will literally run backwards! When your site needs to draw more energy than it is producing (Say, during cloudy conditions or at night), electricity is provided by the power grid in the normal manner and is first paid for by your accumulated credits.



Typical Grid Tied System with Battery Backup

The "Grid-Tie With Battery Backup" PV system incorporates one or more special AC circuits which are not directly connected to the electric grid like the rest of the building, but are always powered through the inverter and/or charge controller. These circuits may power a refrigerator, selected lights, computers or servers... any devices the owner deems essential. The "dual function" inverter can supply the utility grid with any excess power produced by the system like the "grid-tie" inverter, plus the inverter works with the PV modules and battery bank (through the charge controller) to provide AC power to the backup circuits when the grid is down. The charge controller manages the battery voltage, keeping them fully charged when the grid is live, and preventing them from being depleted when the system is drawing power from them.

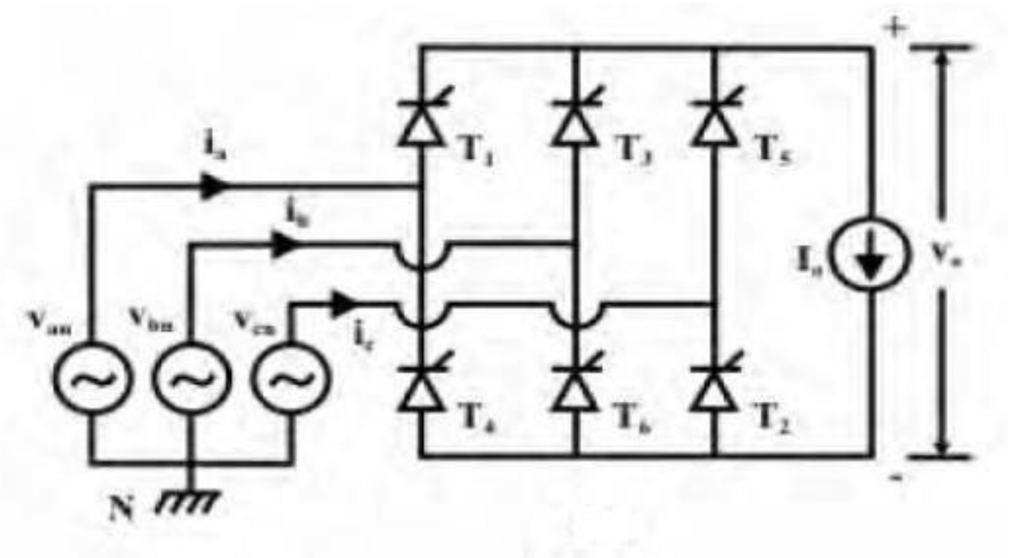


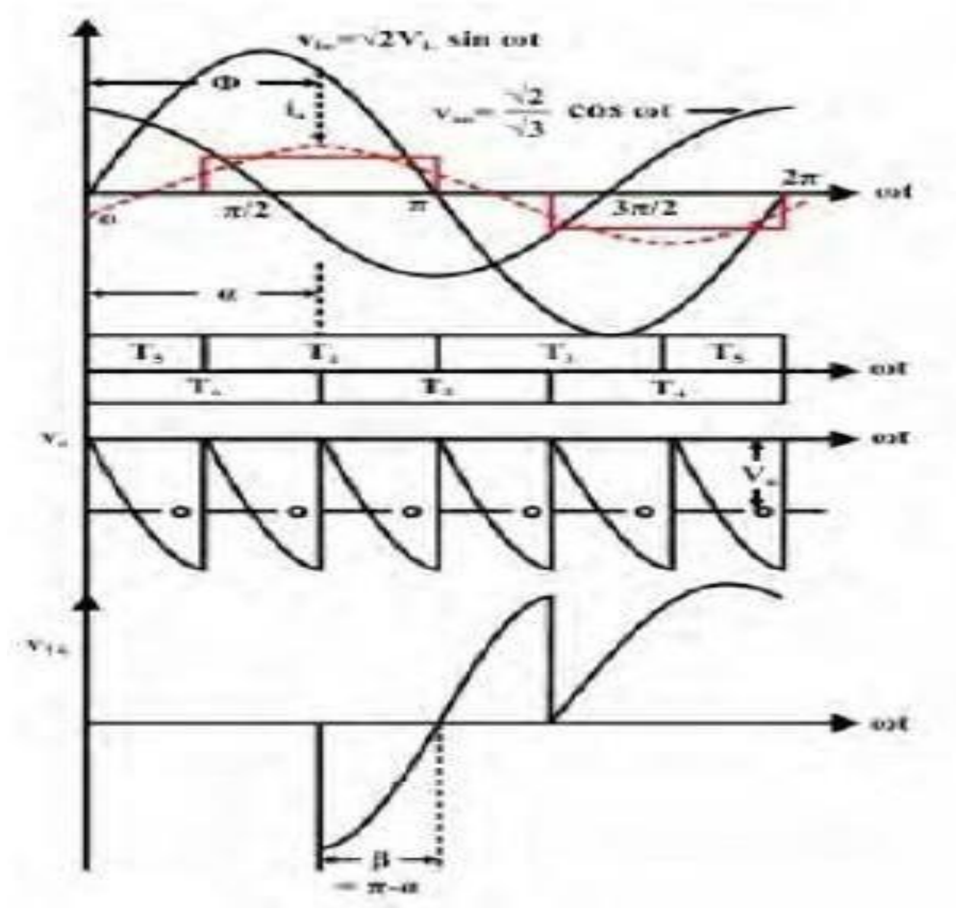
2. Explain the principle and operation of line commutated converters in inverse mode. (M.E-NOV/DEC2013) (M.E-APR/MAY2013)

Line Commutated Converters

The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. Three phase circuits are preferable when large power is involved. The controlled rectifier can provide controllable output dc voltage in a single unit instead of a three phase autotransformer and a diode bridge rectifier. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output dc voltage is obtained by controlling the conduction interval of each thyristor. This method is known as phase control and converters are also called "phase controlled converters". Since thyristors can block voltage in both directions it is possible to reverse the polarity of the output dc voltage and hence feed power back to the ac supply from the dc side. Under such condition the converter is said to be operating in the "inverting mode". The thyristors in the converter circuit are commutated with the help of the supply voltage in the rectifying mode of operation and are known as "Line commutated converter". The same circuit while operating in the inverter mode requires load side counter emf for commutation and is referred to as the "Load commutated inverter".

For any current to flow in the load at least one device from the top group (T1, T3, T5) and one from the bottom group (T2, T4, T6) must conduct. It can be argued as in the case of an uncontrolled converter only one device from these two groups will conduct. Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the input cycle. Now the thyristors are fired in the sequence T1 –T2-T3-T4-T5-T6 with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180° and hence cannot conduct simultaneously. This leaves only six possible conduction mode for the converter in the continuous conduction mode of operation. These are T1T2, T2T3, T3T4, T4T5, and T5T6. If α is made larger than 90° the direction of power flow through the converter will reverse provided there exists a power source in the dc side of suitable polarity. The converter in that case is said to be operating in the inverter mode. It has been explained in connection with single phase converters that the polarity of EMF source on the dc side would have to be reversed for inverter mode of operator. Figure shows the circuit connection and wave forms in the inverting mode of operation where the load current has been assumed to be continuous and ripple free.





Analysis of the converter in the inverting mode is similar to its rectifier mode of operation. The same expressions hold for the dc and harmonic compounds in the output voltage and current. In particular

$$V_o = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha$$

$$i_{a1} = \frac{2\sqrt{3}}{\pi} I_o \cos(\omega t - \alpha)$$

For values of α in the range 90° < or < 180° it is observed from Figure above that the average dc voltage is negative and the displacement angle φ of the fundamental component of the input ac line current is equal to α > 90°. Therefore, power in the ac side flows from the converter to the source. It is observed form Figure above that an outgoing thyristor after commutation is impressed with a negative voltage of duration β=π-α. For successful commutation of the outgoing thyristor it is essential that this interval is larger than the turn off time of the thyristor i.e.,

β > ωtq, tq is the thyristor turn off time

Therefore π-α> ωtq.

This imposes an upper limit on the value of α. In practice this upper value of α is further reduced due to commutation overlap.

3. Draw the schematic of buck-boost converter and explain the operation in detail. (M.E-NOV/DEC2010)

BUCK BOOST CONVERTER

Introduction

The buck—boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is a switched-mode power supply with a similar circuit topology to the boost converter and the buck converter. The output voltage is adjustable based on the duty cycle of the switching transistor. One possible drawback of this converter is that the switch does not have a terminal at ground; this complicates the driving circuitry. Also, the polarity of the output voltage is opposite the input voltage. Neither drawback is of any consequence if the power supply is isolated from the load circuit (ifi for example, the supply is a battery) as the supply and diode polarity can simply be reversed. The switch can be on either the ground side or the supply side.

Principle of Operation

The basic principle of the buck—boost converter is fairly simple

- While in the On-state, the input voltage source is directly connected to the inductor (L). This results in accumulating energy in L. In this stage, the capacitor supplies energy to the output load.
- While in the Off-state, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R.

Compared to the buck and boost converters, the characteristics of the buck—boost converter are mainly:

- Polarity of the output voltage is opposite to that of the input;
- The output voltage can vary continuously from 0 to $-\infty$ (for an ideal converter).
- The output voltage ranges for a buck and a boost converter are respectively 0 to V_i and V_i to ∞

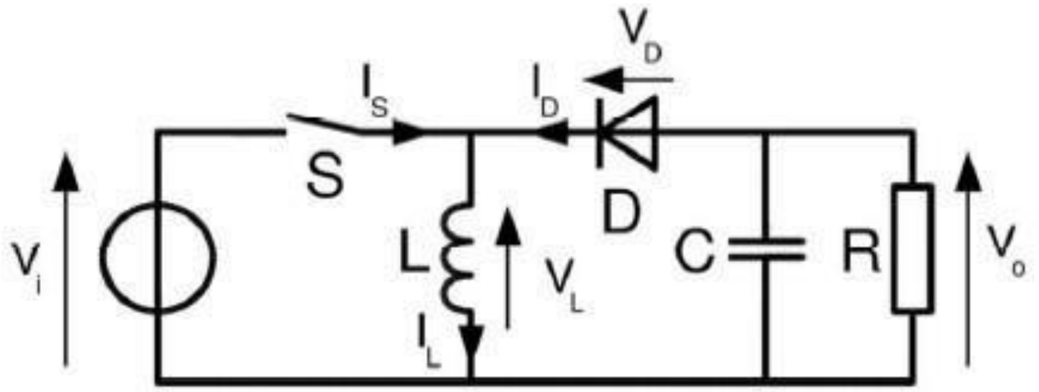
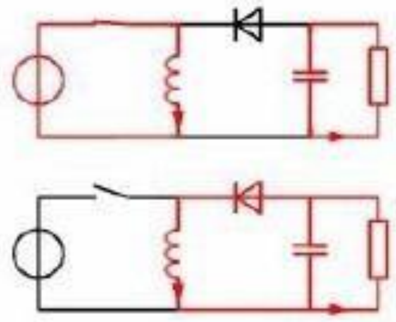


Fig 14 Buck Boost Converter



The two operating states of a buck–boost converter: When the switch is turned-on, the input voltage source supplies current to the inductor, and the capacitor supplies current to the resistor (output load). When the switch is opened, the inductor supplies current to the load via the diode D.

Continuous Conduction Mode

If the current through the inductor L never falls to Zero during a commutation cycle, the converter is said to operate in continuous mode. The current and voltage waveforms in an ideal converter can be seen in Figure below.

From t=0 to t=DT, the converter is in On-State, so the switch S is closed. The rate of change in the inductor current (I_L) is therefore given by

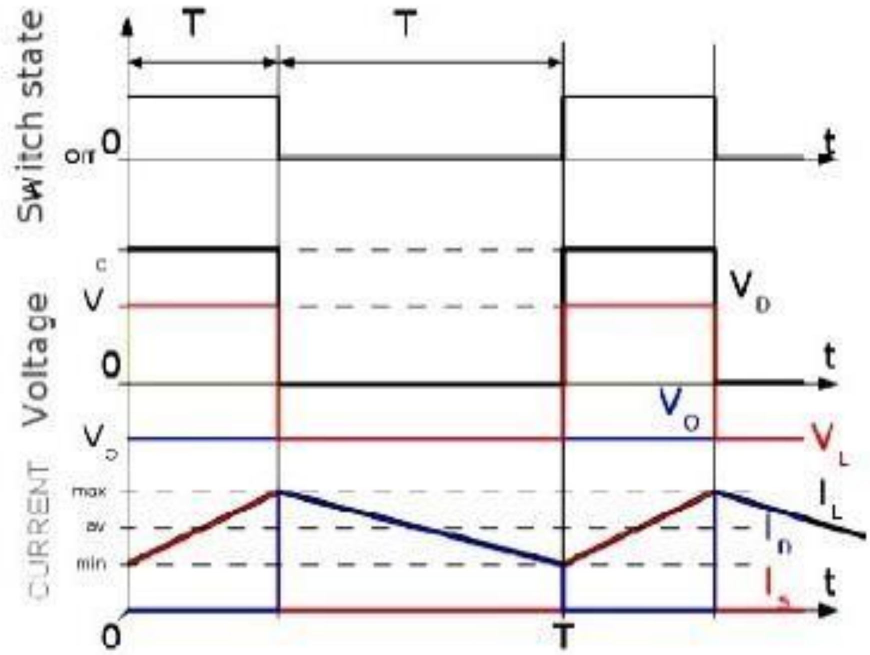
$$\frac{dI_L}{dt} = \frac{V_i}{L}$$

At the end of the On-state, the increase of I_L is therefore:

$$\Delta I_{L_{On}} = \int_0^{DT} dI_L = \int_0^{DT} \frac{V_i}{L} dt = \frac{V_i DT}{L}$$

D is the duty cycle. It represents the fraction of the commutation period T during which the switch is on. Therefore D ranges between 0 (S is never on) and 1 (S is always on). During the Off-state, the switch S is open, so the inductor current flows through the load. If We assume zero voltage drop in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_L is:

$$\frac{dI_L}{dt} = \frac{V_o}{L}$$



Waveforms of current and voltage in a buck–boost converter operating in continuous mode.

Therefore, the variation of I_L during the Off-period is:

$$\Delta I_{L_{Off}} = \int_0^{(1-D)T} dI_L = \int_0^{(1-D)T} \frac{V_o\,dt}{L} = \frac{V_o\,(1-D)\,T}{L}$$

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. As the energy in an inductor is given by:

$$E = \frac{1}{2} L\, I_L^2$$

It is obvious that the value of I_L at the end of the off state must be the same as the value off I_L at the beginning of the On-state, i.e. the sum of the variations of I_L during the on and the off states must be Zero:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = 0$$

Substituting $\Delta I_{L_{On}}$ and $\Delta I_{L_{Off}}$ by their expressions yields:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = \frac{V_i\, D\, T}{L} + \frac{V_o(1-D)T}{L} = 0$$

This can be written as:

$$\frac{V_o}{V_i} = \left(\frac{-D}{1-D}\right)$$

This in return yields that:

$$D = \frac{V_o}{V_o - V_i}$$

From the above expression it can be seen that the polarity of the output voltage is always negative (as the duty cycle goes from 0 to 1), and that its absolute value increases with D, theoretically up to minus infinity as D approaches 1. Apart from the polarity, this converter is either step-up (as a boost converter) or step-down (as a buck converter). This is why it is referred to as a buck—boost converter.

Discontinuous Conduction Mode

In some cases, the amount of energy required by the load is small enough to be transferred in a time smaller than the whole commutation period. In this case, the current through the inductor falls to Zero during part of the period. The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle. Although slight, the difference has a strong effect on the output voltage equation. It can be calculated as follows: As the inductor current at the beginning of the cycle is zero, its maximum value I_{Lmax} (at t= D T) is

$$I_{L_{max}} = \frac{V_i\, D\, T}{L}$$

During the off-period, I_L falls to zero after δ.T:

$$I_{L_{max}} + \frac{V_o\, \delta\, T}{L} = 0$$

Using the two previous equations, δ is:

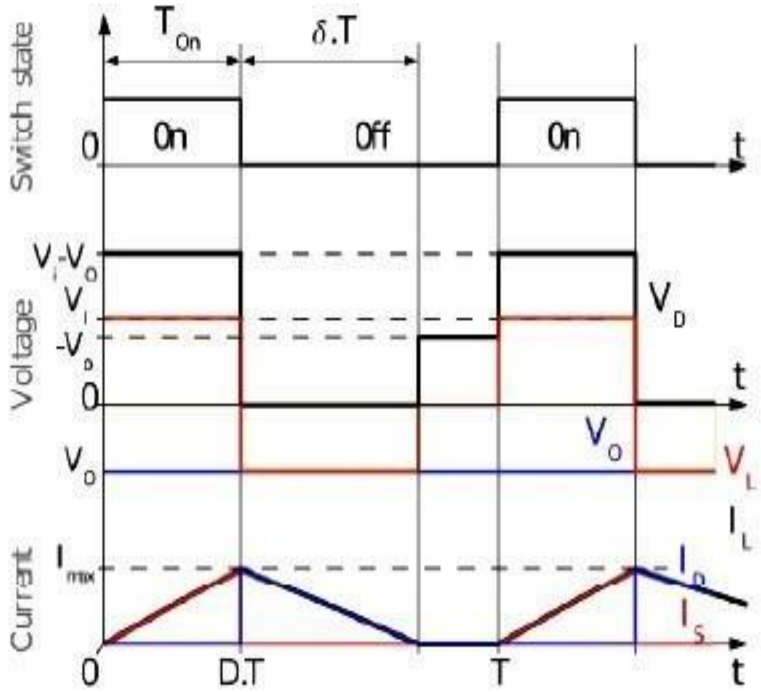
$$\delta = -\frac{V_i\, D}{V_o}$$

The load current I_O is equal to the average diode current (I_D). As can be seen on figure below, the diode current is equal to the inductor current during the off-state. Therefore, the output current can be written as:

$$I_o = \bar{I_D} = \frac{I_{L_{max}}}{2}\delta$$

Replacing $I_{L_{max}}$ and δ by their respective expressions yields:

$$I_o = -\frac{V_i\, D\, T}{2L}\frac{V_i\, D}{V_o} = -\frac{V_i^2\, D^2\, T}{2L\, V_o}$$



Waveforms of current and voltage in a buck–boost converter operating in discontinuous mode

Therefore, the output voltage gain can be written as:

$$\frac{V_o}{V_i} = -\frac{V_i D^2 T}{2L I_o}$$

Compared to the expression of the output voltage gain for the continuous mode, this expression is much more complicated. Furthermore, in discontinuous operation, the output voltage not only depends on the duty cycle, but also on the inductor value, the input voltage and the output current.

4. Explain with neat diagram the philosophy of operation of a solar source fed boost converter. (M.E-APR/MAY2013)

Boost Converter

A boost converter (step-up converter) is a DC-to-DC power converter that steps up voltage (while stepping down current) from its input (supply) to its output (load). It is a class of switched-mode power supply (SMPS) containing at least two semiconductors (a diode and a transistor) and at least one energy storage element: a capacitor, inductor, or the two in combination. To reduce voltage ripple, filters made of capacitors (sometimes in combination with inductors) are normally added to such a converter's output (load-side filter) and input (supply-side filter).

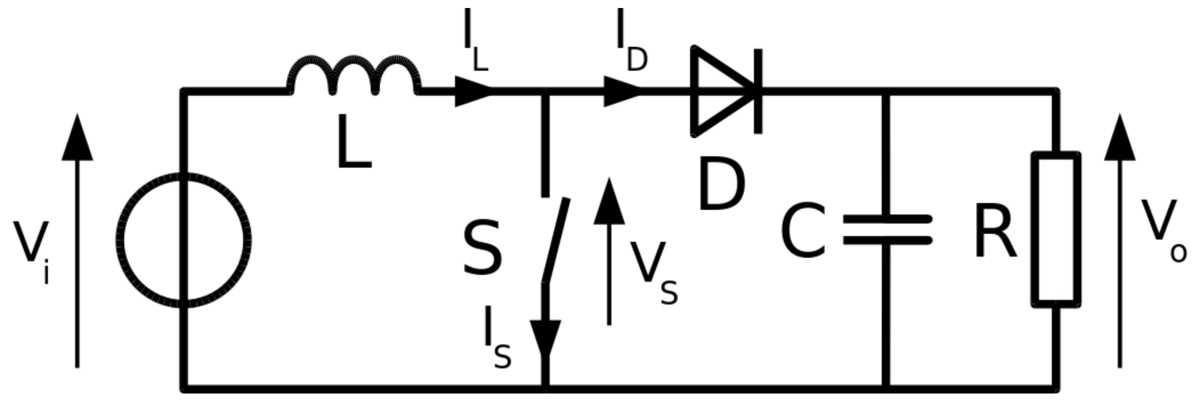
Operation

The key principle that drives the boost converter is the tendency of an inductor to resist changes in current by creating and destroying a magnetic field. In a boost converter, the output voltage is always higher than the input voltage. A schematic of a boost power stage is shown in Figure below.

(a) When the switch is closed, current flows through the inductor in clockwise direction and the inductor stores some energy by generating a magnetic field. Polarity of the left side of the inductor is positive.

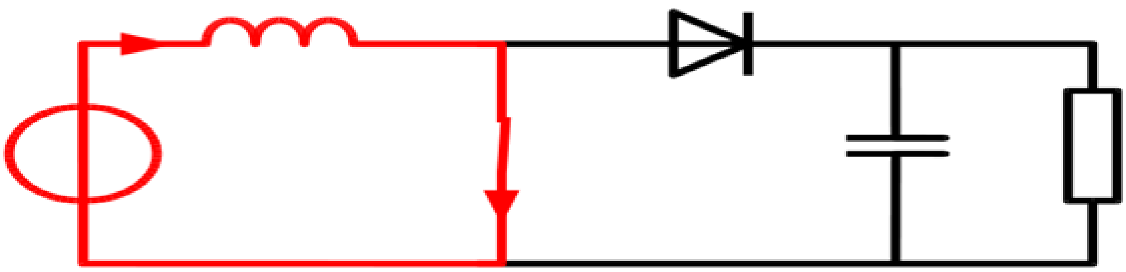
(b) When the switch is opened, current will be reduced as the impedance is higher. The magnetic field previously created will be destroyed to maintain the current towards the load. Thus the polarity will be reversed (means left side of inductor will be negative now). As a result, two sources will be in series causing a higher voltage to charge the capacitor through the diode D.

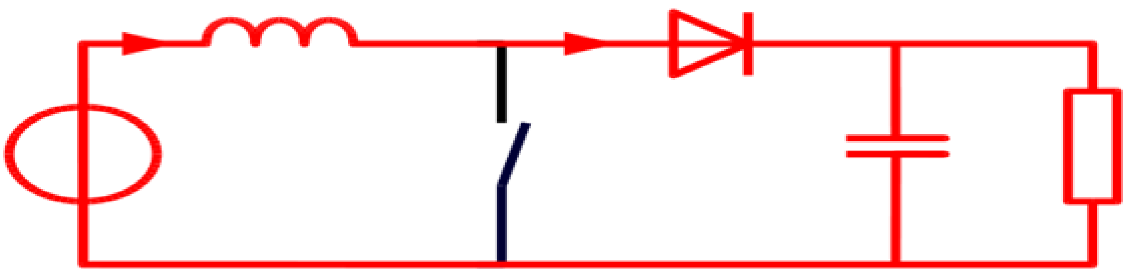
If the switch is cycled fast enough, the inductor will not discharge fully in between charging stages, and the load will always see a voltage greater than that of the input source alone when the switch is opened. Also while the switch is opened, the capacitor in parallel with the load is charged to this combined voltage. When the switch is then closed and the right hand side is shorted out from the left hand side, the capacitor is therefore able to provide the voltage and energy to the load. During this time, the blocking diode prevents the capacitor from discharging through the switch. The switch must of course be opened again fast enough to prevent the capacitor from discharging too much.



The basic principle of a Boost converter consists of 2 distinct states (see figure below):

- in the On-state, the switch S (see figure 1) is closed, resulting in an increase in the inductor current;
- In the Off-state, the switch is open and the only path offered to inductor current is through the fly back diode D, the capacitor C and the load R. These results in transferring the energy accumulated during the On-state into the capacitor.
- The input current is the same as the inductor current as can be seen in figure below. So it is not discontinuous as in the buck converter and the requirements on the input filter are relaxed compared to a buck converter.





Continuous mode

When a boost converter operates in continuous mode, the current through the inductor (I_L) never falls to zero. Figure 3 shows the typical waveforms of currents and voltages in a converter operating in this mode. The output voltage can be calculated as follows, in the case of an ideal converter operating in steady conditions:

During the on state the switch S is closed, which makes the input voltage appear across the inductor, which causes a change in current flowing through the inductor during a time period by the formula

$$\frac{\Delta I_L}{\Delta t} = \frac{V_i}{L}$$

At the end of on state, the increase of I_L is therefore

$$\Delta I_{L_{On}} = \frac{1}{L}\int_0^{DT} V_i dt = \frac{DT}{L}V_i$$

D is the duty cycle. It represents the fraction of the commutation period T during which the switch is On. Therefore, D ranges between 0 (S is never on) and 1 (S is always on).

During the Off-state, the switch S is open, so the inductor current flows through the load. If we consider zero voltage drop in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_L is:

$$V_i - V_o = L\frac{dI_L}{dt}$$

Therefore, the variation of I_L during the Off-period is:

$$\Delta I_{L_{Off}} = \int_{DT}^{T} \frac{(V_i - V_o)\,dt}{L} = \frac{(V_i - V_o)(1 - D)T}{L}$$

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. In particular, the energy stored in the inductor is given by:

$$E = \frac{1}{2}LI_L^2$$

So, the inductor current has to be the same at the start and end of the commutation cycle. This means the overall change in the current (the sum of the changes) is zero:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = 0$$

Substituting $\Delta I_{L_{On}}$ and $\Delta I_{L_{Off}}$ by their expressions yields:

$$\Delta I_{L_{On}} + \Delta I_{L_{Off}} = \frac{V_i DT}{L} + \frac{(V_i - V_o)(1 - D)T}{L} = 0$$

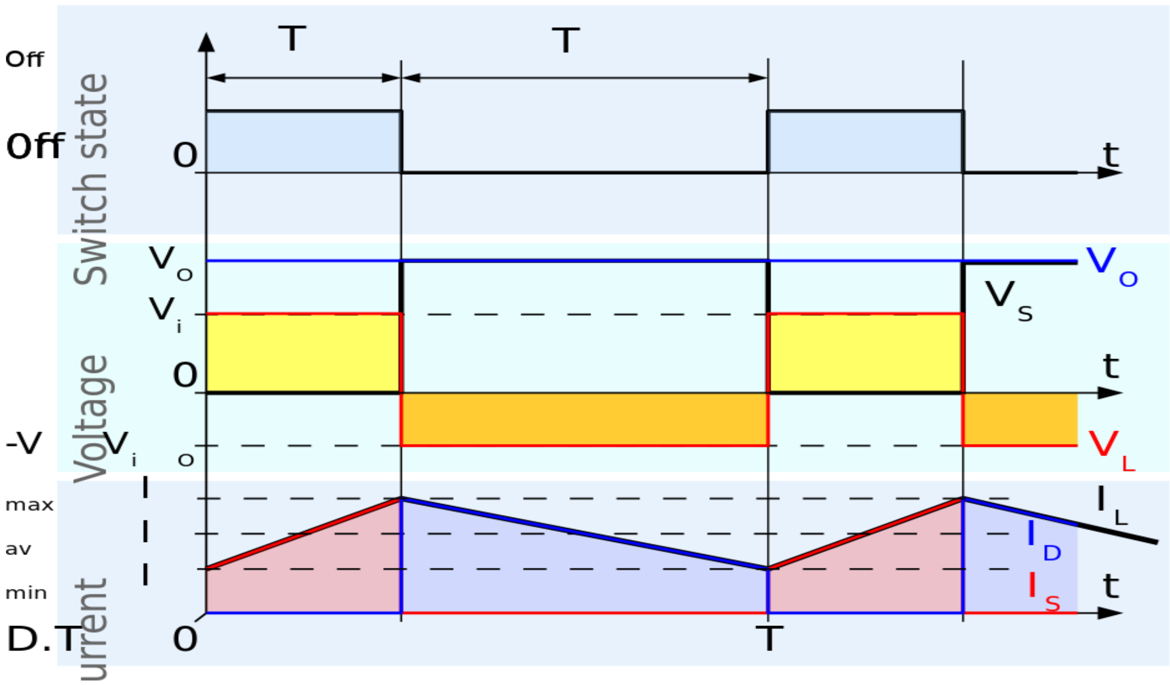
This can be written as:

$$\frac{V_o}{V_i} = \frac{1}{1 - D}$$

The above equation shows that the output voltage is always higher than the input voltage (as the duty cycle goes from 0 to 1), and that it increases with D, theoretically to infinity as D approaches 1. This is why this converter is sometimes referred to as a step-*up* converter.

Rearranging the equation reveals the duty cycle to be:

$$D = 1 - \frac{V_i}{V_o}$$



Waveforms of current and voltage in a boost converter operating in continuous mode.

Discontinuous mode

If the ripple amplitude of the current is too high, the inductor may be completely discharged before the end of a whole commutation cycle. This commonly occurs under light loads. In this case, the current through the inductor falls to zero during part of the period (see waveforms in figure). Although the difference is slight, it has a strong effect on the output voltage equation. The voltage gain can be calculated as follows:

As the inductor current at the beginning of the cycle is zero, its maximum value $I_{L_{Max}}$ (at $t = DT$) is

$$I_{L_{Max}} = \frac{V_i DT}{L}$$

During the off-period, I_L falls to zero after δT:

$$I_{L_{Max}} + \frac{(V_i - V_o)\,\delta T}{L} = 0$$

Using the two previous equations, δ is:

$$\delta = \frac{V_i D}{V_o - V_i}$$

The load current I_o is equal to the average diode current (I_D). As can be seen on figure 4, the diode current is equal to the inductor current during the off-state. Therefore, the output current can be written as:

$$I_o = \bar{I_D} = \frac{I_{L_{max}}}{2}\delta$$

Replacing I_{Lmax} and δ by their respective expressions yields:

$$I_o = \frac{V_i DT}{2L} \cdot \frac{V_i D}{V_o - V_i} = \frac{V_i^2 D^2 T}{2L\,(V_o - V_i)}$$

Therefore, the output voltage gain can be written as follows:

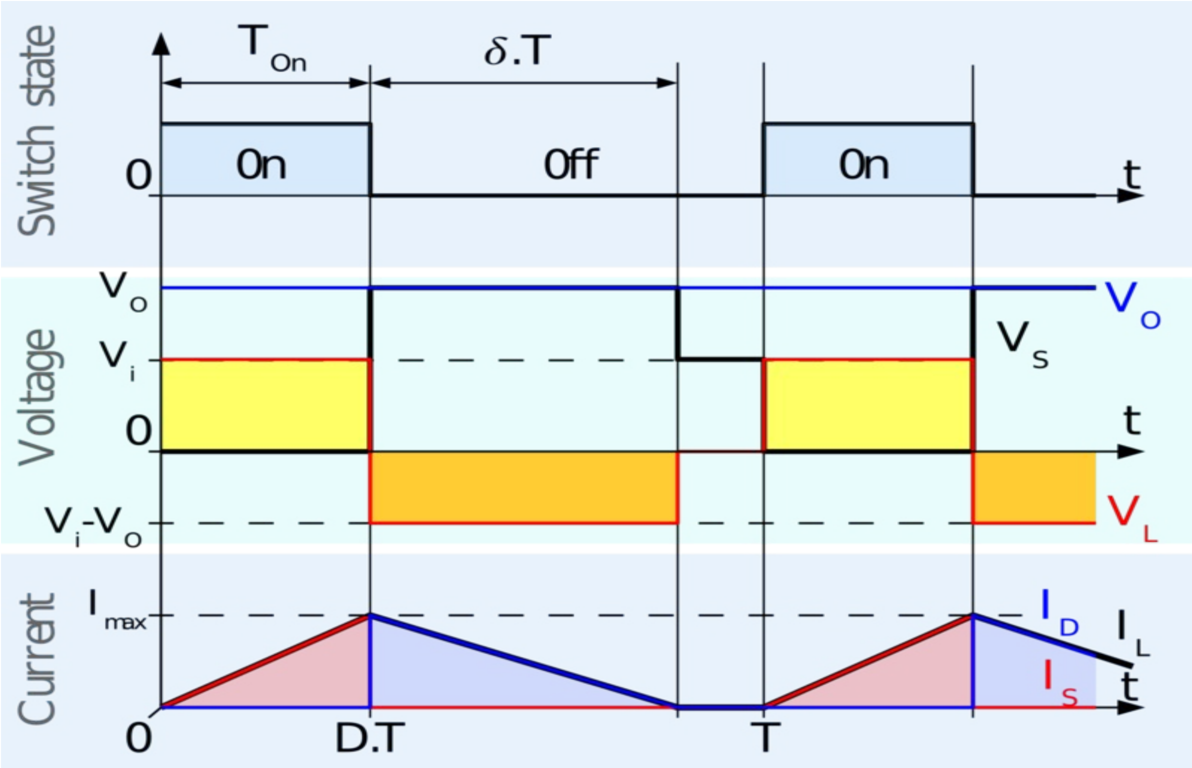
$$\frac{V_o}{V_i} = 1 + \frac{V_i D^2 T}{2 L I_o}$$

Compared to the expression of the output voltage gain for continuous mode, this expression is much more complicated. Furthermore, in discontinuous operation, the output voltage gain not only depends on the duty cycle (D), but also on the inductor value (L), the input voltage (V_i), the commutation period (T) and the output current (I_o).

Substituting $I_o = V_o/R$ into the equation (R is the load), the output voltage gain can be rewritten as:

$$\frac{V_o}{V_i} = \frac{1 + \sqrt{1 + \frac{4D^2}{K}}}{2}$$

where $K = \frac{2L}{RT}$



Waveforms of current and voltage in a boost converter operating in discontinuous mode

5. Explain the need of AC-DC-AC converters for wind energy conversion system. (APR/MAY2017)

AC-DC-AC converters

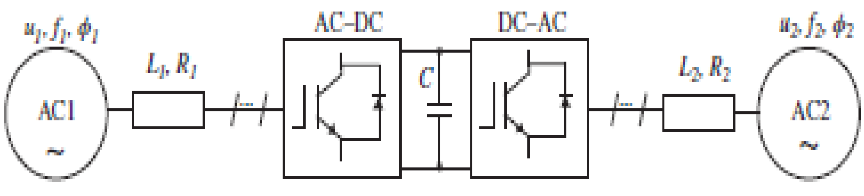
The AC–DC–AC is a connection through a DC-link of two single-phase, three-phase, or multiphase AC circuits with different voltage amplitude *u*, frequency *f*, or phase angle . The major application of AC–DC–AC converters is in adjustable speed drives. However, recently, these converters have begun to play an increasingly important role in *distributed power generation systems* (DPGSs) and *sustainable AC and DC grids*.

There are several possibilities for an AC–DC–AC converter configuration. Recently, bidirectional AC–DC–AC converters are available on the market for different voltage levels. Both parts of the converter (i.e., AC–DC and DC–AC) can be controlled independently. However, in some cases, there is a need for improving the control accuracy and dynamics. Therefore, it is useful to use an additional link between both control algorithms, which operates as an *active power feed forward* (APFF). The APFF gives information about the active power on one side of the AC–DC–AC converter to the other side directly, and consequently, the stability of the DC voltage is improved significantly.

Bidirectional AC–DC–AC Topologies

There are several configurations possible for three-phase to three-phase AC–DC–AC full-bridge converters, which can connect two AC systems. The most popular is a two-level converter, as shown in Figure below , which is used mostly in low voltage and low-power or medium-power applications, for example, adjustable speed drives. On the other hand, three-level *diode-clamped converters* (DCCs) and flying capacitor converters (FCCs) are becoming increasingly popular, but usually in the medium-voltage range for medium- and high-power applications, for example, marine propulsion, renewable energy conversion, rolling mills and railway traction. There are several advantages of multilevel converters, such as lower voltage stress of components, low current and voltage, total harmonic distortion factor and reduced volume of input passive filters. The main differences among the mentioned multilevel topologies are as follows:

- DCC is the most popular topology and needs fewer capacitors. However, for higher voltage levels, it requires serially connected clamping diodes, which increases the losses and switching losses. In addition, for higher voltage levels, the DC capacitor voltage balancing cannot be achieved with classical modulations.
- FCC is less popular because it needs initialization of the FC voltage, and higher switching frequency is required (greater than 1.2 kHz, whereas for high-power applications the switching frequency is usually between 500 and 800 Hz) in high-power applications because of the FC limits, that is, capacitance versus volume.



Another group of AC–DC–AC converters are simplified topologies obtained by reducing the number of power electronic switches. These attempts were based on the idea of replacing one of the semiconductor legs with a split capacitor bank and connecting a one-phase wire to its middle. In simplified topology, the lower number of switching devices, compared with that of a classical three-phase converter, corresponds to a reduced number of control channels and insulated-gate bipolar transistor (IGBT) driver circuits.

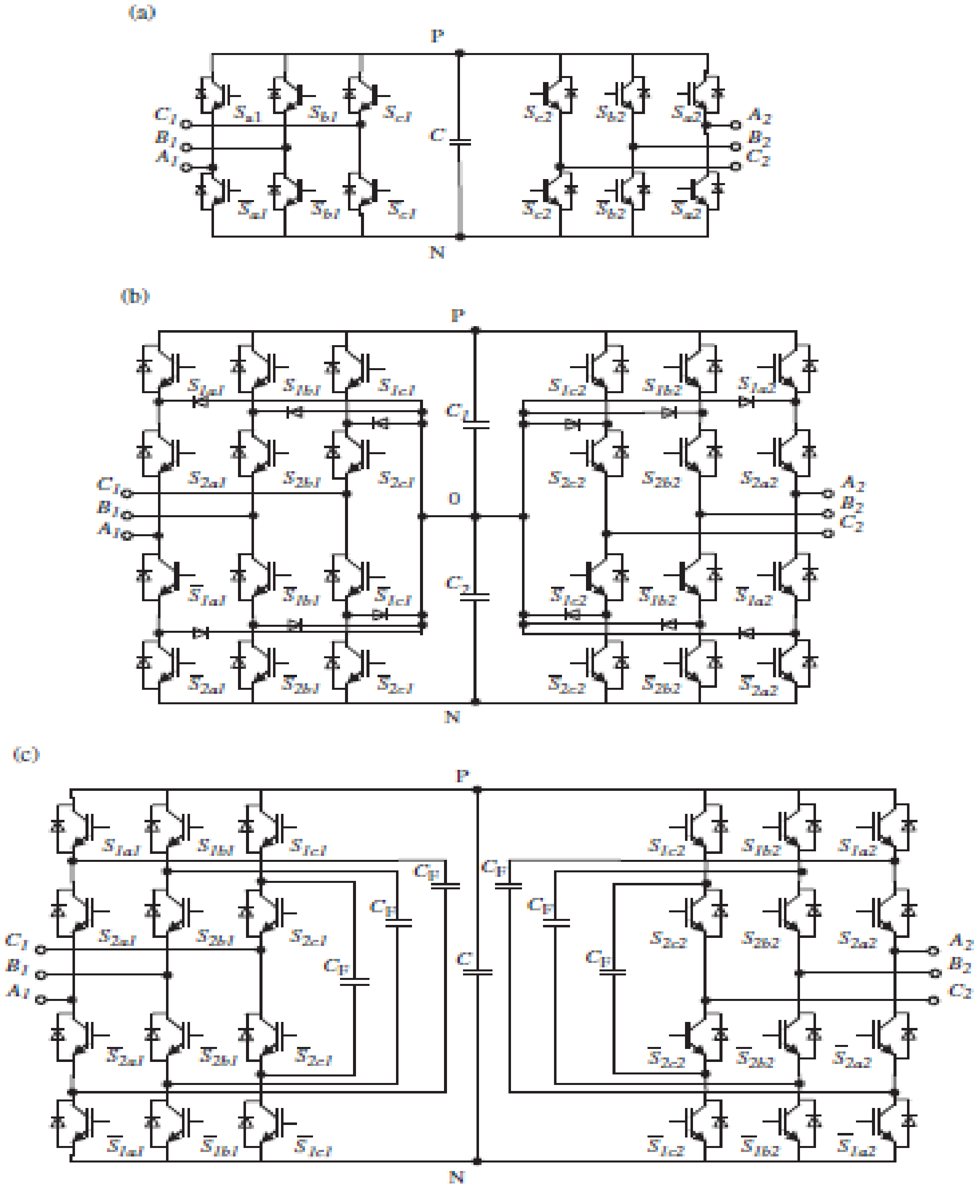


Figure Fully controlled three-phase/three-phase, transistor-based AC–DC–AC converter: (a) two-level (2L-3/3), (b) three-level DCC (3L-DCC-3/3) and (c) three-level FCC (3L-FCC-3/3)

Thus, connecting a three-phase AC system to a single-phase AC system is possible by using a single-standard three-leg integrated power module as the AC–DC–AC converter, as shown in Figure (a). The same concept can be used to simplify an AC–DC–AC converter by connecting one three-phase system to another using only one additional leg, as is shown in Figure (b). Despite the advantages of these solutions, there is a necessity to develop new modulation techniques and to keep the DC voltage significantly high in order to maintain all nominal phase-to-phase converter voltages, which places higher voltage stress on the converter semiconductor devices. This problem can be solved by application of a three-level DCC. When this technology was emerging in industry, not a single integrated power module product for three-level devices was available. Today, manufacturers are selling easy-to-use integrated half-bridge power modules with clamping diodes. New compact devices make it easier to improve the topology with a split capacitor in the DC-link. Thus, the improved topology of a simplified AC–DC–AC converter is shown in Figure below, for applications of three-phase to single-phase, as well as for three-phase to three-phase systems. The first topology is dedicated only to low-power applications, whereas the second is devoted to low- and medium-power applications.
The simplified three-level DCC has several advantages compared with that of a simplified two-level Topology: reduction of machine torque pulsations (mechanical stress in cases where generator/motor application is decreased), additional zero vectors, and reduction in size of passive filters on the AC side.

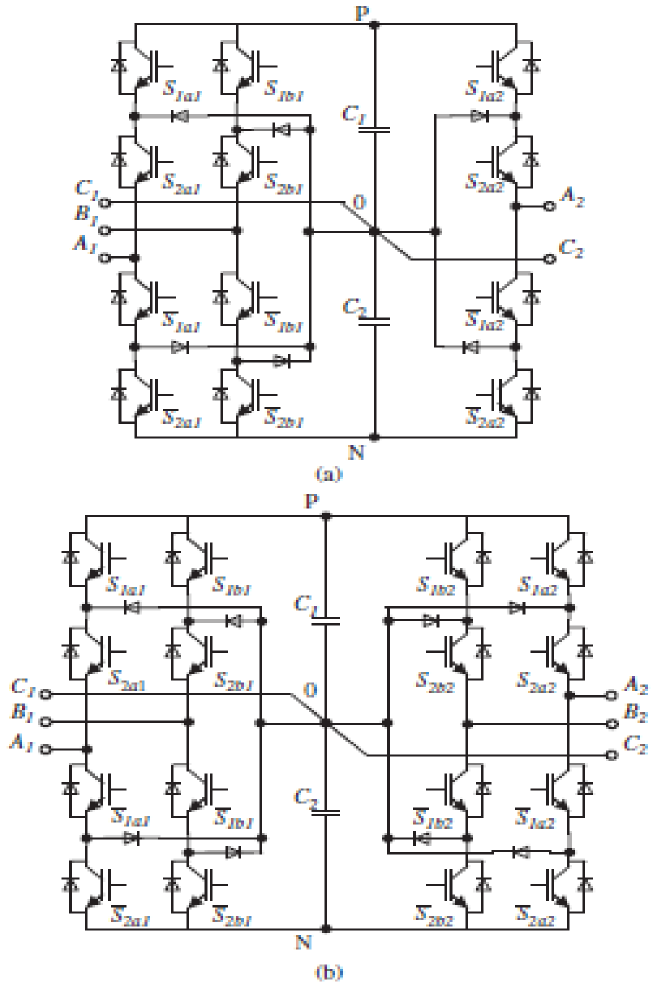


Figure Simplified DCC AC–DC–AC converters: (a) three-phase/one-phase (S3L-DCC 3/1) and (b) three-phase/three-phase (S3L-DCC 3/3)

6. Explain the space vector PWM technique to control 3-phase inverter with neat schematic diagrams. **(M.E-NOV/DEC2016)**

Space vector PWM

At present, the control strategies are implemented in digital systems, and therefore digital modulating techniques are also available. The SV-based modulating technique is a digital technique in which the objective is to generate PWM load line voltages that are on average equal to given load line voltages. This is done in each sampling period by properly selecting the switch states from the valid ones of the VSI (Table below) and by proper calculation of the period of times they are used. The selection and calculation times are based upon the space-vector transformation

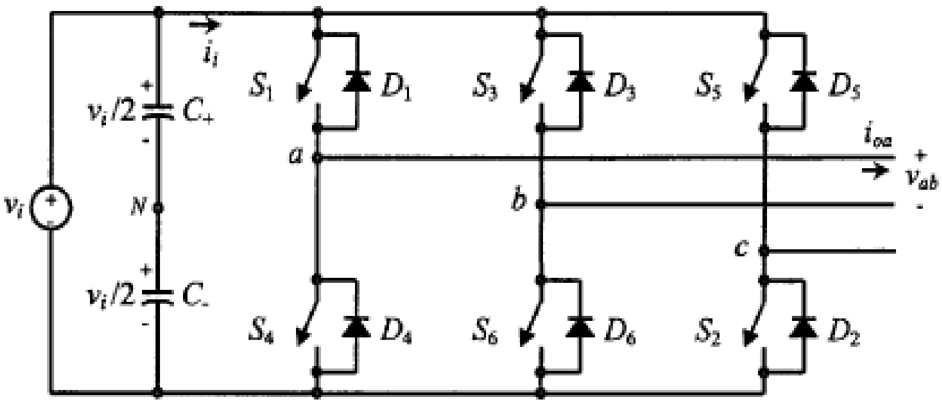


FIGURE Three-phase VSI topology.

TABLE Valild switch states for a three-phase VSI

State	State	v_{ab}	v_b	v_a	Space Vector
1, 2, and 6 are on and 4, 5, and 3 are off	1	v	0	$-v$	$V_1 = 1 + j0.5$
2, 3, and 1 are on and 5, 6, and 4 are off	2	0	v	$-v$	$V_2 = j1.155$
3, 4, and 2 are on and 6, 1, and 5 are off	3	$-v$	v	0	$V_3 = -1 + j0.5$
4, 5, and 3 are on and 1, 2, and 6 are off	4	$-v$	0	v	$V_4 = -1 - j0.5$
5, 6, and 4 are on and 2, 3, and 1 are off	5	0	$-v$	v	$V_5 = -j1.155$
6, 1, and 5 are on and 3, 4, and 2 are off	6	v	$-v$	0	$V_6 = 1 - j0.5$
1, 3, and 5 are on and 4, 6, and 2 are off	7	0	0	0	$V_7 = 0$
4, 6, and 2 are on and 1, 3, and 5 are off	8	0	0	0	$V_8 = 0$

Space-Vector Transformation

Any three-phase set of variables that add up to zero in the stationary abc frame can be represented in a complex plane by a complex vector that contains a real (α) and an imaginary (β) component. For instance, the vector of three-phase line modulating signals can be represented by the complex vector by means of the following transformation:

$$v_{c\alpha} = \frac{2}{3}[v_{ca} - 0.5(v_{cb} + v_{cc})]$$

$$v_{c\beta} = \frac{\sqrt{3}}{3}(v_{cb} - v_{cc})$$

If the line-modulating signals [vc] abc are three balanced sinusoidal waveforms that feature an amplitude vc and an angular frequency ω, the resulting modulating signals in the αβ stationary frame Vc =$[V_c]_{\alpha\beta}$ become a vector of fixed module vc , which rotates at frequency ω (Figure below). Similarly, the SV transformation is applied to the line voltages of the eight states of the VSI normalized with respect to vi (Table above), which generates the eight space vectors as in Figure below. As expected, V1 to V6 are Non null line voltage vectors and V7 and V8 are null line voltage vectors.

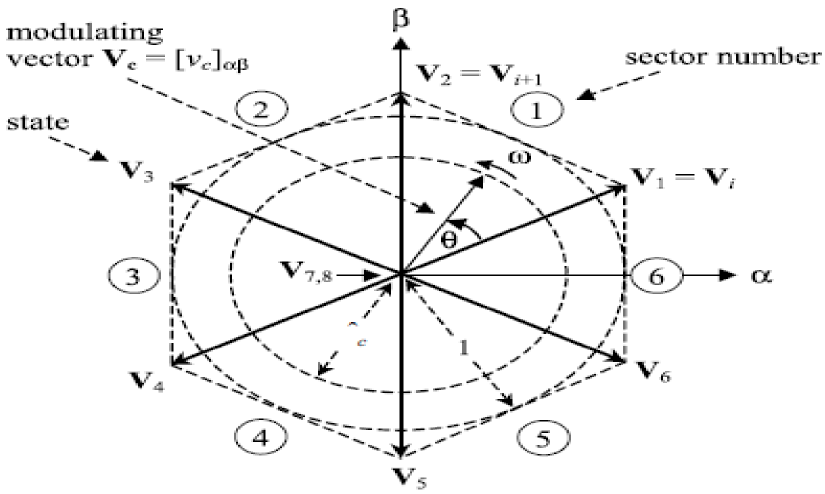


FIGURE The space-vector representation.

The objective of the SV technique is to approximate the line-modulating signal space Vc with the eight space vectors available in VSIs. However, if the modulating signal Vc is laying between the arbitrary vectors Vi and V_{i+1}, only the nearest two nonzero vectors (Vi and Vi+1) and one zero SV (Vz = V7 or V8) should be used. Thus, the maximum load line voltage is maximized and the switching frequency is minimized. To ensure that the generated voltage in one sampling period Ts (made up of the voltages provided by the vectors Vi , Vi+1, and Vz used during times Ti , Ti+1, and Tz) is on average equal to the vector Vc, the following expression should hold:

$$V_c \cdot T_s = V_i \cdot T_i + V_{i+1} \cdot T_{i+1} + V_z \cdot T_z$$

The solution of the real and imaginary parts of Equation above for a line-load voltage that features an amplitude restricted to 0≤Vc≤1 gives

$$T_i = T_s \cdot \hat{v}_c \cdot \sin(\pi/3 - \theta)$$
$$T_{i+1} = T_s \cdot \hat{v}_c \cdot \sin(\theta)$$
$$T_z = T_s - T_i - T_{i+1}$$

The preceding expressions indicate that the maximum fundamental line-voltage amplitude is unity as $0 \leq \theta \leq \pi/3$. This is an advantage over the SPWM technique which achieves√3/2 maximum fundamental line-voltage amplitude in the linear operating region. Although, the SVM technique selects the vectors to be used and their respective on-times, the sequence in which they are used, the selection of the zero space vectors, and the normalized sampled frequency remain undetermined. For instance, if the modulating line-voltage vector is in sector 1 (Figure above), the vectors V1, V2, and Vz should be used within a sampling period by intervals given by T1, T2, and Tz , respectively. The question that remains is whether the sequence (i) V1-V2 -Vz , (ii) Vz -V1 -V2 -Vz , (iii) Vz- V1- V2- V1- Vz , (iv) Vz - V1 - V2 –Vz-V2 - V1 -Vz , or any other sequence should actually be used. Finally, the technique does not indicate whether Vz should be V7, V8, or a combination of both.

Space-Vector Sequences and Zero Space-Vector Selection

The sequence to be used should ensure load line voltages that feature quarter-wave symmetry in order to reduce unwanted harmonics in their spectra (even harmonics). Additionally, the zero SV selection should be done in order to reduce the switching frequency. Although there is not a systematic approach to generate a SV sequence, a graphical representation shows that the sequence Vi , Vi+1, Vz (where Vz is alternately chosen among V7 and V8) provides high performance in terms of minimizing unwanted harmonics and reducing the switching frequency.

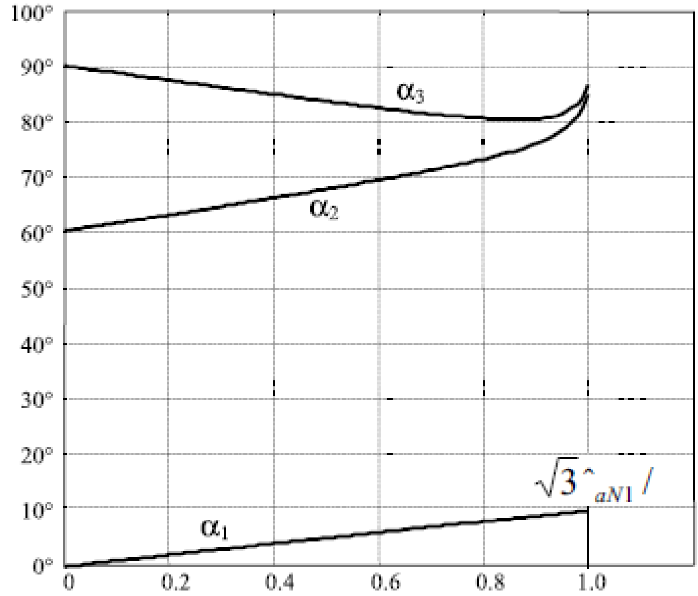


FIGURE Chopping angles for SHE and fundamental voltage control in three-phase VSIs: fifth and seventh harmonic elimination.

7. Explain the three phase uncontrolled rectifiers in detail. (M.E-NOV/DEC2013)

Three Phase Uncontrolled Rectifiers

Three-Phase Full-Wave Rectifier

The full-bridge rectifier is more common since it provides a high output voltage and less ripple. First let us consider the full-bridge circuit under a resistive load as shown in Figure below. Let us assume that v_a, v_b, and v_c are the three phase voltages. The easiest way to approach the full-bridge rectifier circuit is to consider it as a combination of a positive commutating diode groupD1, D2, and D3, and a negative commutating diode group D4, D5, and D6. Since no commutating inductance is included, at any given time only two diodes are conducting simultaneously—one from the positive group and the other from the negative group.

The output voltage V_0, is given by

$V_0=V_{01}-V_{02}$

where $V_{01}$and V_{02} are the output voltages of the positive and negative commuting diode groups to ground, respectively.

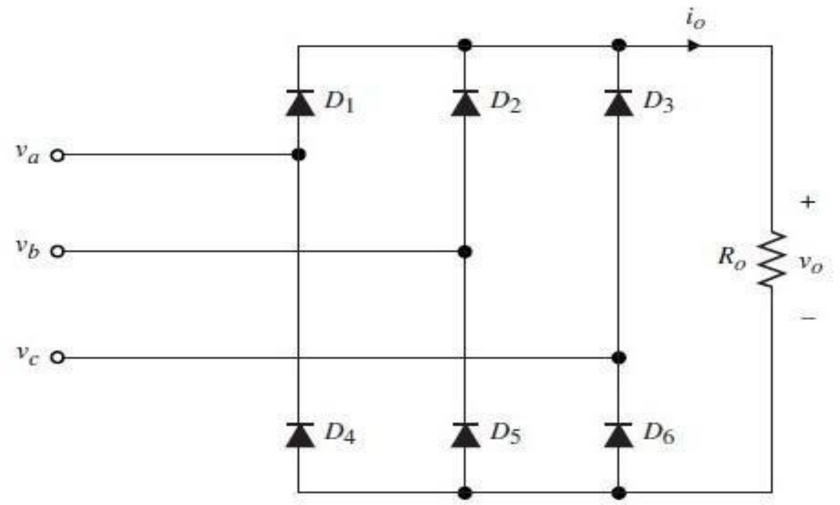


Figure Full-bridge rectifier circuit under resistive load.

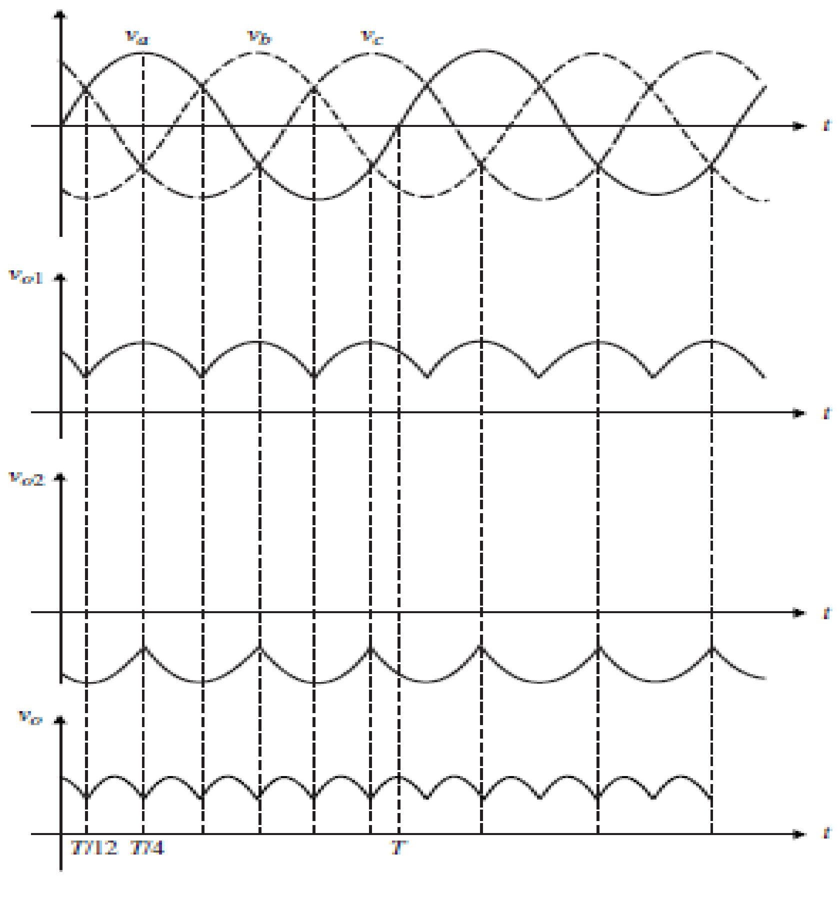


Figure Output voltage waveforms

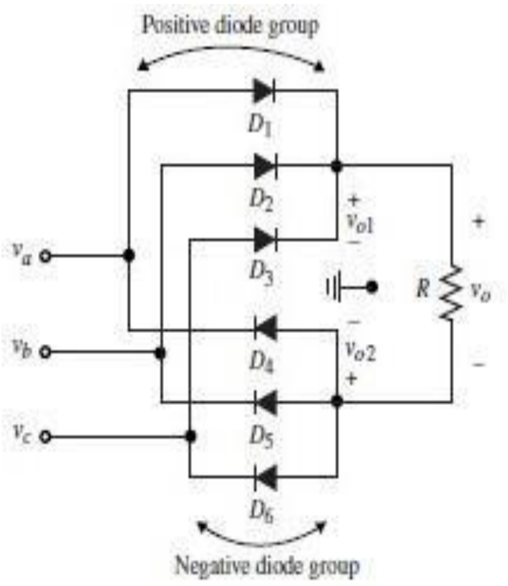


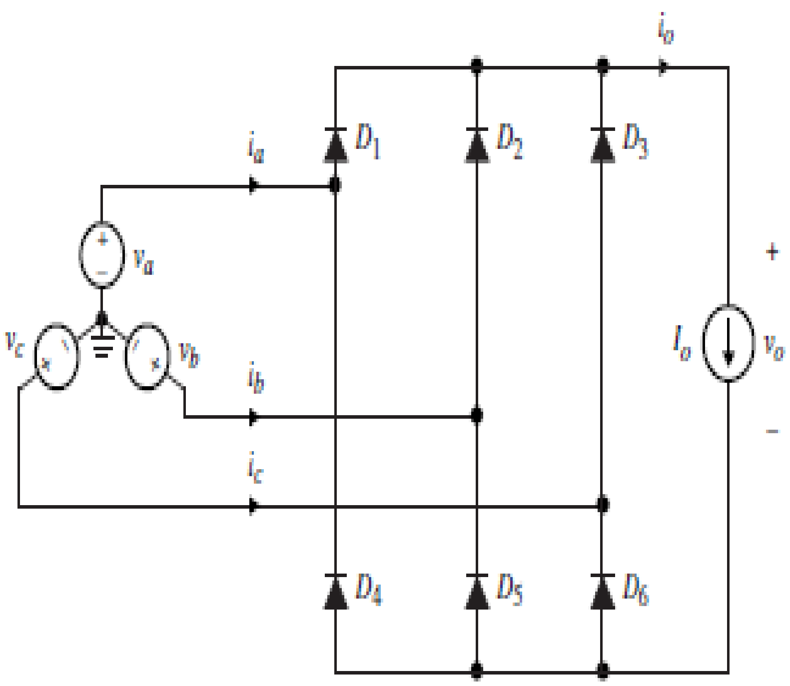
Figure Equivalent circuit

The average output voltage is given by

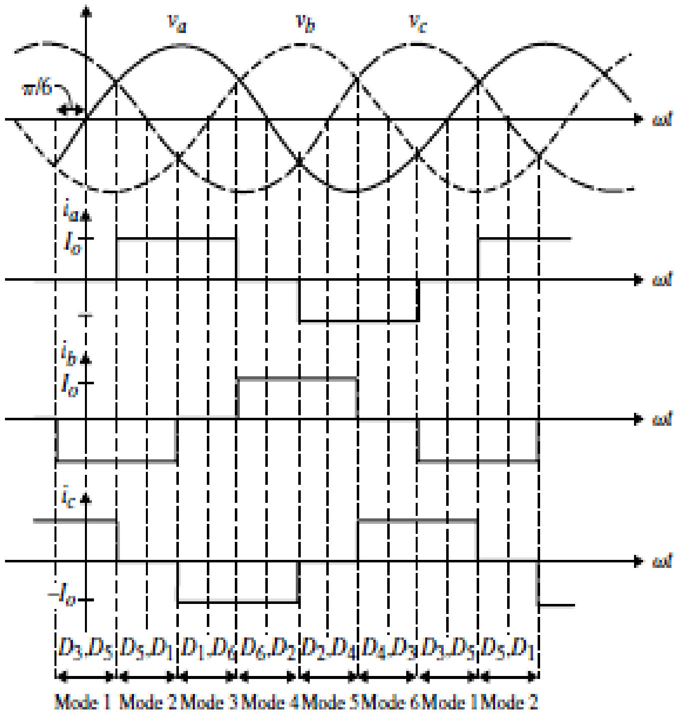
$$V_o = \frac{1}{T/6}\int_{T/12}^{T/4} V_a\, dt$$

$$= \frac{3\sqrt{3}}{\pi} V_s$$

Let us consider the full-bridge rectifier under 21 highly inductive load using a Y- connected voltage source with L/R >>T/6. Table below shows all six modes of operation with the corresponding diode conduction angles and currents, where θ=ωt.



(a)



(b)

Figure (a) Three-phase bridge rectifier with highly inductive load. (b) Phase current waveforms.

Table Conduction Modes

Mode	Conduction angle	Diodes conducting	i_a	i_b	i_c	Most positive absolute voltage
I	$-\pi/6 < \theta < \pi/6$	D_3, D_5	0	$-I_o$	I_o	$\lvert v_b \rvert, v_c$
II	$\pi/6 < \theta < \pi/2$	D_5, D_1	I_o	$-I_o$	0	$v_a, \lvert v_b \rvert$
III	$\pi/2 < \theta < 5\pi/6$	D_1, D_6	I_o	0	$-I_o$	$v_a, \lvert v_c \rvert$
IV	$5\pi/6 < \theta < 7\pi/6$	D_6, D_2	0	I_o	$-I_o$	$v_b, \lvert v_c \rvert$
V	$7\pi/6 < \theta < 9\pi/6$	D_2, D_4	$-I_o$	I_o	0	$\lvert v_a \rvert, v_b$
VI	$9\pi/6 < \theta < 11\pi/6$	D_4, D_3	$-I_o$	0	I_o	$\lvert v_a \rvert, v_c$

The waveforms for the output voltage and the diode and line currents are shown in Fig. (b). the output voltage is the same as that in the resistive case.

8. Draw and discuss the operation of a matrix converter. (M.E-NOV/DEC2013)

Matrix Converter

The matrix converter (MC) is a development of the force commutated cycloconverter (FCC) based on bidirectional fully controlled switches, incorporating PWM voltage control, as mentioned earlier. It provides a good alternative to the double-sided PWM voltage source rectifier-inverters having the advantages of being a single-stage converter with only nine switches for three phase to three-phase conversion and inherent bidirectional power flow, sinusoidal input/output waveforms with moderate switching frequency, the possibility of compact design due to the absence of dc link reactive components and controllable input power factor independent of the output load current. The main disadvantages of the matrix converters developed so far are the inherent restriction of the voltage transfer ratio (0.866), a more complex control and protection strategy, and above all the non availability of a fully controlled bidirectional high-frequency switch integrated in a silicon chip (Triac, though bilateral, cannot be fully controlled). The power circuit diagram of the most practical three-phase to three-phase matrix converter is shown in Figurea, which uses nine bidirectional switches so arranged that any of three input phases can be connected to any output phase as shown in the switching matrix symbol in Figure b.

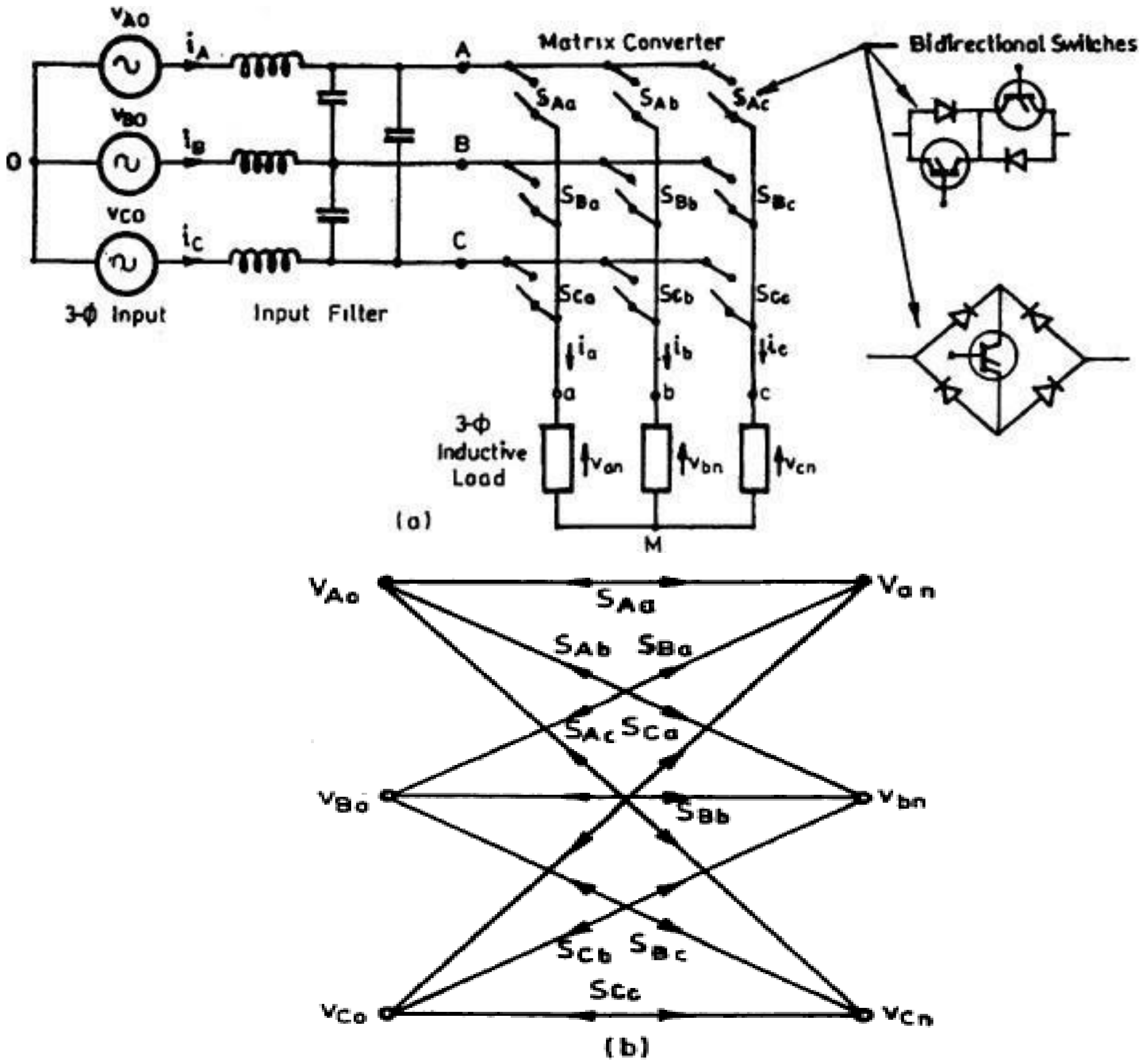


Figure (a) The 3φ-3φ Matrix converter (b) switching matrix symbol for converter

Thus, the voltage at any input terminal may be made to appear at any output terminal or terminals while the current in any phase of the load may be drawn from any phase or phases of the input supply. For the switches, the inverse-parallel combination of reverse-blocking self-controlled devices such as Power MOSFETs or IGBTs or transistor-embedded diode bridge as shown has been used so far. The circuit is called a matrix converter as it provides exactly one switch for each of the possible connections between the input and the output. The switches should be controlled in such a way that, at any time, one and only one of the three switches connected to an output phase must be closed to prevent ‘‘short-circuiting’’ of the supply lines or interrupting the load-current flow in an inductive load. With these constraints, it can be visualized that from the possible 512 states of the converter, only 27 switch combinations are allowed as given in Table below, which includes the resulting output line voltages and input phase currents. These combinations are divided into three groups. Group I consists of six combinations when each output phase is connected to a different input phase. In Group II, there are three subgroups, each having six combinations with two output phases short-circuited (connected to the same input phase). Group III includes three combinations with all output phases short-circuited. With a given set of input three-phase voltages, any desired set of three-phase output voltages can be synthesized by adopting a suitable switching strategy.

TABLE Three-phase/three-phase matrix converter switching combinati ons

Group	a	b	c	v_{ab}	v_{bc}	v_{ca}	i_A	i_B	i_C	S_{Aa}	S_{Ab}	S_{Ac}	S_{Ba}	S_{Bb}	S_{Bc}	S_{Ca}	S_{Cb}	S_{Cc}
	A	B	C	v_{AB}	v_{BC}	v_{CA}	i_a	i_b	i_c	1	0	0	0	1	0	0	0	1
	A	C	B	$-v_{CA}$	$-v_{BC}$	$-v_{AB}$	i_a	i_c	i_b	1	0	0	0	0	1	0	1	0
	B	A	C	$-v_{AB}$	$-v_{CA}$	$-v_{BC}$	i_b	i_a	i_c	0	1	0	1	0	0	0	0	1
I	B	C	A	v_{BC}	v_{CA}	v_{AB}	i_c	i_a	i_b	0	1	0	0	0	1	0	1	0
	C	A	B	v_{CA}	v_{AB}	v_{BC}	i_b	i_c	i_a	0	0	1	1	0	0	0	1	0
	C	B	A	$-v_{BC}$	$-v_{AB}$	$-v_{CA}$	i_c	i_b	i_a	0	0	1	0	1	0	1	0	0
	A	C	C	$-v_{CA}$	0	v_{CA}	i_a	0	$-i_a$	1	0	0	0	0	1	0	0	1
	B	C	C	v_{BC}	0	$-v_{BC}$	0	i_a	$-i_a$	0	1	0	0	0	1	0	0	1
	B	A	A	$-v_{AB}$	0	$-v_{AB}$	$-i_a$	i_a	0	0	1	0	1	0	0	1	0	0
II-A	C	A	A	v_{CA}	0	$-v_{CA}$	$-i_a$	0	i_a	0	0	1	1	0	0	1	0	0
	C	B	B	$-v_{BC}$	0	v_{BC}	0	$-i_a$	i_a	0	0	1	0	1	0	0	1	0
	A	B	B	v_{AB}	0	$-v_{AB}$	i_a	$-i_a$	0	1	0	0	0	1	0	0	1	0
	C	A	C	$-v_{CA}$	$-v_{CA}$	0	i_b	0	$-i_b$	0	0	1	1	0	0	0	0	1
	C	B	C	$-v_{BC}$	v_{BC}	0	0	i_b	$-i_b$	0	0	1	0	1	0	0	0	1
	A	B	A	v_{AB}	$-v_{AB}$	0	$-i_b$	i_b	0	1	0	0	0	1	0	1	0	0
II-B	A	C	A	$-v_{CA}$	v_{CA}	0	$-i_b$	0	i_b	1	0	0	0	0	1	1	0	0
	B	C	B	v_{BC}	$-\ _{BC}$	0	0	$-i_b$	i_b	0	1	0	0	0	1	0	1	0
	B	A	B	$-v_{AB}$	V_{AB}	0	i_b	$-i_b$	0	0	1	0	1	0	0	0	1	0
	C	C	A	0	v_{CA}	$-v_{CA}$	i_c	0	$-i_c$	0	0	1	0	0	1	1	0	0
	C	C	B	0	$-v_{BC}$	v_{BC}	0	i_c	$-i_c$	0	0	1	0	0	1	0	1	0
	A	A	B	0	v_{AB}	$-v_{AB}$	$-i_c$	i_c	0	1	0	0	1	0	0	0	1	0
II-C	A	A	C	0	$-v_{CA}$	v_{CA}	$-i_c$	0	i_c	1	0	0	1	0	0	0	0	1
	B	B	C	0	v_{BC}	$-v_{BC}$	0	$-i_c$	i_c	0	1	0	0	1	0	0	0	1
	B	B	A	0	$-v_{AB}$	v_{AB}	i_c	$-i_c$	0	0	1	0	0	1	0	1	0	0
	A	A	A	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
III	B	B	B	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
	C	C	C	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1

However, it has been shown that regardless of the switching strategy there are physical limits on the achievable output voltage with these converters as the maximum peak-to-peak output voltage cannot be greater than the minimum voltage difference between two phases of the input. The alternative is to use the space vector modulation (SVM) strategy as used in PWM inverters without adding third harmonic components but it also yields the maximum voltage transfer ratio as 0.866. The converter connects any input phase (A, B, and C) to any output phase (a, b, and c) at any instant. When connected, the voltages van, vbn, vcn at the output terminals are related to the input voltages VAo, VBo, VCo, as

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ba} & S_{Ca} \\ S_{Ab} & S_{Bb} & S_{cb} \\ S_{Ac} & S_{Bc} & S_{Cc} \end{bmatrix} \begin{bmatrix} v_{Ao} \\ v_{Bo} \\ v_{Co} \end{bmatrix}$$

where SAa through SCc are the switching variables of the corresponding switches shown . For a balanced linear star-connected load at the output terminals, the input phase currents are related to the output phase currents by

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

The matrix converter should be controlled using a specific and appropriately timed sequence of the values of the switching variables, which will result in balanced output voltages having the desired frequency and amplitude, while the input currents are balanced and in phase (for unity IDF) or at an arbitrary angle (for controllable IDF) with respect to the input voltages. As the matrix converter, in theory, can operate at any frequency, at the output or input, including zero, it can be employed as a three-phase ac/dc converter, dc/three-phase ac converter, or even a buck/boost dc chopper and thus as a universal power converter.

9. Write short notes on PWM inverters. (M.E-NOV/DEC2013)

PWM inverters

The device that converts dc power into ac power at desired output voltage and frequency is called an inverter.

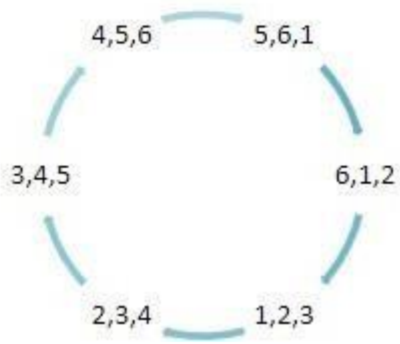
Three phase inverter

When three single phase inverters are connected in parallel a three phase inverter is formed. The gating signal has to be displaced by $120^0$with respect to each other so as achieve three phase balanced voltages. A 3 phase output can be achieved from a configuration of six transistors and six diodes. Two type of control signal can be applied to transistors, they are such as 180^0 or 120^0conduction.

180degree conduction

- WhenQ1 is switched on, terminal a is connected to the positive terminal of dc input voltage.
- When Q4 is switched on terminal a is brought to negative terminal of the dc source.
- There are 6 modes of operation is a cycle and the duration of each mode is 60^0.
- The conduction sequence of transistors is 123,234,345,456,561,612.
- The gating signals are shifted from each other by $60^0$to get 3φbalanced voltages.

Switching states:



V_{RN}	V_{YN}	V_{BN}	V_{RY}	V_{YB}	V_{BR}	V_1
$\frac{V}{3}$	$\frac{-2V}{3}$	$\frac{V}{3}$	V_{ac}	$-V_{dc}$	0	$\frac{2}{\sqrt{3}}(330^0)$
$\frac{2V}{3}$	$\frac{-V}{3}$	$\frac{-V}{3}$	V_{dc}	0	$-V_{dc}$	$\frac{2}{\sqrt{3}}(30^0)$
$\frac{V}{3}$	$\frac{V}{3}$	$\frac{-2V}{3}$	0	V	-V	$\frac{2}{\sqrt{3}}(90^0)$
$\frac{-V}{3}$	$\frac{2V}{3}$	$\frac{-V}{3}$	-V	V	0	$\frac{2}{\sqrt{3}}(150^0)$
$\frac{-2V}{3}$	$\frac{V}{3}$	$\frac{V}{3}$	-V	0	0	$\frac{2}{\sqrt{3}}(210^0)$
$\frac{-V}{3}$	$\frac{-V}{3}$	$\frac{2V}{3}$	0	-V	0	$\frac{2}{\sqrt{3}}(270^0)$

Modes of operation:

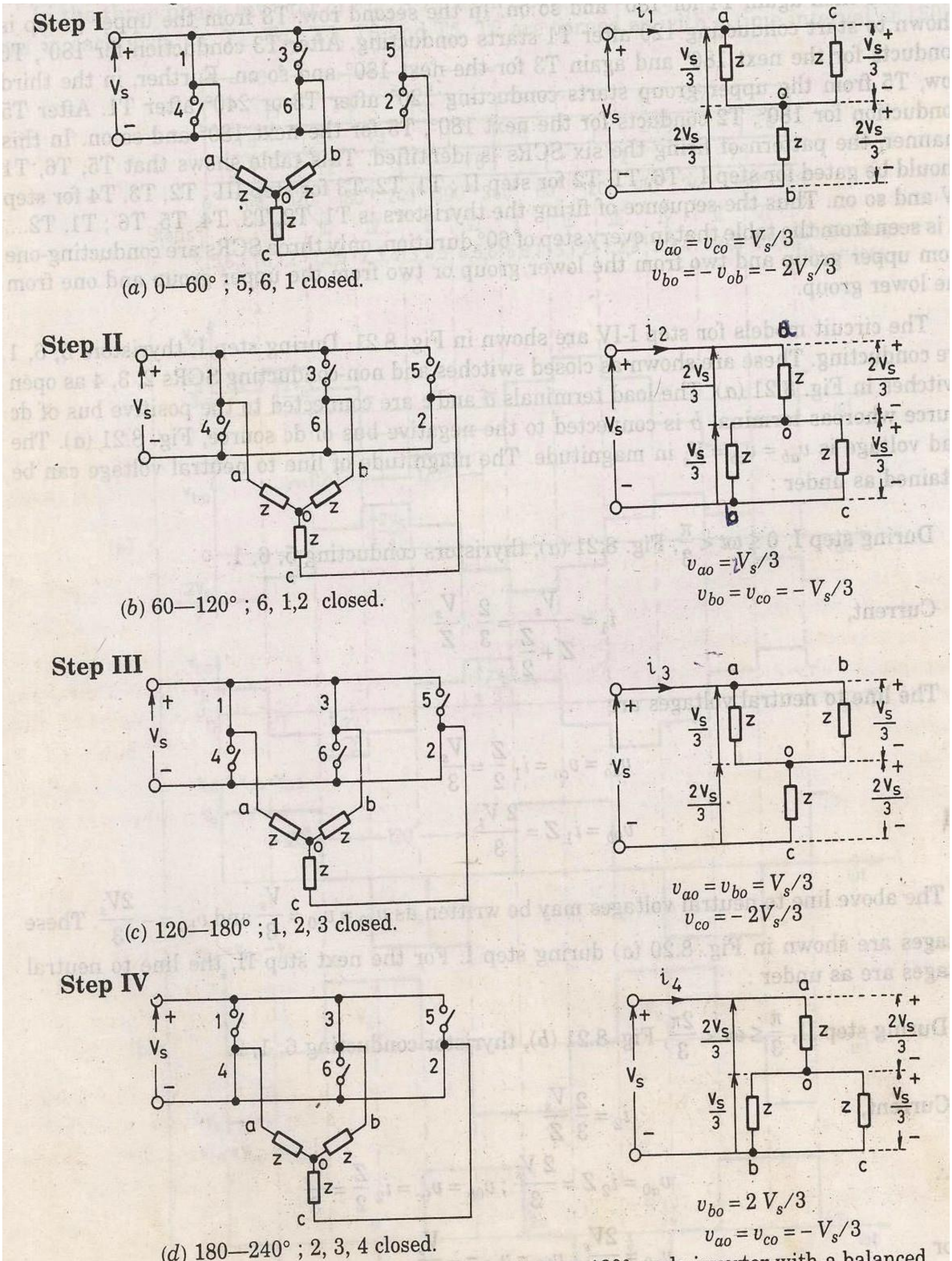


Fig. . Equivalent circuits for a 3-phase six-step 180° mode inverter with a balanced star-connected load.

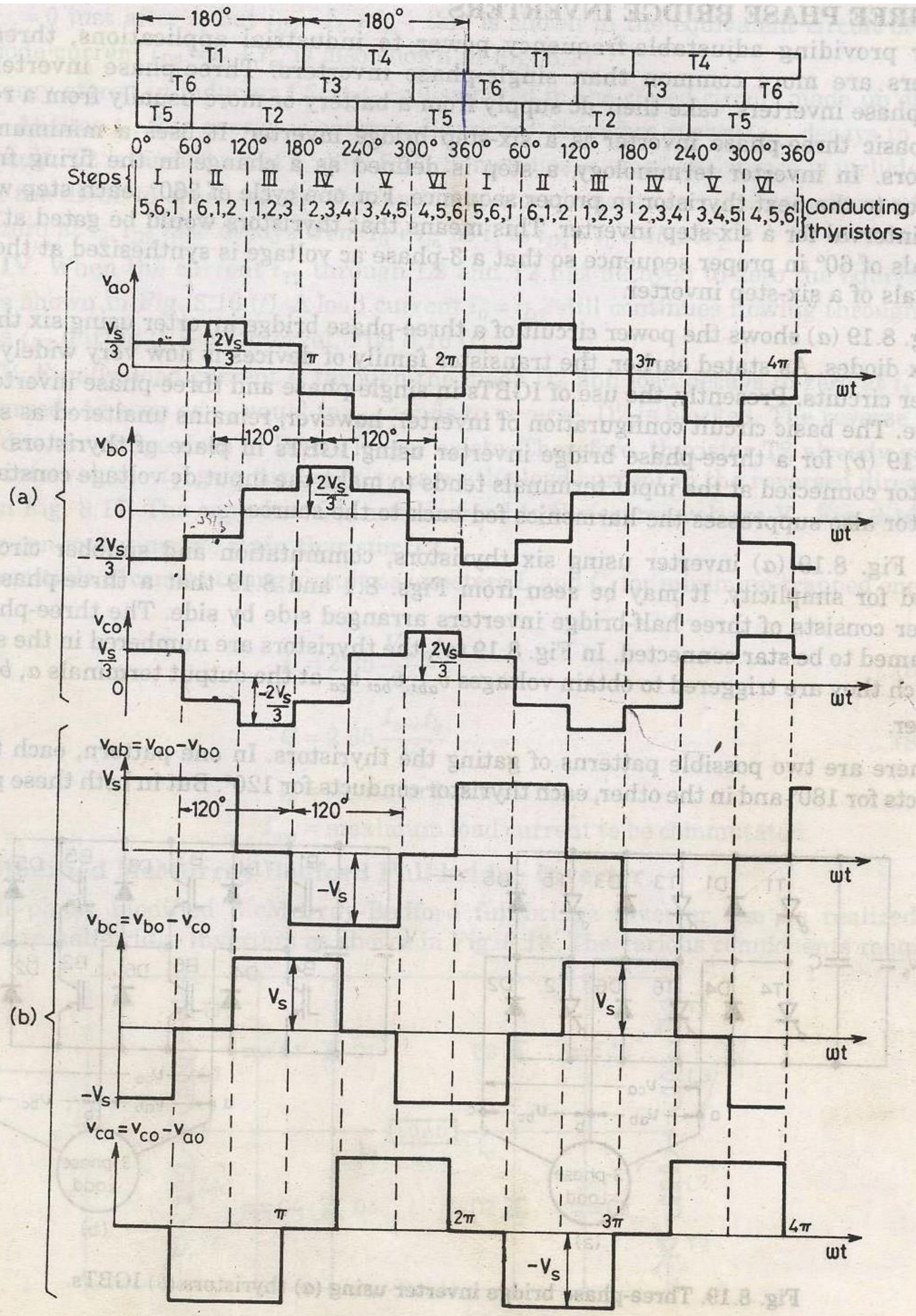
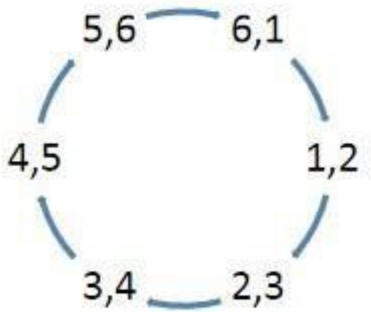


Fig. 8.20. Voltage waveforms for 180° mode 3-phase VSI.

120degree conduction

- The circuit diagram is same as that for 180^0 mode of conduction. Here each thyristor conducts for 120^0
- There are 6 steps each of 60^0duration, for completing one cycle of ac output voltage.



<u>120^0 conduction mode</u>

Step	Thyristor conducting	V_{Rn}	V_{Yn}	V_{Bn}
1	6,1	$V_s/2$	$-V_s/2$	0
2	1,2	$V_s/2$	0	$-V_s/2$
3	2,3	0	$V_s/2$	$-V_s/2$
4	3,4	$-V_s/2$	$V_s/2$	0
5	4,5	$-V_s/2$	0	$V_s/2$
6	5,6	0	$-V_s/2$	$V_s/2$

Modes of operation:

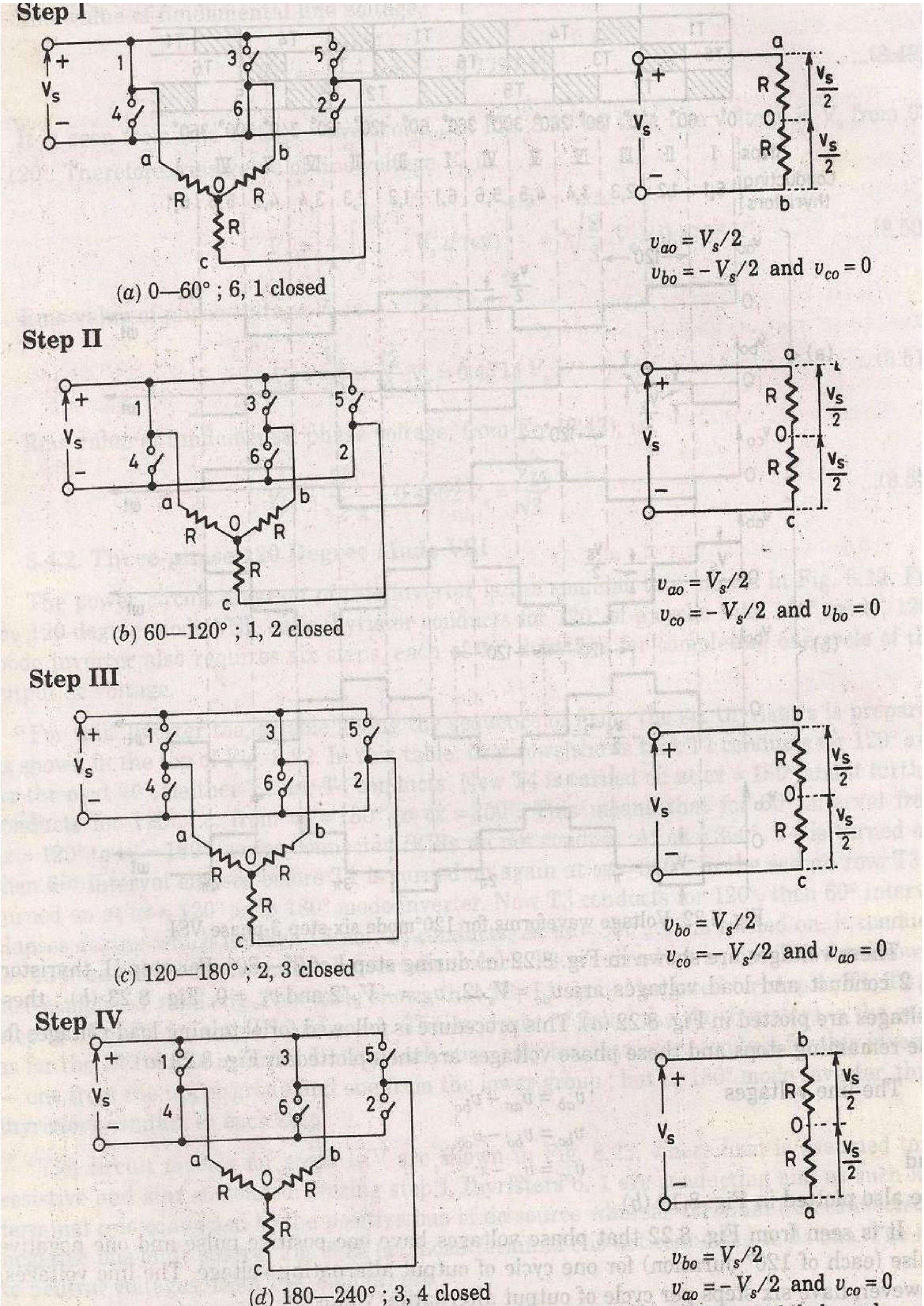


Fig. [illegible] Equivalent circuits for a 3-phase six-step 120° mode inverter with balanced star-connected resistive load.

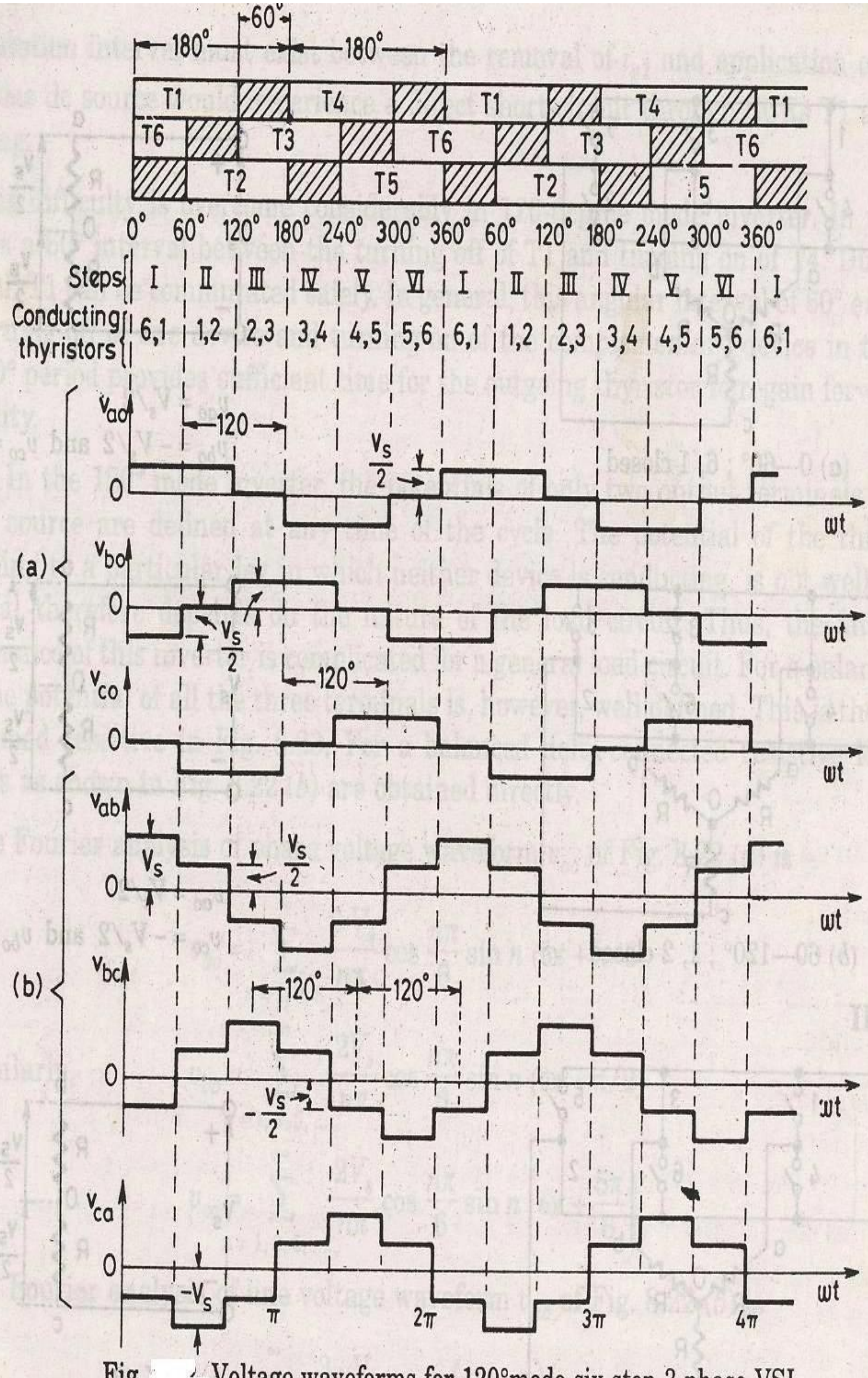


Fig. Voltage waveforms for 120°mode six-step 3-phase VSI.

10. Explain the three phase AC voltage controllers in detail. (M.E-NOV/DEC2010)

Three Phase Ac Voltage Controllers

The analysis of operation of the full-wave controller with isolated neutral as shown in Figure below is quite complicated in comparison to that of a single-phase controller, particularly for an RL or motor load. As a simple example, the operation of this controller is considered here with a simple star-connected R-load. The six SCRs are turned on in the sequence 1-2-3-4-5-6 at 60^0intervals and the gate signals are sustained throughout the possible conduction angle. The output phase voltage waveforms for α=30, 75, and120 degree for a balanced three-phase R-load are shown in Figure. At any interval, either three SCRs or two SCRs, or no SCRs may be on and the instantaneous output voltages to the load are either line-to-neutral voltages (three SCRs on), or one-half of the line-to-line voltage (two SCRs on) or zero (no SCR on). Depending on the firing angle a, there may be three operating modes.

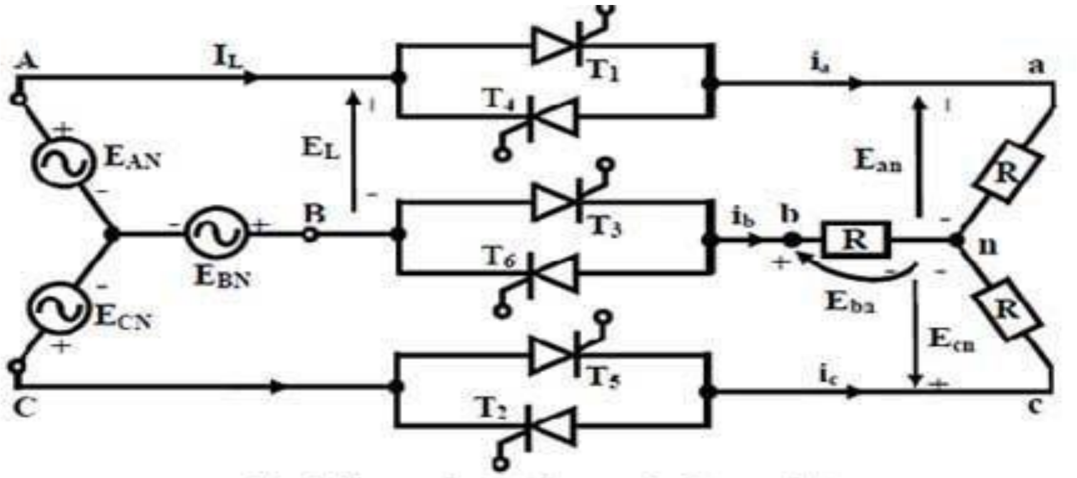


Fig: 1 Three-phase, three-wire Ac regulator

Mode I (also known as Mode 2=3): $0 \leq \alpha \leq 60^0$. There are periods when three SCRs are conducting, one in each phase for either direction or periods when just two SCRs conduct. For example, with $\alpha=30^0$, assume that at ωt=0, SCRs T5 and T6 are conducting, and the current through the R-load in a-phase is zero making van=0. At $\omega t = 30^0$, T1 receives a gate pulse and starts conducting; T5 and T6 remain on and van $=v_{AN}$. The current in T5 reaches zero at 60^0, turning T5 off. With T1 and T6 staying on, van =1/2vAB. At 90^0, T2 is turned on, the three SCRs T1, T2, and T6 are then conducting and van = v_{AN}. At 120^0, T6 turns off, leaving T1 and T2 on, so v_{AN} =1/2vAC. Thus with the progress of firing in sequence until $\alpha=60^0$, the number of SCRs conducting at particular instant alternates between two and three.

Mode II (also known as Mode 2/2): $60^0 \leq \alpha \leq 90^0$Two SCRs, one in each phase, always conduct. For $\alpha=75^0$ as shown in Fig. 16.12b, just prior to $\alpha=75^0$, SCRs T5 and T6 were conducting and van =0. At 75^0 , T1 is turned on, T6 continues to conduct while T5 turns off as v_{CN} is negative; van =1/2vAB. When T2 is turned on at 135^0, T6 is turned off and van= 1/2vAC. The next SCR to turn on is T3, which turns off T1 and van . 0. One SCR is always turned off when another is turned on in this range of α and the output is either one-half line-to-line voltage or zero.

Mode III (also known as Mode 0/2): $90^0 \leq \alpha \leq 150^0$: When none or two SCRs conduct. For $\alpha=120^0$, earlier no SCRs were on and van =0. At $\alpha= 120^0$, SCR T1 is given a gate signal while T6, has a gate signal already applied. As v_{AB} is positive, T1 and T6 are forward-biased and they begin to conduct and van =1/2vAB. Both T1 and T6 turn off when v_{AB} becomes negative. When a gate signal is given to T2, it turns on and T1 turns on again. For $\alpha > 150^0$, there is no period when two SCRs are conducting and the output voltage is zero at $\alpha=150^0$. Thus, the range of the firing angle control is $0 \leq \alpha \leq 150^0$. For star-connected R-load, assuming the instantaneous phase voltages as

$$v_{AN} = \sqrt{2}V_s \sin \omega t$$
$$v_{BN} = \sqrt{2}V_s \sin(\omega t - 120^\circ)$$
$$v_{CN} = \sqrt{2}V_s \sin(\omega t - 240^\circ)$$

the expressions for the rms output phase voltage V_o can be derived for the three modes as

$$0 \leq \alpha \leq 60^\circ \qquad V_o = V_s\left[1 - \frac{3\alpha}{2\pi} + \frac{3}{4\pi}\sin 2\alpha\right]^{1/2}$$

$$60^\circ \leq \alpha \leq 90^\circ \qquad V_o = V_s\left[\frac{1}{2} + \frac{3}{4\pi}\sin 2\alpha + \sin(2\alpha + 60^\circ)\right]^{1/2}$$

$$90^\circ \leq \alpha \leq 150^\circ \qquad V_o = V_s\left[\frac{5}{4} - \frac{3\alpha}{2\pi} + \frac{3}{4\pi}\sin(2\alpha + 60^\circ)\right]^{1/2}$$

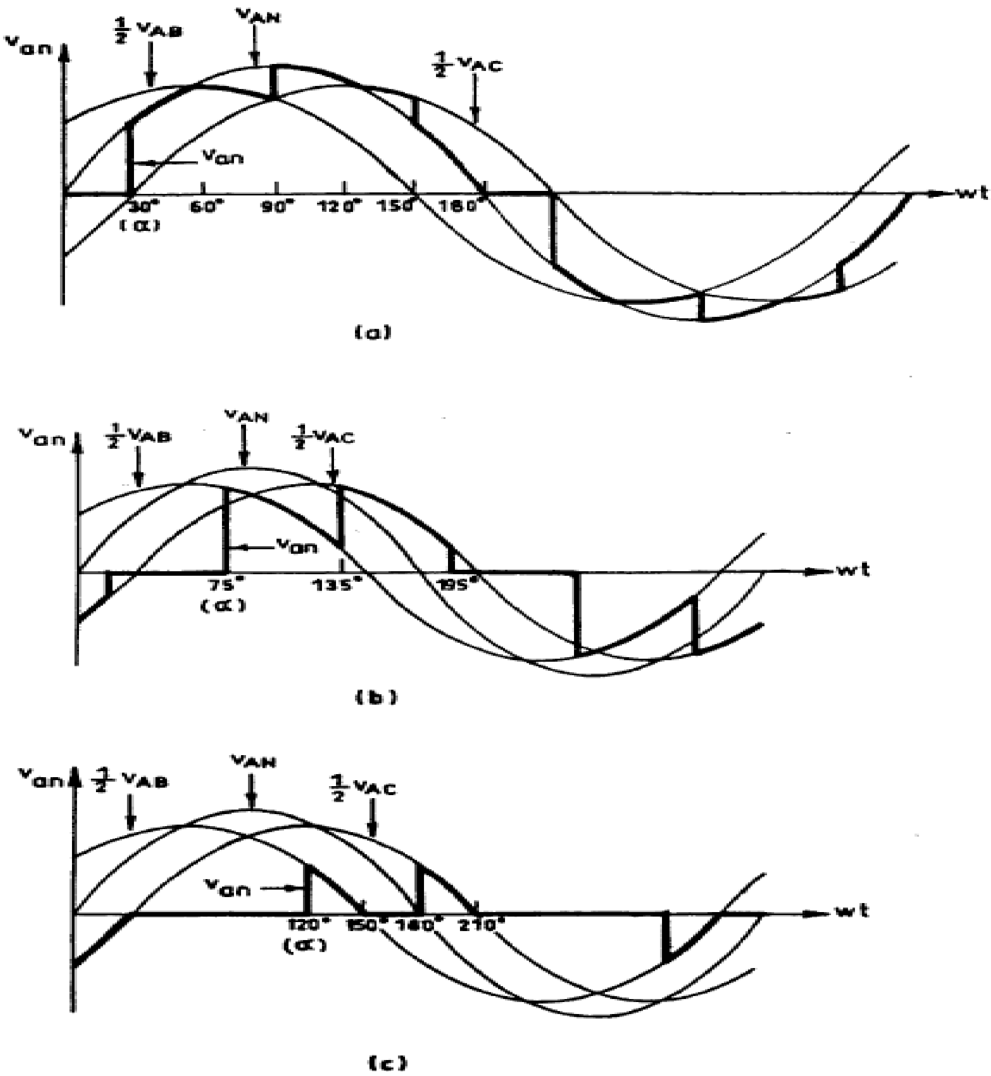


FIGURE Output voltage waveforms for a three-phase ac voltage controller with star-connected R-load: (a) v_{an} for $\alpha = 30^\circ$; (b) v_{an} for $\alpha = \;\, 5^\circ$; and (c) $v_{an} = 120^\circ$.

UNIT-4

PART-B

1. Explain the stand alone operation of variable speed wind energy conversion system. (APR/MAY2017) (M.E-NOV/DEC2010)

Variable speed wind energy conversion system

Variable-speed wind turbines are currently the most used WECS. The variable speed operation is possible due to the power electronic converters interface, allowing a full (or partial) decoupling from the grid. The doubly-fed-induction-generator (DFIG)-based WECS (below Figure), also known as improved variable-speed WECS, is presently the most used by the wind turbine industry. The DFIG is a WRIG with the stator windings connected directly to the three phases, constant-frequency grid and the rotor windings connected to a back-to-back (AC—AC) voltage source converter. Thus, the term "doubly-fed" comes from the fact that the stator voltage is applied from the grid and the rotor voltage is impressed by the power converter. This system allows variable-speed operation over a large, but still restricted, range, with the generator behavior being governed by the power electronics converter and its controllers. The power electronics converter comprises of two IGBT converters, namely the rotor side and the grid side converter, connected with a direct current (DC) link. Without going into details about the converters, the main idea is that the rotor side converter controls the generator in terms of active and reactive power, while the grid side converter controls the DC-link voltage and ensures operation at a large power factor. The stator outputs power into the grid all the time. The rotor, depending on the operation point, is feeding power into the grid when the slip is negative (over synchronous operation) and it absorbs power from the grid when the slip is positive (sub-synchronous operation). In both cases, the power flow in the rotor is approximately proportional to the slip. The size of the converter is not related to the total generator power but to the selected speed variation range. Typically a range of 40% around the synchronous speed is used. DFIG-based WECS are highly controllable, allowing maximum power extraction over a large range of wind speeds.
Furthermore, the active and reactive power control is fully decoupled by independently controlling the rotor currents. Finally, the DFIG-based WECS can either inject or absorb power from the grid, hence actively participating at voltage control.

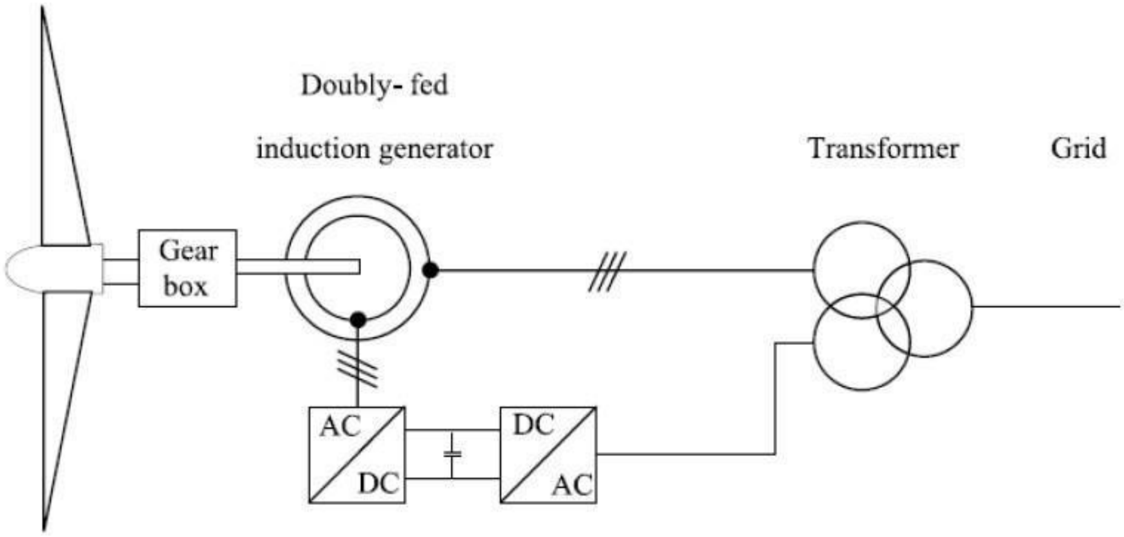


Fig General structure of an improved variable-speed WECS

Full variable-speed WECS are very flexible in terms of which type of generator is used. As presented in Figure below, it can be equipped with either an induction (SCIG) or a synchronous generator. The synchronous generator can be either a wound-rotor synchronous generator (WRSG) or a permanent-magnet synchronous generator (PMSG), the latter being the one mostly used by the wind turbine industry. The back-to-back power inverter is rated to the generator power and its operation is similar to that in DFIG-based WECS. Its rotor-side ensures the rotational speed being adjusted within a large range, whereas its grid-side transfers the active power to the grid and attempts to cancel the reactive power consumption. This latter feature is important especially in the case of SCIG-equipped WECS. The PMSG is considered, in many research articles, a good option to be used in WECS, due to its self—excitation property, which allows operation at high power factor and efficiency. PMSG does not require energy supply for excitation, as it is supplied by the permanent magnets. The stator of a PMSG is wound and the rotor has a permanent magnet pole system. The salient pole of PMSG operates at low speeds, and thus the gearbox can be removed. This is a big advantage of PMSG-based WECS as the gearbox is a sensitive device in wind power systems. The same thing can be achieved using direct driven multi pole PMSG with large diameter. The synchronous nature of PMSG may cause problems during start-up, synchronization and \voltage regulation and they need a cooling system, since the magnetic materials are sensitive to temperature and they can loose their magnetic properties if exposed to high temperatures.

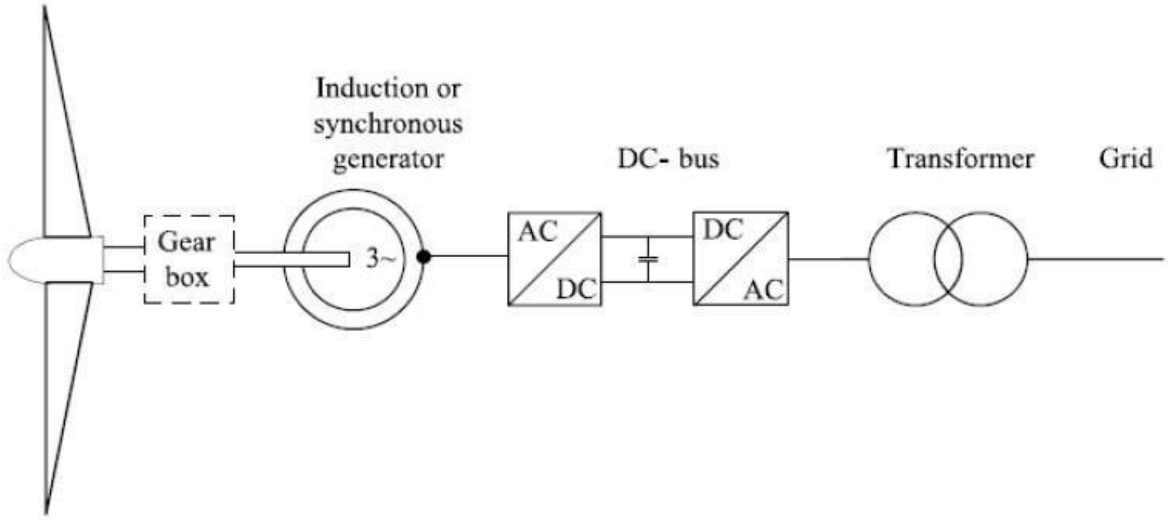


Fig General structure of a full variable-speed WECS

2. Explain the stand alone operation of fixed speed wind energy conversion system. (M.E-NOV/DEC20130

Fixed Speed Wind Energy Conversion System

Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed WECS are typically equipped with squirrel-cage induction generators (SCIG), soft starter and capacitor bank and they are connected directly to the grid, as shown in Figure below. This WECS configuration is also known as the “Danish concept” because it was developed and widely used in Denmark. Initially, the induction machine is connected in motoring regime such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode. As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency. Furthermore, the wind velocity variations will induce only small variations in the generator speed. As the power varies proportionally with the Wind speed cubed, the associated electromagnetic variations are important.

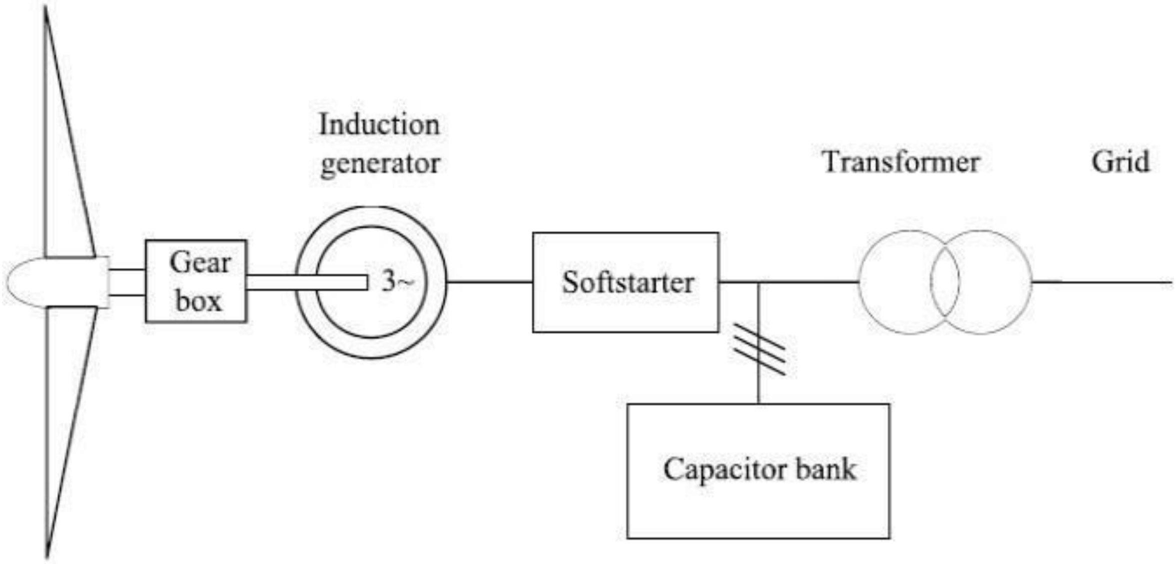


Fig General structure of a fixed-speed WECS

SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. One of the major drawbacks of the SCIG is the fact that there is a unique relation between active power, reactive power, terminal voltage and rotor speed. That means that an increase in the active power production is possible only with an increase in the reactive power consumption, leading to a relatively low full-load power factor. In order to limit the reactive power absorption from the grid, SCIG based WECS are equipped with capacitor banks. The soft starter's role is to smooth the inrush currents during the grid connection.

SCIG-based WECS are designed to achieve maximum power efficiency at a unique wind speed. In order to increase the power efficiency, the generator of some fixed-speed WECS has two winding sets, and thus two speeds. The first set is used at low wind speed (typically eight poles) and the other at medium and large wind speeds (typically four to six poles).
Fixed-speed WECS have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed- speed operation, the mechanical stress is important. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant, stuck to the grid frequency.
An evolution of the fixed-speed SCIG-based WECS are the limited variable speed WECS. They are equipped with a wound-rotor induction generator (WRIG) with variable external rotor resistance; see Figure below. The unique feature of this WECS is that it has a variable additional rotor resistance, controlled by power electronics. Thus, the total (internal plus external) rotor resistance is adjustable, further controlling the slip of the generator and therefore the slope of the mechanical characteristic. Obviously, the range of the dynamic speed control is determined by how big the additional resistance is. Usually the control range is up to 10% over the synchronous speed.

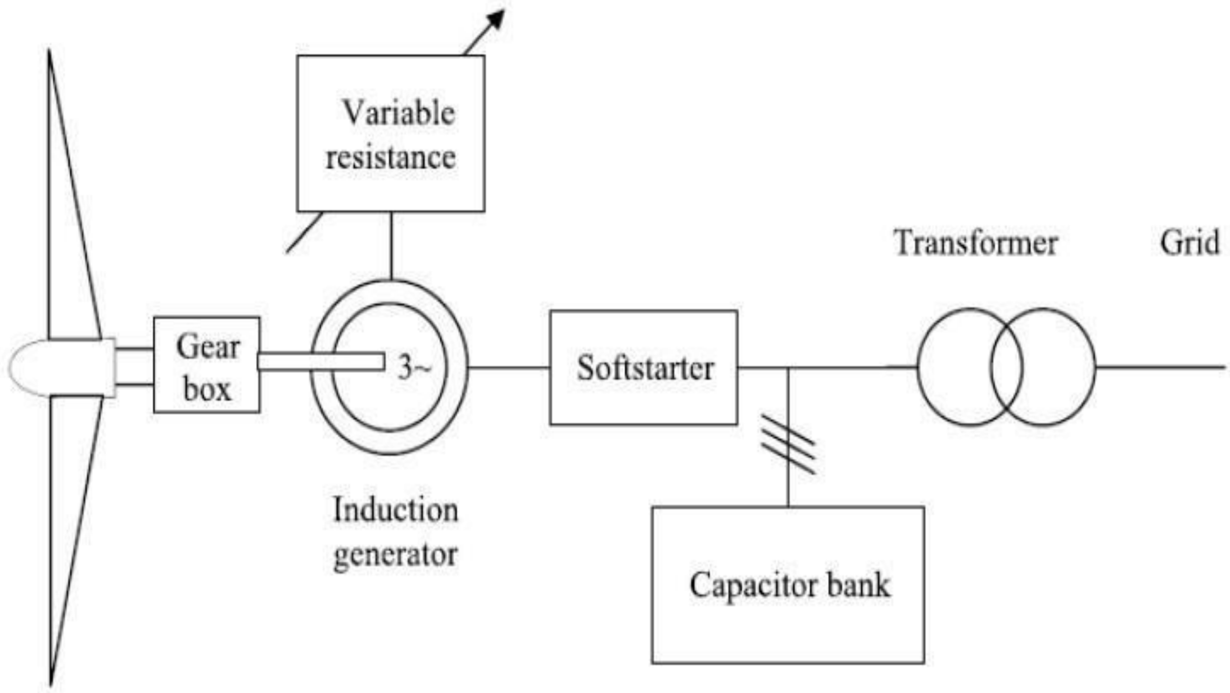


Fig. General structure of a limited variable-speed WECS.

3. Explain the operation of grid integrated PMSG system with a neat block diagram. (APR/MAY2017) (M.E-NOV/DEC2016)(M.E-NOV/DEC2013)(M.E-NOV/DEC2010)

GRID INTEGRATED PMSG SYSTEM

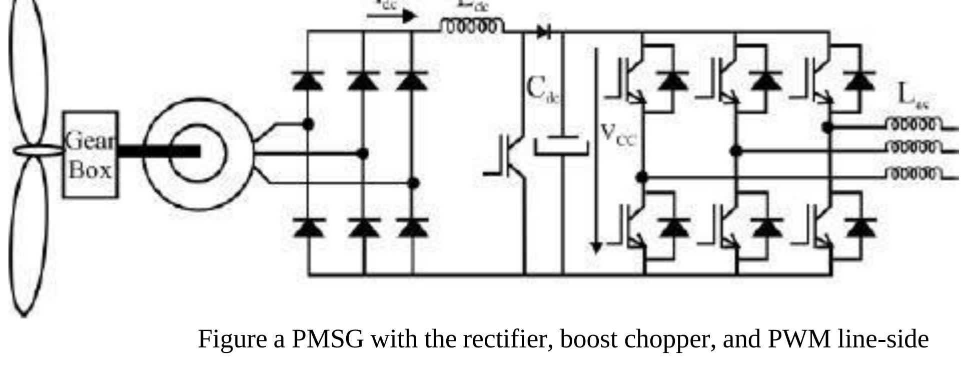


Figure a PMSG with the rectifier, boost chopper, and PWM line-side

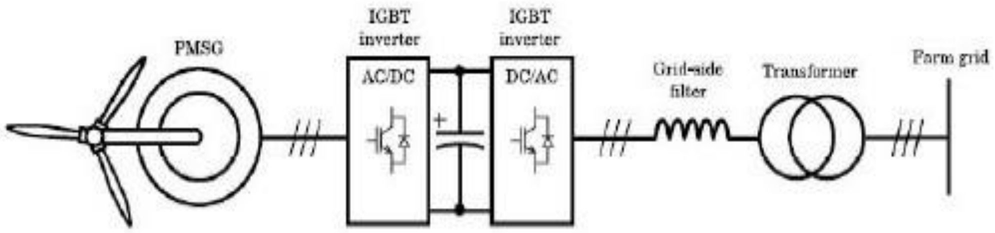


Figure b PMSG with back-to-back PWM converters

A typical power electronics topology that is used for a permanent magnet synchronous generator is shown in Figure a. The three-phase variable voltage, variable frequency output from the wind turbine is rectified using a diode bridge. With the change in the speed of the synchronous generator, the voltage on the DC side of the diode rectifier changes. To maintain a constant DC-link voltage of the inverter, a step-up chopper is used to adapt the rectifier voltage. As viewed from the DC inputs to the inverter, the generator/rectifier system is then modeled as an ideal current source. This rectified output signal from the diode bride is filtered into a smooth DC waveform using a large capacitor. The DC signal is then inverted through the use of semiconductor switches into a three-phase, 50 Hz waveform. This waveform can then be scaled using a transformer to voltage levels required by the utility's AC system. The generator is decoupled from the grid by a voltage-sourced DC-link; therefore, this PE interface provides excellent controllable characteristics for the wind energy system. The power converter to the grid enables a fast control of active and reactive power. However, the negative side is a more complex system where more sensitive power electronic parts are required. The diode rectifier is the most commonly used topology in power electronic applications. For a three-phase system it consists of six diodes. It is shown in Figure a. The diode rectifier can only be used in one quadrant, it is simple and it is not possible to control it. It can be used in some applications such as pre-charging.

Figure b shows the scheme of a full power converter for a wind turbine. The machine- side three-phase converter works as a driver controlling the torque generator, using a vector control strategy. The grid-side three-phase converter permits wind energy transfer into the grid and enables to control the amount of the active and reactive powers delivered to the grid. It also keeps the total-harmonic-distortion (THD) coefficient as low as possible, improving the quality of the energy injected into the public grid. The objective of the dc link is to act as energy storage, so that the captured energy from the wind is stored as a charge in the capacitors and may be instantaneously injected into the grid. The control signal is set to maintain a constant reference to the voltage of the dc link Vdc. An alternative to the power-conditioning system of a wind turbine is to use a synchronous generator instead of an induction one and to replace a three-phase converter (connected to the generator) by a three phase diode rectifier and a chopper, as shown in Figure a. Such choice is based on the low cost as compared to an induction generator connected to a VSI used as a rectifier. When the speed of the synchronous generator alters, the voltage on the dc side of the diode rectifier will change. A step-up chopper is used to adapt the rectifier voltage to the dc-link voltage of the inverter. When the inverter system is analyzed, the generator/rectifier system can be modeled as an ideal current source. The step-up chopper used as a rectifier utilizes a high switching frequency, so the bandwidth of these components is much higher than the bandwidth of the generator. Controlling the inductance current in the step-up converter can control the machine torque and, therefore, its speed.

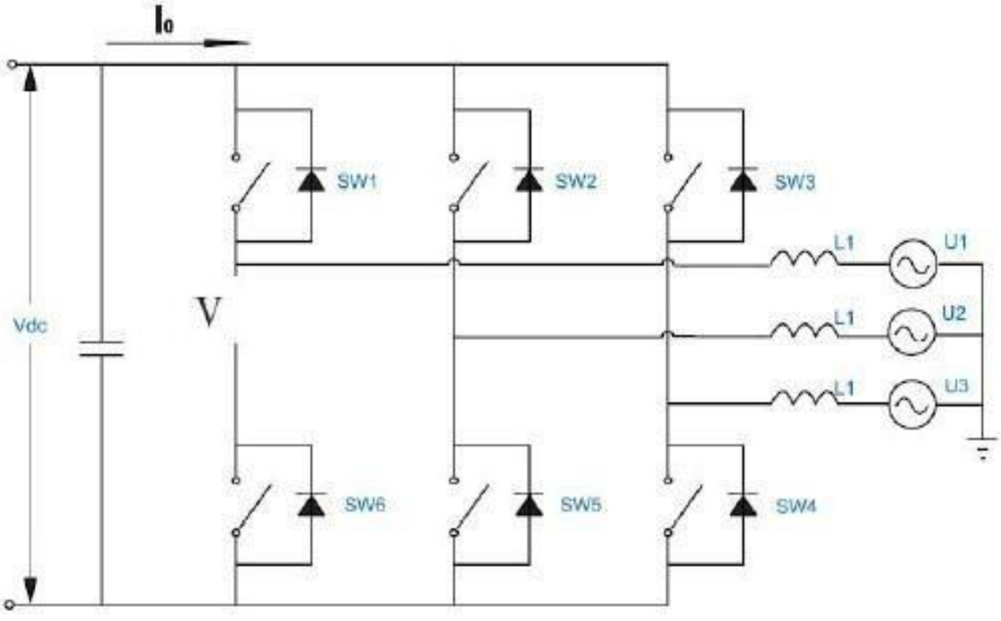
Based on the control design for the back-to-back PWM converter system, various advantages can be obtained such as:

- The line-side power factor is unity with no harmonic current injection (satisfies IEEE 519);
- Wind generator output current is sinusoidal;
- There are no harmonic copper losses;
- The rectifier can generate programmable excitation for the induction generator based system.
- Continuous power generation from zero to the highest turbine speed is possible.
- Power can flow in either direction, permitting the generator to run as a motor for start-up (required for vertical turbine). Similarly, regenerative braking can quickly stop the turbine; and
- Islanded operation of the system is possible with a start-up capacitor charging the battery.

Principle of Operation

Figure below shows the structure of the PWM line side converter. Power flow in the PWM Converter is controlled by adjusting the phase angle δ between the source voltage U1 and the respective converter reflected input voltage VS]. When U1 leads VS1 the real power flows from the ac source into the converter. Conversely, if U1 lags Vs1, power flows from the converter's dc side into the ac source. The real power transferred is given by the Equation below.

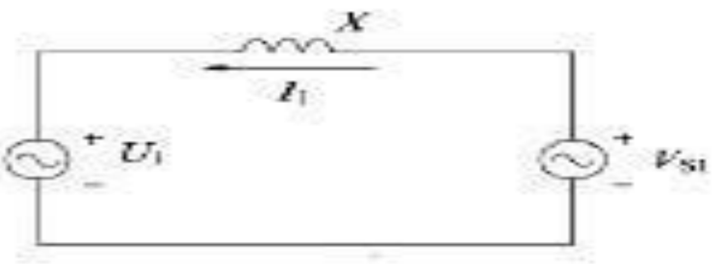
$$P = \frac{V_{S1} U_1}{X_1} \sin(\delta)$$

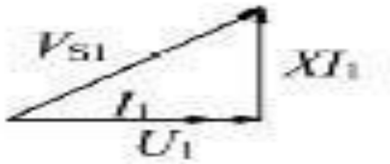


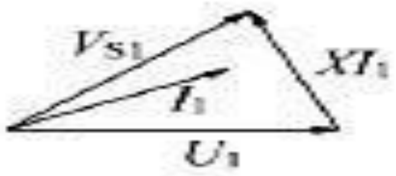
PWM converter.

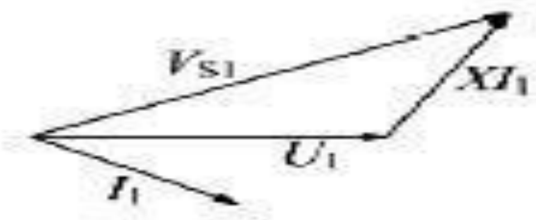
The ac power factor is adjusted by controlling the amplitude of the converter synthesized voltage VS1. The per phase equivalent circuit and phase diagrams of the leading, lagging and unity power factor operation is shown in Figure below. The phasor diagram below shows that to achieve a unity power factor, VS1 has to be,

$$V_{s1} = \sqrt{U_1^2 + (X_1 I_1)^2}$$









4. Explain the block diagram of SCIG based wind energy conversion system. (M.E-NOV/DEC2013)(M.E-NOV/DEC2010)

SCIG based wind energy conversion system

Fixed speed system:

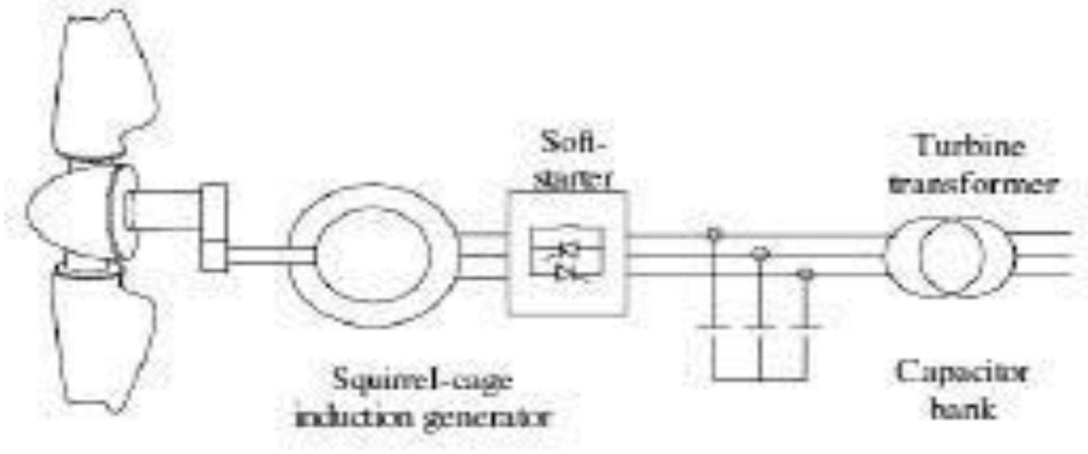


Fig SCIG Connected to Grid

Fixed—speed Wind turbines are electrically fairly simple devices consisting of an aerodynamic rotor driving a low-speed shaft, a gearbox, a high-speed shaft and an induction (sometimes known as asynchronous) generator. From the electrical system viewpoint they are perhaps best considered as large fan drives with torque applied to the low-speed shaft from the wind flow.

It consists of a squirrel-cage induction generator coupled to the power system through a turbine transformer. The generator operating slip changes slightly as the operating power level changes and the rotational speed is therefore not entirely constant. However, because the operating slip variation is generally less than 1%, this type of wind generation is normally referred to as fixed speed. Squirrel-cage induction machines consume reactive power and so it is conventional to provide power factor correction capacitors at each wind turbine.

The function of the soft-starter unit is to build up the magnetic flux slowly and so minimize transient currents during energization of the generator. Also, by applying the network voltage slowly to the generator, once energized, it brings the drive train slowly to its operating rotational speed.

Variable Speed System

The typical configuration of a Variable Speed Grid Connected SCIG based fully rated converter wind turbine is shown in Figure below. This type of turbine may or may not include a gearbox and a wide range of electrical generator types can be employed, for example, induction, wound-rotor synchronous or permanent magnet synchronous. As all of the power from the turbine goes through the power converters, the dynamic operation of the electrical generator is effectively isolated from the power grid. The electrical frequency of the generator may vary as the wind speed changes, while the grid frequency remains unchanged, thus allowing variable-speed operation of the wind turbine.

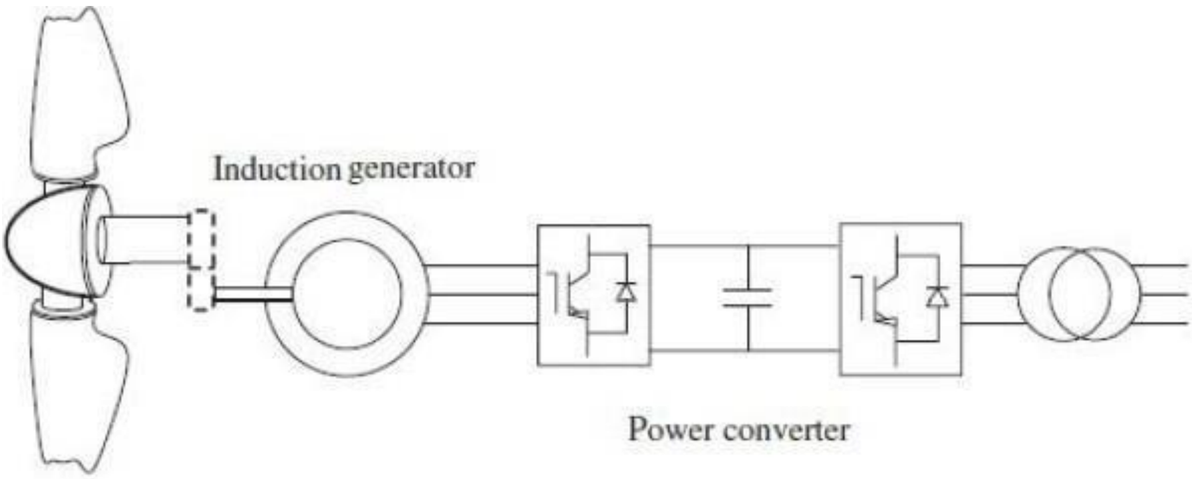


Figure Typical configuration of a fully rated converter-connected wind turbine

The power converters can be arranged in various ways. Whereas the generator-side converter (GSC) can be a diode rectifier or a PWM voltage source converter (VSC), the network- side converter (NSC) is typically a PWM VSC. The strategy to control the operation of the generator and the power flows to the network depends very much on the type of power converter arrangement employed. The network-side converter can be arranged to maintain the DC bus voltage constant with torque applied to the generator controlled from the generator-side converter. Alternatively, the control philosophy can be reversed. Active power is transmitted through the converters with very little energy stored in the DC link capacitor. Hence the torque applied to the generator can be controlled by the network-side converter. Each converter is able to generate or absorb reactive power independently.

5. Write short notes on grid integrated solar system. (M.E-NOV/DEC2010) (M.E-APR/MAY2013)

Photovoltaic (PV) Systems

Photovoltaic (PV) systems convert sunlight to electric current. You are already familiar with some simple PV applications in today's society, such as calculators and wrist watches. More complicated systems provide power for communications satellites, water pumps, and the lights, appliances, and machines in homes and workplaces. Many road and traffic signs along highways are now powered by PV.

PV systems produce some electric current any time the sun is shining, but more power is produced when the sunlight is more intense and strikes the PV modules directly. While solar thermal systems use heat from the sun to heat water or air, PV does not use the sun's heat to make electricity. Instead, electrons freed by the interaction of sunlight with semiconductor materials in PV cells create an electric current. PV modules are much less tolerant of shading than are solar water-heating panels. When siting a PV system, it is most important to minimize any shading of the PV modules.

PV allows you to produce electricity—without noise or air pollution—from a clean, renewable resource. A PV system never runs out of fuel, and it won't increase oil imports.

Block Diagram of Solar Photovoltaic System

Generally there are two types of Solar Photovoltaic System they are

1. Autonomous Solar Photovoltaic system or Stand alone Solar Photovoltaic system.
2. Grid Connected PV system.

a) Without Battery.

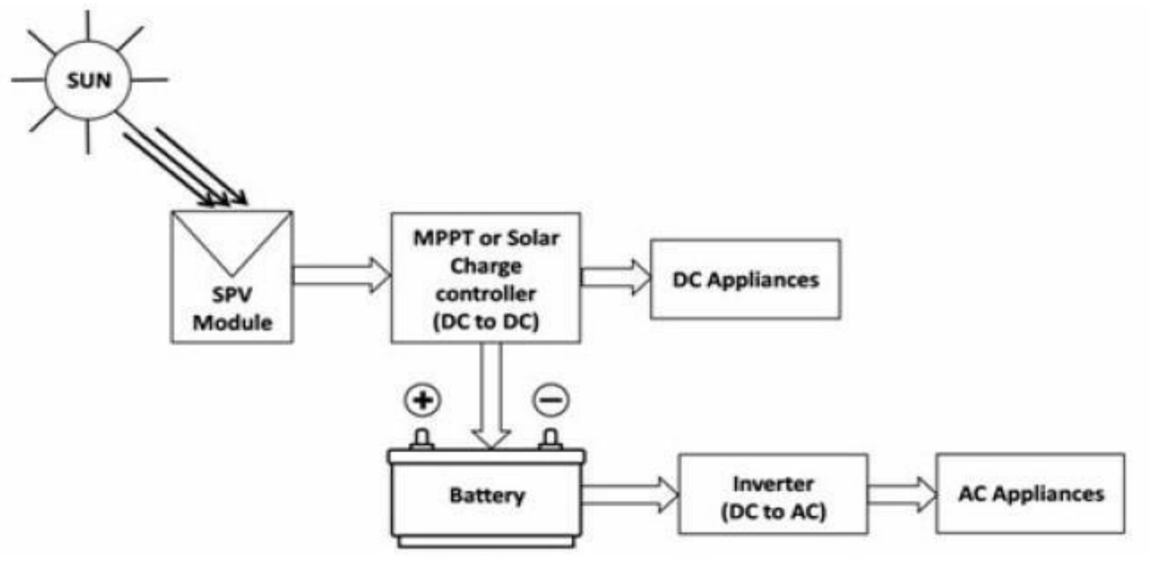
b) With Battery.

Autonomous PV system (or) Stand alone Solar Photovoltaic System (SPV)

A Standalone SPV system is the one which is not connected to the power grid. Standalone PV systems usually have a provision for energy storage. This system has battery support to supply the load requirements during the night hours or even when sunshine is not adequate (Cloudy conditions) during the day.

Block Diagram

Figure shows the block diagram of Standalone SPV system. Power is generated when sun light falls on the SPV module. This power is given to the MPPT or Charge controller block. The function of this block is to control the variation in the output of the SPV module and make it suitable for use at the output according to the supply required by a load. There are two types of the loads: AC and DC. DC components are directly connected to the MPPT or Charge controller block, where as the AC appliances are connected through the Battery and inverter.

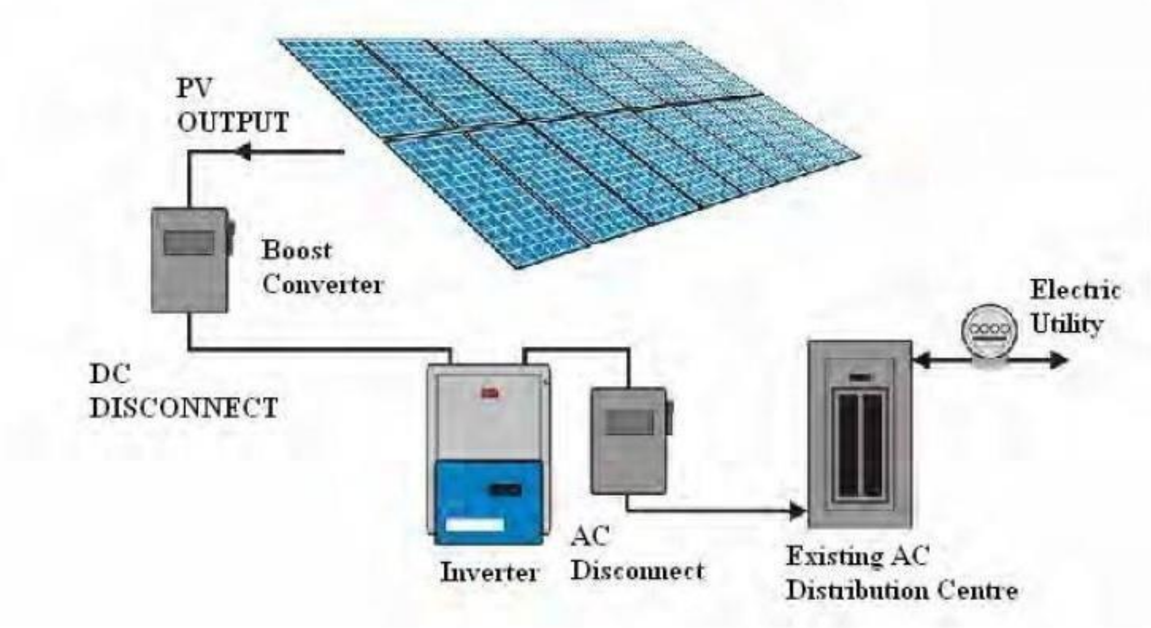


Simple Block Diagram of Standalone SPV system

In this way, a Standalone system is connected depending upon whether only AC load is present or both AC and DC load are present.

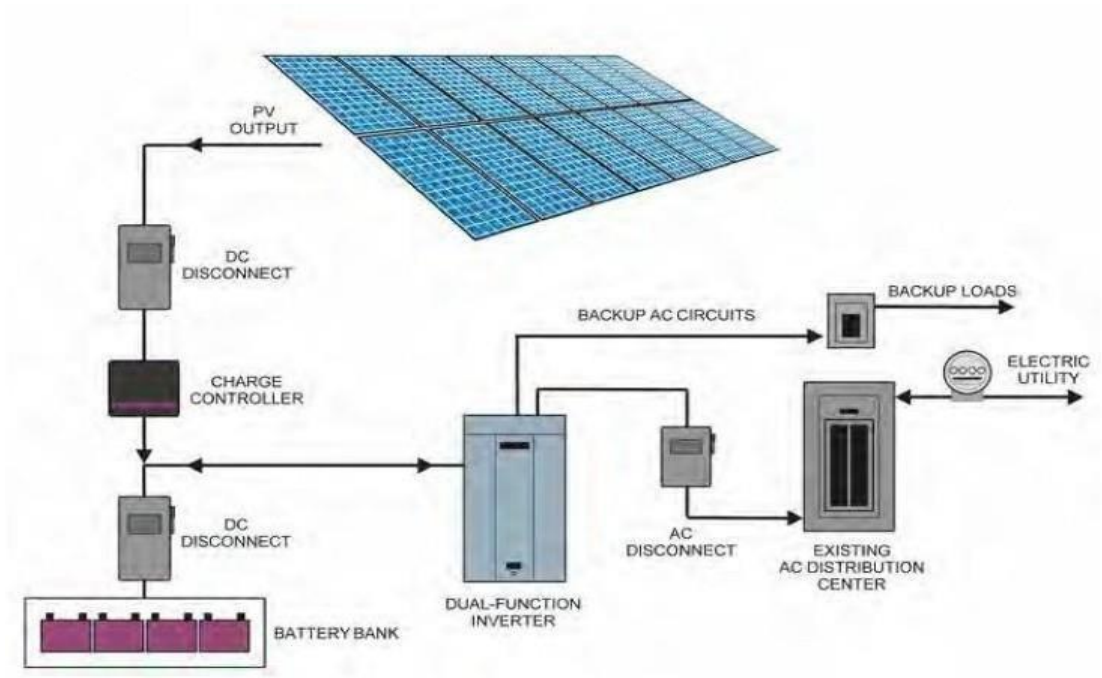
Typical Grid Tied System (Battery less)

There are no batteries to store excess power generated-the electric utility essentially stores it for you through a system called "net-metering." DC (direct current) generated by the PV panels is converted into AC (alternating current) power by the inverter (exactly the same high quality AC current delivered to your site by the utility-provided power grid). Output from the inverter is connected to your existing distribution panel (breaker panel) which feeds the rest of your site. While the system is generating electricity, power needs are provided by the PV system (up to its capacity), reducing or eliminating the power you would have drawn from the utility grid at that time. During periods when your grid-tie system is generating even more energy than your site requires, any excess is fed back into the grid for others to use and the electric utility company "buys" it from you at the retail rate. They provide credits to your account for all the power that is pushed back into the grid through the meter. And your meter will literally run backwards! When your site needs to draw more energy than it is producing (Say, during cloudy conditions or at night), electricity is provided by the power grid in the normal manner and is first paid for by your accumulated credits.



Typical Grid Tied System with Battery Backup

The "Grid-Tie With Battery Backup" PV system incorporates one or more special AC circuits which are not directly connected to the electric grid like the rest of the building, but are always powered through the inverter and/or charge controller. These circuits may power a refrigerator, selected lights, computers or servers... any devices the owner deems essential. The "dual function" inverter can supply the utility grid with any excess power produced by the system like the "grid-tie" inverter, plus the inverter works with the PV modules and battery bank (through the charge controller) to provide AC power to the backup circuits when the grid is down. The charge controller manages the battery voltage, keeping them fully charged when the grid is live, and preventing them from being depleted when the system is drawing power from them.



6. Explain how the insolation and temperature affects the I-V characteristics of a solar cell. (M.E-APR/MAY2013)

Effect of Irradiance and Temperature

The term Irradiance is defined as the measure of power density of sunlight received at a location on the earth and is measured in watt per metre square. Whereas irradiation is the measure of energy density of sunlight .The term Irradiance and Irradiation are related to solar. Components. As the solar insolation keeps on changing throughout the day similarly I-V and P-V characteristics varies. With the increasing solar irradiance both the open circuit voltage and the short circuit current increases and hence the maximum power point varies. Temperature plays another major factor in determining the solar cell efficiency. As the temperature increases the rate of photon generation increases thus reverse saturation current increases rapidly and this reduces the band gap. Hence this leads to marginal changes in current but major changes in voltage. The cell voltage reduces by 2.2Mv per degree rise of temperature. Temperature acts like a negative factor affecting solar cell performance. Therefore solar cells give their full performance on cold and sunny days rather on hot and sunny weather. Nowadays Solar panels are made of non-silicon cells as they are temperature insensitive. Thus the temperature remains close to room temperature.

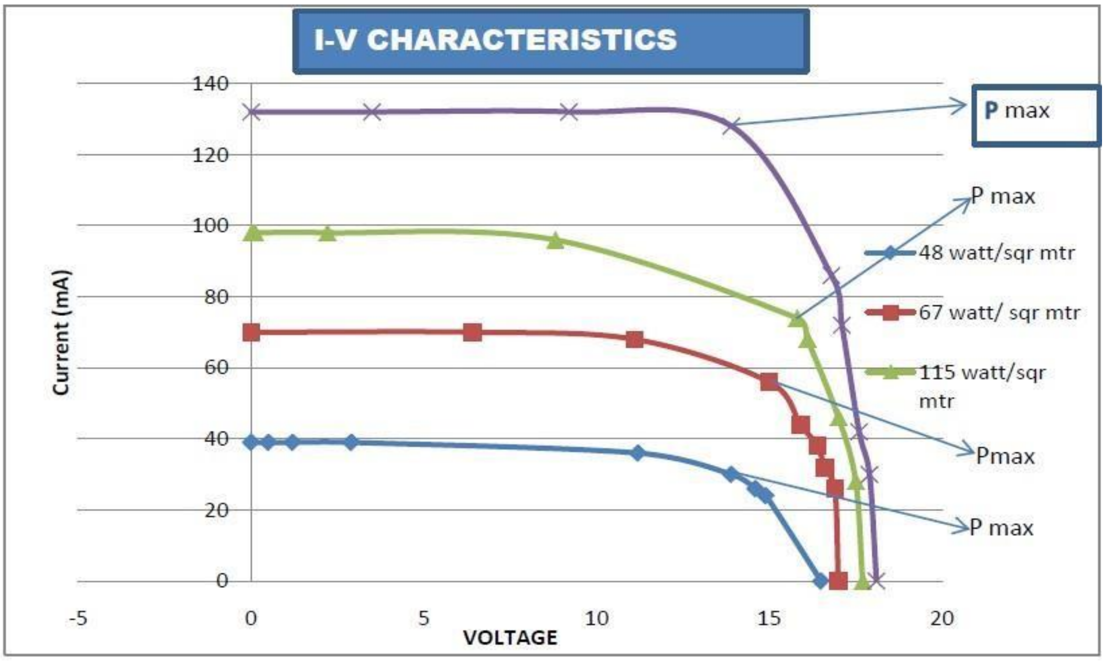


Fig Shows the current versus voltage curve at various irradiance level and the corresponding maximum power point.

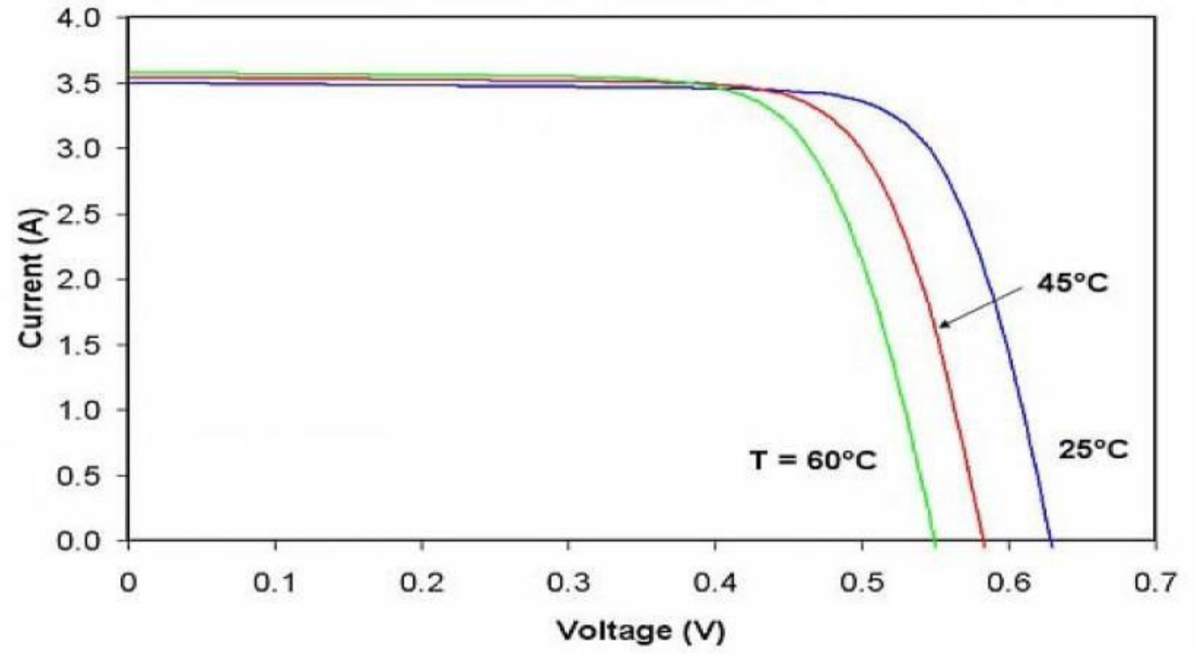


Fig Shows how the I-V curve varies with varying temperature.

7. A HAWT is installed at a location having free wind velocity of 15m/s. The 80m diameter rotor has three blades attached to the hub. Find the rotational speed of the turbine for optimal energy extraction. (M.E-APR/MAY2013)

Given:

Rotor diameter = 80m, r=40m, u_0=15m/s, n=3

Solution:

Tip speed ratio for optimum output, $\lambda_0 = 4\pi/n = 4.188$

Tip speed ratio $\lambda_0 = r\omega/u_0$

$4.188 = (40*\omega)/15$; $\omega = 1.57$; $\omega = 2\pi N/60$

N = 15 rpm.

Therefore, for optimum energy extraction rotor speed should be maintained at 15 rpm.

UNIT-5

PART-B

1. With a neat schematic explain the integration of wind energy system with solar thermal system. (M.E-NOV/DEC2010)

Wind – Photovoltaic systems:

In many regions of the world, wind generators and photovoltaic cells are combined to provide year-round renewable energy to non-grid connected households. This is possible since variations in wind and solar power resources are usually complementary. A wind generator is thus an excellent supplement to the PV system and vice versa. Moreover, interfacing of wind generators and PV cells minimizes battery capacity and extends the battery bank life compared to the storage requirement in solar or wind only systems. Figure below shows a typical wind/PV hybrid system configuration.

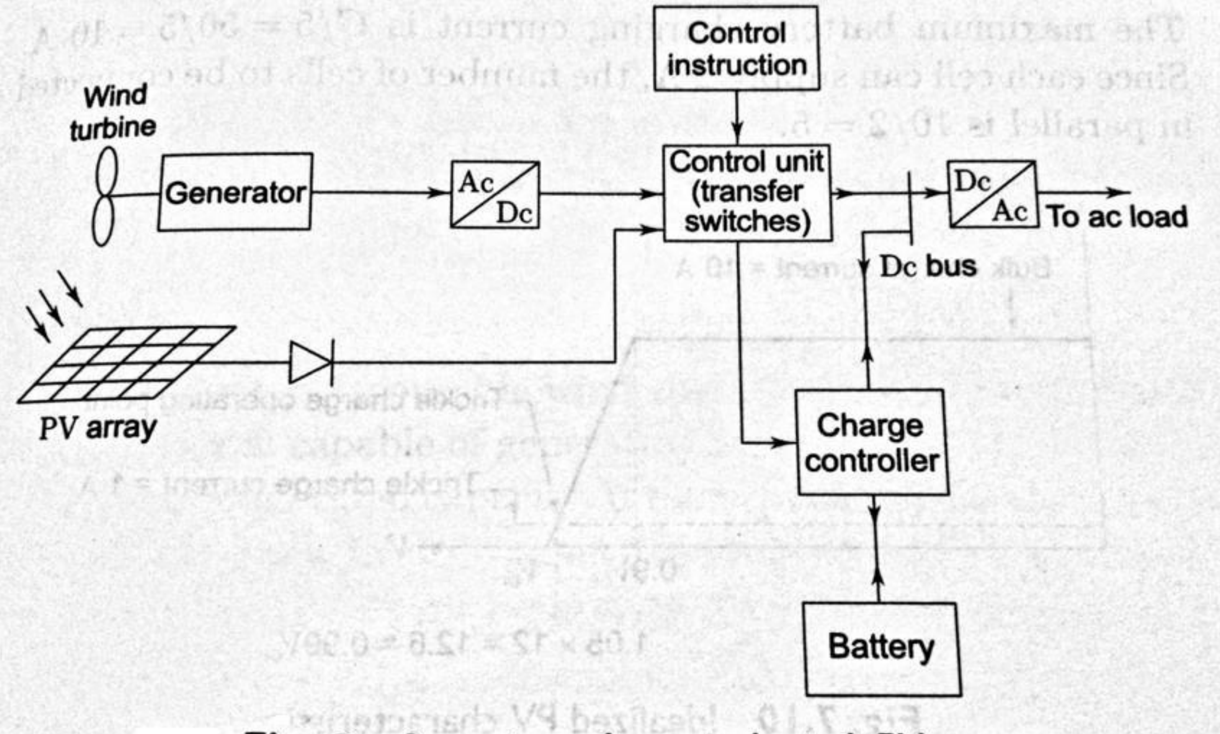


Fig. Configuration of a typical wind–PV system

The ac output of the wind generator feeds a rectifier which is connected in parallel to PV array through a controller to a dc bus. The dc bus also serves as a connection point for the battery through a charge controller. The blocking diode protects the PV array from voltage spikes and prevents the flow of current in the reverse direction at low irradiation. The controller decides the connection of the generating system/battery supply, or its charging, in specific situations and requirements.

2. Explain the incremental conductance based Maximum power point tracking algorithm with a suitable illustration.(M.E-NOV/DEC2016)

Incremental conductance based Maximum power point tracking algorithm:

The incremental conductance (IncCond) method is based on comparing the instantaneous panel conductance with the incremental panel conductance. The input impedance of the DC-DC converter is matched with optimum impedance of PV panel. As noted in literatures, this method has a good performance under rapidly changing conditions. The algorithm uses the fact that the derivative of the output power P with respect to the panel voltage V is equal to zero at the maximum power point:

$$\frac{dP}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV} = 0$$

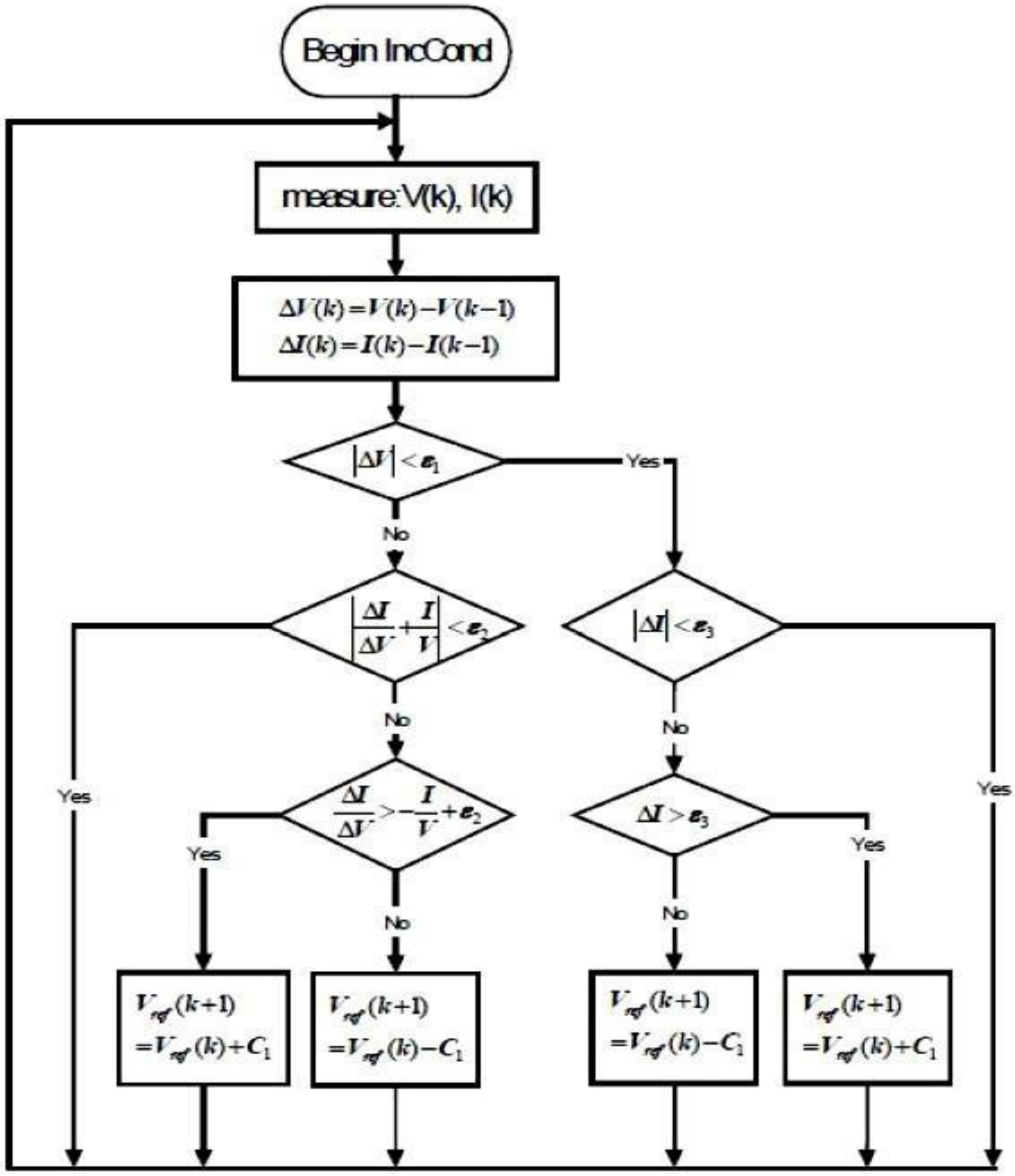


Figure: Incremental conductance algorithm flow chart

One of the advantages of the IncCond algorithm is that it does not oscillate around the MPP. The check of condition dl = O allows it to bypass the perturbation step and therefore maintain a constant operating voltage V once the MPP is found. Furthermore, condition dl > 0 make it possible to determine the relative location of the MPP. This leads to the advantage that an initial adjustment in the wrong direction, as with the "trial and error" P&O method, does not occur. A fast and correct system response to changing operating conditions should be the result yielding high system efficiency. A small marginal error could be added to the maximum power condition. The value of error was determined with consideration of the tradeoff between the problem of not operating exactly at the MPP and the possibility of oscillating around it. It will also depend on the chosen perturbation step size Cl.

3. Explain the various strategies used for the operation of an MPPT. (APR/MAY2017) (M.E-NOV/DEC2013) (M.E-NOV/DEC2013)

METHODS OF MPPT ALGORITHMS

1. Constant Voltage and Current.
2. Perturb-and-Observe.
3. Incremental Conductance.

Constant Voltage and Current Method

The constant voltage algorithm is based on the observation from I-V curves that the ratio of the array's maximum power voltage, Vmp, to its open-circuit voltage, V_{oc}, is approximately constant:

$$Vmp / Voc = K < 1$$

The constant voltage algorithm can be implemented using the flow chart below. The solar array is temporarily isolated from the MPPT, and a Voc measurement is taken. Next, the MPPT calculates the correct operating point and the preset value of K, and adjusts the array's voltage until the calculated Vmp is reached. This operation is repeated periodically to track the position of the MPP. Although this method is extremely simple, it is difficult to choose the optimal value of the constant K. The literature reports success with K values ranging from 73 to 80%. Constant voltage control can be easily implemented with analog hardware. However, its MPPT tracking efficiency is low relative to those of other algorithms. Reasons for this include the aforementioned error in the value of K, and the fact that measuring the open-circuit voltage requires a momentary interruption of PV power. It is also possible to use a constant current MPPT algorithm that approximates the MPP current as a constant percentage of the short-circuit current. To implement this algorithm, a switch is placed across the input terminals of the converter and switched on momentarily. The short-circuit current is measured and the MPP current is calculated, and the PV array output current is then adjusted by the MPPT until the calculated MPP current is reached. This operation is repeated periodically. However, constant voltage control is normally favored because of the relative ease of measuring voltages, and because open-circuiting the array is simple to accomplish, but it is not practically possible to short-circuit the array (i.e., to establish zero resistance across the array terminals) and still make a current measurement.

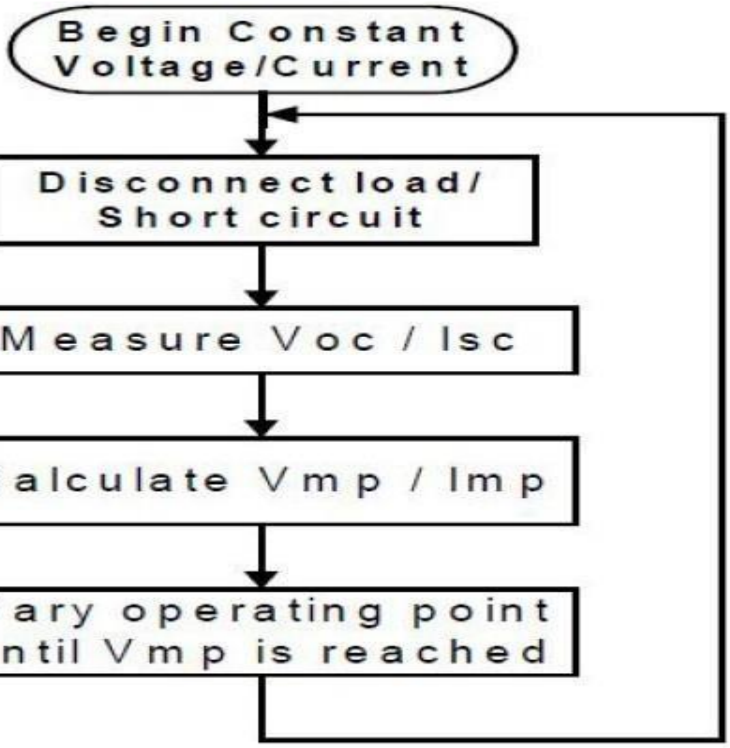
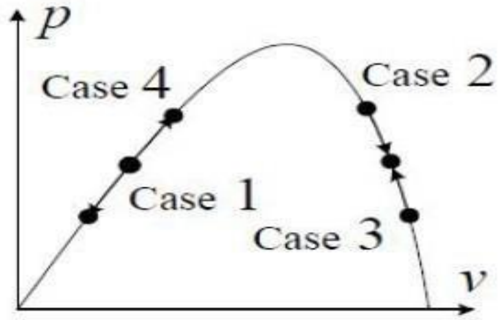


Figure Constant voltage/current algorithm flowchart

Perturb-and-Observe

As the name of the perturb-and-observe (P&O) states, this process works by perturbing the system by increasing or decreasing the array operating voltage and observing its impact on the array output power. The operating voltage is perturbed with every MPPT cycle. As soon as the MPP is reached, V will oscillate around the ideal operating voltage Vmp. Figure below summarized the control action of the P&O method. The value of the reference voltage, Vref, will be changed according to the current operating point. For example, for when the controller senses that the power from solar array increases ($dP > 0$) and voltage decreases ($dV < 0$), it will decrease (-) Vfef by a step size Cl, so V,-Bf is closer to the MPP. The MPP represents the point where Vref and scaled down Vsa become equal.

The oscillation around a maximum power point causes a power loss that depends on the step width of a single perturbation. The value for the ideal step width is system dependent and needs to be determined experimentally to pursue the tradeoff of increased losses under stable or slowly changing conditions. In fact, since the AC component of the output power signal is much smaller than the DC component and will contain a high noise level due to the switching DC-DC converter, an increase in the amplitude of the modulating signal had to be implemented to improve the signal to noise ratio (SNR), however, this will lead to higher oscillations at the MPP and therefore increase power losses even under stable environmental conditions.



Case	dP	dV	Action
1	< 0	< 0	+
2	< 0	> 0	-
3	> 0	< 0	-
4	> 0	> 0	+

Figure Perturb & Observe (P&O) control action

Several improvements of the P&O algorithm have been proposed. One of the simplest entails the addition of a ‘waiting’ function that causes a momentary cessation of perturbations if the algebraic sign of the perturbation is reversed several times in a row, indicating that the MPP has been reached. This reduces the oscillation about the MPP in the steady state and improves the algorithm’s efficiency under constant irradiance conditions. However, it also makes the MPPT slower to respond to changing atmospheric conditions, worsening the erratic behavior on partly cloudy days. Another modification involves measuring the array’s power Pl at array voltage Vl, perturbing the voltage and again measuring the array’s power, P2, at the new array voltage V2, and then changing the voltage back to its previous value and re measuring the array’s power, Pl, at V1. From the two measurements at Vl, the algorithm can determine whether the irradiance is changing. Again, as with the previous modifications, increasing the number of samples of the array’s power slows the algorithm down. Also, it is possible to use the two measurements at Vl to make an estimate of how much the irradiance has changed between sampling periods, and to use this estimate in deciding how to perturb the operating point. This, however, increases the complexity of the algorithm, and also slows the operation of the MPPT. The flow chart for P&O algorithm is shown below

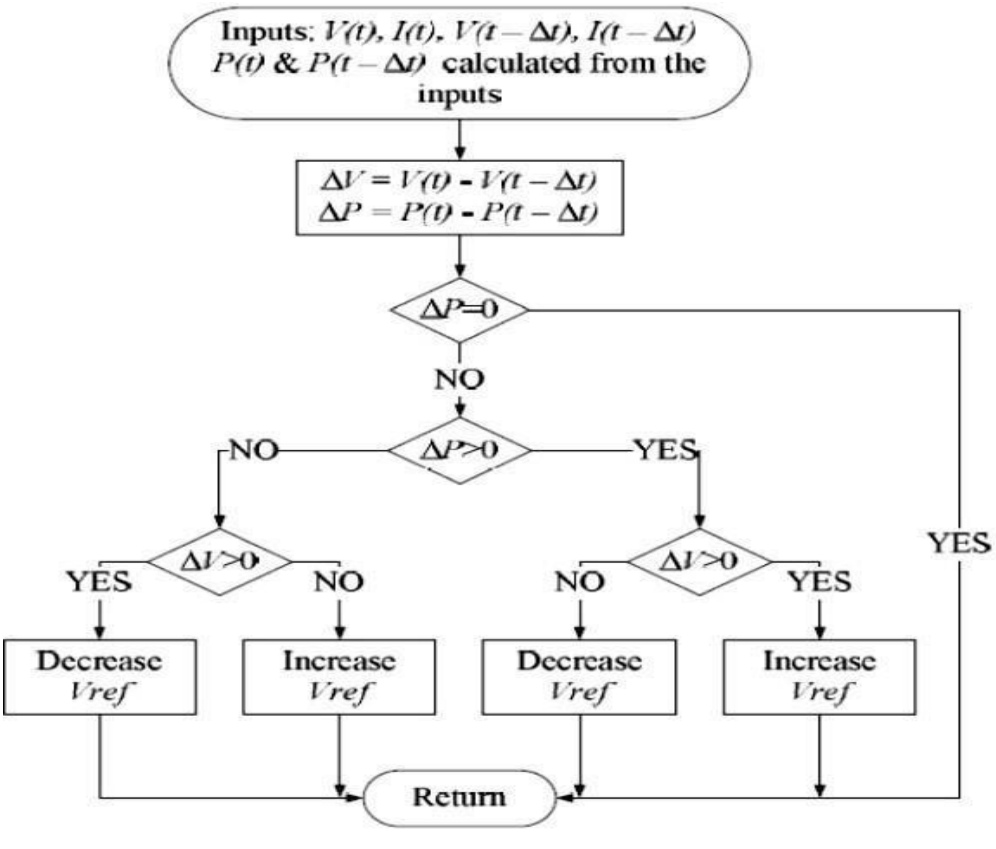


Figure - The flowchart of the P&O Algorithm.

Incremental conductance based Maximum power point tracking algorithm:

The incremental conductance (IncCond) method is based on comparing the instantaneous panel conductance with the incremental panel conductance. The input impedance of the DC-DC converter is matched with optimum impedance of PV panel. As noted in literatures, this method has a good performance under rapidly changing conditions. The algorithm uses the fact that the derivative of the output power P with respect to the panel voltage V is equal to zero at the maximum power point:

$$\frac{dP}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV} = 0$$

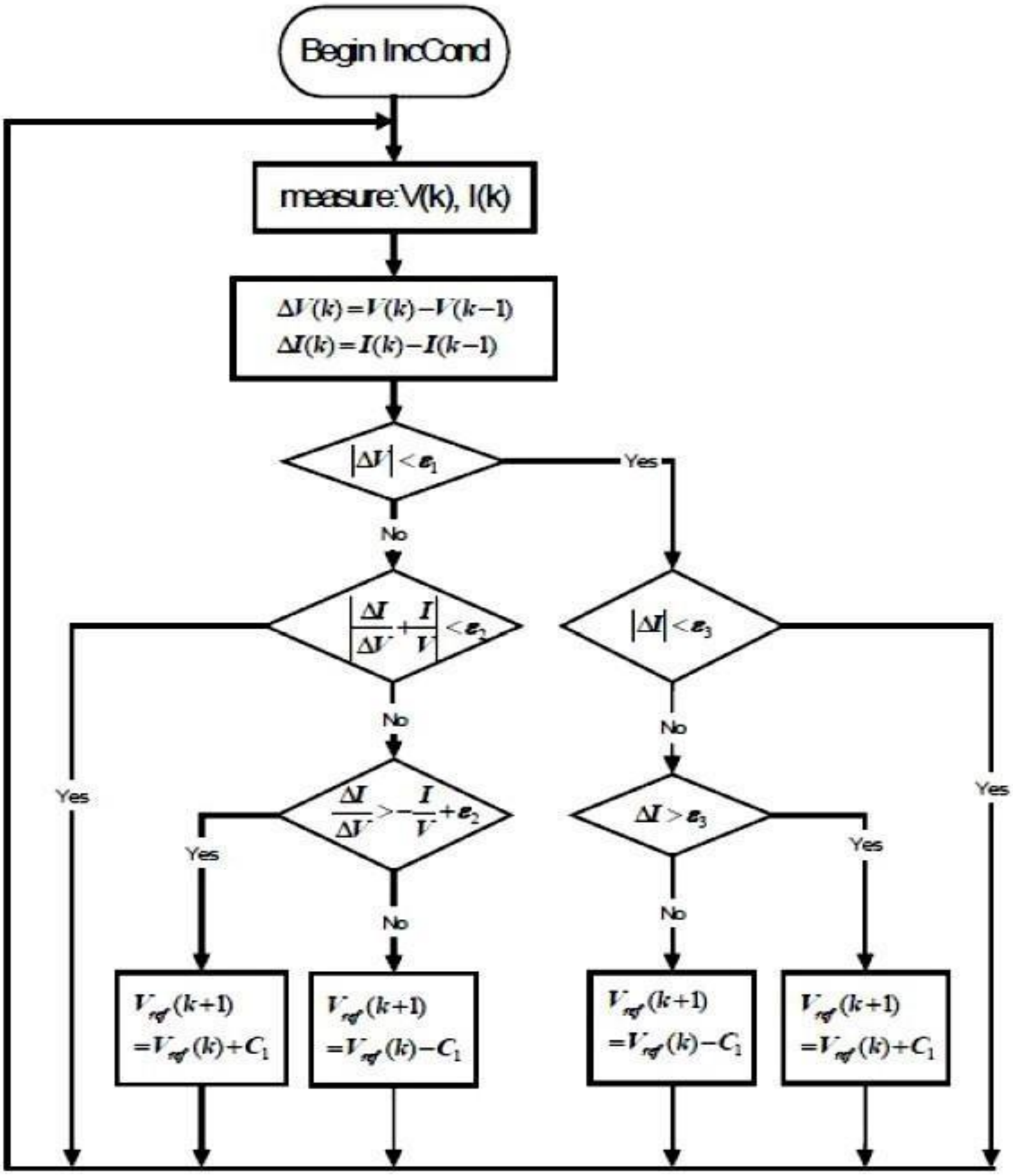


Figure: Incremental conductance algorithm flow chart

One of the advantages of the IncCond algorithm is that it does not oscillate around the MPP. The check of condition dl = O allows it to bypass the perturbation step and therefore maintain a constant operating voltage V once the MPP is found. Furthermore, condition dl > 0 make it possible to determine the relative location of the MPP. This leads to the advantage that an initial adjustment in the wrong direction, as with the “trial and error”

P&O method, does not occur. A fast and correct system response to changing operating conditions should be the result yielding high system efficiency. A small marginal error could be added to the maximum power condition. The value of error was determined with consideration of the tradeoff between the problem of not operating exactly at the MPP and the possibility of oscillating around it. It will also depend on the chosen perturbation step size Cl.

4. Enumerate the importance of MPPT in the operation of a photovoltaic system. (M.E-APR/MAY2013)

Need of Maximum Power Point Tracking for PV systems

The environmental condition under which a solar power system operates can be wide, as shown in I-V curves in Figure l. The current-voltage relation of a solar array is variable throughout the day, as it varies with environmental conditions such as irradiance and temperature. In terrestrial applications, Low Irradiance, Low Temperature (LILT) condition reflects morning condition where the sun just rises. A High Irradiance, High Temperature (HIHT) condition might represent a condition near high noon in a humid area. High Irradiance, Low Temperature (HILT) condition can represent a condition with healthy sunlight in the winter. Finally, condition near sunset can be described by Low Irradiance, High Temperature (LIHT) condition. For space application, LILT characterizes a deep space mission or aphelion period, While HIHT condition is when satellite orbits near the sun (perihelion).

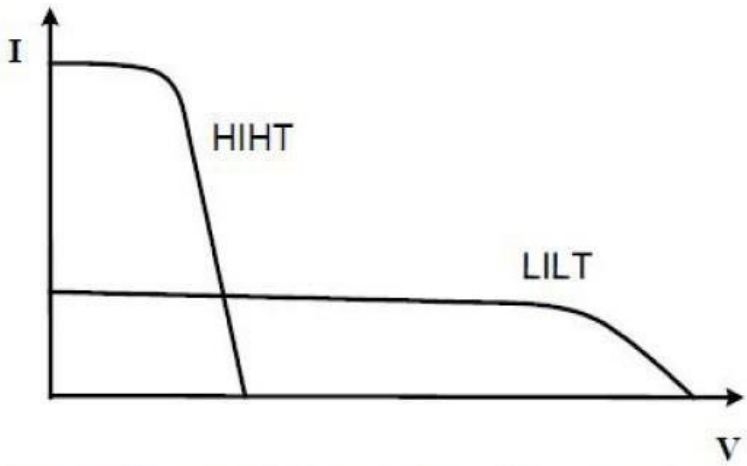


Figure 1: I-V characteristics under wide operating conditions

For a uniformly illuminated array, there is only one single point of operation that will extract maximum power from the array. In a battery charging system where the load seen by the solar modules is a battery connected directly across the solar array terminals, the operating point is determined by the battery’s potential. This operating point is typically not the ideal operating voltage at which the modules are able to produce their maximum available power. In the direct coupled method, in which the solar array output power is delivered directly to the loads, as shown in Figure 2. To match the MPPs of the solar array as closely as possible, it is important to choose the solar array I-V characteristic according to the I-V characteristics of the load. A general approach for the power feedback control is to measure and maximize the power at the load terminal, and it assumes that the solar array maximum power is equal to the maximum load power. However, this maximizes the power to the load not the power from the solar array. The direct-coupled method cannot automatically track the MPPs of the solar array when the insolation or temperature changes. The load parameters or solar array parameters must be carefully selected for the direct coupled method.

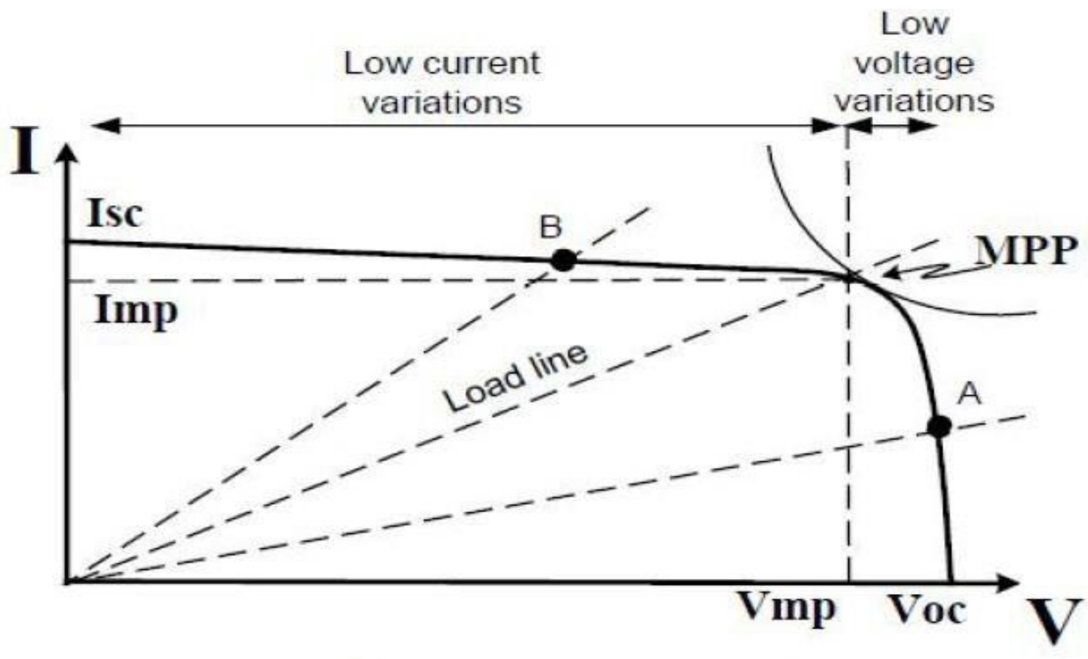


Figure 2: Direct coupled method

To be able to extract the maximum power from the solar array and to track the changes due to environment, therefore, a maximum power point tracking should be implemented. Devices that perform the desired function are known as Maximum Power Point Trackers, also called MPPTs or trackers.

5. Explain the need of hybrid systems for the renewable energy power generation. (M.E-NOV/DEC2010)

- Rapid depletion of fossil fuels has necessitated an urgent need for alternative sources of energy to cater the continuously increasing energy demand.
- Another key reason to reduce our consumption of fossil fuels is the growing global warming phenomena. Environmentally friendly power generation technologies will play an important role in future power supply.
- The renewable energy technologies include power generation from renewable energy sources, such as wind, PV(photovoltaic), MH(micro hydro), biomass, ocean wave, geothermal and tides. In general, the key reason for the deployment of the above energy systems are their benefits, such as supply security, reduced carbon emission, and improved power quality, reliability and employment opportunity to the local people.
- Since the RE resources are intermittent in nature therefore, hybrid combinations of two or more power generation technologies, along with storage can improve system performance.
- Hybrid Renewable Energy System (HRES) combines two or more renewable energy resources with some conventional source (diesel or petrol generator) along with storage, in order to fulfil the demand of an area.
- Hybrid energy systems oftentimes yield greater economic and environmental returns than wind, solar, geothermal or tri-generation stand-alone systems by themselves.

6. Enumerate the importance of MPPT in the operation of a wind energy conversion system.

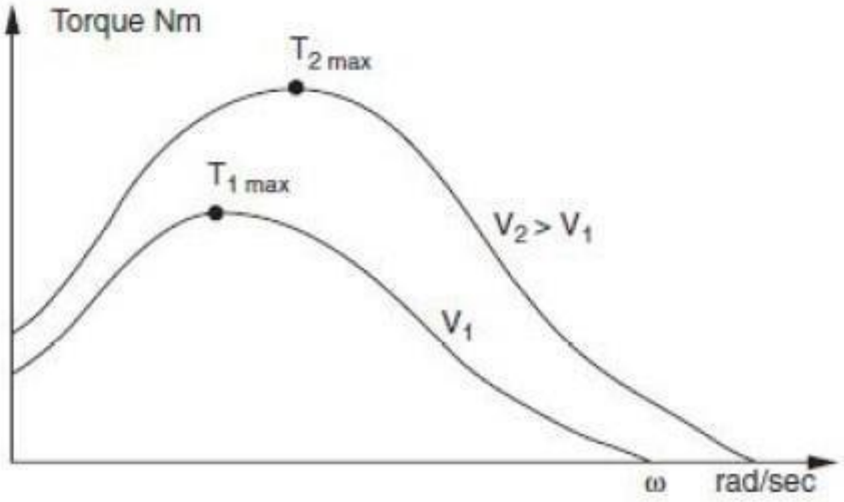
Need of MPPT for Wind Energy Conversion Systems:

The typical turbine torque vs. rotor speed is plotted in Figure below. It shows a small torque at Zero speed, rising to a maximum value before falling to nearly Zero when the rotor just floats with the wind. Two such curves are plotted for different wind speeds V1 and V2, with V; being higher than V1. The corresponding power vs. rotor speed at the two wind speeds are plotted in Figure. As the mechanical power convened into the electric power is given by the product of the torque T and the angular speed, the power is zero at zero speed and again at high speed with zero torque. The maximum power is generated at a rotor speed somewhere in between, as marked by P1max and P2max for speeds V1 and V2, respectively. The speed at the maximum power is not the same speed at which the torque is maximum. The operating strategy of a well-designed wind power system is to match the rotor speed to generate power continuously close to the Pmax points. Because the Pm“ point changes

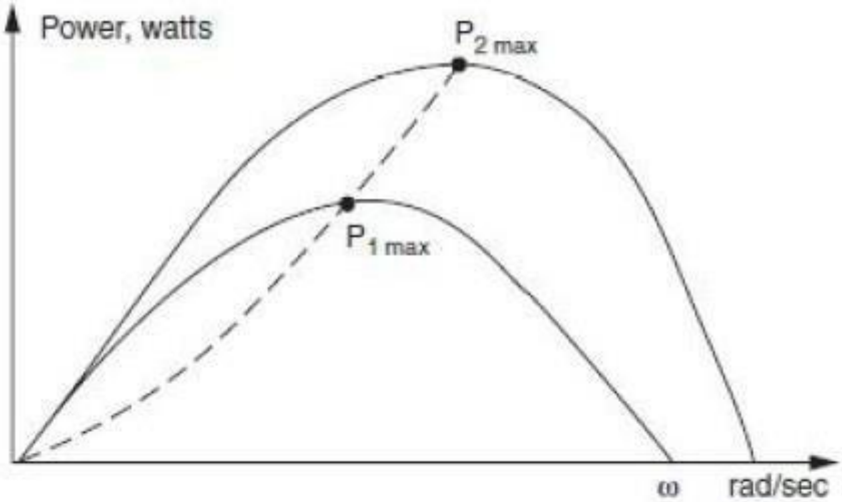
with the wind speed, the rotor speed must, therefore, be adjusted in accordance with the wind speed to force the rotor to work continuously at Pm“. This can be done with a variable-speed system design and operation.
At a given site, the wind speed varies over a wide range from zero to high gust. We define tip speed ratio (TSR) as follows:

$$TSR = \frac{\text{Linear speed of the blade's outermost tip}}{\text{Free upstream wind velocity}} = \frac{\omega R}{V}$$

For a given wind speed, the rotor efficiency Cp varies with TSR. The maximum value of Cp occurs approximately at the same wind speed that gives peak power in the power distribution curve. To capture high power at high wind, the rotor must also turn at high speed, keeping TSR constant at the optimum level.



Wind turbine torque vs. rotor speed characteristic at two wind speeds, V_1 and V_2.

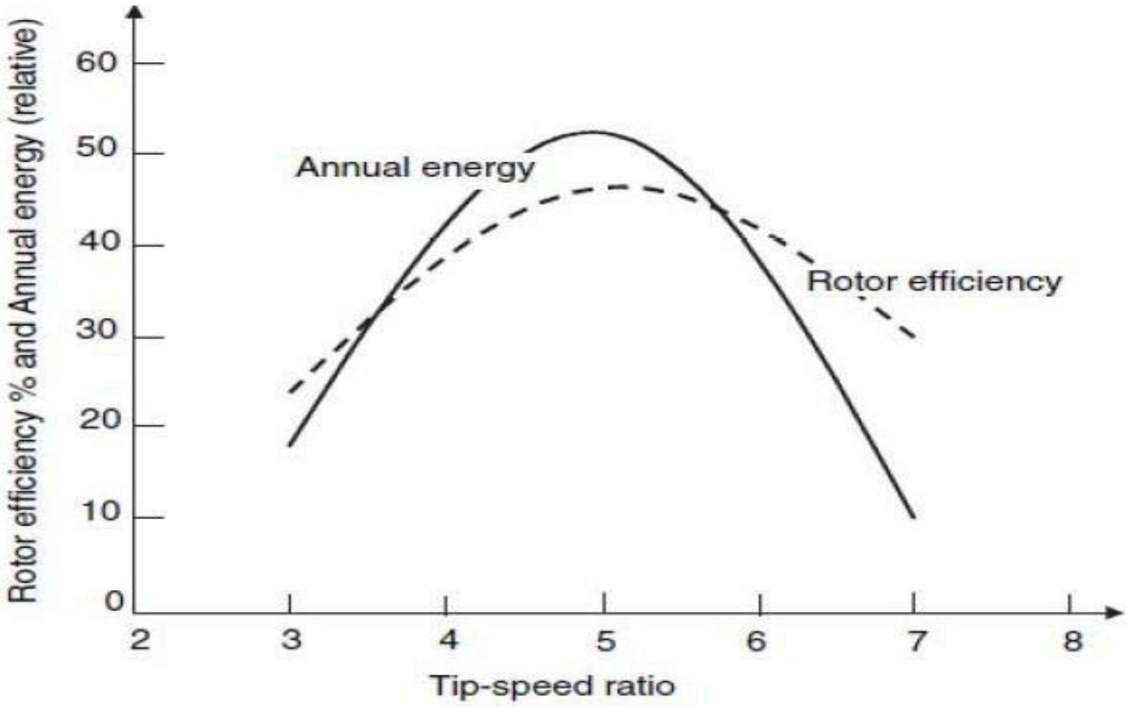


Wind turbine power vs. rotor speed characteristic at two wind speeds, V_1 and V_2.

However, the following three system performance attributes are related to TSR:

1. The maximum rotor efficiency Cp is achieved at a particular TSR, which is specific to the aerodynamic design of a given turbine.
2. The centrifugal mechanical stress in the blade material is proportional to the TSR. The machine working at a higher TSR is necessarily stressed more. Therefore, if designed for the same power in the same wind speed, the machine operating at a higher TSR would have slimmer rotor blades.
3. The ability of a wind turbine to start under load is inversely proportional to the design TSR. As this ratio increases, the starting torque produced by the blade decreases.

A variable-speed control is needed to maintain a constant TSR to keep the rotor efficiency at its maximum. At the optimum TSR, the blades are oriented to maximize the lift and minimize the drag on the rotor. The turbine selected for a constant TSR operation allows the rotational speed of both the rotor and generator to vary up to 60% by varying the pitch of the blades



Rotor efficiency and annual energy production vs. rotor TSR.

7. Draw the basic structure of MPPT and explain the components in it.

To be able to extract the maximum power from the solar array and to track the changes due to environment, therefore, a maximum power point tracking should be implemented. Devices that perform the desired function are known as Maximum Power Point Trackers, also called MPPTs or trackers. A tracker consists of two basic components, as shown in Figure : a switch-mode converter and a control with tracking capability. The switch-mode converter is the core of the entire supply. The converter allows energy at one potential to be drawn, stores as magnetic energy in an inductor, and then releases at a different potential. By setting up the switch-mode section in various topologies, either high-to-low (buck converter) or low-to-high (boost) voltage converters can be constructed. The goal of a switch-mode power supply is to provide a constant output voltage or current. In power trackers, the goal is to provide a fixed input voltage and/or current, such that the array is held at the maximum power point, while allowing the output to match the load voltage.

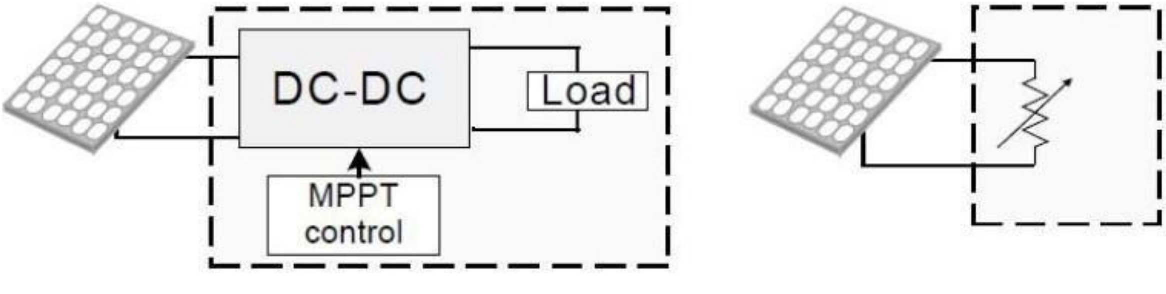


Figure . Basic components of a maximum power pointer tracker

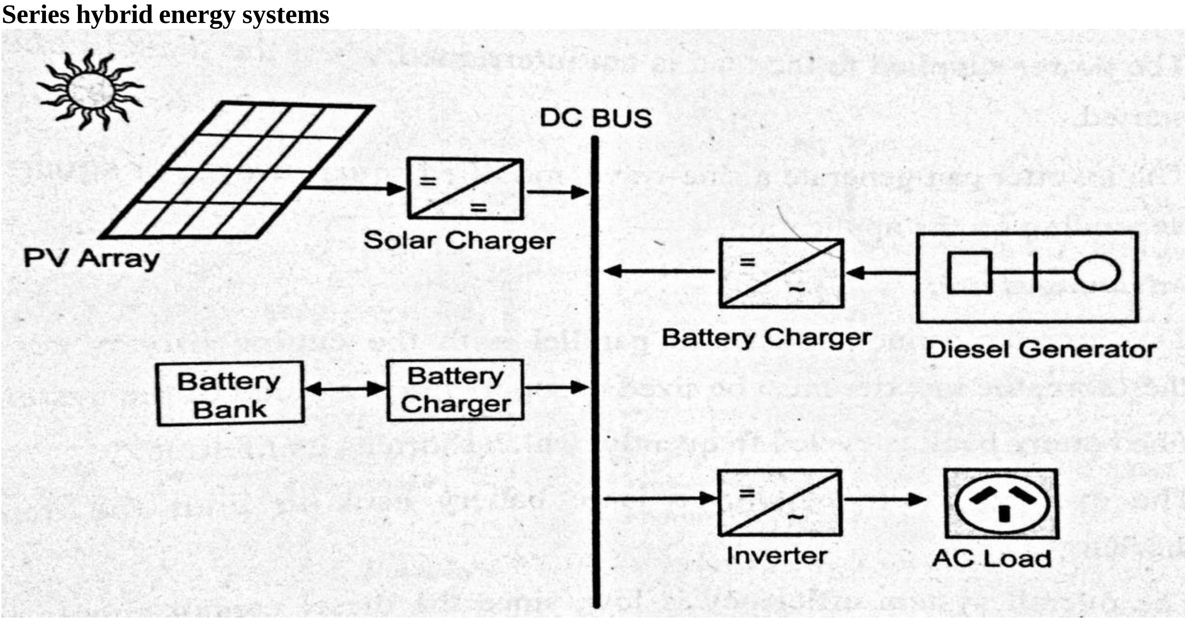
When properly applied, a maximum power point tracking control can prevent the collapse of the array voltage under excessive load demand, particularly when supplying a constant-power type of load. One of the proper approaches is to operate the system in a solar array voltage regulation mode where the array voltage is clamped to a commanding set point, Vmp, which is dynamically updated by the MPPT control circuit. The control processes feedback signals, such as the array current and voltage, to determine a proper direction to move the operating point. Eventually, this continuously updated set point will fluctuate around the voltage corresponding to the array peak power point. By adjusting the operating point of the array to the point Vmp, power output of the array is maximized, and the most efficient use of the solar array may be realized.

8. Explain in detail about the types of PV-Diesel Hybrid System.

TYPES OF PV-DIESEL HYBRID SYSTEMS

Series hybrid energy systems
Switched hybrid energy systems
Parallel hybrid energy systems

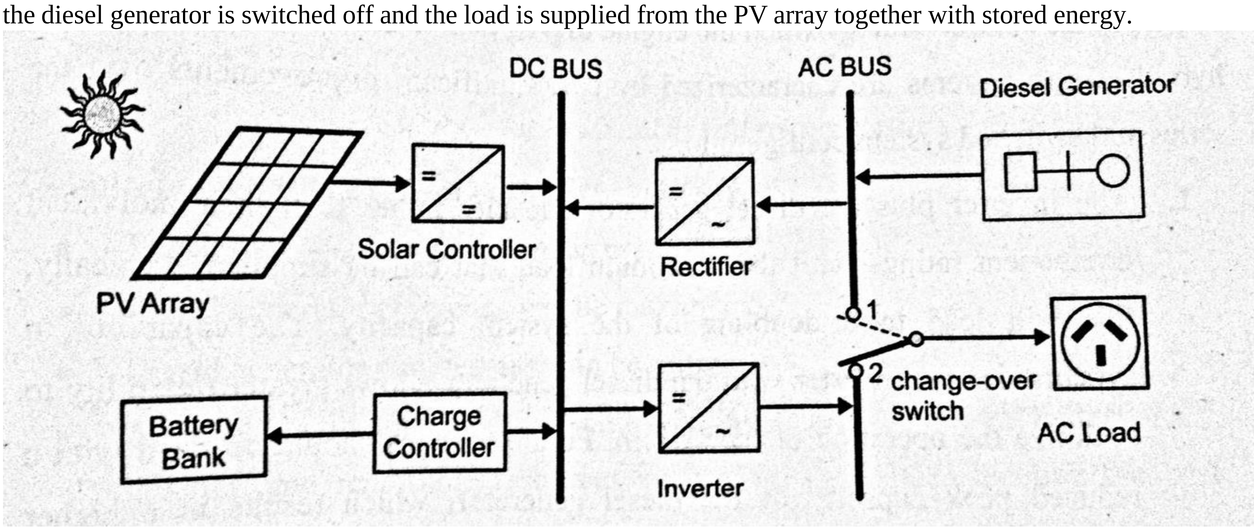
Series hybrid energy systems



The above figure shows a series PV-diesel hybrid system. to ensure reliable operation of series hybrid energy systems, both the diesel generator and inverter have to be sized to meet peak loads. AC power delivered to the load is converted from dc to regulated ac by an inverter or a motor generator unit. The power generated by the diesel generator is first rectified and subsequently converted back to ac before being supplied to the load, which leads to significant conversion losses. The solar controller prevents overcharging of the battery bank from PV generator when PV power exceeds the load demand and batteries are fully charged. The system can be operated in manual or automatic mode, with the addition of appropriate battery voltage sensing and start/stop control of engine-driven generator.

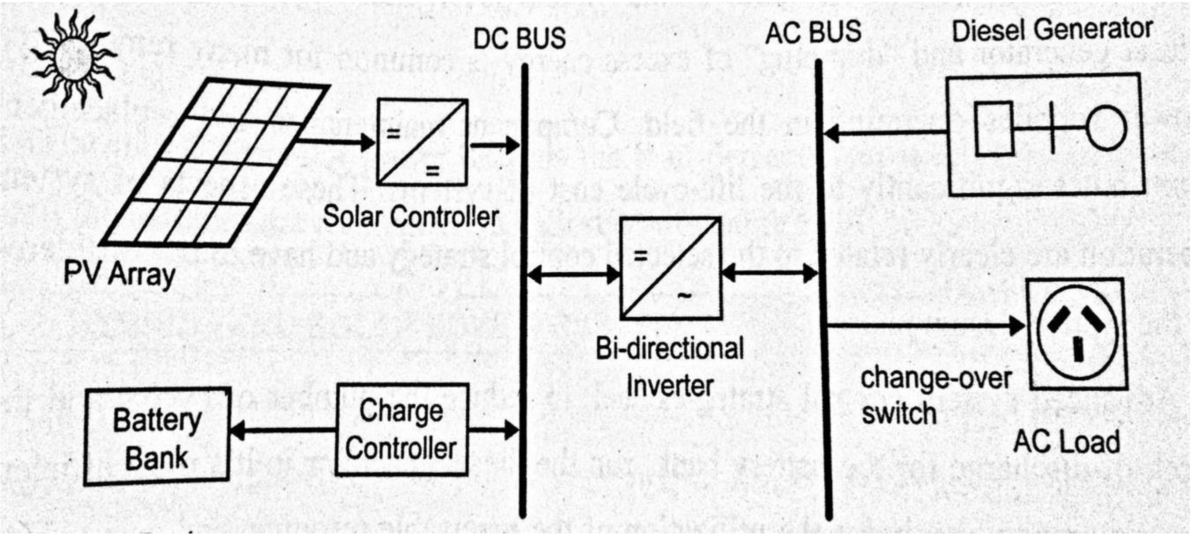
Switched hybrid energy systems

It allows operation with either engine driven generator or the inverter as the ac source, yet no parallel operation of the main generation sources is possible. The diesel generator and renewable energy source can charge the battery bank. The main advantage is that the load can be supplied directly by the engine driven generator, which results in a high overall conversion efficiency. Typically, the diesel generator power will exceed the load demand, with excess energy being used to recharge the battery bank. During periods of low electricity demand the diesel generator is switched off and the load is supplied from the PV array together with stored energy.



Parallel hybrid energy systems

The another configuration called parallel one allows all energy sources to supply the load separately at low or medium load demand, as well as supplying peak loads from combined sources by synchronizing the inverter with alternator output waveform. Such a configuration is represented in the below figure. The bidirectional inverter can charge the battery bank when excess energy is available from engine driven generator, as well as a DC-AC converter. The bidirectional inverter may provide peak saving as part of control strategy when engine driven generator is overloaded.


DC BUS
AC BUS
Diesel Generator
Solar Controller
PV Array
Bi-directional
Inverter
change-over
switch
AC Load
Battery
Bank
Charge
Controller

21/4/17(FN)

Reg. No. : [ ][ ][ ][ ][ ][ ][ ][ ][ ][ ][ ][ ]

Question Paper Code : 71758

B.E./B.Tech. DEGREE EXAMINATION, APRIL/MAY 2017.

Eighth Semester

Electrical and Electronics Engineering

EE 6009 — POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

(Regulations 2013)

Time : Three hours | Maximum : 100 marks

Answer ALL questions.

PART A — (10 × 2 = 20 marks)

1. Give any two environmental aspects of electric energy conversion.
2. Justify how fuel cell becomes renewable energy source.
3. Name any four types of generators used in wind energy conversion systems.
4. Write the significance of reference theory.
5. What is the function of boost converter in solar photovoltaic system?
6. What is called matrix converter?
7. Distinguish between fixed speed and variable speed wind energy conversion system.
8. What are the major problems associated with grid integration of wind energy system?
9. What are the advantages of hybrid renewable energy systems?
10. What is the importance of Maximum Power Point Tracking (MPPT) in the operation of a photovoltaic system?

PART B — (5 × 16 = 80 marks)

11. (a) (i) Discuss the impact of renewable energy based power generation on environmental issues. (8)

(ii) What is Hydrogen energy? Explain the operation of Hydrogen energy system with schematic diagram. (8)

Or

(b) List out the available renewable energy sources. Explain how solar and wind energy sources plays significant role of electric power generation. (16)

12. (a) Draw the equivalent circuit and show the steady state analysis of Permanent Magnet Synchronous Generator (PMSG). Explain the merits and demerits of PMSG for wind energy conversion system. (16)

Or

(b) (i) Explain the operating principle of Squirrel Cage Induction Generator coupled with wind turbine. (8)

(ii) Show the relative merits of wind energy conversion system with Permanent Magnet Synchronous Generator (PMSG), Squirrel Cage Induction Generator (SCIG), and Doubly Fed Induction Generator (DFIG). (8)

13. (a) Draw the schematic diagram of standalone solar photovoltaic system. What are the main components used in it? Explain their functions. (16)

Or

(b) (i) Draw the power circuit of grid interactive inverter and explain its operation. (8)

(ii) Explain the need of AC-DC-AC converters for wind energy conversion system. (8)

14. (a) Draw the general structure of variable speed wind energy conversion for standalone system. Explain the functions of components used. Mention the merits and demerits of variable speed wind energy conversion. (16)

Or

(b) What is the need for grid integration of wind energy system? With power electronic interface circuit, explain how grid integration is done for Permanent Magnet Synchronous Generator (PMSG) based wind energy conversion system. (16)

15. (a) Show the power electronic system used for hybrid solar photovoltaic and wind energy system and explain its operation. Discuss the technical challenges associated in it. (16)

Or

(b) What is called Maximum Power Point Tracking (MPPT)? List out the different types of MPPT algorithms used for solar photovoltaic system with its salient features. Explain the use of MPPT for hybrid wind and photovoltaic energy system. (16)

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Reg. No. :

Question Paper Code : 40985

02/05/18 (FN)

B.E./B.Tech. DEGREE EXAMINATION, APRIL/MAY 2018
Eighth Semester
Electrical and Electronics Engineering
EE 6009 – POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS
(Regulations 2013)

Time : Three Hours | Maximum : 100 Marks

Answer ALL questions

PART – A **(10×2=20 Marks)**

1. What are the advantages of using grid connected solar PV system ?
2. Mention the factors involved in biomass conversion.
3. Draw the angular relationship of abc and dq winding in an induction generator.
4. What are the advantages of permanent magnet synchronous generator ?
5. Draw the block diagram of solar photovoltaic system.
6. What are the factors involved in battery sizing ?
7. What are the classifications in wind energy conversion system based on electrical power output ?
8. List out the problems involved in grid connection.
9. What is the need for hybrid systems ?
10. Draw the PV characteristics of solar PV system and mark the maximum point.

PART – B **(5×16=80 Marks)**

11. a) Briefly explain the working principle of fuel cell. **(16)**

(OR)

b) Discuss the impact of following renewable energy generation on environment.
i) ocean energy ii) wind energy system. **(16)**

12. a) Explain doubly fed induction generator with neat sketch. (16)

(OR)

b) Discuss in detail about the construction and working of permanent magnet synchronous generator. (16)

13. a) Explain with a neat diagram, a power electronic circuit to interface wind electrical system to the grid. (16)

(OR)

b) Discuss the control strategy used in grid interactive inverters. (16)

14. a) Briefly explain the grid integrated SCIG based wind energy conversion system. (16)

(OR)

b) Write a detailed note on standalone operation of photovoltaic system. (16)

15. a) Explain briefly about switched configuration of Diesel-PV hybrid system. (16)

(OR)

b) Explain the following methods of MPPT control algorithm. (16)

i) Incremental conductance method

ii) Fuzzy logic controller.

Reg. No. :

Question Paper Code : 52939

B.E./B.Tech. DEGREE EXAMINATION, APRIL/MAY 2019.

Eighth Semester

Electrical and Electronics Engineering

EE 6009 — POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

(Regulations 2013)

Time : Three hours

Maximum : 100 marks

Answer ALL questions.

PART A — (10 × 2 = 20 marks)

1. State the merits of renewable energy sources.

2. Mention some of the organic materials used in bio-mass plant.

3. Write the advantages of doubly fed Induction generators used in WECS.

4. What is the basic principle of wind energy conversion?

5. Draw the basic block diagram of wind energy conversion system.

6. What is grid interactive inverter?

7. Define pitch control in wind power system.

8. List out the functions of a charge controller in PV system.

9. List the different types of hybrid system.

10. What is MPPT in PV system?

PART B — (5 × 13 = 65 marks)

11. (a) What is a fuel cell? Mention the different types of fuel cell and explain any three them in detail with neat diagrams.

Or

(b) Explain the operating principle of any four types of renewable energy sources.

12. (a) Draw the equivalent circuit and obtain the steady-state analysis of Induction Generator.

Or

(b) Explain the construction and principle of operation of Double fed Induction Generator in detail with neat diagram. Also discuss its characteristics and limitations briefly.

13. (a) Describe any two power conditioning schemes used in photovoltaic systems.

Or

(b) What is a matrix converter? Explain it in detail. Also briefly state its advantages and limitations.

14. (a) (i) Explain the stand-alone operation of fixed speed wind energy conversion system with neat diagram. (10)

(ii) Discuss the factors that affect the output of a PV system. (6)

Or

(b) Explain in detail about the grid integrated permanent magnet synchronous generator in detail with relevant diagram and also discuss the issues of grid connection in detail.

15. (a) What is a hybrid system? Mention the need for hybrid system. Also explain in detail about the series hybrid system with necessary diagrams in detail.

Or

(b) List the different types of MPPT algorithm. Explain the Incremental conductance MPPT algorithm with a neat flow chart.

PART C — (1 × 15 = 15 marks)

16. (a) A three phase diode bridge is supplied by a synchronous generator whose excitation emf is 1.06 p.u. and synchronous reactance is 0.25 p.u. Assuming continuous load current of 0.8 p.u. Determine the percentage of the dc output voltage of its no-load voltage and the total rating of the rectifier. Neglect diode drops.

Or

(b) A horizontal axis wind turbine has a diameter of 6 m. When the wind speed unaffected by the turbine is 10 m/s, the turbine rotates at 300 rpm and produces 5 kw of mechanical power. Find the tip speed ratio and the power coefficient.

25.11.17 AN

Reg. No. :

Question Paper Code : 50467

B.E./B.Tech. DEGREE EXAMINATION, NOVEMBER/DECEMBER 2017

Eighth Semester

Electrical and Electronics Engineering

EE 6009 – POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

(Regulations 2013)

Time : Three Hours Maximum : 100 Marks

Answer ALL questions.

PART – A (10×2=20 Marks)

1. Write down the current equation of solar array.
2. Define specific rated capacity of wind turbine.
3. What is reference frame transformation ?
4. Compare SCIG and DFIG.
5. Draw the block diagram of solar photovoltaic system.
6. What are the advantages of matrix converter ?
7. What are the advantages of variable speed wind turbine conversion system ?
8. Draw the equivalent circuit of a non salient pole synchronous machine.
9. List out the need for hybrid renewable energy system.
10. What is the concept of MPPT ?

PART – B (5×16=80 Marks)

11. a) Explain the construction, working and different characteristics of solar array in detail. (16)

(OR)

b) i) With the neat diagram explain the energy generation using hydrogen energy system. (8)

ii) Describe the concept of electric power generation from Biomass. (8)

12. a) Explain the steady state equivalent circuit model and performance characteristics of squirrel cage induction generator in detail. (16)

(OR)

b) Explain the construction and working of PMSG and analyze the system using steady state equation with phasor diagram. (16)

13. a) Write short notes on :

i) Current regulated PWM inverters. (8)

ii) Selection of inverter. (4)

iii) Selection of battery sizing. (4)

(OR)

b) Explain the different modes of operation of PV fed Buck-Boost converter in detail. (16)

14. a) Explain the operation of fixed speed and semi variable mode of wind energy conversion system with neat sketch. (16)

(OR)

b) Explain the circuit model of grid integrated solar system. (16)

15. a) Explain the operation of autonomous PV system with an MPPT conveter and battery backup with neat sketch. (16)

(OR)

b) Explain any three different configuration of Hybrid renewable energy system in detail. (16)

12/11/18 AN

Reg. No. :

Question Paper Code : 20441

B.E/B.Tech. DEGREE EXAMINATION, NOVEMBER/DECEMBER 2018.

Eighth Semester

Electrical and Electronics Engineering

EE 6009 — POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

(Regulations 2013)

Time : Three hours Maximum : 100 marks

Answer ALL questions.

PART A — (10 × 2 = 20 marks)

1. Write the principle of operation of wind turbine.

2. Mention some types of fuel used in biomass plant.

3. Draw the speed-torque curve of induction generator.

4. Explain briefly, the rotor construction of DFIG.

5. Draw the I-V and P-V characteristics of solar cell.

6. Mention the factors considered in the selection of inverter and battery sizing.

7. Mention some of the issues in stand-alone solar system.

8. Classify the types of WECS based on the rotational speed of turbines.

9. What are the types of hybrid system?

10. Define smart power tracker.

PART B — (5 × 16 = 80 marks)

11. (a) Explain with a neat diagram, the different types of concentrating type solar collector with its operation and working principles. (16)

Or

(b) Explain the following with neat schematics : (16)

(i) Biomass energy system

(ii) Energy from ocean.

12. (a) Illustrate the working and principle of grid connected PMSG in wind power plant. (16)

Or

(b) Discuss the working principle of SCIG connected to a grid network and state its advantage for operating with wind turbine. (16)

13. (a) Explain the operation and control of matrix converter with its circuit diagram and switching condition. (16)

Or

(b) Explain the operation of following converters : (16)

(i) Three phase AC voltage controller

(ii) PWM inverter.

14. (a) Write a brief note on stand-alone operation of fixed and fully variable speed WECS. (16)

Or

(b) Explain the operation of solar model in grid integrated system with and without battery backup. (16)

15. (a) Discuss different hybrid systems configurations consisting of wind turbine and solar power plant. (16)

Or

(b) Explain the factors to be considered for placing the wind-PV system. Discuss its plant details, operating period and environmental aspects for assumed residential load. (16)

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11/11/19/AN

Reg. No. :

Question Paper Code : 91474

B.E./B.Tech. DEGREE EXAMINATIONS, NOVEMBER/DECEMBER 2019

Eighth Semester

Electrical and Electronics Engineering

EE 6009 – POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

(Regulations 2013)

Time : Three Hours Maximum : 100 Marks

Answer ALL questions

PART – A **(10×2=20 Marks)**

1. What is called greenhouse gas effect ?
2. How Fuel Cell is treated as renewable energy source ?
3. Why Permanent Magnet Synchronous Generators are preferred for low speed wind applications ?
4. Distinguish between Squirrel Cage Induction Generator and Doubly fed Induction Generator.
5. What is the need for Buck-Boost converter for solar photovoltaic system ?
6. Write the special requirements of Grid Interactive inverters.
7. What are the technical issues to be considered for grid integration of wind energy conversion ?
8. How grid integrated system for solar PV differs from wind energy system ?
9. What is the need for hybrid energy system ?
10. What is called Maximum Power Point Tracking ?

PART – B (5×13=65 Marks)

11. a) Explain the necessity for use of renewable energy sources and how renewable energy based power generation saves the environment ?

(OR)

b) Discuss the current status of biomass based renewable energy technologies and solar photovoltaic technologies.

12. a) Analyze the dynamic behavior of permanent magnet synchronous generator with respect to wind power variations.

(OR)

b) Draw the basic structure of Squirrel Cage Induction Generator and explain its operation. Also discuss its characteristics and uses.

13. a) Draw the power circuit of Boost converter used for solar Photovoltaic system and explain the operation for changing the DC voltage from one level to another level.

(OR)

b) Draw the power circuit for three phase PWM inverter used for wind energy conversion system and explain its operation.

14. a) Give a block diagram of photovoltaic conversion system which is designed to supply power to stand lone load. Describe the operation of main components used in it.

(OR)

b) With a functional block diagram, describe the functions of main components used in grid connected permanent magnet synchronous generator based wind energy conversion system.

15. a) Explain the various configuration of hybrid energy systems. Write down the merits and demerits of the different configurations.

(OR)

b) Write the commonly used Maximum Power Point Tracking (MPPT) algorithms for solar PV system. With the help of flow chart, explain perturb and observe MPPT algorithm.

PART – C (1×15=15 Marks)

16. a) Develop a block diagram of hybrid PV system which should be able to supply the power to the load for 24 hours without interruption. It should be using solar radiation, diesel and wind as the source of energy.

(OR)

b) A DC fan of 24 W needs to be run on solar PV during day time only. What should be the capacity of PV panel and power converter used in it ? Draw the power circuit configuration. List down all the possible design issues related to this arrangement.

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE3601- PROTECTION AND SWITCHGEAR

SEMESTER VI

REGULATIONS 2021

NOTES

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QUESTION BANK

EE3601 PROTECTION AND SWITCHGEAR

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COURSE OBJECTIVES:

- To understand the significance of protection, protection schemes and role of earthing.
- To study the characteristics, functions and application areas of various relays.
- To acquire practical knowledge about common faults in power system apparatus and applying suitable protective schemes.
- To understand the functioning of static relays and Numerical protection concepts.
- To understand the problems associated with circuit breaking and to discuss about various circuit breakers.

UNIT I PROTECTION SCHEMES 9

Significance and need for protective schemes – nature and causes of faults – types of faults Effects of faults - Zones of protection and essential qualities of protection – Types of Protection schemes - Power system Grounding and Methods of Grounding.

UNIT II BASICS OF RELAYS 9

Operating principles of relays -Universal torque equation - R-X diagram -Electromagnetic Relays - Over current, Directional and non-directional, Distance, Differential, Negative sequence and Under frequency relays.

UNIT III OVERVIEW OF EQUIPMENT PROTECTION 9

Current transformers and Potential transformers and their applications in protection schemes - Protection of transformer, generator, motor, bus bars and transmission line.

UNIT IV STATIC RELAYS AND NUMERICAL PROTECTION 9

Static relays – Phase, Amplitude Comparators – Synthesis of various relays using Static comparators – Block diagram of Numerical relays – Over current protection, transformer differential protection, and distantce protection of transmission lines.

UNIT V CIRCUIT BREAKERS 9

Physics of arcing phenomenon and arc interruption – DC and AC circuit breaking – re-striking voltage and recovery voltage - rate of rise of recovery voltage - current chopping - interruption of capacitive current - resistance switching - Types of circuit breakers – air blast, oil, SF6 and vacuum circuit breakers – comparison of different circuit breakers – HVDC Breaker.

TOTAL : 45 PERIODS

COURSE OUTCOMES:

Upon the successful completion of the course, students will have theability to:

CO1: Understand and select proper protective scheme and type of earthing.

CO2: Explain the operating principles of various relays.

CO3: Suggest suitable protective scheme for the protection of various power system apparatus.

CO4: Analyze the importance of static relays and numerical relays in power system protection.

CO5: Summarize the merits and demerits and application areas of various circuit breakers.

TEXT BOOKS:

1. Sunil S.Rao, 'Switchgear and Protection', Khanna Publishers, New Delhi, Four Edition, 2010.
2. Badri Ram ,B.H. Vishwakarma, 'Power System Protection and Switchgear', New Age International Pvt Ltd Publishers, Second Edition 2011.
3. B.Rabindranath and N.Chander, 'Power System Protection and Switchgear', New Age International (P) Ltd., Second Edition, 2018.
4. Arun Ingole, 'Switch Gear and Protection' Pearson Education, 2018.

REFERENCES

1. Y.G.Paithankar and S.R.Bhide, 'Fundamentals of power system protection', Second Edition,Prentice Hall of India Pvt. Ltd., New Delhi, 2013.
2. C.L.Wadhwa, 'Electrical Power Systems', 6th Edition, New Age International (P) Ltd., 2018
3. VK Metha," Principles of Power Systems", S. Chand, Reprint, 2013
4. Bhavesh Bhalja, R.P. Maheshwari, Nilesh G. Chotani,'Protection and Switchgear' Oxford University Press, 2^{nd} Edition 2018.

UNIT-1

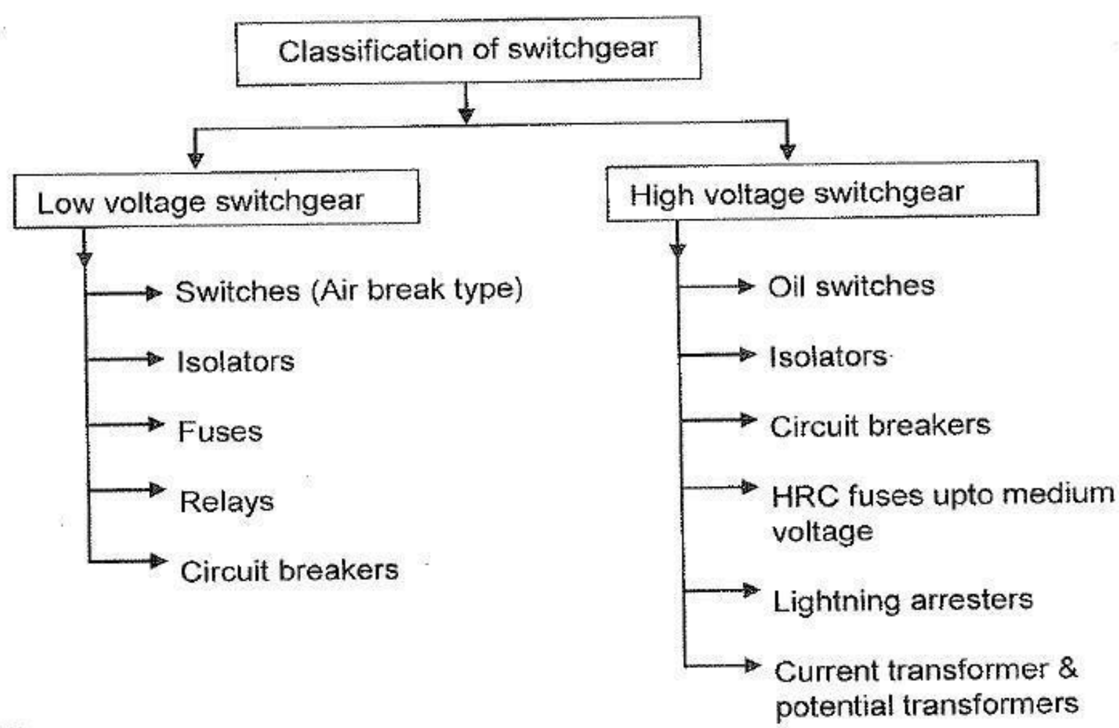
PROTECTION SCHEMES

1. Importance of protective schemes for electrical apparatus and power

system 1.1 Fundamentals of Power System Protection

The purpose of an Electric Power System is to generate and supply electrical energy to consumers. The power system should be designed and managed to deliver this energy to the utilization points with both reliability and economically The capital investment involved in power system for the generation, transmission and distribution is so great that the proper precautions must be taken to ensure that the equipment not only operates as nearly as possible to peak efficiency, but also must be protected from accidents The normal path of the electric current is from the power source through copper (or aluminium) conductors in generators, transformers and transmission lines to the load and it is confined to this path by insulation. The insulation, however, may break down, either by the effect of temperature and age or by a physical accident, so that the current then follows an abnormal path generally known as Short Circuit or Fault

• Any abnormal operating state of a power system is known as FAULT. Faults in general consist of short circuits as well as open circuits. Open circuit faults are less frequent than short circuit faults, and often they are transformed in to short circuits by subsequent events.



1.2 Consequences of occurrence of Faults

Faults are of two type

- Short circuit fault- current
- Open circuit fault- voltage

In terms of seriousness of consequences of a fault , short circuits are of far greater concern than open circuits, although some open circuits present some potential hazards to personnel Classification of short circuited Faults

• Three phase faults (with or without earth connection)
• Two phase faults (with or without earth connection)
• Single phase to earth faults

Classification of Open Circuit Faults

• Single Phase open Circuit
• Two phase open circuit
• Three phase open circuit

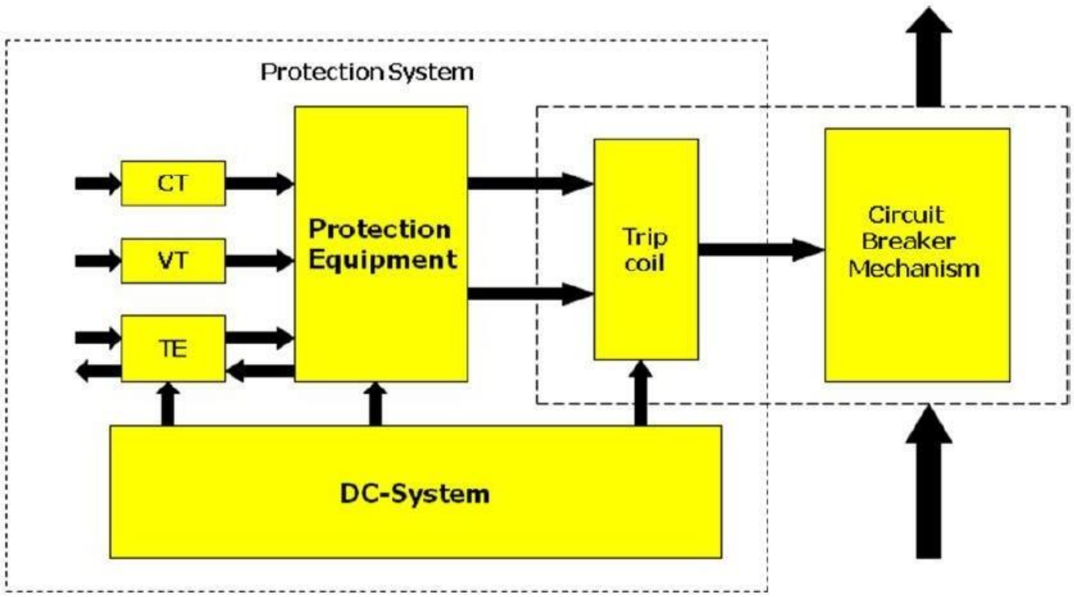
Consequences

• Damage to the equipment due to abnormally large and unbalanced currents and low voltages produced by the short circuits

• Explosions may occur in the equipments which have insulating oil, particularly during short circuits. This may result in fire and hazardous conditions to personnel and equipments

• Individual generators with reduced voltage in a power station or a group of generators operating at low voltage may lead to loss of synchronism, subsequently resulting in islanding.

• Risk of synchronous motors in large industrial premises falling out of step and tripping out.
The general layout of a protection system may be viewed as given in the following figure



1.3 Zones and types of Protection system

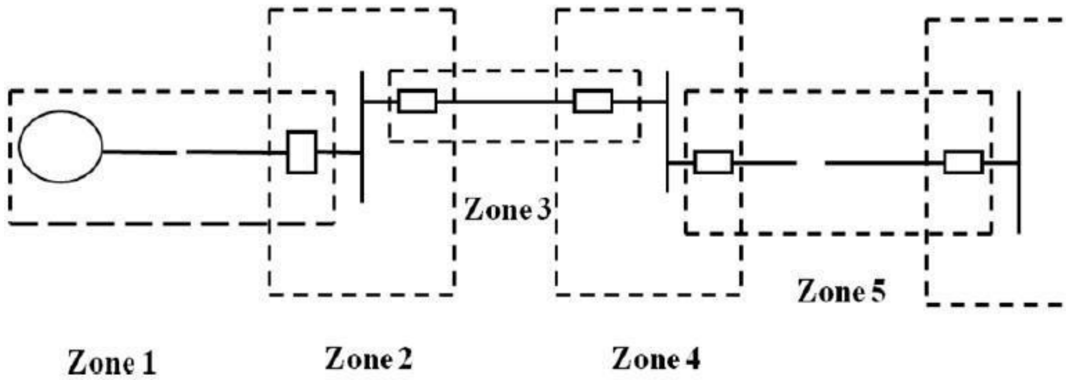
Zones of Protection system

• An electric power system is divided into several zones of protection. Each zone of protection, contains one or more components of a power system in addition to two circuit breakers.

• When a fault occurs within the boundary of a particular zone, then the protection system responsible for the protection of the zone acts to isolate (by tripping the Circuit Breakers) every equipment within that zone from the rest of the system.

• The circuit Breakers are inserted between the component of the zone and the rest of the power system. Thus, the location of the circuit breaker helps to define the boundaries of the zones of protection.

- Different neighbouring zones of protection are made to overlap each other, which ensure that no part of the power system remains without protection. However, occurrence of the fault with in the overlapped region will initiate a tripping sequence of different circuit breakers so that the minimum necessary to disconnect the faulty element



Types of Protection (Primary and Back-up Protection)

Primary Protection

The primary protection scheme ensures fast and selective clearing of any fault within the boundaries of the circuit element, that the zone is required to protect. Primary Protection as a rule is provided for each section of an electrical installation.

However, the primary protection may fail. The primary cause of failure of the Primary Protection system are enumerated below.

1. Current or voltage supply to the relay.
2. D.C. tripping voltage supply
3. Protective relays
4. Tripping circuit
5. Circuit Breaker

Back-up Protection

Back-up protection is the name given to a protection which backs the primary protection whenever the later fails in operation. The back-up protection by definition is slower than the primary protection system. The design of the back-up protection needs to be coordinated with the design of the primary protection and essentially it is the second line of defence after the primary protection system.

1.4 Protection System Requirements and some basic terminologies used

• The fundamental requirements for a protection system are as follows:

Reliability:

It is the ability of the protection system to operate correctly. The reliability feature has two basic elements, which are *dependability* and *security*. The dependability feature demands the certainty of a correct operation of the designed system, on occurrence of any fault. Similarly, the security feature can be defined as the ability of the designed system to avoid incorrect operation during faults. A comprehensive statistical

method based reliability study is required before the protection system may be commissioned. The factors which affect this feature of any protection system depends on some of the following few factors.

- Quality of Component used
- Maintenance schedule
- The supply and availability of spare parts and stocks
- The design principle
- Electrical and mechanical stress to which the protected part of the system is subjected to.

Speed:

Minimum operating time to clear a fault in order to avoid damage to equipment. The speed of the protection system consists primarily of two time intervals of interest.

The Relay Time :

This is the time between the instant of occurrence of the fault to the instant at which the relay contacts open.

The Breaker Time:

This is the time between the instant of closing of relay contacts to the instant of final arc extinction inside the medium and removal of the fault.

Selectivity:

This feature aims at maintaining the continuity of supply system by disconnecting the minimum section of the network necessary to isolate the fault. The property of selective tripping is also known as "discrimination". This is the reason for which the entire system is divided into several protective zones so that minimum protion of network is isolated with accuracy. Two examples of utilization of this feature in a relaying scheme are as follows

a) Time graded systems

b) Unit systems

Sensitivity:

The sensitivity of a relay refers to the smallest value of the actuating quantity at which the relay operates detecting any abnormal condition. In case of an over current relay, mathematically this can be defined as the ratio between the short circuit fault current (I_s) and the relay operating current (I_o). The value of I_o , should not be too small or large so that the relay is either too sensitive or slow in responding.

Stability:

It is the quality of any protection system to remain stable within a set of defined operating narios and procedures. For example the biased differential scheme of differential protection is more stable towards switching transients compared to the more simple and basic Merz Price scheme in differential protection

Adequacy:

It is economically unviable to have a 100% protection of the entire system in concern. Therefore, the cost of the designed protection system varies with the criticality and importance of the protected zone. The protection system for more critical portions

is generally costly, as all the features of a good protection system is maximized here. But a small motor can be protected by a simple thermally operated relay, which is simple and cheap. Therefore, the cost of the protection system should be adequate in its cost. *1.4.7 Some basic terminologies used in protection system* Some basic terminologies commonly used in the protection system are enlisted below. i) Measuring Relay ii) Fault Clearing Time iii) Auxilliary relay iv) Relay Time v) Pick up value vi) Reset Value vii) Drop out viii) Reach (under and over reaches) ix) Relay Burden x) Unit/ Non unit protection xi) All or Nothing relay

1.5 Protection against over voltages due to lightning and switching

Overvoltage Protection

Under Electrical Protection

There are always a chance of suffering an electrical power system from abnormal over voltages. These abnormal over voltages may be caused due to various reason such as, sudden interruption of heavy load, lightening impulses, switching impulses etc. These over voltage stresses may damage insulation of various equipments and insulators of the power system. Although, all the over voltage stresses are not strong enough to damage insulation of system, but still these over voltages also to be avoided to ensure the smooth operation of electrical power system.

Voltage Surge

The over voltage stresses applied upon the power system, are generally transient in nature. Transient voltage or voltage surge is defined as sudden sizing of voltage to a high peak in very short duration. The voltage surges are transient in nature, that means they exist for very short duration. The main cause of these voltage surges in power system are due to lightning impulses and switching impulses of the system. But over voltage in the power system may also be caused by, insulation failure, arcing ground and resonance etc.

The voltage surges appear in the electrical power system due to switching surge, insulation failure, arcing ground and resonance are not very large in magnitude. These over voltages hardly cross the twice of the normal voltage level. Generally, proper insulation to the different equipment of power system is sufficient to prevent any damage due to these over voltages. But over voltages occur in the power system due to lightning is very high. If over voltage protection is not provided to the power system, there may be high chance of severe damage. Hence all over voltage protection devices used in power system mainly due to lightning surges. Let us discuss different causes of over voltages one by one.

Switching Impulse or Switching Surge

When a no load transmission line is suddenly switched on, the voltage on the line becomes twice of normal system voltage. This voltage is transient in nature. When a loaded line is suddenly switched off or interrupted, voltage across the line also becomes high enough current chopping in the system mainly during opening operation of air blast circuit breaker, causes over voltage in the system. During insulation failure, a live conductor is suddenly earthed. This may also caused sudden over voltage in the system. If emf wave produced by alternator is distorted, the trouble of resonance may occur due to 5^{th} or higher harmonics. Actually for frequencies of 5^{th} or higher harmonics, a critical situation in the system so appears, that inductive reactance of the system becomes just equal to capacitive reactance of the system. As these both reactance cancel each other the system becomes purely resistive. This phenomenon is called resonance and at resonance the system voltage may be increased enough.

But all these above mentioned reasons create over voltages in the system which are not very high in magnitude.

But over voltage surges appear in the system due to lightning impulses are very high in amplitude and highly destructive. The affect of lightning impulse hence must be avoided for over voltage protection of power system.

Methods of Protection Against Lightning

These are mainly three main methods generally used for protection against lightning. They are

1. **Earthing screen**.
2. **Overhead earth wire**.

3. **Lighning arrester or surge dividers**.

Earthing Screen

Earthing screen is generally used over electrical sub-station. In this arrangement a net of GI wire is mounted over the sub-station. The GI wires, used for earthing screen are properly grounded through different sub-station structures. This network of grounded GI wire over electrical sub-station, provides very low resistance path to the ground for lightning strokes.

This method of high voltage protection is very simple and economic but the main drawback is, it can not protect the system from travelling wave which may reach to the sub-station via different feeders.

Overhead Earth Wire

This method of over voltage protection is similar as earthing screen. The only difference is, an earthing screen is placed over an electrical sub-station, whereas, overhead earthwire is placed over electrical transmission network. One or two stranded GI wires of suitable cross-section are placed over the transmission conductors. These GI wires are properly grounded at each transmission tower. These overhead ground wires or earthwire divert all the lightning strokes to the ground instead of allowing them to strike directly on the transmission conductors.

Lightning Arrester

The previously discussed two methods, i.e. earthing screen and over-head earth wire are very suitable for protecting an electrical power system from directed lightning strokes but system from directed lightning strokes but these methods can not provide any protection against high voltage travelling wave which may propagate through the line to the equipment of the sub-station.

The lightning arrester is a devices which provides very low impedance path to the ground for high voltage travelling waves.

The concept of a lightning arrester is very simple. This device behaves like a nonlinear electrical resistance. The resistance decreases as voltage increases and vice-versa, after a certain level of voltage.

The functions of a lightning arrester or surge dividers can be listed as below.

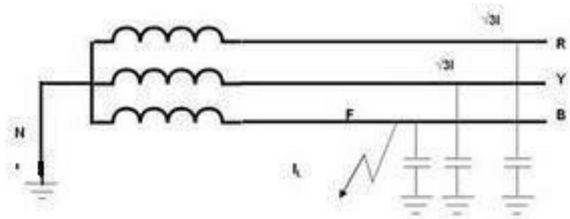
1. Under normal voltage level, these devices withstand easily the system voltage as electrical insulator and provide no conducting path to the system current.
2. On occurrence of voltage surge in the system, these devices provide very low impedance path for the excess charge of the surge to the ground.
3. After conducting the charges of surge, to the ground, the voltage becomes to its normal level. Then lightning arrester regains its insulation properly and prevents regains its insulation property and prevents further conduction of current, to the ground.

There are different types of lightning arresters used in power system, such as rod gap arrester, horn gap arrester, multi-gap arrester, expulsion type LA, value type LA.
In addition to these the most commonly used lightning arrester for over voltage protection now-a-days gapless ZnO lightning arrester is also used.

1.6 Arcing Grounds

Arcing Grounds is a phenomenon which is observed in ungrounded three phase systems. In ungrounded three phase systems operating in a healthy balanced conditions, capacitances are formed between the conductors and ground. The voltage across these capacitances is the phase voltage.

Now, in the event of a ground fault, the voltage across the faulty conductor becomes zero while the voltages across the healthy conductors increase by a factor of 1.732.



The arc caused between the faulty conductor and the ground gets extinguished and restarts many times, this repeated initiation and extinction of the arc across the fault produces severe voltage oscillations of the order of nearly three to four times the nominal voltage.

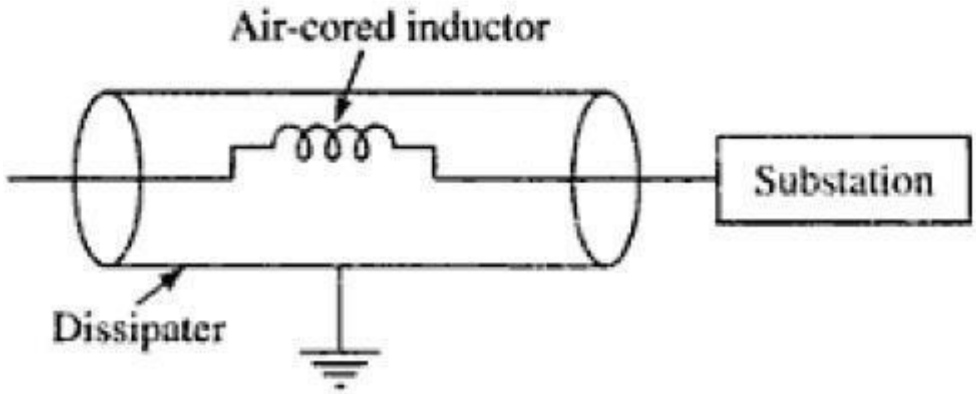
This repeated arcing across the fault due to the capacitances between the conductors and the ground is known as arcing grounds. Arcing grounds can be eliminated by the use of Peterson Coils (see Article) and Arc Suppression Coils

1.7 surge absorber

Surge absorbers are protective devices used to absorb the complete surge i,e. due to lightening surge or any transient surge in the system unlike the lightening arrestor in which a non-linear resistor is provided which provides a low resistance path to the dangerously high voltages on the system to the earth.

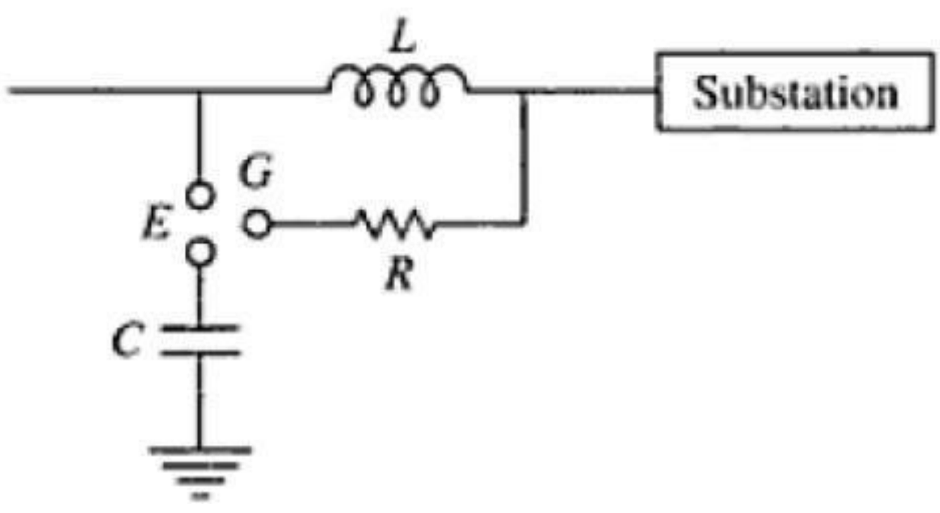
Ferranti surge absorber Surge absorber is of following types:

Ferranti surge absorber: Ferranti surge absorber consists of an air core inductor which is connected in series with the line and surrounded by an earth metallic sheet. The earth metallic sheet is known as dissipater, The dissipater is insulated from the inductor by the air as shown in Figure. This surge absorber acts like an air-cored transformer whose primary is the low inductance inductor and the dissipater as the single-turn short circuit secondary. Whenever a travelling wave is incident on the surge absorber, energy is transformed by mutual inductance between the coil and dissipatcr. Because of the series inductance the steepness of the wave is also reduced.



ERA surge absorber:

An improved form of the surge absorber is the Electrical Research Association (ERA)-type surge Filter as shown in Figure incorporated a gap G and expulsion gap E. When a wave reaches the inductor L, a high voltage is induced across it causing the gap G to break down putting the resistor R and expulsion gap E into circuit. An incoming wave is thus flattened by the inductor and the resistor and its amplitude is reduced by the expulsion gap.



1.8 surge diverter

A **surge arrester** is a device to protect electrical equipment from over-voltage transients caused by external (lightning) or internal (switching) events. Also called a **surge protection device** (SPD) or**transient voltage surge suppressor** (TVSS), this class of device is used to protect equipment in power transmission and distribution systems. (For consumer equipment protection, different products called surge protectors are used.)

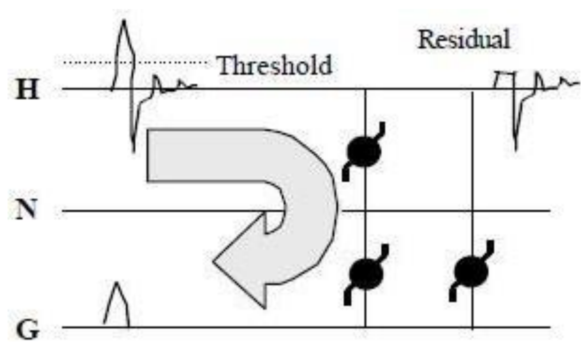
To protect a unit of equipment from transients occurring on an attached conductor, a surge arrester is connected to the conductor just before it enters the equipment. The surge arrester is also connected toground and functions by routing energy from an over-voltage transient to ground if one occurs, while isolating the conductor from ground at normal operating voltages. This is usually achieved through use of a varistor, which has substantially different resistances at different voltages.

Surge arresters are not generally designed to protect against a direct lightning strike to a conductor, but rather against electrical transients resulting from lightning strikes occurring in the vicinity of the conductor. Lightning which strikes the earth results in ground currents which can pass over buried conductors and induce a transient that propagates outward towards the ends of the conductor. The same kind of induction happens in overhead and above ground conductors which experience the passing energy of an atmospheric EMP caused by the lightening flash. Surge arresters only protect against induced transients characteristic of a lightning discharge's rapid rise-time and will not protect against electrification caused by a direct strike to the conductor. Transients similar to lightning-induced, such as from a high voltage system's fault switching, may also be safely diverted to ground; however, continuous overcurrents are not protected against by these devices. The energy in a handled transient is substantially less than that of a lightning discharge; however it is still of sufficient quantity to cause equipment damage and often requires protection.

Without very thick insulation, which is generally cost prohibitive, most conductors running more than a minimal distance, say greater than about 50 feet, will experience lightning-induced transients at some time during use. Because the transient is usually initiated at some point between the two ends of the conductor, most applications install a surge arrester just before the conductor lands in each piece of equipment to be protected. Each conductor must be protected, as each will have its own transient induced, and each SPD must provide a pathway to earth to safely divert the transient away from the protected component. The one notable exception where they are not installed at both ends is in high voltage distribution systems. In general, the induced voltage is not sufficient to do damage at the electric generation end of the lines; however, installation at the service entrance to a building is key to protecting downstream products that are not as robust.

Surge Diverters operation

The event we commonly call a surge is more accurately defined as a high voltage transient or impulse. Surge diverters are designed to divert the impulse away from the sensitive electronic system. That’s why the term diverter is more appropriate – it better describes the function of this device. Surge diverter products commonly use one or more of several electronic components. These include metal oxide varistors (MOVs), silicon avalanche diodes (SADs), and gas tubes. There are differences in how each functions but the intent is the same divert a part of the harmful impulse energy away from the computer or system being protected.



All surge diverters have a voltage threshold, called a “clamping voltage”, at which they began to conduct. Above that threshold, impulses are shunted across the diverter to another pathway. When the impulse voltage once again falls below the threshold, the diverter stops conducting. Surge diverters also have a “clamping response” time or the time required for the device to respond to an impulse. The amount of energy each is capable of handling without being destroyed is also a consideration. Due to these factors, each type of component used in surge diverters has unique advantages and disadvantages. MOVs have a high clamping voltage (300 to 500 volts) and a slow response time.

This means that in best case narios, voltage impulses of less than 500 volts usually enter the computer system unimpeded. In addition, higher voltage events with very fast rise times may pass by the MOV before it is able to respond. And while MOVs can handle a significant amount of energy, they are physically degraded each time they clamp. This characteristic alters their future performance and ultimately leads to physical failure.

These disadvantages have led to the use of the silicon avalanche diode (SAD) either in conjunction with the MOV or in standalone applications. Compared to MOVs, SADs have a faster response time and are not subject to the physical degradation that characterizes MOVs design. The overall energy handling ability of the SAD, however, is not as high, and an impulse that merely degrades and MOV may cause outright destruction of the SAD. To overcome this disadvantage, many surge diverter manufacturers whose designs use standalone SADs will parallel multiple SADs to increase the overall energy handling capability of the protector.

Industry authorities often vigorously debate the effectiveness of this design method. Gas tubes are comparatively slow and have a high clamp voltage. However, they handle almost unlimited amounts of energy. Some surge diverter designs have employed gas tubes as the final line of “brute force” protection to spare the lives of the other surge diverter components in the presence of a catastrophic powerline disturbance. In fact, many surge diverter designs incorporate paralleled MOVs, SADs, and/or gas tubes in an effort to improve performance by combining the relative strengths of each particular component

1.9 neutral earthing

Types of Neutral Earthing in Power Distribution: Introduction:

In the early power systems were mainly Neutral ungrounded due to the fact that the first ground fault did not require the tripping of the system. An unscheduled shutdown on the first ground fault was particularly undesirable for continuous process industries. These power systems required ground detection systems, but locating the fault often proved difficult. Although achieving the initial goal, the ungrounded system provided no control of transient over-voltages. A capacitive coupling exists between the system conductors and ground in a typical distribution system. As a result, this series resonant L-C circuit can create over-voltages well in excess of line-to-line voltage when subjected to repetitive re-strikes of one phase to ground. This in turn, reduces insulation life resulting in possible equipment failure. Neutral grounding systems are similar to fuses in that they do nothing until something in the system goes wrong. Then, like fuses, they protect personnel and equipment from damage. Damage comes from two factors, how long the fault lasts and how large the fault current is. Ground relays trip breakers and limit how long a fault lasts and Neutral grounding resistors limit how large the fault current is.

Importance of Neutral Grounding:

There are many neutral grounding options available for both Low and Medium voltage power systems. The neutral points of transformers, generators and rotating machinery to the earth ground network provides a reference point of zero volts. This protective measure offers many advantages over an ungrounded system, like,

- Reduced magnitude of transient over voltages
- Simplified ground fault location
- Improved system and equipment fault protection

- Reduced maintenance time and expense
- Greater safety for personnel
- Improved lightning protection
- Reduction in frequency of faults.

Method of Neutral Farthing:

There are five methods for Neutral earthing.

- Unearthed Neutral System
- Solid Neutral Earthed System
- Resistance Neutral Earthing System.

1) Low Resistance Earthing. 2) High Resistance Earthing.

- Resonant Neutral Earthing System.
- Earthing Transformer Earthing.

(1) Ungrounded Neutral Systems:

- In ungrounded system there is no internal connection between the conductors and earth.

However, as system, a capacitive coupling exists between the system conductors and the adjacent grounded surfaces. Consequently, the ―ungrounded system‖ is, in reality, a―capacitive grounded system‖ by virtue of the distributed capacitance.

- Under normal operating conditions, this distributed capacitance causes no problems. In fact, it is beneficial because it establishes, in effect, a neutral point for the system; As a result, the phase conductors are stressed at only line-to-neutral voltage above ground.

But problems can rise in ground fault conditions. A ground fault on one line results in full line-to-line voltage appearing throughout the system. Thus, a voltage 1.73 times the normal voltage is present on all insulation in the system. This situation can often cause failures in older motors and transformers, due to insulation breakdown.

Advantage:

1. After the first ground fault, assuming it remains as a single fault, the circuit may continue in operation, permitting continued production until a convenient shut down for maintenance can be scheduled.

Disadvantages:

1. The interaction between the faulted system and its distributed capacitance may cause transient overvoltages (several times normal) to appear from line to ground during normal switching of a circuit having a line-to ground fault (short). These over voltages may cause insulation failures at points other than the original fault.
2. A second fault on another phase may occur before the first fault can be cleared. This can result in very high line-to-line fault currents, equipment damage and disruption of both circuits.
3. The cost of equipment damage.
4. Complicate for locating fault(s), involving a tedious process of trial and error: first isolating the correct feeder, then the branch, and finally, the equipment at fault. The result is unnecessarily lengthy and expensive down downtime.

(2)Solidly Neutral Grounded Systems:

• Solidly grounded systems are usually used in low voltage applications at 600 volts or less.

• In solidly grounded system, the neutral point is connected to earth.

• Solidly Neutral Grounding slightly reduces the problem of transient over voltages found on the ungrounded system and provided path for the ground fault current is in the range of 25 to 100% of the system three phase fault current. However, if the reactance of the generator or transformer is too great, the problem of transient over voltages will not be solved.

While solidly grounded systems are an improvement over ungrounded systems, and speed up the location of faults, they lack the current limiting ability of resistance grounding and the extra protection this provides. To maintain systems health and safe, Transformer neutral is grounded and grounding conductor must be extend from the source to the furthest point of the system within the same raceway or conduit. Its purpose is to maintain very low impedance to ground faults so that a relatively high fault current will flow thus insuring that circuit breakers or fuses will clear the fault quickly and therefore minimize damage. It also greatly reduces the shock hazard to personnel

• If the system is not solidly grounded, the neutral point of the system would ―float‖ with respect to ground as a function of load subjecting the line-to-neutral loads to voltage unbalances and instability.

• The single-phase earth fault current in a solidly earthed system may exceed the three phase fault current. The magnitude of the current depends on the fault location and the fault resistance. One way to reduce the earth fault current is to leave some of the transformer neutrals unearthed.

Advantage:

• The main advantage of solidly earthed systems is low over voltages, which makes the earthing design common at high voltage levels (HV).

Disadvantage:

• This system involves all the drawbacks and hazards of high earth fault current: maximum damage and disturbances.

• There is no service continuity on the faulty feeder.

• The danger for personnel is high during the fault since the touch voltages created are high.

Applications:

• Distributed neutral conductor.

• 3-phase+neutraldistribution.

(3)Resistance earthed systems:

• Resistance grounding has been used in three-phase industrial applications for many years and it resolves many of the problems associated with solidly grounded and ungrounded systems.

• Resistance Grounding Systems limits the phase-to-ground fault currents. The reasons for limiting the Phase to ground Fault current by resistance grounding are:

• To reduce burning and melting effects in faulted electrical equipment like switchgear, transformers, cables, and rotating machines.

• To reduce mechanical stresses in circuits/Equipments carrying fault currents.

• To reduce electrical-shock hazards to personnel caused by stray ground fault.

• To reduce the arc blast or flash hazard.

• To reduce the momentary line-voltage dip.

• To secure control of the transient over-voltages while at the same time.

• To improve the detection of the earth fault in a power system.

• Grounding Resistors are generally connected between ground and neutral of transformers, generators and grounding transformers to limit maximum fault current as per Ohms Law to a value which will not damage the equipment in the power system and allow sufficient flow of fault current to detect and operate Earth protective relays to clear the fault. Although it is possible to limit fault currents with high resistance Neutral grounding Resistors, earth short circuit currents can be extremely reduced. As a result of this fact, protection devices may not sense the fault.

• Therefore, it is the most common application to limit single phase fault currents with low resistance Neutral Grounding Resistors to approximately rated current of transformer and / or generator.

• In addition, limiting fault currents to predetermined maximum values permits the designer to selectively coordinate the operation of protective devices, which minimizes system disruption and allows for quick location of the fault.

There are two categories of resistance grounding:

• Low resistance Grounding.

• High resistance Grounding.

Ground fault current flowing through either type of resistor when a single phase faults to ground will increase the phase-to-ground voltage of the remaining two phases. As a result, conductor insulation and surge arrestor ratings must be based on line-to-line voltage. This temporary increase in phase-to- ground voltage should also be considered when selecting two and three pole breakers installed on resistance grounded low voltage systems. Neither of these grounding systems (low or high resistance) reduces arc-flash hazards associated with phase-to-phase faults, but both systems significantly reduce or essentially eliminate the arc-flash hazards associated with phase-to-ground faults. Both types of grounding systems limit mechanical stresses and reduce thermal damage to electrical equipment, circuits, and apparatus carrying faulted current. The difference between Low Resistance Grounding and High Resistance Grounding is a matter of perception and, therefore, is not well defined. Generally speaking high-resistance grounding refers to a system in which the NGR let-through current is less than 50 to 100 A. Low resistance grounding indicates that NGR current would he above 100 A. A better distinction between the two levels might be alarm only and tripping. An alarm-only system continues to operate with a single ground fault on the system for an unspecified amount of time. In a tripping system a ground fault is automatically removed by protective relaying and circuit interrupting devices. Alarm-only systems usually limit NGR current to 10 A or less

Rating of The Neutral grounding resistor:

• Voltage: Line-to-neutral voltage of the system to which it is connected.

• Initial Current: The initial current which will flow through the resistor with rated voltage applied.

• Time: The ―on time‖ for which the resistor can operate without exceeding the allowable temperature rise.

A) Low Resistance Grounded:

• Low Resistance Grounding is used for large electrical systems where there is a high investment in capital equipment or prolonged loss of service of equipment has a significant economic impact and it is not commonly used in low voltage systems because the limited ground fault current is too low to reliably operate breaker trip units or fuses. This makes system selectivity hard to achieve. Moreover, low resistance grounded systems are not suitable for 4-wire loads and hence have not been used in commercial market applications

A resistor is connected from the system neutral point to ground and generally sized to permit only 200A to 1200 amps of ground fault current to flow. Enough current must flow such that protective devices can detect the faulted circuit and trip it off-line but not so much current as to create major damage at the fault point.

Advantage:

• Limits phase-to-ground currents to 200-400A.

Since the grounding impedance is in the form of resistance, any transient over voltages are quickly damped out and the whole transient overvoltage phenomena is no longer applicable. Although theoretically possible to be applied in low voltage systems (e.g. 480V),significant amount of the system voltage dropped across the grounding resistor, there is not enough voltage across the arc forcing current to flow, for the fault to be reliably detected. For this reason, low resistance grounding is not used for low voltage systems (under 1000 volts line to-line).

• Reduces arcing current and, to some extent, limits arc-flash hazards associated with phase-to-ground arcing current conditions only.
• May limit the mechanical damage and thermal damage to shorted transformer and rotating machinery windings.

Disadvantages:
• Does not prevent operation of over current devices.
• Does not require a ground fault detection system.
• May be utilized on medium or high voltage systems.
• Conductor insulation and surge arrestors must be rated based on the line to-line voltage. Phase-to-neutral loads must be served through an isolation transformer.
• Used: Up to 400 amps for 10 sec are commonly found on medium voltage systems.

B)High Resistance Grounded:
• High resistance grounding is almost identical to low resistance grounding except that the ground fault current magnitude is typically limited to 10 amperes or less. High resistance grounding accomplishes two things.

The first is that the groundfault current magnitude is sufficiently low enough such that no appreciable damage is done at the fault point. This means that the faulted circuit need not be tripped off-line when the fault first occurs. Means that once a fault does occur, we do not know where the fault is located. In this respect, it performs just like an ungrounded system. The second point is it can control the transient overvoltage phenomenon present on ungrounded systems if engineered properly.
• Under earth fault conditions, the resistance must dominate over the system charging

capacitance but not to the point of permitting excessive current to flow and thereby excluding continuous operation

• High Resistance Grounding (HRG) systems limit the fault current when one phase of the system shorts or arcs to ground, but at lower levels than low resistance systems.
• In the event that a ground fault condition exists, the HRG typically limits the current to 5-10A.
• HRG‘s are continuous current rated, so the description of a particular unit does not include a time rating. Unlike NGR‘s, ground fault current flowing through a HRG is usually not of significant magnitude to result in the operation of an over current device. Since the ground fault current is not interrupted, a ground fault detection system must be installed.
• These systems include a bypass contactor tapped across a portion of the resistor that pulses (periodically opens and closes). When the contactor is open, ground fault current flows through the entire resistor. When the contactor is closed a portion of the resistor is bypassed resulting in slightly lower resistance and slightly higher ground fault current.

• To avoid transient over-voltages, an HRG resistor must be sized so that the amount of ground fault current the unit will allow to flow exceeds the electrical system‘s charging current. As a rule of thumb, charging current is estimated at 1A per 2000KVA of system capacity for low voltage systems and 2A per 2000KVA of system capacity at 4.16kV.

• These estimated charging currents increase if surge suppressors are present. Each set of suppressors installed on a low voltage system results in approximately 0.5 A of additional charging current and each set of suppressors installed on a 4.16kV system adds 1.5 A of additional charging current.

• A system with 3000KVA of capacity at 480 volts would have an estimated charging current of 1.5A.Add one set of surge suppressors and the total charging current increases by 0.5A to 2.0A. A standard 5A resistor could be used on this system. Most resistor manufacturers publish detailed estimation tables that can be used to more closely estimate an electrical system‘s charging current.

Advantages:

1. Enables high impedance fault detection in systems with weak capacitive connection to earth

2. Some phase-to-earth faults are self-cleared.

3. The neutral point resistance can be chosen to limit the possible over voltage transients to 2.5 times the fundamental frequency maximum voltage.

4. Limits phase-to-ground currents to 5-10A.

5. Reduces arcing current and essentially eliminates arc-flash hazards associated with phase-to-ground arcing current conditions only.

6. Will eliminate the mechanical damage and may limit thermal damage to shorted transformer and rotating machinery windings.

7. Prevents operation of over current devices until the fault can be located (when only one phase faults to ground). **8**. May be utilized on low voltage systems or medium voltage systems up to 5kV. IEEE Standard 141-1993 states that ―high resistance grounding should be restricted to 5kV class or lower systems with charging currents of about 5.5A or less and should not be attempted on 15kV systems, unless proper grounding relaying is employed‖. 9. Conductor insulation and surge arrestors must be rated based on the line to-line voltage. Phase-to-neutral loads must be served through an isolation transformer.

Disadvantages:

1. Generates extensive earth fault currents when combined with strong or moderate capacitive connection to earth Cost involved.

2. Requires a ground fault detection system to notify the facility engineer that a ground fault condition has occurred.

(4)Resonant earthed system:

• Adding inductive reactance from the system neutral point to ground is an easy method of limiting the available ground fault from something near the maximum 3 phase short circuit capacity (thousands of amperes) to a relatively low value (200 to 800 amperes).

• To limit the reactive part of the earth fault current in a power system a neutral point reactor can be connected between the transformer neutral and the station earthing system.

• A system in which at least one of the neutrals is connected to earth through an

1. Inductive reactance.
2. Petersen coil / Arc Suppression Coil / Earth Fault Neutralizer.

• The current generated by the reactance during an earth fault approximately compensates the capacitive component of the single phase earth fault current, is called a resonant earthed system.

• The system is hardly ever exactly tuned, i.e. the reactive current does not exactly equal the capacitive earth fault current of the system.

• A system in which the inductive current is slightly larger than the capacitive earth fault current is over compensated. A system in which the induced earth fault current is slightly smaller than the capacitive earth fault current is under compensated

• However, experience indicated that this inductive reactance to ground resonates with the system shunt capacitance to ground under arcing ground fault conditions and creates very high transient over voltages on the system.

• To control the transient over voltages, the design must permit at least 60% of the 3 phase short circuit current to flow underground fault conditions.

Petersen Coils:

• A Petersen Coil is connected between the neutral point of the system and earth, and is rated so that the capacitive current in the earth fault is compensated by an inductive current passed by the Petersen Coil. A small residual current will remain, but this is so small that any arc between the faulted phase and earth will not be maintained and the fault will extinguish. Minor earth faults such as a broken pin insulator, could be held on the system without the supply being interrupted. Transient faults would not result in supply interruptions.

• Although the standard ‗Peterson coil' does not compensate the entire earth fault current in a network due to the presence of resistive losses in the lines and coil, it is now possible to apply ‗residual current compensation' by injecting an additional 180° out of phase current into the neutral via the Peterson coil. The fault current is thereby reduced to practically zero. Such systems are known as ‗Resonant earthing with residual compensation', and can be considered as a special case of reactive earthing.

• Resonant earthing can reduce EPR to a safe level. This is because the Petersen coil can often effectively act as a high impedance NER, which will substantially reduce any earth fault currents, and hence also any corresponding EPR hazards

Advantages:

• Small reactive earth fault current independent of the phase to earth capacitance of the system.

• Enables high impedance fault detection.

Disadvantages:

• Risk of extensive active earth fault losses.

• High costs associated.

(5)Earthing Transformers: For cases where there is no neutral point available for Neutral Earthing (e.g. for a delta winding), an earthing transformer may be used to provide a return path for single phase fault currents In such cases the impedance of the earthing transformer may be sufficient to act as effective earthing impedance. Additional impedance can be added in series if required. A special ‗zig-zag' transformer is sometimes used for earthing delta windings to provide a low zero-sequence impedance and high positive and negative sequence impedance to fault currents.

UNIT II

BASICS OF RELAYS

2.1 Electromagnetic Relay

Electromagnetic relays are those relays which are operated by electromagnetic action. Modern electrical protection relays are mainly micro processor based, but still electromagnetic relay holds its place. It will take much longer time to be replaced the all electromagnetic relays by micro processor based static relays. So before going through detail of protection relay system we should review the various types of electromagnetic relays. Electromagnetic Relay Working

Practically all the relaying device are based on either one or more of the following types of electromagnetic relays.

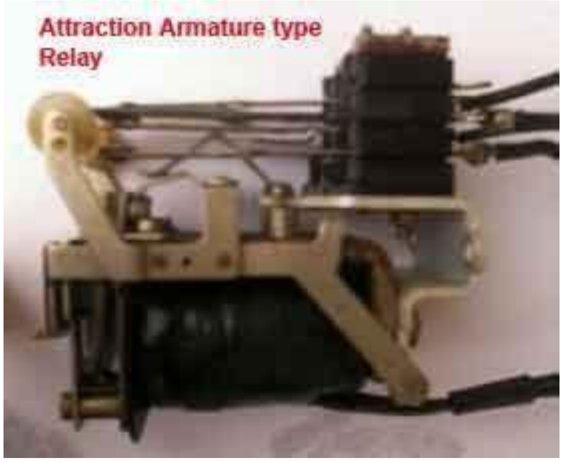
1. Magnitude measurement,
2. Comparison,
3. Ratio measurement.

Principle of electromagnetic relay working is on some basic principles. Depending upon working principle the these can be divided into following types of electromagnetic relays.

1. Attracted Armature type relay,
2. Induction Disc type relay,
3. Induction Cup type relay,
4. Balanced Beam type relay,
5. Moving coil type relay,
6. Polarized Moving Iron type relay.

Attraction Armature Type Relay

Attraction armature type relay is the most simple in construction as well as its working principle. These types of electromagnetic relays can be utilized as either magnitude relay or ratio relay. These relays are employed as auxiliary relay, control relay, over current, under current, over voltage, under voltage and impedance measuring relays.



Hinged armature and plunger type constructions are most commonly used for these types of electromagnetic relays. Among these two constructional design, hinged armature type is more commonly used.

We know that force exerted on an armature is directly proportional to the square of the magnetic flux in the air gap. If we ignore the effect of saturation, the equation for the force experienced by the armature can be expressed as,

$$F = (KI^2 - K')$$

Where F is the net force, K' is constant, I is rms current of armature coil, and K' is the restraining force.

The threshold condition for relay operation would therefore be reached when $KI^2 = K'$.
If we observe the above equation carefully, it would be realized that the relay operation is dependent on the constants K' and K for a particular value of the coil current.
From the above explanation and equation it can be summarized that, the operation of relay is influenced by

1. Ampere – turns developed by the relay operating coil,
2. The size of air gap between the relay core and the armature,
3. Restraining force on the armature.

Construction of Attracted Type Relay

This relay is essentially a simple electromagnetic coil, and a hinged plunger. Whenever the coil becomes energized the plunger being attracted towards core of the coil. Some NO-NC (Normally Open and Normally Closed) contacts are so arranged mechanically with this plunger, that, NO contacts become closed and NC contacts become open at the end of the plunger movement. Normally attraction armature type relay is dc operated relay. The contacts are so arranged, that, after relay is operated, the contacts cannot return their original positions even after the armature is de energized. After relay operation, this types of electromagnetic relays are reset manually.

Attraction armature relay by virtue of their construction and working principle, is instantaneous in operation.

Induction Disc Type Relay

Induction disc type relay mainly consists of one rotating disc.

Induction Disc type Relay Working

Every induction disc type relay works on the same well known Ferraries principle. This principle says, a torque is produced by two phase displaced fluxes, which is proportional to the product of their magnitude and phase displacement between them. Mathematically it can be expressed as-

$$T = K\phi_1\phi_2 \sin\theta$$

Induction Disc Type Relay

The induction disc type relay is based on the same principle as that of an ammeter or a volt meter, or a wattmeter or a watt hour mater. In induction relay the deflecting torque is produced by the eddy currents in an aluminium or copper disc by the flux of an ac electromagnet. Here, an aluminium (or copper) disc is placed between the poles of an AC magnet which produces an alternating flux φ lagging from I by a small angle. As this flux links with the disc, there must be an induced emf E_2 in the disc, lagging behind the flux φ by 90^o. As the disc is purely resistive, the induced current in the disc I_2 will be in phase with E_2. As the angle between φ and I_2 is 90°, the net torque produced in that case is zero. As,

$$T = \phi I_2 \cos 90^\circ = 0$$

In order to obtain torque in induction disc type relay, it is necessary to produce a rotating field.

Pole Shading Method of Producing Torque in Induction Disc Relay

In this method half of the pole is surrounded with copper ring as shown. Let φ_1 is the flux of unshaded portion of the pole. Actually total flux divided into two equal portions when the pole is divided into two parts by a slot.

$$Total\ flux,\ \phi = \phi_1 + \phi_2$$

As the one portion of the pole is shaded by copper ring. There will be induced current in the shade ring which will produce another flux φ_2' in the shaded pole. So, resultant flux of shaded pole will be vector sum of & phi;1 and φ_2. Say it is φ_2, and angle between φ_1 and φ_2 is θ. These two fluxes will produce a resultant torque,

$$T = K\phi_1\phi_2 \sin\theta$$

There are mainly three types of shape of rotating disc are available for induction disc type relay. They are spiral shaped, round and vase shaped, as shown. The spiral shape is done to compensate against varying restraining torque of the control spring which winds up as the disc rotates to close its contacts. For most designs, the disc may rotate by as much as 280°. Further, the moving contact on the disc shift is so positioned that it meets the stationary contacts on the relay frame when the largest radius section of the disc is under the electromagnet. This is done to ensure satisfactory contact pressure in induction disc type relay.

Where high speed operation is required, such as in differential protection, the angular travel of the disc is considerably limited and hence circular or even vane types may be used in induction disc type electromagnetic relay.

Some time it is required that operation of an induction disc type relay should be done after successful operation of another relay. Such as inter locked over current relays are generally used for generator and bus bar protection. In that case, the shading band is replaced by a shading coil. Two ends of that shading coil are brought out across a normally open contact of other control device or relay. Whenever the latter is operated the normally open contact is closed and makes the shading coil short circuited. Only after that the over current relay disc starts rotating.

One can also change the time / current characteristics of an induction disc type relay, by deploying variable resistance arrangement to the shading coil.

Induction disc relay fed off a negative sequence filter can also be used as Negative-sequence protection device for alternators.

Induction Cup Type Relay

Induction cup type relay can be considered as a different version of induction disc type relay. The working principle of both type of relays are more or less some. Induction cup type relay are used where, very high speed operation along with polarizing and/or differential winding is requested. Generally four pole and eight pole design are available. The number of poles depends upon the number of winding to be accommodated.

The inertia of cup type design is much lower than that of disc type design. Hence very high speed operation is possible in induction cup type relay. Further, the pole system is designed to give maximum torque per KVA input. In a four pole unit almost all the eddy currents induced in the cup by one pair of poles appear directly under the other pair of poles – so that torque / VA is about three times that of an induction disc with a c-shaped electromagnet.

Induction cup type relay is practically suited as directional or phase comparison units. This is because, besides their sensitivity, induction cup relay have steady non vibrating torque and their parasitic torque due to current or voltage alone are small.

Induction Cup Type-Directional or Power Relay

It in a four pole induction cup type relay, one pair of poles produces flux proportional to voltage and other pair of poles produces flux proportional to current. The vector diagram is given below,

The torque $T_1 = K\varphi_{vi}.\varphi_i.\sin(90° - \theta)$ assuming flux produced by the voltage coil will lag 90° behind its voltage. By design, the angle can be made to approach any value and a torque equation $T = K.E.I.\cos(\varphi - \theta)$ obtained, where θ is the E - I system angle.

Accordingly, induction-cup type relay can be designed to produced maximum torque When system angle θ = 0° or 30° or 45° or 60°. The former is known as power relays as they produce maximum torque when θ = 0° and latter are known as directional relays – they are used for directional discrimination in protective schemes under fault conditions, as they are designed to produce maximum torque at faulty conditions.

2.2 Over Current Relay Working Principle Types

In an over current relay or o/c relay the actuating quantity is only current. There is only one current operated element in the relay, no voltage coil etc. are required to construct this protective relay.

Working Principle of Over Current Relay

In an over current relay, there would be essentially a current coil. When normal current flows through this coil, the magnetic effect generated by the coil is not sufficient to move the moving element of the relay, as in this condition the restraining force is greater than deflecting force. But when the current through the coil increased, the magnetic effect increases, and after certain level of current, the deflecting force generated by the magnetic effect of the coil, crosses the restraining force, as a result, the moving element starts moving to change the contact position in the relay.

Although there are different **types of over current relays but basic working principle of over current relay** is more or less same for all.

Types of Over Current Relay

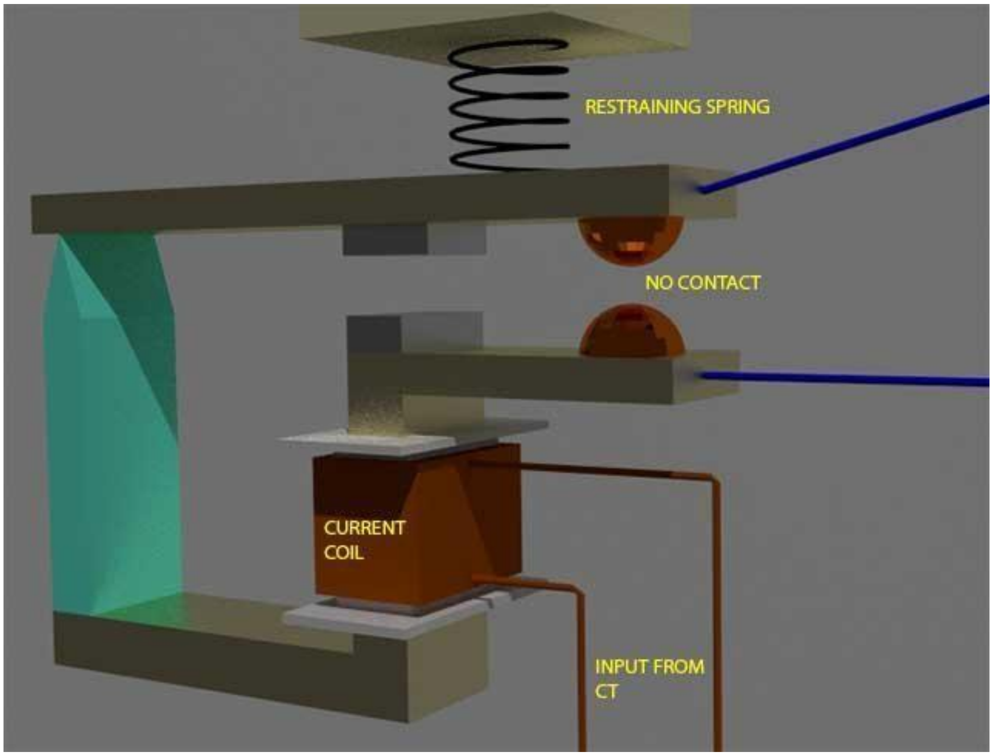
Depending upon time of operation, there are various **types of OC relays**, such as,

1. **Instantaneous over current relay**.
2. **Definite time over current relay**.
3. **Inverse time over current relay**.

Inverse time over current relay or simply inverse OC relay is again subdivided as inverse definite minimum time **(**IDMT**),** very inverse time**,** extremely inverse time over current relay or OC relay**.**

Instantaneous Over Current Relay

Construction and working principle of **instantaneous over current relay quite simple.**



Here generally a magnetic core is wound by current coil. A piece of iron is so fitted by hinge support and restraining spring in the relay, that when there is not sufficient current in the coil, the NO contacts remain open. When current in the coil crosses a present value, the attractive force becomes sufficient to pull the iron piece towards the magnetic core and consequently the No contacts are closed.

The preset value of current in the relay coil is referred as pick up setting current. This relay is referred as instantaneous over current relay, as ideally, the relay operates as soon as the current in the coil gets higher than pick up setting current. There is no intentional time delay applied. But there is always an inherent time delay which can not be avoided practically. In practice the operating time of an instantaneous relay is of the order of a few milliseconds. Fig.

2.3 Directional Over Current Relays

1. When fault current can flow in both the directions through the relay, at its location. Therefore, it is necessary to make the relay respond for a particular defined direction, so that proper discrimination is possible. This can be achieved by introduction of directional control elements.
2. These are basically power measuring devices in which the system voltage is used as a reference for establishing the relative phase of the fault current.

Basically, an AC directional relay can recognize certain difference in phase angle between two quantities, just as a D.C. directional relay recognize difference in polarity

The polarizing quantity of a directional relay

1. It is the reference against which the phase angle of the other quantity is compared. Consequently the phase angle of the polarizing quantity must remain fixed when other quantity suffers wide change in phase angle.
2. The voltage is chosen as the “polarizing” quantity in the current-voltage induction type directional relay.
3. Four pole induction cup construction is normally used.

2.4 Distance relay

Distance relay is used for the protection of transmission line & feeders In a distance relay, instead of comparing the local line current with the current at far end of line, the relay compares the local current with the local voltage in the corresponding phase or suitable components of them

Principle of operation of distance relay

1. The basic principle of measurement involves the comparison of fault current seen by the relay with the voltage at relaying point; by comparing these two quantities.

2. It is possible to determine whether the impedance of the line up to the point of fault is greater than or less than the predetermined reach point impedance

There are two types of torques

1. Restraining torque

$$T_r \alpha V_F^2$$

2. Operating torque

$$T_0 \alpha I_F^2$$

The relay trips when T_0 greater than T_r

$$KI_F^2 > V_F^2$$

$$\frac{V_F}{I_F} < \sqrt{K}$$

The constant K depends on the design of the electromagnets.

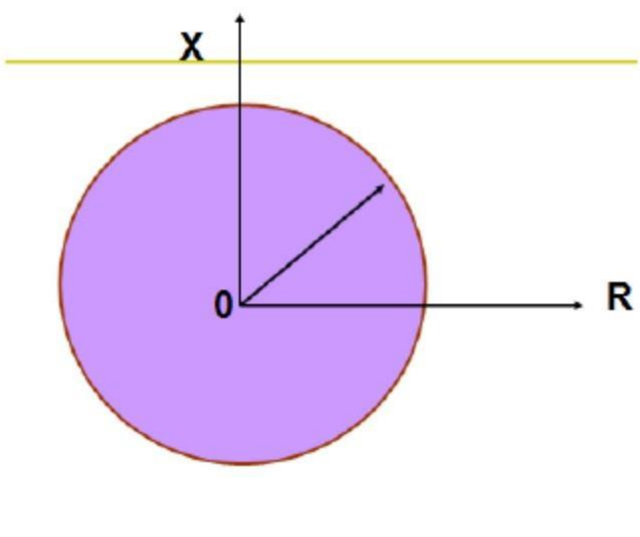
Types of distance relay Distance relays are classified depending on their operating characteristic in the R-X plane

- Impedance Relay
- Mho Relay
- Reactance Relay

2.5 IMPEDANCE RELAY:

The torque equation T, for such a relay the current actuates the operating torque and the voltage actuates the restraining torque, with the usual spring constant K4.

$$T = K_1 I^2 + K_2 V^2 + K_4$$



Considering K2 to be negative (as it produces the restraining torque) and neglecting the torque component due to spring, the equation represents a circle in the R-X plane.

DISADVANTAGE OF IMPEDANCE RELAY

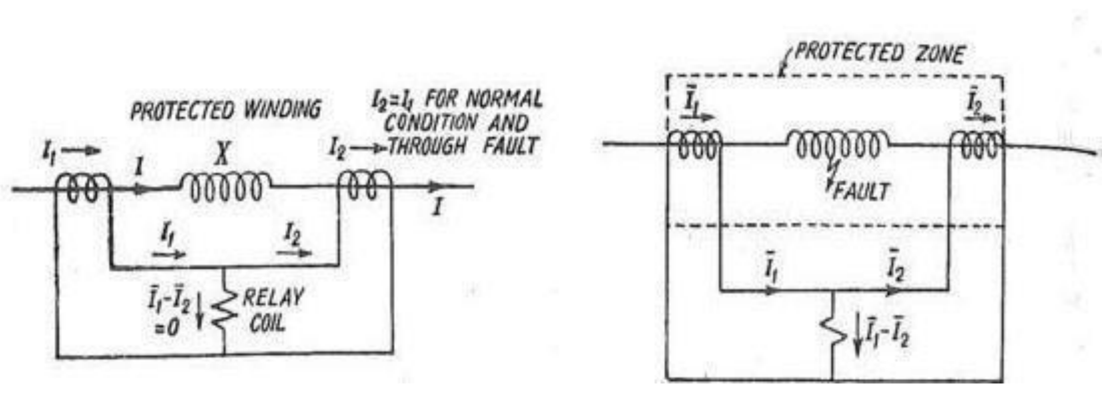
1. It is not directional.
2. It is affected by the Arc resistance
3. It is highly sensitive to oscillations on the power system, due to large area covered by its circular characteristic

2.6 Differential Relay

One of the most prevalent and successful method of protecting a circuit is to arrange relays to compare the currents entering and leaving it, which should be the same under normal conditions and during an external fault. Any difference current must be flowing in to a fault within the protected circuit

Principle of circulating current differential (MERZ-PRIZE) protection

The figure below illustrates the principle of differential protection of generator and transformer, X is the winding of the protected machine. Where there is no internal fault, the current entering in X is equal in phase and magnitude to current leaving X. The CT's have such a ratio that during the normal conditions or for external faults (Through Faults) the secondary current of CT's are equal. These current say I1 and I2 circulate in the pilot wire. The polarity connections are such the current I1 and I2 are in the same direction of pilot wire during normal condition or external faults. Relay operation coil is connected at the middle of pilot wires. Relay unit is of over current type



During normal condition and external fault the protection system is balanced and the CT's ratios are such that secondary currents are equal. These current circulate in pilot wires. The vector differential current I1- I2 which flow through the relay coil is zero. I1-I2 = 0 (normal condition or external faults) This balance is disturbed for internal faults. When fault occurs in the protected zone, the current entering the protected winding is no more equal to the leaving the winding because some current flows to the fault. The differential I1-I2 flows through the relay operating coil and the relay operates if the operating torque is more than the restraining torque. The current I1 and I2 circulate in the secondary circuit. Hence CT's does not get damaged. Polarities of CT's should be proper, otherwise the currents I1 and I2 would add up even for normal condition and mal operate the relay.

Differential Protection current balance

• When this system is applied to electrical equipment (Generator stator windings, Transformer, Bus bars etc.) it is called differential current protection.

• When it is applied to lines and cables it is called pilot differential protection because pilot wires or an equivalent link or channel is required to bring the current to the relay from the remote end of the line.

The CTs at both ends of the protected circuit connected so that for through load or through fault conditions current circulates between the interconnected CTs. The over-current relay is normally connected across equipotential points and therefore doesn‟t operate.

• Circulating current balance methods are widely used for apparatus protection where CTs are within the same substation area and interconnecting leads between CTs are short (e.g. generator stator windings, Transformer, Bus bars etc.)

• The circulating current balance method is also called longitudinal differential protection or Merz-Price differential protection system.

• The current in the differential relay would be proportional to the phasor difference between the currents that enter and leave the protected circuit. If the current through the relay exceeds the pick-up value, then the relay will operate.

Demerits of a Differential Relay(Merz Price Scheme)

- **Unmatched characteristics of C.T.s** :

Though the saturation is avoided, there exist difference in the C.T. characteristics due to ratio error at high values of short circuit currents. This causes an appreciable difference in the secondary currents which can operate the relay. So the relay operates for through external faults. This difficulty is overcome by using percentage differential relay. In this relay, the difference in current due to the ratio error exists and flows through relay coil. But at the same time the average current (I1 + I2/2) flows through the restraining coil which produces enough restraining torque. Hence relay becomes inoperative for the through faults.

- **Ratio change due to tap change**:

To alter the voltage and current ratios between high voltage and low voltage sides of a power transformer, a tap changing equipment is used. This is an important feature of a power transformer. This equipment effectively alters the turns ratio. This causes unbalance on both sides. To compensate for this effect, the tapping can be provided on C.T.s also which are to be varied similar to the main power transformer. But this method is not practicable. The percentage differential relays ensure relays ensure the stability with respect to the amount of unbalance occurring at the extremities of the tap change range.

- **Difference in lengths of pilot wires**:

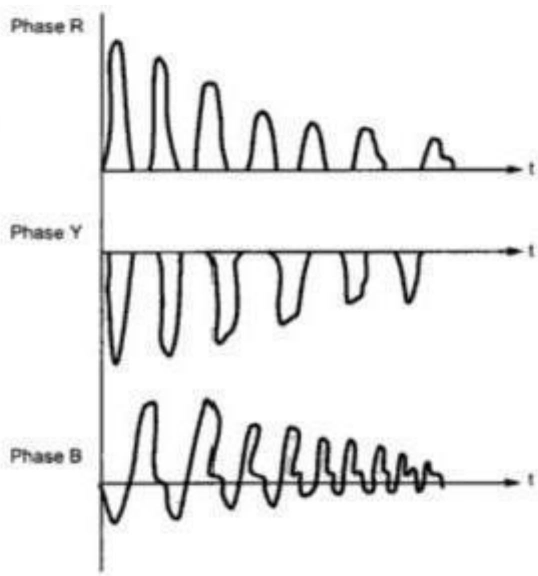
Due to the difference in lengths of the pilot wires on both sides, the unbalance condition may result. The difficulty is overcome by connecting the adjustable resistors in pilot wires on both sides. These are called balancing resistors. With the help of these resistors, equipotential points on the pilot wires can be adjusted. In percentage differential relays the taps are provided on the operating coil and restraining coil to achieve an accurate balance.

- **Magnetizing current inrush**:

When the transformer is energized, the condition initially is of zero induced E.m.f. A transient inflow of magnetizing current occurs in to the transformer. This current is called magnetizing inrush current. This current may be as great as 10 times the full load current of the transformer. This decays very slowly and is bound to operate differential protection of the transformer falsely, because of the temporary difference in magnitude of the primary and secondary currents.
The factors which affect the magnitude and direction of the magnetizing inrush current can be one of the following reasons.

a. Size of the transformer.
b. Size of the power system
c. Type of magnetic material used for the core.
d. The amount of residual flux existing before energizing the transformer.
e. The method by which transformer is energized.

If the transformer is energized when the voltage wave is passing through zero, the magnetizing current inrush is maximum. At this instant, the current and flux should be maximum in highly inductive circuit. And in a half wave flux reversal must take place to attain maximum value in the other half cycles. If the residual flux exists, the required flux may be in same or opposite direction. Due to this magnetizing current inrush is less or more. If it is more, it is responsible to saturate the core which further increases its component. This current decays rapidly for first few cycles and then decays slowly. The time constant L/R of the circuit is variable as inductance of circuit varies due to the change in permeability of the core. The losses in the circuit damp the inrush currents. Depending on the size of the transformer, the time constant of inrush current varies from 0.2 sec to 1 sec. The waveforms of magnetizing inrush current in three phases are shown in the figure below.



2.7 Static relays

Advantages of static relays

• Due to the amplification of energizing signals obtainable, the sources need only provide low power. Therefore the size of the associated current and voltage transformers could be reduced.
• Improved accuracy and selectivity.
• Fast operation of relays and hence fast clearance of faults.
• Flexibility of circuitry would allow new and improved characteristics.
• The relays would be unaffected by the number of operations.

Basic circuits employed

• Timers
• Phase comparators
• Amplitude Comparator
• Level detectors
• Integrators
• Polarity detectors

High reliability operational amplifiers are used for realizing the basic components of static relays.

UNIT III

OVERVIEW OF EQUIPMENT PROTECTION

PROTECTION OF FEEDERS

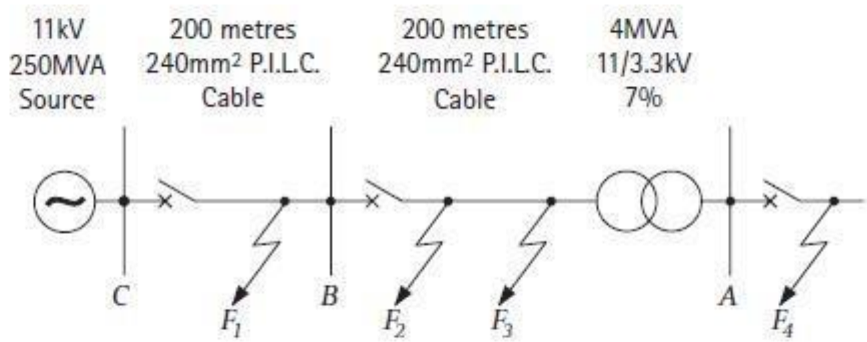
3.1 Over current and earth fault protection

It is customary to have two elements of over current and one element of earth fault protection system in the most elementary form of protection of three phase feeders. Different types of feeders employ the over current protection along with the directional relay so that proper discrimination of an internal fault is possible. Some examples are illustrated below.

Application of directional relays to parallel feeders

It may be seen from the below given parallel feeders that the relays placed at the load side of both the lines use directional element which respond to a direction away from the bus bars. Similarly, the relays placed at the source side do not require any directional element.

A similar concept of discrimination is also utilized in the below given ring main feeder and a feeder fed from both the sides. It can be observed that relays placed near the bus connecting the sources, don not have any directional feature, where as the rest of the buses, respond to a direction always away from the source. It is good practice to locate a fault any where among different sections of the feeders and check whether that particular section only is isolated without disrupting the power flow in other sections.

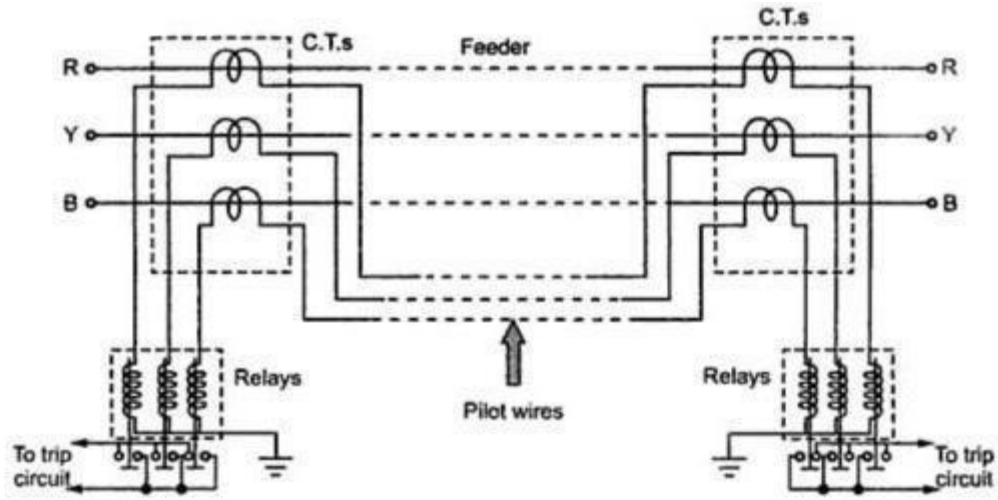


Pilot wire schemes for feeder protection

In differential protection scheme, the current entering at one end of the line and leaving from other end of the line is compared. The pilot wires are used to connect the relays. Under normal working condition, the two currents at both ends are equal and pilot wires do not carry any current, keeping relays inoperative. Under an internal fault condition, the two currents at both the ends are no longer same, this causes circulating current flow through pilot wires and makes the relay to trip. The various schemes used with this method of protection are, 1. Merz-Price Voltage Balance System 2. Translay Scheme

Merz-Price Voltage Balance System

The figure below shows Merz-Price voltage balance system used for the three phase feeders.



Under normal condition, current entering the line at one end is equal to current leaving from the other end. Therefore, equal and opposite voltages are induced in the secondaries of C.T.s. at the two ends resulting in no current flow, through the relay. Under fault condition, two currents at the two ends are different. Thus the secondary voltages of both the end C.T.s differ from each other. This circulates a circulating current through the pilot wires and the relays. Thus the relays trip the circuit breakers to isolate the faulty section.

The advantages of this method are as follows

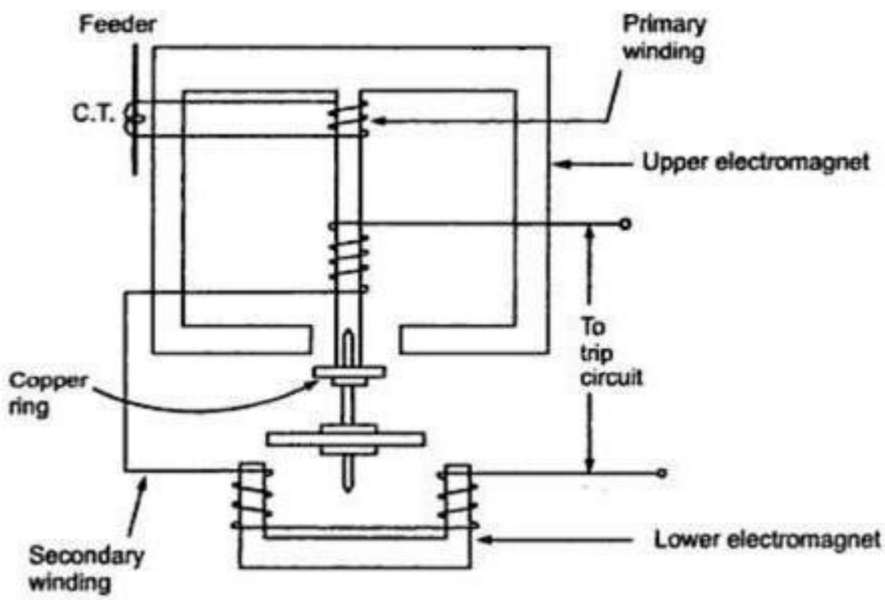
1. It can be used for parallel as well as ring main system.
2. It provides instantaneous protection to ground faults.

The limitations of this method are as follows

1. The C.T.s used must match accurately.
2. The pilot wires must be healthy without discontinuity.
3. Economically not suitable as the cost is high due to long pilot wires.
4. Due to long pilot wires, capacitive effects adversely bias the operation of the relays.
5. The large voltage drop in the pilot wires requiring better insulation.

Translay Scheme

The translay relay is another type of differential relay. The arrangement is similar to overcurrent relay but the secondary winding is not closed on itself. Additionally copper ring or copper shading bands are provided on the central limb as shown in the figure below.



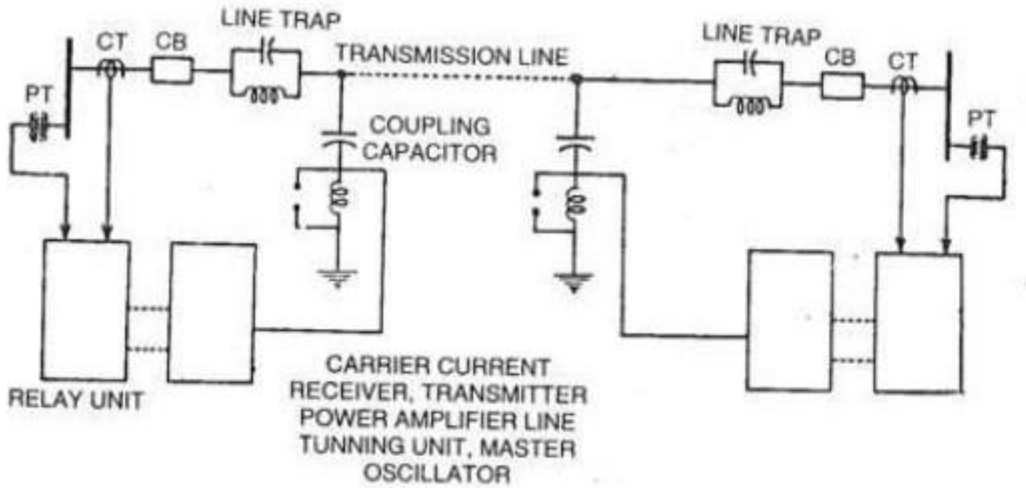
Role of copper ring:

Mainly relays may operate because of unbalance in the current transformers. The copper rings are so adjusted that the torque due to current induced in the copper ring due to primary winding of relay is restraining and do not allow the disc to rotate. It is adjusted just to neutralize the effect of unbalance existing between the current transformers. The copper rings also neutralize the effect of pilot capacitive currents. Though the feeder current is same at two ends, a capacitive current may flow in the pilots. This current leads the secondary voltage by 90o. The copper rings are adjusted such that no torque is exerted on the disc, due to such capacitive pilot currents. Therefore in this scheme the demerits of pilot relaying scheme is somewhat taken care of.

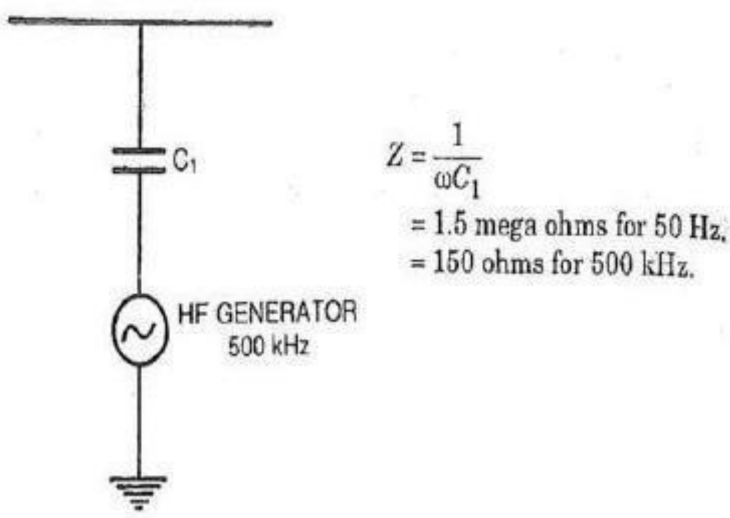
The **advantages** of this scheme are,

1. Only two pilot wires are required.
2. The cost is very low.
3. The current transformers with normal design can be employed.
4. The capacitive effects of pilot wire currents do not affect the operation of the relays.

Carrier Current unit protection system



Schematic diagram of the carrier current scheme is shown below. Different basic components of the same are discussed below. The Coupling capacitor These coupling capacitors (CU) which offer low reactance to the higher frequency carrier signal and high reactance to the power frequency signal. Therefore, it filters out the low (power) frequency and allows the high frequency carrier waves to the carrier current equipments. A low inductance is connected to the CU, to form a resonant circuit.

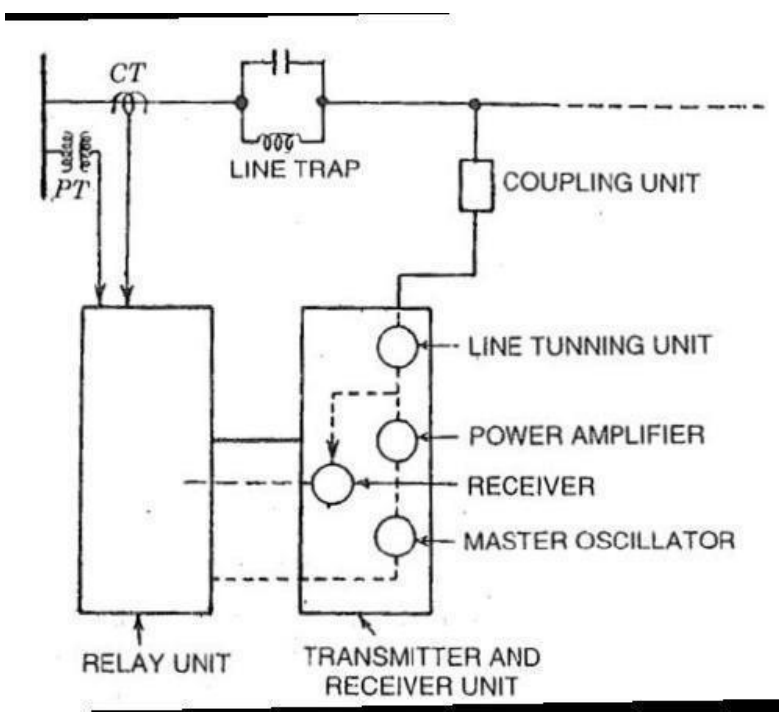


Wave Traps

The Wave traps (also known as Line Trap) are inserted between the busbar and the connection of the CU. These traps are L and C elements connected in parallel, and they are tuned in such a manner that they offer low reactance to the power frequency signals and high reactance to the carrier waves. They ensure that neither of these different frequency signals get mixed up before being received at the bus bar. Both the CU and the Wave traps are protected from switching and lightening surges, with the help suitably designed Spark Gaps or Varistors. Frequency spacing Different frequencies are used in adjacent lines and the wave traps ensure that carrier signals of other lines do not enter a particular line section. Therefore, proper choice of frequency bands for different lines are adopted.

Transmitter Unit

In a Transmitter unit, the carrier frequency in the range of 50 to 500 KHz of constant magnitude is generated in the oscillator, which is fed to an amplifier. Amplification is required to overcome any loss in the coupling equipments, weather conditions, Tee connections in the lines of different size and length. The amplifier and the oscillators are constantly energized and a connection is made between the two with the help of a control unit.



The Receiver unit consists of an attenuator and a Band pass filter, which restricts the acceptance of any unwanted signals. The unit also has matching transformer to match the line impedance and that of the receiver unit.

3.2 TRANSFORMER PROTECTION

INTRODUCTION

• The power transformer is one of the most important links in a power transmission and distribution system.

• It is a highly reliable piece of equipment. This reliability depends on

• adequate design

• careful erection

• proper maintenance

• application of protection system.

PROTECTION EQUIPMENT INCLUDES

1. Surge diverters
2. Gas relay: It gives early warning of a slowly developing fault, permitting shutdown and repair before severe damage can occur.
3. Electrical relays.

• The choice of suitable protection is also governed by economic considerations. Although this factor is not unique to power transformers, it is brought in prominence by the wide range of transformer ratings used(few KVA to several hundreds MVA)

• Only the simplest protection such as fuses can be justified for transformers of lower ratings.

• for large transformers best protection should be provided.

TYPES OF FAULTS AFFECTING POWER TRANSFORMER

- THROUGH FAULTS
  a) Overload conditions.
  b) External short-circuit conditions.

The transformer must be disconnected when such faults occur only after allowing a predetermined time during which other protective gears should have operated.

- INTERNAL FAULTS

The primary protection of a power transformer is intended for conditions which arises as a result of faults inside the protection zone.

1. Phase-to-earth fault or phase- to- phase fault on HV and LV external terminals
2. Phase-to-earth fault or phase-to- phase fault on HV and LV windings.
3. Interturn faults of HV and LV windings.
4. Earth fault on tertiary winding, or short circuit between turns of a tertiary windings.

5. So called „incipient‟ faults which are initially minor faults, causing gradually developing fault. These types of faults are not easily detectable at the winding terminals by unbalance current or voltage.

NATURE & EFFECT OF TRANSFRMER FAULTS

A faults on transformer winding is controlled in magnitude by

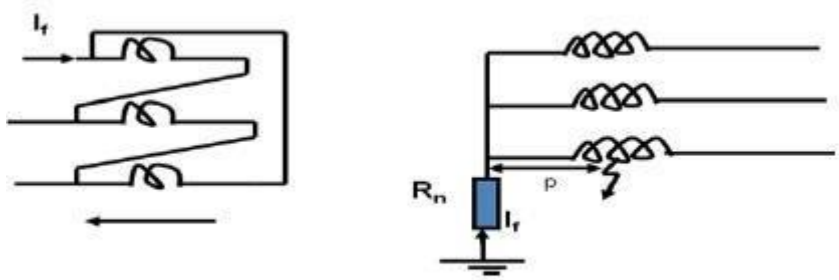
a) Source & neutral earthing impedance

b) Leakage reactance of the transformer

c) Position of the fault on the winding.

Following distinct cases are examined below (1) Star connected winding with neutral point earthed through an impedance

Earth fault on resistance earthed star winding



Transformer differential protection

Basic discussions related to the Merz-Price Scheme and its limitations which are taken care by the biased differential scheme, are omitted for repetition

Basic considerations

a. Transformation ratio

- The nominal currents in the primary and secondary sides of the transformer vary in inverse ratio to the corresponding voltages. This should be compensated for by using different transformation ratios for the CTs on the primary and secondary sides of the transformer.

b. Current Transformer Connections

- When a transformer is connected in star/delta, the secondary current has a phase shift of 300 relative to the primary
- This phase shift can be offset by suitable secondary CT connections

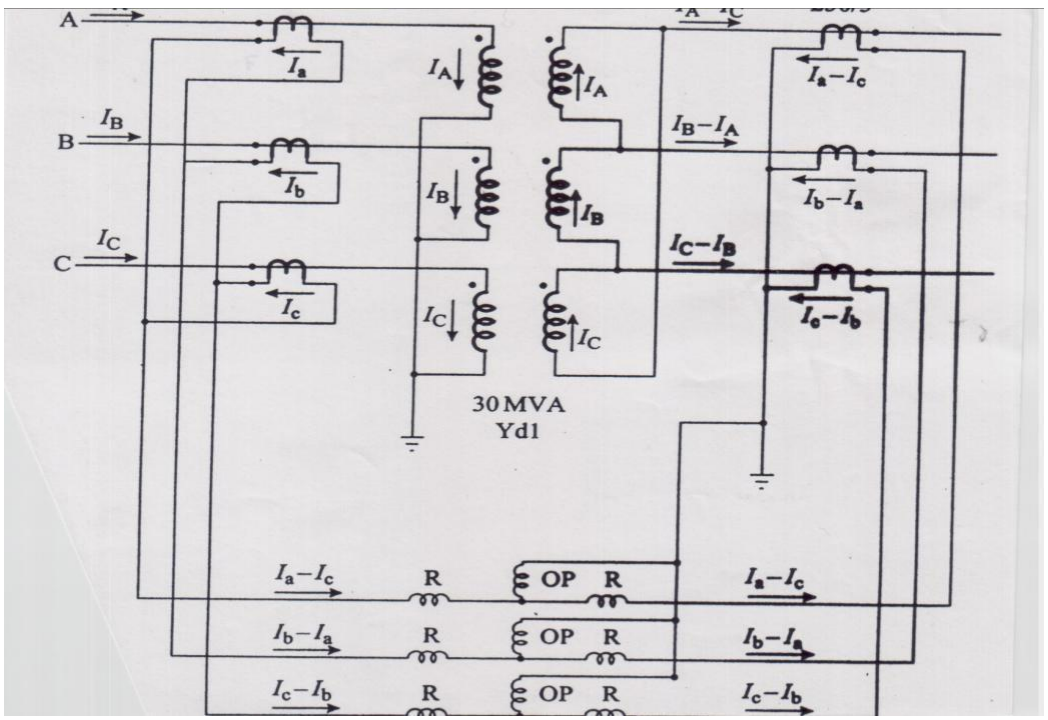
- The zero-sequence currents flowing on the star-side of the transformer will not produce current outside the delta on the other side. The zero sequence current must therefore be eliminated from the star-side by connecting the CTs in delta.
- • The CTs on delta side should be connected in star in order to give 300 phase shift.
- • When CTs are connected in delta, their secondary ratings must be reduced to 1/3 times the secondary ratings of the star-connected transformer, in order that the currents outside the delta may balance with the secondary currents of the star-connected CTs.
- • If transformers were connected in star/star, the CTs on both sides would need be connected in delta-delta.

c. Bias to cover tap-changing facility and CT mismatch

- • If the transformer has the benefit of a tap changer, it is possible to vary its transformation ratio for voltage control.
- • The differential protection system should be able to cope with this variation.
- • This is because if the CTs are chosen to balance for the mean ratio of the power transformer, a variation in ratio from the mean will create an unbalance proportional to the ratio change. At maximum through fault current, the spill output produced by the small percentage unbalance may be substantial
- • Differential protection should be provided with a proportional bias of an amount which exceeds in effect the maximum ratio deviation. This stabilizes the protection under through fault conditions while still permitting the system to have good basic sensitivity.

d. Magnetization Inrush

- The magnetizing inrush produces a current flow into the primary winding that does not have any equivalent in the secondary winding. The net effect is thus similar to the situation when there is an internal fault on the transformer.
- Since the differential relay sees the magnetizing current as an internal fault, it is necessary to have some method of distinguishing between the magnetizing current and the fault current using one or all of the following methods.
- Using a differential relay with a suitable sensitivity to cope with the magnetizing current, usually obtained by a unit that introduces a time delay to cover the period of the initial inrush peak.
- • Using a harmonic-restraint unit, or a supervisory unit, in conjunction with a differential unit.
- • Inhibiting the differential relay during the energizing the transformer.



Compared to the differential protection used in generators, there are certain important points discussed below which must be taken care of while using such protection for the power transformers.

1. In a power transformer, the voltage rating of the two windings is different. The high voltage winding is low current winding while low voltage winding is high current winding. Thus there always exists difference in current on the primary and secondary sides of the power transformer. Hence if C.T.s of same ratio are used on two sides, then relay may get operated through there is no fault existing.

To compensate for this difficulty, the current ratios of C.T.s on each side are different. These ratios depend on the line currents of the power transformer and the connection of C.T.s. Due to the different turns ratio, the currents fed into the pilot wires from each end are same under normal conditions so that the relay remains inoperative. For example if K is the turns ratio of a power transformer then the ratio of C.T.s on low voltage side is made K times greater than that of C.T.s on high voltage side.

2. In case of power transformers, there is an inherent phase difference between the voltages induced in high voltage winding and low voltage winding. Due to this, there exists a phase difference between the line currents on primary and secondary sides of a power transformer. This introduces the phase difference between the C.T. secondary currents, on the two sides of a power transformer. Through the turns ratio of C.T.s are selected to compensate for turns ratio of transformer, a differential current may result due to the phase difference between the currents on two sides. Such a different current may operate the relay though there is no fault. Hence it is

necessary to correct the phase difference. To compensate for this, the C.T. connections should be such that the resultant currents fed into the pilot wires from either sides are displaced in phase by an angle equal to the phase shift between the primary and secondary currents. To achieve this, secondaries of C.T.s on star connected side of a power transformer are connected in delta while the secondaries of C.T.s on delta connected side of a power transformer are connected in star.

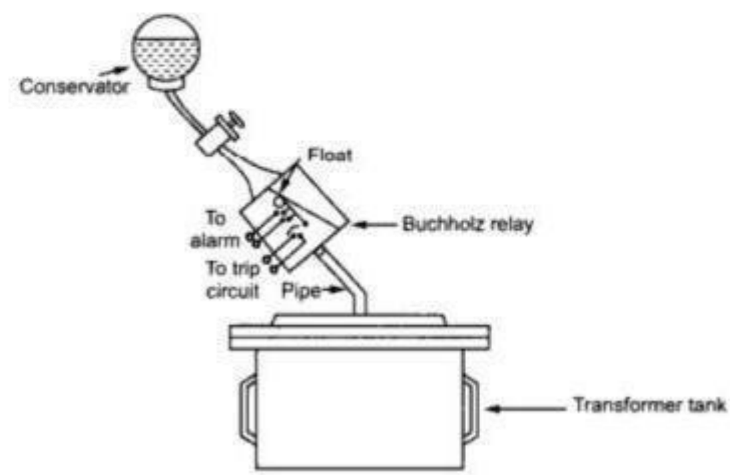
Buchholz relay

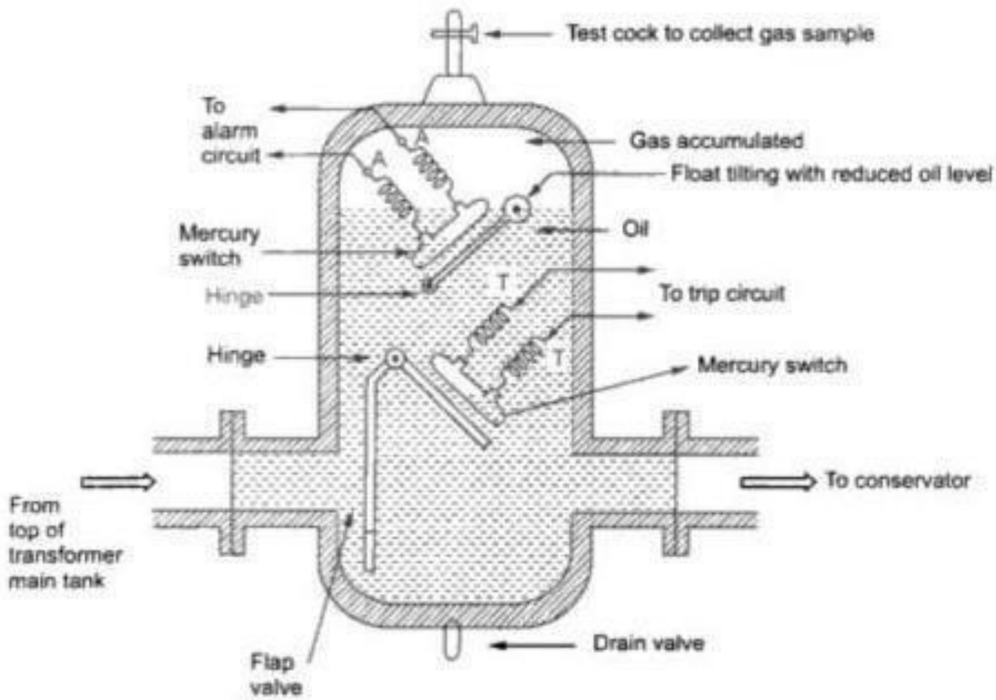
All faults below the oil in transformer result in the localized heating & breakdown of the oil, some degree of arcing will always take place in a winding fault & the resulting decomposition of it will release gases such as hydrogen, carbon monoxide & hydrocarbons.

• When the fault is of a very minor type, such as hot joints gas is released slowly, but a major fault involving severe arcing causes rapid release of large volumes of gas as well as oil vapour.

• Such incipient faults of smaller or larger magnitudes can be detected by a gas actuated relay known as Bucholtz Relay.

The Bucholtz Relay is contained in a cast housing which is connected as shown below between the conservator tank and main tank of the transformer.





Under normal conditions, the Buchholz relay is full of oil. It consists of a cast housing containing a hinged hollow float. A mercury switch is attached to a float. The float being rotated in the upper part of the housing. Another hinged flap valve is located in the lower part which is directly in the path of the oil between tank and the conservator. Another mercury switch is attached to a flap valve. The float closes the alarm circuit while the lower flap valve closes the trip circuit in case of internal faults.

Operation

There are many types of internal faults such as insulation fault, core heating, bad switch contacts, faulty joints etc. which can occur. When the fault occurs the decomposition of oil in the main tank starts due to which the gases are generated. As mentioned earlier, major component of such gases is hydrogen. The hydrogen tries to rise up towards conservator but in its path it gets accumulated in the upper part of the Buchholz relay. Through passage of the gas is prevented by the flap valve.

When gas gets accumulated in the upper part of housing, the oil level inside the housing falls. Due to which the hollow float tilts and closes the contacts of the mercury switch attached to it. This completes the alarm circuit to sound an alarm. Due to this operator knows that there is some incipient fault in the transformer. The transformer is disconnected and the gas sample is tested. The testing results give the indication, what type of fault is started developing in the transformer.

Hence transformer can be disconnected before grows into a serious one. The alarm circuit does not immediately disconnect the transformer but gives only an indication to the operator. This is because sometimes bubbles in the oil circulating system may operate the alarm circuit even though actually there is no fault. However if a serious fault such as internal short circuit between phases, earth fault inside the tank etc. occurs then the considerable amount of gas gets generated. In that case, due to a fast reduction in the level of oil, the pressure in the tank increases. Due to this the oil rushes towards the conservator. While doing so it passes through the relay where flap valve is present. The flap valve gets deflected due to the rushing oil and operates the mercury switch, thereby energizing the trip circuit which opens the circuit breaker of transformer is totally disconnected from the supply. The connecting pipe between the tank and the conservator should be as straight as possible and should slope upwards conservator at a small angle from the horizontal. This angle should be around 100. For the economic considerations, Buchholz relays are not provided for the transformer having rating below 500 KVA.

Advantages

The various advantages of the Buchholz relay are,

1. Normally a protective relay does not indicate the appearance of the fault. It operates when fault occurs. But Buchholz relay gives an indication of the fault at very early stage, by anticipating the fault and operating the alarm circuit. Thus the transformer can be taken out of service before any type of serious damage occurs.

2. It is the simplest protection in case of transformers.

Limitations

The various limitation of the Buchholz relay are,

1. Can be used only for oil immersed transformers having conservator tanks.
2. Only faults below oil level are detected.
3. Setting of the mercury switches cannot be kept too sensitive otherwise the relay can operate due to bubbles, vibration, earthquakes mechanical shocks etc.
4. The relay is slow to operate having minimum operating time of 0.1 seconds and average time of 0.2 seconds.

Applications

The following types of transformer faults can be protected by the Buchholz relay and are indicated by alarm:

1. Local overheating
2. Entrance of air bubbles in oil
3. Core bolt insulation failure
4. Short circuited laminations
5. Loss of oil and reduction in oil level due to leakage

6. Bad and loose electrical contacts
7. Short circuit between phases
8. Winding short circuit
9. Bushing puncture
10. Winding earth fault.

3.3 Generator protection

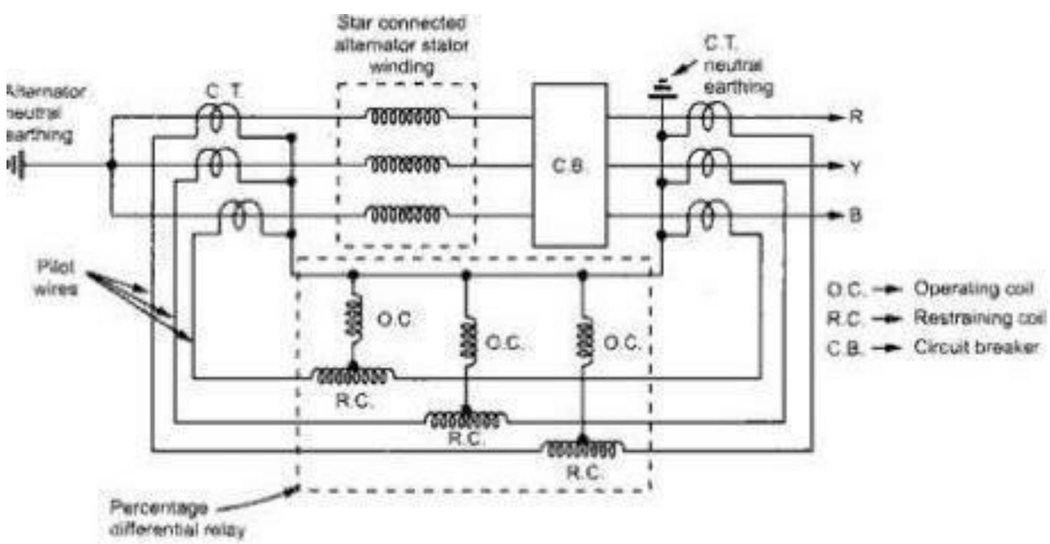
INTRODUCTION

- The range of size of generators extends from a few hundred KVA to more than 500MVA
- Small and Medium sized sets may be directly connected to the distribution system

A larger unit is usually associated with an individual transformer, through which the set is coupled to the EHV transmission system. No switchgear is provided between the generator and transformer, which are treated as a unit.

Biased Differential scheme (Merz-Price Scheme) for protection of Generators.

This is most commonly used protection scheme for the alternator stator windings. The scheme is also called biased differential protection and percentage differential protection. The figure below shows a schematic arrangement of Merz-Price protection scheme for a star connected alternator.



The differential relay gives protection against short circuit fault in the stator winding of a generator. When the neutral point of the windings is available then, the C.T.s may be connected in star on both the phase outgoing side and the neutral earth side, as shown in the above figure. But, if the neutral point is not available, then the phase side CTs are connected in a residual connection, so that it can be made suitable for comparing the current with the generator ground point CT secondary current. The restraining coils are energized from the secondary connection of C.T.s in each phase, through pilot wires. The operating coils are energized by the tappings from restraining coils and the C.T. neutral earthing connection.

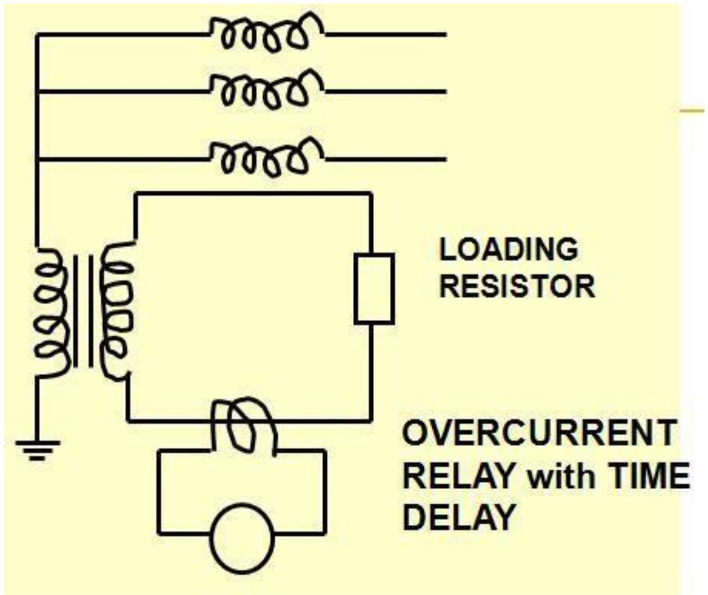
The similar arrangement is used for the delta connected alternator stator winding, as shown below.

This scheme provides very fast protection to the stator winding against phase to phase faults and phase to ground faults. If the neutral is not grounded or grounded through resistance then additional sensitive earth fault relay should be provided. The advantages of this scheme are,
1. Very high speed operation with operating time of about 15 msec. 2. It allows low fault setting which ensures maximum protection of machine windings. 3. It ensures complete stability under most severe through and external faults. 4. It does not require current transformers with air gaps or special balancing features.

Earth fault protection of Generators

The neutral point of the generator is usually earthed, so as to facilitate the protection of the stator winding and associated system. Impedance is inserted in the earthing lead to limit the magnitude of the earth fault current. Generators which are directly connected to the transmission or distribution system are usually earthed through a resistance which will pass approximately rated current to a terminal earth fault. In case of generator-transformer unit, the generator winding and primary winding of a transformer can be treated as an isolated system that is not influenced by the earthing requirements of the transmission system. Modern practice is to use a large earthing transformer (5-100 KVA) – the secondary winding which is designed for 100-500V is loaded with a resistor of a value, which when referred through the transformer ratio, will pass a suitable fault current. The resistor is therefore of low value and can be of rugged construction. It is important that the earthing transformer never becomes saturated, otherwise a very undesirable condition of ferro resonance may occur.

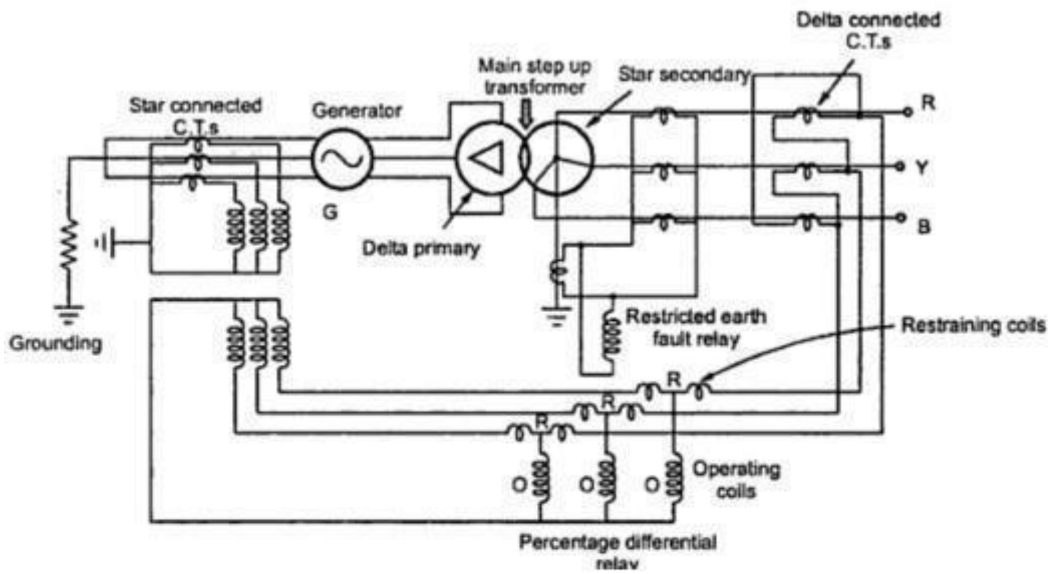
Earth fault protection can be obtained by applying a relay to measure the transformer secondary current by connecting a voltage measuring relay in parallel with the load resistor



Generator and Transformer Unit Biased Differential Protection

In a high voltage transmission system, the bus bars are at very high voltages than the generators. The generators are directly connected to step up transformer to which it is connected, together from a generator transformer unit. The protection of such a unit is achieved by differential protection scheme using circulating current principle. While providing protection to such a unit, it is necessary to consider the phase shift and current transformation in the step up transformer. The figure in the following page, shows a biased differential protection scheme used for generator transformer unit. The zone of such a scheme includes the stator windings, the step up transformer and the intervening connections. The transformer is delta-star hence the current transformers on high voltage side are delta connected while those on generator side are star connected. This cancels the displacement between line currents introduced by the delta connected primary of the transformer. Where there is no fault, the secondary currents of the current transformer connected on generator side are equal to the currents in the pilot wires from the secondaries of the delta connected current transformers on the secondary of main transformer. When a fault occurs, the pilot wires carry the differential current to operate the percentage differential relay.

For the protection against the earth faults, an earth fault relays is put in the secondary winding of the main step up transformers as shown. In such a case, differential protection acts as a backup protection to the restricted earth fault protection. This overall differential protection scheme does not include unit transformer as a separate differential scheme is provided it.



PHASE FAULT

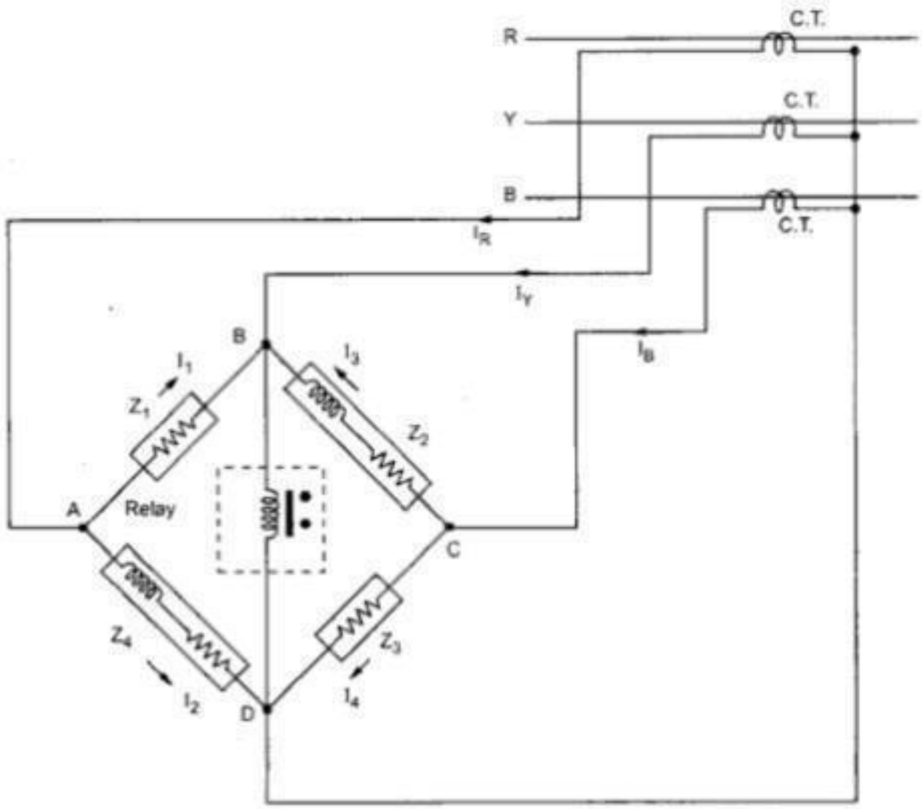
- Phase-phase faults clear of earth are less common. They may occur on the end portion of stator coils or in the slots if the winding involves two coil sides in the same slot. In the later case the fault will involve earth in a very short time.
- Phase fault current is not controlled by the method of earthing the neutral point.

INTERTURN FAULTS

- Interturn faults are also uncommon, but not unknown
- A greatest danger arising from failure to deal with interturn faults quickly is fire. A large portion of the insulation is inflammable

Negative sequence protection

The negative sequence component can be detected by the use of a filter network. Many negative sequence filter circuits have been evolved. One typical negative sequence filter circuit is as follows



Basically it consists of a resistance bridge network as depicted in the first figure showing the circuit connection. The magnitudes of the impedances of all the branches of the network are equal. The impedances Z1 and Z3 are purely resistive while the impedances Z2 and Z4 are the combinations of resistance and reactance. The currents in the branches Z2 and Z4 lag by 60o from the currents in the branches Z1 and Z3. The vertical branch B-D basically consists of an over current element with inverse time characteristics having negligible impedance compared to the bridge impedances.

3.4 protection of bus bars

The protection scheme for a power system should cover the whole system against all probable types of faults. Unrestricted forms of line protection such as over current and distance systems, meet this requirement, although faults in the Bus bar zone are cleared only after some time delay. If unit protection is applied to feeder and plant the bus bars are not inherently protected. Bus bars have been left without specific protection. Different bus bar faults are as follows. BUSBAR FAULTS

- Majority of bus faults involve one phase and earth, but faults arise from many causes and a significant number are inter-phase clear of earth.
- With fully phase-segregated metal clad gear, only earth faults are possible ,and a protective scheme need have earth fault sensitivity only.

- For outdoor busbars , protection schemes ability to respond to inter-phase faults clear of earth is an advantage

TYPES OF PROTECTION SCHEMES

- System protection used to cover bus bars
- Frame –earth protection
- Differential protection

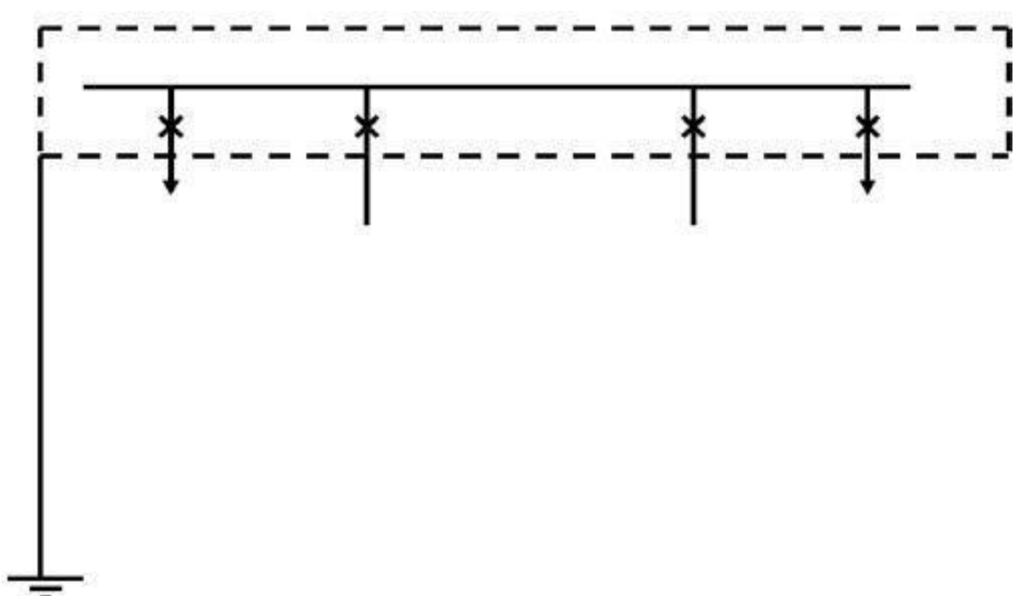
SYSTEM PROTECTION

- A system protection that includes over current or distance systems will inherently give protection cover to the bus bars.
- Over current protection will only be applied to relatively simple distribution systems, or as a back-up protection set to give considerable time delay. Distance protection will provide cover with its second zone.
- In both cases, therefore ,the bus bar protection so obtained is slow

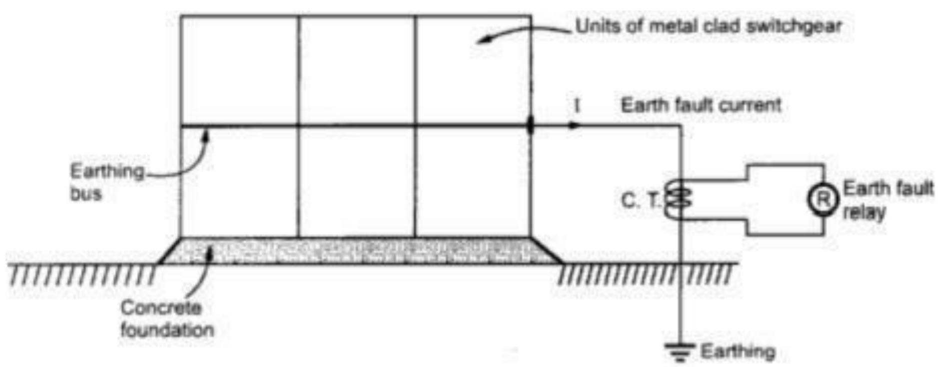
Frame-earth Protection

- This is purely an earth fault system, and in principle involves simply measuring the fault current flowing from the switchgear frame to earth. To this end a current transformer is

mounted on the earthing conductor and is used to energize a simple instantaneous relay.



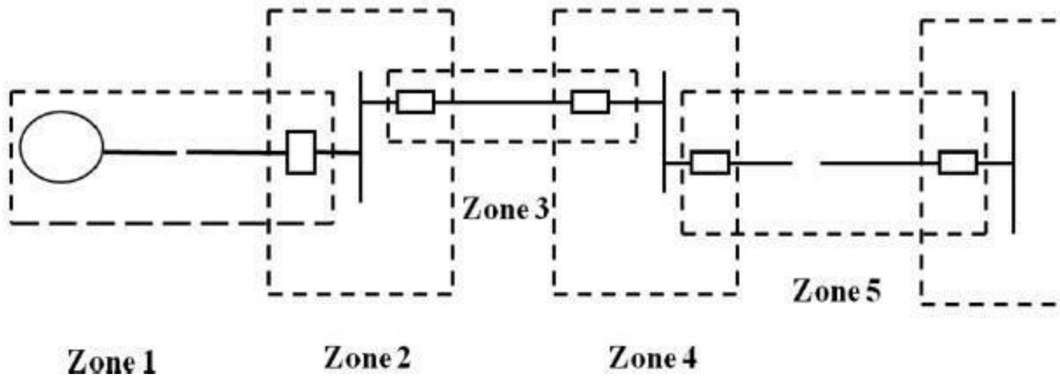
This protection is nothing but the method of providing earth fault protection to the bus bar assembly housed in a frame. This protection can be provided to the metal clad switchgear. The arrangement is shown in the figure below. The metal clad switchgear is lightly insulated from the earth. The enclosure of the frame housing different switchgears and bus bars is grounded through a primary of current transformer in between. The concrete foundation of switchgear and the other equipments are lightly insulated from the ground. The resistance of these equipments with earth is about 12 ohms. When there is an earth fault, then fault current leaks from the frame and passes through the earth connection provided. Thus the primary of C.T. senses the current due to which current passes through the sensitive earth fault relay, thereby operating the relay.



3.5 Zones and types of Protection system

Zones of Protection system

- An electric power system is divided into several zones of protection. Each zone of protection, contains one or more components of a power system in addition to two circuit breakers.
- When a fault occurs within the boundary of a particular zone, then the protection system responsible for the protection of the zone acts to isolate (by tripping the Circuit Breakers) every equipment within that zone from the rest of the system.
- The circuit Breakers are inserted between the component of the zone and the rest of the power system. Thus, the location of the circuit breaker helps to define the boundaries of the zones of protection.
- Different neighbouring zones of protection are made to overlap each other, which ensure that no part of the power system remains without protection. However, occurrence of the fault with in the overlapped region will initiate a tripping sequence of different circuit breakers so that the minimum necessary to disconnect the faulty element



Types of Protection (Primary and Back-up Protection)

Primary Protection

The primary protection scheme ensures fast and selective clearing of any fault within the boundaries of the circuit element, that the zone is required to protect. Primary Protection as a rule is provided for each section of an electrical installation.

However, the primary protection may fail. The primary cause of failure of the Primary Protection system are enumerated below.

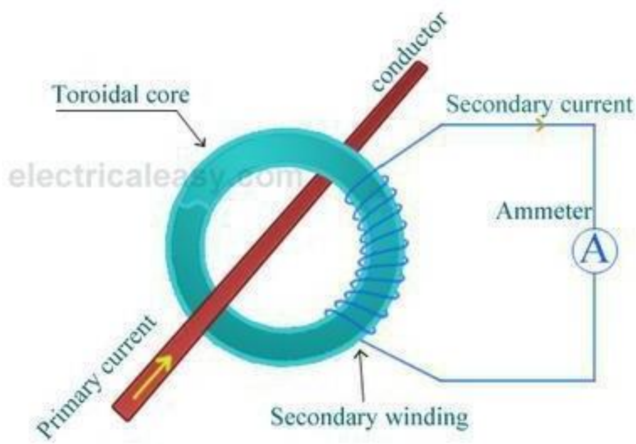
1. Current or voltage supply to the relay.
2. D.C. tripping voltage supply
3. Protective relays
4. Tripping circuit
5. Circuit Breaker

Back-up Protection

Back-up protection is the name given to a protection which backs the primary protection whenever the later fails in operation. The back-up protection by definition is slower than the primary protection system. The design of the back-up protection needs to be coordinated with the design of the primary protection and essentially it is the second line of defence after the primary protection system.

3.6 CTs and PTs and their applications in protection schemes.

Current transformers are generally used to measure currents of high magnitude. These transformers step down the current to be measured, so that it can be measured with a normal range ammeter. A Current transformer has only one or very few number of primary turns. The primary winding may be just a conductor or a bus bar placed in a hollow core (as shown in the figure). The secondary winding has large number turns accurately wound for a specific turns ratio.

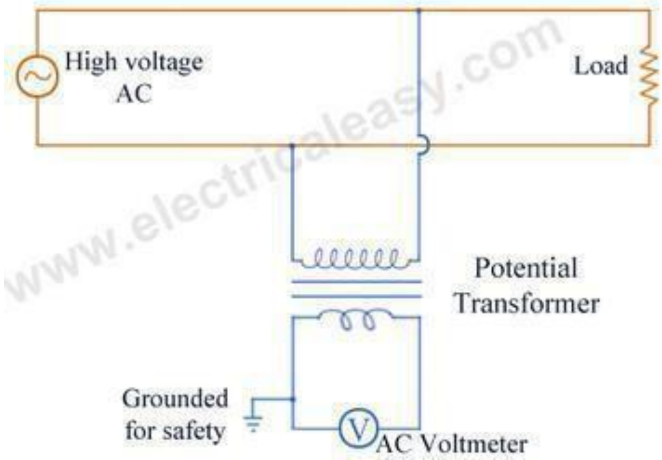


Thus the current transformer steps up (increases) the voltage while stepping down (lowering) the current. Now, the secondary current is measured with the help of an AC ammeter. The turns ratio of a transformer is NP / NS = IS / IP

- UPS systems
- Transfer switches
- Motor-generator sets
- Commercial sub-metering,
- CT 's in one package for 3-phase metering
- Accurate measuring for metering/WATT/VAR
- Current sensing, recording, monitoring & control
- Control panels and drives
- Standard CT used as measuring standard for comparison
- Winding temperature indicator (WTI) for power transformers
- Summation current transformers.

Potential Transformer (PT)

Potential transformers are also known as voltage transformers and they are basically step down transformers with extremely accurate turns ratio. Potential transformers step down the voltage of high magnitude to a lower voltage which can be measured with standard measuring instrument. These transformers have large number of primary turns and smaller number of secondary turns. A potential transformer is typically expressed in primary to secondary voltage ratio. For example, a 600:120 PT would mean the voltage across secondary is 120 volts when primary voltage is 600 volts.


High voltage
AC
Load
Potential
Transformer
Grounded
for safety
V
AC Voltmeter

UNIT IV
STATIC RELAYS AND NUMERICAL PROTECTION

4.1 Formation of arc during circuit breaking

The phenomena of Arc

During opening of current carrying contacts in a circuit breaker the medium in between opening contacts become highly ionized through which the interrupting current gets low resistive path and continues to flow through this path even after the contacts are physically separated. During the flowing of current from one contact to other the path becomes so heated that it glows in the form of an arc.

Arc in circuit breaker

Whenever, the contacts of circuit breaker open while carrying load there is an arc in the medium between the separating contacts of the circuit breaker. As long as this arc is sustained in between the contacts, the current through the circuit breaker will not be interrupted totally. For total interruption of current, the arc needs to be quenched as quickly as possible. The main designing criteria of a circuit breaker is to provide appropriate technology of arc quenching in circuit breaker to fulfill quick and safe current interruption. So before going through different arc quenching techniques employed in circuit breaker, it is first necessary to understand the phenomena of arc in circuit breaker.

Role of arc in circuit breaker

When two current carrying contacts open, an arc bridges the contact gap through which the current gets a low resistive path to flow so there will not be any sudden interruption of current. As there is no sudden and abrupt change in current during opening of the contacts, there will not be any abnormal switching over voltage in the system. Let i is the current flowing through the contacts just before they open and L is the system inductance, switching over voltage during opening of contacts, may be expressed as $V = L.(di/dt)$ where di/dt rate of change of current with respect to time during opening of the contacts. In the case of alternating current arc is momentarily extinguished at every current zero. After crossing every current zero the medium between separated contacts gets ionized again during next cycle of current and the arc in circuit breaker is reestablished. To make the interruption complete and successful, this re-ionization in between separated contacts to be prevented after a current zero.

If arc in circuit breaker is absence during opening of current carrying contacts, there would be sudden and abrupt interruption of current which will cause a huge switching overvoltage sufficient to severely stress the insulation of the system. On the other hand, the arc provides a gradual but quick, transition from the current carrying to the current breaking states of the contacts.

Arc Interruption or Arc Quenching or Arc Extinction Theory

At high temperature the charged particles in a gas move rapidly and randomly, but in absence of electric field, no net motion occurs. Whenever an electric field is applied in the gas, the charged particles gain drift velocity superimposed on their random thermal motion. The drift velocity is proportional to the voltage gradient of the field and particle mobility. The particle mobility depends upon the mass of the particle, heavier particles, lower the mobility. The mobility also depends upon mean free paths available in the gas for random movement of the particles. Since every time a particle collides, it loses its directed velocity and has to be re-accelerated in the direction of electric field again. Hence net mobility of the particles is reduced. If the medium has high pressure, it becomes denser and hence, the gas molecules come closer to each other, therefore collision occurs more frequently which lowers the mobility particles. The total current by charged particles is directly proportional to their mobility. Therefore the mobility of charged particles depends upon the temperature, pressure of the gas and as well as nature of the gas. Again the mobility of gas particles determines the degree ionization of gas.

So from above explanation we can say that ionization process of gas depends upon nature of gas (heavier or lighter gas particles), pressure of gas and temperature of gas. As we said earlier the intensity of arc column depend up on the presence of ionized media between separated electrical contacts, hence, special attention should be given in reducing ionization or increasing deionization of media between contacts. That is why the main designing feature of circuit breaker is to provide different pressure control methods, cooling methods for different arc media in between circuit breaker contacts.

HEAT LOSS FROM ARC

Heat loss from an arc in circuit breaker takes place through conduction, convection as well as radiation. In circuit breaker with plain break arc in oil, arc in chutes or narrow slots nearly all the heat loss due to conduction. In air blast circuit breaker or in breaker where a gas flow is present between the electrical contacts, the heat loss of arc plasma occurs due to convection process. At normal pressure the radiation is not a significant factor but at higher pressure the radiation may become a very important factor of heat dissipation from arc plasma. During opening of electrical contacts, the arc in circuit breaker is produced and it is extinguished at every zero crossing, getting established again during the next cycle. The final arc extinction or arc quenching in circuit breaker can be achieved by rapid increase of the dielectric strength in the medium between the contacts so that the arc gets quenched after the first zero crossing. This rapid increase of dielectric strength in between circuit breaker contacts is achieved either by deionization of gas in the arc media or by replacing ionized gas by cool and fresh gas. There are various deionization processes applied for arc extinction in circuit breaker, let us discussed in brief.

DEIONIZATION OF GAS DUE TO INCREASING PRESSURE

If pressure of the arc path increases, the density of the ionized gas is increased which means, the particles in the gas come closer to each other and as a result the mean free path of the particles is reduced. This increases the collision rate and as we discussed earlier at every collision the charged particles loss their directed velocity along electric field and again they are re-accelerated towards field. It can be said that over all mobility of the charged particles is reduced so the voltage required to maintain the arc is increased. Another effect of the increased density of particles is a higher rate of deionization of gas due to the recombination of oppositely charged particles.

The rate of ionization of gas depends upon the intensity of impact during collision of gas particles. The intensity of impact during collision of particles again depends upon velocity of random motions of the particles. This random motion of a particle and its velocity increases with increase of temperature of the gas. Hence it can be concluded like that if temperature of a gas is increased; its ionization process is increased and opposite statement is also true that is if the temperature is decreased the rate of ionization of gas is decreased means deionization of gas is increased. Therefore more voltage required to maintain arc plasma with a decreased temperature. Finally it can be said that the cooling effectively increases the resistance of the arc.

The insulating material (may be fluid or air) used in circuit breaker should serve two important functions as follows:

1. It should provide sufficient insulation between the contacts when circuit breaker opens.
2. It should extinguish the arc occurring between the contacts when circuit breaker opens.

Methods of arc interruption

There are two methods by which interruption is done.

1. High resistance method.
2. Low resistance method or zero interruption method.

In high interruption method we can increase the electrical resistance many times to such a high value that it forces the current to reach to zero and thus restricting the possibility of arc to be struck again. Proper steps must be taken in order to ensure that the rate at which the resistance is increased or decreased is not abnormal because it may lead to generation of harmful induced voltages in the system. The arc resistance can be increased by various methods like lengthening or cooling of the arc etc.

Limitations of high resistance method: Arc discharge has a resistive nature due to this most of the energy is received by circuit breaker itself hence proper care should be taken during the manufacturing of circuit breaker like mechanical strength etc. Therefore this method is applied in dc power circuit breaker, low and medium ac power circuit breaker.

Low resistance method is applicable only for ac circuit and it is possible there because of presence of natural zero of current. The arc gets extinguished at the natural zero of the ac wave and is prevented from restricting again by rapid building of dielectric strength of the contact space.

There are two theories which explains the phenomenon of arc extinction:

1. Energy balance theory,
2. Voltage race theory.

Before going in details about these theories, we should know the following terms.
Restriking voltage: It may be defined as the voltage that appears across the breaking contact at the instant of arc extinction.

Recovery voltage :

It may be defined as the voltage that appears across the breaker contact after the complete removal of transient oscillations and final extinction of arc has resulted in all the poles.

Active recovery voltage :

It may be defined as the instantaneous recovery voltage at the instant of arc extinction.

Arc voltage :

It may be defined as the voltage that appears across the contact during the arcing period, when the current flow is maintained in the form of an arc. It assumes low value except for the point at which the voltage rise rapidly to a peak value and current reaches to zero.

4.2 AC and DC circuit breaking

DC circuit breakers and AC breaker main difference is the ability to arc. Because the exchange of each cycle, have had zero, zero easy to extinction in the past, but has not been zero DC switching, arc extinguishing ability is poor, so to add additional interrupter device. DC arc is generally difficult, but the exchange has zero, breaking easily. Exchange can be derived for the DC circuit breaker protection, attention to three changes: 1, overload and short circuit protection.

1. long delay overload protection.

By thermal-action (double metal components) for long delay overload protection, the source of its action as I2R, AC RMS and DC current equal to the average, there is no need to use any restructuring. However, the large current size, to the current transformer secondary current heat who can not be used due to transformer can not be used on DC circuits. Release long delay if the overload is the use of electromagnetic type (hydraulic type, that is, oil cup), then the delayed release characteristics to change, the minimum operating current to 110% -140% bigger, so the whole electromagnetic Release not be used for DC circuits (such as the use will have to re-design).

2.short circuit protection.

Thermal - Magnetic AC circuit breaker short-circuit protection is the use of magnetic system, which is used by the filtering of the rectifier circuit (DC), need to exchange the original setting current value multiplied by a factor of

1. Electromagnetic type of short circuit protection and thermal dynamic electromagnetic same.

2. circuit breaker accessories, such as shunt release, under voltage release, electrically operated institutions; shunt, under voltage are voltage coil, as long as the line voltage, is used for systems, need not be Any change can be used for DC system. Auxiliary and alarm contacts, AC and DC common. Electric operating mechanism for the DC Time to re-design.

3. unlike the exchanges as DC current zero-crossing characteristics, dc short circuit current (or even multiple small fault current) is breaking; arc out all the difficulties, so wiring should be two extreme ways or three poles in series increase the fracture, so that the fracture energy to bear part of the arc.

• DC arcs are to be interrupted by increasing the resistance interruption method in which resistance of the arc is increased so that the arc voltage can no longer maintain the current and the arc is extinguished.

• Size of DC circuit breaker increases as the voltage level increases.

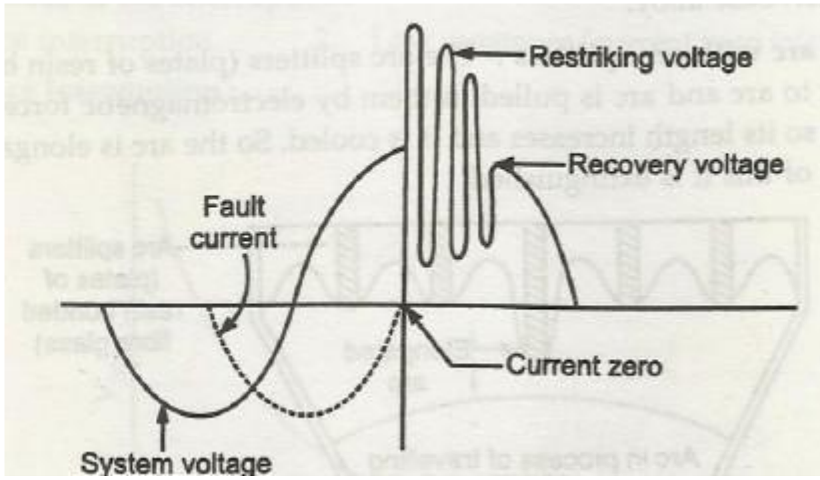
• AC arcs current reduces to zero in each cycle (2 times)

• If the circuit breaker contacts are opened at time when the current passed through zero and dielectric strength of the medium is build up rapidly so that arc cannot strike again then arc can be extinguished successfully.

• Size of AC circuit breaker can be small compared to same voltage DC circuit breaker.

4.3 Restriking voltage and recovery voltage

It is the transient voltage that appears across the contacts at or near current zero during arcing period.If dielectric strength rise is greater than the rise of restriking voltage then the arc will not restrike.



RestrikingVoltage :

it is the transient voltage that exists during the arcing time. (natural frequency kHz).

Recovery Voltage :

it is the rms voltage after final arc extinction. (normal frequency 50 or 60 Hz).

both voltages appear between circuit breaker poles.

- A circuit breaker is a piece of equipment which can Make or break a circuit either manually or by remote control under normal conditions.
- Break a circuit automatically under fault condition
- Make a circuit either manually or by remote under fault condition
- Circuit Breaker consists of fixed and moving contacts called electrodes
- Under normal operating condition these contacts remain closed and will not open automatically unless the system becomes faulty .These contacts can be opened manually or by remote control.
- When a fault occurs in a circuit the trip coils of the circuit breaker get energized and the moving contacts are pulled apart by some mechanism ,thus opening the circuit.

4.4 Rate of rise of recovery voltage

It is the rate of increase of restriking voltage and is abbreviated by R.R.R.V. its unit is kV/m sec.Consider the fig2 below showing the opening of circuit breaker under fault conditions. Before current interruption, the capacitance C is short circuited by the fault and the short circuit current through the breaker is limited by inductance L of the system

The short circuit current will lag the voltage by 90° where i represents the short circuit current and *ea* represents the arc voltage. Under short circuit condition the entire generator voltage appears across inductance L. when the contacts are opened and the arc finally extinguishes at some current zero, the generator voltage *e* is suddenly applied to the inductance and capacitance in series. This L-C combination forms an oscillatory circuit produces a transient of frequency;*fn*= 1/ [2π(LC)1/2] , which appears across the capacitor and hence across the contacts of the circuit breaker. This transient voltage is known as restriking voltage and may reach an instantaneous peak value twice the peak phase neutral voltage i.e. 2 *Em*.

It is R.R.R.V, which decides whether the arc will re-strike. If R.R.R.V is greater than the rate of rise of dielectric strength between the contacts, the arc will re-strike. The arc will fail to re-strike if R.R.R.V is less than the rate of increase of dielectric strength between the contacts of the breaker.

The value of R.R.R.V depends on:

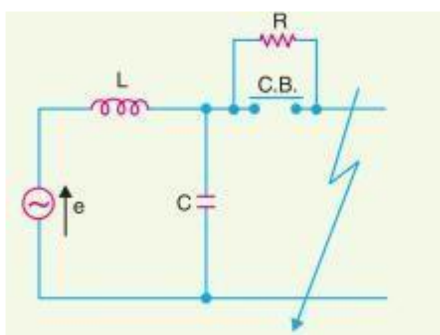
- Recovery voltage
- Natural frequency of oscillations

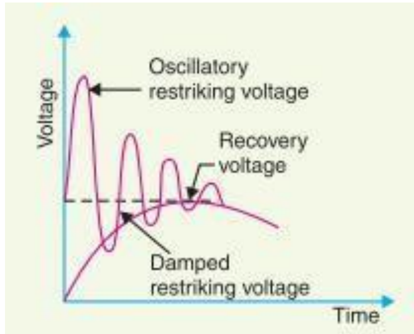
4.5 Resistance switching

To reduce the restriking voltage, RRRV and severity of the transient oscillations, a resistance is connected across the contacts of the circuit breaker.

This is known as resistance switching. The resistance is in parallel with the arc. A part of the arc current flows through this resistance resulting in a decrease in the arc current and increase in the deionization of the arc path and resistance of the arc.

This process continues and the current through the shunt resistance increases and arc current decreases. Due to the decrease in the arc current, restriking voltage and RRRV are reduced. The resistance may be automatically switched in with the help of a sphere gap as shown in Fig. The resistance switching is of great help in switching out capacitive current or low inductive current.



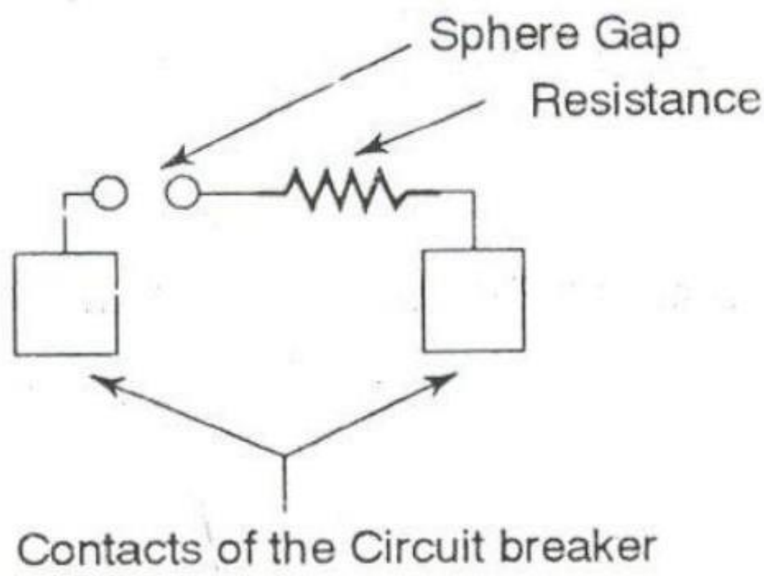


The analysis of resistance switching can be made to find out the critical value of the shunt resistance to obtain complete damping of transient oscillations. Figure 5.8 shows the equivalent electrical circuit for such an analysis.

Unipolar switching

Unipolar systems usually have a dielectric that is a simple TMO. Examples are NiO [12], CuO, CoO, Fe2O3 , HfO, TiO2Ta2O5 , Nb2O5 [10,11]. These systems are good insulators with a large resistivity. They would normally not show any RS effect. To get the systems into the switching regime it is usually required to perform and initial ‗electroforming' step. In this process, a strong electric field is applied, which brings the system close to the dielectric break down. A full break down is prevented by a current limitation or compliance. After this ‗SET' procedure, the resistance of the device shows a significant decrease, reaching a ‗low resistance' state, *R*LO , which is stable, i.e., non-volatile. This state has an ohmic *I-V* characteristic at low bias. To switch the system to the ‗high resistance' state, *R*HI ,a voltage has to be applied to the device, with either the same or opposite polarity than the previously applied ‗forming' voltage. In this ‗RESET' step, the resistance of the system suddenly increases, back to a ‗high resistance' value close to the original one.

No current compliance should be used in the RESET step. In fact, the resistance change occurs when the current through the device becomes larger than the value of the compliance. To SET the system again in the low resistance state, a voltage with current compliance has to be once again applied, similarly to the forming step. The system's resistance suddenly decreases down to a value close to *R*LO at a threshold voltage *Vth* , which is smaller that the forming one. The SET and RESET switching process can be repeated may times. The magnitude of resistance change typically remains within well-defined values, however some dispersion is often observed. An example of a typical electroforming and successive RESET and SET steps are shown in Fig



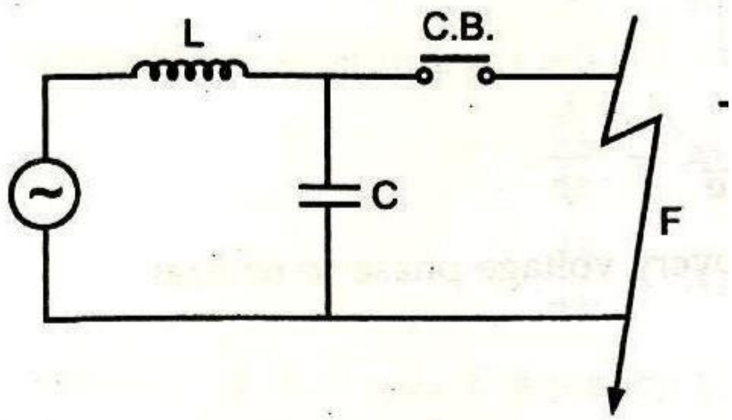
Bipolar switching

Bipolar resistive switching has been observed in a variety of ternary oxides with perovskite structure such as SrTiO3(STO), SrZrO3 , and also in more complex systems such as the _colossal‘ magnetoresistive manganites LSMO, LCMO, PCMO, PLCMO, and even in cuprate superconductors YBCO and BSCCO. Some reports indicate that better performance may be obtained by small chemical substitution, such as Bi:SrTiO3 and Cr:SrTiO3 . These bipolar systems may be either insulators or poor metals. Strong hysteresis in the two-terminal resistance is often observed without the need of an initial forming step. Nevertheless, electro-forming usually done, as it may improve the reproducibility of resistive switching, but this initial forming step remains not well understood [13].

The choice of a proper electrode material for each dielectric is an important issue for bipolar devices. Sawa and collaborators have performed a systematic study, concluding that a key feature for RS is the formation of Shottky barriers [10]. In fact, the observed scaling of *R*HI and *R*LO with the geometry of the devices indicate that the phenomenon should take place at the electrode/oxide interfaces.

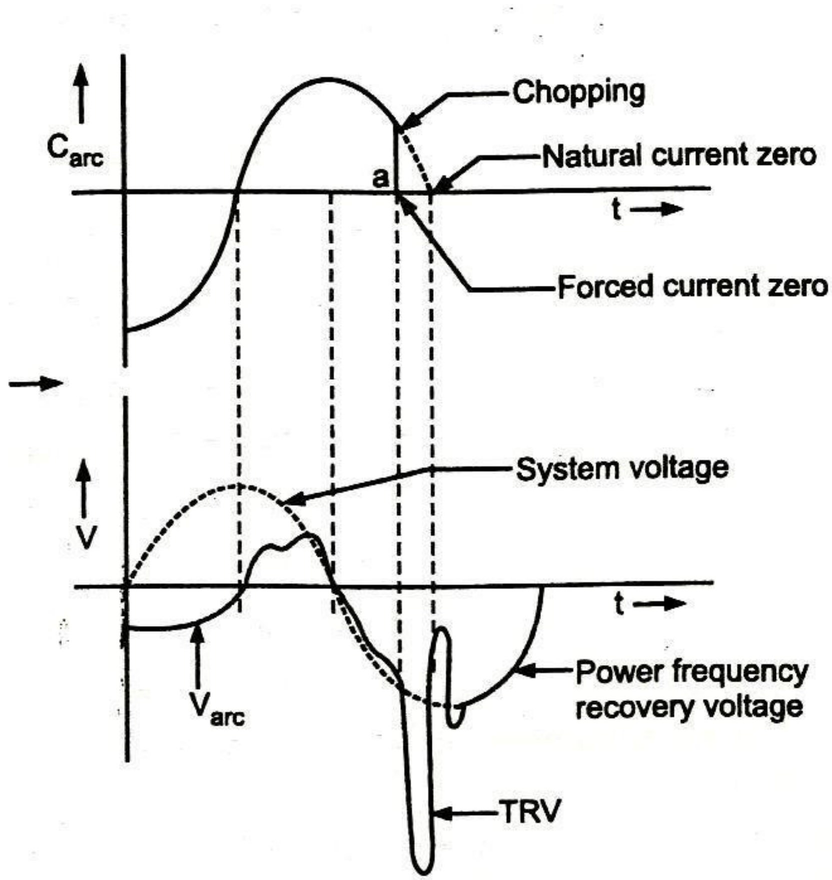
4.6 current chopping

Current chopping is a term that came to our vocabulary with the advent of vacuum switching which was commercially started back in the 1950‘s. Earlier switching means in air or oil are in terms of dielectric recovery rate relatively slow and as the main contacts would part the arc would go through several zero crossings before it would finally go out and the dielectric strength across the now open gap be strong to prevent a restrike, and thus continuation of current for a further half cycle. With the introduction of vacuum as a dielectric medium that has a completely different characteristic to that of air or oil dielectrics in so much that it has a very rapid dielectric recovery rate. Upon opening the main contacts of a vacuum interrupter whether is be a circuit breaker or a contactor, high velocity movements are easily obtained because of the low mass and small movements required to obtain arc isolation up to limited high voltages. As such, the arc will be extinguished at the first current zero and within half a cycle. Because of the rapid recovery rate of the dielectric, the arc, in vacuum interrupter will tend to go out before current zero which will result in an instantaneous current drop to zero and lead to an induced voltage or voltage transient being generated to down-stream equipment.



This can be seen by calculating the formula. Vt = IC xZ0 Vt – Voltage Transient IC – Current Chop Z0 – Surge Impedance Therefore if the current chop is .9 of an amp and the surge impedance is 3,000 ohm‘s, the voltage transient will equal 2700 volts on top of the RMS system voltage whether it be 4160 or 5KV. However if the current chop is 5 amps times surge impedance of 3,000 ohms, then the voltage transient can equal 15KV on top of the RMS supply voltage. You will notice from the above that some assumptions are made with regards to surge impedance values which are difficult to obtain and vary per circuit. In addition, the voltage transient value that a motor or dry type transformer will withstand is difficult to obtain from motor and transformer manufacturers. Therefore Joslyn Clark has taken the approach in their designs by the contact material mix gives an interrupt characteristic more than capable of handling the maximum horsepower rating lock rotor currents in terms of interrupt level and keeping the chopping current to an absolute minimum.

Over the years this philosophy has proven itself as unlike other manufacturers we have yet to see motor insulation problems created by our contactor. The motors manufactured to NEMA design standards which we consider high class or on motors produced to IEC standards which we consider to be of a lower class, cheaper version.


Chopping
Natural current zero
a
t
Forced current zero
System voltage
V
t
Power frequency
recovery voltage
TRV

UNIT V

CIRCUIT BREAKERS

5.1 Rating of Circuit Breaker

The **rating of a circuit breaker** includes,

1) Rated short circuit breaking current.
2) Rated short circuit making current.
3) Rated operating sequence of circuit breaker.
4) Rated short time current.

Short circuit breaking current of circuit breaker

This is the maximum short circuit current which a circuit breaker can withstand before it. Finally cleared by opening its contacts. When a short circuit flows through a circuit breaker, there would be thermal and mechanical stresses in the current carrying parts of the breaker. If the contact area and cross-section of the conducting parts of the circuit breaker are not sufficiently large, there may be a chance of permanent damage in insulation as well as conducting parts of the CB. The short circuit current has a certain value at the instant of contact separation. The breaking current refers to value of current at the instant of the contact separation. The rated values of transient recovery voltage are specified for various rated voltage of circuit breakers. For specified conditions of rated TRV and rated power frequency recovery voltage, a circuit breaker has a certain limit of breaking current. This limit is determined by conducting short circuit type tests on the circuit breaker. The waveforms of short circuit current are obtained during the breaking test. The evaluation of the breaking current is explained in Fig. 3. The breaking current is expressed by two values. The r.m.s values of a.c. components are expressed in KA. the standard values being 8, 10, 12.5, 16, 20, 25, 31.5, 40, 45, 63, 80 and 100KA. The earlier practice was to express the rated breaking capacity of a circuit breaker in terms of MVA given as follows Rated Breaking MVA capacity = $\sqrt{3}$ x KV x KA Where MVA = Breaking capacity of a circuit breaker kV KV = Rated voltage KA = Rated breaking current.

This practice of specifying the breaking capacity in terms of MVA is convenient while calculating the fault levels. However, as per the revised standards, the breaking capacity is expressed in KA for specified conditions of TRV and this method takes into account both breaking current and TRV. The breaking capacity can be both symmetrical and asymmetrical in nature. In asymmetrical breaking capacity the DC component of the current is added. While selecting the circuit breaker for a particular location in the power system the fault level at that location is determined. The rated breaking current can then be selected from standard range.

Rated short circuit making capacity

The short circuit making capacity of circuit breaker is expressed in peak value not in rms value like breaking capacity.It may so happen that circuit breaker may close on an existing fault. In such cases the current increase to the maximum value at the peak of first current loop. The circuit breaker should be able to close without hesitation as contact touch. The circuit breaker should be able to withstand the high mechanical forces during such a closure. These capabilities are proved by carrying out making current test. The rated short circuit making current of a circuit breaker is the peak value of first current loop of short circuit current (I pk)Which the circuit breaker is capable of making at its rated voltage. The rated short circuit making current should be least 2.5 times the r.m.s. value of a.c. component of rated breaking current . Rated making current = 1.8 x √2 x Rated short circuit breaking = 2.5 x Rated short circuit breaking current In the above equation the factor √2 convert the r.m.s value to peak value. Factor 1.8 takes into account the doubling effect of short circuit current with consideration to slight drop in current during the first quarter cycle .

Rated operating sequence or duty cycle of circuit breaker

This is mechanical duty requirement of circuit breaker operating mechanism. The sequence of rated operating duty of a circuit breaker has been specified as O – t – CO – t‟ – CO Where O indicates opening operation of the CB. CO represents closing operation immediately followed by an opening operation without any intentional time delay. t‟ is time between two operations which is necessary to restore the initial conditions and / or to prevent undue heating of conducting parts of circuit breaker. t = 0.3 sec for circuit breaker intended for first auto re closing duty, if not otherwise specified. Suppose rated duty circle of a circuit breaker is 0 – 0.3 sec – CO – 3 min – CO. This means, an opening operation of circuit breaker is followed by a closing operation after a time interval of 0.3 sec, then the circuit breaker again opens without any intentional time delay. After this opening operation the CB is again closed after 3 minutes and then instantly trips without any intentional time delay.

Rated short time current

This is the current limit which a circuit breaker can carry safely for certain specific time without any damage.

The circuit breakers do not clear the short circuit current as soon as any fault occurs in the system. There always some intentional and an intentional time delays present between the instant of occurrence of fault and instant of clearing the fault by CB. This delay is present because of time of operation of protection relays, time of operation of circuit breaker and also there may be some intentional time delay imposed in relay for proper coordination of power system protection. Hence, after fault, a circuit breaker has to carry the short circuit for certain time. The summation of all time delays should not be more than 3 seconds, hence a circuit breaker should be capable of carrying a maximum fault current for at least this short period of time. The short circuit current may have two major affects inside a circuit breaker.

1. Because of the high electric current, there may be high thermal stress in the insulation and conducting parts of CB.

2. The high short circuit current, produces significant mechanical stresses in differentcurrent carrying parts of the circuit breaker.

A circuit breaker is designed to withstand these stresses. But no circuit breaker has to carry a short circuit current not more than a short period depending upon the coordination of protection. So it is sufficient to make CB capable of withstanding affects of short circuit current for a specified short period.

The rated short time current of a circuit breaker is at least equal to rated short circuit breaking current of the circuit breaker.

Rated voltage of circuit breaker

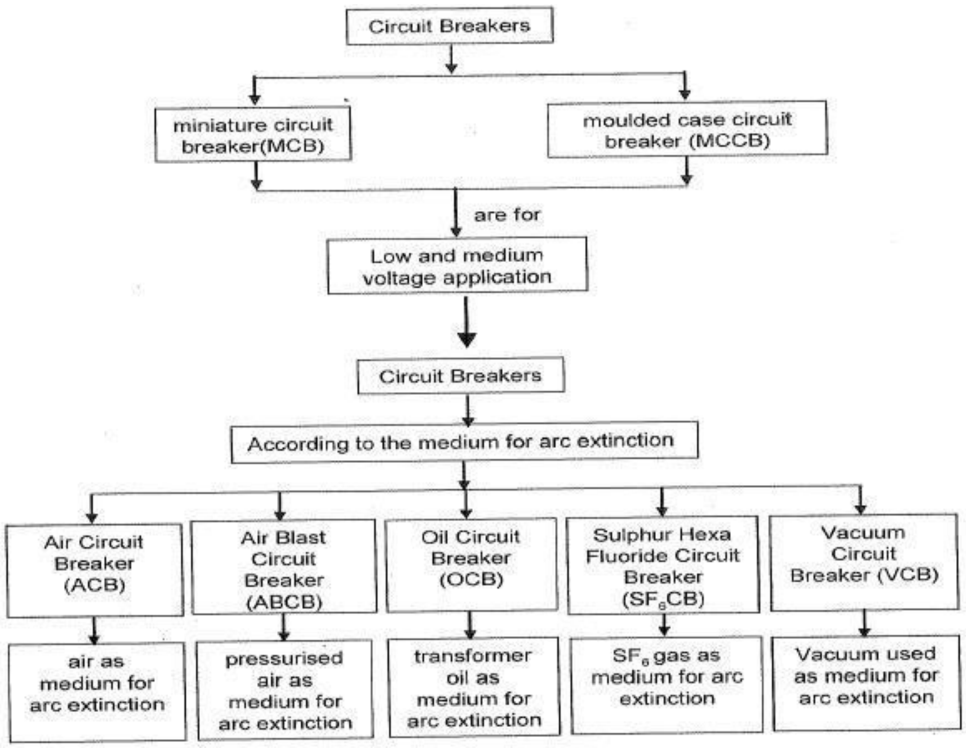
Rated voltage of circuit breaker depends upon its insulation system. For below 400 KV system, the circuit breaker is designed to withstand 10% above the normal system voltage. For above or equal 400 KV system the insulation of circuit breaker should be capable of withstanding 5% above the normal system voltage. That means, rated voltage of circuit breaker corresponds to the highest system voltage. This is because during no load or small load condition the voltage level of power system is allowed rise up to highest voltage rating of the system. A circuit breaker is also subject to two other high voltage condition.

1) Sudden disconnection of huge load for any other cause, the voltage imposed on the CB and also between the contacts when the CB is open, may be very high compared to higher system voltage. This voltage may be of power frequency but does not stay for very long period as this high voltage situation must be cleared by protective switchgear. But a circuit breaker may have to withstand this power frequency over voltage, during its normal life span.

The Circuit Breaker must be rated for power frequencies withstand voltage for a specific time only. Generally the time is 60 seconds. Making power frequency withstand capacity, more than 60 second is not economical and not practically desired as all the abnormal situations of electrical power system are definitely cleared within much smaller period than 60 seconds.

2) Like other apparatuses connected to power system, a circuit breaker may have also to face lightening impulse and switching impulses during its life span.

The insulation system of CB has to withstand these impulse voltage waveform. So a circuit breaker is designed to withstand this impulse peaky voltage for microsecond range only.



5.2 Air blast circuit breaker

This type of circuit breakers, is those kind of circuit breaker which operates in air at atmospheric pressure. After development of oil circuit breaker, the medium voltage air circuit breaker (ACB) is replaced completely by oil circuit breaker in different countries. But in countries like France and Italy, ACBs are still preferable choice up to voltage 15 KV. It is also good choice to avoid the risk of oil fire, in case of oil circuit breaker. In America ACBs were exclusively used for the system up to 15 KV until the development of new vacuum and SF6 circuit breakers.

Working principle of air circuit breaker(ACB)

The working principle of this breaker is rather different from those in any other types of circuit breakers. The main aim of all kind of circuit breaker is to prevent the reestablishment of arcing after current zero by creating a situation where in the contact gap will withstand the system recovery voltage. The air circuit breaker does the same but in different manner. For interrupting arc it creates an arc voltage in excess of the supply voltage. Arc voltage is defined as the minimum voltage required maintaining the arc. This circuit breaker increases the arc voltage by mainly three different ways,

1. It may increase the arc voltage by cooling the arc plasma. As the temperature of arc plasma is decreased, the mobility of the particle in arc plasma is reduced, hence more voltage gradient is required to maintain the arc.

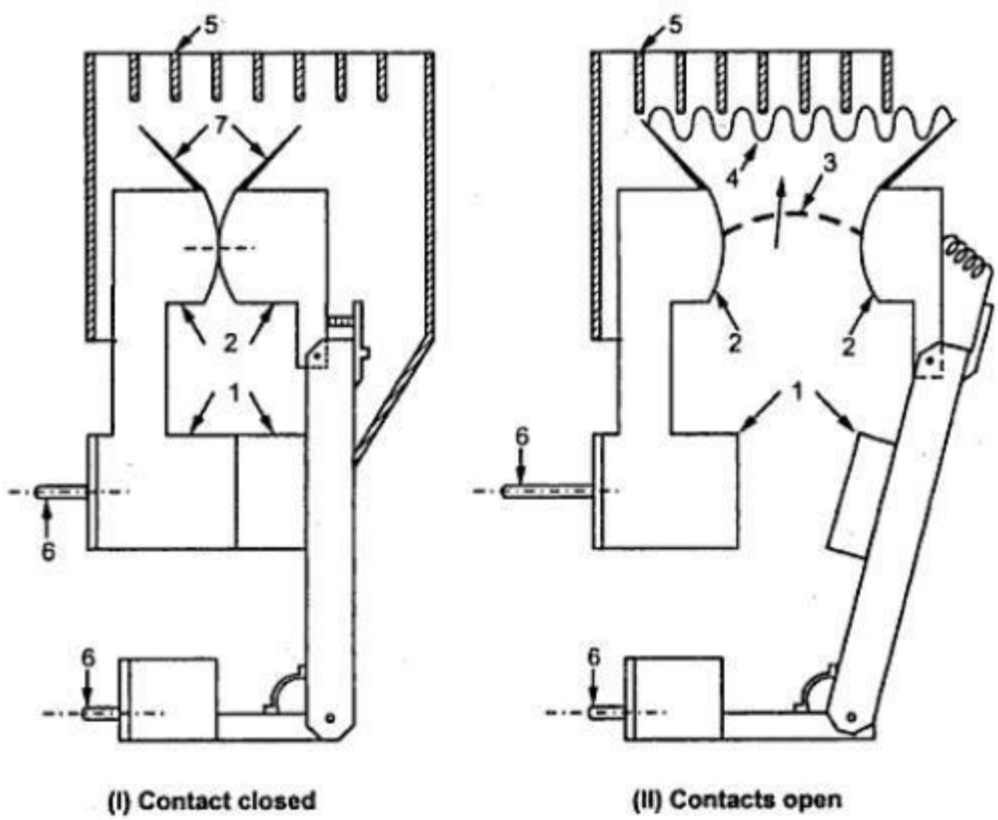
2. It may increase the arc voltage by lengthening the arc path. As the length of arc path is increased, the resistance of the path is increased, and hence to maintain the same arc current more voltage is required to be applied across the arc path. That means arc voltage is increased.

3. Splitting up the arc into a number of series arcs also increases the arc voltage.

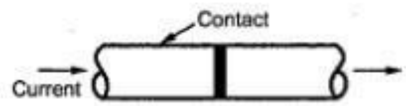
The *first objective* is usually achieved by forcing the arc into contact with as large an area as possible of insulating material. Every air circuit breaker is fitted with a chamber surrounding the contact. This chamber is called „arc chute‟. The arc is driven into it. If inside of the arc chute is suitably shaped, and if the arc can conform to the shape, the arc chute wall will help to achieve cooling. This type of arc chute should be made from some kind of refractory material

The *second objective* that is lengthening the arc path is achieved concurrently with the first objective. If the inner walls of the arc chute is shaped in such a way that the arc is not only forced into close proximity with it but also driven into a serpentine channel projected on the arc chute wall. The lengthening of the arc path increases the arc resistance.

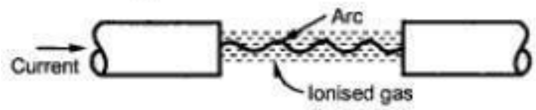
The *third objective* is achieved by using metal arc slitter inside the arc chute. The main arc chute is divided into numbers of small compartments by using metallic separation plates. These metallic separation plates are actually the arc splitters and each of the small compartments behaves as individual mini arc chute. In this system the initial arc is split into a number of series arcs, each of which will have its own mini arc chute.



1. Main contacts 4. Arcsplitterplates
2. Arcing contacts 5.Current carrying terminals
3. Arc rifling in the direction of the arrow 6. Arc runners Arc getting split



(a) Contact closed



(b) Contacts separated

In the air reservoir there is a high pressure air stored between 20 to 30 kg/cm2. And that air is taken from compressed air system. On the reservoir there are three hollow insulator columns mounted with valves at their base. On the top of the hollow insulator chambers there are double arc extinguishing chambers mounted. The current carrying parts connect the three arc extinction chambers to each other in series and the pole to the neighboring equipment, since there exist a very high voltage between the conductor and the air reservoir, the entire arc extinction chamber assembly is mounted on insulators. Since there are three double arc extinction poles in series, there are six breakers per pole. Each arc extinction chamber consists of one twin fixed contact. There are two moving contacts. The moving contacts can move axially so as to open or close. Its opening or closing mechanism depends on spring pressure and air pressure.

The operation mechanism operates the rods when it gets a pneumatic or electrical signal. The valves open so as to send the high pressure air in the hollow of the insulator. The high pressure air rapidly enters the double arc extinction chamber. As the air enters into the arc extinction chamber the pressure on the moving contacts becomes more than spring pressure and it causes the contacts to be open.

The contacts travel through a short distance against the spring pressure. At the end of contacts travel the part for outgoing air is closed by the moving contacts and the entire arc extinction chamber is filled with high pressure air, as the air is not allowed to go out. However, during the arcing period the air goes out through the openings and takes away the ionized air While closing, the valve is turned so as to close connection between the hollow of the insulator and the reservoir.

The valve lets the air from the hollow insulator to the atmosphere. As a result the pressure of air in the arc extinction chamber is dropped down to the atmospheric pressure and the moving contacts close over the fixed contacts by virtue of the spring pressure, the opening is fast because the air takes a negligible time to travel from the reservoir to the moving contact. The arc is extinguished within a cycle. Therefore, air blast circuit breaker is very fast in breaking the current. Closing is also fast because the pressure in the arc extinction chamber drops immediately as the value operates and the contacts close by virtue of the spring pressure.

Advantages:

- How air blast circuit breaker is better than oil circuit breaker:
- The growth of dielectric strength is so rapid that final contact gap needed for arc extinction is very small, this reduces the size of device.
- The risk of fire is eliminated.
- Due to lesser arc energy, air blast circuit breakers are very suitable for conditions where frequent operation is required.
- The arcing products are completely removed by the blast whereas the oil deteriorates with successive operations; the expense of regular oil is replacement is avoided.
- The energy supplied for arc extinction is obtained from high pressure air and is independent of the current to be interrupted.
- The arcing time is very small due to the rapid buildup of dielectric strength between contacts. Therefore, the arc energy is only a fraction that in oil circuit breakers, thus resulting in less burning of contacts.

Disadvantages:

- Considerable maintenance is required for the compressor plant which supplies the air blast.
- Air blast circuit breakers are very sensitive to the variations in the rate of restriking voltage.
- Air blast circuit breakers are finding wide applications in high voltage installations.Majority of circuit breakers for voltages beyond 110 kV are of this type.

5.3 Oil circuit breakers

Types Of Oil Circuit Breakers

Oil circuit breakers can be classified into following types:

1) Bulk oil circuit breakers

which use a large quantity of oil. In this circuit breaker the oil serves two purposes. Firstly it extinguishes the arc during opening of contacts and secondly it insulates the current conducting parts from one another and from the earthed tank. Such circuit breakers are classified into:

- Plain oil circuit breakers
- Arc control circuit breakers

In the former type no means is available for controlling the arc and the contacts are exposed to the whole of the oil in the tank. In the latter special arc control devices are employed to get the beneficial action of the arc as efficiently as possible

2) Low oil circuit breakers,

which use minimum amount of oil. In such circuit breakers oil is used only for arc extinction, the current conducting parts are insulated by air or porcelain or organic insulating material.

Construction

There are two chambers in a low oil circuit breaker; the oil in each chamber is separated from each other. The main advantage of this is that low oil is required and oil in second chamber won‘t get polluted. Upper chamber is called the circuit breaker chamber and lower one is called the supporting chamber. Circuit breaking chamber consists of moving contact and fixed contact. Moving contact is connected with a piston it‘s just for the movement of the contact and no pressure build due to its motion. There are two vents on fixed contact they are axial vent for small current produced in oil due to heating of arc and radial vents for large currents. The whole device is covered using Bakelite paper and porcelain for protection. Vents are placed in a tabulator.

Operation

Under normal operating conditions, the moving contacts remain engaged with the upper fixed contact. When a fault occurs, the moving contact is pulled down by the tripping springs and an arc is struck. The arc vaporizes oil and produces gases under high pressure. This action constrains the oil to pass through a central hole in the moving contact and results in forcing series of oil through the respective passages of the turbulator.The process of tabulation is orderly one, in which the sections of arc are successively quenched by the effect of separate streams of oil, moving across each section in turn and bearing away its gases

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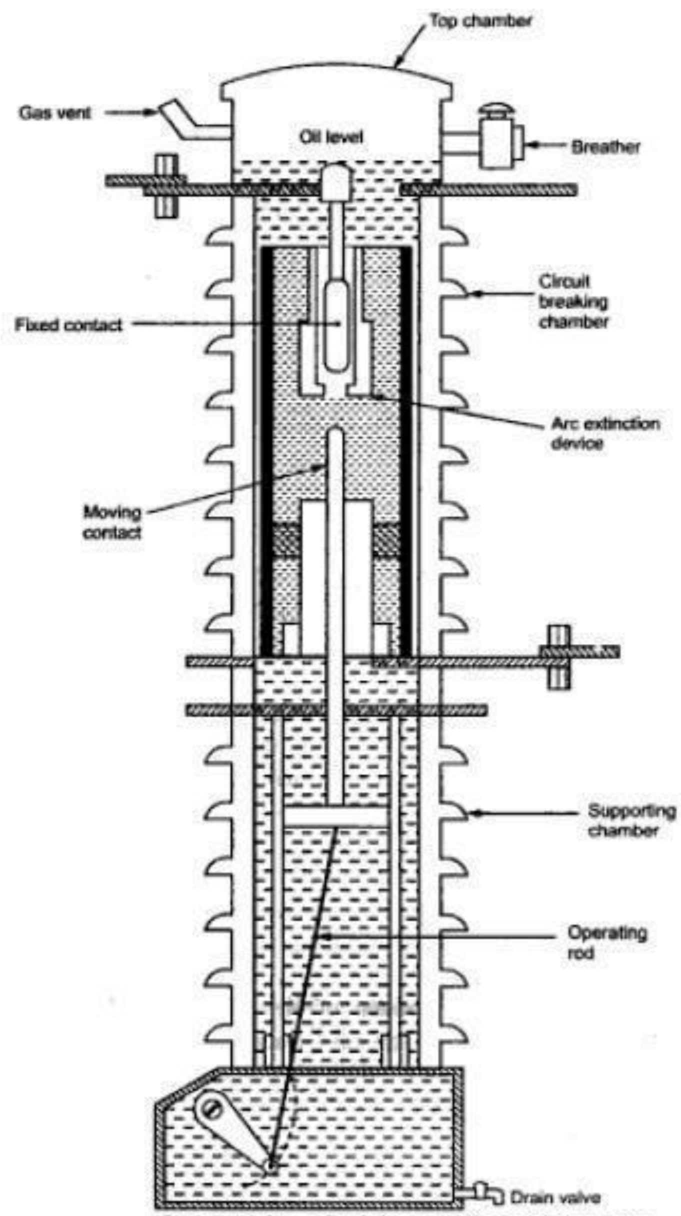
Advantages

A low oil circuit breaker has following advantages compared to bulk oil circuit breaker

- It requires lesser quantity of oil
- It requires smaller space
- There is reduced risk of fire
- Maintenance problems are reduced

Disadvantages

- Low oil circuit breaker has following disadvantages compared to bulk oil circuit breaker
- Due to smaller quantity of oil, the degree of carbonization is increased
- There is a difficulty of removing the gases from the contact space in time
- The dielectric strength of oil deteriorates rapidly due to high degree of carbonization.



Construction of minimum oil circuit breaker

5.4 SF6 circuit breaker.

At this point we are aware that the medium in which arc extinction of the circuit breaker takes place greatly influences the important characteristics and life of the circuit breaker. the working of a vacuum circuit breaker was illustrated. We already know that the use of vacuum circuit breaker is mainly restricted to system voltage below 38 kV. The characteristics of vacuum as medium and cost of the vacuum CB does not makes it suitable for voltage exceeding 38 kV. In the past for higher transmission voltage Oil Circuit Breaker (OCB) and Air Blast Circuit Breaker (ABCB) were used. These days for higher transmission voltage levels SF6 Circuit Breakers are largely used. OCB and ABCB have almost become obsolete. In fact in many installations SF6 CB is used for lower voltages like 11 kV, 6 kV etc.. i)sulphur Hexafluoride symbolically written as SF6 is a gas which satisfy the requirements of an ideal arc interrupting medium. So SF6 is extensively used these days as an arc interrupting medium in circuit breakers ranging from 3 kv upto 765 kv class. In addition to this SF6 is used in many electrical equipments for insulation. Here first we discuss in brief, some of the essential properties of SF6 which is the reason of it's extensive use in circuit breakers

SF6 gas has high dielectric strength which is the most important quality of a material for use in electrical equipments and in particular for breaker it is one of the most desired properties. Moreover it has high Rate of Rise of dielectric strength after arc extinction.

This characteristics is very much sought for a circuit breaker to avoid restriking.

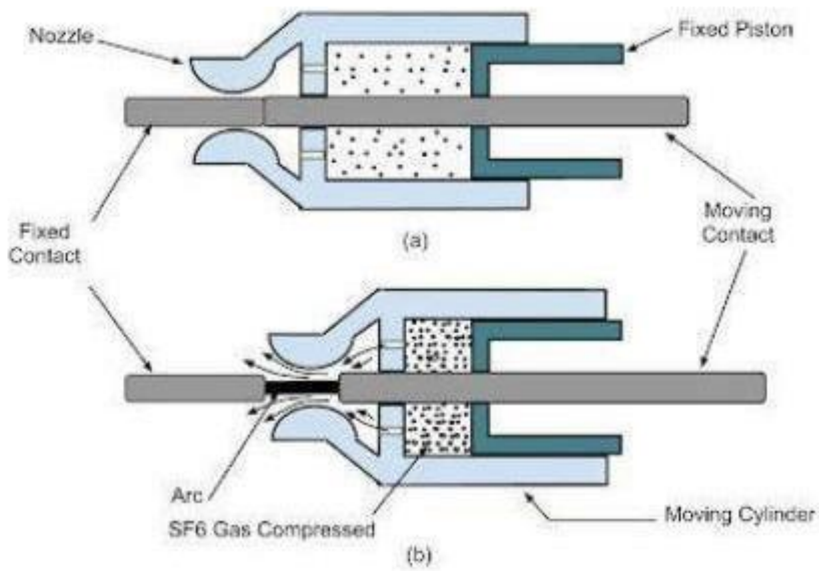
- SF6 is colour less, odour less and non toxic gas.
- SF6 is an inert gas. So in normal operating condition the metallic parts in contact with the gas are not corroded. This ensures the life of the breaker and reduces the need for maintenance.
- SF6 has high thermal conductivity which means the heat dissipation capacity is more. This implies greater current carrying capacity when surrounded by SF6 .
- The gas is quite stable. However it disintegrates to other fluorides of Sulphur in the presence of arc. but after the extinction of the arc the SF6 gas is reformed from the decomposition.
- SF6 being non-flammable so there is no risk of fire hazard and explosion.

A sulfur hexafluoride circuit breaker uses contacts surrounded by sulfur hexafluoride gas to quench the arc. They are most often used for transmission-level voltages and may be incorporated into compact gas-insulated switchgear. In cold climates, supplemental heating or de-rating of the circuit breakers may be required due to liquefaction of the SF6 gas.

Advantages:

- Due to superior arc quenching property of sf6 , such breakers have very short arcing time

- Dielectric strength of sf6 gas is 2 to 3 times that of air, such breakers can interrupt much larger currents.
- Gives noiseless operation due to its closed gas circuit
- Closed gas enclosure keeps the interior dry so that there is no moisture problem
- There is no risk of fire as sf6 is non-inflammable
- There are no carbon deposits
- Low maintenance cost, light foundation requirements and minimum auxiliary equipment
- sf6 breakers are totally enclosed and sealed from atmosphere, they are particularly suitable where explosion hazard exists



Disadvantages:

- sf6 breakers are costly due to high cost of sf6
- sf6 gas has to be reconditioned after every operation of the breaker, additional equipment is required for this purpose

CONSTRUCTION, PRINCIPLE OF OPERATION

The construction and working principles of SF6 circuit breaker varies from manufacturer to manufacturer. In the past double pressure type of SF6 breakers were used. Now these are obsolete. Another type of SF6 breaker design is the self blast type, which is usually used for medium transmission voltage. The Puffer type SF6 breakers of single pressure type are the most favored types prevalent in power industry. Here the working principle of Puffer type breaker is illustrated (Fig-A)

As illustrated in the figure the breaker has a cylinder and piston arrangement. Here the piston is fixed but the cylinder is movable. The cylinder is tied to the moving contact so that for opening the breaker the cylinder along with the moving contact moves away from the fixed contact (Fig-A(b)). But due to the presence of fixed piston the SF6 gas inside the cylinder is compressed. The compressed SFe gas flows through the nozzle and over the electric arc in axial direction. Due to heat convection and radiation the arc radius reduces gradually and the arc is finally extinguished at current zero.

The dielectric strength of the medium between the separated contacts increases rapidly and restored quickly as fresh SF6 gas fills the space. While arc quenching, small quantity of SF6 gas is broken down to some other fluorides of sulphur which mostly recombine to form SF6 again. A filter is also suitably placed in the interrupter to absorb the remaining decomposed byproduct.

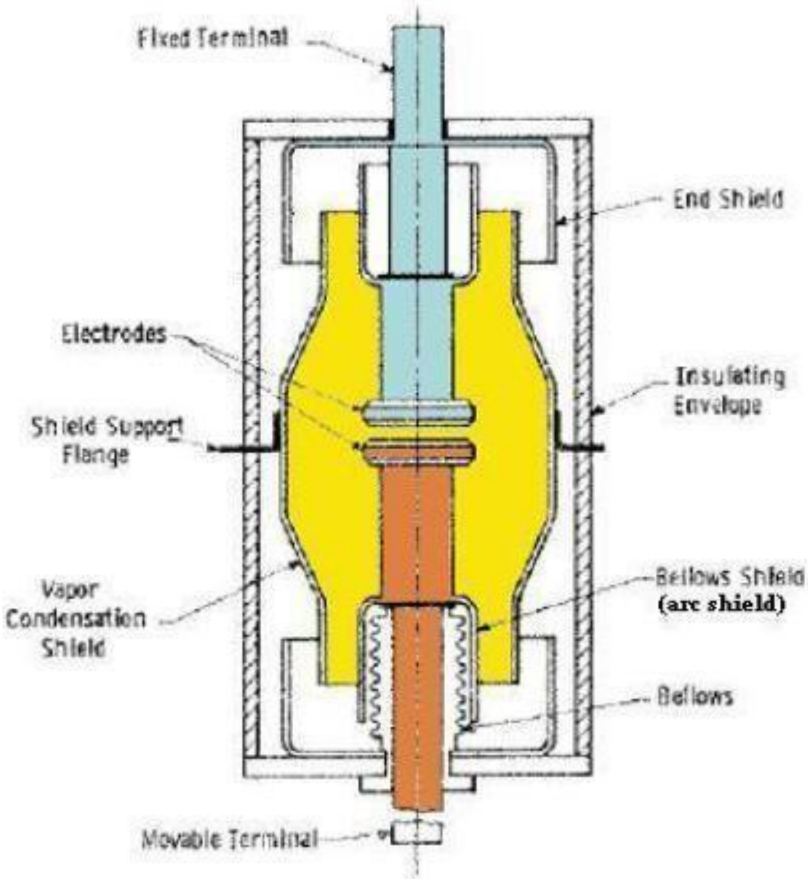
The gas pressure inside the cylinder is maintained at around 5 kgf per sq. cm. At higher pressure the dielectric strength of the gas increases. But at higher pressure the SF6 gas liquify at higher temperature which is undesired. So heater is required to be arranged for automatic control of the temperature for circuit breakers where higher pressure is utilised. If the SF6 gas will liquify then it loses the ability to quench the arc. Like vacuum breaker, SF6 breakers are also available in modular design form so that two modules connected in series can be used for higher voltage levels. SF6 breakers are available as both live tank and dead tank types. In Fig-B above a live tank outdoor type 400 kV SF6 breaker is shown.

5.5 vacuum circuit breakers

In this breaker, vacuum is being used as the arc quenching medium. Vacuum offers highest insulating strength, it has far superior arc quenching properties than any other medium. When contacts of a breaker are opened in vacuum, the interruption occurs at first current zero with dielectric strength between the contacts building up at a rate thousands of times that obtained with other circuit breakers. **Principle:** When the contacts of the breaker are opened in vacuum (10 -7 to 10 -5 torr), an arc is produced between the contacts by the ionization of metal vapours of contacts. The arc is quickly extinguished because the metallic vapours, electrons, and ions produced during arc condense quickly on the surfaces of the circuit breaker contacts, resulting in quick recovery of dielectric strength. As soon as the arc is produced in vacuum, it is quickly extinguished due to the fast rate of recovery of dielectric strength in vacuum

Construction:

Fig shows the parts of a typical vacuum circuit breaker. It consists of fixed contact, moving contact and arc shield mounted inside a vacuum chamber. The movable member is connected to the control mechanism by stainless steel bellows .This enables the permanent sealing of the vacuum chamber so as to eliminate the possibility of leak .A glass vessel or ceramic vessel is used as the outer insulating body. The arc shield prevents the deterioration of the internal dielectric strength by preventing metallic vapours falling on the inside surface of the outer insulating cover.



Working:

When the breaker operates the moving contacts separates from the fixed contacts and an arc is struck between the contacts. The production of arc is due to the ionization of metal ions and depends very much upon the material of contacts. The arc is quickly extinguished because the metallic vapours, electrons and ions produced during arc are diffused in short time and seized by the surfaces of moving and fixed members and shields. Since vacuum has very fast rate of recovery of dielectric strength, the arc extinction in a vacuum breaker occurs with a short contact separation.

Advantages:

- They are compact, reliable and have longer life.
- There are no fire hazards
- There is no generation of gas during and after operation
- They can interrupt any fault current. The outstanding feature of a VCB is that it can break any heavy fault current perfectly just before the contacts reach the definite open position.
- They require little maintenance and are quiet in operation

- Can withstand lightning surges
- Low arc energy
- Low inertia and hence require smaller power for control mechanism.

Applications:

- For outdoor applications ranging from 22 kV to 66 kV. Suitable for majority of applications in rural area.

5.6 testing of circuit breakers

Primary injection test

For primary injection testing, high current is injected on the primary side of the current transformer. The entire chain – current transformer, conductors, connection points, relay protection and sometimes circuit breakers as well is covered by the test. The system being tested must be taken out of service during primary injection testing. Testing is usually conducted in connection with commissioning. The only way to verify that a direct-acting low voltage circuit breaker operates properly is to inject a high current.

Motion

A high-voltage breaker is designed to interrupt short-circuit current in a controlled manner. This puts great demands on the mechanical performance of all components in the interrupter chamber as well as the operating mechanism. It has to operate at a specific speed in order to build up adequate pressure to allow for cooling stream of air, oil or gas (depending on the type of breaker) to extinguish the arc that is generated after the contact separation until the next zerocrossing. It is important to interrupt the current to prevent a re-strike. This is accomplished by making sure that the contacts move apart far enough from each other before the moving contact has entered the so-called damping zone. The distance throughout which the breaker's electric arc must be extinguished is usually called the arcing zone. From the motion curve, a velocity or acceleration curve can be calculated in order to reveal even marginal changes that may have taken place in the breaker mechanics. The contact travel motion is captured by connecting a travel transducer on the moving part of the operating mechanism. The transducer provides an analogue voltage relative to the movement of the contact. The motion is presented as a curve where distance vs. time allows for further analysis. From the motion curve, a velocity or acceleration curve can be calculated in order to reveal changes in the breaker mechanics that may affect the breakers operation.

Travel

The travel trace indicates the instantaneous position of the circuit beaker contacts during an operation. This gives important information such as total travel, overtravel, rebound, undertravel, contact wipe or penetration of movingcontact or operating-rod position at the time of close or open, and anomalies which are evident from the trace.

Speed

Speed is calculated between two points on this motion curve. The upper point is defined as a distance in length, degrees or percentage of movement from a) the breaker's closed or open position, or b) the contact-closure or contact- separation point. The time that elapses between these two points ranges from 10 to 20 ms, which corresponds to 1-2 zero-crossovers. The lower point is determined based on the upper point. It can either be a distance below the upper point or a time before the upper point. The single most important benefit derived from the instantaneous velocity and acceleration curves is the insight that they provide into the forces involved during the operation of a circuit breaker.

Acceleration

Average acceleration can be calculated from the velocity trace.

Damping

Damping is an important parameter to monitor and test as the stored energy an operating mechanism use to open and close a circuit breaker is considerable. The powerful mechanical stress can easily damage the breaker and/or reduce the breaker's useful life. The damping of opening operations is usually measured as a second speed, but it can also be based on the time that elapses between two points just above the breaker's open position.

EE 2402 — PROTECTION AND SWITCHGEAR **Question bank**

UNIT 1

INTRODUCTION

PART A

1. What is surge absorber? How do they differ from surge diverter?
2. What is meant by insulation co-ordination?
3. Define the terms a) pick up value b) Reset value
3. What is time setting and plug setting multiplier ?
4. What are the causes of over voltages?
5. Define the term arcing ground
6. How the transmission lines are protected against direct lightning strokes?
7. What is a Peterson Coil?
8. List the merits and demerits of solid grounding
9. Defined the term switch gear
10. What type relay is best suited for long distance very high voltage transmission lines?
11. Define selectivity of protective relaying
12. Mention the different sources of over voltages in power system
13. List the basic requirements of lightning arrester
14. What are the demerits of a resistance grounded system?
15. Defined Breaker time
16. What are the causes over voltages on power system?
17. What is meant by voltage surge?
18. What is ground wire?
19. What is a protector tube?
20. Define basic impulse level.
21. A relay is connected to 400/5 ratio current transformer with current setting of 150%.Calculate the Plug Setting Multiplier when circuit carries a fault current of 4000 A
21. List the common protective scheme which are used for modern power system protection
22. What is the need for calculation short circuit current
23. What is the need for power system earthing
24. What is the need for protection
25. What are the protective zone of the power system

26. List at least two merits of resistance grounded system
27. How is arcing around avoided

PART B

1. Describe the essential qualities of a protective relaying
2. Briefly explain the various methods of overvoltage protection of Overhead transmission line
3. With a neat block diagram, explain the operating principle of Peterson coil
4. Discuss the symmetrical components methods to analyze an unbalanced system
5. Write short note on surge absorber
6. Discuss the basic ideas of insulation coordination in the practical power System
7. Discuss and compare the various methods of neutral earthing
8. What do you understand by a zone of protection? Discuss various types of Zones of protection.
9. Describe types of lightning arrester
10. What are the requirements of a ground wire for protecting power conductors against direct lightning stroke? Explain how they are achieved in practice

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UNIT II

OPERATING PRINCIPLES AND RELAY CHARACTERISTICS

PART A

1. List the basic requirements of protective relay
2. What are the merits of mho relay?
3. Write the applications of attracted armature type electromagnetic relay
4. What are the different types of electromagnetic relays?
5. What is an under frequency relay?
6. What are the uses of Buchholz's relay?
7. What is meant by drop off / pick up ratio?
8. What is the need of relay coordination?
9. What are the different inverse time characteristics of over current relays? Mention how characteristics can be achieved in practice for an electromagnetic relay.
10. What are the advantages of static relays?
11. Write the applications of distance relay.
12. What type relay is best suited for long distance very high voltage

transmission lines?

13. What is meant by relay operating time?
14. Write the function of earth fault relay
15. List out the applications of static relays
16. Compare Static and Electromagnetic relay
17. What are the advantages of over current relays over electromagnetic types?
18. Define the term pilot with reference to power line protection.
19. What are the features of directional relay?
20. State the advantages, disadvantage and applications of electromagnetic relays
21. Give the block diagram for a basic static distance relay scheme
22. Draw the characteristics of a directional impedance relay and mho relay on an R-X diagram
23. What are the function of protective relay
24. What is relay
25. What is meant by biasing of relay
26. What is meant by time setting multiplier in protective relay
27. A relay is connected to 400/5 ratio current transformer with current setting of 150%. Calculate the Plug Setting Multiplier when circuit carries a fault current of 4000A.

PART B

1. Describe the construction and operation of an electromagnetic inductive relay with neat diagrams

2 Explain the principle of distance relays stating clearly the difference between impedance relay, reactance and mho relay. Indicate the difference on R-X diagrams and show where each type is suitable.

3 Describe the construction and operation of an electromagnetic relay with neat diagram

4. Describe the construction and principle of operation of an induction type directional over current relay Also explain its operational characteristics

5. Explain with the help of neat diagrams the construction and working of induction type directional power relay & non-directional over current relay

6. i) What is a static relay? What are the merits and demerits of static relays over electromagnetic relays also mention its applications. (8)

   ii) Explain with the help of neat sketch the working principle and operation of attracted armature type electromagnetic relay (8)

7. Describe the operating principle, constructional features and area of applications of directional relay. How do you implement directional feature in the over current relay?

8. Explain MHO relay characteristic on the R-X diagram. Discuss the range setting of various distances relays placed on a particular location

9. Write short notes on the following

   (a) Under frequency relays (8)

   (b) Negative sequence relays (8)

10. i) A 3-Phase 11KV,25000KVA alternator with X_{go}=0.05 p.u , X_1=0.15 p.u & X_2=0.15 p.u is grounded through a reactance of 0.3 ohms .calculate the Line current for a single line to ground fault (8)

    ii) Write about the classifications of relays. (8)

UNIT III

APPARATUS PROTECTION

PART A

1. Define the term pilot with reference to power line protection
2. Give the limitations of Merz Price protection?
3. List out the applications of Buchholz's relay.
4. What are the causes of over speed and how alternators are protected from it?
5. What are the problems arising in differential protection in power transformer and how are they overcome?
6. Define the term burden on CT.
7. What is meant by time graded protection?
8. Explain the secondary of the current transformer should not be open.
9. What is R-X diagram?
10. Write the function of earth fault relay.
11. What is over fluxing protection of a transformer?
12. What is current grading of relays?
13. What is the most severe fault in the transmission line?
14. Write the effects of loss of excitation.
15. Classify the various bus bar faults
16. Why the secondary of C.T should not be open
17. Classify the various bus bar faults
18. List the common faults that occur in a generator
19. Which type of relays are used to protect transmission line

20. What are the faults which will occur in an alternator
21. Which type of relay is used to protect transmission line
22. What are the common methods used for line protection
23. Mention the different between CT used for protection and measurement
24. What are the problems associated with bus zone differential protection
25. What are the main safety device available with transformer

PART B

1. Explain with the help of neat sketch the working principle and operation of under frequency relay
2. Explain with a neat diagram the application of Merz price circulating current principle for the protection of the alternator.
3. Describe the construction and working of Buchholz relay
4. A star connected 3-phase,20MVA,11KV Alternator has a per phase reactance of 0.75 ohms/phase .It is protected by Merz price circulating current principle which is to operate for fault currents not less than 175A. Calculate the value of earthing resistance to be provided in order to ensure only 10% of the alternator winding remains unprotected.
5. Explain the features that cause difficulty in applying Merz-Price Circulating current principle to a power transformers
6. A three phase of 220/11000 line volts is connected in star/delta. The protective transformers on 220V side have a current ratio of 600/5.What should be the current transformer ratio on 11000V side.
7. Describe the differential pilot wire method of protection of feeder.
8. Describe the types of protective schemes employed for the protection of field winding and loss excitation of alternator.
9. With aid of neat schematic diagram, describe the percentage differential protection scheme of a transformer.
10. Explain the principle of percentage biased differential protection with necessary diagrams. Also discuss its applications
11. Explain Mho relay characteristics on R-X diagram. Discuss the range settings of various distance relays placed on a particular location.
12. Explain with the help of neat sketch, the working principle and operation of negative sequence relay.
13. A 10 MVA, 6.6 kV, 3 phase star connected alternator is protected by Merz-Price circulating current system. If the ratio of the current transformers is 1000/5, the minimum operating current for the relay is 0.75 A and the neutral point earthing resistance is 6 Ω. Calculate
14. i) The percentage of each of the stator windings which is unprotected against earth faults when the machine is operating at normal voltage. (8)

ii)The minimum resistance to provide protection for 90% of the stator winding. (8)

15. Explain in detail, operation of measuring CT and protection CT with distinctive sketch
16. A 3 phase transformer having line voltage ratio of 440 V / 11 kV is connected in star – delta. The protection transformer on the LV side has a ratio of 500 / 5. What must be the ratio of the protection transformer connected on HV side?

UNIT IV

THEORY OF CIRCUIT INTERRUPTION

PART A

1. List the factors affecting the transient recovery voltage.
2. Define the term "rate of rise of recovery voltage".
3. Give the difference between isolator and circuit breaker.
4. Mention the methods of arc interruption.
5. Differentiate a.c. and d.c. circuit circuit breaking
6. Discuss the arc phenomenon in a circuit breaker.
7. What are the basic requirements of a circuit breaker?
8. What are the disadvantages of an Air blast circuit breaker?
9. What is meant by recovery voltage?
10. What is resistance switching?
11. What do you meant by current chopping?
12. What is the importance of arc resistance? On which factor does it depend?
13. State the different methods of arc extinction
14. Define restriking voltage
15. What are the problems encountered in the interruption of capacitive currents
16. What are the methods used in quenching the arc circuit breaker
17. List the factors on which the arc resistance depends
18. Distinguish between recovery voltage and restriking voltage
19. What is the principle involved in High resistance interruption

PART B

1. Discuss the recovery rate theory and energy balance theory of arc interruption scheme of a transformer.
2. Explain the phenomenon of current chopping in a circuit breaker. What is the effect of current Chopping on the circuit breaker as well as on the system?
3. Derive an expression for Restriking voltage and rate of rise of restriking voltage in terms of system Voltage, inductance up to the fault location and bushings to earth capacitance of the circuit breaker.
4. i) Write short note on resistance switching.(8)

   ii) Describe the operating principle of DC circuit breaker.(8)
5. (i) Calculate the RRRV of 132 kV circuit breaker with neutral earthed circuit breaker data as : broken current is symmetrical, restriking voltage has frequency of 20 kHz, power factor is 0.15. Assume fault is also earthed.(8)

   (ii)Discuss the selection of circuit breakers for different ranges of system voltages (8)
6. State the principle of arc extinction. What are the methods of arc extinction? Describe them in detail.

UNIT V
CIRCUIT BREAKERS
PART A

1. What are the ratings of a circuit breaker?
2. What are the quenching factors in an Oil circuit breaker?
3. What is meant by making capacity of a circuit breaker?
4. How do you classify the circuit breakers.
5. Suggest a suitable choice of circuit breakers for the following voltage ranges:
   (a) 3.3kV to 33kV, (b) 400kV to 760kV.
6. What is Peterson coil? What protective functions are performed by this device?
7. Give the advantage of SF_6 circuit breaker over Air blast circuit breaker.
8. A three-phase oil circuit breaker is rated at 1500 A, 1000MVA and 33kV Find (a) rated symmetrical breaking current, (b) making capacity.
9. What are the disadvantages of an Air blast circuit breaker?
10. What are the basic requirements of a circuit breaker?
11. Write the operational difference between fuse and circuit breakers?
12. Enumerate the breaking capacity of circuit breaker.
13. How do you classify circuit breaker.

14. List the factors affecting the Transient Recovery voltage.
15. What are the significance of reliability tests on circuit breaker
16. What are the advantages of SF6 breakers
17. List the routine tests that are carried out on circuit breaker
18. What are the advantages of oil circuit breaker
19. What are the application of air blast circuit breaker
20. What are the disadvantage the plain break oil circuit breaker
21. Classify different types of circuit breaking.

PART B

1. With a neat diagram, discuss the constructional details and operational features of a typical minimum oil circuit breaker. Also state its advantages and disadvantages over others.
2. Explain the properties of vacuum, arc phenomenon, constructional details, working principle, merits and applications of vacuum circuit breakers.
3. Explain in detail the constructional features, principle of working, advantages and applications of SF_6 circuit breaker with a neat diagram.
4. Briefly describe the testing of circuit breakers
5. (i) A 50 Hz, 3 phase alternator has rated voltage 12 kV, connected to circuit breaker, inductive reactance 5 ohms/phase, C= 3μF. Determine maximum RRRv, peak restriking voltage and frequency of oscillations. (8)

   (ii) Discuss the selection of circuit breakers for different ranges of system voltages (8)
6. With a neat block diagram, explain the construction, operating principles and merits of air blast circuit breaker.
7. Write brief note on

   (i) Vacuum circuit breaker (8)

   (ii) Testing of circuit breaker. (8)
8. Discuss how breaking capacity and making capacity of a circuit breaker are tested in a laboratory type testing stations.

	UNIT I PROTECTION SCHEMES
	PART A
1.	**How does the over voltage surge affect the power system?**
	The over voltage of the power system leads to insulation breakdown of the equipment. It causes the line insulation to flash over and may also damage the nearby transformer, generators and the other equipment connected to the line.
2.	**State the essential qualities of protection.**
	i) Reliability – Ability of relay to operate under predetermined conditions. ii) Selectivity-Ability of protective system to identify the faulty part correctly. iii) Fastness of operation – Disconnection of faulty system as fast as possible. iv) Discrimination –Ability to distinguish between normal and abnormal operating conditions v) Sensitivity-Ability of the system to operate with low value of actuating quantity.
3.	**Give the consequences of short circuit or What are the effects of short circuit faults in power system if uncleared? (Nov/Dec 2018) (April/May 2019)**
	When a short-circuit occurs, the current in the system increases to an abnormally high value while the system voltage decreases to a low value. The heavy current due to short-circuit causes excessive heating which may result in fire or explosion. Sometimes short-circuit takes the form of an arc and causes considerable damage to the system. If the voltage remains low for even a few seconds, the consumer's motors may shut down and generators on the power system may become unstable due to loss of synchronism.
4.	**What is the need of relay coordination?**
	The operation of a relay should be fast and selective, i.e., it should isolate the fault in the shortest possible time causing minimum disturbance to the system. Also, if a relay fails to operate, there should be sufficiently quick backup protection so that the rest of the system is protected. By coordinating relays, faults can always be isolated quickly without serious disturbance to the rest of the system.
5.	**Define Energizing quantity.**

	It is the electrical quantity i.e., current or voltage either alone or in combination with other electrical quantities required for the functioning of the relay. The quantity either current or voltage which is the input to the relay energizes the trip coil of the relay which in turn trips the circuit in case of faults.
6.	**What is protected zone? (Apr/May 2015) (Apr/May 2019) (Apr/May 2021)**
	Protected zones are those which are directly protected by a protective system such as relays, fuses, or switchgears. When a fault occurs in a zone, it can be immediately detected and isolated by a protection scheme which is dedicated to that zone. To limit the extent of the fault, power system protection is arranged in zones. Ideally, the zones of protection should overlap, so that no part of the power system is left unprotected.
7.	**What are the various faults that would affect an alternator?**
	i)Phase to phase faults ii) Phase to earth faults iii) Inter turn faults iv) Earth faults v) Fault between turns vi) Loss of excitation due to fuel failure vii) Over speed viii) Loss of drive ix) Vacuum failure resulting in condenser pressure rise, resulting in shattering of the turbine low pressure casing.
8.	**State the significance of double line fault.**
	Double line to ground fault occurs when two lines are short circuited and is in contact with the ground. This type of fault occurrence ranges from 15 to 25%. It has no zero sequence component and the positive and negative sequence networks are connected in parallel. Since zero sequence components are absent there is no circulating current.
9.	**What is primary protection? (Nov/Dec 2017)**
	Primary protection is the protection in which the fault occurring in a line will be cleared by its own relay and circuit breaker. It serves as the first line of defense. Primary protection provides quick-acting and selective clearing of a fault within the boundary of the circuit section or element it protects.
10.	**What are the different types of earthing ? (Apr/May 2015) (Apr/May 2021)**
	i.Solid earthing –Neutral directly connected to earth by metallic connection. ii.Resistive earthing-Neutral is connected to earth through a metallic resistor. iii.Reactance earthing –Reactance is connected between neutral and earth. iv.Resonant earthing-Has arc suppression coil to make the arcing earth fault self extinguishing

11.	**State the significance of single line to ground fault.**
	In single line to ground fault all the sequence networks are connected in series. All the sequence currents are equal and the fault current magnitude is three times its sequence currents.
12.	**What is surge absorber? How do they differ from surge diverter? (Nov/Dec 2011)**
	Surge absorber is a device designed to protect electrical equipment from transient high voltage to limit the duration and amplitude of the following current. Surge diverter discharges the impulse surge to the earth and dissipates energy in the form of heat.
13.	**Define the term "insulation coordination" (Nov/Dec 2011)**
	The selection of the insulation strength of equipment in relation to the voltages, which can appear on the system for which the equipment is intended and considering the service environment and the characteristics of the available protective device**.**
14.	**What are the various types of faults occurring in a power system? (May/June 2012)(May/June 2014) (May/June 2017) (Nov/Dec 2017)**
	Series Fault: a) One open conductor fault b) Two open conductor fault Shunt Fault: (a) Symmetrical or balanced fault (i) Three phase Fault (LLLG) (b) Unsymmetrical or unbalanced fault (i) Line to line fault(LL)(ii) Line to ground fault (LG)(iii) Double line to ground fault.(LLG).
15.	**How are arcing grounds avoided? (May/June 2012)**
	The presence of inductive and capacitive currents in the isolated neutral system leads to formation of arcs called as arcing grounds. The surge voltage due to arcing ground can be removed by using the arc suppression coil or Peterson coil. The arc suppression coil has an iron cored tapped reactor connected in neutral to ground connection. The reactor of the arc suppression coil extinguishes the arcing ground by neutralizing the capacitive current.
16	**What are the effects of power system faults? (Nov/Dec 2012)**
	i) Increase in current above rated value which can damage the power system equipment ii) Over heating due to increase in current causes Insulation failure iii) The heavy currents produce over heating and high mechanical stress which

	causes equipment damage.
17	**What is back up protection? (Nov/Dec 2012)**
	Back up protection is the second line of defense, which operates if the primary protection fails to activate within a definite time delay. The backup protection provides the back up to the main protection whenever it fails in operation or its cut out for repairs. The backup protection is essential for the proper working of the electrical system.
18	**What is meant by pick-up current? (May/June 2013)(Nov/Dec 2014)**
	The minimum current at which the relay armature is attracted to close the trip circuit is called pick-up current. In most of the relays, the pick up current is also indicated in the relay name plate details.
19	**Write the sources of fault power. (Nov/Dec 2013)**
	The fault power can be originated from the generation (faults in alternator) or transmission (short circuit) or from the distribution side(loads). Also the fault power can be from external sources like lightning.
20	**List out the duties of fault limiting reactors. (Nov/Dec 2013)**
	The duties of fault limiting reactors are to i) limit the fault current and to eliminate the arcing ground. ii) Limiting the fault current and avoid spreading of fault to maintain continuity of supply. Protect various equipment from overheating and failure due to excessive short circuit forces.
21	**What are the functions of protective relays? (May/June 2013) (Apr/May 2015)**
	To detect the fault and initiate the operation of the circuit breaker and to isolate the defective element from the rest of the system, thereby protecting the system from damages occurring due to fault.
22	**What is the necessity for earthing? (Nov/Dec 2014) (May/June 2014) (Nov/Dec 2015)(Nov/Dec 2019)**
	When earthing is provided it ensures the safety of personnel against electrical shocks and avoids accidents. The potential of earthed body does not reach to dangerously high value above earth since it is connected to earth. Also the earth fault current flows through the earthing and may cause operation of fuse or an

	earth relay.
23.	**What is the difference between short circuit and an overload?(Nov/Dec2015)(May/June2016)**
	On the occurrence of short circuit, the voltage at the point of fault falls to zero and the current in the network increases abnormally to a higher value. But in the case of overload reduction in the terminal voltage of the equipment occurs but the voltage will never fall to zero. Similarly the current also increases to a higher value but not as high as in the case of short circuit.
24	**What is the difference between primary and back up protection? (May/June 2016) (Nov / Dec 2019)**
	Primary protection is the protection in which the fault occurring in a line will be cleared by its own relay and circuit breaker. It serves as the first line of defense. Instantaneous relays are used. Back up protection is the second line of defense, which operates if the primary protection fails to activate within a definite time delay. Relays with definite time lag is used.
25	**Why earth wire is provided in overhead transmission lines? (May/June 2016) (Nov / Dec 2019)**
	Earthing wire usually consists of a Low Resistance wire connected to earth or buried into Earth. It's nothing but a Low Resistance path. Whenever there is a fault or abnormal operation or any external activities, the current flows through the earth wire and charges are discharged into the ground. If a fault occurs, current follows through earth wire first and the electrical equipment is protected.
26	**What do you mean by dead spot in zones of protection?**
	In practice, various protective zones are overlapped. The overlapping of protective zones is done to ensure complete safety of each and every element of the system. The zone which is unprotected is called dead spot. The zones are overlapped and hence there is no chance of existence of a dead spot in a system. If there are no overlaps, then dead spot may exist which means the circuit breakers lying within the zone may not trip even though the fault occurs. This may cause damage to the healthy system.

27	**State the difference between circuit breaker and switch. (May/June 2017)**

Circuit breaker	Switch
a. A mechanical switching device capable of making, carrying and breaking currents under normal conditions and abnormal conditions like short circuit.	a. A mechanical switching device capable of making , carrying and breaking currents under normal conditions but not breaking under abnormal conditions such as short circuit.
b. It is an automatic device.	b. A switch is operated manually.

28	**Why protection scheme is required for power system? (April/May 2018)**
	An electrical power system consists of generators, transformers, transmission lines and distribution stations etc., Short circuits and other abnormalities often occur in power systems which cause heavy short circuit currents. The heavy current associated with short circuits will cause damage to the equipment if suitable protective relays and circuit breakers are not provided.
29	**Write down the importance of symmetrical components for fault current calculation. (April/May 2018)**
	The method of symmetrical components is used to simplify fault analysis by converting a three-phase unbalanced system into two sets of balanced phasors and a set of single-phase phasors, or symmetrical components. These sets of phasors are called the positive, negative, and zero-sequence components. These components enable the simplified analysis of power systems under faulted or other unbalanced conditions. Once the system is solved in the symmetrical component domain, the results can be transformed back to the phase domain.
30	**How protective relays are classified based on functions? (Nov/Dec 2018)**
	The protective relays are classified in the following few categories. • Directional Over current Relay • Distance Relay • Over voltage Relay • Differential Relay • Reverse Power Relay
	Part B
1.	What do you understand by a zone of protection? Discuss various zones of protection. **(Nov/Dec 2015) (April/may 2018) (Nov/Dec 2018) (April/May**

	2019) (Apr/May 2021) (May/June 2016) (April/May 2021)
2.	(i) Briefly discuss the role of protective relays in a modern power system. **(Nov/ Dec 2012)** (ii)Describe the essential qualities of protective relaying system **(May/June 2012) (Dec 2014) (Nov/Dec 2018) (April/May 2019) (Apr/May 2021) (May/June 2016) (Nov/ Dec 2012)**
3.	Briefly discuss the operation of the following: i) Surge absorbers and surge diverters ii) Petersons coil **(Apr/May 2015) (Nov/Dec 2014) (May/June 2012) (Nov/Dec 2014))(May/June 2016) (April/May 2019) (May/June 2017)**
4.	Write short notes on the following: i) Various principles of power system protection ii) Power system earthing iii) Insulation co- ordination (**May/June 2013)(May/June 2014)**
5.	i) Discuss the importance of the protective scheme employed against lightning and switching surges. **(May/June 2013)** (ii) Enumerate the basic ideas of insulation coordination. **(Nov/Dec 2013)(May/June 2014) (Apr/May 2015)**
6.	Briefly explain the various methods of overvoltage protection of overhead transmission line **(May/June 2014) (Nov/Dec 2011)**
7.	Discuss the need and compare various methods of neutral earthing? **(May/June 2016) (April/may 2018) (Nov/Dec 2018) (May/June 2016) (April/may 2018) (Nov/Dec 2018) (Nov/Dec 2019)**
8.	Classify the different types of faults in power system. Which of these are more frequent? **(Nov/Dec 2015) (May/June 2016) (April/May 2019) (Nov/Dec 2019) (April/May 2018)**
9.	A 132kV, 3 phase, 50 cycles, overhead line, 50km, long has a capacitance to earth for each line of 0.0157 μF/km. Determine the inductance and kVA rating of the arc suppression coil. **(Nov/Dec 2016)** **Probable Part C**
10.	Explain the method of calculating fault current using symmetrical components. **(Nov/Dec 2016) (May/June 2017)**
11.	Explain the various methods of neutral grounding. **(Nov/ Dec 2017)**
	UNIT II BASICS OF RELAYS
	Part A
1.	**Name the different kinds of over current relays**

	Depending on time of operation **i.** Instantaneous Overcurrent relays- No time lag **ii.** Inverse definite time relays-Definite time characteristics **iii.** Inverse definite minimum time relays-Core saturation at a later stage. **iv.** Very inverse relays – Core saturation at a further later stage. **v.** Extremely inverse relays – Has inverse nature for entire working range. Depending upon directional feature **i.** Induction type non-directional over current relay – watthour meter type **ii.** Induction type directional over current relay- Reverse power relay. **iii.** Current differential relay-Actuates based on differential current
2.	**Define operating time of a relay.**
	It is the time which elapses from the instant at which actuating quantity exceeds the relay pick up value to the instant at which the relay closes its contacts. With Relays that have multiple pairs of contacts, if there are no other conditions, then the operating time is the time required for the slowest pair of contacts to operate.
3.	**Define resetting time of a relay.**
	It is the time which elapses from the moment the actuating quantity falls below its reset value to the instant when the relay comes back to its normal (initial) position.
4.	**What is 'Time grading' of relays. (Nov/Dec 2018)**
	It is the setting of time of operation of various relays protecting the different sections of a line. It is set so that the relay which is nearest to the fault location alone will operate first and clear the fault.
5.	**Compare Over and Under current relays? (Nov/Dec 2019)**
	Over current relays are those that operate when the current in a line exceeds a predetermined value. (e.g.: Induction type non-directional/directional over current relay, differential over current relay) whereas Undercurrent relays are those which operate whenever the current in a circuit/line drops below a predetermined value.(e.g.: differential over-voltage relay)
6.	**What is biased differential beam relay?**
	The biased beam relay is designed to respond to the differential current in terms of its fractional relation to the current flowing through the protected zone. It is essentially an over-current balanced beam relay type with an additional

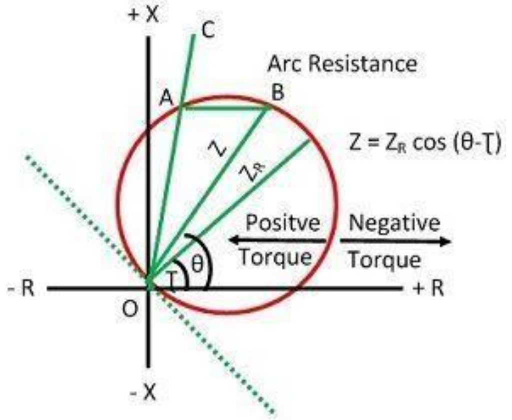
	restraining coil. The restraining coil produces a bias force in the opposite direction to the operating force.
7.	**Give the limitations of Merz Price protection.**
	Since neutral earthing resistances are often used to protect circuit from earth-fault currents, it becomes impossible to protect the whole of a star-connected alternator. If an earth-fault occurs near the neutral point, the voltage may be insufficient to operate the relay. Also it is extremely difficult to find two identical CT's. In addition to this, there always an inherent phase difference between the primary and the secondary quantities and a possibility of current through the relay even when there is no fault.
8.	**Why is an under-frequency relay required in a power system? (May/June 2012) (Nov/Dec 2013) (Nov/Dec2014) (April/May 2019) (Apr/May 2021)**
	An under-frequency relay is one which operates when the frequency of the system (usually an alternator or transformer) falls below a certain value. Under frequency relays are used to shed automatically certain portion of load whenever the system frequency falls to such a low level which threatens the stability of the power system.
9.	**What are the features of directional relay?**
	i. High speed operation ii. High sensitivity iii. Ability to operate at low voltages iv. Adequate short-time thermal ratio v. Burden must not be excessive.
10.	**What is static relay?**
	It is a relay in which measurement or comparison of electrical quantities is made in a static network which is designed to give an output signal when a threshold condition is passed which operates a tripping device.
11.	**What is a programmable relay?**
	A static relay which has one or more programmable units such as microprocessors or microcomputers embedded in its circuit is called a programmable relay. Programmable relays involve numerical computations based on computerized algorithms for calculating the fault current to actuate

	the relay.
12.	**What are the advantages of static relay over electromagnetic relay? (Nov/Dec 2011) (May/June 2014) (Nov/Dec 2014) (Apr/May 2021)**
	i) Low power consumption as low as 1mW ii) No moving contacts; hence associated problems of arcing, contact bounce, erosion, replacement of contacts iii) No gravity effect on operation of static relays. Hence can be used in vessels ie, ships, aircrafts etc. iv) A single relay can perform several functions like over current, under voltage, single phasing protection by incorporating respective functional blocks. This is not possible in electromagnetic relays v) Static relay is compact
13	**What is earth fault protection?**
	A ground fault (earth fault) is any failure that allows unintended connection of power circuit conductors with the earth. Such faults can cause objectionable circulating currents and may energize the housings of equipment at a dangerous voltage. Under such condition residual current flowing to the ground is calculated. Such a protective scheme used for the protection of an element of a power system against earth faults is called as earth fault protection
14	**List out the applications of static relays. (Nov/Dec 2012)) (May/June 2016)**
	Applications of Static Relays include i) Protection of generators ii) Protection of transformers iii) Protection of transmission lines, and iv) Protection of motors.
15.	**What is meant by directional relay? (May/June 2012)**
	A directional relay detects the whether the point of fault lies in the forward or reverse direction with respect to relay location. The relay which can sense the direction of power flow and act for a particular direction of power flow is called directional relay. It is very useful in the protection of power alternators or three phase generators connected to grid.
16.	**What is meant by differential relay? (May/June 2013) (Apr/May 2015)**
	A differential relay is one that operates when the phasor difference of two or more similar electrical quantities exceeds a predetermined value. It has two coils viz., operating coil which produces operating torque and restraining coil which produces restraining torque. If the operating coil current exceeds the set value determined by restraining coil, the relay operates.

17.	**What are the types of fuses? (Nov/Dec 2013)**
	Low voltage fuses i) Semi-enclosed rewireable fuse ii)HRC fuse High voltage fuses i) cartridge type ii)liquid type iii)metal clad type.
18.	**List out the different types of distance relay.(May/June 2014)**
	Dependent on the ratio of V and I there are three types of distance relays which are i) Impedance relay which is based on measurement of impedance Z ii) Reactance relay which is based on measurement of reactance X iii) Admittance or Mho relay which is based on measurement of component of admittance Y.
19	**In what way distance relay is superior to over current protection? (Nov/Dec 2015)**
	Distance relays are preferred to overcurrent relays because they are not nearly so much affected by changes in short-circuit-current magnitude as overcurrent relays are, and, hence, are much less affected by changes in generating capacity and in system configuration. This is because distance relays achieve selectivity on the basis of impedance rather than current.
20	**Where are negative sequence relays employed?**
	Negative sequence relays are employed for negative sequence protection of generators against the unbalanced load condition. The negative phase sequence filter along with the over current relay provides the necessary protection against the unbalanced loads.
21	**Write the effects of arc resistance.**
	The effect of arc resistance is most significant on short lines where the reach of the relay setting is small. It can be a problem if the fault occurs near the end of the reach. High fault-arc resistances tend to occur during midspan flashovers to ground on transmission lines carried on wood poles without earth wires. These problems can usually be overcome by using relays having different shaped characteristics.

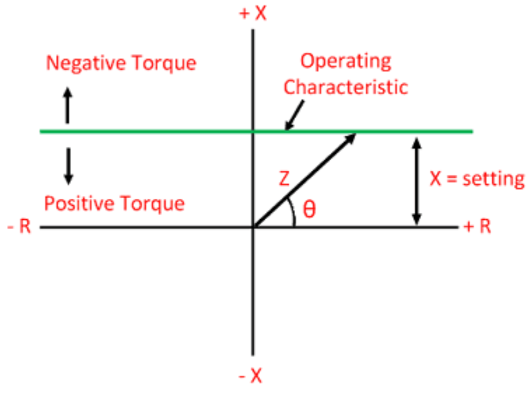
22	**What is the significance of PSM and TSM? (Nov/Dec 2016)**
	Time setting multiplier TSM: TSM determines the operating time of the relay. Lower the value of TSM, lower will be the operating time. Plug setting multiplier PSM: The plug position ensures the current setting value of the relay. Plug setting multiplier (PSM) indicates the severity of the fault.
23	**A relay is connected to 400/5 ratio current transformer with current setting of 150%. Calculate the plug setting multiplier when circuit carries a fault current of 4000A. (Nov/Dec 2016)**
	Fault Current = 4000A C.T. ratio = 400/5 Fault current in the relay coil = 4000 * (5/400) = 50A Plug Setting Multiplier (PSM) = Fault Current in the relay coil / (Rated secondary C.T. Current * Current setting) Plug Setting Multiplier (PSM) = 50 / (5*1.5) = 6.667
24	**Why shaded ring is provided in induction disc relay? (May/June 2017)**
	In the induction disc relay, a metal disc is allowed to rotate between two electromagnets. The shaded pole structure is generally actuated by current flowing in a single coil on a magnetic structure containing an air gap.The air gap flux produced by this current is split into two out-of-phase components by a so called "shading ring" generally of copper, that encircles part of the pole face of each pole at the air gap.
25	**Give the principle of negative sequence relay. (Nov/Dec 2017)**
	A relay which protects the electrical system from negative sequence component is called a negative sequence relay or unbalance phase relay. The actuating quantity is negative sequence current. When the negative sequence current exceeds a certain value, the relay operates. This is used to protect electrical machines against overheating due to unbalanced currents.
26	**Write the torque equation of the universal relay. (Nov/Dec 2017)**
	$T=K_1I^2+K_2V^2+K_3VI \cos(\theta - \tau) + K_4$ where K_1, K_2, K_3 are the tap setting or constant of Voltage V and current I. The K_4 is the mechanical restraint due to spring or gravity.
27	**Mention the principle of operation of distance relay. (April/May 2018)**

	There is one voltage element from potential transformer and a current element fed from current transformer of the system. The deflecting torque is produced by secondary current of CT and restoring torque is produced by voltage of potential transformer. In normal operating condition, restoring torque is more than deflecting torque. Hence relay will not operate. But in faulty condition, the current becomes quite large whereas voltage becomes less. Consequently, deflecting torque becomes more than restoring torque and dynamic parts of the relay starts moving which ultimately close the No contact of relay. Hence clearly operation or working principle of distance relay depends upon the ratio of system voltage and current.
28	**Determine the plug setting multiplier of a 5 ampere, 3 second over current relay having a current setting of 125% and a time setting multiplier of 0.6 connected to supply circuit through a 400/5 current transformer when the circuit carries a fault current of 4000A. (April/may 2018)**
	Plug Setting Multiplier = Fault current in relay coil/(Rated CT secondary current * Current Setting) Fault current in relay coil = 4000*(5/400) = 50A. Therefore, PSM= 50/(5*1.25)=8
29	**What are the factors affecting the performance of differential relays? (Nov/Dec 2018)**
	Phasor sum of currents – a sensitive relay can operate to a very small difference in two currents even though no fault has occurred. CT ratio-CT ratios on both sides should be equal. Unequal ratios may cause a residual current which mal operates the relay Polarity of transformers- The polarity of the transformers have to be equal. Otherwise a circulating current may result which can be erroneously identified as fault current.
30	**Draw R-X diagram for the reactance, mho relay and Simple Impedance Relay (April/May 2019) (Apr/May 2021)**

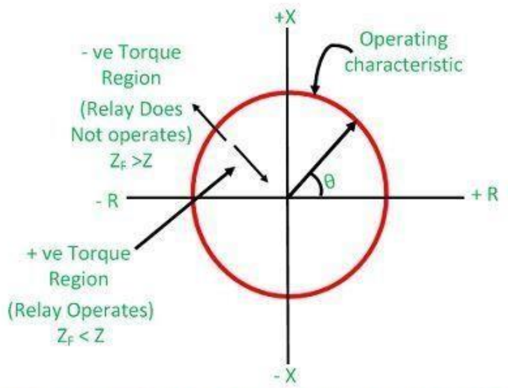


Operating Characteristic of Mho Relay

Circuit Globe



Operating Characteristic of Reactance Type Distance Relay



Operating Characteristic of an Impedance Relay on an R-X Diagram

Circuit Globe

R-X diagram for mho relay is circle with radius $Z=Z_r\cos(\Theta-\tau)$

R-X diagram for reactance relay is a straight line passing through positive X axis.

R-X diagram for Simple Impedance Relay is a circle with centre as origin passing through all four quadrants.

31 Classify Electromagnetic Relays (Nov/Dec 2019)

Electromagnetic Relays Can be Classified into

i. Attraction Type relays
ii. Induction type Relays

Attraction type relays can be classified as Plunger type, Hinged type and Balanced Beam type

Induction type can be classified into

i. Moving Iron Relay
ii. Induction Disc Type Wattmeter type relay
iii. Induction Cup Type Relay

	Part B
1.	Describe the construction and operation of over current relay with directional Scheme**. (June 2014) (Nov/Dec 2015). (May/June 2016) (Nov/ Dec 2012) (April/may 2019) (Apr/May 2021) Probable Part C**
2.	Explain MHO relay characteristic on the R- X diagram. Discuss the range setting of various distance relays placed on a particular location. **(Nov/ Dec 2012) (May/June 2016)**
3.	**(i)** What are the different inverse-time characteristics of over current relays and mention how to characteristics can be achieved in practice for an electromagnetic relay? **(Nov/Dec 2018)** **(ii)** Mention the advantages of static relays**. (Nov/Dec 2014).**
4.	Explain the principle of percentage biased differential relay with necessary diagrams. Also discuss its application. **(May/June 2012)**
5.	With neat block diagram, explain the construction and operating principle of electromagnetic relay. **(Nov/Dec 2013) (Nov/Dec 2018)**
6.	Explain the operation of i) Negative sequence relay ii) Static relay. iii) under frequency relay **(Apr/May 2015) (April/may 2018) (April/may 2019) (Apr/May 2021)**
7.	Explain with the help of neat diagram the construction and working of induction type directional power relay **(Nov/Dec 2015)(Apr/May 2021)**. **(May/June2013)**
8.	What is universal torque equation? Using this equation derive the following operating characteristics. i) Impedance relay ii) Reactance relay iii) Mho relay. **(May/June 2013) (Nov/Dec 2015) (May/June 2016) (Nov/Dec 2013) (May/June 2017) (April/may 2018)**
9.	Draw and explain about differential protection of transmission lines. **(Apr/May 2015) (April/may 2018)**
10.	With necessary sketches discuss in detail about electromagnetic attraction type relays. **(May/June 2017) (Nov/ Dec 2017)**
11.	Describe the construction and principle of operation of non-directional induction type over current relay. **(Nov/ Dec 2017) (Nov/Dec 2019)**
12.	Explain about various differential relays in detail. **(Nov/Dec 2019)**

13.	A20 MVA transformer which is used to operate at 30% overload feeds a 11 kV bus bar through a circuit breaker. The transformer circuit breaker is equipped with a 1000/5 current transformer and the feeder circuit breaker with 400/5 current transformer and both the current transformers feed IDMTL relays having the following characteristics.

Plug Setting	2	3	5	10	15	20
Multiplier time (s)	10	6	4.1	3	2.5	2.2

The relay on the feeder circuit breaker has 125% plug setting and a 0.3 time multiplier setting. If a fault current of 5000 A flows from the transformer to the feeder, Determine
i) Operating time of feeder relay.
ii) Suggest a suitable plug setting and time multiplier setting of the transformer relay to ensure adequate discrimination of 0.58 between the transformers relay and feeder relay.

	UNIT III OVERVIEW OF EQUIPMENT PROTECTION
	PART A
1.	**What are the causes of over speed and how alternators are protected from it? (April/may 2018)**
	Sudden loss of all or major part of the load causes over-speeding in alternators. Modern alternators are provided with mechanical centrifugal devices mounted on their driving shafts to trip the main valve of the prime mover when a dangerous over-speed occurs.
2.	**What is the role of Buchholz's relay? (Nov/Dec 2019)**
	Bucholz relay is used to give an alarm in case of incipient (slow developing) faults in the transformer and to disconnect the transformer from the supply in the event of severe internal faults. It is usually used in oil immersion transformers with a rating over 750KVA.
3.	**What are the various faults that would affect an alternator? (May/June 2013) (Apr/May 2015))(May/June 2016)**
	(a) Stator faults i) Phase to phase faults ii) Phase to earth faults iii) Stator inter turn faults (b) Rotor faults i)Rotor earth faults ii)Field over loading iii) Heating of rotor c)Abnormal Running Conditions i) Over speeding ii) Over loading iii) Unbalanced Loading iv)Over voltage v)Failure of Prime mover.

4.	**What are faults associated with a transformer?**
	a) Overheating b) Winding Faults i)phase to phase fault ii) Earth fault iii)Interturn faults c)Open circuits d)Through faults e)Over fluxing.
5.	**What are the main safety devices available with transformer? (May/June 2012)**
	Oil level gauge – conservator has oil level gauge which gives alarm when the oil level goes above or below the normal Sudden pressure relay- This protection detects a sudden rate-of-increase of pressure inside the tap changer oil enclosure. Oil temperature indicator – Measures the temperature of the oil on the top of the transformer (which generally should be less than the winding temperature). Winding temperature indicator- Identifies the hottest part of the winding.
6.	**What are the limitations of Buchholz relay? (May/June 2017)**
	(a) Only fault below the oil level are detected.(b) Mercury switch setting should be very accurate, otherwise even for vibration, there can be a false operation.(c) The relay is of slow operating type, which is unsatisfactory.
7.	**What are the problems arising in differential protection in power transformer and how are they overcome? (May/June 2012) (Nov/Dec 2015)**
	i) Difference in lengths of pilot wires on either sides of the relay. This is overcome by connecting adjustable resistors to pilot wires to get equipotential points on the pilot wires. ii) Difference in CT ratio error difference at high values of short circuit currents that makes the relay to operate even for external or through faults. This is overcome by introducing bias coil.iii) Tap changing alters the ratio of voltage and currents between HV and LV sides and the relay will sense this and act. Bias coil will solve this. iv) Magnetizing inrush current will be identified as short circuit current. A harmonic restraining unit is added to the relay which will block it when the transformer is energized.
8.	**What is REF relay?**
	REF is the abbreviated form for Restricted Earth Fault relay. When the fault occurs very near to the neutral point of the transformer, the voltage available to drive the earth circuit is very small, which may not be sufficient to activate the relay, unless the relay is set for a very low current. Hence the zone of

	protection in the winding of the transformer is restricted to cover only around 85%. Hence the relay is called REF relay.
9.	**What is over fluxing protection in transformer? (Nov/Dec 2016)**
	If the turn's ratio of the transformer is more than 1:1, there will be higher core loss and the capability of the transformer to withstand this is limited to a few minutes only. This phenomenon is called over fluxing.
10.	**Why bus-bar protection is needed? (May/June 2013) (April/may 2019)**
	(i) Fault level at bus-bar is high (ii) The stability of the system is affected by the faults in the bus zone.(iii) A fault in the bus bar causes interruption of supply to a large portion of the system network.
11.	**What are the causes of bus zone faults?**
	i)Failure of support insulator resulting in earth fault ii) Flashover across support insulator during over voltage iii)Heavily polluted insulator causing flashover iv) Earthquake, mechanical damage etc.
12.	**What are the problems in bus zone differential protection?**
	i)Large number of circuits, different current levels for different circuits for external faults ii) Saturation of CT cores due to dc component and ac component in short circuit currents. The saturation introduces ratio error. iii) Sectionalizing of the bus makes circuit complicated. iv) Setting of relays need a change with large load changes.
13.	**What are the disadvantages of time graded protection?**
	i) Time lag is not desirable on short circuits ii) Not suitable for ring main distribution iii) Difficult to coordinate & needs changes with new connection iv) Not suitable for long distance relaying.
14.	**How does the over voltage surge affect the power system?**
	The over voltage of the power system leads to insulation breakdown of the equipment. It causes the line insulation to flash over and may also damage the nearby transformer, generators and the other equipment connected to the line.
15.	**What is the general connection rule for Current transformers in differential protection?**
	If the windings of the power transformer are delta connected then the current transformers are star connected and if the windings of the power transformer

	are star connected then the current transformers are delta connected.
16.	**Write the coordination equation for inverse over-current relay?**
	$T_A=T_B+CB_B+O_A+F$ Where T_A operating time of relay at station A,T_B operating time of relay at station B,CB_B operating time of circuit breaker at station B,O_A over travel time of relay at station A,F factor of safety
17.	**Explain why secondary of current transformer should not be open. (Nov/Dec 2011)(Dec 2014) (Apr/May 2015) (May/June 2016)**
	Current transformers generally work at a low flux density. Core is then made of very good metal to give small magnetizing current. On open-circuit, secondary impedance now becomes infinite and the core saturates. This induces a very high voltage in the primary upto approximately system volts and the corresponding volts in the secondary will depend on the number of turns. Since secondary of CT has more turns compared to the primary, the voltage generated on the open-circuited CT will be high, leading to flashovers. Hence as a safety precaution, CT secondary should not be open-circuited.
18.	**What is meant by time graded system protection? (Nov/Dec 2018)**
	In a time graded system, the operating time of the relay is increased from the far end of protected circuit towards the generating source. Definite time overcurrent relays are used which after a preset time will trip the circuit. The difference in time setting of the two adjacent relays are kept at 0.5s. This difference is to cover the operating time of CB and errors in CT and relay.
19.	**Write the function of earth fault relay. (Nov/Dec 2012)**
	Earth fault relay is used for the protection of an element of a power system against earth faults. Earth relay calculates the residual current. If the residual current is zero the relay will not operate. Restricted earth fault relay is used in differential protection which will not operate for external faults.
20.	**What is meant by relay operating time? (Nov/Dec 2012)**
	It is the time which elapses from the instant at which actuating quantity exceeds the relay pick up value to the instant at which the relay closes its contacts.
21.	**What are the different types of zones of protection? (Nov/Dec 2013)**

	The different zones of protection are as follows Primary protection and backup protection Back up protection can be classified as follows. • Relay backup protection • Breaker backup protection • Remote backup protection • Centrally co-ordinated backup protection
22.	**State the methods of protection of busbars. (Nov/Dec 2014) (Nov/Dec 2016)**
	i)Frame leakage protection of busbar ii) Circulating current protection of busbar iii) High impedance differential protection of busbar
23.	**List the applications of current transformer. (May/June 2014)**
	i) To the supply the stepped down current to the relay coil in the event of any overloading or short-circuiting of the equipment lines. ii) To measure power of a load in conjunction with a wattmeter. The secondary of the CT is connected to the current coil of the wattmeter. iii) To measure large currents in conjunction with medium/Small range meters.
24.	**Give examples of Unit and Non – Unit Protection Schemes (Nov/Dec 2015)**
	The concept of 'Unit Protection', describes the concept of sections of the power system that are protected individually as a complete unit without reference to other sections. The protection scheme for that section can interrupt falut without secondary intervention from backup protection. Examples. of Unit Protection: Differential Protection, Overcurrent Protection. Example of Non – Unit Protection: Distance Protection.
25.	**What are the difficulties encountered through differential protection? (May/June 2017)**
	Though the saturation in Current transformer is avoided, there exist difference in the C.T. characteristics due to ratio error at high values of short circuit currents. This causes an appreciable difference in the secondary currents which can operate the relay. So the relay operates for external faults. Due to the difference in lengths of the pilot wires on both sides, the unbalance condition may result. Due to the magnetizing current inrush current in transformers which may be as great as 10 times the full load current of the transformer, the

	differential relay may operate falsely.
26.	**What is the need of instrumentation transformer? (May/June 2017)**
	Instrument transformers are high accuracy electrical devices used to isolate or transform voltage or current levels. The most common usage of instrument transformers is to measure high voltage or high current (with common meters) by safely isolating secondary control circuitry from the high voltages or currents.
27.	**Why secondary of a transformer should not be opened? (Nov/Dec 2017) (Apr/May 2021)**
	The secondary side of a current transformer should never be kept in open condition because, when kept open, there is a very high voltage found across the secondary side. This high voltage causes a high magnetizing current to build up on the secondary side which in turn causes high flux and makes the core to saturate.
28.	**List the types of bus bar protection. (Nov/Dec 2017)**
	Frame-Earth Protection Differential Protection for Sectionalized Busbars High-Impedance Differential Protection Low-Impedance Differential Protection Digital Busbar Protection
29.	**What are the protection methods used for transmission lines? (Apr/may 2018)**
	i) Overcurrent protection – Direction, Time and Current graded methods ii) Distance protection - Simple Impedance Relay; Mho relay; Reactance relay iii)Carrier aided protection of transmission lines based on carrier frequency communication through power transmission networks.
30.	**In the event of fault in generator windings, the field excitation should be suppressed as early as possible. Why? (Nov/Dec 2018)**
	Failure of excitation that is failure of field system in the generator makes the generator run at a speed above the synchronous speed. In that situation the generator or alternator becomes an induction generator which draws magnetizing current from the system. Although this situation does not create

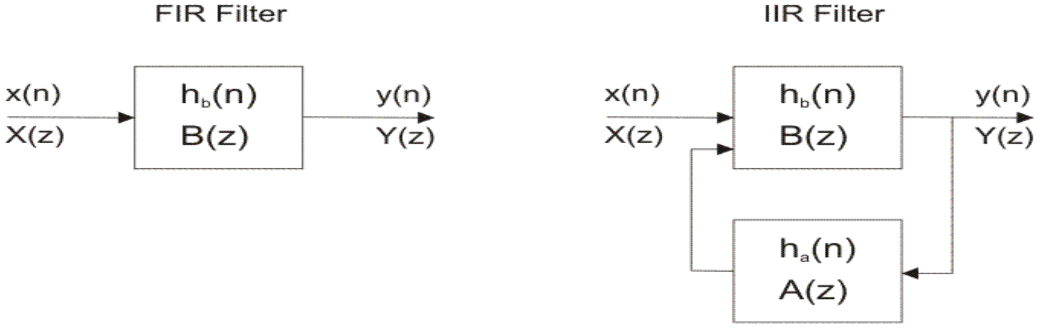
	any problem in the system immediately but over loading of the stator and overheating of the rotor due to continuous operation of the machine in this mode may create problems in the system in long-run. Therefore special care should be taken for rectifying the field or excitation system of the generator immediately after failure of that system. The generator should be isolated from rest of the system till the field system is properly restored.
31.	**Which type of protection is used for EHV and UHV lines? (Nov/Dec 2018)**
	Carrier current protective scheme Very fast fault clearing is obtained During synchronizing power surges, tripping does not occur. Pilot wire protective scheme Economical Capacitive effects of pilot wire currents do not affect relay operation.
32.	**What are the errors in CT? (April/may 2019)**
	Ratio Errors: It is defined as the ratio of the magnitude of the difference between the nominal and actual ratio with respect to the actual ratio. **Phase Angle Errors:** For a ideal CT the angle between the primary and reversed secondary current vector is zero. But for an actual CT there is always a difference in phase between two since primary current must supply the component of the exiting current. The angle between the above two phases in termed as **phase angle error in current transformer** or CT.
33.	**How are alternators protected against over speeding? (Nov/Dec 2019)**
	Speed Governors are used to reduce the supply of steam to the alternator using a linkage mechanism. The reduction in steam input to the turbine reduces its speed thereby controlling the frequency. Apart from this numerical relays, which sense the speed and cut off the supply of steam to turbine can also be used.
34.	**Enumerate the concept of ring feeder. (Apr/May 2021)**
	The feeders in this system form a loop which starts from the substation bus-bars, runs through the load area feeding distribution transformers and returns to the substation busbars. In this network topology, one ring network of distributors is fed by more than one feeder. In this case, if one feeder is under fault or maintenance, the ring feeder is still energized by other feeders

	connected to it. It is also known as ring main distribution system.
	Part B
1.	Identify and explain the different protection schemes necessary for the protection of 3 phase alternators with suitable circuit diagram. **(Nov/ Dec 2012) (Apr/May 2015)**
2.	i) Explain the factors which cause difficulty in applying Merz-Price circulating current principle to a power transformer. ii) A three phase transformer of 220/11000 line volts is connected in star/delta. The protective transformers on 220 V side have a current ratio of 600/5. What should be the current transformer ratio on 11000 V side? **(Nov/Dec 2011)**
3.	**i)** With aid of neat schematic diagram, describe the percentage differential protection scheme of a transformer and generator. **(Nov/ Dec 2012) (Nov/Dec 2014)** **ii)** Describe the differential pilot wire method of protection of feeder. **(Nov/Dec 2011)**
4.	Discuss how the generator is protected against an inter turn faults with necessary diagram.
5.	Explain what is meant by distance protection and why it is superior to other types of protection for an overhead transmission line. Also describe the operating characteristics of distance relays on the impedance plane and discuss their limitations **(May/June 2012) (Nov/Dec 2013) (Nov/Dec 2014) (May/June 2014)**
6.	**i)** Describe the construction and working of Buchholz relay. **(April/may 2018)** ii) Discuss the time graded over current protection for parallel feeders. **(May/June 2013)**
7.	**i)** Explain with the neat diagram the application of Merz-price circulating current principle for protection of stator of the alternator. **(Apr/May 2015) (Apr/May 2021)** ii) What is the role of instrument transformer in protective schemes? Explain in detail about instrument transformers **(May/June 2013) (May/June 2017)**

8.	**i)** Describe the differential protective schemes of transformer **(May/June2014) (May/June 2016) (April/may 2019) (May/June 2014) (Nov/ Dec 2017)** **ii)** Enumerate the protective scheme employed for the bus bar. **(Nov/Dec 2013) (May/June 2016)(May/June 2014) (April/may 2018) (Apr/May 2021)**
9.	Briefly discuss the protective devices used for the protection of a large transformer. **(Nov/Dec 2014) (April/may 2019)**
10.	Explain about carrier aided protection of transmission lines and various relays associated with it **(Apr/May 2015) (Nov/Dec 2015)**
11.	Why is harmonic restrained differential relay used for protecting large size transformer? Describe its working and construction. **(Nov/Dec 2015) (Nov/Dec 2018)**
12.	With neat sketches, explain the different types of protective schemes for transmission lines. **(May/June 2016) (April/may 2019)**
13.	Draw and explain protection scheme of an A.C. induction motor. **(Nov/Dec 2016)**
14.	(i) A generator is protected by restricted earth fault protection. The generator ratings are 13.2kV, 10 MVA. The percentage of winding protected against phase to ground is 85%. The relay setting is such that it trips for 20% out of balance. Calculate the resistance to be added in the neutral to ground connection. **Probable Part C (Nov/Dec 2016)**
15.	Give a brief account on the protection of generator using differential (Merz-Price) and biased differential protection scheme**. (Nov/ Dec 2017) (Nov/Dec 2019)**
16.	With neat sketches, explain the different types of protective schemes for motors. **(April/may 2018)**
17.	A star connected, 3 phase , 10 MVA, 6.6 kV alternator has a per phase reactance of 10%. It is protected by Merz-price circulating current principle which is set to operate for fault currents not less than 175A. Calculate the value of earthing resistance to be provided to ensure that only 10% of the alternator

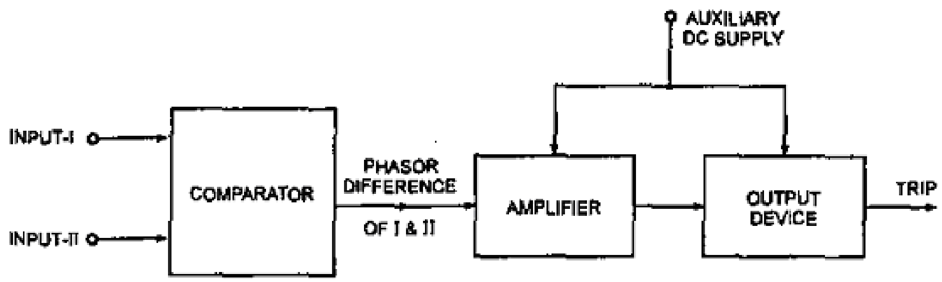
	winding remains unprotected. **(April/may 2018)**
18.	An alternator rated at 10kV protected by the balanced circulating current system has its neutral grounded through a resistance of 10ohms protective relay is set to operate when there is an out of balance of 1.8A in the pilot wires which are connected to the secondary windings of 1000/5 CT ratio. Determine the percentage of windings which remain unprotected and minimum value of earthing resistance to protect 80% of the winding. **(Nov/Dec 2018)**
19.	What are the problems arising in differential protection in power transformer and how are they overcome? **(April/may 2019) (Probable Part C)**
20.	The neutral point of 3 phase 20 MVA 11 kv transformer earthed through resistance of 5 ohms relay set to operate for out of balance current of 1.5 A. CT ratio is 1000:5. What % of winding is unprotected? Also Find the resistance required to have 90 % winding protection. **(Nov/Dec 2019) (Probable Part C)**
21.	A synchronous generator rated at 25KV protected by circulating current system having neutral grounded through a resistance of 10 ohms. The differential protection relay is set to operate when there is an out of balance current of 4A the CTs ratio of 1000/5A. Determine. (a) The % of winding remains unprotected. **(b)** Value of earth resistance to achieve 75% protective of winding. **(Apr/May 2021)** **Probable Part C**
	UNIT IV STATIC RELAYS AND NUMERICAL PROTECTION
	Part – A
1.	**Define static relay? (Nov/Dec 2017) (April/may 2019)**
	It is a relay in which measurement or comparison of electrical quantities is made in a static network which is designed to give an output signal when a threshold condition is passed which operates a tripping device.
2.	**What is CPMC?**
	It is combined protection, monitoring and control system incorporated in the

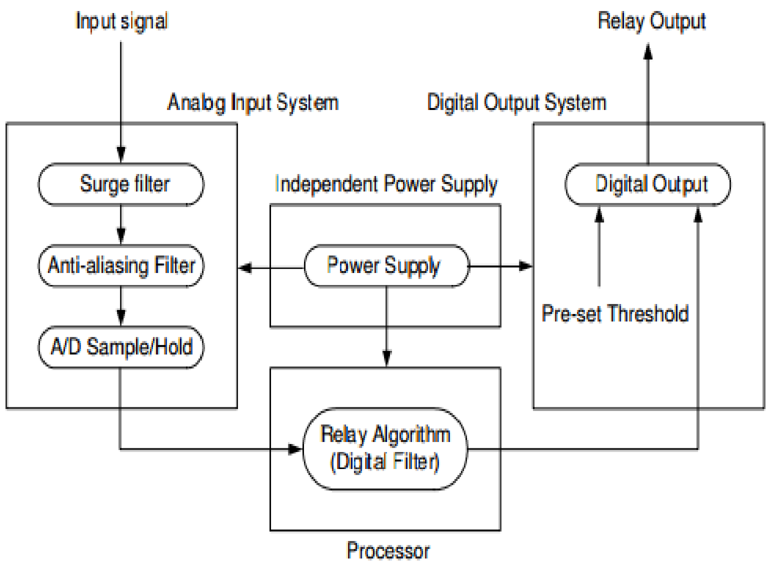
	static system. For example static relays employ microprocessor units which incorporate protection principles such as overcurrent, inverse time etc., in their operation. Also these units sense the fault current each and every time. The fault current can also be controlled by changing the code embedded into the processor.
3.	**What are the advantages of static relay over electromagnetic relay? (Nov/Dec 2018) (Nov / Dec 2019)**
	• Low power consumption as low as 1mW • No moving contacts; hence associated problems of arcing, contact bounce, erosion, replacement of contacts • No gravity effect on operation of static relays. Hence can be used in vessels ie, ships, aircrafts etc. • A single relay can perform several functions like over current, under voltage, single phasing protection by incorporating respective functional blocks. This is not possible in electromagnetic relays • Static relay is compact. Superior operating characteristics and accuracy • Static relay can think , programmable operation is possible with static relay • Effect of vibration is nil, hence can be used in earthquake-prone areas • Simplified testing and servicing. Can convert even non-electrical quantities to electrical in conjunction with transducers.
4.	**What is pick up value?**
	It is the minimum current in the relay coil at which the relay starts to operate. The relay shouldn't operate when the current does not exceed the pick up value. Pick up value of static relays are set through resistance networks like ladder networks which restrain the operation of relay through inherent resistances connected with the comparator circuits.
5.	**Define target.**
	It is the indicator used for showing the operation of the relay. This helps the operator to know the cause of tripping of the circuit breaker. Relays may be fitted with a "target" or "flag" unit, which is released when the relay operates, to display a distinctive coloured signal when the relay has tripped. In Numerical relays target may be depicted by a binary 0 or 1.

6.	**Define blocking.**
	Blocking is preventing the relay from tripping due to its own characteristics or due to additional relays. False operation of relay may lead to unnecessary opening of circuit.
7.	**What are the advantages of numerical relays over conventional relays? (May/June 2014) (May/June 2015) (Nov/Dec 2016) (April/May 2019)**
	The advantages of numerical relays are • No moving parts and therefore no friction • Easy to replace and service. • Numeric relays are not affected by gravity • Are compact and has modular arrangement • Various characteristics can be obtained.
8.	**What are the drawbacks of analogue and active analogue filters? (May/June 2014)**
	The drawbacks of analogue and active analogue filters are • They are bulky, especially inductors require large space • High precision components are needed making them expensive • Their characteristics drift with respect to time and temperature • Filters for very low frequencies need impracticably high component values • They are not programmable and adaptable
9.	**Draw the block diagram of FIR and IIR filter.**
	 **X(n) -Input parameters** **Y(n) – Output parameters** **h_b(n) – Feedforward gain** **h_a(n) – Feedback gain**
10.	**Compare FIR and IIR filters**

S.No	FIR Filter	IIR Filter
1.	Difficult to control and have no particular phase	Always make a linear phase.
2.	FIR is always stable	IIR can be unstable
3.	FIR has no limited cycles	Can have limited cycles
4.	FIR has no analog history	IIR is derived from analog.
5.	FIR can always be made casual	IIR filters make polyphase implementation possible
6.	FIR filters are Finite IR filters which are required for linear-phase characteristics.	IIR is infinite and used for applications where linear characteristics are not of concern.

11.	**What is Fourier analysis?**
	The analysis of a complex waveform expressed as a series of sinusoidal functions, the frequencies of which form a harmonic series. If a function is periodic, then it can be written as a discrete sum of trigonometric or exponential functions with specific frequencies.
12.	**What is discrete Fourier transform?**
	As the name implies, the Discrete Fourier Transform (DFT) is purely discrete: discrete-time data sets are converted into a discrete-frequency representation. This is in contrast to the DTFT that uses discrete time, but converts to continuous frequency. Since the resulting frequency information is discrete in nature, it is very common for computers to use DFT calculations when frequency information is needed.
13.	**What is Aliasing?**
	Aliasing is a phenomenon where the high frequency components of the sampled signal interfere with each other because of inadequate sampling. It results in loss of signal and its place will be taken by a different lower frequency wave.
14.	**What is sampling?**
	Sampling is the process of converting a signal (for example, a function of continuous time or space) into a numeric sequence (a function of discrete time or space). In other words sampling is the reduction of a continuous-time signal

	to a discrete-time signal. A common example is the conversion of a sound wave (a continuous signal) to a sequence of samples (a discrete-time signal).
15.	**What is sample and hold circuit?**
	A sample and hold circuit is an analog device that samples (captures, grabs) the voltage of a continuously varying analog signal and holds (locks, freezes) its value at a constant level for a specified minimum period of time. Sample and hold circuits and related peak detectors are the elementary analog memory devices. They are typically used in analog-to-digital converters to eliminate variations in input signal that can corrupt the conversion process.
16.	**What is digital filter?**
	In signal processing, a digital filter is a system that performs mathematical operations on a sampled, discrete-time signal to reduce or enhance certain aspects of that signal. This contrasts with the other major type of electronic filter, the analog filter, which is an electronic circuit operating on continuous-time analog signals.
17.	**Draw the block diagram of static differential relay**
	 Comparator – Compares two input signals and gives an error signal as output. Amplifier –Amplifies the error to the signal level required to actuate the output device Output device – The relay or the coil that serves as a base for tripping of circuit breaker.
18.	**Draw the block diagram of numerical relay**



Anti Aliasing Filter: The anti aliasing filters are basically low pass filters are basically low pass filters which block unwanted frequencies.

The Digital input output system This system actually gathers data and status reports of C.B. contacts status, other relay states, reset signals etc. Also the output systems generate and provide the tripping, alarm and any other control signal

A/D Sample/Hold : With the help of analog to digital converter, the equivalent digital form of analog input signal can be achieved.

Power Supply: It is used to supply power for various electronic circuits. It is powered by local station battery provided with charger.

Digital Filter: Samples the signal which are spread in time.

19. **Draw the block diagram of static over current relay.**

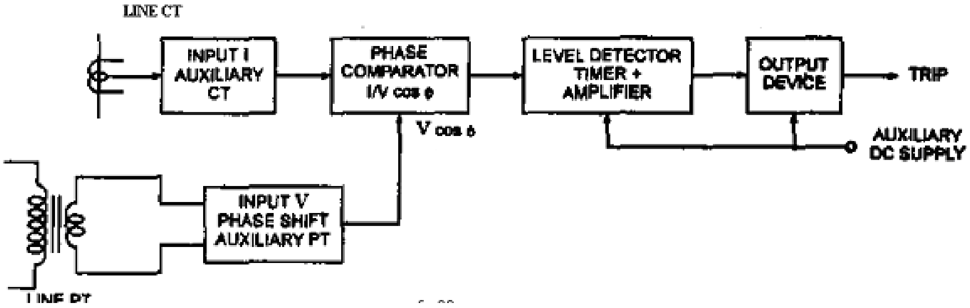
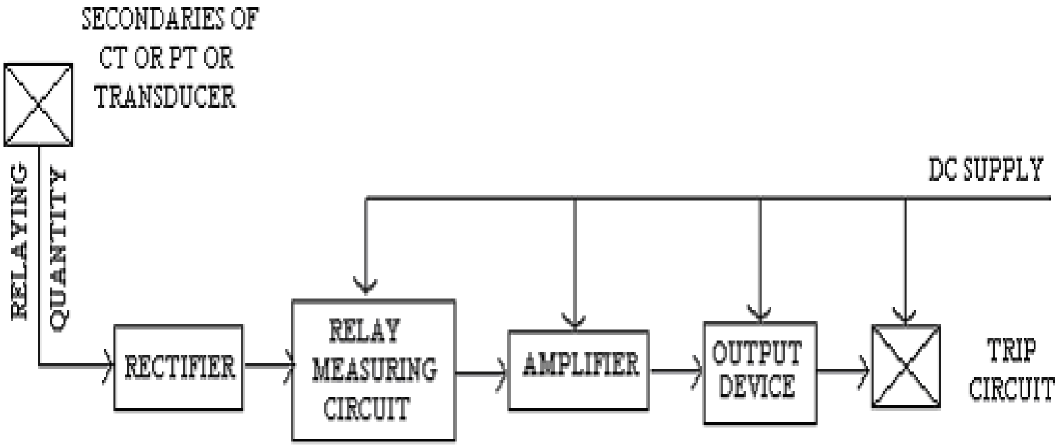
Phase Comparator – compares the phase of two signals

Input- Obtained from two auxiliary CTs and phase shifted voltage obtained fron another one CT

Level Detector – Used to generate trip signal by identifying offset

Amplifier – Used to increase the signal level to match the electrical signal levels

Output Device- can be a tripping circuit to generate trip signal

	
20.	**Draw the block diagram of static relay.**
	 Input – Obtained from the auxiliary CTs Rectifier- Converts the AC signal to DC signal Relay Measuring Circuit- Can be Single input, two input or multiple input device. Also a deciding signal generator. Amplifier - Used to increase the signal level to match the electrical signal levels Output Device- can be a tripping circuit to generate trip signal
21.	**What are the building blocks of static relay? or What are the basic circuits in static relay? (April/may 2018) (Nov/Dec 2018)**

	Building blocks of static relay are: Relaying quantity – Can be the output of CT or PT or Transducer or combination of various signals Input Element – May be a Rectifier which converts the AC signal to DC signal Measuring Element – Compares the output the input element with set value. It can be amplitude of phase comparator Output Element – Amplifies the signal obtained from the measuring element. Basically an amplifier Feed Element – Provides dc supply for the proper functioning of various other electronic circuits.
22.	**What is least error squared technique? (May/June 2015)**
	The least error squared technique is directly related to the Fourier technique. If a given function were to be synthesized by using a dc component, a sine wave of fundamental frequency and harmonics of this fundamental, then the amplitudes of various components given by the Fourier analysis are the ones which give the least squared error. We can directly find out the amplitudes of the components by using the LES technique.
23.	**List out the applications of static relays (SSR). (Nov/Dec 2016) (May/June 2016)**
	1. The main application of SSR is to switch the high amount of AC power using low power DC signal. 2. SSRs are used for automatic heater control in baking ovens. 3. SSRs are used in the hydraulic system with the electronic control mechanism 4. SSRs are used in Lift circuits, automatic sliding door circuits. 5. SSRs are used for motor control using PLC, microprocessors, etc.
24.	**State Nyquist–Shannon sampling theorem (May/June 2017)**
	If a function x(t) contains no frequencies higher than B hertz, it is completely determined by giving its ordinates at a series of points spaced 1/(2B) seconds apart. A band limited signal can be reconstructed exactly if it is sampled at a rate atleast twice the maximum frequency component in it. $f_s \geq 2f_m$ where fs = sampling frequency; fm = frequency of the signal which is reconstructed.
25.	**Write about numerical transformer differential protection. (May/June 2017)**
	It provides fast and selective tripping for two winding transformer. It quickly discriminates between faults that occur in the protected zone and those

	occurring outside this zone and thus provides selective and fast tripping. The faults within protected zone are short circuit between turns, windings and cables and earth faults inside transformer housing and protected zone. It discriminates between above internal faults and the operational conditions like inrush, over-fluxing and faults external to protected zone using numerical algorithms.
26.	**What is phase comparator? (Nov/Dec 2017)**
	A phase detector or phase comparator is a frequency mixer, analog multiplier or logic circuit that generates a voltage signal which represents the difference in phase between two signal inputs. It is an essential element of the phase-locked loop (PLL).
27.	**List out the advantages of numerical protection. (April/may 2018) (Nov/Dec 2019) (Apr/May 2021)**
	• The numerical relay relies on one system for all approach and use indication on LCD for relay activation, ensuring less space. • Since the numerical relay system relies on software, customized modifications can be made for getting the desired protection features. This saves the cost of replacing hardware. Fewer interconnections ensure reliability. • The range of operation of traditional models is narrow while numerical relays are diverse and evolution adaptable. • It also has the feature of auto resetting and self-diagnosis. • The benefit of using microprocessor based relays in the numerical system is that it gives minimum burden on the instrument transformers. The sensitivity of the system is pretty high and boasts a high pickup ratio.
	PART B
1.	Describe the Mann and Morrison method applied to numerical distance protection of a transmission line. **(May/June 2014)**
2.	Develop the differential equation algorithm for distance protection of a transmission line. **(May/June 2014)**
3.	Explain the block diagram of numerical relay and explain the various

	components of numerical relays. **(May/June 2017)**
4.	Explain sampling theorem and application of sampling theorem to digital protection.
5.	State and explain Shannon's sampling theorem.
6.	Explain the sample derivative methods of estimating the RMS value Phase angle of a signal. Clearly state the underlying software.
7.	What are the advantages and disadvantages of a half cycle window? Explain.
8.	Explain the statement that all numerical relays have the same hardware but what distinguishes the relay is the underlying software. **(Probable Part C)**
9.	Explain in detail the numerical over current protection of transmission line. Derive the necessary equations. **(May/June 2015)**
10.	Explain with a neat diagram the numerical transformer differential protection scheme. **(May/June 2015) (Nov/Dec 2019)**
11.	Explain synthesizes of mho relay using static phase comparator? **(Nov/Dec 2016) (Apr/May 2021)**
12.	Explain the numerical over current protection and numerical transformer differential protection. **(Nov/Dec 2016)**
13.	With a neat sketch discuss in detail about the synthesis of reactance relay using phase comparator. **(May/June 2017)**
14.	Explain with neat block diagram the operation static relay and list its advantages and disadvantages. **(Nov/ Dec 2017)**
15.	Describe the operation of static over current relay with neat diagram. **(Nov/ Dec 2017) (April/may 2019)**
16.	(a) Compare static relays with numerical relays. (b) Explain the advantages of numerical relays. **(April/may 2018)**
17.	Describe the construction, working principle and operation of static overcurrent relay. **(April/may 2018) (Apr/May 2021)**
18.	Discuss in detail, integrating and instantaneous type static amplitude comparators. Illustrate your answer with appropriate circuits and waveforms. **(Nov/Dec 2018) (Nov/Dec 2019)**
19.	How static overcurrent relays are different from electromechanical relays? Explain how the operation of instantaneous relay is achieved using electronic

	relays? **(Nov/Dec 2018)**
20.	Explain the operation of distance protection of transmission lines using static comparators with neat diagram. **(April/May 2019)**
	UNIT V CIRCUIT BREAKERS
	Part A
1.	**What is dielectric test of a circuit breaker?**
	It consists of over voltage withstand test of power frequency lightning and impulse voltages. Tests are done for both internal and external insulation with switch in both open and closed conditions.
2.	**Define composite testing of a circuit breaker.**
	In this method the breaker is first tested for its rated breaking capacity at a reduced voltage and afterwards for rated voltage at a low current. It is the combination of both field type testing station and laboratory type testing station. This method does not give a proper estimate of the breaker performance.
3.	**What is making capacity? (Nov/Dec 2015)**
	It is the capacity of the circuit breaker to reclose after a short circuit. It is expressed as per the following expression. 1.414 * 1.8* symmetrical breaking capacity = 2.55 * symmetrical breaking capacity. It is expressed in kA (RMS) at contact separation
4.	**What are the advantages of synthetic testing methods?**
	i) The breaker can be tested for desired transient recovery voltage and RRRV. ii) Both test current and test voltage can be independently varied. This gives flexibility to the test iii) The method is simple iv) With this method a breaker capacity (MVA) of five times of that of the capacity of the test plant can be tested.
5.	**Write are the types of test conducted on circuit breakers. (May/June 2012) (Apr/May 2015)**

	The types of test conducted in the circuit breakers are Type test ii) Routine test iii) Reliability test iv) Commissioning test v) Development test vi) Dielectric tests Type test can also be classified into: mechanical performance test, (ii) thermal test, (iii) dielectric test and (iv) short circuit tests.
6.	**What are the features of SF_6 gas?**
	It has good dielectric strength and excellent arc quenching property. It is inert, non-toxic, non-inflammable and heavy. At atmospheric pressure, its dielectric strength is 2.5 times that of air. At three times atmospheric pressure, its dielectric strength is equal to that of the transformer oil. It is also an electronegative gas.
7.	**Give the advantage of SF_6 circuit breaker over air blast circuit breaker (May/June 2013) (Apr/May 2015) (May/June 2016)**
	The advantages of SF_6 circuit breakers over air blast circuit breakers are as follows: i) SF_6 has excellent arc extinguishing properties whereas air has relatively inferior arc extinguishing properties. ii) SF_6 circuit breakers are maintenance free whereas considerable maintenance is required for the compressor plant which supplies air blast in case of air blast circuit breakers.
8.	**What is meant by electro negativity of SF_6 gas?**
	SF_6 has high affinity for electrons. When a free electron comes and collides with a neutral gas molecule, the electron is absorbed by the neutral gas molecule and negative ion is formed. This is called as electro negativity of SF_6 gas.
9.	**What are the merits of using oil as an arc quenching medium? (April/may 2019)**
	It absorbs the arc energy to decompose the oil into gases which have excellent cooling properties. It acts as an insulator and permits smaller clearance between live conductors and earthed components.
10.	**What are the advantages of air blast circuit breaker over oil circuit**

	breaker?
	i)The risk of fire is diminished ii)The arcing time is very small due to rapid buildup of dielectric strength between contacts iii)The arcing products are completely removed by the blast whereas oil deteriorates with successive operations
11.	**What are the types of air blast circuit breaker?**
	The types of air blast CBs are as follows: i) Axial-blast type – moving contact is in contact with fixed contact. ii) Cross blast – blast pipe is in perpendicular with the movement of moving contact
12.	**What are the disadvantages of MOCB over a bulk oil circuit breaker?**
	The disadvantages of MOCB over a bulk oil circuit breaker are: i) The degree of carbonization is increased due to smaller quantity of oil ii) There is difficulty of removing the gases from the contact space in time iii)The dielectric strength of the oil deteriorates rapidly due to high degree of carbonization.
13.	**What are the advantages of MOCB over a bulk oil circuit breaker? (Nov/Dec2019)**
	The advantages of Minimum oil CB over Bulk oil CB are as follows: i) It requires lesser quantity of oil ii) It requires smaller space iii) There is a reduced risk of fire iv) Maintenance problem are reduced.
14.	**What are the advantages of oil as arc quenching medium?**
	The advantages of oil as arc quenching medium are: The oil has a high dielectric strength and provides insulation between the contact after the arc has been extinguished. The oil used in circuit breaker provides a small clearance between the conductors and the earth components. The hydrogen gas is formed in the tank which has a high diffusion rate and good cooling properties.
15.	**What are demerits of MOCB?**
	The demerits of MOCB are: i)Short contact life ii)Frequent maintenance iii)Possibility of explosion iv)Larger arcing time for small currents v)Prone to restricts

16.	**Mention different types of circuit breakers? (May/June 2012)**
	i) Air break circuit breaker ii) Oil circuit breaker iii) Minimum oil circuit breaker iv) Air blast circuit breaker v) SF_6 circuit breaker vi)Vacuum circuit breaker
17.	**What are the different types of oil circuit breakers?**
	The different types of oil circuit breakers (which use oil as arc quenching medium) are i) Plain break oil circuit breakers ii) Arc control circuit breakers iii) Minimum oil circuit breakers
18.	**What are the advantages of using vacuum as an arc interrupting medium?**
	Vacuum offers the utmost insulating strength. Interruption occurs in the first current zero. So it has superior arc quenching properties than any other medium. Also the dielectric strength of vacuum is superior to those of porcelain, oil, air and SF_6.
19.	**Write any two properties of contact material used in vacuum circuit breaker?**
	i)Good electrical conductivity to pass normal load currents without over heating. ii)Good thermal conductivity to dissipate rapidly the large heat generated during arcing iii) Ability to endure mechanical damage during arcing iv) Resistive to corrosion and other electrochemical phenomena.
20.	**What are the basic requirements of circuit breaker? (Nov/Dec 2011)**
	i)To make or break a circuit either manually or by remote control under normal conditions ii) Break a circuit automatically under fault condition iii) Make a circuit automatically either manually or by remote control after the fault is cleared. iv) To endure mechanical damage and resistant to atmospheric conditions and be durable and reliable under all weather conditions.
21.	**Write the difference between fuse and circuit breaker. (Nov/Dec**

	2012)(May/June 2014) (Apr/May 2021)

Fuse	Circuit Breaker
Works on the thermal and electrical properties of the conducting materials	Works on the switching principle and electromagnetism
Fuse can only be used once	A circuit breaker can be used many numbers of times
Automatic operation	Can either be automatic or manually operated
Low Cost	High Cost

22.	**Enumerate breaking capacity of circuit breaker. (Nov/Dec 2012) (Nov/Dec 2014)**
	The capacity of the circuit breaker which can break under specified conditions of recovery voltage. The breaking capacity of a circuit breaker is expressed in MVA and given as 1.732 * (rated voltage in kV) *(rated current in kA).
23.	**Write the ratings of the circuit breaker. (Nov/Dec 2013)**
	The ratings of circuit breakers are: i) Rated voltage ii) Rated insulation level iii) Rated normal current iv) Rated frequency v) Rated duration of short circuit vi) Rated short circuit breaking current vii) Rated short circuit making current viii) Rated peak withstand current ix) Rated TRV for terminal fault x) rated operating sequence xi) Rated supply voltage for opening and closing devices and auxiliary circuits xii) Rated pressure of compressed gas for interruption
24.	**Define the opening time of circuit breaker. (May/June 2014)**
	The time interval which is passed in between the energization of the trip coil to the instant of contact separation is caused the opening times. It is dependent on fault current level.
25.	**What is meant by current chopping? (Nov/Dec 2014) (April/may 2019) (Apr/May 2021)**
	At the time of interruption of a large fault current, the arc energy is high enough to keep the arc column ionized until the arc is interrupted at natural

	current zero. On the other hand, while interrupting small inductive currents such as unloaded currents of transformers and currents of shunt reactor, there is a possibility of overvoltage depending on the value of the chopping current. This small inductive current is interrupted just before natural current zero and thus induces high transient voltages, which is known as current chopping.
26.	**What is resistance switching? (Nov/Dec 2013)** It is the method of connecting a resistance in parallel with the contact space (arc). The inserted resistance reduces the re striking voltage frequency and it diverts part of the arc current. It assists the circuit breaker in interrupting the magnetizing current and capacity current.
27.	**What is an arc?**
	Arc is a phenomenon occurring when the two contacts of a circuit breaker separate under heavy load or fault or short circuit condition. When a short circuit current of usually 10 times greater than the normal circuit flows through the circuit breaker under fault condition. During this if the circuit breaker opens its contacts then the contact area reduces which increases current density (electron density) further it increases the temperature near the contacts. This temperature ionizes the medium (oil, air, gas) between the contacts which forces the medium to acts a conductor for electron flow. This instant electron discharge with high temperature is known as arc.
28.	**Give the two methods of arc interruption? (May/June 2012) (Apr/May 2015)**
	i) High resistance interruption:-the arc resistance is increased by elongating, and splitting the arc so that the arc is fully extinguished. ii)Current zero method:-The arc is interrupted at current zero position that occurs100 times a second in case of 50Hz power system frequency in AC.
29.	**What is restriking voltage? (Nov/Dec 2011) (May/June 2017)**
	Restriking voltage is the transient voltage appearing across the breaker contacts immediately after the opening of breaker contacts. It is also called Transient Recovery Voltage (TRV). Restriking voltage is associated with high frequency which die out quickly. Even though restriking voltage is lasts for very short duration, its importance for breaker fault clearing cannot be ignored
30.	**What is meant by recovery voltage? (Nov/Dec 2011) (May/June 2013)**

	The power frequency RMS voltage appearing across the breaker contacts after the arc is extinguished and transient oscillations die out is called recovery voltage. It is a critical parameter for fault interruption by a high-voltage circuit breaker, its characteristics (amplitude, rate of rise) can lead either to a successful current interruption or to a failure
31.	**Define the term RRRV? (May/June 2012) (Apr/May 2015)**
	The transient voltage which appears across the circuit breaker contacts at the instant of arc extinction is called restriking voltage. RRRV is the Rate of Rise of Restriking Voltage, expressed in volts per microsecond. It is the rate at which the restriking voltage changes per microsecond. It is closely associated with natural frequency of oscillation.
32.	**What is the main problem of the circuit breaker?**
	When the contacts of the breaker are separated, an arc is struck between them. This arc delays the current interruption process and also generates enormous heat which may cause damage to the system or to the breaker itself.
33.	**What are the factors the arc resistance depends upon?**
	Degree of ionization- If there are less number of ionized particles between contacts then the arc resistance increases. Length of the arc- The arc resistance is a function of length of arc which is nothing but separation between contacts. More the length, more is the arc resistance. Cross section area of the arc- If the arear of cross section of the arc is less then arc resistance is large
34.	**Mention the details circuit breaker rating**
	i) Rated voltage & rated current ii)Rated Frequency iii)Rated breaking capacity, symmetrical & asymmetrical iv)Rated making capacity v)Rated short time current vi)Rated operating duty
35.	**What are the factors the ARC phenomenon depends upon? (May/June 2013)**
	i) The nature and pressure of the medium ii) The external ionizing and de-ionizing agent present iii) Voltage across the electrodes and its variation with time iv) The nature shape & separation of electrodes v) The nature and shape of vessel and its position in relation to the electrodes

36.	**Define symmetrical breaking capacity. (Nov/Dec 2017)**
	The symmetrical value of breaking capacity is the value of the symmetrical breaking current which the circuit breaker can break at the stated recovery voltage and restriking voltage under prescribed condition.
37.	**What are the two theories explaining current zero interruption?**
	The two theories explaining current zero interruption are: Recovery rate theory or voltage race theory or slepian's theory. Describes the process as race between dielectric strength and restriking voltage. Energy balance theory or Cassie's theory. Cassie stated that the reestablishment of arc or interruption of arc is an energy balance process.
38.	**What are the factors the recovery voltage depends upon? (Nov/Dec 2011)**
	Power factor – For zero power factor the instantaneous voltage gives more transient Armature reaction- For demagnetizing armature reaction, the power frequency component of transient voltage is less Natural Frequency – With increase in frequency the rate of rise of TRV at current zero increases.
39.	**What is the basic requirement of DC circuit breaking?**
	Lengthening of the arc is basic requirements of D.C circuit breaker. Loss of energy increases with increasing length of arc and more power will be required to maintain the arc.
40.	**What are the problems associated with DC circuit breakers?**
	i) Natural current zero does not occur as in the case of A.C circuit breakers. ii) The amount of energy to be dissipated during the short interval of breaking is very high as compared to conventional A.C circuit breakers.
41.	**What is the purpose of protective spark gap?**
	A protective spark gap can be used across the circuit breaker to reduce the size of commutation capacitor. The spark gap acts as an energy dissipating device for high frequency currents.
42.	**List out the various methods of arc interruptions. (Nov/Dec 2012) (Apr/May 2015) (Nov/Dec 2019)**

	The various methods of arc interruptions are: High resistance interruption – Resistance of current path is increased rapidly. Low Resistance or Current Zero interruption – At natural current zero point of a.c wave the arc is interrupted. Artificial Current zero interruption – Employed in dc systems to make current zero artificially.
43.	**How do you classify the circuit breakers? (Nov/Dec 2012) (Nov/Dec 2014)**
	The circuit breakers are classified as: Air break circuit breaker, Oil circuit breaker, Air blast circuit breaker SF_6 circuit breaker, Vacuum circuit breaker
44.	**What is meant by auto reclosing? (Nov/Dec 2013) (May/June 2016)**
	In electric power distribution, an auto reclosure is a circuit breaker equipped with a mechanism that can automatically close the breaker after it has been opened due to a fault. It is a phenomenon in which the breaker tries to reconnect the line between two points with the delay or without delay.
45.	**Write the function of isolating switch. (Nov/Dec 2013) (May/June 2016)**
	A disconnector, disconnect switch or isolator switch is used to ensure that an electrical circuit is completely de-energized for service or maintenance. The disconnector is usually not intended for normal control of the circuit, but only for safety isolation. Disconnector can be operated either manually or automatically (motorized disconnector).
46.	**Mention any two advantages of vacuum circuit breakers.(Nov/Dec 2014)**
	They are compact in size and have longer life. ii) There are no fire hazards.iii) No generation of gas during and after operation. iv)They require less maintenance and quiet in operation. v) They can withstand lightning surges.
47.	**Why current chopping is not required in MOCB?**
	MOCB has superior arc quenching properties when compared to air blast circuit breakers due to the cooling oil and hence there is no special mechanism required for current chopping.

48.	**How does a circuit breaker differ from a switch? (Nov/Dec 2015) (May/June 2016)**
	Switches are not automatic as they need to be manually turned on or off while circuit breakers just trips off on certain conditions. Switches allow users to cut off power supply to a certain area or equipment while circuit breakers are more preventive in nature. Circuit breakers are essentially automatic off switches designed for a very specific purpose, which is to prevent unnecessary electrical circuit damage.
49.	**Name the materials used for contacts of vacuum circuit breakers. (Nov/Dec 2015)**
	The material used for current carrying contacts plays an important role in the performance of the vacuum circuit breaker. The alloys like, Copper-bismuth or copper-chrome are the ideal material to make VCB contacts.
50.	**What is the difference between re-striking voltage and recovery voltage? (Nov/Dec 2016)**
	Re-striking voltage: It is the transient voltage appearing across the breaker contacts at the instant of arc being extinguished. Recovery voltage: The power frequency RMS voltage appearing across the breaker contacts after the arc is extinguished and transient oscillations die out is called recovery voltage. If restriking voltage rises more rapidly than the dielectric strength then the arc persists whereas the recovery voltage is equal to the normal system voltage after arc extinction.
51.	**State the difference between D.C. and A.C. circuit breaking. (Nov/Dec 2016)**
	DC circuit breaker, like their name suggests, is used for the protection of electrical devices that operate with direct current. The main difference between direct current and alternating current is that in DC the voltage output is constant, while in AC it cycles several times per second. DC circuit breakers are frequently used in applications such as battery powered electric circuits, such as those found in homes with solar panels whereas ac circuit breakers are used in protection of power system components. With the advent of HVDC systems DC breaking has gained prominence in research.

52.	**What is rupturing Capacity of a circuit breaker? (May/June 2017)**
	Rupturing capacity is the current that a fuse, circuit breaker, or other electrical apparatus can interrupt without being destroyed or causing an electric arc with unacceptable duration. The prospective short-circuit current which can occur under short circuit conditions should not exceed the rated breaking capacity of the apparatus. This is an important consideration in the design of circuit breakers.
53.	**What are the factors responsible for increase in arc resistance? (April/May 2018)**
	• The arc resistance increases when ionized particle between contact decreases. • As the separation between contact increases and length of the arc also increases which increases the arc resistance • With decrease in cross section area of the arc the arc resistance increases
54.	**A circuit breaker is rated as 1500A, 1000MVA, 3second, 3 phase oil circuit breaker . Find the rated making current. (April/may 2018)**
	Given:Breaking capacity= 1000MVA; Breaking current = 1500A; Soln: Making current = 2.55*breaking current=2.55*1500=3825A.
55.	**Why rate of rise of restriking voltage plays an important role in circuit breaker operation? (Nov/Dec 2018)**
	The rate of rise of restriking voltage denotes the rate at which transient voltage increases or decreases. This factor plays an important role in circuit breaker operation since it decides the interruption of current by the circuit breaker. Transient recovery voltage depends upon natural frequency and power factor.
56.	**Why oil circuit breakers are not suitable for heavy current interruption at low voltages? (Nov/Dec 2018)**
	Oil circuit breakers cannot be used for heavy current interruption because high current causes arc which produces flammability of oil. Thus it requires high maintenance. The arcing products may deteriorate the quality of oil by the time, so fresh oil and maintenance is needed at regular interval.

57.	**What are the differences between MCB and MCCB?**
	<u>MCB-Miniature Circuit Breaker</u> MCB is an electromechanical device which guards an electrical circuit from an over current, that may effect from short circuit, overload or imperfect design. This is a better option to a Fuse since it doesn't require alternate once an overload is identified. **<u>MCCB-Molded Case Circuit Breaker</u>** The MCCB is used to control electric energy in distribution n/k and is having short circuit and overload protection. This circuit Breaker is an electromechanical device which guards a circuit from short circuit and over current.
	Part B
1.	Explain with neat sketch, the construction and working of minimum oil circuit breaker. What are its main advantages and disadvantages? **(May/June 2016) (Nov/Dec 2019)**
2.	**i)** Describe the various types of rating of circuit breaker **(May/June 2012) (May/June 2013) (Nov/Dec 2015)** **ii)** Describe the various methods of testing of circuit breaker **(Nov/Dec 2014)(May/June 2014) (May/June 2016) (Nov/ Dec 2012)**
3.	Discuss the selection of circuit breakers for different ranges of system voltages. **(Nov/ Dec 2012)**
4.	With a neat block diagram, explain the construction, operating principle and applications of SF_6 circuit breaker. What are its advantages over other circuit breaker? **(Apr/May 2015) (May/June 2014) (Dec 2014) (Nov/Dec 2015) (Nov/Dec 2019).**
5.	With neat sketches, explain the construction and operating principle of air break CB **(Nov/Dec 2013) (Nov/Dec 2015)**
6.	Compare the performance, characteristics, and application of different types of circuit breaker. **(Apr/May 2015)**
7.	What are the requirements of a contact material for a vacuum circuit breaker? Why current chopping is not a serious problem with this circuit breaker? **(May 2015) (May/June 2017) (April/may 2018) (April/may 2019) (Apr/May 2021)**
8.	With neat sketch explain the principles of axial blast circuit breaker. Enumerate

	the advantages and disadvantages of air blast circuit breakers. **(Apr/May 2015) (Nov/Dec 2018) (May/June 2017) (April/may 2018) (April/may 2019) (Apr/May 2021)**
9.	What are the various types of operating mechanism which are used for opening and closing of the contacts of a CB? Discuss their merits and demerits.
10.	In a short circuit test on a 130 kV ,3Φ system , the breaker gave the following results : p.f of fault 0.45, recovery voltage 0.95 times full line voltage , breaker current symmetrical, and restriking transient had a natural frequency 16 kHz .determine average RRRV. Assume fault is grounded.
11.	In a 220 kV system, the reactance and capacitance up to the location of circuit breaker is 8Ω and 0.025 μF respectively. A resistance of 600 Ω is connected across the contacts of the circuit breaker. Determine the following: Natural frequency of oscillation Damped frequency of oscillation. Critical value of resistance which will give no transient oscillation. The value of resistance which will give damped frequency of oscillation, one fourth of the natural frequency of oscillation. **Probable Part C**
12.	i)Explain how arc is initiated and sustained when the circuit breaker contacts break ii)What is current chopping? Explain how can the effect of current chopping be minimized? **(Nov/Dec 2011)**
13.	i) Derive an expression for the rate of rise of restriking voltage in a circuit breaker ii)Describe the operating principle of DC circuit breaker. **(Nov/Dec 2013) (Nov/Dec 2011)(May/June 2014). (Apr/May 2015) (Nov/Dec 2014) (May/June 2016) (Nov/Dec 2016) (April/may 2019)**
14.	Discuss the recovery rate theory and energy balance theory of arc interruption in a circuit breaker. **(Apr/May 2015) . (May/June 2016)**
15.	Discuss the problems associated with the interruptions of low inductive current and the fault occurs nearer to the substation. **(Nov/ Dec 2012) (Nov/Dec 2014) (Nov/Dec 2015)**
16.	Explain the phenomenon of current chopping and capacitive current breaking with diagram and waveforms. **(May/June 2012, 2013, 2014, 2017) (Nov/Dec 2013) (Apr/May 2015) ((Nov/Dec 2015) (May/June 2016)**
17.	Explain the methods of arc interruption. **(May/June 2014) (Nov/Dec 2011) (April/may 2019)**

18.	In short circuit test on a 3 pole, 132kV, circuit breaker, the following observations are made. Power factor for fault = 0.4, recovery voltage 0.9 times full line value, the breaking current symmetrical, frequency of oscillation of restriking voltage 16kHz. Assume neutral is grounded and fault is not grounded. Determine RRRV. **(Nov/Dec 2016)** **Probable Part C**
19.	Write short notes on Resistance switching**. (Nov/ Dec 2017) (April/may 2018) (Nov/Dec 2018) (Apr/May 2021)**
20.	Explain the characteristics, working and limitations of MCB and MCCB.

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE3602- POWER SYSTEM OPERATION & CONTROL

SEMESTER VI

REGULATIONS 2021

NOTES

&

QUESTION BANK

EE3602 POWER SYSTEM OPERATION AND CONTROL

COURSE OBJECTIVES:

To impart knowledge on,

• The significance of power system operation and control.

• Real power– frequency interaction and design of power– frequency controller.

• Reactive power– voltage interaction and the compensators for maintaining the voltage profile.

• The generation scheduling and economic operation of power system.

• SCADA and its application for real time operation and control of power systems.

UNIT I INTRODUCTION 9 Power scenario in Indian grid – National and Regional load dispatching centres – Requirements of good power system – Necessity of voltage and frequency regulation – real power vs frequency and reactive power vs voltage control loops - System load variation, load curves – Load forecasting – Computational methods in load forecasting – Load shedding and Islanding – deregulation - Basics of electrical energy tariff.

UNIT II REAL POWER FREQUENCY CONTROL 9 Basics of speed governing mechanisms and modelling – Speed regulation of two generators in parallel Load Frequency Control (LFC) of single area system – Static and dynamic analysis – LFC of two area system –Tie line modelling – Block diagram representation of two area system – Static and dynamic analysis – Tie line with frequency bias control – State variable model – Integration of economic dispatch control with LFC.

UNIT III REACTIVE POWER – VOLTAGE CONTROL 9 Generation and absorption of reactive power – Basics of reactive power control – Automatic Voltage Regulator (AVR) – Brushless AC excitation system – Block diagram representation of AVR loop static and dynamic analysis – Stability compensation – Voltage drop in transmission line – Methods of reactive power injection – Tap changing transformer, SVC and STATCOM for voltage control.

UNIT IV ECONOMIC OPERATION OF POWER SYSTEM 9 Statement of economic dispatch problem – Input and output characteristics of thermal plant incremental cost curve – Optimal operation of thermal units without and with transmission losses (no derivation of transmission loss coefficients) – Lambda–iteration method – Base point and participation factors method. Statement of Unit Commitment (UC) problem – Constraints on UC problem – Solution of UC problem using priority list – Special aspects of short term and long-term hydrothermal scheduling problems.

UNIT V COMPUTER AIDED CONTROL OF POWER SYSTEM 9 Need of computer control of power system – Concept of energy control centers and functions – PMU system monitoring, Data acquisition and controls – System hardware configurations – SCADA and EMS functions – State estimation – Measurements and errors – Weighted least square estimation – Various operating states – State transition diagram. TOTAL: 45 PERIODS

COURSE OUTCOMES:

On the successful completion of the course, students will be able to:

CO1: Understand the day – to – day operation of power system.

CO2: Model and analyse the control actions that are implemented to meet the minute-to minute variation of system real power demand.

CO3: Model and analyze the compensators for reactive power control and various devices used for voltage control.

CO4: Prepare day ahead and real time economic generation scheduling.

CO5: Understand the necessity of computer control of power systems.

TEXTBOOKS: 1. Olle. I. Elgerd, 'Electric Energy Systems theory – An introduction', McGraw Hill Education Pvt. Ltd., New Delhi, 2 nd edition, 2017.

2. Allen. J. Wood and Bruce F. Wollen berg, 'Power Generation, Operation and Control', John Wiley & Sons, Inc., 3rd edition, 2013.

3. Abhijit Chakrabarti and Sunita Halder, 'Power System Analysis Operation and Control', PHI learning Pvt. Ltd., New Delhi, Fourth Edition, 2018.

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1. Kothari D.P. and Nagrath I.J., 'Power System Engineering', Tata McGraw–Hill Education, Second Edition, Reprint 2018.

2. Hadi Saadat, 'Power System Analysis', McGraw Hill Education Pvt. Ltd., New Delhi, 23rd reprint, 2015.

3. Kundur P., 'Power System Stability and Control, McGraw Hill Education Pvt. Ltd., New Delhi, 12th reprint, 2015.

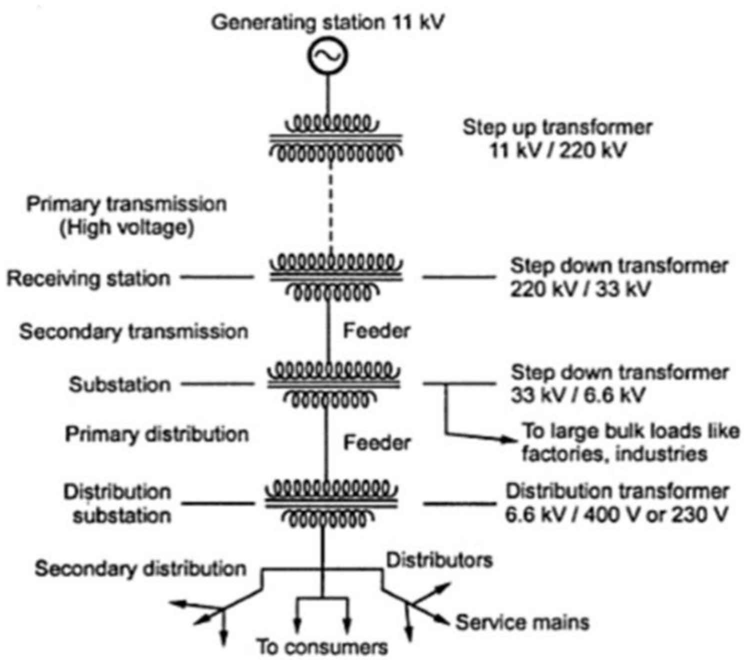
4. B.M. Weedy, B.J. Cory et al, ‘Electric Power systems’, Wiley, Fifth Edition, 2012.

UNIT 1-PRELIMINARIES ON POWER SYSTEM OPERATION AND CONTROL

Overview of Power System:

- Generation
- Transmission &
- Distribution

Structure of power system



Components of Power system

- Generator – Converts mechanical energy to electrical energy
  [6.6KV, 10.5KV, 11KV, 13.8KV & 15.75KV]
- Transformer – Transfer energy for one circuit to another circuit without changing the frequency

(for increasing & decreasing the Voltage level)

- Transmission Lines – Power transfer from one location to another
- Distribution Lines – Distributes power to commercial, domestic & small consumers
  - ✓ Primary Transmission Lines –11KV/110KV or 132KV or 220KV or 400KV or 765KV
  - ✓ Secondary Transmission Lines – (step down value) 66KV or 33KV or 22 KV or 11KV.
  - ✓ Primary Distribution Line- 3Φ, 3 wire system, 33 KV or 66KV feeder
  - ✓ Secondary Distribution Line- 400 V (for 3Φ) or 230 V (for 1Φ)

Power scenario in Indian grid

- India is the world's third largest producer and third largest consumer of electricity.
- The national electric grid in India has an installed capacity of 371.054 GW as of 30 June 2020.
- Renewable power plants, which also include large hydroelectric plants, constitute 35.94% of India's total installed capacity.
- During the 2018-19 year, the gross electricity generated by utilities in India was 1,372 TWh and the total electricity generation (utilities and non utilities) in the country was 1,547 TWh. (1 Twh = 3.6 x 10^{15} joules)
- The gross electricity consumption in 2018-19 was 1,181 kWh per capita.
- India has a surplus power generation capacity but lacks adequate distribution infrastructure.
- To address this, the Government of India launched a program called "Power for All" in 2016.
- The program was accomplished by December 2018 in providing the necessary infrastructure to ensure uninterrupted electricity supply to all households, industries, and commercial establishments.
- India's electricity sector is dominated by fossil fuels, in particular coal, which during the 2018-19 fiscal year produced about three-quarters of the country's electricity.
- The government is making efforts to increase investment in renewable energy.
- The government's National Electricity Plan of 2018 states that the country does not need more non-renewable power plants in the utility sector until 2027, with the commissioning of 50,025 MW coal-based power plants under construction and addition of 275,000 MW total renewable power capacity after the retirement of nearly 48,000 MW old coal-fired plants

Important Terms

Load Dispatching Center :

- The Load Dispatch Department is the nerve centre for the operation , planning , monitoring and control of the power system .
- Electricity cannot be stored and has to be produced when it is needed. It is therefore essential that power system is planned and operated optimally & economically.

Objective of Load Dispatch Center :

- Matching the power demand with system integrity , reliability and security of generation and transmission facilities
- Regulating the system frequency .
- Optimum utilisation of resources.
- Quick restoration of normalcy after system disturbances.

Power grid is divided into 5 regions:

1. Northern Power Grid
2. Eastern Power Grid
3. Western Power Grid
4. Southern Power Grid
5. North-Eastern Power Grid

Load Dispatching Center
NLDC- National Load Dispatch Center
RLDC- Regional Load Dispatch Center
SLDC- State Load Dispatch Center

Necessity of voltage and frequency regulation :

Need for voltage Regulation:

- The transmission lines and the distribution lines need voltage control at various stages to maintain the voltage at the last consumer premise within permissible limits .
- Below normal voltage reduces the output from equipments (eg;light output from lamp).
- Above voltage reduces the life of the equipments
- Both over voltage and under voltage are detrimental to electrical appliances.
- Electric motors will tend to run on over speed when they are fed with higher voltages resulting vibration and mechanical damage.
- Over voltage may also cause insulation failure.
- For a specified power rating, when the supply voltage is less, the current drawn is more and it will give rise to heating problems.
- Therefore it is essential to keep voltage variation within the tolerance.

Need for Frequency Regulation:

- In any power system, if the frequency changes, there won't be required receiving end voltages.
- If the systems with two different frequencies are connected in parallel, it will spoil the system. In order to make two system at same frequency, frequency converting stations or links are required
- Three phase a.c. motors run at speeds that are directly proportional to the frequency.
- Variation of system frequency will affect the motor performance.
- The blades of steam and water turbines are designed to operate at a particular speed. Frequency variations will cause change in speed. This will result in excessive vibration and cause damage to the turbine blades.
- Frequency error may produce havoc in the digital storage and retrieval process.
- Therefore it is essential to keep the system frequency constant.

P-F AND Q-V CONTROL STRUCTURE :

BASIC PF AND QV CONTROL LOOPS

1.Static changes ΔP_i in the real bus power affect the bus phase angle and not the bus voltage magnitudes.
This change affects the real line flows and not the reactive line flows.
2.Static changes ΔQ_i in the reactive power affect the bus voltage magnitudes and the phase angle.
This change affects the reactive line flows and not the real line flows.
3.A static change in the reactive bus power affects the bus voltage at the

particular bus and has little effect on the magnitude of voltage.

Q-V CONTROL LOOP

- The automatic voltage regulator circuit is used for voltage control .
- This bus bar voltage is stepped down using a potential transformer to a small value of voltage.
- This is sent to the rectifier circuit which converts Ac voltage into DC voltage and a filter circuit is used in this removes the harmonics .
- The voltage V, thus rectified is compared with a reference voltage v_{ref} in the comparator and a voltage error signal is generated .
- The amplified form of this voltage gives a condition for the exciter to increase or decrease the filter current based on its polarity.
- The output of the generator is stepped up using a transformer and fed to the bus bar .
- Thus the voltage is regulated and controlled in the control loop circuit.

P-F CONTROL LOOP

Primary ALFC:

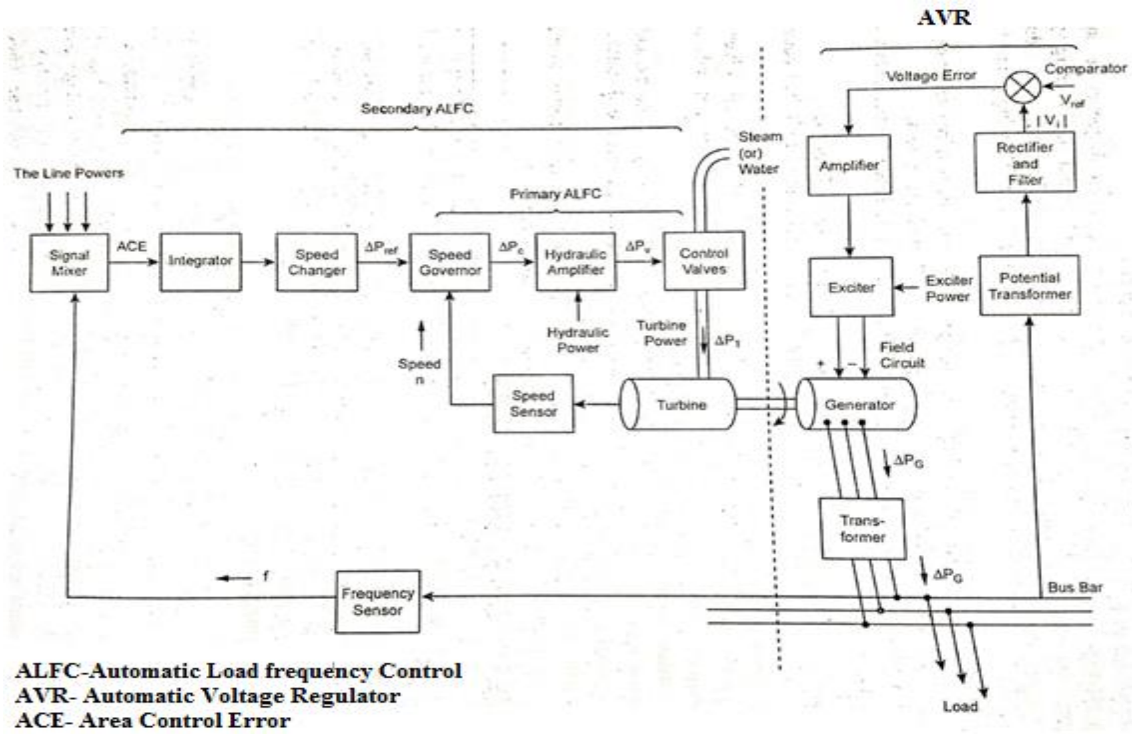
- The circuit primarily controls the steam valve leading to the turbine. A speed sensor senses the speed of the turbine.
- This is compared with a reference speed, governor whose main activity is to control the speed of the steam by closing and opening of the control valve i.e if the differential speed is low ,then the control valve is opened to let out the steam at high speed, thereby increasing turbine's speed and vice versa.
- The control of speed in turn controls the frequency.

Secondary ALFC:

- The circuit involves a frequency sensor that senses the frequency of the bus bar and compare it with tie line power frequencies in the signal mixer.
- The output of this is an area control error which is sent to the speed changer through integrator .
- The speed changer gives the reference speed to the governor. Integral controller is used to reduce the steady state frequency change to zero.
- Thus, the two loops together help in controlling the speed which in turn controls the frequency, since $N \alpha f$.

Using the relation, Speed

$$N = \frac{120f}{P}$$



Automatic load frequency and voltage regulator control loops

- The primary ALFC loop makes the initial coarse readjustment of frequency.
- The secondary ALFC loop takes over the fine adjustment of the frequency by resetting through integral action, the frequency error to zero.

Basic Definitions:

Hot reserve:

Hot reserve is that reserve generating capacity which is in Operation but is not in service.

ii) Cold reserve:

It is that reserve generating Capacity which is available for service but is not in Operation.

iii) Installed Reserve:

Installed Reserve is that generating capacity which is the power intended to be always available.

iv) Spinning Reserve

Spinning Reserve is that reserve generating Capacity which is connected to the bus and is ready to take load.

v) Firm Power

It is the maximum power (thermal or Mechanical) continuously available for conversion of electric power

vi) Spill Power

It is the power that is produced during floods in hydro power station

OVERVIEW OF POWER SYSTEM CONTROL:

- Speed regulation of the governor
- Controls the boiler pressure, temperature & flows
- Speed regulation concerned with steam input to turbine
- Load is inversely proportional to speed
- Governor senses the speed & gives command signal
- Steam input changed relative to the load requirement.

Governor Control

Governor is A device used to control the speed of a prime mover. A governor protects the prime mover from overspeed and keeps the prime mover speed at or nearthe desired revolutions per minute. When a prime mover drives an alternator supplying electrical power at a given frequency, a governor must be used to hold the prime mover at a speed that will yield this frequency. An unloaded diesel engine will fly to pieces unless it is under governor control.

Load frequency control

1. Sense the bus bar frequency & power frequency
2. Difference fed to the integrator & to speed changer
3. Tie line frequency maintained constant

Economic dispatch control

1. When load distribution between a number of generator units considered optimum schedule affected when increase at one replaces a decreases at other.
2. Optimum use of generators at each station at various load is known as economicdispatch control.

Automatic voltage regulator

1. Regulate generator voltage and output power
2. Terminal voltage & reactive power is also met

System voltage control

Control the voltage within the tolerable limits. Devices used are

1. Static VAR compensator
2. Synchronous condenser
3. Tap changing transformer
4. Switches
5. Capacitor
6. Reactor

Security control

1. Monitoring & decision

2. Control

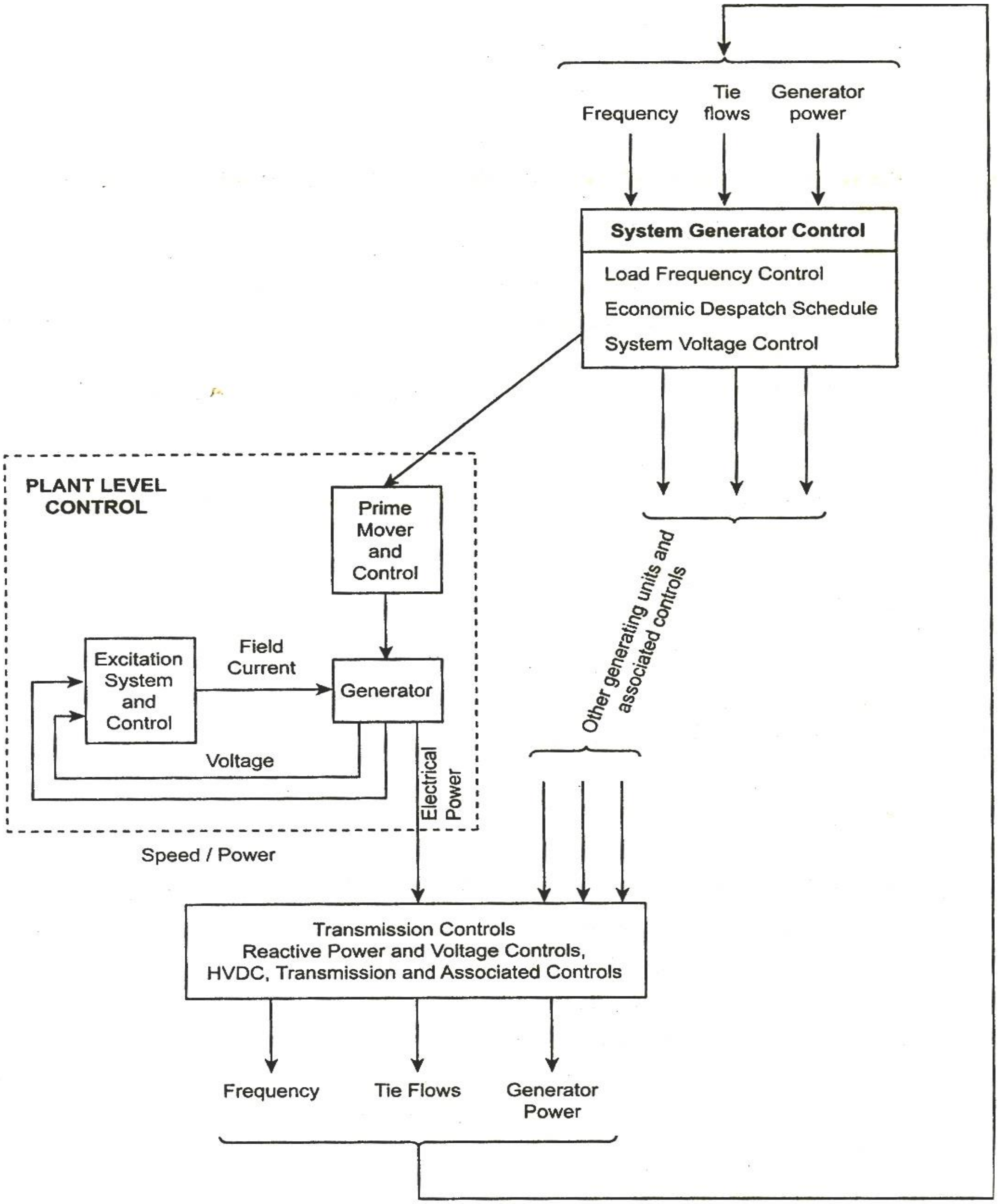
Monitoring & decision:

1. Condition of the system continuously observed in the control centers by relays.

2. If any continuous severe problem occurs system is in abnormal condition.

Control:

1. Proper commands are generated for correcting the abnormality in protecting the system
2. If no abnormality is observed, then the normal operation proceeds for next interval.
3. Central controls are used to monitor the interconnected areas
4. Inter connected areas can be tolerate larger load changes with smaller frequency deviations
5. Central control centre monitors information about frequency, generating unit outputs andtie line power flows to interconnected areas.
6. This information is used by automation load frequency control in order to maintain areafrequency at its scheduled value.



Frequency
Tie flows
Generator power
System Generator Control
Load Frequency Control
Economic Despatch Schedule
System Voltage Control
PLANT LEVEL CONTROL
Prime Mover and Control
Excitation System and Control
Field Current
Generator
Voltage
Electrical Power
Speed / Power
Other generating units and associated controls
Transmission Controls
Reactive Power and Voltage Controls,
HVDC, Transmission and Associated Controls
Frequency
Tie Flows
Generator Power

Governor:

The power system is basically dependent upon the synchronous generator and its satisfactory performance. The important control loops in the system are:

(i) Frequency control, and

(ii) Automatic voltage control.

Frequency control is achieved through generator control mechanism. The governing systems for thermal and hydro generating plants are different in nature since, the inertia of water that flows into the turbine presents additional constrains which are not present with steam flow in a thermal plant. However, the basic principle is still the same; i.e. the speed of the shaft is sensed and compared with a reference, and the feedback signal is utilized to increase or decrease the power generated by controlling the inlet valve to turbine of steam or water

Fundamentals of Speed Governing Mechanism

- The real power in a power system is being controlled by controlling the driving torques of the individual turbines of the system.
- The speed governor is the main primary tool for the load frequency control, whether the machine is used alone to feed a smaller system or it is a part of the most elaborate arrangement.
- By controlling the position of the control valve or gate, the flow of high pressure steam through the turbine can be controlled.

Speed Governing Mechanism

The speed governing mechanism includes the following parts.

Speed Governor:

It is an error sensing device in load frequency control. It includes all the elements that are directly responsive to speed and influence other elements of the system to initiate action.

Governor Controlled Valves:

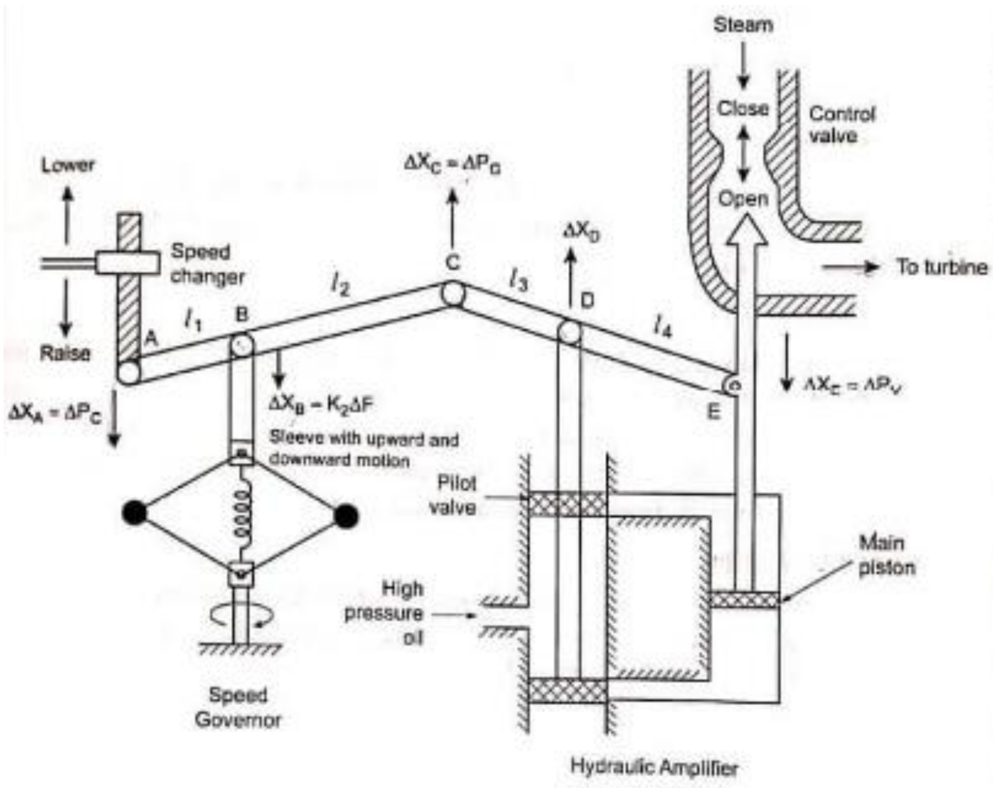
They control the input to the turbine and are actuated by the speed control mechanism.

Speed Control Mechanism:

It includes all equipment such as levers and linkages, servomotors, amplifying devices and relays that are placed between the speed governor and the governor controlled valves.

Speed Changer:

It enables the speed governor system to adjust the speed of the generator unit while in operation.



The pilot valve v operates to increase or decrease the opening of the steam inlet valve V. Let XB and Xc be the changes in the position of the pilot valve v and control valve V responding to a change in governor position. X_A due to load. When the pilot valve is closed XB= 0 and Xc == 0, (Le.,) the control valve is not completely closed, as the unit has to supply its no-load losses. Let be the no-load angular speed of the turbine. As load is applied, the speed falls and through the linkages the governor operates to move the piston P downwards along with points A and B. The pilot valve v admits soil under n and lifts it up so that the input is increased and speed rise. If the link B_e is removed then the pilot valve comes to rest only when the speed returns to its original value. An "isochronous" characteristic will be obtained with such an arrangement where speed is restored to its preload.

With the link Be, the steady state is reached at a speed slightly lower than the no load speed giving a drooping characteristic for the governor system. A finite value of the steady state speed regulation is obtained with this arrangement. For a given speed changer position, the per unit steady state speed regulation is defined by Steady state speed regulation = No-Nr/N

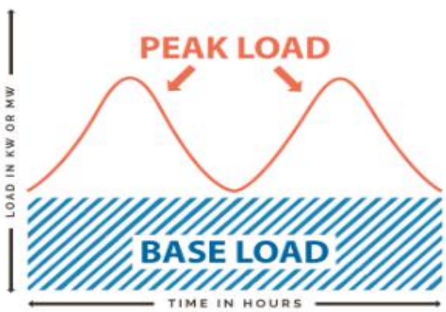
Where No = Speed at no - load

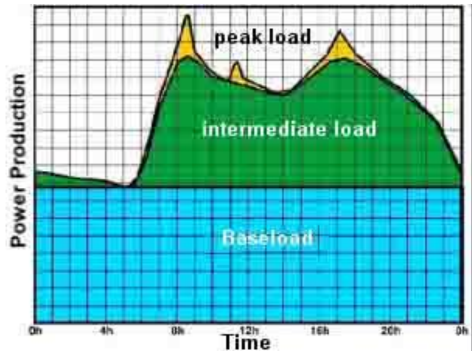
N r = Rated speed

N = Speed at rated load

System Load Variation:

- Load is the device that taps energy from the network
- The variation of load on power station with respect to time.
- Base load is the level that it typically does not go below, that is, the basic amount of electricity that is always required.
- Peak load is the daily fluctuation of electricity use. It is usually lowest in the wee hours of the morning and highest in the early evening.





Types of Load:

- Residential Load or Domestic load
- Commercial load
- Industrial load
- Agricultural load
- Municipal load

Domestic:

Lights, fans, domestic appliances like heaters, refrigerators, airconditioners, mixers, ovens, small motors etc.
Demand factor = 0.7 to 1.0; Diversity factor = 1.2 to 1.3; Load factor = 0.1 to 0.15

Commercial:

Lightings for shops, advertising hoardings, fans, AC etc.

Demand factor = 0.9 to 1.0; Diversity factor = 1.1 to 1.2; Load factor = 0.25 to 0.3

Industrial:

Small scale industries: 0-20kWMedium scale industries: 20- 100kW Large scale industries:
above 100kW

Industrial loads need power over a longer period which remainsfairly uniform throughout the day

For heavy industries:

Demand factor = 0.85 to 0.9; Load factor = 0.7 to 0.8

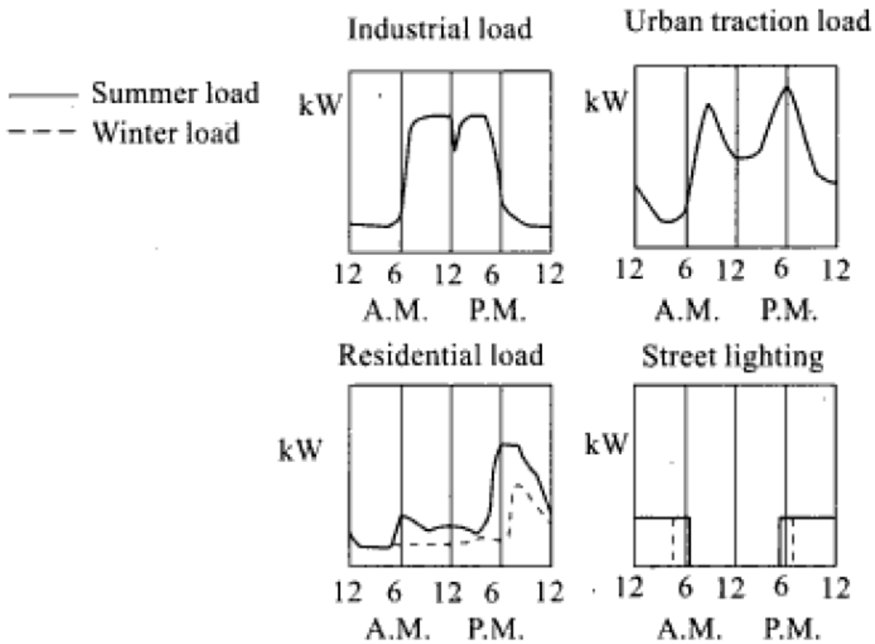
Agriculture:

Supplying water for irrigation using pumps driven by motors

Demand factor = 0.9 to 1; Diversity factor = 1.0 to 1.5; Load factor = 0.15 to 0.25

Other Loads:

Bulk supplies, street lights, traction, government loads which have theirown peculiar characteristics



Categories of load:

(i) Motor loads -70 %

(ii) Heating and Lighting equipment -25%

(iii) Electronic devices – 5%

Heating load : R is constant and P α V^2

Lighting load is independent frequency and P α $V^{1.6}$

Voltage and Frequency dependency loads:

- Lighting, heaters, ovens
- Composite loads
- Induction motor loads

Load duration curve

When an elements of a load curve are arranged in the order of descending magnitudes.

Load curves

The curve showing the variation of load on the power station with respect to time

Types of Load Curve:

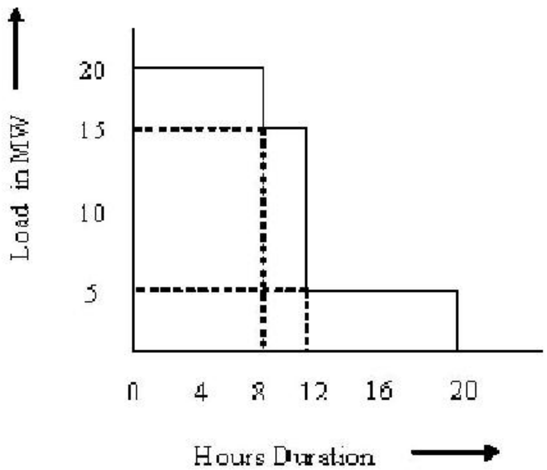
- Daily load curve–Load variations during the whole day

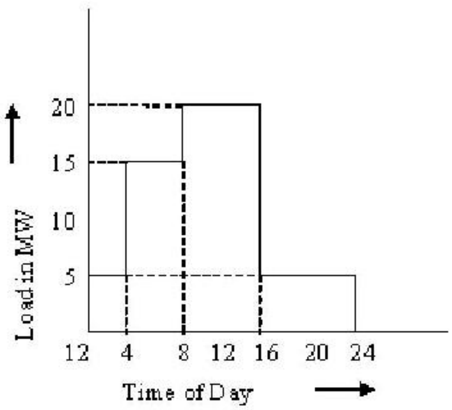
- Monthly load curve–Load curve obtained from the daily load curve

- Yearly load curve-Load curve obtained fromthe monthly load curve

Load duration curve:

When an elements of a load curve are arranged in the order of descending magnitudes.





The load duration curve gives the data in a more presentable form

- The area under the load duration curve is equal to that of the corresponding load curve
- The load duration curve can be extended to include any period of time

System load characteristics

- Connected load
- Maximum demand
- Average load
- Load factor
- Diversity factor
- Plant capacity factor
- Plant use factor

Connected load

It is the sum of continuous ratings of all the equipment connected to supply system

Maximum demand

It is the greatest demand of load on the power station during a given period.

Average load

The average of loads occurring on the power station in a given period (day or month or year

$$\text{Average load} = \frac{\text{Area (in kWh) under daily load curve}}{\text{24 hours}}$$

Load factor

The ratio of average load to the maximum demand during a given period is known as load factor.

Load factor = (average load)/ (maximum demand)

Diversity factor

The ratio of the sum of individual maximum demand on power station isknown as diversity factor.

Diversity factor = (sum of individual maximum demand)/(maximum demand).

Plant Capacity Factor:

It is the ratio of actual energy produced to the maximum possible energy that could have been produced during a given period.

Plant Use Factor:

It is the ratio of kWh generated to the product of plant capacity and the number of hours for which the plant was in operation.

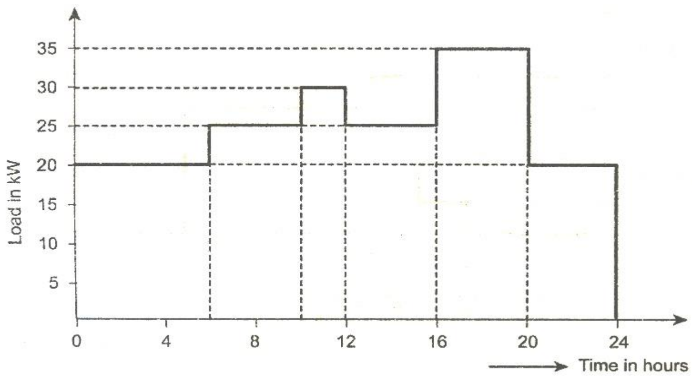
$$Plant\ \ use\ \ factor = \frac{Station\ \ output\ \ in\ \ kWh}{Plant\ cpacity\ \ x\ Hours\ of\ \ use}$$

Problems:

A Generating station has the following Daily Load cycle.

Time(hrs)	0-6	6-10	10-12	12-16	16-20	20-24
Load(Mw)	20	25	30	25	35	20

1. Draw the Load curve & calculate i) Maximum Demand ii) Units Generated/Day iii) Average Load iv) Load factor (Nov/Dec-2012)



i) Maxi Demand = 35 MW =35, 000 KW

ii) Units Generated / Day = Area Under the load curve in kwhr

$= (16*20+4*25 +2*30 + 4*25 + 4*35 + 4*20)*10^3$

$= 600*10^3$kwhrs

iii) Average Load = (Units Generated / Day) / (Hours in a Day)

$= 600*10^3/24$

= 25,000kw

iv) Load factor = Average Load / Maxi Demand

$=25000 / 35*10^3$

=0.7143 (or)

=71.43%

2. The Maximum Demand on a power station is 100MW. If the annual load factor is 40%, calculate the total energy Generated in a year.

Given:

Maximum Demand=100Mw

Actual Load factor=40%

To find:

Total Generated in a year

Solution:

Energy Generated in a year

= Maximum Demand* Load factor*Hours in a Year

= 100*0.4*8760

$=350.4*10^3$Mwhrs.

Load fore Casting:

The load on their system should estimate in advance. This estimation in advance is known as Load fore casting.

i) Need for load forecasting:

Need for load forecasting are:

a) To meet out the future demand

b) Long –term forecasting is required for preparing maintenance schedule of the generating units, planning future expansion of the system.

c) For day-to-day operation, short term load forecasting is needed in order to commit enough generating capacity for the forecasting demand and for maintaining the required spinning reserve.
d) Very short term load forecasting are used for generation and distribution. i.e., economic generation scheduling and load dispatching.
Medium term load forecasting is needed for predicted monsoon acting and hydro availability and allocating spinning reserves.

Classification load forecasting:

Forecast	Lead Time	Application
Very short term	Few minutes to half an hour	Real time control, real time security evaluation
Short term	Half an hour to a few hours	Allocation of spinning reserve, unit commitment maintenance scheduling
Medium term	Few days to a few weeks	Planning or seasonal peak-winter, summer
Long term	Few months to a few years	To plan the growth of the generation capacity.

Forecasting techniques

- Three broad categories based on:
    - Extrapolation
        - Time series method
        - Use historical data as the basis of estimating future outcomes.
    - Correlation
        - Econometric forecasting method
        - identify the underlying factors that might influence the variable that isbeing forecast.
    - Combination of both

Extrapolation

- Based on curve fitting to previous data available.
- With the trend curve obtained from curve fitted load can be forecasted at any futurepoint.
- Simple method and reliable in some cases.
- Deterministic extrapolation:

    - Errors in data available and errors in curve fitting are not accounted.
- Probabilistic extrapolation
    - Accuracy of the forecast available is tested using statistical measures such asmean and variance.
- Standard analytical functions used in trend curve fitting are:
    - Straight line:
    - Parabola:
    - s curve:
    - Exponential:
    - Gompertz:
- Best trend curve is obtained using regression analysis.
- Best estimate may be obtained using equation of the best trend curve.

Correlation

- Relates system loads to various demographic and economic factors.
- Knowledge about the interrelationship between nature of load growth and othermeasurable factors.
- Forecasting demographic and economic factors is a difficult task.
- No forecasting method is effective in all situations.
- Designer must have good judgment and experience to make a forecasting methodeffective.

Impact of weather in load forecasting

- Weather causes variations in domestic load, public lighting, commercial loads etc.
- Main weather variables that affect the power consumption are:

- Temperature
- Cloud cover
- Visibility
- precipitation

- First two factors affect the heating/cooling loads
- Others affect lighting loads
- Average temperature is the most significant weather dependent factor that influences load variations.
- Temperature and load are not linearly related.
- Non-linearity is further complicated by the influence of
- Humidity
- Extended periods of extreme heat or cold spells
- In load forecast models proper temperature ranges and representative average temperatures which cover all regions of the area served by the electric utility should beselected.
- Cloud cover is measured in terms of:
- height of cloud cover
- Thickness
- Cloud amount
- Time of occurrence and duration before crossing over a population area.
- Visibility measurements are made in terms of meters/kilometers with fog indication.
- To determine impact of weather variables on load demand, it is essential to analyze data concerning different weather variables through the cross-section of area served by utility and calculate weighted averages for incorporation in the modeling.

Peak load forecasting

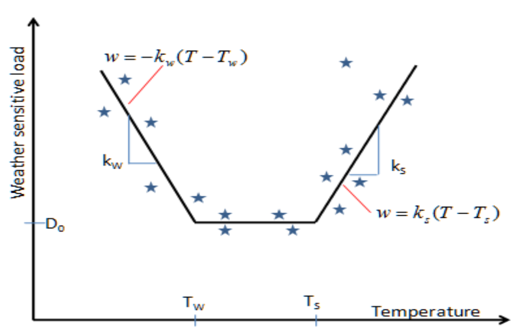
- Extrapolate historical demand data

- Weather conditions can be included
- Basic approach for weekly peak demand forecast is:
- Determine seasonal weather load model.
- Separate historical weather-sensitive and non-weather sensitive components of weekly peak demand using weather load model.
- Forecast mean and variance of non-weather-sensitive component of demand.
- Extrapolate weather load model and forecast mean and variance of weather sensitive component.
- Determine mean, variance and density function of total weekly forecast.
- Calculate density function of monthly/annual forecast.
- Assume that the seasonal variations of the peak demand are primarily due to weather.
- Otherwise, before step-3 can be undertaken, any additional seasonal variation remaining after weather-sensitive variations must be removed
- To use the proposed forecasting method, a data base of at least 12 years is recommended.
- To develop weather load models daily peaks and coincident weather variable values areneeded.
- Plot a scatter diagram of daily peaks versus an appropriate weather variables.
- Dry-bulb temperature and humidity

Using curve fitting three line segments can be defined in the example

Parameters ofthe model:

$$
\begin{aligned}
w &= k_S\,(T - T_S) && if\ T > T_S \\
&= -k_W\,(T - T_W) && if\ T < T_W \\
&= 0 && if\ T_W \le T \le T_S
\end{aligned}
$$



Where slopes : K_s and k_W

Threshold temperatures: T_S and T_W

UNIT – II

REAL POWER AND FREQUENCY CONTROL

TECHNICAL TERMS

Control area: Most power systems normally control their generators in unison. The individual control loops have the same regulation parameters. The individual generator turbines tend to have the same response characteristics then it is possible to let the control loop in the whole system which then would be referred to as a control area.

Power Pool: An association of two or more interconnected electric systems having an agreement to coordinate operations and planning for improved reliability and efficiencies.

Prime Mover: The engine, turbine, water wheel, or similar machine that drives an electric generator; or, for reporting purposes, a device that converts energy to electricity directly (e.g., photovoltaic solar and fuel cell(s)).

Pumped-Storage Hydroelectric Plant: A plant that usually generates electric energy during peak-load periods by using water previously pumped into an elevated storage reservoir during off-peak periods when excess generating capacity is available to do so. When additional generating capacity is needed, the water can be released from the reservoir through a conduit to turbine generators located in a power plant at a lower level.

Regulation: The governmental function of controlling or directing economic entities through the process of rulemaking and adjudication

Reserve Margin (Operating): The amount of unused available capability of an electric power system at peak load for a utility system as a percentage of total capability.

Restructuring: The process of replacing a monopoly system of electric utilities with competing sellers, allowing individual retail customers to choose their electricity supplier but still receive delivery over the power lines of the local utility. It includes the reconfiguration of the vertically-integrated electric utility.

Retail Wheeling: The process of moving electric power from a point of generation across one or more utility-owned transmission and distribution systems to a retail customer.

Revenue: The total amount of money received by a firm from sales of its products and/or services, gains from the sales or exchange of assets, interest and dividends earned on investments, and other increases in the owner's equity except those arising from capital adjustments.

Scheduled Outage: The shutdown of a generating unit, transmission line, or other facility, for inspection or maintenance, in accordance with an advance schedule.

Real power: The real power in a power system is being controlled by controlling the driving torque of the individual turbines of the system.

LOAD FREQUENCY CONTROL

The following basic requirements are to be fulfilled for successful operation of the system:

1. The generation must be adequate to meet all the load demand
2. The system frequency must be maintained within narrow and rigid limits.
3. The system voltage profile must be maintained within reasonable limits and
4. In case of interconnected operation, the tie line power flows must be maintained at the specified values.

When real power balance between generation and demand is achieved the frequency specification is automatically satisfied. Similarly, with a balance between reactive power generation and demand, voltage profile is also maintained within the prescribed limits. Under steady state conditions, the total real power generation in the system equals the total MW demand plus real power losses. Any difference is immediately indicated by a change in speed or frequency. Generators are fitted with speed governors which will have varying characteristics: different sensitivities, dead bands response times and droops. They adjust the input to match the demand within their limits. Any change in local demand within permissible limits is absorbed by generators in the system in a random fashion.

An independent aim of the automatic generation control is to reschedule the generation changes to preselected machines in the system after the governors have accommodated the load change in a random manner. Thus, additional or supplementary regulation devices are needed along with governors for proper regulation.

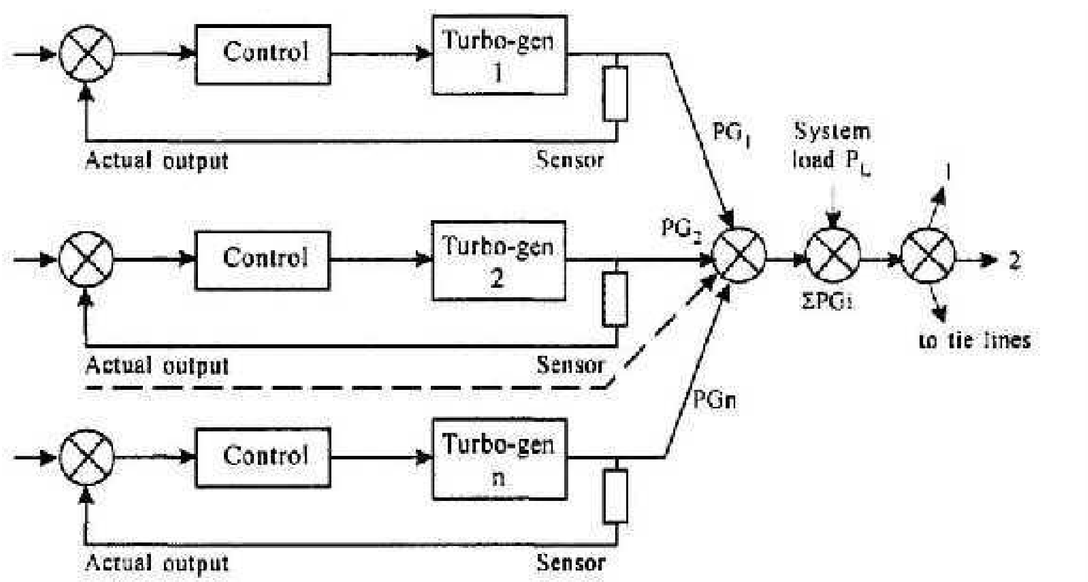
The control of generation in this manner is termed load-frequency control. For interconnected operation, the last of the four requirements mentioned earlier is fulfilled by deriving an error signal from the deviations in the specified tie-line power flows to the neighboring utilities and adding this signal to the control signal of the load-frequency control system. Should the generation be not adequate to balance the load demand, it is imperative that one of the following alternatives be considered for keeping the system in operating condition:

I. Starting fast peaking units.

2. Load shedding for unimportant loads, and

3. Generation rescheduling.

It is apparent from the above that since the voltage specifications are not stringent. Load frequency control is by far the most important in power system control.



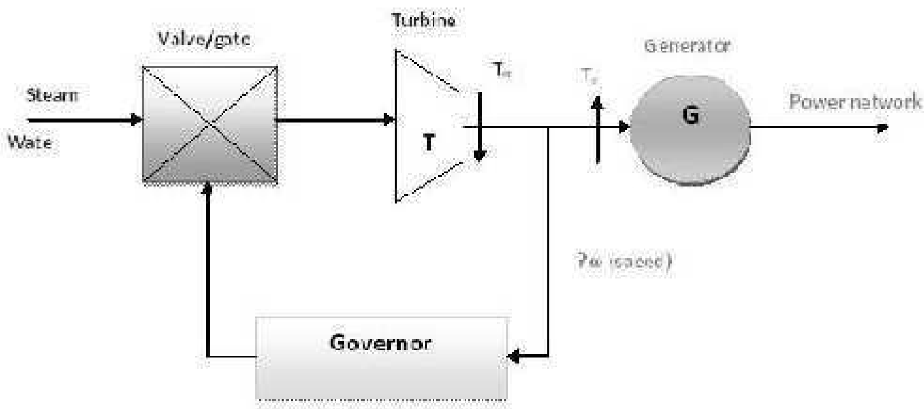
The block schematic for Load frequency control

In order to understand the mechanism of frequency control, consider a small step increase in load. The initial distribution of the load increment is determined by the system impedance; and the instantaneous relative generator rotor positions. The energy required to supply the load increment is drawn from the kinetic energy of the rotating machines. As a result, the system frequency drops. The distribution of load during this period among the various machines is determined by the inertias of the rotors of the generators partaking in the process. This problem is studied in stability analysis of the system.

After the speed or frequency fall due to reduction in stored energy in the rotors has taken place, the drop is sensed by the governors and they divide the load increment between the machines as determined by the droops of the respective governor characteristics. Subsequently, secondary control restores the system frequency to its normal value by readjusting the governor characteristics.

AUTOMATIC LOAD FREQUENCY CONTROL

The ALFC is to control the frequency deviation by maintaining the real power balance in the system. The main functions of the ALFC are to i) to maintain the steady frequency; ii) control the tie-line flows; and iii) distribute the load among the participating generating units. The control (input) signals are the tie-line deviation ΔPtie (measured from the tie- line flows), and the frequency deviation Δf (obtained by measuring the angle deviation Δδ). These error signals Δf and ΔPtie a r e amplified, mixed and transformed to a real power signal, which then controls the valve position. Depending on the valve position, the turbine (prime mover) changes its output power to
establish the real power balance. The complete control schematic is shown in Fig3.3

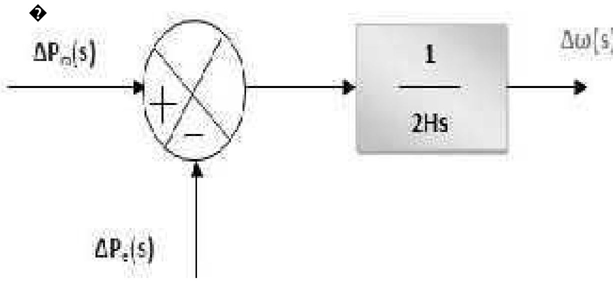


The Schematic representation of ALFC system

For the analysis, the models for each of the blocks in Fig2 are required. The generator and the electrical load constitute the power system. The valve and the hydraulic amplifier represent the speed governing system.Using the swing

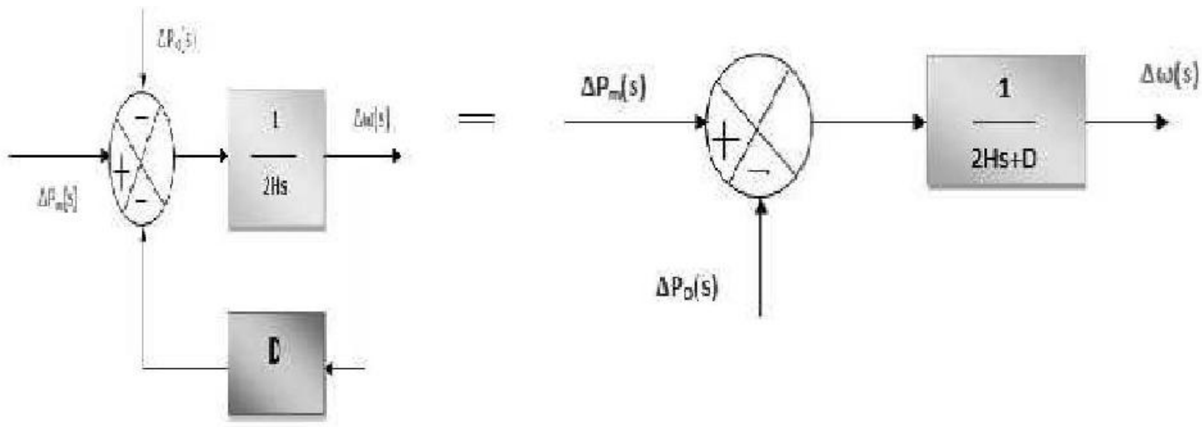
equation, theegenerator can b Using the swing equation, the generator can be modeled

by �



Block Diagram Representation Of The Generator

The load on the system is composite consisting of a frequency independent component and a frequency dependent component. The load can be written as Pe = P0 + Pf

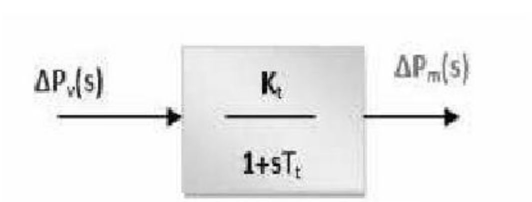


Block Diagram Representation Of The Generator And Load

where, Pe is the change in the load;
P0 is the frequency independent load component; Pf is the frequency dependent load component.

Pf = D where, D is called frequency characteristic of the load (also called as damping constant) expressed in percent change in load for 1% change in frequency. If D=1.5%, then a
1% change in frequency causes 1.5% change in load. The combined generator and the load (constituting the power system) can then be represented as shown in Fig3.5

The turbine can be modeled as a first order lag as shown in the Fig2.6



Turb ine Mc :l.

G(s) =

Pm (□) / Pv (□) = K□

Δ

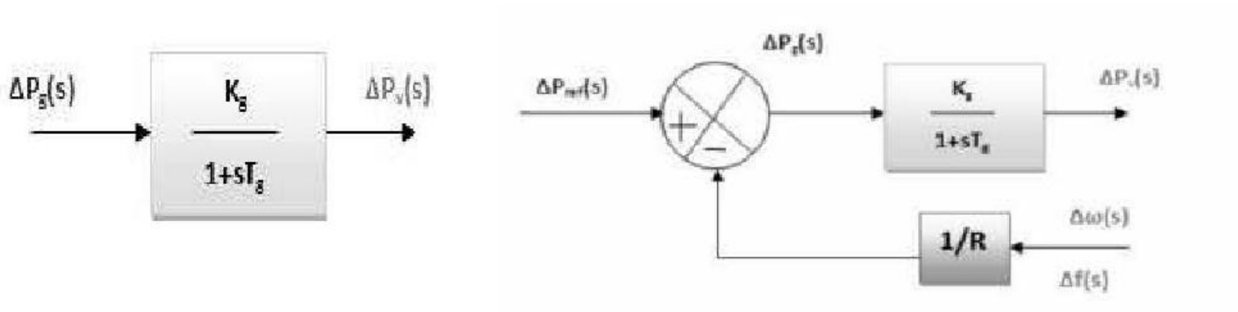
Gt(s) is the TF of the turbine; PV(s) is the change in valve output (due to action). Pm(s) is the change in the turbine output

The governor can similarly modeled as shown inig2F.7. The output of the governor is by

Where ΔP_{ref} is the reference set power, and Δw/R is the power given by governor speed characteristic. The hydraulic amplifier transforms this signal Pg into valve/gate position corresponding to a power PV.

Thus

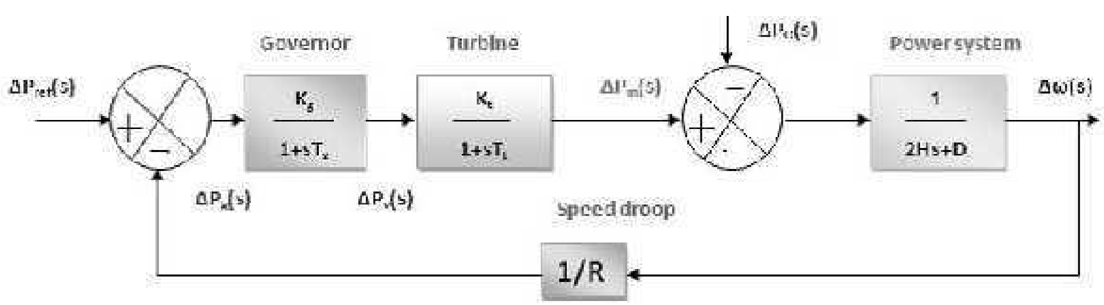
PV(s) = (Kg/ (1+sTg)) _Pg(s).



Block Diagram Representation Of The Governor

LFC control of single area and derive the steady state frequency error.

All the individual blocks can now be connected to represent the complete ALFC loop as



Block diagram representation of the ALFC

Static Power Generation

We have

$\Delta P_G(s) = k_G k_t / (1+sT_G)(1+sT_t)[\Delta P_c(s) - 1/R \Delta F(s)]$

The generator is synchronized to a network of very large size. So, the speed or frequency will be essentially independent of any changes in a power output of the generator

ie, $\Delta F(s) = 0$

Therefore $\Delta P_G(s) = k_G k_t / (1+sT_g)(1+sT_t) * \Delta P_c(s)$

Steady state response

(i)Controlled case:

To find the resulting steady change in the generator output:

Let us assume that we made a step change of the magnitude ΔP_c of the speed changer For step change, $\Delta P_c(s) = \Delta P_c/s$

$\Delta P_G(s) = k_G k_t / (1+sT_g)(1+sT_t). \Delta P_c(s)/s$

$s\Delta P_G(s) = k_G k_t / (1+sT_g)(1+sT_t). \Delta P_c(s)$

Applying final value theorem,

$\Delta P_{G\ (stat)} = \Delta$

(ii)Uncontrolled case

Let us assume that the load suddenly increases by small amount ΔP_D. Consider there is no external work and the generator is delivering a power to a single load.

Since ΔP_c=0, kgkt=1

It has been shown that the load frequency control system posses inherently steady state error for a step input. Applying the usual procedure, the dynamic response of the control loop can be evaluated so that the initial response also can be seen for any overshoot.

For this purpose considering the relatively larger time constant of the power system the governor action can be neglected, treating it as instantaneous action. Further the turbine generator dynamics also may be neglected at the first instant to derive a simple expression for the time response.

$\Delta P_G(s) = 1/(1+sT_G)(1+sT_t)[-\Delta F(s)/R]$ For

a step change $\Delta F(s) = \Delta f/s$ Therefore

$\Delta P_G(s) = 1/(1+sT_G)(1+sT_t)[-$

$\Delta F/sR]$ $\Delta f/\Delta P_{G\,(stat)} = -R$ Hz/MW

Steady State Performance of the ALFC Loop

In the steady state, the ALFC is in 'open' state, and the output is obtained by substituting $s \rightarrow 0$ in the TF.

With $s \rightarrow 0$, Gg(s) and Gt(s) become unity, then,(note that ΔPm =ΔPT = PG =ΔPe = ΔPD; That is turbine output = generator/electrical output = load demand)

$\Delta Pm = \Delta Pref - (1/R)\,\Delta\omega$ or $\Delta Pm = \Delta Pref - (1/R)\Delta f$

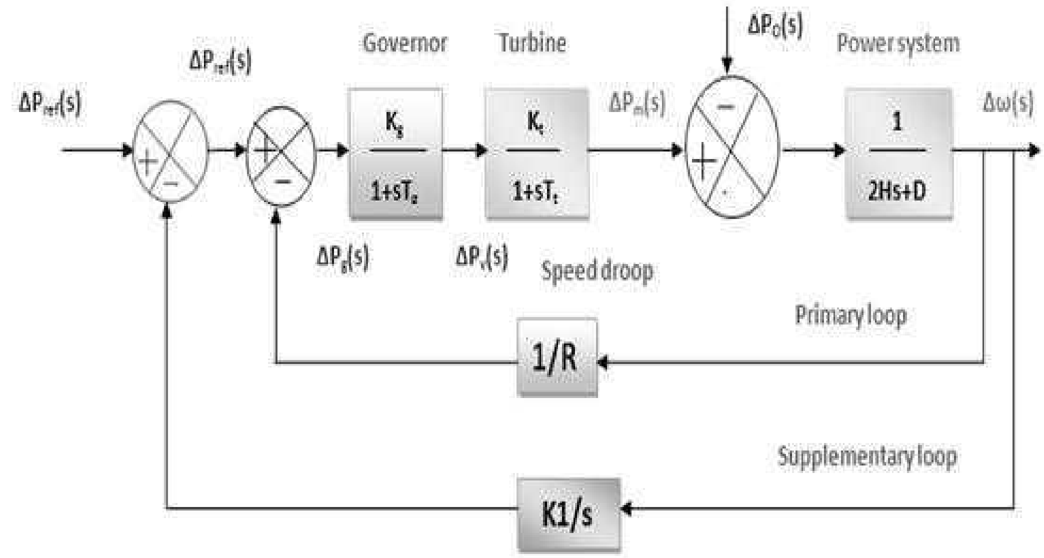
When the generator is connected to infinite bus ($\Delta f = 0$, and $\Delta V = 0$), then $\Delta Pm = \Delta Pref$.

If the network is finite, for a fixed speed changer setting ($\Delta Pref = 0$), then

$\Delta Pm = (1/R)\Delta f$ orΔf=RPm.

Concept of AGC (Supplementary ALFC Loop)

The ALFC loop shown in is called the primary ALFC loop. It achieves the primary goal of real power balance by adjusting the turbine output ΔPm to match the change in load demand ΔPD. All the participating generating units contribute to the change in generation. But a change in load results in a steady state frequency deviation Δf. The restoration of the frequency to the nominal value requires an additional control loop called the supplementary loop. This objective is met by using integral controller which makes the frequency deviation zero. The ALFC with the supplementary loop is generally called the AGC. The block diagram of an AGC is shown in Fig3.9. The main objectives of AGC a r e i) to regulate t h e frequency (using b o t h primary a n d supplementary controls); ii) and to maintain the scheduled tie-line flows. A secondary objective of the AGC is to distribute the required change in generation among the connected generating units economically (to obtain least operating costs).



Block diagram representation of the AGC

AGC in a Single Area System

In a single area system, there is no tie-line schedule to be maintained. Thus the function of the AGC is only to bring the frequency to the nominal value. This will be achieved using the supplementary loop (as shown in Fig.3.9) which uses the integral controller to change the reference power setting so as to change the speed set point.

The integral controller gain KI n e ed s to be adjusted for satisfactory response (in terms of overshoot, settling time) of the system. Although each generator will be having a separate speed governor, all the generators in the control area are replaced by a single equivalent generator, and the ALFC for the area corresponds to this equivalent generator.

Dynamic Response of the One-Area System

`Now we are going to study the effect of a disturbance in the system derived above. Both loss of generation and loss of load can be simulated by imposing a positive or negative step input on the variable P_{load}. A change of the set value of the system frequency f_0 is not considered as this is not meaningful in real power systems. From the block diagram in Figure 3.9 it is straightforward to derive the transfer function between

ΔP_{load} and Δf $(\Delta P^{set}_{ref} - 0)$:

$$\Delta f(s) = \frac{1 + sT_t}{\left(\frac{1}{S} + \frac{1}{D_l}\right)(1 + sT_t) + \left(\frac{2W_0}{f_0} + \frac{2HS_B}{f_0}\right)s(1 + sT_t)}\Delta P_{load}(s)$$

The step response for

$$\Delta P_{load}(s) = \frac{\Delta P_{load}}{s}$$

$$\Delta f_{\infty} = \lim_{s \to 0}(s \cdot \Delta f(s)) = \frac{\Delta P_{load}}{\frac{1}{S} + \frac{1}{D_l}} = \frac{\Delta P_{load}}{\frac{1}{D_R}} = \Delta P_{load} \cdot D_R$$

with

$$\frac{1}{D_R} = \frac{1}{S} + \frac{1}{D_l}$$

In order to calculate an equivalent time constant Teq, Tt is put to 0. This can be done since for realistic systems the turbine controller time constant Tt is much smaller than the time constant

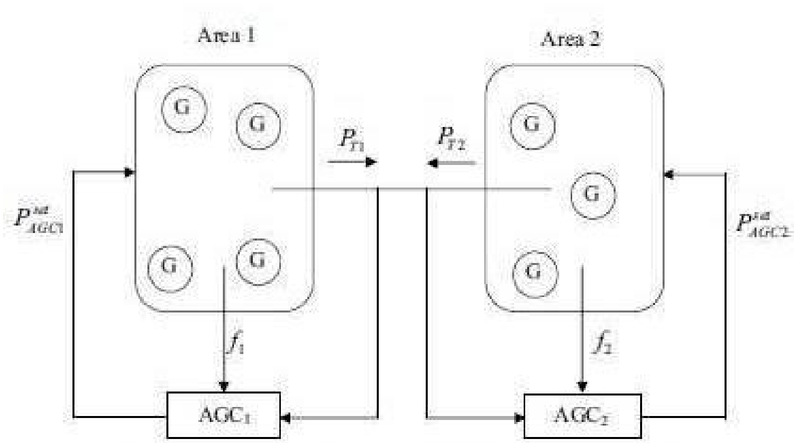
AGC IN A MULTI AREA SYSTEM

In an interconnected (multi area) system, there will be one ALFC loop for each control area (located at the ECC of that area). They are combined as shown in Fig2.10 for the interconnected system operation. For a total change in load of ΔPD, the steady state Consider a two area system as depicted in Figure 3.10. The two secondary frequency controllers, AGC1 and AGC2, will adjust the power reference values of the generators participating in the AGC. In an N-area system, there are N controllers AGCi, one for each area

A block diagram of such a controller is given in Figure 4.2. A common way is to implement this as a proportional-integral (PI) controller:

Deviation in frequency in the two areas is given by

$\Delta f = \Delta\omega_1 = \Delta\omega_2$

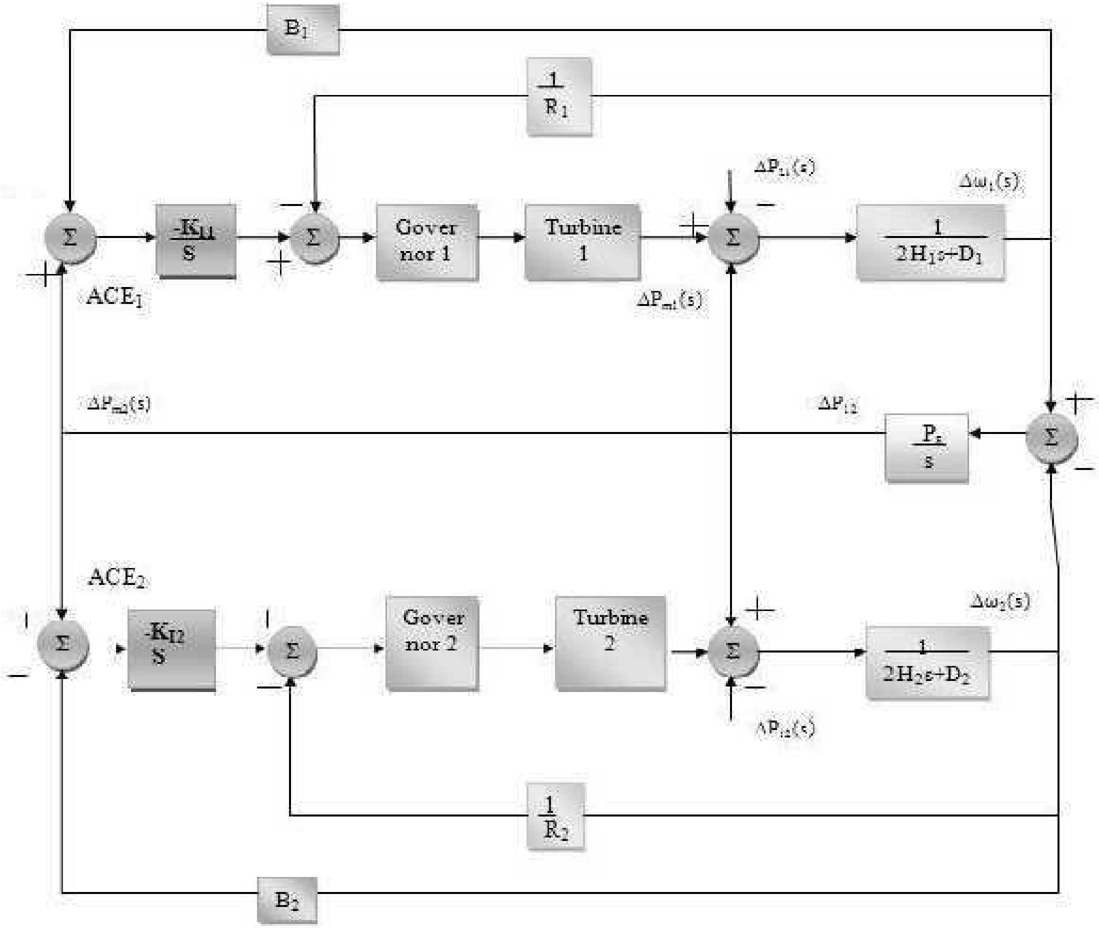


$\beta 1 = D1 + 1/R1$

Substituting these equations, yields

$(1/R1 + D1)\ \Delta f = -\Delta P12 - \Delta Pm$

$(1/R2 + D2)\ \Delta f = -\Delta P12 - \Delta Pm$



A G C for a multi-area operation

DYNAMIC RESPONSE OF LOAD FREQUENCY CONTROL LOOPS

It has been shown that the load frequency control system posses inherently steady state error for a step input. Applying the usual procedure, the dynamic response of the control loop can be evaluated so that the initial response also can be seen for any overshoot.

For this purpose considering the relatively larger time constant of the power system the governor action can be neglected, treating it as instantaneous action. Further the turbine generator dynamics also may be neglected at the first instant to derive a simple expression for the time response.

It has been proved that

$$\Delta F(S) = -\frac{G_P}{1+\frac{1}{R}G_S G_{TG} G_P}\Delta P_D(S)$$

For a step load change of magnitude k

$$\Delta P_D(S) = \frac{-k}{S}$$

Neglecting the governor action and turbine dynamics

$$\Delta F(S) = -\frac{G_P}{1+\frac{1}{R}G_P}\frac{k}{S}$$

$$= -\left(\frac{K_P}{1+ST_P}\right)\frac{1}{\left(1+\frac{1}{R}\frac{K_P}{1+ST_P}\right)}\frac{k}{S}$$

Applying partial fractions

$$\Delta F(S) = -\frac{K_P k}{T_P}\left(\frac{1}{S\left[S+\left(\frac{1}{T_P}+\frac{K_P}{RT_P}\right)\right]}\right) - \frac{K_P k}{T_P}\left[\frac{1}{S\left[S-\frac{1}{T_P}+\frac{K_P}{RT_P}\right]}\right]$$

INTERCONNECTED OPERATION

Power systems are interconnected for economy and continuity of power supply. For the interconnected operation incremental efficiencies, fuel costs. Water availability, generation limits, tie line capacities, spinning reserve allocation and area commitment's are important considerations in preparing load dispatch schedules.

Flat Frequency Control of lnter- connected Stations

Consider two generating stations connected by a tie line as in Fig3.12.For a load increment on station B, the kinetic energy of the generators reduces to absorb the same. Generation increases in both the stations A and B, and frequency will be less than normal at the end of the governor response period. The load increment will be supplied partly by A and partly by B. The tie line power flow will change thereby. If a frequency controller is placed at B, then it will shift the governor characteristic at B parallel to itself as shown in Fig and the frequency will be restored to its normal value fs' reducing the change in generation in A to zero.

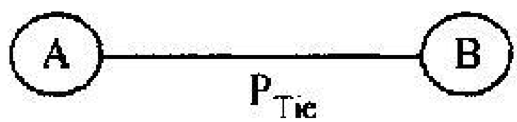


Figure 3.12.Two area with tie line power

Assumption in Analysis:

The following assumptions are made in the analysis of the two area system:

1. The overall governing characteristic of the operating units in any area can be represented by
   a linear curve of frequency versus generation.
2. The governors in both the areas start acting simultaneously to changes in their respective areas.
3. Supplementary control devices act after the initial governor response is over

The following time instants are defined to explain the control sequence:

To=is the instant when both the areas are operating at the scheduled frequency
and Tie=line interchange and load change takes place.

tl = the instant when governor action is initiated at both A and B.

t2 =the instant when governor action ceases.

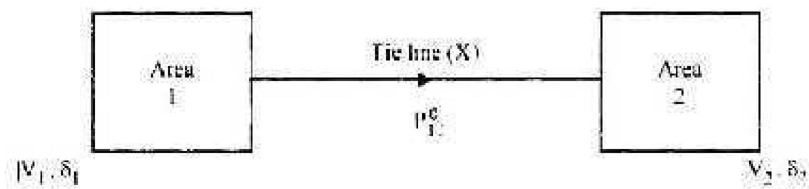
t3 =the instant when regulator action begins.

t4 = the instant when regulator action ceases.

`While the initial governor response is the same as for the previous case, the action of the controller in B will force the generation in area B to absorb the load increment in area A. When the controller begins to act at t3, the governor characteristic is shifted parallel to itself in B till the entire load increment in A is absorbed by B and the frequency is restored to normal. Thus, in this case while the frequency is regulate on one hand, the tie-line schedule is not maintained on the other hand.

If area B, which is in charge of frequency regulation, is much larger than A, then load changes in A will not appreciably affect the frequency of the system. Consequently, it can be said that flat frequency control is useful only when a small system is' connected to a much larger system.

3.10.4. Two Area Systems - Tie-Line Power Model:



Two Area Systems - Tie-Line Power

Consider two inter connected areas as shown in figure operating at the same frequency fl while a power Power flow from area I to area 2

let V1 and V 2 be the voltage magnitudes

δ 1, δ 2 voltage phase angles at the two ends of the tie-line While P flows from area I to area 2 then,

$$P_{12}^0 = \frac{|V_1||V_2|}{X}\sin(\delta_1^0 - \delta_2^0)$$

Where X is the reactance of the line. If the angles change by f1o1, and f102 due to load changes in areas I and 2 respectively. Then, the tie-line power changes by

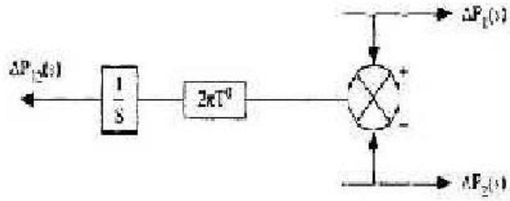
$$\Delta P_2 = \frac{|V_1^0||V_2^0|}{X}\cos(\delta^0 - \delta_2^0)(\Delta P_1 \quad \Delta P_2)$$

$$\frac{\Delta P_{12}}{\Delta\delta - \Delta\delta_2} = \frac{\Delta P_{12}}{\Delta\delta} \text{ MW/radian}$$

$$\Delta P_{12} - T^0(\Delta\delta_1^0 - \Delta\delta_2^0)$$

$$\Delta\omega = \frac{d}{dt}\Delta\delta$$

Block diagram for tie-line power



$$\frac{P_{r1}}{P_{r2}} = a_{12}$$

$$\Delta P_{21}(S) = \frac{2\pi T_{21}^{0}}{S}\left[\Delta F_2(S) - \Delta F_1(S)\right]$$

$$\frac{2\pi T_{21}^{0}\, a_{12}}{S}\left[\Delta F_1(S) - \Delta F_2(S)\right]$$

Dynamic Response:

Let us now turn our attention during the transient period for the sake of simplicity. We shall assume the two areas to be identical .Further we shall be neglecting the time constants of generators and turbines as they are negligible as compared to the time constants of power systems. The equation may be derived for both controlled and uncontrolled cases. There are four equations with four variables, to be determined for given PDl and PD2. The dynamic response can be obtained; even though it is a little bit involved. For simplicity assume that the two areas are equal. Neglect the governor and turbine dynamics, which means that the dynamics of the system under study is much slower than the fast acting turbine-governor system in a relative sense. Also assume that the load does not change with frequency (D, = D2 = D = 0).

$$\left\{-\frac{1}{R_1}\Delta F_1(S)\left[\frac{K_S}{1+ST_{S1}}\right]\left[\frac{K_{TG1}}{1+ST_{TG2}}\right] - \Delta P_{D1}(S) - \Delta P_{12}(S)\right\}\frac{K_{P1}}{1+ST_{P1}} = \Delta F_1(S)$$

$$\left\{-\frac{1}{R_2}\Delta F_2(S)\left[\frac{K_{S2}}{1-ST_{S2}}\right]\left[\frac{K_{TG2}}{1+ST_{TG2}}\right] - \Delta P_{D2}(S) - \Delta P_{21}(S)\right\}\frac{K_{P2}}{1+ST_{P2}} = \Delta F_2(S)$$

$$\Delta P_{12}(S) = \frac{2\pi T^0}{S}\left[\Delta F_1(S) - \Delta F_2(S)\right]$$

$$\Delta P_{21}(S) = -\Delta P_{21}(S)$$

We obtain under these assumptions the following relations

$$\Delta P_{12}(S) = \frac{\left[\Delta P_{D2}(S) - \Delta P_{D1}(S)\right]\frac{f^0}{2SH}}{\frac{S}{2\pi T^0} + \frac{2f^0}{2\pi T^0} + \frac{Sf^0}{2\pi R T^0\, 2SH}}$$

$$= \frac{\left[\left[\Delta P_{D2}(S) - \Delta P_{D1}(S)\right]\frac{\pi f^0 T^0}{SH}\right]}{S + \frac{2f^0 \pi T^0}{SH} + \frac{f^0}{2RH}}$$

$$= \frac{\pi f^0 T^0}{H}\frac{\left[\Delta P_{D2}(S) - \Delta P_{D1}(S)\right]}{S^2 + \left(\frac{f^0}{2RH}\right)S + \left(\frac{2f^0 \pi T^0}{H}\right)}$$

The denominator is of the form

$$\left(S^2 + 2KS + \omega^2\right) = (S+K)^2 + (\omega^2 - K^2)$$

where $K = \frac{f^0}{4RH}$ and $\omega = \sqrt{\frac{2\pi f^0 T^0}{H}}$

setting $\sqrt{\omega^2 - K^2}$ as ω_0.

$$\omega_0 = \sqrt{\frac{2\pi T^0 f^0}{H} - \left(\frac{f^0}{4RH}\right)^2}$$

No hat both K and ro2 are positive. From the roots of the characteristic equation we notice tha e system is stable and damped. The frequency of the damped oscillations is given by Since Hand f_o are constant, the frequency of oscillations depends upon the regulation parameter R. Low R gives high K and high damping and vice versa .We thus conclude from the preceding analysis that the two area system, just as in the case of a single area system in the uncontrolled mode, has a steady state error but to a lesser extent and the tie line power deviation and frequency deviation exhibit oscillations that are damped out later.

UNIT-III

REACTIVE POWER

VOLTAGE CONTROL

REACTIVE POWER

Reactive power is an odd topic in AC (Alternating Current) power systems, and it's usually explained with vector mathematics or phase-shift sine wave graphs. However, a non-math verbal explanation is possible. Note that Reactive power only becomes important when an "electrical load" or a home appliance contains coils or capacitors. If the electrical load behaves purely as a resistor, (such as a heater or incandescent bulb for example,) then the device consumes "real power" only. Reactive power and "power factor" can be ignored, and it can be analyzed using an AC version of Ohm's law. Reactive power is simply this: when a coil or capacitor is connected to an AC power supply, the coil or capacitor stores electrical energy during one-fourth of an AC cycle. But then during the next quarter-cycle, the coil or capacitor dumps all the stored energy back into the distant AC power supply.

Ideal coils and capacitors consume no electrical energy, yet they create a significant electric current. This is very different from a resistor which genuinely consumes electrical energy, and where the electrical energy flows continuously in one direction; moving from source to load. In other words, if your electrical appliance contains inductance or capacitance,
then electrical energy will periodically return to the power plant, and it will flow back and forth across the power lines. This leads to an extra current in the power lines, a current which heats the power lines, but which isn't used to provide energy to the appliance. The coil or capacitor causes electrical energy to begin "sloshing" back and forth between the appliance and the distant AC

Generator. Electric companies must install heavier wires to tolerate the excess current, and they will charge extra for this "unused" energy. This undesired "energy sloshing" effect can be eliminated. If an electrical load contains both a coil and capacitor, and if their resonant frequency is adjusted to exactly 60Hz, then the coil and capacitor like magic will begin to behave like a pure resistor. The "energy sloshing" still occurs, but now it's all happening between the coil and capacitor, and not in the AC power lines. So, if your appliance contains a large coil induction motor, you can make the motor behave as a pure resistor, and reduce the current in the power lines by connecting the right value of capacitance across the motor coil. Why is reactive power so confusing? Well, the math is daunting if not entirely obscure. And the concept of "imaginary power" puts many people off. But this is not the only problem. Unfortunately most of us are taught in grade school that an electric current is a flow of energy, and that energy flows back and forth in AC power lines. This is completely wrong. In fact the energy flows constantly forward, going from source to load. It's only the charges of the metal wires which flow back and forth.

----

2. GENERATION AND ABSORPTION OF REACTIVE POWER

Synchronous Generators:

Synchronous machines can be made to generate or absorb reactive power depending upon the excitation (a form of generator control) applied. The ability to supply reactive power is determined by the short circuit ratio.

Synchronous Compensators:

Certain smaller generators, once run up to speed and synchronized to the system, can be declutched from their turbine and provide reactive power without producing real power.

Capacitive and Inductive Compensators:

These are devices that can be connected to the system to adjust voltage levels .A capacitive compensator produces an electric field thereby generating reactive power An inductive compensator produces a magnetic field to absorb reactive power. Compensation devices are available as either capacitive or inductive alone or as a hybrid to provide both generation and absorption of reactive power.

1. Overhead lines and underground cables, when operating at the normal system voltage, both produce strong electric fields and so generate reactive power.

2. When current flows through a line or cable it produces a magnetic field which absorbs reactive power.

3. A lightly loaded overhead line is a net generator of reactive power while a heavily loaded line is a net absorber of reactive power.

4. In the case of cables designed for use at 275 or 400kV the reactive power generated by the electric field is always greater than the reactive power absorbed by the magnetic field and so cables are always net generators of reactive power.

5. Transformers always absorb reactive power.

4.METHODS OF VOLTAGE CONTROL

Reactors:

Inductive reactors absorb reactive power and may be used in circuits, series or shunt connected, while series connected reactors are used to limit fault currents, shunt reactors are used for var control. Reactors installed at line ends and intermediate substations can compensate up to 70% of charging power while the remaining 30% power at no-load can be provided by the under excited operation of the generator with increase in load, generator excitation may be increased with reactors gradually cut-out. Figure shows some typical shunt reactor arrangements.

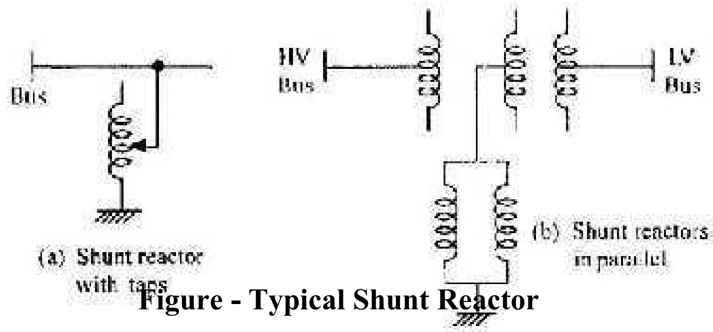
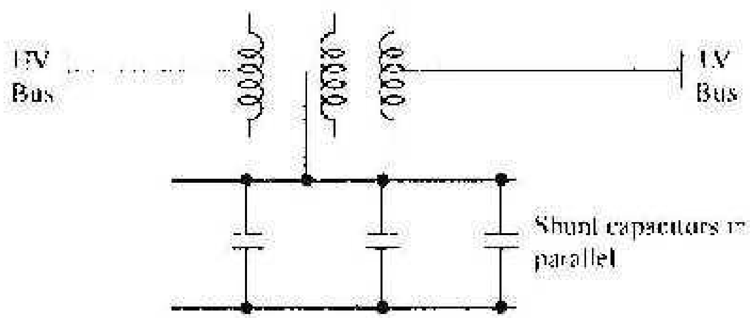


Figure - Typical Shunt Reactor

Shunt Capacitors:

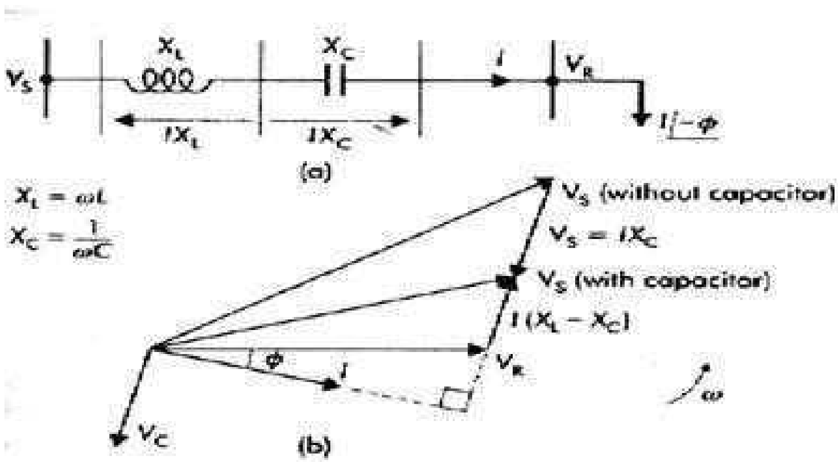
Capacitors produce var and may be connected in series or shunt in the system. Series capacitors compensate the line reactance in long overhead lines and thus improve the stability limit. However, they give rise to additional problems like high voltage transients, sub-synchronous resonance, etc. Shunt capacitors are used for reactive compensation. Simplicity and low cost are the chief considerations for using shunt capacitor. Further, for expanding systems additions can be made. Fig. shows the connected of shunt capacitors through the tertiary of a transformer.



Shunt capacitor

Series capacitors:

Here the capacitors are connected in series with the line. The main aim is to reduce the inductive reactance between supply point and the load. The major disadvantage of the method is, whenever short circuit current flows through the capacitor, protective devices like spark gaps and non linear resistors are to be in corporated. Phasor diagram for a line with series capacitor is shown in the figure (b).



a) Series capacitor b) Phasor diagram

Relative merits between shunt and series capacitors.

1. If the load var requirement is small, series capacitors are of little help.

2. If the voltage drop is the limiting factor, series capacitors are effective; also to some extent the voltage fluctuations can be evened.

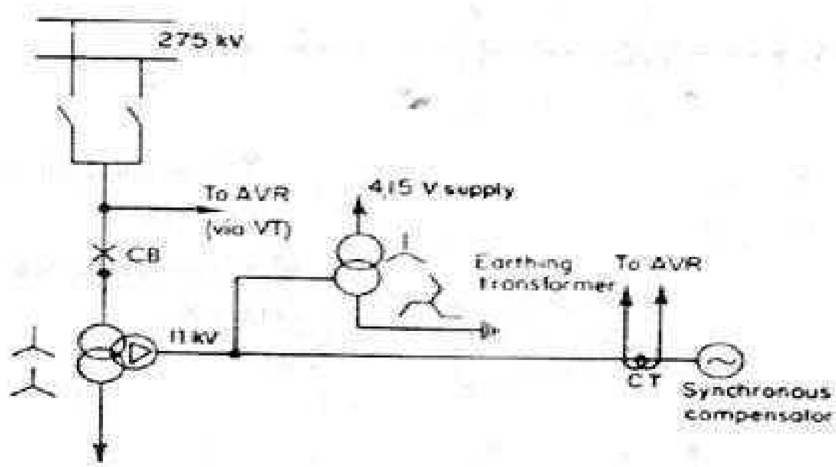
3. If the total line reactance is high, series capacitors are very effective and stability is improved.

4. With series capacitors the reduction in line current is small, hence if the thermal considerations limits the current, little advantage is from this, so shunt compensation is to be used.

Synchronous compensators:

A synchronous compensator is a synchronous motor running without a mechanical load and depending on the excitation level; it can either absorb or generate reactive power. When used with a voltage regulator the compensator can automatically run overexcited at times of high loads and under excited at light loads. A typical connection of a compensator is shown in the figure along with the associated voltage – var output characteristics

A great advantage of the method is the flexible operation for all load conditions. Being a rotating machine, its stored energy is useful for riding through transient disturbances, including voltage drops.



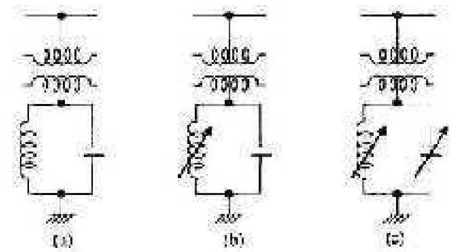
Synchronous Compensator

Even though the capacitors and reactors in are shown in figure connected to the low voltage side of a down transformer, the capacitor banks may be distributed between high and low voltage buses. The capacitor bank often includes, in part, harmonic filters which prevent the harmonic currents from flowing in the transformer and the high voltage system. Filters for the 5th and 7th harmonics are generally provided. The thyristor controlled reactor (TCR) is operated on the low voltage bus. In another form of the compensator illustrated in Figure the reactor compensator is connected to the secondary of a transformer.

With this transformer, the reactive power can be adjusted to anywhere between 10% to the rated value. With a capacitor bank provided with steps, a full control range from capacitive to inductive power can be obtained. The reactor's transformer is directly connected to the line, so that no circuit breaker is needed.

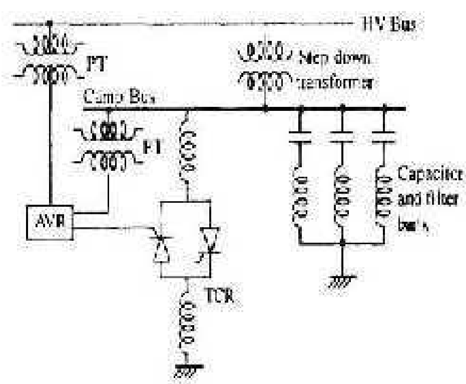
3. Static VAR compensators:

In Recent years reactive compensation of charging power is made feasible with the application of 3-phase, thyristor, and power controller circuits with automatic control functions.



Static VAR Compensator

The term static var compensator is applied to a number of static var compensation devices for use in shunt reactive control. These devices consist of shunt connected, static reactive element (linear or non linear reactors and capacitors) configured into a var compensating system. Some possible configurations are shown in above Figure. Even though the capacitors and reactors in are shown in figure connected to the low voltage side of a down transformer, the capacitor banks may be distributed between high and low voltage buses. The capacitor bank often includes, in part, harmonic filters which prevent the harmonic currents from flowing in the transformer and the high voltage system. Filters for the 5th and 7th harmonics are generally provided. The thyristor controlled reactor (TCR) is operated on the low voltage bus. In another form of the compensator illustrated in Figure the reactor compensator is connected to the secondary of a transformer.



Reactor Compensator

The primary winding is star connected with neutral grounded, suitable to the thyristor network. The secondary reactor is normally nonexistent, as it is more economical to design the reactor transformer with 200% leakage impedance between primary and secondary windings. The delta connected tertiary winding will effectively compensate the triple harmonics. The capacitor bank is normally subdivided and connected to the substation bus bar via one circuit breaker per sub bank. The regulator generates firing pulses for the thyristor network in such a way that the reactive power required to meet the control objective at the primary side of the compensator is obtained. The reactor transformer has a practically linear characteristic from no load to full load condition. Thus, even under all stained over voltages; hardly any harmonic content is generated due to saturation. The transformer core has non ferromagnetic .Gaps to the required linearity.

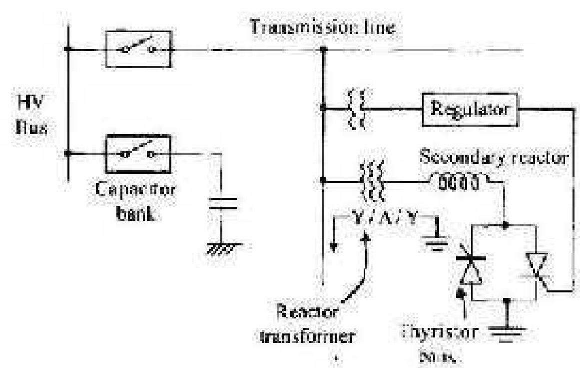
The following requirements are to be borne in mind while designing a compensator.

1. Reaction should be possible, fast or slow, whenever demanded. No switching of capacitor should take place at that time to avoid additional transients in the system. Commutation from capacitor to reactor and vice versa should be fast.

2. No switching of the capacitors at the high voltage bus bar, so that no higher frequency Transients is produced at EHV level.

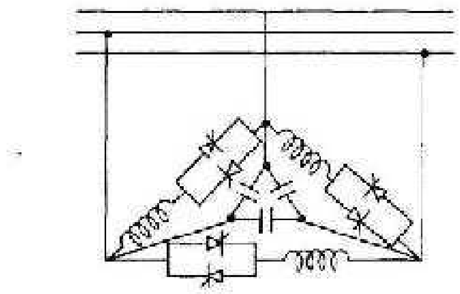
3. Elimination of higher harmonics on the secondary side and blocking them from entering the system.

In a three phase system the thyristor controlled inductors are normally delta connected as shown in Figure to compensate unbalanced loads and the capacitors may be star or delta connected



Unbalanced loads

In the thyristor controlled reactor, the inductive reactance is controlled by the thyristors. For a limited range of operation the relationship between the inductive current i_L and the applied voltage V is represented in Figure. As the inductance is varied, the susceptance varies over a range within the limits B_{Lmin} and B_{Lmax} (corresponding to X_{Lmax} and X_{Lmin}) while the voltage Changes by v volts.

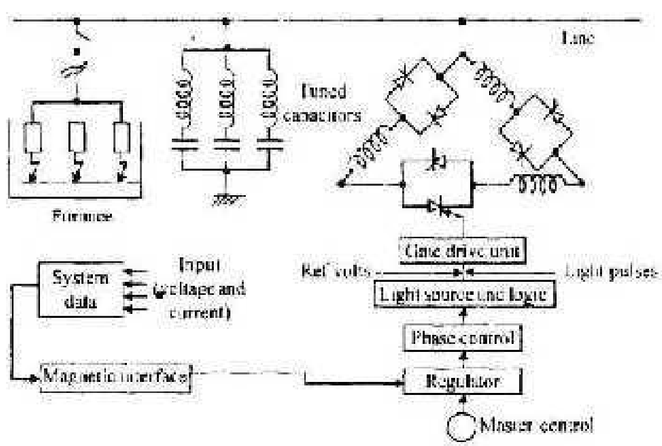


Fixed capacitor, thyristor controlled inductor type var compensator

Unbalanced loads

The current flowing in the inductance would be different in each half cycle, varying with the conduction angle such that each successive half cycle is a smaller segment of a sine wave. The fundamental component of inductor current is then reduced to each case. Quick control can be exercised within one half cycles, just by giving a proper step input to the firing angle control Static var compensators when installed reduce the voltage swings at the rolling mill and power system buses in drive system applications. They compensate for the average reactive power requirements and improve power factor.

Electric arc furnaces impose extremely difficult service requirements on electrical power systems since the changes in arc furnace load impedance are rapid. Random and non symmetrical. The three phases of a static var compensator can be located independently so that it compensates for the unbalanced reactive load of the furnace and the thyristor controller will respond quickly in order to minimize the voltage fluctuations or voltage flicker seen by the system.



Application of the static VAR compensator

Thus, the furnace characteristics are made more acceptable to the power system by the static var compensator. Above figure shows the application of the static var compensator to an arc furnace installation for reactive power compensation at the HV bus level.

TYPES OF SVC

1. Variable impedance type
2. Current source type
3. Voltage source type

The followings are the basic types of reactive power control elements which makes all or parts of SVC

Saturated reactor

1. Thyristor controlled Reactor
2. Thyristor switched capacitor
3. Thyristor Switched Reactor
4. Thyristor controlled Transformer

APPLICATION OF STATIC VAR COMPENSATOR

- Connected to the power system, to regulate the transmission voltage ("Transmission SVC")
- Connected near large industrial loads, to improve power quality ("Industrial SVC")

EXCITATION SYSTEMS REQUIREMENTS

1. Meet specified response criteria.
2. Provide limiting and protective functions are required to prevent damage to itself, the generator, and other equipment.
3. Meet specified requirements for operating flexibility
4. Meet the desired reliability and availability, by incorporating the necessary level of redundancy and internal fault detection and isolation capability.

ELEMENTS OF EXCITATION SYSTEM

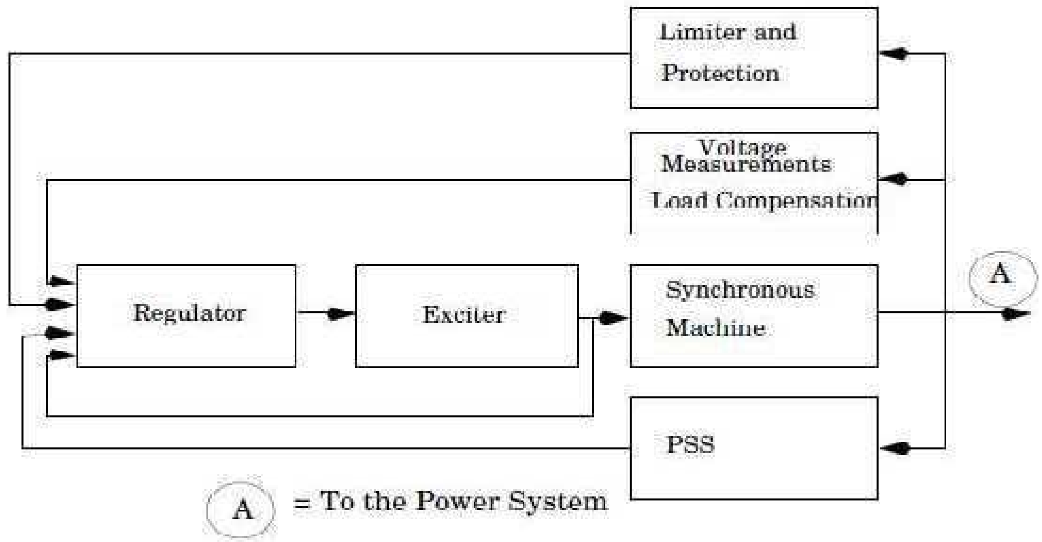
Exciter*:* provides dc power to the synchronous machine field winding constituting the power stage of the excitation system.

Regulator: Process and amplifies input control signals to a level and form appropriate for control of the exciter. This includes both regulating and excitation system stabilizing function.

Terminal voltage transducer and load compensator: Senses generator terminal voltage, rectifier and filters it to dc quantity, and compares it with a reference which represents the desired terminal voltage.

Power system stabilizer: provides an additional input signal to the regulator to damp power system oscillation.

Limiters and protective circuits: These include a wide array of control and protective function which ensure that the capability limits of the exciter and synchronous generator are not exceeded.



Schematic picture of a synchronous machine with excitation system with several control, protection, and supervisory functions.

TYPES OF EXCITATION SYSTEM

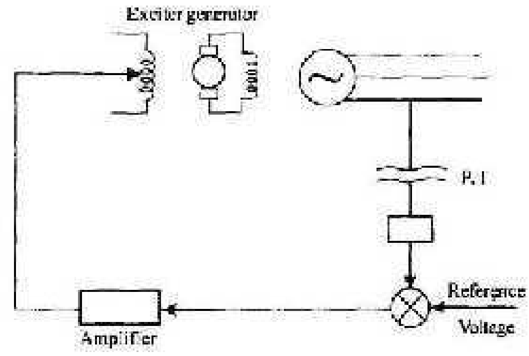
Today, a large number of different types of exciter systems are used. Three main types can be distinguished:

- **DC excitation system**, where the exciter is a DC generator, often on the same axis as the rotor of the synchronous machine.
- **AC excitation system**, where the exciter is an AC machine with rectifier.
- **Static excitation system**, where the exciting current is fed from a controlled rectifier that gets its power either directly from the generator terminals or from the power plant's auxiliary power system, normally containing batteries. In the latter case, the synchronous machine can be started against an unenergised net, "black start". The batteries are usually charged from the net.

Block Schematic of Excitation Control:

A typical excitation control system is shown in Fig. The terminal voltage of the alternator is sampled, rectified and compared with a reference voltage; the difference is amplified and fed back to the exciter field winding to change the excitation current.

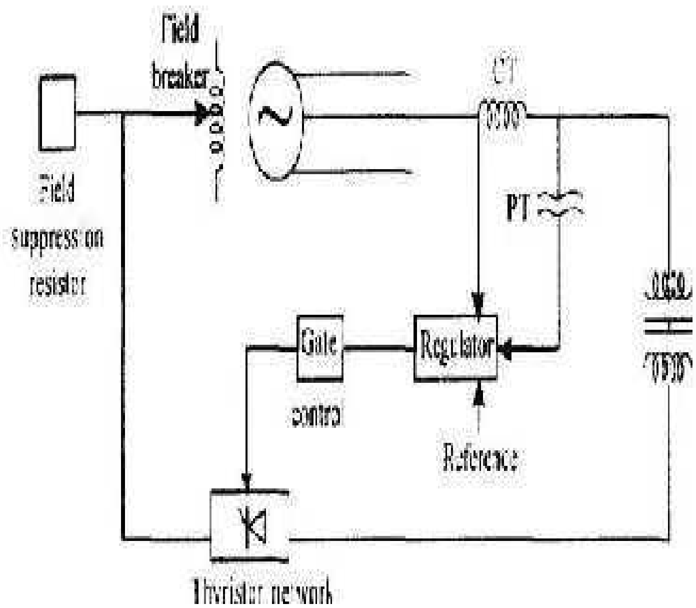
Block Diagram of excitation system**:**



Block Diagram of Excitation System

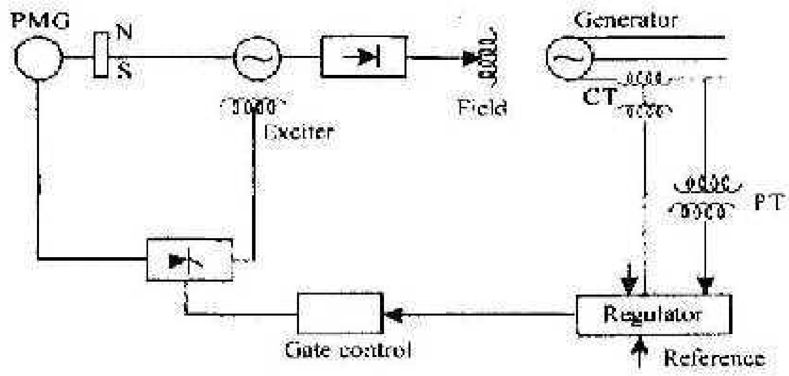
Static Excitation System:

In the static excitation system, the generator field is fed from a thyristor network shown in Fig. It is just sufficient to adjust the thyristor firing angle to vary the excitation level. A major advantage of such a system is that, when required the field voltage can be varied through a full range of positive to negative values very rapidly with the ultimate benefit of generator Voltage regulation during transient disturbances. The thyristor network consists of either 3-phase fully controlled or semi controlled bridge rectifiers. Field suppression resistor dissipates Energy in the field circuit while the field breaker ensures field isolation during generator faults.



Static Excitation System

Brushless Excitation Scheme:

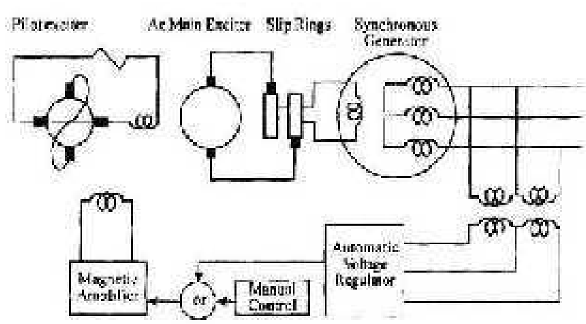


Brushless Excitation Scheme:

In the brushless excitation system of an alternator with rotating armature and stationary field is employed as the main exciter. Direct voltage for the generator excitation is obtained by rectification through a rotating, semiconductor diode network which is mounted on the generator shaft itself. Thus, the excited armature, the diode network and the generator field are rigidly connected in series. The advantage of this method of excitation is that the moving contacts such as slip rings and brushes are completely eliminated thus offering smooth and maintenance-free operation.

A permanent-magnet generator serves as the power source for the exciter field. The output of the permanent magnet generator is rectified with thyristor network and is applied to the exciter field. The voltage regulator measures the output or terminal voltage, compares it with a set reference and utilizes the error signal, if any, to control the gate pulses of the thyristor network.

AC Excitation system:

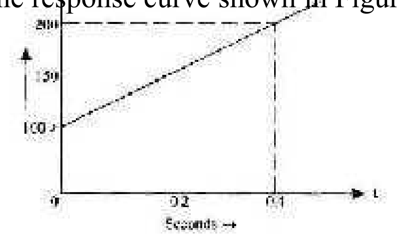


Ac Excitation System

Where V_1 is the terminal voltage and V_{ref} is the reference voltage.

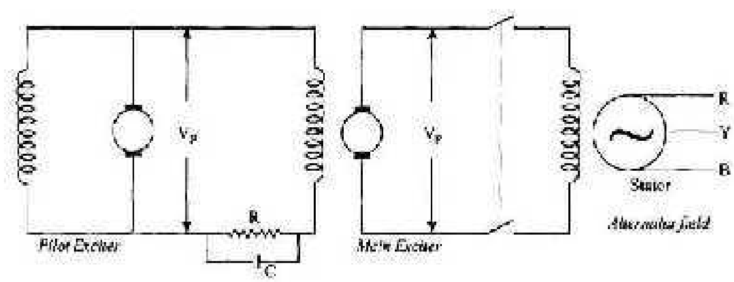
Exciter ceiling voltage: It is defined as the maximum voltage that may be attained by an exciter with specified conditions of load.

Exciter response: It is the rate of increase or decrease of the exciter voltage. When a change in this voltage is de the response curve shown in Figure.



Exciter Response

Exciter builds up: The exciter build up depends upon the field resistance and the charging of its value by cutting or adding. The greatest possible control effort is the complete shorting of the field rheostat when maximum current value is reached in the field circuit. This can be done by closing the contactor.



AC excitation operations

When the exciter is operated at rated speed at no load, the record of voltage as function of time with a step change that drives the exciter to its ceiling voltage is called the exciter build up curve. Such a response curve is show in Figure.4.14

$$\text{Response ratio} = \frac{Cd}{0a(0.5)} \text{ p.u. V / sec}$$

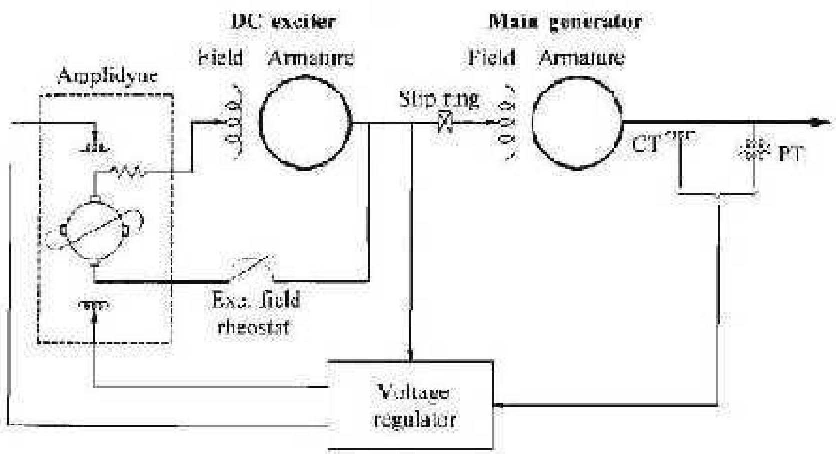
Response ratio	Conventional Exciter	SCR exciter
0.5	1.25-1.35	1.2
1.0	1.4-1.5	1.2-1.25
1.5	1.55-1.65	1.3-1.4
2.0	1.7-1.8	1.45-1.55
4.0		2.0-2.1

Comparison between Exciters

In general the present day practice is to use 125V excitation up to IOMVA units and 250V systems up to 100MVA units. Units generating power beyond IOOMVA have excitation system voltages variedly. Some use 350V and 375V system while some go up to 500V excitation system.

DC Excitation System

The excitation system of this category utilize dc generator as source of excitation power and provide current to the rotor of the synchronous machine through slip ring. The exciter may be driven by a motor or the shaft of the generator. It may be either self excited or separately excited. When separately excited, the exciter field is supplied by a pivot exciter comprising a permanent magnet generator. Below figure a simplified schematic representation of a typical dc excitation system. It consists of a dc commutator exciter which supplies direct current to the main generator field through slip ring.



DC Excitation System

Dc machine having two sets of brush 90 electrical degree apart, one set on its direct (d) axis and the other set on its quadrature (q) axis. The control field winding is located on the d axis. A compensating winding in series with the d axis armature current, thereby cancelling negative feedback of the armature reaction. The brushes on the q axis are shorted, and very little control field power is required to produce a large current in the q axis armature. The q axis current is supplied mechanically by the motor.

RECENT DEVELOPMENT AND FUTURE TRENDS

The advances in excitation system over the last 20 years have been influenced by development in solid state electronics. Development in analogue integrated circuitry has made it possible to easily implemented complex control strategies.

The latest development in excitation system has been the introduction of digital technology. Thyristor continue to be used for the power stage. The control, protection, and logic function have been implemented digitally, essentially duplicating the function previously provided by analog circuitry.

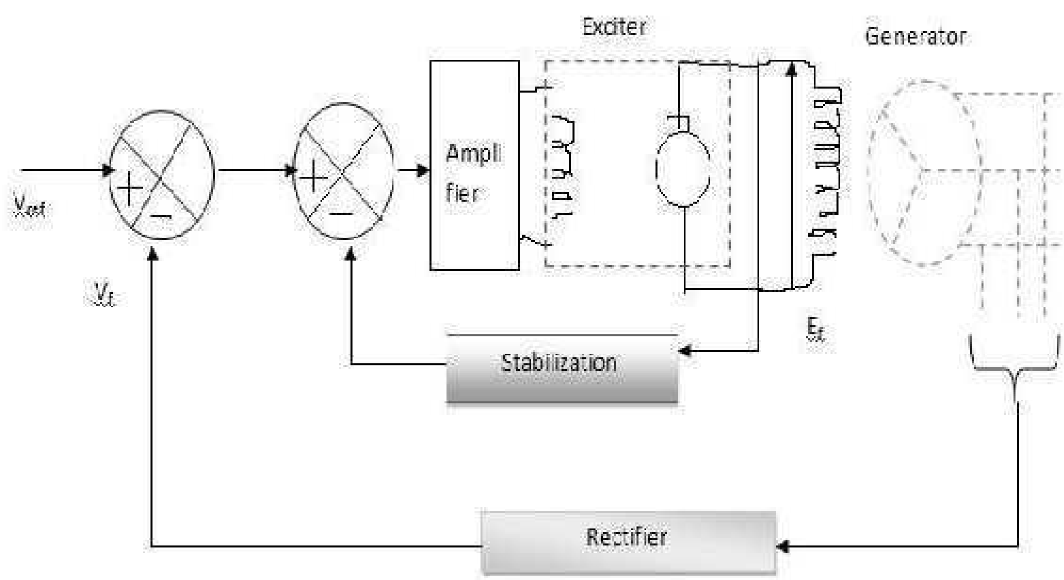
MODELING OF EXCITATION SYSTEM

Mathematical model of excitation system are essential for the assessment of desired performance requirement, for the design and coordination of supplementary control and protective circuits, and for system stability studies related to the planning and purpose of study.

Generator Voltage Control

The voltage control system is also called as excitation control system or automatic voltage regulator (AVR).

For the alternators, the excitation is provided by a device (another machine or a static device) called exciter. For a large alternator the exciter may be required to supply a field current of as large as 6500A at 500V and hence the exciter is a fairly large machine. Depending on the way the dc supply is given to the field winding of the alternator (which is on the rotor), the exciters are classified as: i) DC Exciters; ii) AC Exciters; and iii) Static Exciters. Accordingly, several standard block diagrams are developed by the IEEE working group to represent the excitation system.

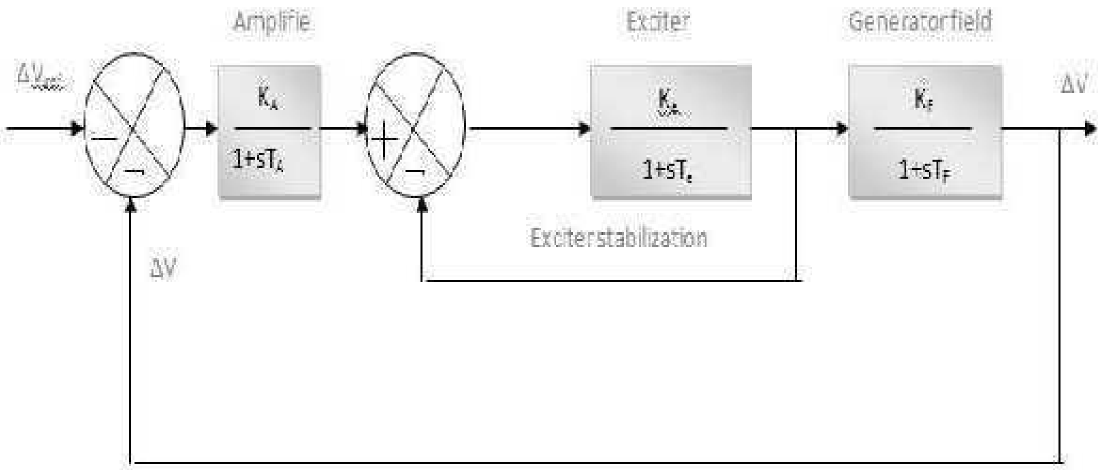


A schematic of Excitation (Voltage) Control System.

A simplified block diagram of the generator voltage control system .The generator terminal voltage Vt is compared with a voltage reference Vref to obtain a voltage error signal ΔV. This signal is applied to the voltage regulator shown as a block with transfer function KA/ (1+TAs). The output of the regulator is then applied to exciter shown with a block of transfer function Ke/ (1+Tes). The output of the exciter Efd is then applied to the field winding which adjusts the generator terminal voltage. The generator field can be represented by a block with a transfer function KF/(1+sTF). The total transfer function

$$\frac{\Delta V}{\Delta V_{re}} = \frac{G(s)}{1+G(s)} \quad \text{Where,} \quad G(s) = \frac{K_A K_e K_F}{(1+sT_A)(1+sT_e)(1+sT_F)}$$

The stabilizing compensator shown in the diagram is used to improve the dynamic response of the exciter. The input to this block is the exciter voltage and the output is a stabilizing feedback signal to reduce the excessive overshoot.



A simplified block diagram of Voltage (Excitation) Control System.

Performance of AVR loop

The purpose of the AVR loop is to maintain the generator terminal voltage with in acceptable values. A static accuracy limit in percentage is specified for the AVR, so that the terminal voltage is maintained within that value. For example, if the accuracy limit is 4%, then the terminal voltage must be maintained within 4% of the base voltage.

STEADY STATE PERFORMANCE EVALUATION

The control loop must regulate the output voltage VI so that the error is made equal to zero. It is also imperative that the response must be reasonably fast, yet not cause any instability problem.

The performance of the AVR loop is measured by its ability to regulate the terminal voltage of the generator within prescribed static accuracy limit with an acceptable speed of response. Suppose the static accuracy limit is denoted by Ac in percentage with reference to the nominal value. The error voltage is to be less than (Ac/100)Δ|V|ref.

From the block diagram, for a steady state error voltage Δe;

$$\Delta e = \Delta\,[V]ref - \Delta\,[V]t < \frac{AC}{100} = \Delta\,[V]ref$$

$$\Delta e = \Delta\,[V]ref - \Delta\,[V]t = \Delta\,[V]ref - \frac{G(s)}{1+G(s)}\Delta\,[V]ref$$

$$= 1 - \frac{G(s)}{1+G(s)}\Delta\,[V]ref$$

For constraint input condition (s-0)

$$\Delta e = 1 - \frac{G(s)}{1+G(s)}\Delta\,[V]ref$$

$$= 1 - \frac{G(0)}{1+G(0)}\Delta\,[V]ref$$

$$= \frac{1}{1+G(0)}\Delta\,[V]ref$$

$$= \frac{1}{1+K}\Delta\,[V]ref$$

K= G (0) is the open loop gain of the AVR .Hence

$$\frac{1}{1+K}\Delta\,[V]ref < \frac{AC}{100} = \Delta\,[V]ref$$

The steady state voltage error Δe_{ss} is given by

$$\Delta e_{ss} = \Delta|V|^0_{ref} - \Delta V_{ss}$$

$$= \Delta|V|^0_{ref} - \frac{G(0)}{1+G(0)}\Delta|V|^0_{ref}$$

where G(0) is the value of G(s) as $s \rightarrow 0$ (i.e.) the steady state value

$$= \frac{1+G(0)-G(0)}{1+G(0)}\Delta|V|^0_{ref}$$

$$= \frac{1}{1-G(0)}\Delta|V|^0_{ref}$$

$$G(0) = \frac{KA}{(1+0)}\frac{K_e}{(1+0)}\frac{K_{gf}}{(1+0)} = K$$

$$\Delta e_{ss} = \frac{1}{1+K}$$

Larger the overall gain of the forward block gain K smaller is the steady state error. But too large a gain K cans instability.

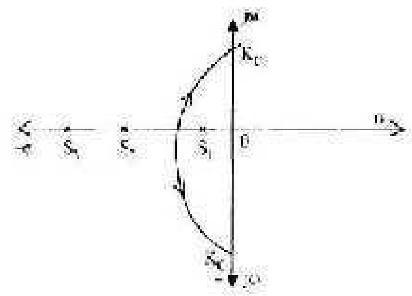
DYNAMIC RESPONSE OF VOLTAGE REGULATION CONTROL:

Consider

$$\Delta V(t) = L^{-1}\left[\Delta V_{ref}(S)\frac{G(S)}{1 - G(S)}\right]$$

The response depends upon the roots of the characteristic eqn. 1 + G(S) = o.

As there are three time constants, we may write the three roots as S1, S2 and S3. A typical root locus plot is shown in Figure



Root locus

From the plot, it can be observed that at gain higher than Kc the control loop becomes ln stable.

UNIT –IV

ECONOMIC OPERATION OF POWER SYSTEM

ECONOMIC DISPATCH

Economic Operation of Power Systems

One of the earliest applications of on-line centralized control was to provide a central facility, to operate economically, several generating plants supplying the loads of the system. Modern integrated systems have different types of generating plants, such as coal fired thermal plants, hydel plants, nuclear plants, oil and natural gas units etc. The capital investment, operation and maintenance costs are different for different types of plants.

The operation economics can again be subdivided into two parts.

i) Problem of *economic dispatch*, which deals with determining the power output of each plant to meet the specified load, such that the overall fuel cost is minimized.

ii) Problem of *optimal power flow*, which deals with minimum – loss delivery, where in the power flow, is optimized to minimize losses in the system. In this chapter we consider the problem of economic dispatch.

During operation of the plant, a generator may be in one of the following states:

i) Base supply without regulation: the output is a constant.

ii) Base supply with regulation: output power is regulated based on system load.

iii) Automatic non-economic regulation: output level changes around a base setting as area control error changes.

iv) Automatic economic regulation: output level is adjusted, with the area load and area control error, while tracking an economic setting.

Regardless of the units operating state, it has a contribution to the economic operation,

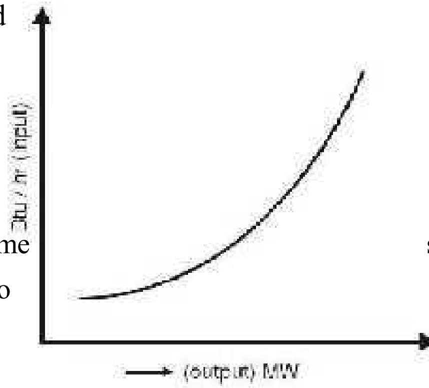
even though its output is changed for different reasons. The factors influencing the cost of generation are the generator efficiency, fuel cost and transmission losses. The most efficient generator may not give minimum cost, since it may be located in a place where fuel cost is high. Further, if the plant is located far from the load centers, transmission losses may be high and running the plant may become uneconomical. The economic dispatch problem basically determines the generation of different plants to minimize total operating cost.

Modern generating plants like nuclear plants, geo-thermal plants etc, may require capital Investment of millions of rupees. The economic dispatch is however determined in terms of fuel cost per unit power generated and does not include capital investment, maintenance, depreciation, start-up and

Performance Curves

Input-Output Curve

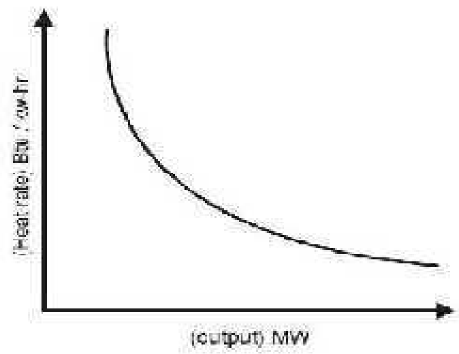
This is the fundame s a plot of the input in British thermal units (Btu) per ho nt in MW as shown in Fig 2.1



Input – output curve

Heat Rate Curve

The heat rate is the ratio of fuel input in Btu to energy output in KWh. It is the slope of the input – output curve at any point. The reciprocal of heat – rate is called fuel –efficiency. The heat rate curve is a plot of heat rate versus output in MW.

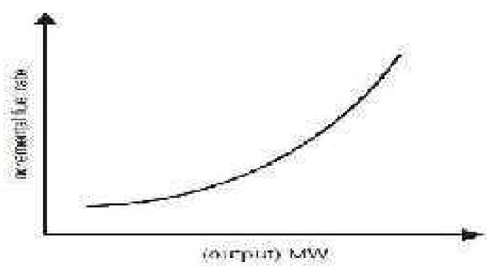


Heat rate curve.

Incremental Fuel Rate Curve

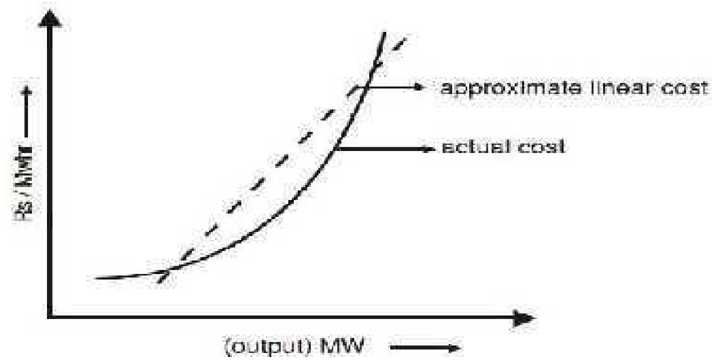
The incremental fuel rate is equal to a small change in input divided by the corresponding change in output.

Incremental fuel rate =Δ*Input*/Δ *Output*



INCREMENTAL COST

The incremental cost is the product of incremental fuel rate and fuel cost (Rs / Btu or \$ /Btu). The curve in shown in Fig. 4. The unit of the incremental fuel cost is Rs / MWh or \$ /MWh.



Incremental cost curve

In general, the fuel cost Fi for a plant, is approximated as a quadratic function of the generated output PGi.

$$F_i = a_i + b_i P_{Gi} + c_i P_G^2 \text{ Rs / h} \quad \text{--------------------------------} \quad (4)$$

The incremental fuel cost is given by

— Rs / MWh ---------------------------------- (5)

The incremental fuel cost is a measure of how costly it will be produce an increment of power. The incremental production cost, is made up of incremental fuel cost plus the incremental cost of labour, water, maintenance etc. which can be taken to be some percentage of the incremental fuel cost, instead of resorting to a rigorous mathematical model. The cost curve can be approximated by a linear curve. While there is negligible operating cost for a hydel plant, there is a limitation on the power output possible. In any plant, all units normally operate between PGmin, the minimum loading limit, below which it is technically infeasible to operate a unit and PGmax, which is the maximum output limit.

Solution Methods:

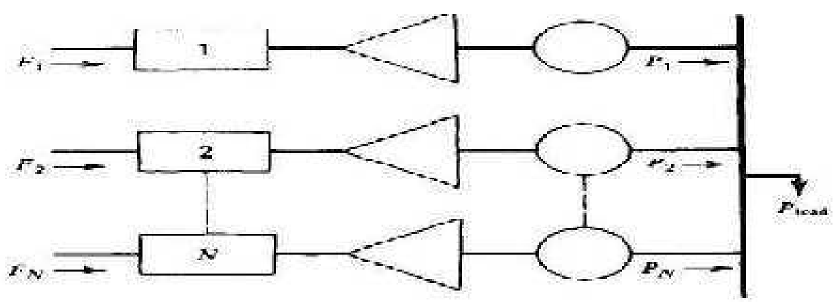
1. Lagrange Multiplier method
2. Lamda iteration method
3. Gradient method
4. Dynamic programming
5. Evolutionary Computation techniques

The Economic Dispatch Problem without Loss.

This system consists of ***N*** thermal-generating units connected to a single bus-bar serving a received electrical load P_{load} input to each unit, shown as F_I,represents the cost rate of the unit. The output of each unit, $\mathbf{P_i}$, is the electrical power generated by that particular unit. The total cost rate of this system is, of course, the sum of the costs of each of the individual units. The essential constraint on the operation of this system is that the sum of the output powers must equal the load demand.Mathematically speaking, the problem may be stated very concisely. That is, an objective function, F_T, is equal to the total cost for supplying the indicated load. The problem is to minimize F_T subject to the constraint that the sum of the powers generated must equal the received load. Note that any transmission losses are neglected and any operating limits are not explicitly stated when formulating this problem. That is,

$$F_T = F_1 + F_2 + F_3 + \cdots + F_N$$
$$= \sum_{i=1}^{N} F_i(P_i)$$
$$\phi = 0 = P_{load} - \sum_{i=1}^{N} P_i$$

-- (6)



N thermal units committed to serve a load of P_{load}.

This is a constrained optimization problem that may be attacked formally using advanced calculus methods that involve the Lagrange function. In order to establish the necessary conditions for an extreme value of the objective function, add the constraint function to the objective function after the constraint function has been multiplied by an undetermined multiplier. This is known as the ***Lagrange function*** and is shown in Eq(7)

$$\mathscr{L} = F_T + \lambda\phi \quad \text{---} (7)$$

The necessary conditions for an extreme value of the objective function result when we take the first derivative of the Lagrange function with respect to each of the independent variables and set the derivatives equal to zero. In this case,there are N+1 variables, the ***N*** values of power output, P_i, plus the undetermined Lagrange multiplier, **λ.** The derivative of the Lagrange function with respect to the undetermined multiplier merely gives back the constraint equation. On the other hand, the ***N*** equations that result when we take the

partial derivative of the Lagrange function with respect to the power output values one at a time give the set of equations shown as Eq. 8.

$$\frac{dF_i}{dP_i} = \lambda \qquad N \text{ equations}$$

$$P_{i,\min} \le P_i \le P_{i,\max} \qquad 2N \text{ inequalities}$$

$$\sum_{i=1}^{N} P_i = P_{\text{load}} \qquad 1 \text{ constraint}$$

When we recognize the inequality constraints, then the necessary conditions may be expanded slightly as shown in the set of equations making up

Thermal System Dispatching With Network Losses Considered

symbolically an all-thermal power generation system connected to an equivalent load bus through a transmission network. The economic dispatching problem associated with this particular configuration is slightly more complicated to set up than the previous case. This is because the constraint equation is now one that must include the network losses. The

objective function, F_T, is the same as that defined for Eq.10

$$P_{\text{load}} + P_{\text{loss}} - \sum_{i=1}^{N} P_i = \phi = 0 \quad \text{------------------} (10)$$

The same procedure is followed in the formal sense to establish the necessary conditions for a minimum-cost operating solution, The Lagrange function is shown in Eq.11. In taking the derivative of the Lagrange function with respect to each of the individual power outputs, P_i, it must be recognized that the loss in the transmission network, P_{loss} is a function of the network impedances and the currents flowing in the network. For our purposes, the currents will be considered only as a function of the independent variables P_i and the load P_{load} taking the derivative of the Lagrange function with respect to any one of the ***N*** values of P_i results in Eq. 11. collectively as the *coordination equations.*

$$\mathcal{L} = F_T + \lambda \phi$$

$$\frac{\partial \mathcal{L}}{\partial P_i} = \frac{dF_i}{dP_i} - \lambda \left(1 - \frac{\partial P_{loss}}{\partial P_i}\right) = 0$$

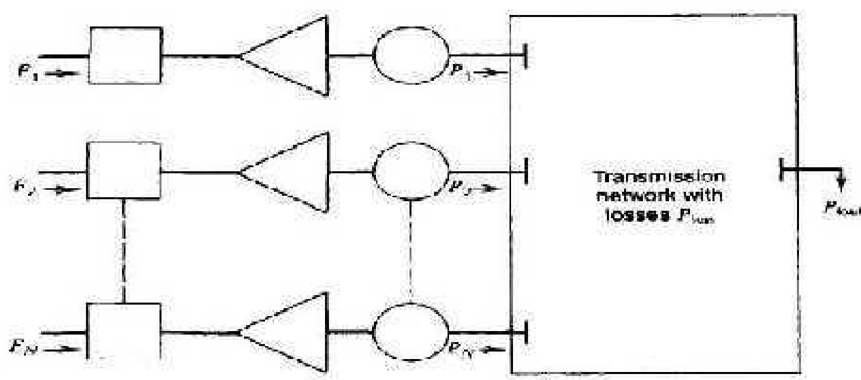
or

$$\frac{dF_i}{dP_i} + \lambda \frac{\partial P_{loss}}{\partial P_i} = \lambda$$

$$P_{load} + P_{loss} - \sum_{i=1}^{N} P_i = 0$$

It is much more difficult to solve this set of equations than the previous set with no losses since this second set involves the computation of the network loss in order to establish the validity of the solution in satisfying the constraint equation. There have been two general approaches to the solution of this problem. The first is the development of a mathematical expression for the losses in the network solely as **a** function of the power output of each of the units. This is the loss-formula method discussed at some length in Kirchmayer's

Economic Operation of ***Power*** **Systems**. The other basic approach to the solution of this problem is to incorporate the power flow equations as essential constraints in the formal establishment of the optimization problem. This general approach is known as the optimal powerflow**.**



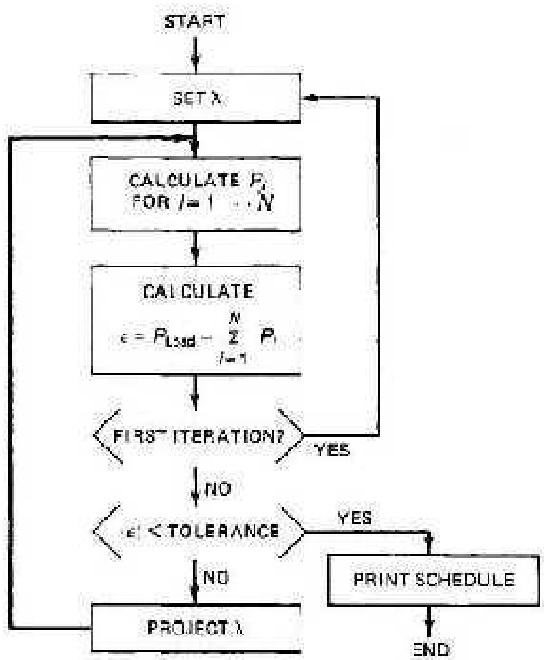
N thermal units serving load through transmission network

The Lambda-Iteration Method

block diagram of the lambda-iteration method of solution for the all-thermal, dispatching problem-neglecting losses. We can approach the solution to this problem by considering a graphical technique for solving the problem and then extending this into the area of computer algorithms. Suppose we have a three-machine system and wish to find the optimum economic operating point. One approach would be to plot the incremental cost characteristics for each of these three units on the same graph,

In order to establish the operating points of each of these three units such that we have minimum cost and at the same time satisfy the specified demand, we could use this sketch and a ruler to find the solution. That is, we could assume an incremental cost rate ***(λ)*** and find the power outputs of each of the three units for this value of incremental cost. the three units for this value of incremental cost. Of course, our first estimate will be incorrect. If we have assumed the value of incremental cost such that the total power output is too low, we must increase the ***3.*** value and try another solution. With two solutions, we can extrapolate (or interpolate) the two solutions to get closer to the desired value of total received power. By

keeping track of the total demand versus the incremental cost, we can rapidly find the desired operating point. If we wished, we could manufacture a whole series of tables that would show the total power supplied for different incremental cost levels and combinations of units. That is, we will now establish a set of logical rules that would enable us to accomplish the same objective as we have just done with ruler and graph paper. The actual details of how the power output is established as a function of the incremental cost rate are of very little importance.



Lambda-iteration method

We could, for example, store tables of data within the computer and interpolate between the stored power points to find exact power output for a specified value of incremental cost rate. Another approach would be to develop an analytical function for the power output as a function of the incremental cost rate, store this function (or its coefficients) in the computer, and use this to establish the output of each of the individual units.

This procedure is an iterative type of computation, and we must establish stopping rules. Two general forms of stopping rules seem appropriate for this application..The lambda-iteration procedure converges very rapidly for this particular type of optimization problem. The actual computational procedure is slightly more complex than that indicated ,since it is necessary to observe the operating limits on each of the units during the course of the computation. The well-known Newton-Raphson method may be used to project the incremental cost value to drive the error between the computed and desired generation to zero

Base Point and Participation Factors

This method assumes that the economic dispatch problem has to be solved repeatedly by moving the generators from one economically optimum schedule to another as the load changes by a reasonably small amount. We start from a given schedule-the ***base point.*** Next, the scheduler assumes a load change and investigates how much each generating unit needs to be moved (i.e.,“participate” in the load change) in order that the new load be served at the most economic operating point.Assume that both the first and second derivatives in the cost versus power output function are available (Le., both *F;* and *Fy* exist). The incremental cost th

t 0 for **a** small change in power output on this single unit,

$$\Delta\lambda_i = \Delta\lambda \cong F_i''(P_i^0)\Delta P_i \quad \text{-- (13)}$$

This is true for each of t on the system, so that

$$\Delta P_1 = \frac{\Delta\lambda}{F_1''}$$

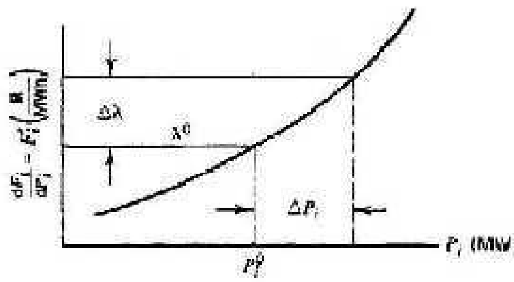
$$\Delta P_2 = \frac{\Delta\lambda}{F_2''}$$

$$\vdots$$

$$\Delta P_N = \frac{\Delta\lambda}{F_N''}$$

---------------------------------------(14)

The total change in generation (=change in total system demand) is, of course, the sum of the individual unit changes. Let P_d be the total demand on the generators (where P_{load}+P_{loss}&),



$$\Delta P_D = \Delta P_1 + \Delta P_2 + \cdots + \Delta P_N = \Delta\lambda \sum_i \left(\frac{1}{F_i''}\right)$$

-- (15)

The earlier equation, 15, can be used to find the ***participation factor*** for each unit as follows

$$\left(\frac{\Delta P_i}{\Delta P_D}\right) = \frac{(1/F_i'')}{\sum_i \left(\frac{1}{F_i''}\right)}$$

----
(16)

The computer implementation of such a scheme of economic dispatch is straightforward. It might be done by provision of tables of the values of *FY* as a function of the load levels and devising a simple scheme to take the existing load plus the projected increase to look up these data and compute the factors. somewhat less elegant scheme to provide participation factors would involve a repeat economic dispatch calculation at**.** The base-point economic generation values are then subtracted from the new economic generation values and the difference divided to provide the participation factors. This scheme works well in computer implementations where the execution time for the economic dispatch is short and will always give consistent answers when units reach limits, pass through break points on piecewise linear incremental cost functions, or have nonconvex cost curves.

UNIT COMMITMENT

The life style of a modern man follows regular habits and hence the present society also follows regularly repeated cycles or pattern in daily life. Therefore, the consumption of electrical energy also follows a predictable daily, weekly and seasonal pattern. There are periods of high power consumption as well as low power consumption. It is therefore possible to commit the generating units from the available capacity into service to meet the demand. The previous discussions all deal with the computational aspects for allocating load to a plant in the most economical manner. For a given combination of plants the determination of optimal combination of plants for operation at any one time is also desired for carrying out the aforesaid task. The plant commitment and unit ordering schedules extend the period of optimization from a few minutes to several hours. From daily schedules weekly patterns can be developed. Likewise, monthly, seasonal and annual schedules can be prepared taking into consideration the repetitive nature of the load demand and seasonal variations. Unit commitment schedules are thus required for economically committing the units in plants to service with the time at which individual units should be taken out from or returned to service.

Constraints in Unit Commitment

Many constraints can be placed on the unit commitment problem. The list presented here is by no means exhaustive. Each individual power system, power pool, reliability council, and so forth, may impose different rules on the scheduling of units, depending on the generation makeup, load-curve characteristics,
and such.

Spinning Reserve

Spinning reserve is the term used to describe the total amount of generation available
from all units synchronized (i.e., spinning) on the system, minus the present load and losses being supplied. Spinning reserve must be carried so that the loss of one or more units does not cause too far a drop in system frequency. Quite simply, if one unit is lost, there must be ample reserve on the other units to make up for the loss in a specified time period.Spinning reserve must be allocated to obey certain rules, usually set by regional reliability councils (in the United States) that specify how the reserve is to be allocated to various units. Typical rules specify that reserve must be a given

percentage of forecasted peak demand, or that reserve must be capable of making up the loss of the most heavily loaded unit in a given period of time.Others calculate reserve requirements as a function of the probability of not having sufficient generation to meet the load.Not only must the reserve be sufficient to make up for a generation-unit failure, but the reserves must be allocated among fast-responding units and slow-responding units. This allows the automatic generation control system to restore frequency and interchange quickly in the event of a generating-unit outage. Beyond spinning reserve, the unit commitment problem may involve various classes of "scheduled reserves" or "off-line" reserves. These include quick-start

diesel or gas-turbine units as well as most hydro-units and pumped-storage hydro-units that can be brought on-line, synchronized, and brought up to full capacity quickly. **As** such, these units can be "counted" in the overall reserve assessment, as long as their time to come up to full capacity is taken into account. Reserves, finally, must be spread around the power system to avoid transmission system limitations (often called "bottling" of reserves) and to allow various parts of the system to run as "islands," should they become electrically disconnected.

Thermal Unit Constraints

Thermal units usually require a crew to operate them, especially when turned on and turned off. A thermal unit can undergo only gradual temperature changes, and this translates into a time period of some hours required to bring the unit on-line. **As** a result of such restrictions in the operation of a thermal plant, various constraints arise, such as:

1. Minimum up time: once the unit is running, it should not be turned off immediately

2. Minimum down time: once the unit is decommitted, there is a minimum time before it can be recommitted.

3.* Crew constraints:** if a plant consists of two or more units, they cannot both be turned on at the same time since there are not enough crew members to attend both units while starting up. In addition, because the temperature and pressure of the thermal unit must be moved slowly, a certain amount of energy must be expended to bring the unit on-line. This energy does not result in any MW generation from the unit and is brought into the unit commitment problem as a ***start-up *cost.* The start-up cost can vary from a maximum "cold-start" value to a

much smaller value if the unit was only turned off recently and is still relatively close to

operating temperature. There are two approaches to treating a thermal unit during its down period. The first allows the unit's boiler to cool down and then heat back up to operating temperature in time for a scheduled turn on. The second (called *banking)*requires that sufficient energy be input to the boiletojustmaintain operating temperature. The costs for the two can be compared so that, if possible, the best approach (cooling or banking) can be chosen.

C_f= fixed cost (includes crew expense, maintenance expenses) (in R)

α = thermal time constant for the unit

t = time (h) the unit was cooled

Start-up cost when banking = C_t x ***t*** x F+C_f

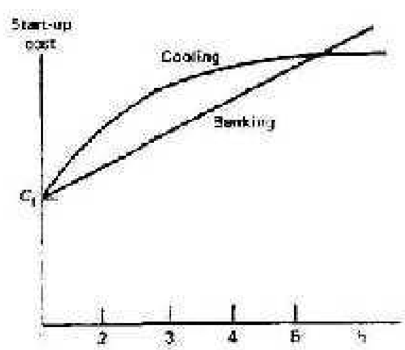
C_t = cost (MBtu/h) of maintaining unit at operating temperature

Up to a certain number of hours, the cost of banking will be less than the cost of cooling, as is illustrated in Figure 5.3.Finally, the capacity limits of thermal units may change frequently, due to maintenance or unscheduled outages of various equipment in the plant; this must also be taken

Other Constraints

Hydro-Constraints

Unit commitment cannot be completely separated from the scheduling of hydro-units. In this text, we will assume that the hydrothermal scheduling (or "coordination") problem can be separated from the unit commitment problem. We, of course, cannot assert flatly that our treatment in this fashion will always result in an optimal solution.



Hydro-Constraints

Must Run

Some units are given a must-run status during certain times of the year for reason of voltage support on the transmission network or for such purposes as supply of steam for uses outside the steam plant itself.

Fuel Constraints

We will treat the "fuel scheduling" problem system in which some units have limited fuel, or else have constraints that require them to burn a specified amount of fuel in a given time, presents a most challenging unit commitment problem.

Unit Commitment Solution Methods

The commitment problem can be very difficult. **As** a theoretical exercise, let us postulate the following situation.

1. We must establish a loading pattern for *M* periods.
2. We have *N* units to commit and dispatch.
3. The ***M*** load levels and operating limits on the ***N*** units are such that any one unit can supply the individual loads and that any combination of units can also supply the loads.

Next, assume we are going to establish the commitment by enumeration (brute force). The total number of combinations we need to try each hour is,

$$C(N,1) + C(N,2) + \dots + C(N, N-1) + C(N,N) = 2N - 1 \text{------------------------(18)}$$

Where C (N, j) is the combination of ***N*** items taken *j* at a time. That is,

$$C(N,j) = \left[\frac{N!}{(N-j)!\,j!}\right]$$
$$j! = 1 \times 2 \times 3 \times \dots \times j \text{ ---------------------------(19)}$$

These very large numbers are the upper bounds for the number of enumerations required. Fortunately, the constraints on the units and the load-capacity relationships of typical utility systems are such that we do not approach these large numbers. Nevertheless, the real practical barrier in the optimized unit commitment problem is the high dimensionality of the possible solution space.

The most talked-about techniques for the solution of the unit commitment problem are:

1. Priority-list schemes,
2. Dynamic programming (DP),
3. Lagrange relation (LR).

Priority-List Method for unit commitment solution:

The simplest unit commitment solution method consists of creating a priority list of units. **As** a simple shut-down rule or priority-list scheme could be obtained after an exhaustive enumeration of all unit combinations at each load level. The priority list of Example 5B could be obtained in a much simpler manner by noting the full- load average production cost of each unit, where the full-load average production cost is simply the net heat rate at full load multiplied by the fuel cost.

Priority List Method:

Priority list method is the simplest unit commitment solution which consists of creating a priority list of units.

Full load average production cost= Net heat rate at full
load X Fuel
cost Assumptions:

1. No load cost is zero
2. Unit input-output characteristics are linear between zero output and full load
3. Start up costs are a fixed amount
4. Ignore minimum up time and minimum
down time Steps to be followed

1. Determine the full load average production cost for each units
2. Form priority order based on average production cost
3. Commit number of units corresponding to the priority order
4. Alculate PG1, PG2 ………….PGN from economic dispatch problem for the feasible
combinations only

Dynamic-Programming Solution

Dynamic programming has many advantages over the enumeration scheme, the chief advantage being a reduction in the dimensionality of the problem. Suppose we have found units in a system and any combination of them could serve the (single) load. There would be

a maximum of **24** - 1 = 15 combinations to test. However, if a strict priority order is imposed, there are only four combinations to try:

Priority 1 unit

Priority 1 unit + Priority 2 unit

Priority 1 unit + Priority 2 unit + Priority **3** unit

Priority 1 unit + Priority **2** unit + Priority **3** unit + Priority **4** unit

The imposition of a priority list arranged in order of the full-load averagecost rate would result in a theoretically correct dispatch and commitment only if:

1. No load costs are zero.
2. Unit input-output characteristics are linear between zero output and full load.
3. There are no other restrictions.
4. Start-up costs are a fixed amount.

In the dynamic-programming approach that follows, we assume that:

1. A *state* consists of an array of units with specified units operating and
2. The start-up cost of a unit is independent of the time it has been off-line
3. There are no costs for shutting down a unit.
4. There is a strict priority order, and in each interval a specified minimum the rest off-line. (i.e., it is a fixed amount).amount of capacity must be operating.

A feasible state is one in which the committed units can supply the required load and that meets the minimum amount of capacity each period.

Forward DP Approach

One could set up a dynamic-programming algorithm to run backward in time starting from the final hour to be studied, back to the initial hour. Conversely, one could set up the algorithm to run forward in time from the initial hour to the final hour. The forward approach has distinct advantages in solving generator unit commitment. For example, if the start-up cost of a unit is a function of the time it has been off-line (i.e., its temperature), then a forward dynamic-program approach is more suitable since the previous history of the

unit can be computed at each stage. There are other practical reasons for going forward. The initial conditions are easily specified and the computations can go forward in time as long as required. **A** forward dynamic-programming algorithm is shown by the flowchart

The recursive algorithm to compute the minimum cost in hour *K* with combinati

$$F_{cost}(K,I)= \min[P_{cost}(K,I)+S_{cost}(K-1,L:K,I)+F_{cost}(K-1,L)] \text{ ---------------- } \quad (20)$$

$F_{cost}(K, I)$ = least total cost to arrive at state (K , I)

$P_{cost}(KI,)$ = production cost for state(K ,I)

$S_{cost}(K - 1, L: K, I)$= transition cost from state (K - 1, L) to state (K , **I**)

State **(K, 1)** is the Zth combination in hour **K.** For the forward dynamic programming approach, we define a **strategy** as the transition, or path, from one state at a given hour to a state at the next hour.

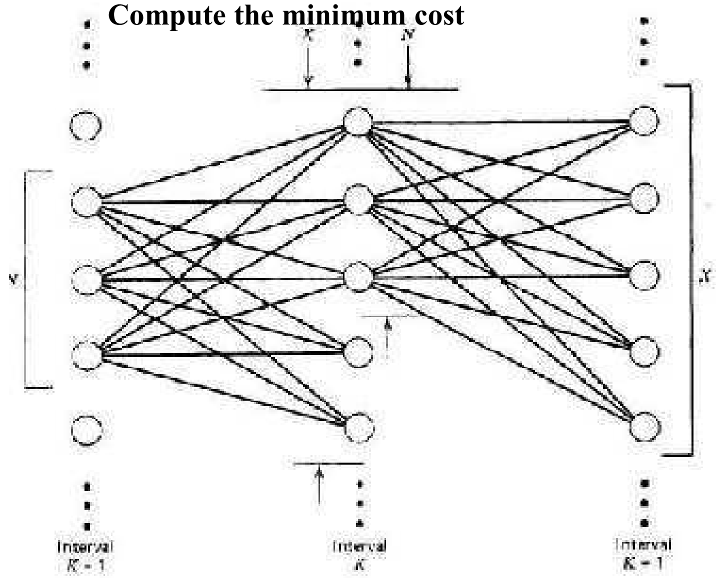
Note that two new variables, X and **N,** have been introduced

X = number of states to search each period

N = number of strategies, or paths, to save at each step

These variables allow control of the computational effort (see below Figure).For complete enumeration, the maximum number of the value of *X* or ***N*** is $2^n - 1$

Compute the minimum cost



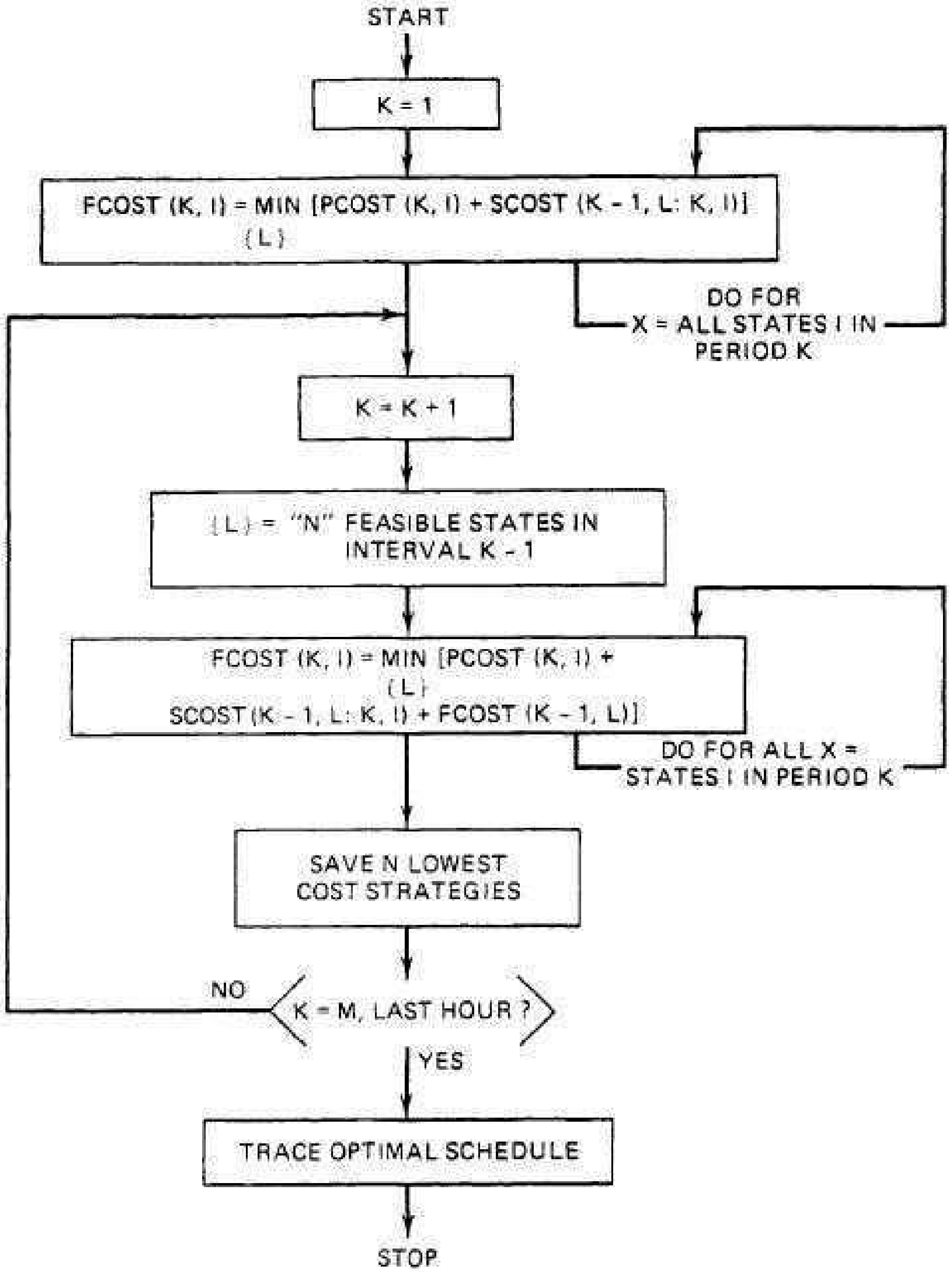


Figure: Forward DP Approach

UNIT – V

COMPUTER CONTROL OF POWER SYSTEMS

ENERGY CONTROL CENTRE

The energy control center (ECC) has traditionally been the decision-center for the electric transmission and generation interconnected system. The ECC provides the functions necessary for monitoring and coordinating the minute-by-minute physical and economic operation of the power system. In the continental U.S., there are only three interconnected regions: Eastern, Western, and Texas, but there are many *control areas*, with each control area having its own ECC.

Maintaining integrity and economy of an inter-connected power system requires significant coordinated decision-making. So one of the primary functions of the ECC is to monitor and regulate the physical operation of the interconnected grid.

Most areas today have a two-level hierarchy of ECCs with the Independent System Operator (ISO) performing the high-level decision-making and the transmission owner ECC performing the lower-level decision-making.

A high-level view of the ECC is illustrated.Where we can identify the substation, the remote terminal unit (RTU), a communication link, and the ECC which contains the energy management system (EMS). The EMS provides the capability of converting the data received from the substations to the types of screens observed.

In these notes we will introduce the basic components and functionalities of the ECC. Note that there is no chapter in your text which provides this information.

Regional load control centre:

It decides generation allocation to various generating stations within the region on the basics of equal incremental operating cost considering line losses are equal and Frequency control in the region.

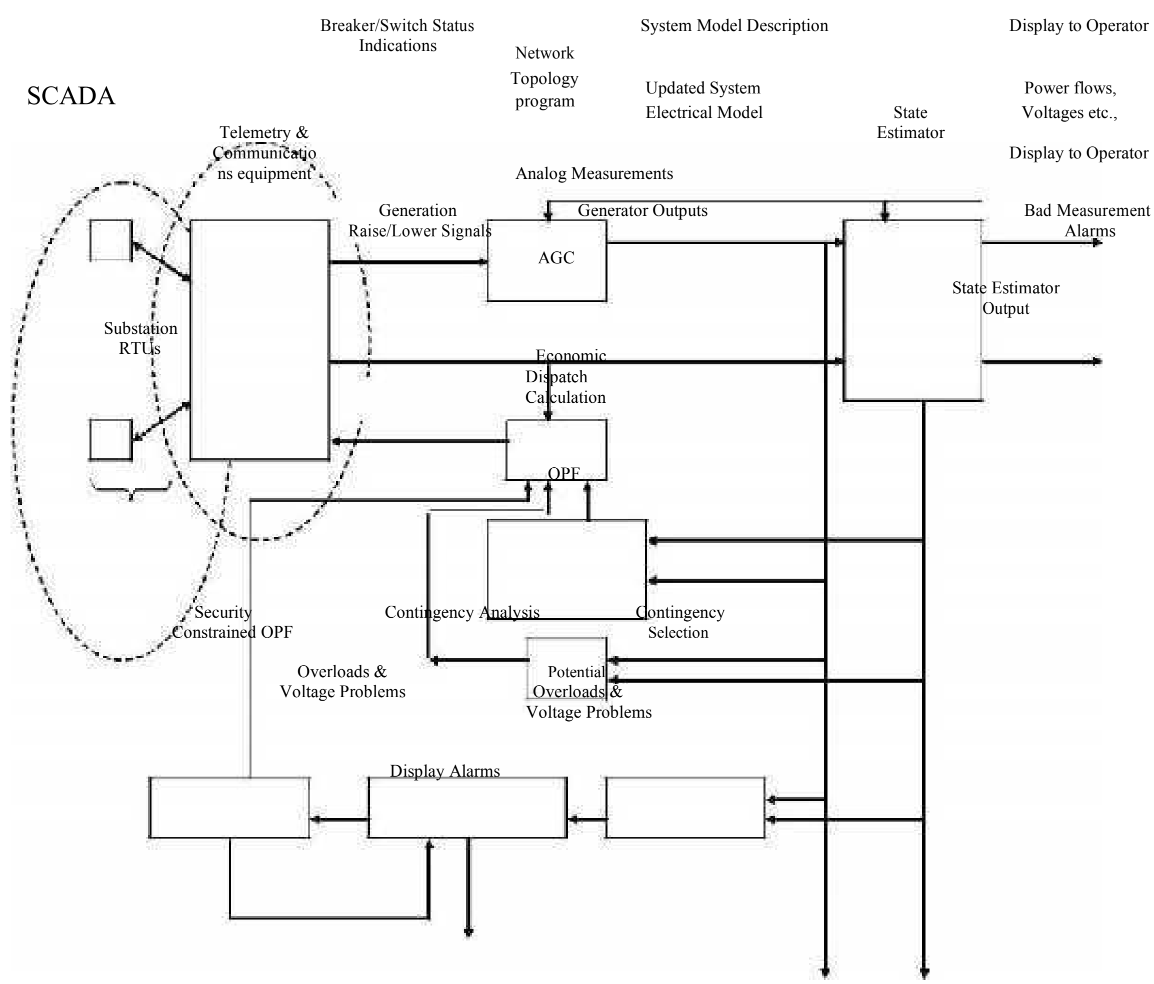
Plant load control room:

It decides the allocation of generation of various units in the plant on the basis of:

1. Equal incremented operating cost of various units
2. Minimize the reactive power flow through line so as to minimize line loss and maintain voltage levels and Frequency control in the plant.

ECC Components

The system control function traditionally used in electric utility operation consists of three main integrated subsystems: the energy management system (EMS), the supervisory control and data acquisition (SCADA), and the communications interconnecting the EMS and the SCADA (which is often thought of as part of the SCADA itself). Figure 3 provides a block diagram illustration of these three integrated subsystems. The SCADA and communications subsystems are indicated in the dotted ovals at the top left hand corner of the figure. The rest of the figure indicates the EMS. We will describe each one in the following subsections.



System control subsystems: EMS, SCADA, and Communications

We distinguish EMS from distribution management systems (DMS). Both utilize their own SCADA, but for different functions. Whereas EMS/SCADA serves the high voltage bulk transmission system from the ECC, the DMS/SCADA serves the low voltage, distribution system from a distribution dispatch center. We are addressing in these notes the EMS/SCADA.

Operation of control centre:

- **Monitoring**
- **Data acquisition and Remote control**

level control

1. Turbine – governor to adjust generation to balance changing load-instantaneous control.
2. AGC (called load frequency control (LFC)) maintains frequency and net power interchange.
3. Economic Dispatch Control (EDC) distributes the load among the units such that fuel cost is minimum.

B. Primary Voltage control

1. Excitation control
2. Transmission voltage control, SVC, Shunt capacitors, transformer taps…

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2. SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA)

There are two parts to the term SCADA *Supervisory control* indicates that the operator, residing in the energy control center (ECC), has the ability to control remote equipment. *Data acquisition* indicates that information is gathered characterizing the state of the remote equipment and sent to the ECC for monitoring purposes.

The monitoring equipment is normally located in the substations and is consolidated in what is known as the remote terminal unit (RTU). Generally, the RTUs are equipped with microprocessors having memory and logic capability. Older RTUs are equipped with modems to provide the communication link back to the ECC, whereas newer RTUs generally have intranet or internet capability.

Relays located within the RTU, on command from the ECC, open or close selected control circuits to perform a supervisory action. Such actions may include, for example, opening or closing of a circuit breaker or switch, modifying a transformer tap setting, raising or lowering generator MW output or terminal voltage, switching in or out a shunt capacitor or inductor, and the starting or stopping of a synchronous condenser.

Information gathered by the RTU and communicated to the ECC includes both analog information and status indicators. Analog information includes, for example, frequency, voltages, currents, and real and reactive power flows. Status indicators include alarm signals (over-temperature, low relay battery voltage, illegal entry) and whether switches and circuit breakers are open or closed. Such information is provided to the ECC through a periodic scan of all RTUs. A 2 second scan cycle is typical.

Functions of SCADA Systems

1. Data acquisition
2. Information display.
3. Supervisory Control (CBs:ON/OFF, Generator: stop/start, RAISE/LOWER command)
4. Information storage and result display.
5. Sequence of events acquisition.
6. Remote terminal unit processing.
7. General maintenance.
8. Runtime status verification.
9. Economic modeling.
10. Remote start/stop.
11. Load matching based on economics.
12. Load shedding.

- **Control functions**
  - Cont rol and monitoring of switching devices, tapped transformers, auxiliary devices, etc.
  - Bay-and a station-wide interlocking Automatic functions such as load shedding, power restoration, and high speed bus bar transfer
  - Time synchronization by radio and satellite clock signal
- **Monitoring functions:**
  - Measurement and displaying o fcurrent, voltage, frequency, active and reactive power, energy, temperature, etc.
  - Alarm functions. Storage and evaluation of time stamped events.
- **Protection functions:**
  - Substation protection functions includes theonitoring of events like star ,tripindication andrelay opratingtime and setting and. adigofre.ayparameters.

➢

Protection of bus bars. Line feeders, transformers, generators.

Communication technologies

The form of communication required for SCADA is *telemetry*. Telemetry is the measurement of a quantity in such a way so as to allow interpretation of that measurement at a distance from the primary detector. The distinctive feature of telemetry is the nature of the translating means, which includes provision for converting the measure into a representative quantity of another kind that can be transmitted conveniently for measurement at a distance. The actual distance is irrelevant.

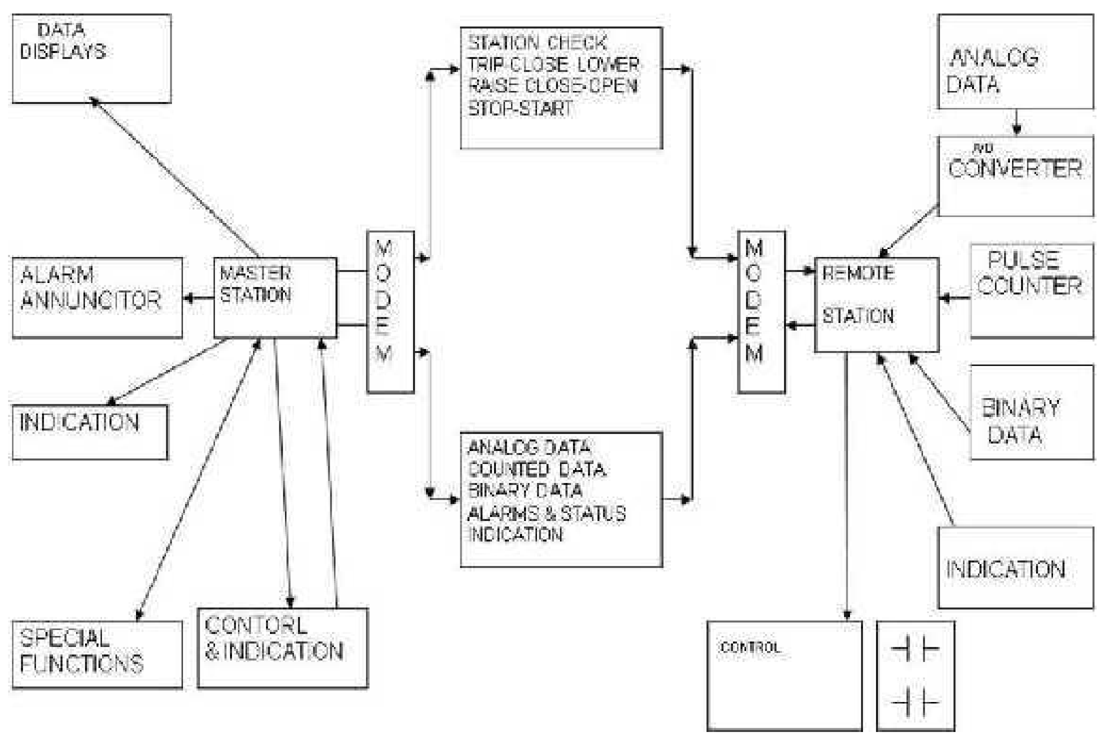
Telemetry may be analog or digital. In analog telemetry, a voltage, current, or frequency proportional to the quantity being measured is developed and transmitted on a communication channel to the receiving location, where the received signal is applied to a meter calibrated to indicate the quantity being measured, or it is applied directly to a control device such as a ECC computer.

Forms of analog telemetry include variable current, pulse-amplitude, pulse-length, and pulse-rate, with the latter two being the most common. In digital telemetry, the quantity being measured is converted to a code in which the sequence of pulses transmitted indicates the quantity. One of the advantages to digital telemetering is the fact that accuracy of data is not lost in transmitting the data from one location to another. Digital telemetry requires analog to digital (A/D) and possible digital to analog (D/A) converters, as illustrated in

The earliest form of signal circuit used for SCADA telemetry consisted of twisted pair wires; although simple and economic for short distances, it suffers from reliability problems due to breakage, water ingress, and ground potential risk during faults

Improvements over twisted pair wires came in the form of what is now the most common, traditional type of telemetry mediums based on leased-wire, power-line carrier, or microwave. These are *voice grade* forms of telemetry, meaning they represent communication channels suitable for the transmission of speech, either digital or analog, generally with a frequency range of about 300 to 3000 Hz

SCADA requires communication between Master control station and Remote control station:



Master and Remote station

Leased-wire means use of a standard telephone circuit; this is a convenient and straightforward means of telemetry when it is available, although it can be unreliable, and it requires a continual outlay of leasing expenditures. In addition, it is not under user control and requires careful coordination between the user and the telephone company. Power-line carrier (PLC) offers an inexpensive and typically more reliable alternative to leased-wire. Here, the transmission circuit itself is used to modulate a communication signal at a frequency much greater than the 60 Hz power frequency. Most PLC occurs at frequencies in the range of 30-500 kHz. The security of PLC is very high since the communication equipment is located inside the substations. One disadvantage of PLC is that the communication cannot be made through open disconnects, i.e., when the transmission line is outaged. Often, this is precisely the time when the communication signal is needed most. In addition, PLC is susceptible to line noise and requires careful signal-to-noise ratio analysis. Most PLC is strictly analog although digital PLC has become available from a few suppliers during the last few years.

Microwave radio refers to ultra-high-frequency (UHF) radio systems operating above
1 GHz. The earliest microwave telemetry was strictly analog, but digital microwave communication is now quite common for EMS/SCADA applications. This form of communication has obvious advantages over PLC and leased wire since it requires no physical conducting medium and therefore no right-of-way. However, line of sight clearance is required in order to ensure reliable communication, and therefore it is not applicable in some cases.

A more recent development has concerned the use of fiber optic cable, a technology capable of extremely fast communication speeds. Although cost was originally prohibitive, it has now decreased to the point where it is viable. Fiber optics may be either run inside underground power cables or they may be fastened to overhead transmission line towers just below the lines. They may also be run within the shield wire suspended above the transmission lines.

One easily sees that communication engineering is very important to power system control. Students specializing in power and energy systems should strongly consider taking communications courses to have this background. Students specializing in communication should consider taking power systems courses as an application area.

ENERGY MANAGEMENT SYSTEM (EMS)

The EMS is a software system. Most utility companies purchase their EMS from one or more EMS vendors. These EMS vendors are companies specializing in design, development, installation, and maintenance of EMS within ECCs. There are a number of EMS vendors in the U.S., and they hire many power system engineers with good software development capabilities.

During the time period of the 1970s through about 2000, almost all EMS software applications were developed for installation on the control centers computers.

An attractive alternative today is, however, the application service provider, where the software resides on the vendor‟s computer and control center personnel access it from the Internet. Benefits from this arrangement include application flexibility and reliability in the software system and reduced installation cost.

One can observe from Figure 3 that the EMS consists of 4 major functions: network model building (including topology processing and state estimation), security assessment, automatic generation control, and dispatch. These functions are described in more detail in the following subsections.

Energy management is the process of monitoring, coordinating, and controlling the generation, transmission and distribution of electrical energy. The physical plant to be managed includes generating plants that produce energy fed through transformers to the high-voltage transmission network (grid), interconnecting generating plants, and load centers. Transmission lines terminate at substations that perform switching, voltage transformation, measurement, and control. Substations at load centers transform to sub transmission and distribution levels. These lower-voltage circuits typically operate radially, i.e., no normally closed paths between substations through sub transmission or distribution circuits.(Underground cable networks in large cities are an exception.)

Since transmission systems provide negligible energy storage, supply and demand must be balanced by either generation or load. Production is controlled by turbine governors at generating plants, and automatic generation control is performed by control center computers remote from generating plants. Load management, sometimes called demand-

Side management, extends remote supervision and control to subtransmission and distribution circuits, including control of residential, commercial, and industrial loads.

Functionality Power EMS:

1. System Load Forecasting-Hourly energy, 1 to 7 days.
2. Unit commitment-1 to 7days.
3. Economic dispatch
4. Hydro-thermal scheduling- up to 7 days.
5. MW interchange evaluation- with neighboring system
6. Transmission loss minimization
7. Security constrained dispatch
8. Maintenance scheduling
9. Production cost calculation

Power System Data Acquisition and Control

A SCADA system consists of a master station that communicates with remote terminal units (RTUs) for the purpose of allowing operators to observe and control physical plants. Generating plants and transmission substations certainly justify RTUs, and their installation is becoming more common in distribution substations as costs decrease. RTUs transmit device status and measurements to, and receive control commands and setpoint data from, the master station. Communication is generally via dedicated circuits operating in the range of 600 to 4800 bits/s with the RTU responding to periodic requests initiated from the master station (polling) every 2 to 10 s, depending on the criticality of the data.

The traditional functions of SCADA systems are summarized:

• Data acquisition: Provides telemetered measurements and status information to operator.

• Supervisory control: Allows operator to remotely control devices, e.g., open and close

circuit breakers. A "select before operate" procedure is used for greater safety.

• Tagging: Identifies a device as subject to specific operating restrictions and prevents unauthorized operation.

• Alarms: Inform operator of unplanned events and undesirable operating conditions. Alarms

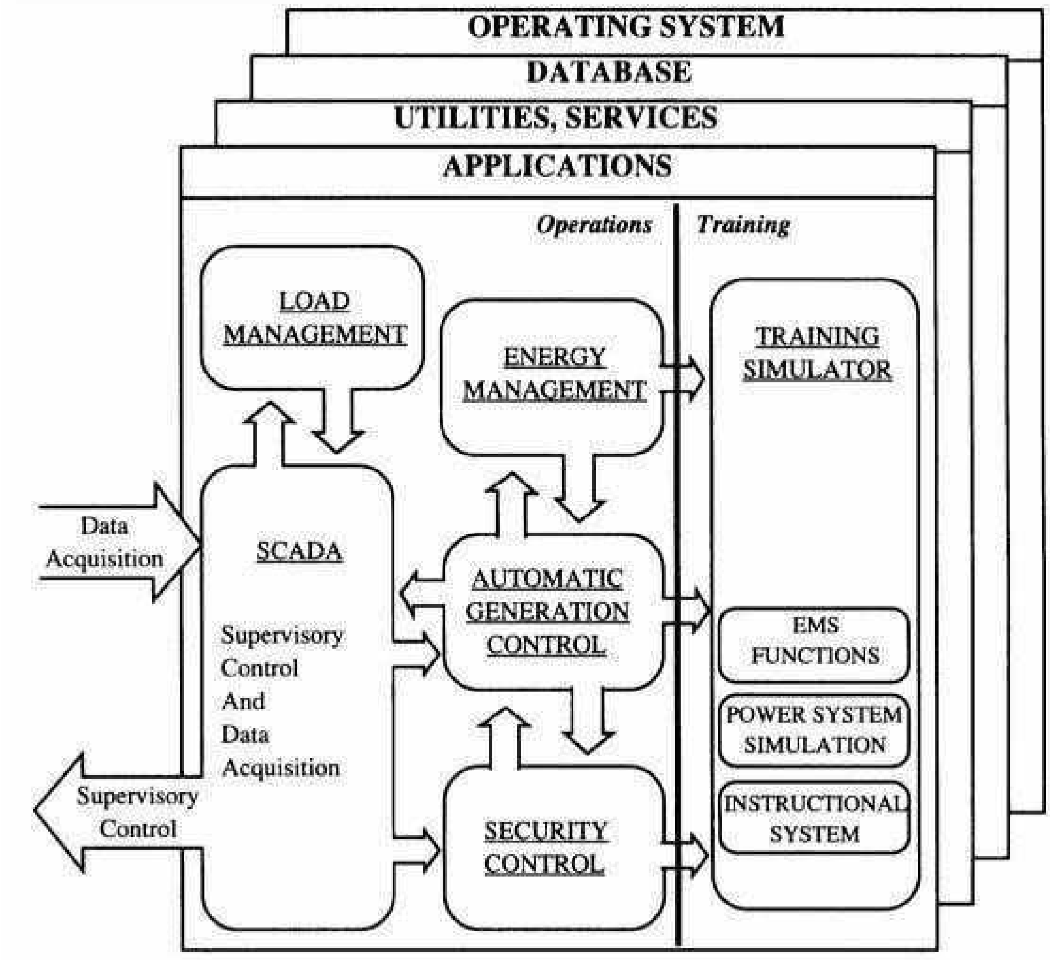
are sorted by criticality, area of responsibility, and chronology.

Acknowledgment may be required

• Logging: Logs all operator entry, all alarms, and selected information.

• Load shed: Provides both automatic and operator-initiated tripping of load in response to system emergencies.

• Trending: Plots measurements on selected time scales.



Layers of a modern EMS.

Since the master station is critical to power system operations, its functions are generally distributed among several computer systems depending on specific design. A dual computer system configured in primary and standby modes is most common. SCADA functions are listed below without stating which computer has specific responsibility.

- Manage communication circuit configuration
- Downline load RTU files
- Maintain scan tables and perform polling
- Check and correct message errors
- Convert to engineering units
- Detect status and measurement changes
- Monitor abnormal and out-of-limit conditions
- Log and time-tag sequence of events
  Detect and annunciate alarms

• Respond to operator requests to:

– Display information

– Enter data

– Execute control action

– Acknowledge alarms Transmit control action to RTUs
• Inhibit unauthorized actions

• Maintain historical files

• Log events and prepare reports

• Perform load shedding

Automatic Generation Control

Automatic generation control (AGC) consists of two major and several minor functions that operate online in realtime to adjust the generation against load at minimum cost. The major functions are load frequency control and economic dispatch, each of which is described below. The minor functions are reserve monitoring, which assures enough reserve on the system; interchange scheduling, which initiates and completes scheduled interchanges; and other similar monitoring and recording functions.

Load Frequency Control

Load frequency control (LFC) has to achieve three primary objectives, which are stated below in priority order:

1. To maintain frequency at the scheduled value

2. To maintain net power interchanges with neighboring control areas at the scheduled values

3. To maintain power allocation among units at economically desired values.

The first and second objectives are met by monitoring an error signal, called *area control error* (ACE), which is a combination of net interchange error and frequency error and represents the power imbalance between generation and load at any instant. This ACE must be filtered or smoothed such that excessive and random changes in ACE are not translated into control action. Since these excessive changes are different for different systems, the filter

parameters have to be tuned specifically for each control area.

The filtered ACE is then used to obtain the proportional plus integral control signal.tThis control signalismodified bylimiters, deadbands, and gainconstants that are tuned to the particular system. This control signal is then divided among the generating units under control by using participation factors to obtain *unit control errors* (UCE).

These participation factors may be proportional to the inverse of the second derivative of the cost of unit generation so that the units would be loaded according to their costs, thus meeting the third objective. However, cost may not be the only consideration because the different units may have different response rates and it may be necessary to move the faster generators more to obtain an acceptable response. The UCEs are then sent to the various units under control and the generating units monitored to see that the corrections take place. This control action is repeated every 2 to 6 s. In spite of the integral control, errors in frequency and net interchange do tend to accumulate over time. These time errors and accumulated interchange errors have to be corrected by adjusting the controller settings according to procedures agreed upon by the whole interconnection. These accumulated errors as well as ACE serve as performance measures for LFC.

The main philosophy in the design of LFC is that each system should follow its own load very closely during normal operation, while during emergencies; each system should contribute according to its relative size in the interconnection without regard to the locality of the emergency. Thus, the most important factor in obtaining good control of a system is its inherent capability of following its own load. This is guaranteed if the system has adequate regulation margin as well as adequate response capability. Systems that have mainly thermal generation often have difficulty in keeping up with the load because of the slow response of the units.

SECURITY ANALYSIS & CONTROL:

Security monitoring is the on line identification of the actual operating conditions of a power system. It requires system wide instrumentation to gather the system data as well as a means for the on line determination of network topology involving an open or closed position of circuit breakers. A state estimation has been developed to get the best estimate of the status

.the state estimation provides the database for security analysis shown in fig.5.6.

- **Data acquisition**:

1. To process from RTU
2. To check status values against normal value
3. To send alarm conditions to alarm processor
4. To check analog measurements against limits.

- **Alarm processor:**

1. To send alarm messages
2. To transmit messages according to priority

- **Status processor:**

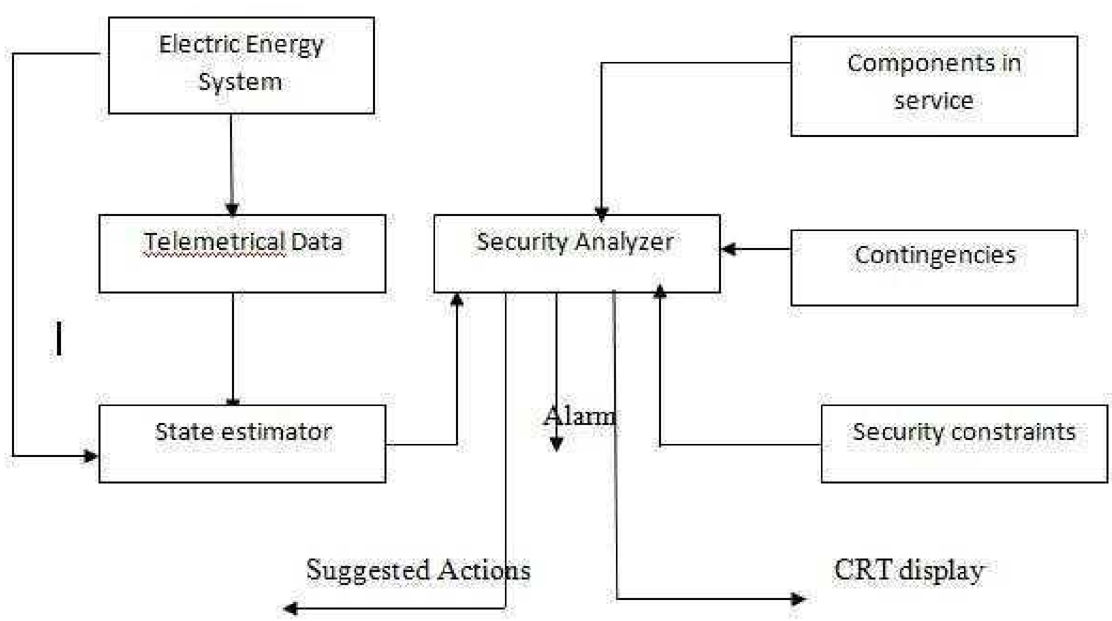
1. To determine status of each substation for proper connection.

- **Reserve monitor:**

1. To check generator MW output on all units against unit limits

- **State estimator:**

1. To determine system state variables
2. To detect the presence of bad measures values.
3. To identify the location of bad measurements
4. To initialize the network model for other programs



Practical Security Monitoring System

System Security

1. System monitoring.
2. Contingency analysis.
3. Security constrained optimal power flow

Security Assessment

Security assessment determines first, whether the system is currently residing in an acceptable state and second, whether the system would respond in an acceptable manner and reach an acceptable state following any one of a pre-defined contingency set. A *contingency* is the unexpected failure of a transmission line, transformer, or generator.Usually, contingencies result from occurrence of a *fault*, or short-circuit, to one of these components. When such a fault occurs, the protection systems sense the fault and remove the component, and therefore also the fault, from the system.Of course, with one less component, the overall system is weaker, and undesirable effects may occur. For example, some remaining circuit may overload, or some bus may experience an undervoltage condition. These are called *static* security problems.

Dynamic security problems may also occur, including uncontrollable voltage decline, generator overspeed (loss of synchronism), or undamped oscillatory behavior.

Security Control

Power systems are designed to survive all probable contingencies. A contingency is defined as an event that causes one or more important components such as transmission lines, generators, and transformers to be unexpectedly removed from service. Survival means the system stabilizes and continues to operate at acceptable voltage and frequency levels without loss of load. Operations must deal with a vast number of possible conditions experienced by the system, many of which are not anticipated in planning. Instead of dealing with the impossible task of analyzing all possible system states, security control starts with a specific state: the current state if executing the real-time network sequence; a postulated state if executing a study sequence. Sequence means sequential execution of programs that perform the following steps:

1. Determine the state of the system based on either current or postulated conditions.

2. Process a list of contingencies to determine the consequences of each contingency on the system in its specified state.

3. Determine preventive or corrective action for those contingencies which represent unacceptable risk.

Security control requires topological processing to build network models and uses large-scale AC network analysis to determine system conditions. The required applications are grouped as a network subsystem that typically includes the following functions:

• **Topology processor**: Processes real-time status measurements to determine an electrical connectivity (bus) model of the power system network.

• **State estimator:** Uses real-time status and analog measurements to determine the „„best""

estimate of the state of the power system. It uses a redundant set of measurements; calculates voltages, phase angles, and power flows for all components in the system; and reports overload conditions.

• **Power flow:** Determines the steady-state conditions of the power system network for a specified generation and load pattern. Calculates voltages, phase angles, and flows across the entiresystem.

• **Contingency analysis:** Assesses the impact of a set of contingencies on the state of the power system and identifies potentially harmful contingencies that cause operating limit violations.

Optimal power flow: Recommends controller actions to optimize a specified objective function (such as system operating cost or losses) subject to a set of power system operating constraints.

• Security enhancement: Recommends corrective control actions to be taken to alleviate an existing or potential overload in the system while ensuring minimal operational cost.

• Preventive action: Recommends control actions to be taken in a "preventive" mode before a

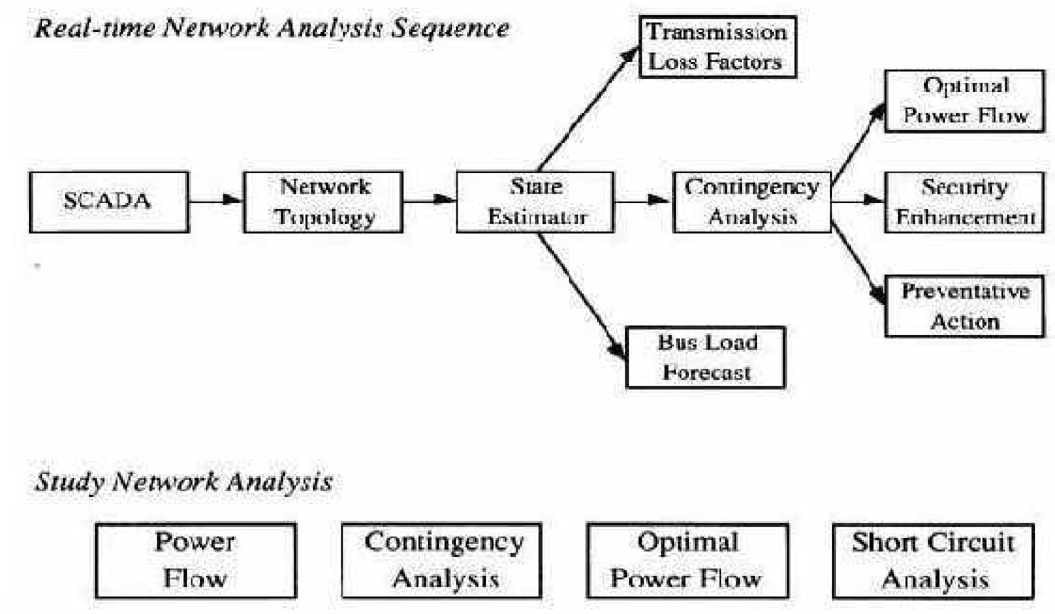
contingency occurs to preclude an overload situation if the contingency were to occur.

• Bus load forecasting: Uses real-time measurements to adaptively forecast loads for the electrical connectivity (bus) model of the power system network

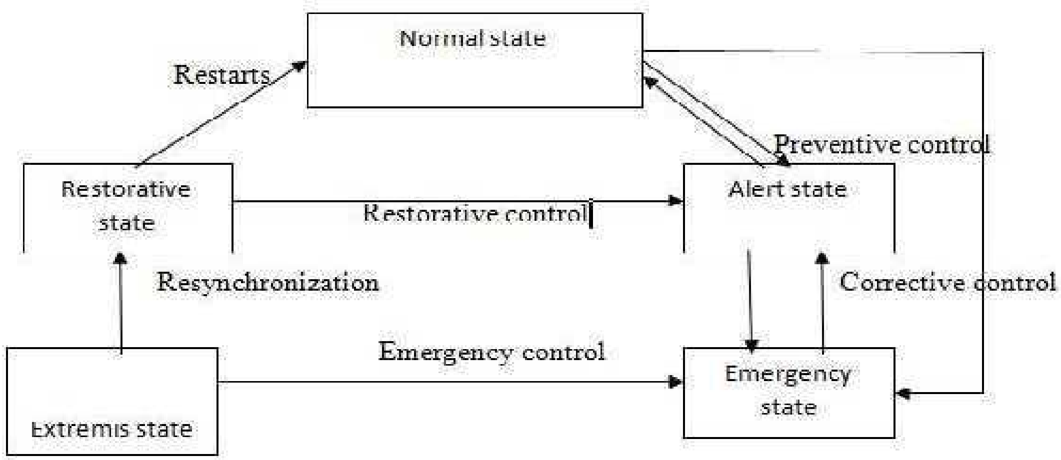
• Transmission loss factors: Determines incremental loss sensitivities for generating units;

calculates the impact on losses if the output of a unit were to be increased by 1 MW.

• Short-circuit analysis: Determines fault currents for single-phase and three-phase faults for fault locations across the entire power system network.



VARIOUS OPERATING STATES:



Operating states

1. Normal state
2. Alert state
3. Emergency state
4. Extremis state
5. Restorative state

➢ **Normal state:**

A system is said to be in normal if both load and operating constraints are satisfied .It is one in which the total demand on the system is met by satisfying all the operating constraints.

- **Alert state**:

A normal state of the system said to be in alert state if one or more of the postulated contingency states, consists of the constraint limits violated. When the system security level falls below a certain level or the probability of disturbance increases, the system may be in alert state .All equalities and inequalities are satisfied, but on the event of a disturbance, the system may not have all the inequality constraints satisfied. If severe disturbance occurs, the system will push into emergency state. To bring back the system to secure state, preventive control action is carried out.

- **Emergency state:**

The system is said to be in emergency state if one or more operating constraints are violated, but the load constraint is satisfied .In this state, the equality constraints are unchanged. The system will return to the normal or alert state by means of corrective actions, disconnection of faulted section or load sharing.

- **Extremis state:**

When the system is in emergency, if no proper corrective action is taken in time, then it goes to either emergency state or extremis state. In this regard neither the load or nor the operating constraint is satisfied, this result is islanding. Also the generating units are strained beyond their capacity .So emergency control action is done to bring back the system state either to the emergency state or normal state.

- **Restorative state:**

From this state, the system may be brought back either to alert state or secure state .The latter is a slow process. Hence, in certain cases, first the system is brought back to alert state and then to the secure state .This is done using restorative control action

EE3602 - POWER SYSTEM OPERATION AND COTROL
SHORT QUESTIONS AND ANSWERS
UNIT-I - INTRODUCTION

1. What is load curve?

The curve drawn between the variations of load on the power station with reference to time is known as load curve. There are three types, Daily load curve, Monthly load curve, Yearly load curve.

2. What is daily load curve?

The curve drawn between the variations of load with reference to various time period of day is known as daily load curve.

3. What is monthly load curve?

It is obtained from daily load curve. Average value of the power at a month for a different time periods are calculated and plotted in the graph which is known as monthly load curve.

4. What is yearly load curve?

It is obtained from monthly load curve which is used to find annual load factor.

5. What is connected load?

It is the sum of continuous ratings of all the equipments connected to supply systems.

6. What is Maximum demand?

It is the greatest demand of load on the power station during a given period.

7. What is Demand factor?

It is the ratio of maximum demand to connected load.

Demand factor= (max demand)/ (connected load)

8. What is Average demand?

The average of loads occurring on the power station in a given period (day or month or year) is known as average demand.

Daily avg demand = (no of units generated per day)/ (24 hours)

Monthly avg demand = (no of units generated in month)/ (no of hours in a month) Yearly avg demand = (no of units generated in a year)/ (no of hours in a year)

9. What is Load factor?

The ratio of average load to the maximum demand during a given period is known as load factor. Load factor = (average load)/ (maximum demand)

10. What is Diversity factor?

The ratio of the sum of individual maximum demand on power station is known as diversity factor. Diversity factor = (sum of individual maximum demand)/ (maximum demand).

11. What is Capacity factor?

This is the ratio of actual energy produced to the maximum possible energy that could have been produced during a given period.

Capacity factor= (actual energy produced) / (maximum energy that have been produced)

12. What is Plant use factor?

It is the ratio of units generated to the product of plant capacity and the number of hours for which the plant was in operation. Units generated per annum= average load * hours in a year

13. What is Load duration curve?

When the load elements of a load curve are arranged in the order of descending magnitudes the curve then obtained is called load duration curve.

UNIT-II – REAL POWER FREQUENCY CONTROL

1. What is the major control loops used in large generators?

The major control loops used in large generators are

1. Automatic voltage regulator (AVR)
2. Automatic load frequency control (ALFC).

2. What is the use of secondary loop?

A slower secondary loop maintains the fine adjustment of the frequency, and also by reset action maintains proper MW interchange with other pool members. This loop is insensitive to rapid load and frequency changes but focuses instead on drift like changes which take place over periods of minutes.

3. What is the adv of AVR loop over ALFC?

AVR loop is much faster than the ALFC loop and therefore there is a tendency, for the VR dynamics to settle down before they can make themselves felt in the slower load frequency control channel.

4. What is the diff. between large and small signal analysis?

Large signal analysis is used where voltage and power may undergo sudden changes of magnitude that may approach 100 percent of operating values. Usually this type of analysis leads to differential equations of non-linear type. Small signal analysis is used when variable excursions are relatively small, typically at most a few percent of normal operating values.

5. What is the exciter?

The exciter is the main component in AVR loop. It delivers the DC power to the generator field. It must have adequate power capacity and sufficient speed of response (rise time less than 0.1 sec).

6. What is the function of AVR?

The basic role of the AVR is to provide constancy of the generator terminal voltage during normal, small and slow changes in the load.

7. Write about static AVR loop.

In a static AVR loop, the execution power is obtained directly from the generator terminals or from the station service bus. The AC power is rectified by thyristor bridges and fed into the main generator field via slip rings. Static exciters are very fast and contribute to proved transient stability.

8. Write the static performance of AVR loop.

The AVR loop must regulate the terminal |V| to within required static accuracy limit. Have sufficient speed of response. Be stable.

9. What is the disadvantage of high loop gain? How is to be eliminated?

High loop gain is needed for static accuracy but this causes undesirable dynamic response, possibly instability. By adding series AND/OR feedback stability compensation to the AVR loop, this conflicting situation can be resolved.

10. What are the effects of generator loading in AVR loop?

Added load does not change the basic features of the AVR loop, it will however affect the values of both gain factor Kf and the field constant. High loading will make the generator work at higher magnetic saturation levels. This means smaller changes in |E| for incremental increases in if, translating into the reduction of KF. The field time constant will likewise decreases as generator loading closing the armature current paths. This circumstance permits the formation of transient stator currents the existence of which yields a lower effective field induction.

11. What are the functions of ALFC?

The basic role of ALFC‟s is to maintain desired MW output of a generator unit and assist in controlling the frequency of large interconnection. The ALFC also helps to keep the net interchange of power between pool members at predetermined values. Control should be applied in such a fashion that highly differing response characteristics of units of various types are recognized. Also unnecessary power output changes should be kept at a minimum in order to reduce wear of control valves.

12. Specify the disadvantage of ALFC loop.

The ALFC loop wills main control only during normal changes in load and frequency. It is typically unable to provide adequate control during emergency situations, when large MW imbalances occur.

13. How is the real power in a power system controlled?

The real power in a power system is being controlled by controlling the driving torque of the individual turbines of the system.

14. What is the need for large mechanical forces in speed-governing system?

Very large mechanical forces are needed to position the main valve against the high stream pressure and these forces are obtained via several stages of hydraulic amplifiers

UNIT-III - REACTIVE POWER -VOLTAGE CONTROL

1. What are the sources of reactive power? How it is controlled?

The sources of reactive power are generators, capacitors, and reactors. These are controlled by field excitation. Give some excitation system amplifier. The excitation system amplifiers are,

a) Magnetic amplifier
b) Rotating amplifier
c) Modern electronic amplifier

2. When is feedback stability compensation used?

High loop gain is needed for static accuracy but this causes undesirable dynamic response, possibly instability. This conflicting situation is resolved by adding feedback stabling compensation to the AVR loop.

3. Give the characteristics of line compensators.

The characteristics of line compensators are, a. Ferranti effect is minimized.

b. Under excited operation of synchronous generator is not required.

4. What is known as bank of capacitors? How it is adjusted?

When a number of capacitors are connected in parallel to get the desired capacitance, it is known as bank of capacitors. These can be adjusted in steps by switching (mechanical).

5. What is the disadvantage of switched capacitors are employed for compensation?

When switched capacitors are employed for compensation, these should be disconnected immediately under light load conditions to avoid excessive voltage rise and Ferro resonance in presence of transformers.

6. What are the effects of capacitor in series compensation circuit?

The effects of capacitor in series compensation circuit are, Voltage drop in the line reduces. Prevents voltage collapse. Steady state power transfer increases. Transient stability limit increases.

7. Give two kinds of capacitors used in shunt compensator.

The two kinds of capacitors used in shunt compensator are, a. Static Var Compensator (SVC): These are banks of capacitors (sometimes inductors also for use under light load conditions).

8. What is synchronous condenser?

It is a synchronous motor running at no-load and having excitation adjustable over a wide range. It feeds positive VARs into the line under overexcited conditions and negative VARs when under excited.

9. Write about Static VAR Compensator (SVC).

These comprise capacitor bank fixed or switched or fixed capacitor bank and switched reactor bank in parallel. These compensators draw reactive power from the line thereby regulating voltage, improve stability (steady state and dynamic), control overvoltage and reduce voltage and current unbalances. In HVDC application these compensators provide the required reactive power and damp out sub harmonic oscillations.

10. What is Static VAR Switches or Systems?

Static VAR compensators use switching for var control. These are also called static VAR switches or systems. It means that terminology wise SVC=SVS. And we will use these interchangeably.

11. Give some of the Static compensators schemes.

a. Saturated reactor b. Thyristor- Controlled Reactor (TCR) c. Thyristor Switched capacitor (TSC) d. Combined TCR and TSC compensator.

12. What is tap changing transformers?

All power transformers and many distribution transformers have taps in one or more windings for changing the turn ratio. It is called tap changing transformers.

13. Write the types of tape changing transformers.

a. Off- load tap changing transformers. b. Tap changing under load transformers.

14. What is the use of off-load tap changer and TCUL?

The off- load tap changers are used when it is expected that the ratio will need to be changed only infrequently, because of load growth or some seasonal change. TCUL is used when changes in ratio may be frequent or when it is undesirably to de-energize the transformer to change the tap.

UNIT-IV – COMMITMENT AND ECONOMIC DISPATCH

1. Define economic dispatch problem.

The objective of economic dispatch problem is to minimize the operating cost of active power generation.

2. Define incremental cost.

The rate of change of fuel cost with active power generation is called incremental cost. Write the load balance equation? Pg-pd-pl=0.

3. Define base point.

The present operating point of the system is called base point.

4. Define participation factor.

The change in generation required to meet power demand is called as participation factor.

5. Define hydrothermal scheduling problem.

The objective is to minimize the thermal generation cost with the constraints of water availability.

6. Define unit commitment.

Commitment of minimum generator to meet the required demand.

7. Define spinning reserve.

It is the term describes the total amount of generation availability from all units synchronized on the system.

8. What is meant by scheduled reserve?

These include quick start diesel turbine units as well as most hydro units and pumped storage hydro units that can be brought online, synchronized and brought up to full capacity quickly.

9. What are the thermal unit constraint?

Minimum up time, minimum down time crew constraints.

10. Define minimum up time.

Once the unit is running, it should not be turned off immediately.

11. Define min.down time.

Once the unit is decommited, there is a minimum time before it can be recommended.

12. Define crew constraints.

If a plant consist of two (or) more units, all the units cannot be turned on at the same time since there are not enough crew members to attend both units while starting up.

13. What are the two approaches to treat a thermal unit to operating temperature?

The first allow the unit boiler to cool down and then heat backup to operating temperature in time for a scheduled turn on. The second requires that sufficient energy be input to the boiler to just maintain operating temperature.

14. What are the techniques for the solution of the unit commitment problem?

Priority list method dynamic programming Lagrange relation

15. What are the assumptions made in dynamic programming problem?

A state consists of an array of units with specified units operating and the rest of the time. The startup cost of a unit is independent of the time it has been offline. There are no costs for shutting down the units.

16. Define long range hydro scheduling problem.

The problem involves the long range of water availability and scheduling of reservoir water releases. For an interval of time that depends on the reservoir capacities.

17. What is the optimization technique for long range hydro scheduling problem?

Dynamic programming composite hydraulic simulation methods statistical production cost.

18. Define short range hydro scheduling problem.

It involves the hour by hour scheduling of all generators on a system to achieve minimum production condition for the given time period.

19. Define system blackout problem.

If any event occurs on a system that leaves it operating with limits violated, the event may be followed by a series of further actions that switch other equipment out of service. If the process of cascading failures continues, the entire system of it may completely collapse. This is referred as system blackout.

20. What is meant by cascading outages?

If one of the remaining lines is now too heavily loaded, it may open due to relay action, thereby causing even more load on the remaining lines. This type of process is often termed as cascading outage.

UNIT-V – COMPUTER CONTROL OF POWER SYSTEMS

1. What are the functions of control center?

System monitoring contingency analysis security constrained optimal power flow.

2. What is the function of system monitoring?

System monitoring provides up to date information about the power system.

3. Define scada system.

It stands for supervisory control and data acquisition system, allow a few operators to monitor the generation and high voltage transmission systems and to take action to correct overloads.

4. What are the states of power system?

Normal state alert mode contingency mode emergency mode. Define normal mode? The system is in secure even the occurrence of all possible outages has been simulated the system remain secure is called normal mode.

5. Define alert mode.

The occurrence of all possible outages the system does not remain in the secure is called alert mode.

6. What are the distribution factors?

Line outage distribution factor, generation outage distribution factor.

7. Define state estimation.

State estimation is the process of assigning a value to an unknown system state variable based on measurements from that system according to some criteria.

8. Define max. Likelihood criterion.

The objective is to maximize the probability that estimate the state variable x, is the true value of the state variable vector (i.e, to maximize the P(x) =x).

9. Define weighted least-squares criterion.

The objective is to minimize the sum of the squares of the weighted deviations of the estimated measurements z, from the actual measurement.

10. Define minimum variance criterion.

The objective is to minimize the expected value of the squares of the deviations of the estimated components of the state variable vector from the corresponding components of the true state variable vector.

11. Define must run constraint.

Some units are given a must run status during certain times of the year for reason of voltage support on the transmission network.

12. Define fuel constraints.

A system in which some units have limited fuel or else have constraints that require them to burn a specified amount of fuel in a given time.

13. What are the assumptions made in priority list method?

No load cost is zero unit input-output characteristics are linear between zero output and full load there are no other restrictions startup cost are affixed amount.

14. State the adv of forward DP approach.

If the start up cost of a unit is a function of the unit is a function of the time it has been offline, then a forward dynamic program approach is more suitable since the previous history of the unit can be computed at each stage.

15. State the dis.adv of dynamic programming method.

It has the necessity of forcing the dynamic programming solution to search over a small number of commitment states to reduce the number of combinations that must be tested in each period.

16. What are the known values in short term hydro scheduling problem?

The load, hydraulic inflows & uit availabilities are assumed known. The states of the system were measured and transmitted to a control center by means of telemetry system.

17. What are the functions of security constraints optimal power flow?

In this function, contingency analysis is combined with an optimal power flow which seeks to make changes to the optimal dispatch of generation. As well as other adjustments, so that when a security analysis is run, no contingency result in violations.

18. Define the state of optimal dispatch.

This is the state that the power system is in prior to any contingency. It is optimal with respect to economic operation but may not be secure.

19. Define post contingency.

This is the state of the power system after a contingency has occurred. Define secure dispatch? This is state of the power system with with no contingency outages, but with correction to the operating parameters to account for security violations.

20. What are the priorities for operation of modern power system?

Operate the system in such a way that power is delivered reliably. Within the constraints placed on the system operation by reliability considerations, the system will be operated most economically.

21. What is meant by linear sensitivity factor?

Many outages become very difficult to solve if it is desired to present the results quickly. Easiest way to provide quick calculation of possible overloads is linear sensitivity factors.

22. What are linear sensitivity factors?

Generation shift factors line outage distribution factors.

23. What are the uses of line distribution factor?

It is used to apply to the testing for overloads when transmission circuits are lost.

24. What is meant by external equvalencing?

In order to simplify the calculations and memory storage the system is sub divided into 3 sub systems called as external equvalencing.

16 MARKS

UNIT 1

1. What are the components of speed governor system of an alternator? Derive a transfer function and sketch a block diagram.
2. With neat sketch describe the P-F and Q-V control structure.
3. Briefly discuss the classification of loads and list out the important characteristics of various types of loads.
4. Problem (Load Curve)
5. Explain the method availabilities for providing economic operation of power system.
6. Write short notes on load v curve load duration curve energy curve.
7. Explain about spinning reserve, hot reserve, cold reserve.

UNIT 2

1. Explain load frequency control.
2. Draw the block diagram of LFC control of single area and derive the dynamic response.
3. Develop the block diagram model of uncontrolled two area load frequency control system and explain the salient features under static conditions.
4. Explain Interconnected operation.
5. Explain the solution technology for solving priority list method by dynamic programming method.
6. Explain the static state estimation of power system.

UNIT 3

1. Draw the circuit diagram for a typical excitation system and derive the transfer function model and draw the block diagram.
2. Discuss generation and absorption of reactive power.
3. Explain different types of static VAR compensators with a phasor diagram.
4. Discuss about the various methods of voltage control.
5. Derive the relations between voltage, power and reactive power at a node for applications in power system control.

UNIT 4

1. Derive the coordination equation with losses neglected.
2. Derive the coordination equation of an ‘n’ bus power system taking into account the effect of system losses.
3. Derive the expression for base point and participation method.
4. State the unit commitment problem. With the help of flowchart explain forward dynamic programming solution method.
5. Explain Priority list method using full Load average production cost. State the merits and demerits.
6. Numerical problems in economic dispatch & unit commitment

UNIT 5

1. Briefly discuss the various functions of energy control centre.
2. Explain the different operating states of power system with state transition diagram.
3. Explain the hardware components of SCADA with neat diagram and also mention the functions of it.
4. Explain about power system security
5. What is EMS? What are its major functions in power system operation and control?

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE3001- UTILIZATION AND CONSERVATION OF ELECTRICAL ENERGY

SEMESTER V

REGULATIONS 2021

NOTES

&

QUESTION BANK

EE3001 UTILIZATION AND CONSERVATION OF ELECTRICAL ENERGY LT P C 3 0 0 3

COURSE OBJECTIVES:

- To know various electric drives and traction motors with applications
- To introduce the energy saving concept by different ways of illumination.
- To understand the different methods of electric heating and electric welding.
- To know the conversion of solar and wind energies into electrical energy for different applications.
- To study the domestic utilization of electrical energy.

UNIT I ELECTRIC DRIVES AND TRACTION (7+2 Skill) 9

Fundamentals of electric drive - choice of an electric motor - application of motors for particular services traction generator set, traction motors, power transformers - characteristic features of traction motor - systems of railway electrification - electric braking - train movement and energy consumption - traction motor control - track equipment and collection gear.

UNIT II ILLUMINATION (7+2 Skill) 9

Introduction - definition and meaning of terms used in illumination engineering - classification of light sources - incandescent lamps, sodium vapour lamps, mercury vapour lamps, fluorescent lamps – design of illumination systems - indoor lighting schemes - factory lighting halls - outdoor lighting schemes - flood lighting - street lighting - energy saving lamps, LED

.UNIT III HEATING AND WELDING (7+2 Skill) 9

Introduction - advantages of electric heating – modes of heat transfer - methods of electric heating - resistance heating - arc furnaces - induction heating - dielectric heating - electric welding – types - resistance welding - arc welding - power supply for arc welding - radiation welding.

Unit IV ENERGY CONSERVATION AND ITS IMPORTANCE (7+2 Skill) 9

Energy conservation act 2001 and its Features-Review of Industrial Energy Conservation-Energy conservation in electrical Industries-Simulation study of energy conservation using power factor controller. (Three phase circuit simulation with and without capacitor)

UNIT V DOMESTIC UTILIZATION OF ELECTRICAL ENERGY (7+2 Skill) 9

House wiring - working principle of air conditioning system, Induction based appliances, Online an OFF line UPS, Batteries - Power quality aspects – nonlinear and domestic loads – Earthing syste for Domestic, Industrial and Substation.

TOTAL: 45 PERIODS

SKILL DEVELOPMENT ACTIVITIES (Group Seminar/Mini Project/Assignment/Conte Preparation/Quiz/Surprise Test/Solving Problems) 10

1. Choosing electrical motors for drives and traction applications.
2. A general design procedure for lighting schemes.
3. Design of heating element and study of welding methods.
4. Practical case studies of energy conservation.
5. Power requirement for different domestic appliances.

COURSE OUTCOMES:

At the end of the course, students should have the:

CO1 Ability to choose suitable electric drives for different applications

CO2 Ability to design the illumination systems for energy saving

CO3 Ability to demonstrate the utilization of electrical energy for heating and welding purposes

CO4 Ability to know the effective usage of solar and wind energies for electrical applications

CO5 Ability to do electric connection for any domestic appliance like refrigerator, batte charging circuit for a specific household application.

CO6 To illustrate the need for energy conservation and to simulate three phase pow control.

TEXT BOOKS:

1. N.V. Suryanarayana, "Utilisation of Electric Power", Wiley Eastern Limited, New Ag International Limited, 1994 & Second Edition 2017 Feb.
2. J.B.Gupta, "Utilisation Electric power and Electric Traction", S.K.Kataria and sons, 200 2012th Edition, 2013, January.
3. G.D.Rai,"Non-Conventional Energy sources",Khanna publications Ltd.,New Delhi 1998
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5. Industrial Energy Conservation, Volume I-II, S C Bhatia, Sarvesh Devraj, Energy conservation and Managment by Akshay A pujara1st edition, June 2018.

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1. R.K.Rajput, Utilisation of Electric Power, Laxmi publications 2nd Edition 2016.
2. H.Partab, Art and Science of Utilisation of Electrical Energy", Edition, Dhanpat Rai and Co

Jan 18
May 18

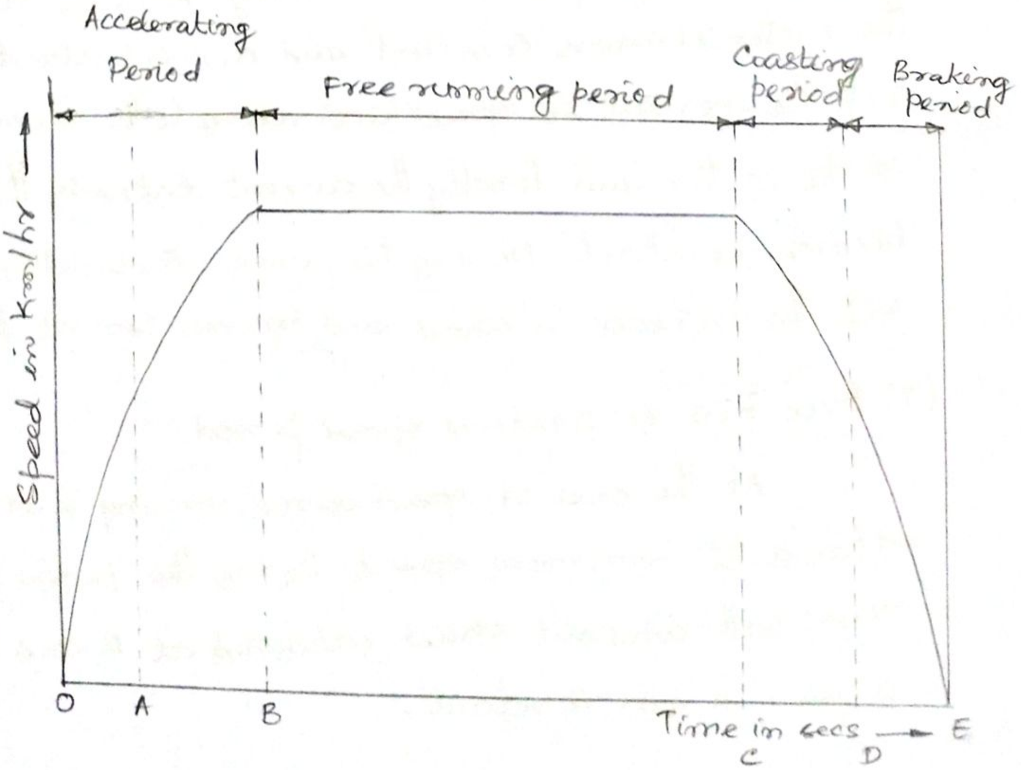
Speed-time curve for train movement:

The movement of the train and their energy consumption can be studied by means of speed-time and speed distance curves, which shows the speed at different time instants after start of run and speed at different distances from the starting point respectively. Of the two, the speed-time curve is generally used.

The curve drawn between speed in km/hr along Y axis and time in seconds along x-axis is called speed-time curve. The speed-time curve gives the complete information about the motion of the train.

This curve gives the speed at various time instants after the start of run directly. Slope of the curve at any point gives the speed at that instant. The area under the curve gives the total distance travelled by the train. Figure shows a typical speed-time curve for a main line service.

Typical speed-time curve



The speed time curve consists of

(1) Acceleration period

(2) Free running (or) Constant speed period

(3) Coasting period

(4) Braking period

(1) Acceleration period:

It consists of two parts

(a) Constant acceleration (or) acceleration while notching up

(b) Speed curve running (or) acceleration on speed curve

(a) Constant acceleration (or) acceleration during notching up:

During constant acceleration period (OA), the current is maintained approximately constant and the voltage across the motor is gradually increased by cutting out the starting resistance. The tractive effort is constant and therefore acceleration remains constant during this period.

(b) Speed curve running (or) acceleration on speed curve:

During speed curve running (AB), the voltage across the motor remains constant and current starts decreasing with the increase in speed according to the characteristics of the motor and finally the current taken by the motor becomes constant. During this period acceleration decreases with the increase in speed and becomes zero at point B.

(2) Free run (or) constant speed period:

At the end of speed curve running i.e at B, the train attains the maximum speed. During this period, the train runs with constant speed attained at B and the power drawn is also constant.

(3) Coasting period:

At the end of the free running period i.e, at C, power supply to the motor is cut off and the train is allowed to run under its own momentum. The speed starts decreasing because of resistance to the motion of train. The rate of decrease of speed during coasting period is known as "coasting retardation".

(4) Retardation (or) Braking period:

At the end of coasting period i.e, at D, the brakes are applied to bring the train to rest. During this period, the speed rapidly decreases and finally comes to zero.

Types of speed in Traction:

(1) Crest speed:

The maximum speed attained by the train during the run is known as "crest speed".

(2) Average speed:

It is the ratio of distance covered between two stops divided by the actual time of run.

$$\text{Average speed} = \frac{\text{Distance between 2 stops}}{\text{Actual time of run}}$$

(3) Schedule speed:

The ratio of distance covered between 2 stops and total time of run including time of stop is known as "Schedule speed."

$$\text{Schedule speed} = \frac{\text{Distance between 2 stops}}{\text{Actual time of run + stop time}}$$

Characteristic features of Traction motor:

Mechanical features:

(1) A traction motor must be mechanically strong and robust.

(2) It should be capable of withstanding severe mechanical vibrations.

(3) The traction motor should be light in weight and it should occupy small space.

(4) The traction motor must be totally enclosed type, to avoid entering of dust, water, etc.

(5) The overall diameter of motor must be small.

Electrical features:

(1) High starting torque → motor to develop high T_{st}

(2) Simple speed control → motor speed control should be simple

(3) Possibility of Dynamic (or) Regenerative breaking

(4) capability of withstanding voltage fluctuation
The motor must be ↑ without affecting its performance.

(5) Overload capacity → It should be capable of taking excessive load

(6) Parallel running → In traction work, 2 or 4 motors per car are required. Its characteristics should be such that they share the load almost equally.

System of Railway electrification (or) Supply system for traction:

Based on the available supply, the track electrification systems are classified as

(1) DC system

(2) 1Φ A.C. System

(3) 3Φ A.C. System

(4) Composite system

(a) 1Φ to DC system

(b) 1Φ to 3Φ system

D.C. system:

* The motor selected should be able to operate on DC supply. Examples for such vechicles operating on DC supply are tram ways and trolly buses.

* DC Series motors are used in tram ways and trolly buses. The operating voltages of DC system are 600V, 750V, 1500V and 3000V.

* The voltages at 600-750V is universally employed for tramways in the urban area and for suburban, main line railways 1500-3000V is used.

* The DC supply for traction motor can be obtained from substations equipped with rotary converters (or) thyristor converters.

Single phase A.C. system:

* In this system, usually AC series motors are used. The distribution voltage is normally between 15-25KV at a frequency of 16.7 Hz or 25 Hz.

* The main reason for operating at reduced frequency in AC series motor is that it is more efficient at low frequency.

* The high voltage is stepped down to low voltage of 300-400 V with the help of step down transformers.

* Also low frequency operation of transmission lines reduces the line reactance and also the voltage drop. 1ϕ AC system is mainly used for main line service.

Three phase AC system:

* In this system, usually 3ϕ Induction motors are used. The operating voltage of induction motor is 3000 to 3600 V at 50 Hz or 16.7 Hz.

* The reasons for using 3ϕ induction motors are

(1) Simple and robust construction
(2) high efficiency
(3) Automatic regenerative breaking.

In addition to the above advantages, the induction motors suffer from the following draw backs

(1) Low starting torque
(2) high starting current
(3) Absence of speed control

The 3ϕ AC system is mainly adopted for the services where the output power required is high and regeneration of electrical energy is possible.

Composite System:

It is classified into two types

(a) Single phase AC to DC system
(b) 1ϕ AC to 3ϕ AC system (or) Kando system

Single phase AC to DC system:

In this system, the advantages of both 1ϕ and DC systems are combined to get high voltage for distribution in order to reduce the losses, and DC series motor is used for producing the necessary torque. Also, 1ϕ AC distribution network results in minimum cost with high transmission efficiency.

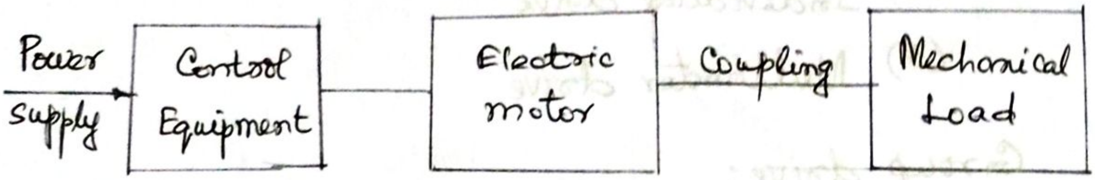
Normal operating voltage employed for distribution is 25 KV at normal frequency of 50Hz. This type of track electrification is used in India.

1φ to 3φ system (or) Kando system:

In this system, 1φ AC is used for distribution network, since 1φ distribution system is cheap. 3φ induction motors are used as traction motors because of their simple and robust construction.

The voltage used for distribution network is about 15-25 KV at 50Hz. This single phase supply is converted to 3φ supply with the help of phase converters. The high voltage is stepped down to low voltage using step down transformers to feed the 3φ induction motor.

Basic elements of an electric Drive:



Many industrial equipments driving a load need a prime mover. Some of the prime movers are turbines, diesel engine. But most commonly used prime mover is an electric motor. The main advantage of an electric motor is, its various characteristics like speed-torque, speed current, etc which can be adjusted by a suitable control equipment. The operating conditions of an electric motor can be changed as per the load demand with the help of control equipment. Also, electric motors can be changed as per the load demand have a good starting torque and can be started on load. Some industrial equipments need very precise speed control. With the help of an electric motor such a speed control upto the accuracy of 1% also can be achieved, using a suitable control equipment. Also, Electric motors are easy to maintain.

A control equipment consists of contactors, relays switches and electronic devices like diodes, transistors and thyristors.

Advantages of an Electric Drive:

(1) Easy speed control

(2) Electric braking can be employed in easy manner.

(3) The operation is pollution free.

(4) The efficiency is higher.

(5) Most of the electric drives are self starting.

(6) Compared to other prime movers, noise is less in electric drives and lower maintenance.

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Types of Electric drives (or) Classification of electric drives

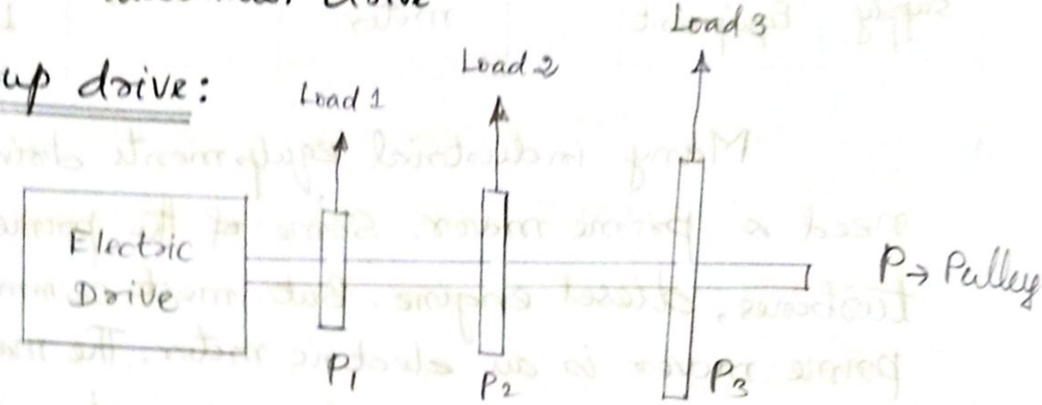
Electrical drives are classified into 3 types, namely

(1) Group drive

(2) Individual drive

(3) Multimotor drive

Group drive:



This type of drive consists of only one electric motor which drives several machines. Such a system were many machines are drived on one shaft and driven by a single electric motor is called a group drive.

Now, the various machines connected to same shaft may require different speeds. This is possible with multi stepped pulleys and belts. The main advantage of this drive is that the rating of an electric drive can be smaller than sum of the ratings of all the machines connected to the shaft.

Disadvantages:

(1) more power loss

(2) Low efficiency

(3) The system is unsafe.

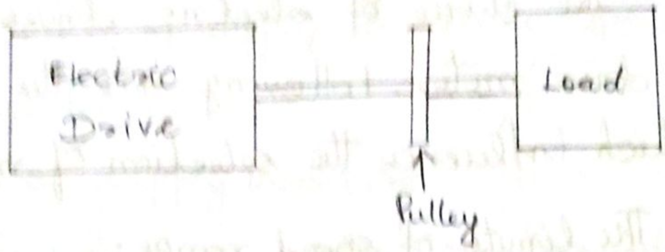
(4) Noise produced is much higher.

(5) If there is any fault in the motor, all the equipments become idle.

Example: Motor (or) drives used in floor/rice mills.

Nov 2018 (2) ① What are the ...

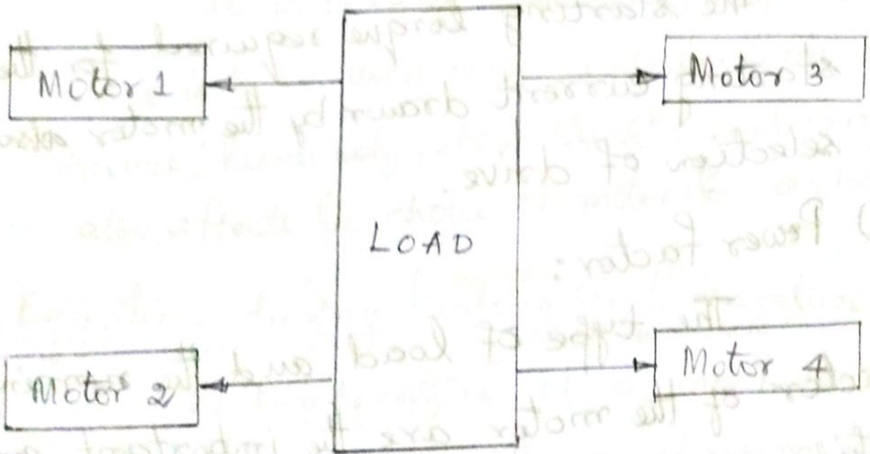
Individual drive:



If, a single motor is used to drive a single machine (Load) and all the connected mechanisms belonging to the same machine then the system is called individual drive. The best example for such drive is a lathe machine.

In lathe machine, a single motor drives a shaft, moves the feed and also drives cooling and lubricating pumps. In some cases, a load and the motor form a single unit. If some parts require different speeds, the gear arrangement is used.

Multimotor drive:



This type of drive has more than one motor for each working machine (Load). Each motor is used to drive only one of the many working mechanisms. Such a system facilitates automatic control for each mechanism and increases the overall productivity.

Example: Cranes, Conveyor belts and rolling mills.

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Factors influencing the choice of Electrical drives:

The choice of electric drives means the selection of drive motor. Following are the various factors which influence the selection of motor to drive the load

(1) The limits of speed range:

The range of speed control requirred for the load. The speed regulation also affects the choice of motor.

(2) Efficiency:

The motor effeciency varies as load varies. So the efficiency under variable speed operation affects the choice of motor.

(3) Braking:

Easy and effective braking are the require-ments of a good drive. (Also quick & reliable)

(4) starting requirements:

The starting torque required for the load & the starting current drawn by the motor also affects the selection of drive.

(5) Power factor:

The type of load and the running power factor of the motor are the important considerations while selecting a drive motor.

(6) Load factor:

The load factor gives how much time the motor is in operation contenuously. The load factor and duty cycle of the motor influences the selection of drive

(7) Availability of supply:

The motors available are ac or dc motors. But the availability of supply decides the type of motor to be selected for the drive.

(8) Effects of supply variations:

There is a possibility of frequent supply variations. The motor selected must be able to withstand such supply variations.

(9) Economical aspects:

The size and rating of motor decides its initial cost. While the various losses and temperature rise decides its running cost. These economical aspects must be considered while selecting a drive.

(10) Reliability of operation:

It is important to study stable operation of an electric drive. This includes the reliability of operation of an electric drive.

(11) Environmental effects:

It is possible that the atmosphere where an electric drive is to be used may contain some chemical gases, fumes, humidity, etc.. Such a contaminated atmosphere also affects the choice of motor for a drive.

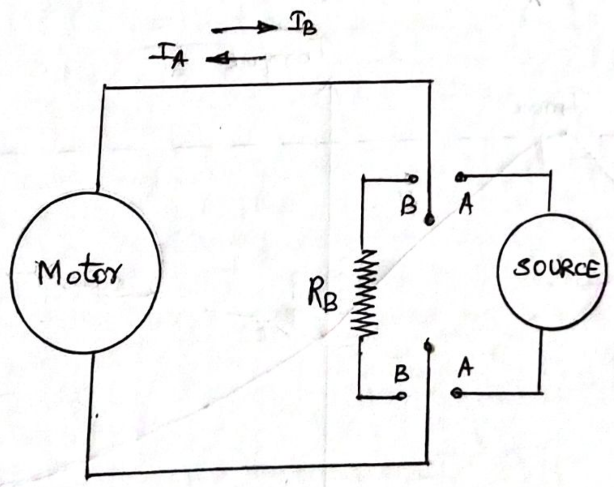
Braking of an Induction motor:

The mechanical brakes (or) electric brakes can be used to bring an electric motor to rest quickly. But with mechanical brakes, smooth stop is not possible. Also, the linings, levers and other mechanical arrangements are necessary to apply mechanical brakes. Mechanical brakes also depends on the skill of the operator. Whereas, an electric braking is easy and reliable, hence it is used to stop the induction motors very quickly. Eventhough, the motor is brought to rest electrically, to maintain its state of rest, a mechanical brake is must.

There are 3 different types of braking

(1) Dynamic (or) Rheostatic braking
(2) Plugging (or) Reverse current braking
(3) Regenerative braking.

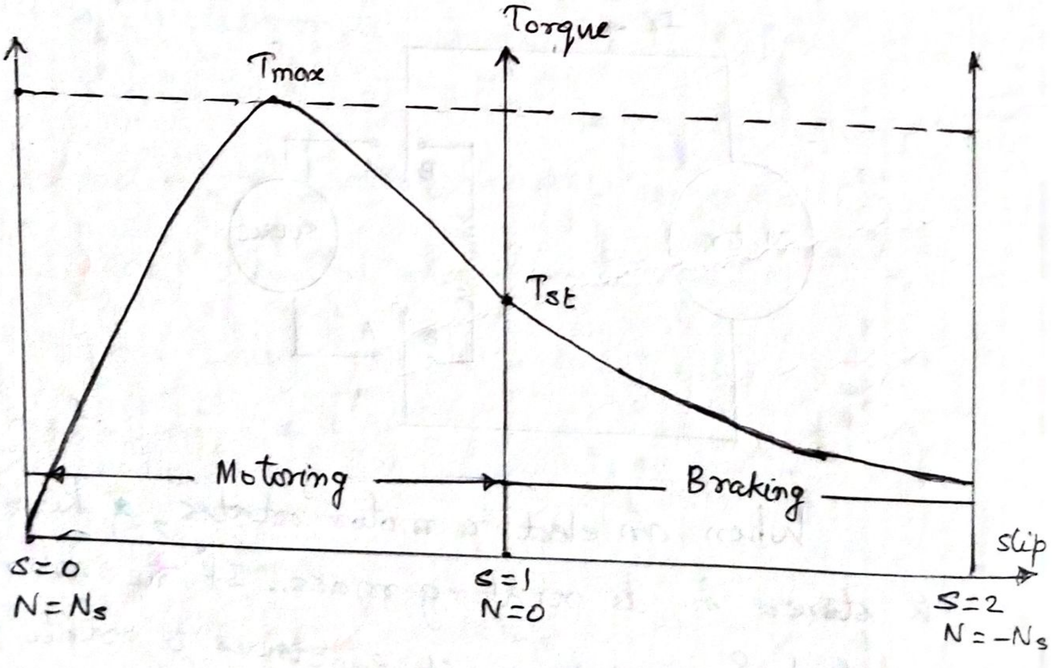
Dynamic (or) Rheostatic braking:



When an electric motor rotates, kinetic energy is stored in its rotating mass. If the motor is disconnected from supply, it continues to rotate for a period of time until the kinetic energy is totally dissipated in the form of rotational losses. The faster the dissipation of the kinetic energy, the more rapid is the braking.

During the dynamic braking, the kinetic energy of the motor is converted into electrical energy. This energy is dissipated in resistive elements. A circuit for rheostatic braking is shown in figure. When the machine is connected to terminal A, it runs as a motor. While the motor is rotating, kinetic energy is stored in its rotating mass. When the machine is connected to terminal A, power flows from source to motor.

If the terminals of the motor is disconnected from the source and connected to the terminal B, the braking resistance R_B is connected across the motor terminals. The energy stored in the rotating mass is dissipated in the braking resistance R_B. The current I_B flows from motor to braking resistance. If the value of resistor is smaller, the energy dissipated is faster and braking is also faster.

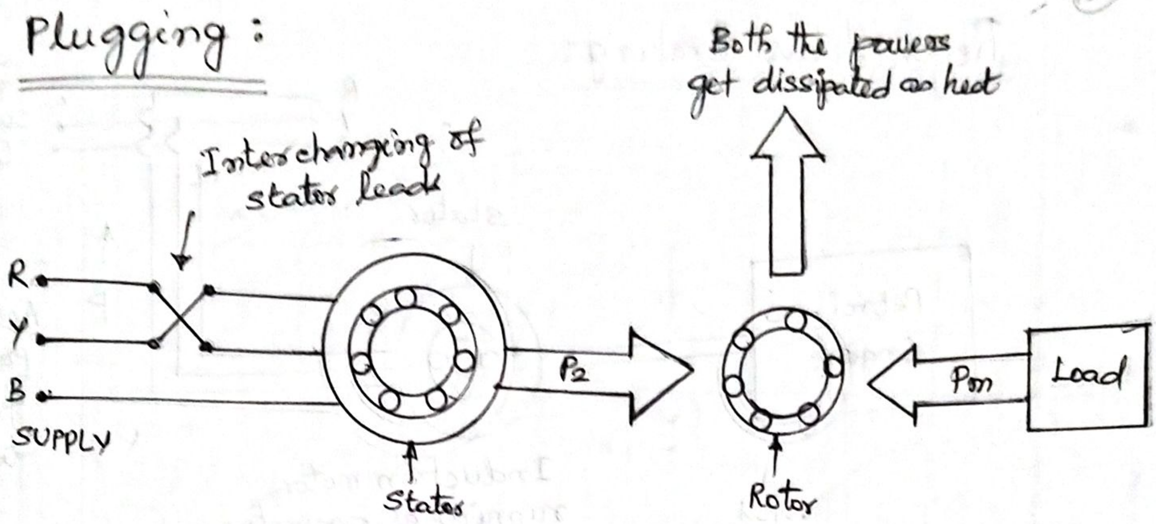


Torque-slip characteristics

Note:

Dynamic braking is used mainly in crane.

Plugging :

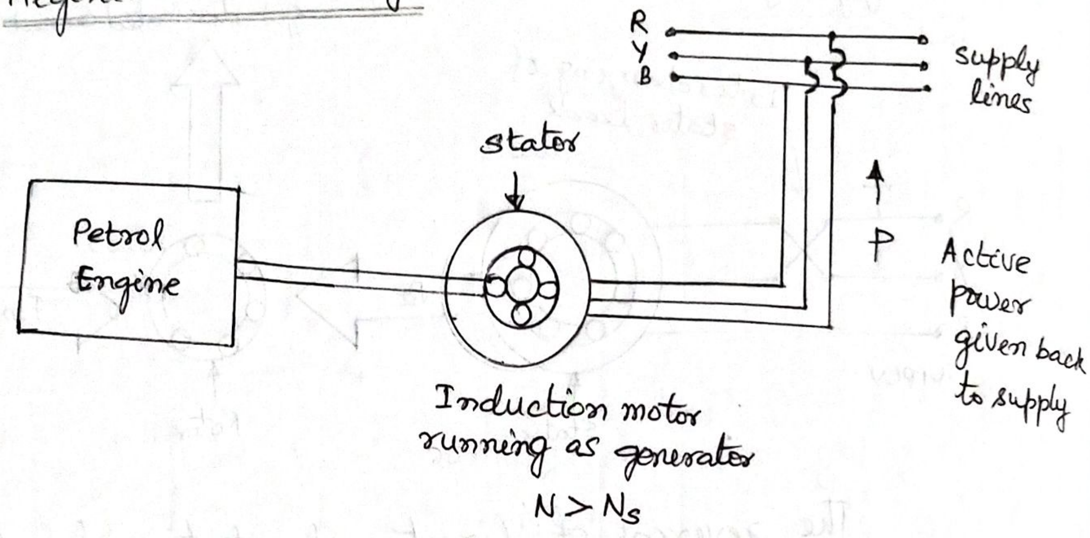


The reversal of direction of rotation of motor is the main principle in plugging of motor. In case of induction motor, it can be quickly stopped by interchanging any two stator leads. Due to this, the direction of rotating magnetic field gets reversed suddenly. This produces a torque in the reverse direction and the motor tries to rotate in opposite direction. Effectively the brakes are applied to stop the motor.

One important aspect about plugging is production of very high heat in the rotor. While plugging, the load keeps on revolving and the rotor absorbs kinetic energy from the revolving load causing speed to reduce. The corresponding mechanical power P_m is entirely dissipated as heat in the rotor. Since, the stator is connected to supply, rotor continues to ~~rotate~~ receive power P_2 from stator which also gets dissipated as heat in the rotor.

The plugging should not be done frequently as due to high heat produced, the rotor may attain high temperature which can melt the rotor bars and even may over heat the stator as well.

Regenerative Braking:



The input power to a 3ϕ induction motor is gn by

$$P_{in} = 3 V_{ph} I_{ph} \cos\phi$$

V_{ph}, I_{ph} - Phase voltage & phase current

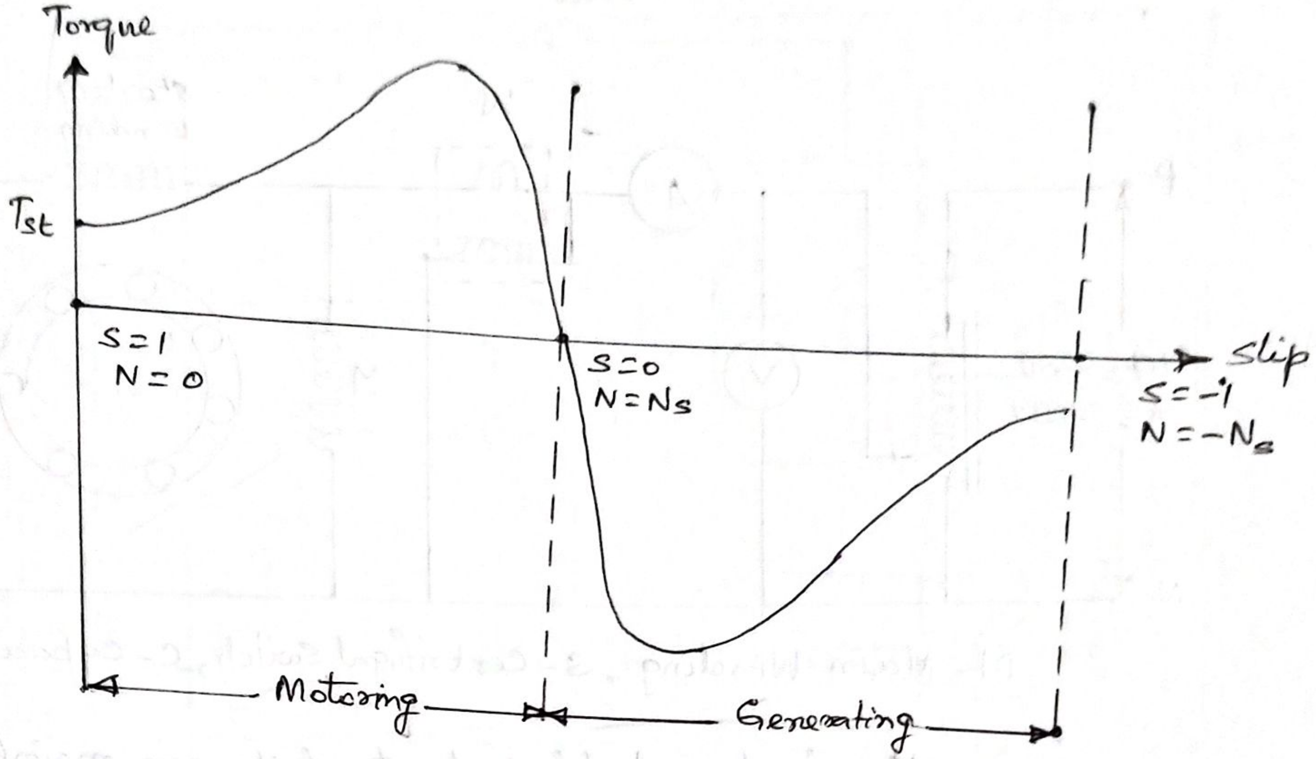
ϕ - angle between V_{ph} and I_{ph}

The value of ϕ is less than 90° for motoring action.

If the rotor speed is increased greater than the synchronous speed with the help of external device (Petrol engine), it acts as an induction generator. It converts the input mechanical energy to electrical energy which is given back to the supply lines. It delivers active power to the 3 phase line. The angle ϕ becomes greater than 90°. Since, the power flow reverses, the rotor induced emf and rotor current directions also reverses. So, the rotor produces torque in the opposite direction to achieve the braking. Since, the electrical energy is given back to the supply lines while braking, it is called regenerative braking.

(P.T.O.)

Torque-slip characteristics of Regenerative Braking (Next Page)


Torque
Tst
S=1
N=0
S=0
N=Ns
Slip
S=-1
N=-Ns
Motoring
Generating

Unit – 2 ILLUMINATION

Definitions used in Illumination Engineering

1. Luminous Flux:

It is defined as the total quantity of **light energy emitted per second** from a light source.

Luminous Flux, $\Phi = \frac{Light\ Energy\ (Q)}{Time\ in\ Seconds\ (t)}$

2. Lumen:

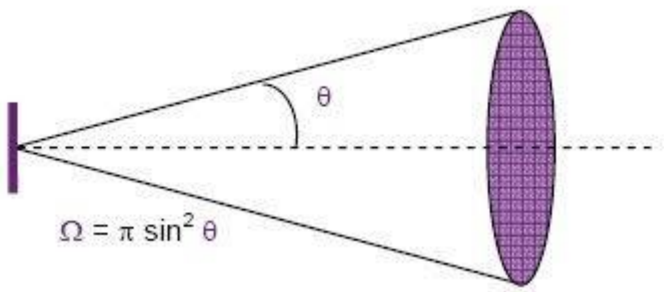
The lumen is the unit of luminous flux. It is the **amount of luminous flux emitted by a source** of one candle power in a unit solid angle.

Lumens = Candle power x solid angle.

3. Candle Power:

It is defined as the **number of lumens given out by the source** in a unit solid angle in a given direction. It is denoted by CP.

Candle power = $\frac{Lumens}{Solid\ Angle}$



4. Illumination:

When the light falls upon any surface, the phenomenon is called illumination. It is defined as the **number of lumens falling on the surface per unit area.**

Illumination, E = $\frac{Lumens(F)}{Area\ (A)}$

5. Luminous Intensity:

The amount of **light output falling on unit square metre** of surface is called luminous intensity. The unit of luminous intensity is Lux (Lumens per square metre)

6. Mean Horizontal Candle Power: (MHCP)

The **mean of candle power in all directions in the horizontal plane** containing the source of light is called mean horizontal candle power.

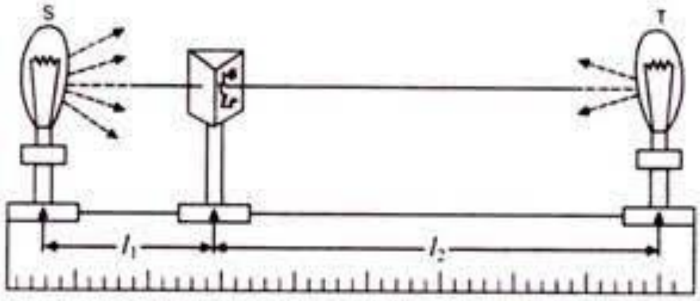


Fig. 7.21. *Measurement of Candle Power*

7. Mean Spherical Candle Power: (MSCP)

The **mean of candle power in all directions in all planes** from the source of light is called mean spherical candle power.

8. Mean Hemi Spherical Candle Power: (MHSCP)

The **mean of candle power in all directions above or below the horizontal plane** passing through the source of light is called mean hemi spherical candle power.

9. Reduction factor:

It is the ratio of mean spherical candle power to the mean horizontal candle power of a source of light.

Reduction factor = $\frac{MSCP}{MHCP}$

10. Utilisation Factor:

It is the ratio of total lumens reaching the working plane to the total lumens given out by the lamp.

Utilisation Factor = $\frac{\text{Total lumens reaching the working plane}}{\text{Total lumens given out by the lamp}}$

11. Depreciation Factor:

It is the ratio of initial light output to the ultimate maintained light output on the working plane. Its value is more than one.

12. Waste light factor:

Whenever a surface is illuminated by a number of sources of light, there is always a certain amount of waste of light on account of overlapping and falling of light outside the surface.

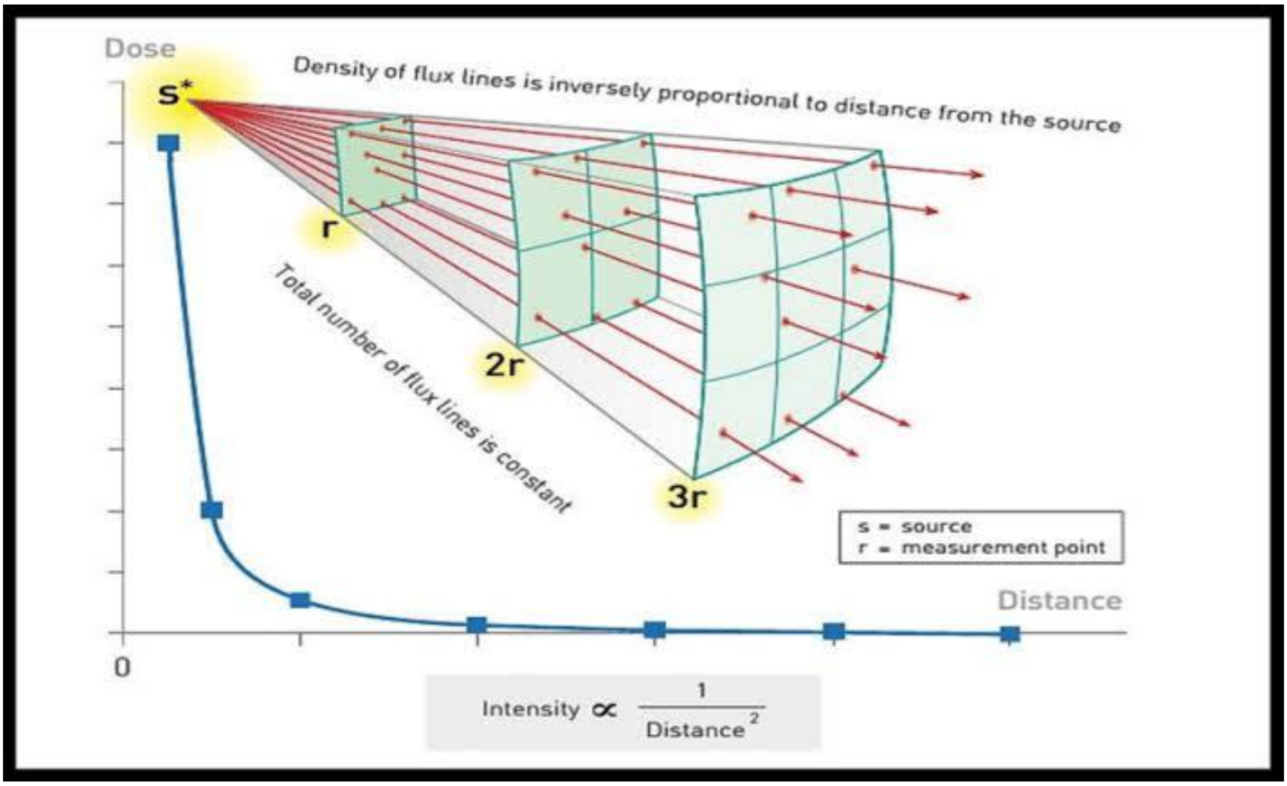
The effect is taken into account by multiplying the theoretical value of lumens required by 1.2 for rectangular areas and 1.5 for irregular areas.

LAWS OF ILLUMINATION:

There are two laws of illumination, namely

1. Law of inverse squares
2. Lambert's cosine law

Law of inverse squares:



Illumination at a point is inversely proportional to square of its distance from the point source and directly proportional to the luminous intensity (CP) of the source of light in that direction.

Lambert’s cosine law:

$$\frac{AB}{AC} = \frac{1}{\cos\theta}$$

and the illumination decreases in the ratio $\frac{\cos\theta}{1}$.

Fig. 7.6 (*b*). ***Lambert’s Cosine Law***

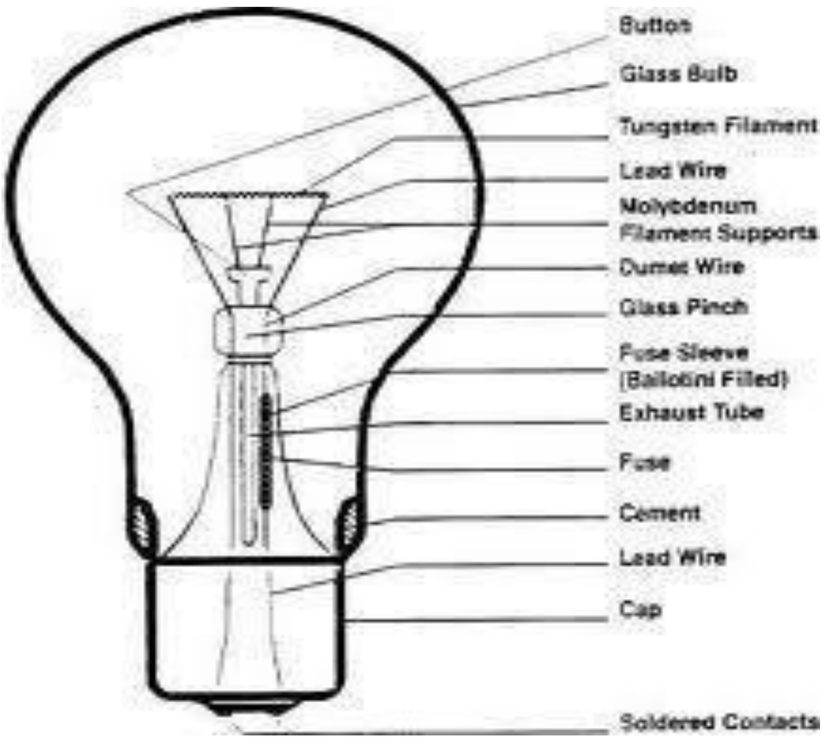
The expression for the illumination then becomes

$$E = \frac{I\cos\theta}{r^2}$$

The illumination at a point on a surface is proportional to cosine of the angle which ray makes with the normal to the surface at that point.

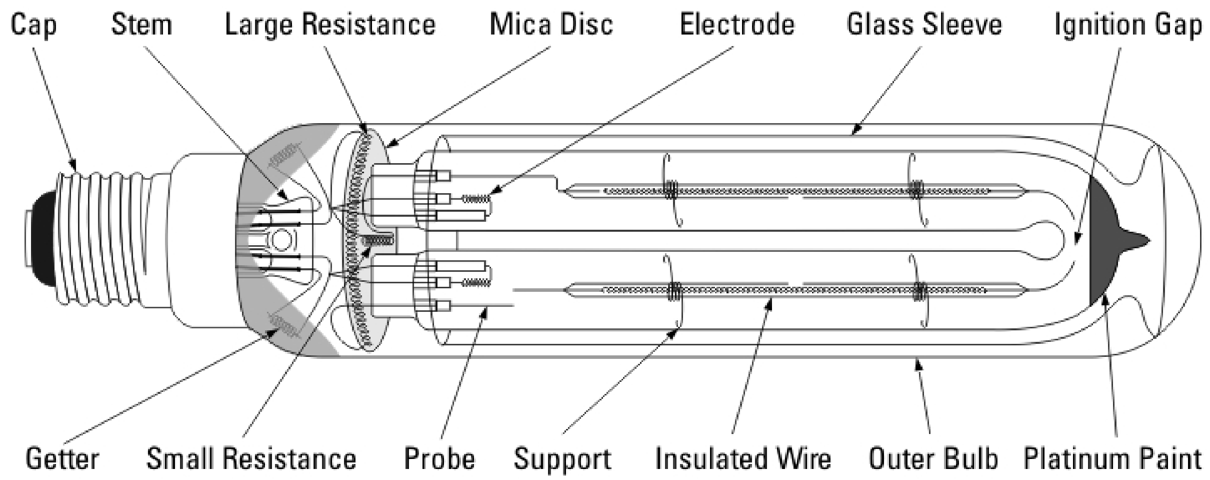
INCANDESCENT LAMP:

- **Available in 25W, 40W, 60W,75W, 100W, 150W, 200W, etc.,**



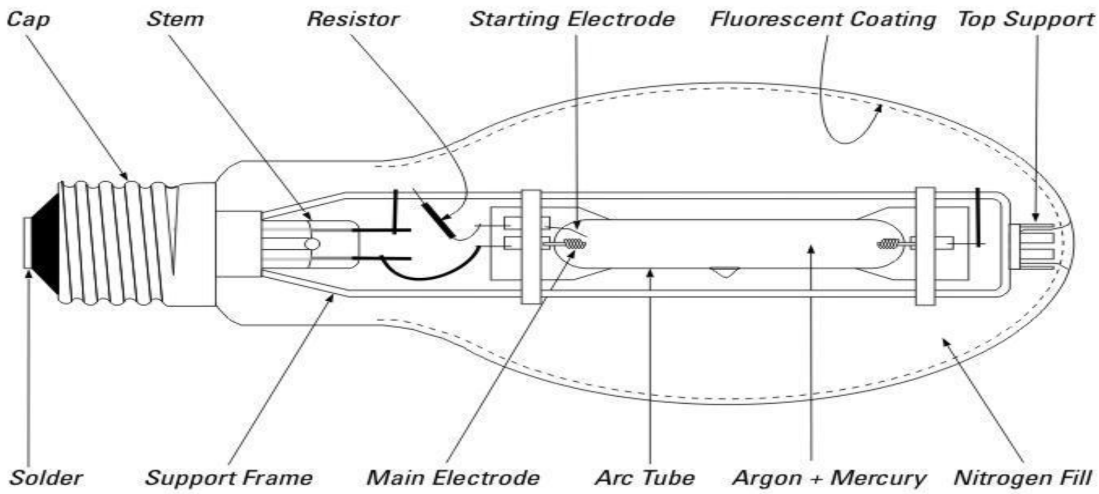
- Incandescent means producing visible light by heating an object.
- Hence, it Produces light by heating a metal filament wire to a high temperature until it glows.
- The hot filament is protected from oxidation in the air with a glass enclosure that is filled with inert gas or evacuated.
- Most bulbs are used in a socket which provides mechanical support and electrical connections.
- Incandescent bulbs are manufactured in a wide range of sizes, light output, and voltage ratings, from 1.5 volts to about 300 volts.
- They require no external regulating equipment, have low manufacturing costs, and work equally well on either alternating current or direct current.
- It is widely used in household and commercial lighting, for portable lighting such as table lamps, car headlamps, and for decorative and advertising lighting.
- Some applications of the incandescent bulb use the heat generated by the filament, such as incubators, heat lights for reptile tanks, for industrial heating and drying processes.

SODIUM VAPOUR LAMP:



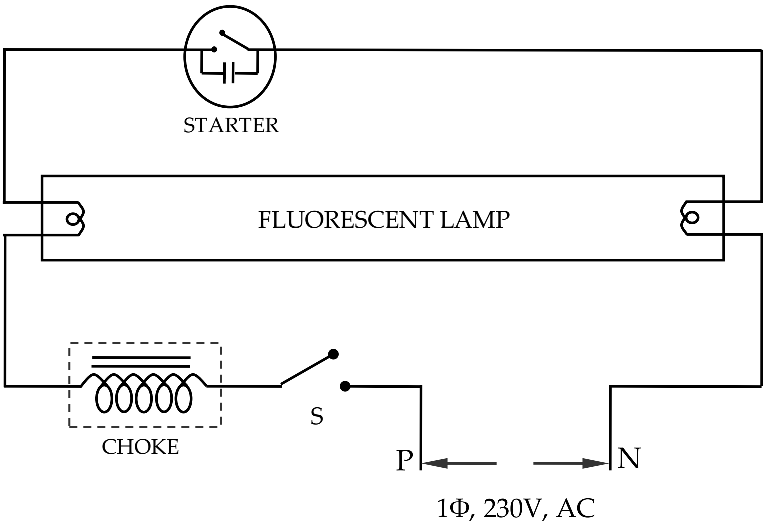
- Sodium along with small quantity of neon or argon gas is filled in the inner tube.
- Such lamps are manufactured in 45, 60, 85 and 140 W ratings
- The average life is about 24000 hours and is not affected by voltage variations.
- The major application of this type of lamp is for highway and general outdoor lighting where colour discrimination is not required, such as street lighting, parks, rail yards, storage yards etc.
- Higher voltage is required to initiate the arc. An igniter is used for this purpose.
- The lamp takes 5 to 10 minutes to give full brightness.

MERCURY VAPOUR LAMP:



- It consists of an inner quartz arc tube and outer borosilicate glass envelope.
- The inner quartz tube is able to withstand an arc temperature of 1300˚K
- The outer tube is able to withstand only 700˚K
- Between 2 tubes nitrogen gas is filled to provide thermal insulation
- The arc tube contains the mercury and argon gas.
- Its operational function is same as fluorescent lamp.
- 2 main electrodes and 1 starting electrode are inside the arc tube.
- When the supply voltage is given to the mercury lamp, this voltage comes across the starting electrode and the adjacent main electrode as well as across 2 main electrodes.
- As the gap between main electrode and starting electrode is small, the voltage gradient is high.
- Because of this high voltage gradient, a local argon arc is created, but the current gets limited by a starting resistor.
- The initial arc heats up the Mercury and vaporizes it and this mercury vapour helps to strike the main arc soon.
- The resistance of the main arc current control resistor is less than the resistance in the initial arc.
- For this reason initial arc stops and main arc continuous to operate. It takes 5-7 minutes to make all of the mercury to be vaporized completely.

FLUORESCENT LAMP:



Fluorescent lamp consists of a long tube coated inside with phosphor powder (White Colour). The gas present inside is mercury and argon at low pressure. In order to make a tube light self starting a starter and choke is connected in the circuit as shown. The choke is used to increase the voltage to almost 1000 V at the time of starting, while glowing it controls the rate of change of current. The purpose of starter is to produce high rate of change of current which induces high voltage in the inductance by means of breaking and making the circuit (reason for flickering).

WORKING:

The lamp, an iron cored choke and a starter are connected in series. When the switch is closed, current flows and glow discharge heats up the bimetallic strips of the starter which bend to close the contacts. This closure of the contacts tends to short circuit the glow discharge and as the bimetallic strips cool down, the contacts are opened. This making and braking of the circuit, induces a high voltage (nearly 1000) causing an arc to strike between the electrodes of the tube. Once the arc is struck, a small voltage is enough to maintain it.

OUT DOOR LIGHTING:

There are two types of outdoor lighting

1. Street Lighting
2. Flood Lighting

STREET LIGHTING:

The main purpose of street lighting are

1. For safety and convenience in streets at nights through adequate visibility
2. To increase the attractiveness of the streets
3. To increase community value of the streets
4. The obstructions on the road are clearly visible to the drivers of the vehicles

Requirements of street lighting are

1. The level of illumination has to be low for economic reasons
2. Colour of the objects is not important
3. There should be no glare as far as possible
4. The mounting height of the light **is 8 m**
5. The standard spacing between the lamps is **50 m**
6. Mercury vapour and Sodium vapour lamps are used for street lighting
7. Illumination required for different areas of street lighting are

Road junctions & Important shopping centres	-	30 lumens / m^2
Sub urban Streets	-	4 lumens / m^2
Average well lighted streets	-	8-15 lumens/m^2

FLOOD LIGHTING:

- Flood lighting means flooding of large surfaces with light from powerful projectors
- A special reflector and housing is employed in flood lighting in order to concentrate the light emitted from the lamp into a relatively narrow beam, which is called Flood light projector.
- This projector consists of a reflecting surface that may be a silvered glass or stainless steel.
- The efficiency of silvered glass is about 85 to 90 %

1. Aesthetic Flood lighting:

- For enhancing beauty of buildings at night such as public places, ancient buildings and monuments, religious buildings on festive occasions.

2. Industrial and Commercial Flood lighting:

- For illuminating railway yards, sports stadiums, car parks, construction sites, quarries.

3. Advertising:

- Flood lights are used for advertisement boards and for the decoration of houses, etc.,
- For Flood lighting ground surfaces, the lamps are placed at sufficient heights on poles. The main consideration is to reduce glare.

Types of Flood lighting:

(1) Enclosed type

It consists of a lamp with reflector both being placed inside a metal case fitted with glass plate. This is very expensive, but beam can be accurately controlled.

(2) Open Type

It is less costly and suitable for direct lighting. The reflector throws light in horizontal and downward directions. The reflector does not protect the lamp from rain, etc.,

ENERGY SAVING LAMPS:

- Energy saving lamps are sources of artificial light that employ advanced technology to reduce the amount of electricity used to generate light compared to filament bulbs (incandescent lamps).
- Examples of Energy saving lamps are
    1. Fluorescent lamps – Regular & Compact
    2. Light Emitting Diodes (LED)
- Light Emitting Diodes and Compact Fluorescent lamps have revolutionized energy efficient lighting
- CFLs are miniature versions of full sized fluorescent lamps. They screw into standard lamp sockets.
- LEDs are very small, very efficient solid bulbs. LED technology is advancing rapidly with many new bulb styles. Initially more expensive than CFLs and now the price of LED bulbs is going down each year as the manufacturing technology continuous to improve.

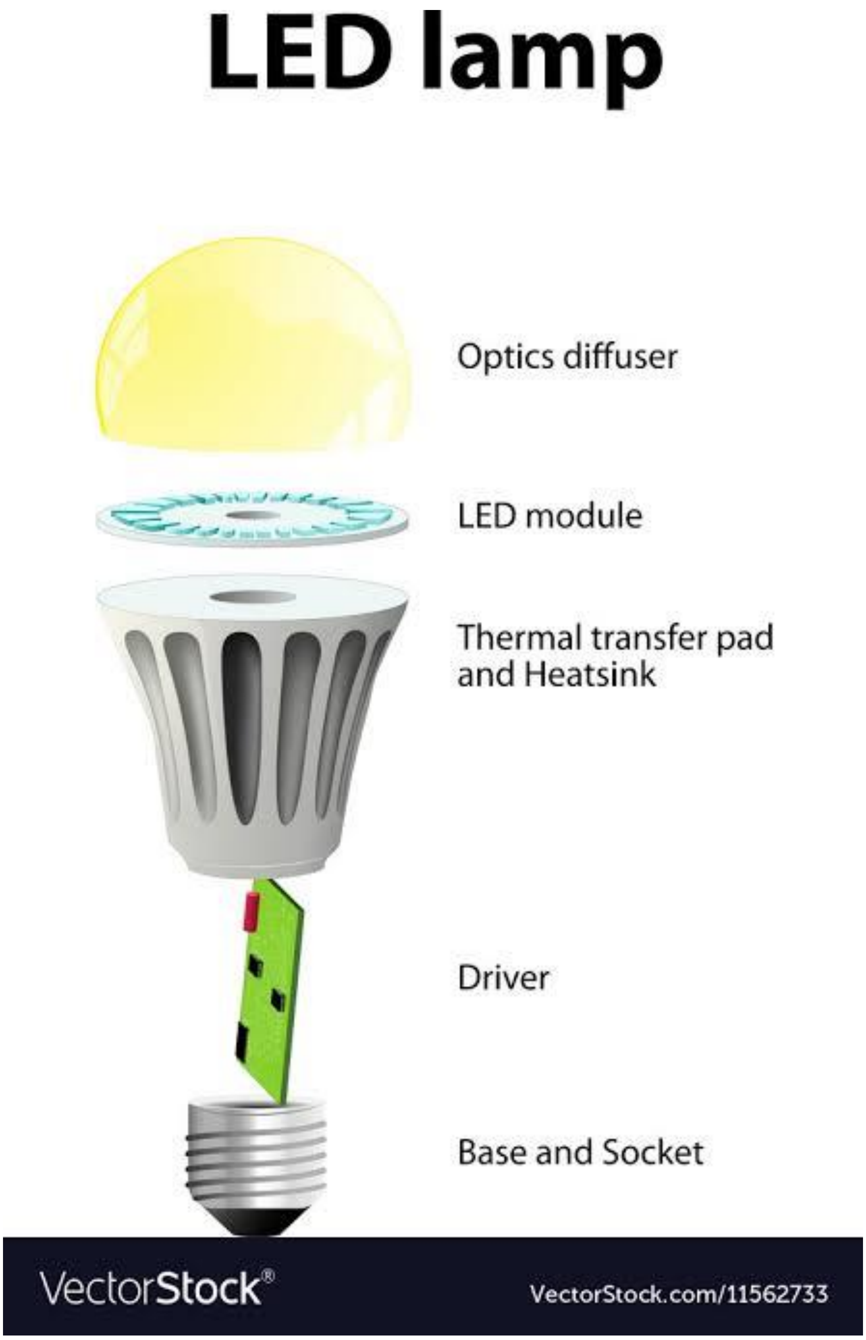
Best energy saving practices:

- Installation of CFLs in place of incandescent lamps
- Installation of metal halide lamps in place of Mercury / Sodium vapour lamps
- Installation of LED panel indicator lamps in place of filament lamps
- Installation of microprocessor based controllers for dimming / switching ckts
- Installation of separate transformer for lighting
- Installation of electronic ballasts in place of conventional ballasts

Advantages of electronic ballasts over conventional ballasts

- Energy saving upto 35 %
- Lights instantly
- Improved power factor
- Operates in low voltage also
- Less in weight
- Increases the life of lamp.

LED LAMPS:



- Diffuser - a device which spreads the light from a light source evenly and reduces shadows
- LED module consists of many LEDs connected in series depends on output required
- Heat sink – the driver circuit in the LED bulb generate heat. Since the lamp is completely sealed unit, all that heat would soon built up and damage the components. To avoid this heat sink is used to cool them.
- Base: Usually either a screw-in or bayonet fitting is used to fix the bulbs in the holder.

<u>Advantages of LED bulbs:</u>

1. Long lasting - LED bulbs last up to 10 times that of CFLs
2. Cool – Compared to incandescent lamps, the heat produced by LED bulbs is very less.
3. More efficient - LED bulbs use only 1/3rd of electricity compared to CFL and 1/10th of electricity compared to incandescent bulbs.
4. Maximum brightness instantly unlike CFLs which takes few minutes to warm up.
5. LEDs are also very tough and durable.
6. Cost effective – although LEDs are initially expensive, the cost is recovered over time.

O.C phase voltage (sec) $= \sqrt{(V_A + 27)^2 + (45)^2}$

$= \sqrt{(38.5 + 27)^2 + (45)^2} = 79.51$

Total KVA taken from the supply } = 3 × current drawn/ph × secondary/ph × 10^{-3}

$= 3 \times 9000 \times 79.5 \times 10^{-3}$

$Q = 2{,}146$ KVA

(7) Find the current per phase in a 3ϕ arc furnace to melt 5 metric tonne of steel in one hour @ an overall efficiency of 50%., if the arc is 115V, initial temperature 30°c, melting point of steel = 1370°c, specific heat of steel 278 J/kg/°c, latent heat of steel is 3700 J/kg

Solution:

Energy required to melt 5 tonne of steel

$H = m\{s[\theta_2 - \theta_1] + L\}$

$= 5000 \times \{278(1370 - 30) + 3700\}$

$= 20476 \times 10^5$ J $= \frac{20476 \times 10^5}{3.6 \times 10^6} = 568.77$ Kwh

Time taken in melting of steel = 1 hour

∴ Average o/p = $\frac{\text{Total energy reqd in kwh}}{\text{Time of melting in hours}}$

$= \frac{568.77 \text{ kwh}}{1 \text{ h}}$

$= 568.77$ kW

$$\text{Actual input} = \frac{\text{Average output}}{\text{Overall efficiency}}$$

$$= \frac{568.77}{0.5}$$

Actual input = 1137.55 kW

Also, power input $= 3 E_{ph} I_{ph} \cos\phi$ $\quad \cos\phi = 1$

$$1137.55 = 3 * 115 * I_{ph}$$

$$I_{ph} = \frac{1137.55}{3 * 115} \times 1000$$

$I_{ph} = 3298$ Amps

(8) Following data relates to a 3 φ electric arc furnace.

current drawn = 400 A

Arc voltage = 20 V

Resistance of T/f referred to secondary = 0.002 V

Reactance of T/f referred to sec = 0.006 V.

(i) calculate p.f and kW drawn from supply.

(ii) If the overall efficiency of furnace is 60% and find the time required to melt 2.0 tonnes of steel, if latent heat of steel = 37.2 kJ/kg, specific heat of steel = 0.5 kJ/kg°c, melting point of steel = 1370°c and initial temp of steel = 25°c.

__Solution:__

Voltage drop due to T/f resistance $= IR_t = 400 \times 0.002$
$= 0.8$ V.

Voltage drop due to T/f reactance $= IX_t = 400 \times 0.06$
$= 2.4$ V

Due to resistive nature of arc, O.C T/f Voltage/ph

$$V_{ph} = \sqrt{(0.8+20)^2 + (2.4)^2}$$

$= 20.94V$.

(i) p.f of supply $= \frac{20+0.8}{20.94} = 0.99$ lag

Total power drawn $= 3 V_{ph} I_{ph} \cos\phi$

$= 3 \times 20.94 \times 400 \times 0.99$

$= 24.877$ KW

Avg power d

Heat energy required to melt 2.0 tonne of steel

$$H = m[S(\theta_2 - \theta_1) + L]$$

? $= 2000[0.5(1370-25) + 37.2]$

$= 1419.4$ KJ

$H = 0.3943$ kWh → Avg o/p $= \frac{0.3943}{\eta}$

power Used $= 24.877 \times 0.6$ $= \frac{0.3943}{0.6}$

$= 14.93$ KW =

(ii) Time required to melt the steel

$= \frac{\text{Actual heat required}}{\text{power used}}$

$= \frac{0.3943}{14.93}$ $= \frac{0.3943/0.6}{24.877}$

$= 0.0264$ hour

$= 1.58$ Min

$t = 95.07$ sec.

(9) A low frequency induction furnace operating @ 10 V in the secondary circuit take 500 kW @ 0.5 pf., when the hearth is full. If the sec voltage be maintained @ 10 V, estimate the power absorbed and the pf when the hearth is half full. Assume the resistance of the sec circuit to be doubled and reactance remains the same.

Soln:

$$P = VI\cos\phi$$

$$500 \times 1000 = 10 \times I \times 0.5$$

$$I = \frac{500000}{5}$$

$$\boxed{I = 100000 \text{ A}}$$

If 'R' is the total resistance of the sec, then

$$I^2R = 500\times10^3 \text{ (or) } R = \frac{500\times10^3}{(100000)^2} = \frac{1}{20{,}000}\Omega.$$

$$\text{Imp, } Z = \frac{V}{I} = \frac{10}{100000} = \frac{1}{10{,}000}\Omega = 0.5\times10^{-4}\Omega.$$

$$\text{Reactance, } X = \sqrt{Z^2 - R^2} = \sqrt{\left(\frac{1}{10{,}000}\right)^2 - \left(\frac{1}{20{,}000}\right)^2} = 0.866\times10^{-4}\Omega.$$

When hearth is half full, $R = 1\times10^{-4}\Omega$

$X = 0.866\times10^{-4}\Omega$

$$\therefore Z = \sqrt{(1\times10^{-4})^2 + (0.866\times10^{-4})^2} = 1.323\times10^{-4}\Omega.$$

$$\text{power factor} = \frac{R}{Z} = \frac{1\times10^{-4}}{1.323\times10^{-4}} = 0.756 \text{ lag}$$

$$\text{Secondary current, } I = \frac{V}{Z} = \frac{10}{1.323\times10^{-4}} = 75.593 \text{ A}$$

$$\text{power drawn, } P = I^2R = (75593)^2\times10^{-4}.$$

$$\boxed{P = 571.43 \text{ kW}}$$

(10) Determine the amount of energy required to melt 2 tonne of Zinc in 1 hour if it operates @ an efficiency of 70 %. The specific heat of Zinc is equals to 0.1. The latent heat of Zinc = 26.67 Kcal / kg, the melting point is 480°c, and the initial temp is 25°c.

Soln:-

$m = 2 \text{ tonne} = 2 \times 1000 = 2000 \text{ kg}$ $S = 0.1$

$t = 1 \text{ hour}$. $L = 26.67 \frac{\text{Kcal}}{\text{kg}}$

$\eta = 70\%$

$\theta_1 = 25°c$

$\theta_2 = 480°c$

The energy required for melting

$$H = m[S(\theta_2 - \theta_1) + L]$$

$$= 2000[0.1(480° - 25) + 26.67]$$

$$H = 144,340 \text{ Kcal}$$

$$H = 144,340 \times 10^3 \text{ cal}$$

$$= \frac{144,340 \times 10^3}{0.239}$$

$$= 603933054 \text{ J}$$

$$= 603933054 * 2.78 \times 10^{-7} \text{ kWh}$$

$$H = 167.89 \text{ kWh}$$

$$\text{Energy input} = \frac{\text{Average o/p}}{\text{overall } \eta}$$

$$= \frac{167.89}{0.7}$$

$$= 239.42 \text{ kWh}$$

Also Energy $= I^2 R t$

power $= \frac{\text{Energy}}{\text{time}} = \frac{239.42 \text{ KW}}{1}$?

power = 239.42 KW

(11) A 3ϕ arc furnace takes 7500 A when the arc voltage is 75V. The circuit comprising the T/F & the electrodes excluding the arc has a reactance of 0.003Ω & a resistance of 0.002Ω. The steel has a specific heat of 278 J/kg/°c a Latent heat of fusion 37000 J/kg & melting point is 1370°c. Assume furnace overall efficiency as 50% & initial temperature of steel as 15°c.

Determine

(i) The time taken to melt 5 tonnes of steel

(ii) The KVA taken from the supply.

(iii) the electrical efficiency.

Solution

Arc Resistance/ph $= \frac{75}{7500} = 0.01\Omega$.

Drop due to $R_t = I R_t = 7500 * 0.002 = 15V$

Drop due to $X_t = I X_t = 7500 * 0.003 = 22.5V$

Now, $V = \sqrt{(E_A + IR_t)^2 + (IX_t)^2}$

$= \sqrt{(75+15)^2 + (22.5)^2} = 92.769V$

$\cos\phi = \frac{E_A + IR_t}{V}$

$= \frac{75+15}{92.769} = 0.97 \text{ (lag)}$

Heat required to melt 5 tonnes of steel

$H = m[S(\theta_2 - \theta_1) + L]$

$= 5000[278(1370 - 15) + 37000]$

$= 2.06845 * 10^9$ J

$= 2.06845 \times 10^9 * 2.78 * 10^{-7}$

$\boxed{H = 575.029 \text{ kWh}}$

Actual heat required $= \frac{H}{\eta}$?

$= \frac{575.029}{0.5}$

$= 1150.058$ kWh.

power input $= 3 V I \cos\phi * 10^{-3}$ kW

$= 3 * 92.769 * 7500 * 0.97 * 10^{-3}$

$\boxed{\text{power i/p} = 2024.68 \text{ kW}}$

(i) Time Required $= \frac{\text{Actual heat required}}{\text{power input}}$

$= \frac{1150.058}{2024.68}$

$= 0.568$ hour

$\boxed{t = 34.08 \text{ Min}}$

(ii) The KVA taken from the supply $= 3 V I \times 10^{-3}$

$= 3 * 92.769 * 7500 * 10^{-3}$

$\boxed{Q = 2087.30 \text{ KVA}}$

(iii) The electrical efficiency $(\eta_e) = \frac{P_A}{P_{i/p}}$

$$\% \eta_e = \frac{3 * 75 * 7500}{2024.68 * 1000} * 100$$

$$\eta_e = 83.33 \%$$

—×—

About Arc furnace:

* An arc furnace is either cylindrical or conical in shape. The interior of the furnace viz. bottom, side walls and top are lined with refractory bricks which can withstand very high temperature.

The electrodes are introduced either thro' the top or from the side walls. The furnace has an entry for introducing charge into it and an outlet point for taking out molten metal. All the entry and exit points are thermally insulated. The furnace can be tilted to take out the molten metal. The mechanism consists of a motor and pinion arrangement.

Generally, carbon, graphite and self baking electrodes are used. The electrodes are cylindrical in shape with diameters ranging from 18 cm to 27 cm. Carbon electrodes are used for manufacture of ferro-alloys, aluminium, calcium carbide, phosphorus etc.,

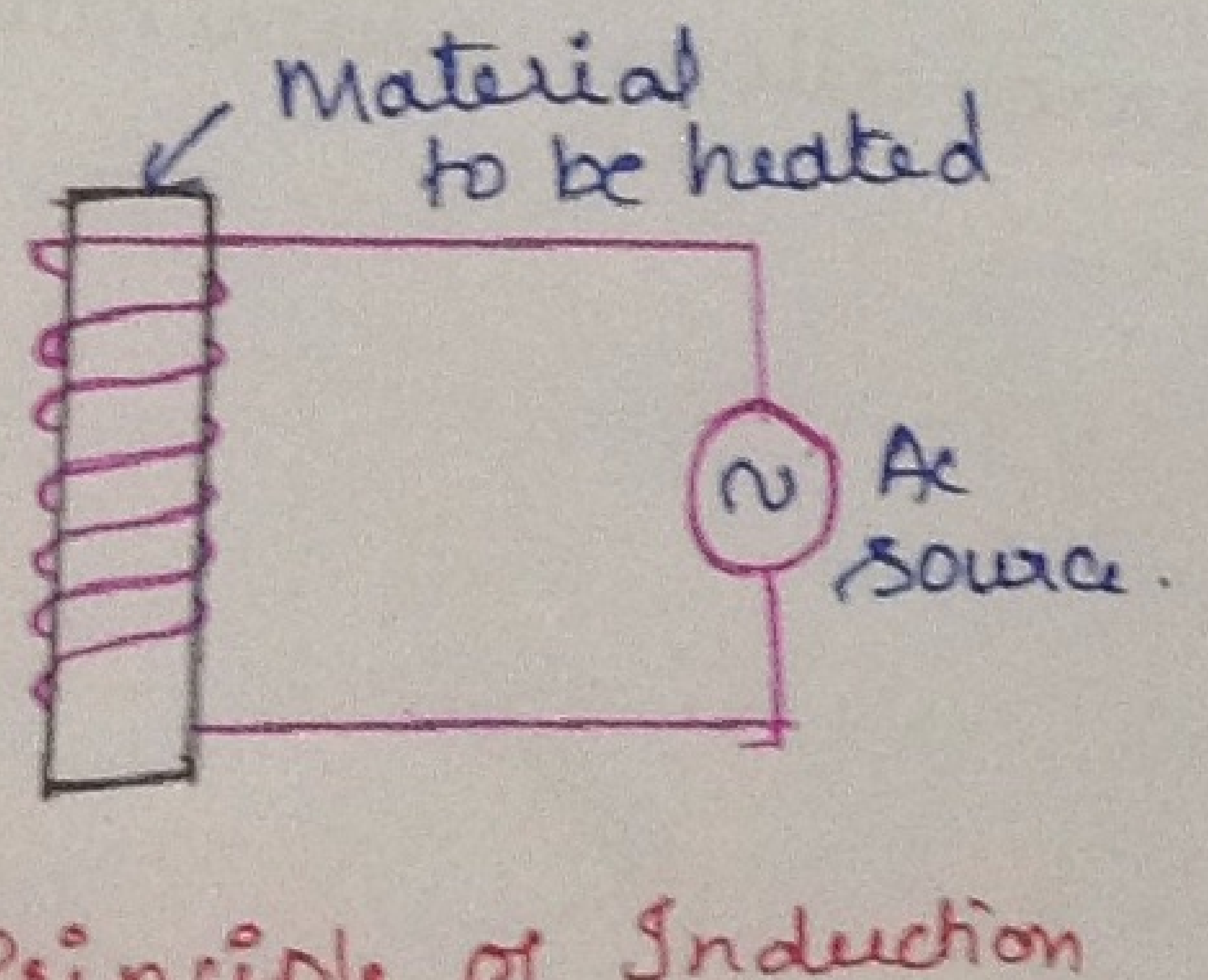
Induction Heating:

Induction heating is based on Faraday's Law of Electromagnetic Induction. A material develops heat if no of wires are wound over it and fed with Ac supply. The current passing thro' the wires, sets up flux in the material leading to induced emf in the material. This emf causes flow of current in the material producing heat similar to current passing thro' any resistance.

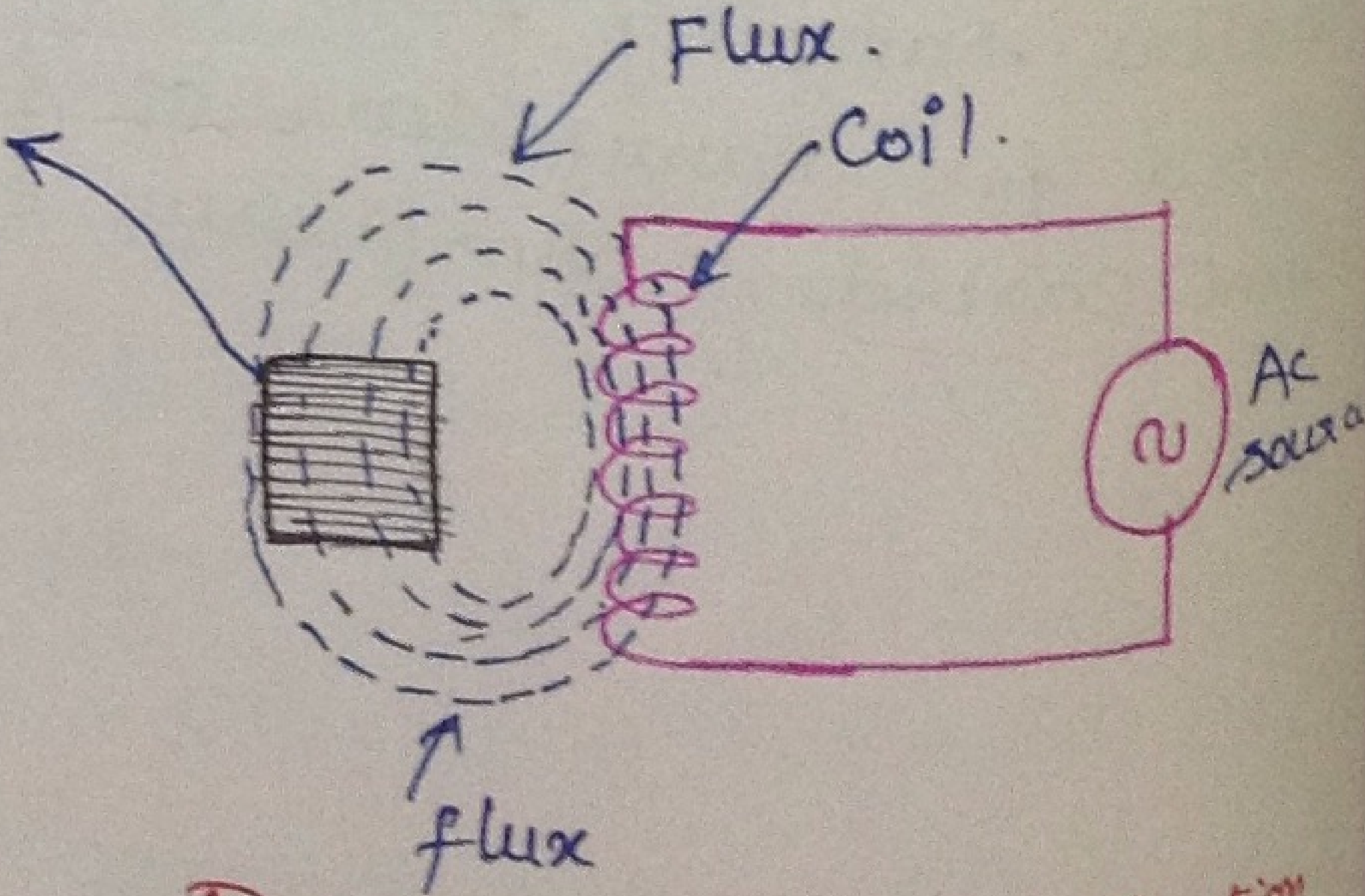
The heat is produced in the material by eddy currents. If the material is magnetic, then heat is produced by both eddy current and hysteresis effect.

This method of heating is applicable to conducting and magnetic materials only.

The materials can be heated in two ways. In one method, the coils are wound over the material directly. In second method, emf is induced in the material by a coil @ some distance.



Principle of Induction - Heating



Indirect method of Induction - Heating

Heat generated by Induction heating depends on the following factors:

(i) Magnitude of current
(ii) Frequency of applied voltage.
(iii) Reciprocal of distance between coil and material to be heated.
(iv) Permeability of material.

It is clear from above that for higher heat generation, magnitude of current must be high, frequency must be high, distance between the coil and the material should be minimum (for Indirect method) and permeability of material must be high.

All conducting + non-magnetic material have permeability of one. Hence, this method of heating is best suited for magnetic material.

Characteristics of Induction heating:

The characteristics of Induction heating are following:

(i) Heating confined to surface:

Induction heating causes rapid heating of outer surface of material. This is due to skin effect in which current tends to crowd around the surface. Because inductance of inner surface is more than the outer surface hence current confines itself to outer surface. The current follows path of least impedance and over the surface.

UNIT - IV Heating and Welding.

Syllabus:

Heating

* Introduction
* Advantages of Electric heating
* Modes of heat transfer.
* Methods of Electric heating.
  - → Resistance heating
  - → Arc Furnaces
  - → Induction heating
  - → Dielectric heating.

Welding

* Electric Welding
* Methods of Electric Welding
  - → Resistance welding
  - → Arc welding
* Power supply for arc welding
* → Radiation welding.

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Introduction:

Heat plays a major role in everyday life. All heating requirements in domestic purposes such as cooking, room heater, immersion water heaters, and electric toasters and also in industrial purposes such as welding, melting of metals, tempering, hardening and drying can be met easily by electric heating over the other forms of conventional heating. Heat and electricity are interchangeable.

Heat also can be produced by passing the current through material to be heated. This is called "electric heating"

There are various methods of heating a material but electric heating is considered far superior compared to the heat produced by coal, oil & Natural-gas.

Advantages of Electric Heating:

The various advantages of electric heating over other types of heating are:

1. Economical:

Electric heating equipment is cheaper; they do not require much skilled persons, therefore the maintenance cost is less.

2. Cleanliness:

Since dust and ash are completely eliminated in the electric heating, it keeps surrounding cleanly.

3. pollution free:

As there are no flue gases in the electric heating, atmosphere around is pollution free

4. Easy of control:

In this heating, temperature can be controlled and regulated accurately either manually or automatically

5. Uniform heating:

With electric heating, the substance can be heated uniformly, throughout whether it may be conducting or non-conducting material.

6. High efficiency:

In non-electric heating, only 40-60% of heat is utilised but in electric heating 75-100% of heat can be successfully utilised. So, overall efficiency of electric heating is very high.

7. Automatic protection:

Protection against over current and over heating can be provided by using fast control devices.

8. Heating of non-conducting Materials.

The heat developed in the non-conducting material such as wood and porcelain is possible only through the electric heating.

9. Better working conditions:

No irritating noise is produced with electric heating and also radiating losses are low.

10. **Less floor area:**

Due to the compactness of electric furnace, floor area required is less.

11. **High temperature:**

High temperature can be obtained by the electric heating except the ability of the material to withstand the heat.

12. **Safety:**

The electric heating is quite safe.

Modes of Heat transfer:

The transmission of the heat energy from one body to another because of the temperature gradient takes place by any of the following methods.

1. Conduction,
2. Convection, or
3. Radiation.

Conduction:

In this method, a molecule of substance gets heated and transfer heat to adjacent molecule. The adjacent molecule upon receiving heat transfers to its adjacent molecule and so on till the temperature gradient persists.

Consider a metallic plate being heated @ one end by placing it on a burning candle. The temperature of metallic plate rises near the candle end and slowly the other end of plate also gets heated up due to heat transfer from the candle end. This is conduction mode of heat transfer.

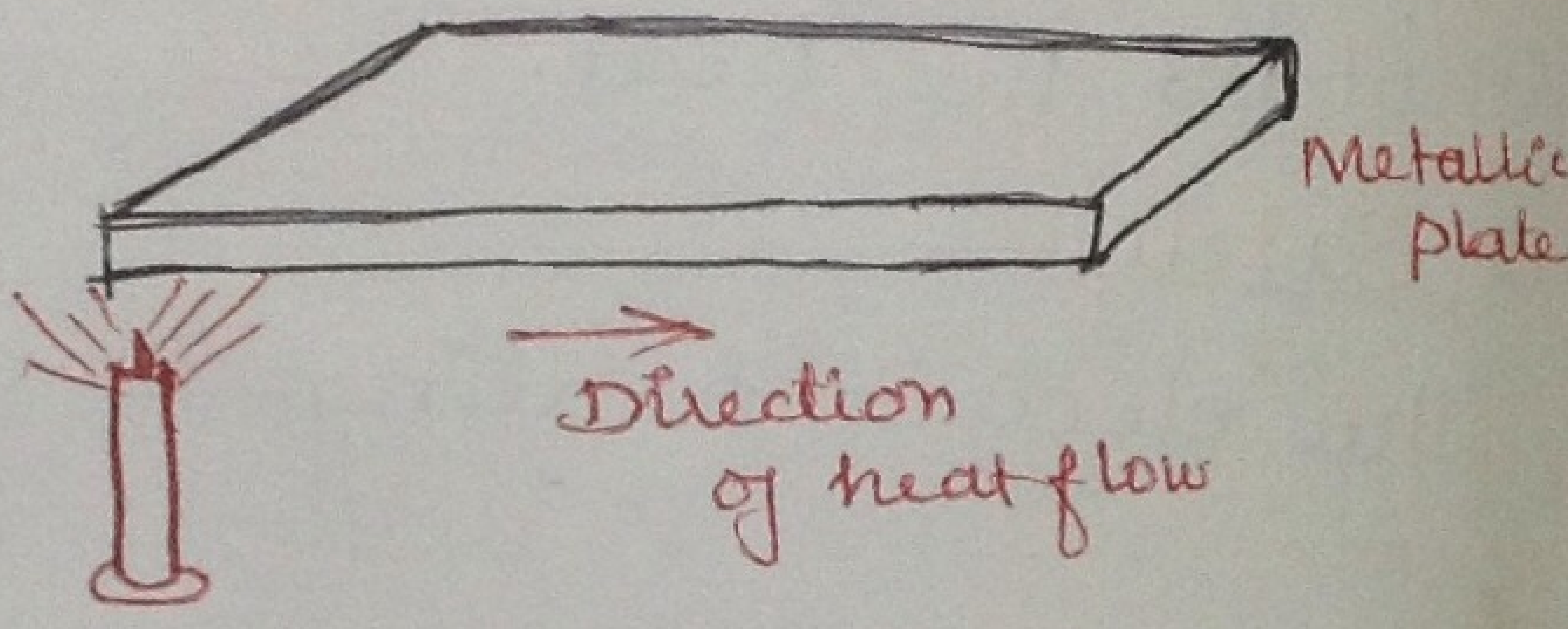


fig: conduction of heat

The Metallic plate has a X-sec area $= A\ m^2$

Thickness of the plate $= t$ mt

Temperature @ two ends of plate $= T_1$ & T_2 °C

Then quantity of heat passed in time T hours is given by.

$$Q = \frac{KA}{t}(T_1 - T_2)T$$

where K = coefficient of thermal conductivity in W/m °C

(ii) Convection:

This form of heat transfer takes place in liquids and gases. Transfer of heat caused by movement of molecules from cooler to warmer regions of lower density is called convection

Heat transfer by convection mode depends upon thermodynamic transport properties (density, specific heat, viscocity etc), geometry of surface, prevailing thermal condition and nature of fluid flow.

Transfer of heat by convection can be represented by the following equation:

$$Q = hA(t_1 - t_2)$$

Where Q = rate of heat transfer

A = area exposed to heat transfer.

t_1 = temperature of source

t_2 = temperature of fluid

h = coefficient of conductive heat transfer.

(iii) Radiation:

In this mode of heat transfer, the heat reaches from source to load without the presence of material medium. This is due to the reason that, heat is an electromagnetic radiation and it travels like light waves or radio waves. All hot bodies emit radiation and cold bodies receive it. For example, the heat energy from sun reaches earth through the space.

The rate of heat radiation is given by Stefan's law

$$H = 5.72 \times 10^4 ke \left[\left(\frac{T_1}{1000} \right)^4 - \left(\frac{T_2}{1000} \right)^4 \right] W/m^2$$

where

T_1 = Temperature of source in K (Kelvin)

T_2 = Temperature of substance in K (Kelvin)

k = constant called radiant efficiency.

e = emissivity (it is unity for black body + 0.9 for resistance heating element)

Introduction:

What is Heating:

Making something warmer (or) Hotter is called "Heating"

Why heating is necessary?

Nowadays, Heating plays a vital role in everyday life. It is basic need for every living thing. without heating there is no fora and fauna.

Invention of wheel and discovery of fire are the turning points which changed the human civilization in a drastic way.

How heating is produced?

Heating is produced in two ways

1. Natural (eg. Sun)
2. Artificial (gas, coal, oil, Electric heating)

In this chapter, we are going to discuss about the Electric heating.

Electric heating.

* Electric heating is any process in which Electrical energy is converted to "Heat energy".
* Electric heating works on the principle of 'Joule Heating' (An electric current flows through a resistor converts electrical energy into heat energy) (or)

Heat can be produced by passing the current through the materials to be heated. This is known as 'Electric Heating'.

Eg: Let us take the case of solid material which as Resistance 'R' ohms & current flowing through it is I amps for 't' seconds, than Heat produced in the Material will be

$$H = I^2 R t \text{ Joules}$$

Domestic applications of Electric Heating:

* Room heater
* Immersion heater
* Hot plates for cooking
* Geysers
* Electric kettles
* Electric iron
* Electric toasters
* Electric oven for baking, etc.,

Industrial applications of Electric heating

* Melting of metals
* Electric Welding
* Moulding of glass
* Moulding of plastic components.
* Baking of Insulator
* Making of plywoods etc.,

Classification of Electric Heating

Electric Heating can be broadly classified as
(a) power frequency heating
(b) high frequency heating.

(a) power frequency heating can be further classified as
(i) Resistance heating
(ii) Arc Heating.

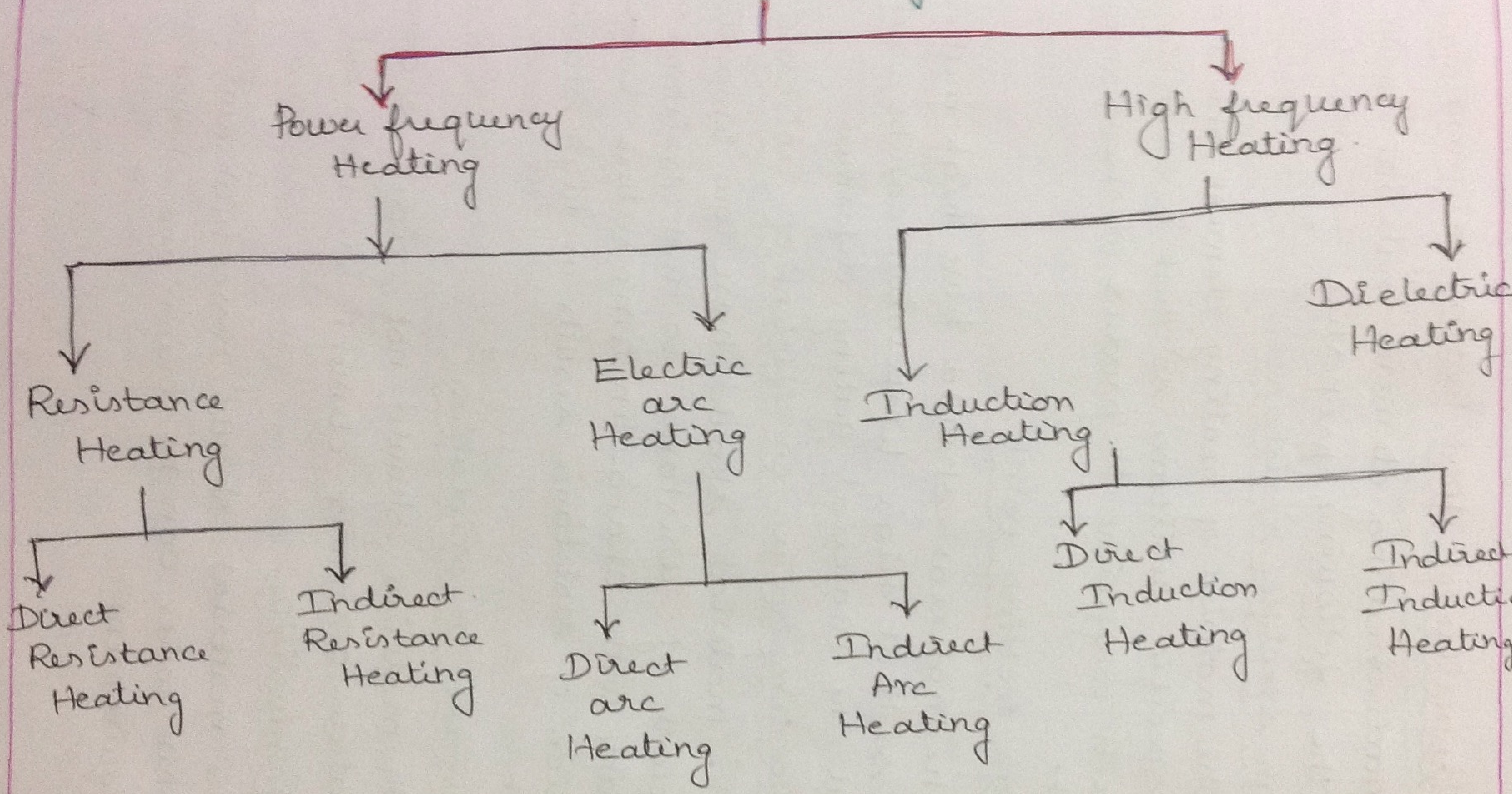
(i) Resistance heating can be further classified as
(a) Direct resistance heating
(b) Indirect resistance "

(ii) Arc Heating can be further classified as
(a) Direct arc heating
(b) Indirect arc heating

(b) High frequency heating can be further classified as
(i) Induction heating
(ii) Dielectric heating.

(i) Induction heating can be further classified as
(a) Direct Induction heating
(b) Indirect Induction heating

Electric Heating.



~~Pss~~ Properties of good heating element Materials

A good heating element material should posses the following properties:

(i) High specific resistance.

The material of heating element should have high specific resistance so that a small length of wire is sufficient to produce desired amount of heat.

(ii) High Melting point

The material should have high melting point so that high temperature can be reached without the material getting deformed

(iii) Low temperature co-efficient of resistance

The material should have low temperature coefficient of resistance so that resistance may not vary with change in temperature. Large variation of resistance results in high starting current.

(iv) Resistant to oxidation:

The material should not oxidize @ operating temperature otherwise element will wear out soon

(v) High ductility:

The material should posses high ductility so that thin wires can be drawn and shaped as per requirement

(vi) **High Mechanical Strength:**

The material should posses high mechanical strength so that the element can be easily fabricated and withstand rigours of installation and operation.

Heating Materials:

The various heating element materials used are following:

(i) **Nichrome:** Nichrome is an alloy of nickel (80%) and chromium (20%). It is suitable for an operating temperature of 1150°c.

(ii) **Ni-Cr-Fe alloy:** It is composed of 65% nickel, 15% chromium and 20% Iron. It is suitable for an operating temperature of 950°c. This material is cheap and strong.

(iii) **Fe-Cr-Al alloy:** It is composed of 70% iron, 25% chromium and 5% aluminium. It is suitable for an operating temperature of 1200°c. It is also known as 'Kanthal'. It is resistant to oxidation.

(iv) **Ni-Cu alloy:** It is composed of 45% Nickel and 55% copper. It is suitable for an operating temperature of 400°c. It is also known as 'Eureka'. It has extremely low resistance temp. co-eff.

(v) **Silicon Carbide:** Its operating temp is 1500°c.

vi) **Molybdenum resistor:** " is 1650°c

vii) **Tungstun resistor:** " " is 2000°c

viii) **Graphite resistor:** " " is 600°c

Properties of heating material.

Property	Ni-Cr	Ni-Cr-Fe	Ni-Cu	Fe-Cr-Al
1. Composition	80% Ni 20% Cr	65% Ni, 15% Cr, 20% Fe	45% Ni 55% Cu	70% Fe 25% Cr, 5% Al
2. Max. operating Temperature	1150°c	950°c	400°c	1200°c
3 Specific Resistance @ 20°c	109 $\mu\Omega/cm^3$	110 $\mu\Omega/cm^3$	49 $\mu\Omega/cm^3$	140 $\mu\Omega/cm^3$
4 Specific gravity	8.36	8.28	8.88	7.2.

Resistance Heating:

The Resistance heating is based on the principle that a current passing through a conductor produces heat due to I^2R losses. The maximum temperature that can be achieved is 1000°c. This method of heating is used for drying and baking, heat treatment of metals, domestic cooking etc,

(a) Direct resistance heating:

In this method, electric current is passed through the body be be heated. Heat is developed in the body due to I^2R losses. It is an efficient method of heating as the heat is produced in the body itsey

Applications:

(i) Resistance welding.

(ii) Electrode boiler for heating water

(b) Indirect Resistance heating:

In this method, current is passed through a heating element (made of high resistance material). The heat developed in the heating element is transferred to the body by radiation and convection.

Applications:

(i) Resistance ovens.

(ii) Immersion heaters

(iii) Domestic cooking ovens.

(iv) Heat treatment of metals.

Types of resistance heating Furnace:

There are two types of resistance heating furnace viz

(i) Direct heating resistance Furnace &

(ii) Indirect heating resistance Furnace.

(i) Direct heating resistance Furnace.

This type of furnace consists of a thermally insulated closed chamber having two electrodes suspended into the charge. When supply is given, current flows through electrode and the charge. Heat is developed due to I^2R losses taking place in charge. Three phase AC supply uses three electrodes and dc supply and 1Ø AC supply uses two electrodes.

When metals are to be heated then to prevent short circuit between electrodes, a highly resistive powder is sprinkled over the charge.

This method of heating is efficient, however automatic temperature control is not possible due to inability to control current flowing thro' charge.

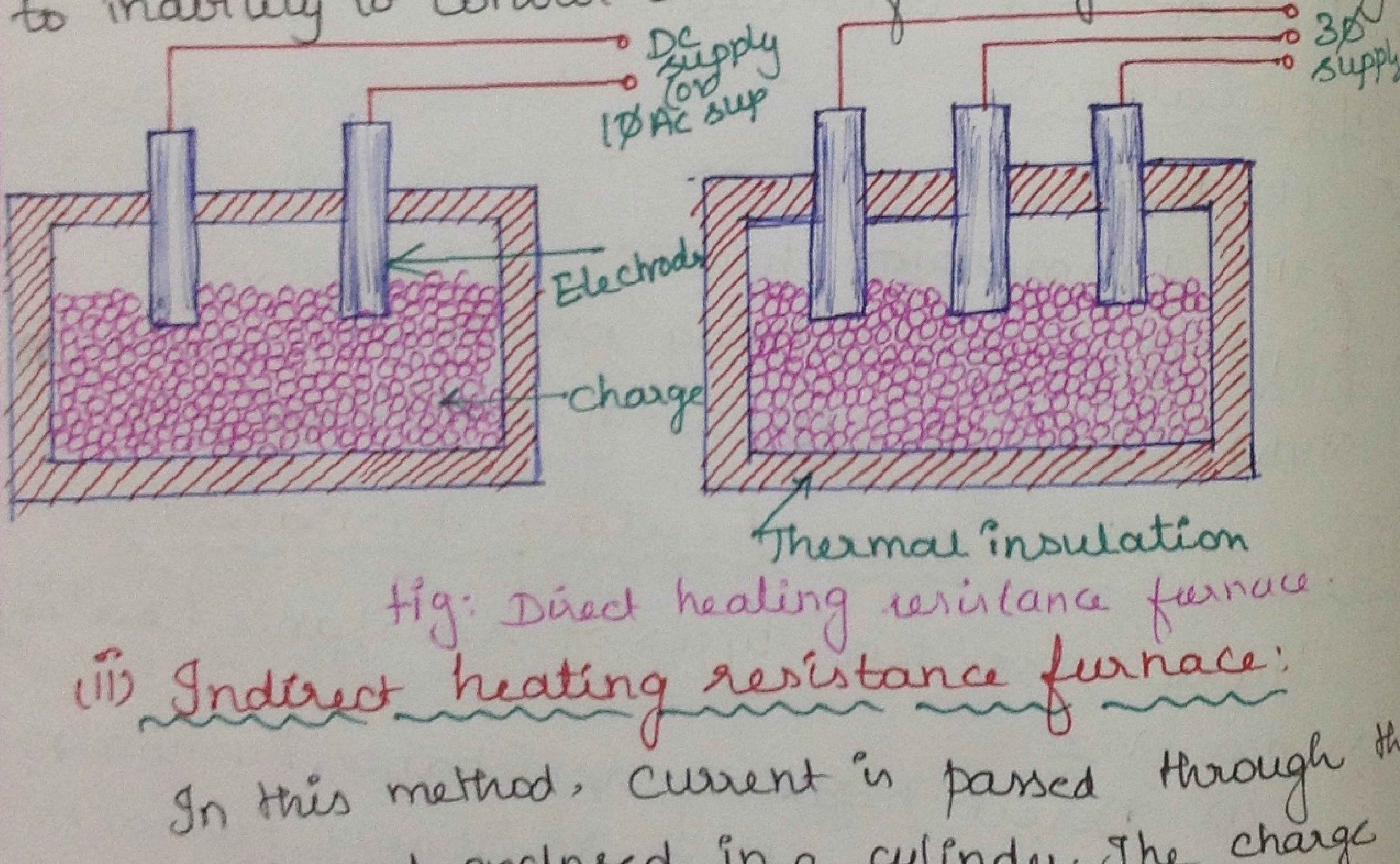


fig: Direct heating resistance furnace.

(ii) Indirect heating resistance furnace:

In this method, current is passed through the heating element enclosed in a cylinder. The charge surrounds this cylinder. The heat produced in the heating element is conveyed to the charge through radiation and convection.

This type of heating provides uniform temperature and its control.

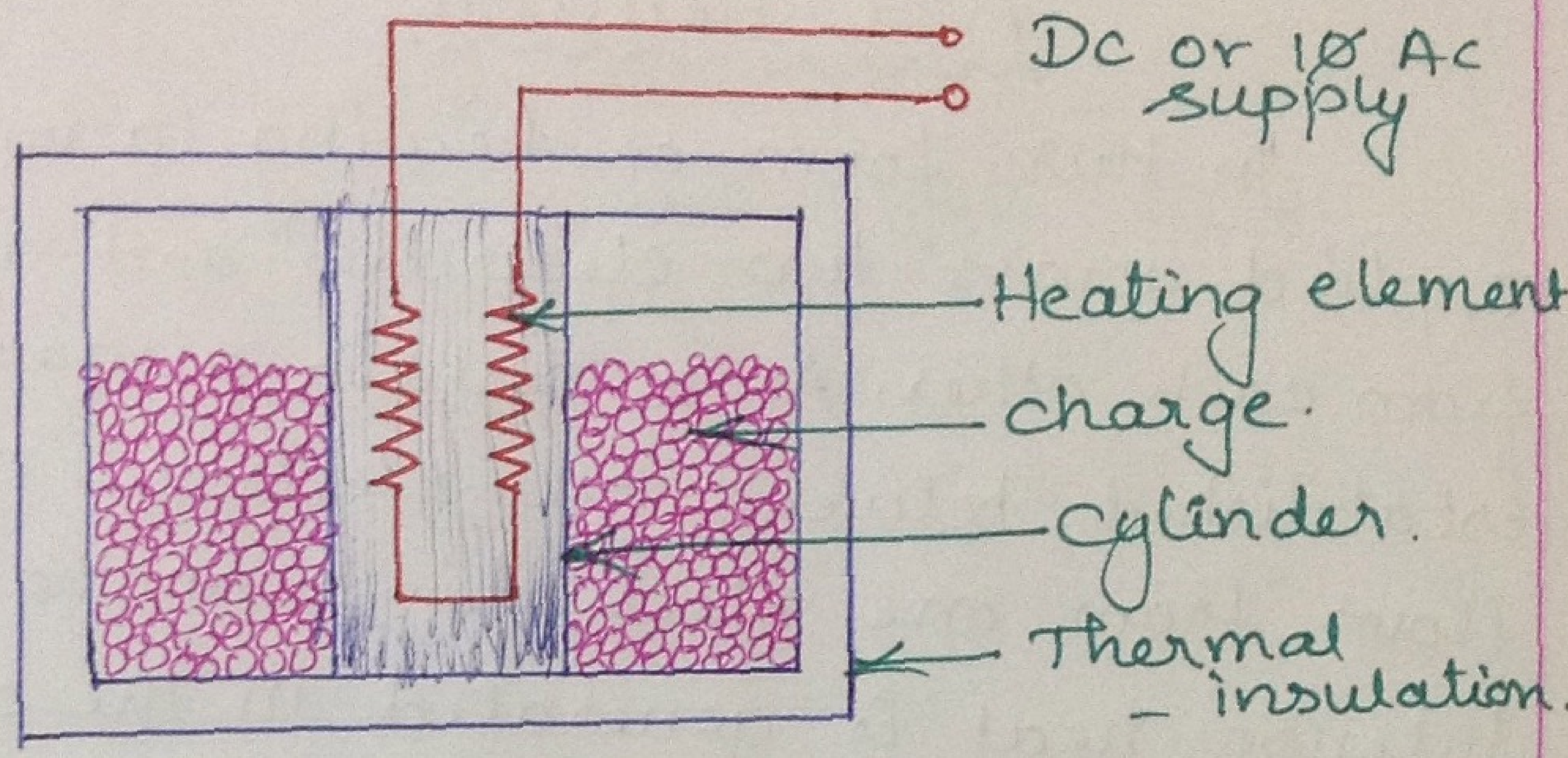


fig: Indirect heating resistance furnace

Applications of Resistance Heating:

The following are applications of resistance heating

(i) Heat treatment of metals (hardening, annealing, etc
(ii) Drying and baking of insulators
(iii) Drying and baking of potteries, paper, textile etc
(iv) Storing of enamelled wire
v) Domestic cooking
vi) Drying of varnish coatings
vii) Vulcanising & hardening of synthetic material.
viii) Melting of non-ferrous metals.
ix) Pre-heating of plastics before moulding
x) Softening of thermo-plastic sheets.
xi) Immersion heaters
xii) Resistance melting

ARC Heating.

In this form of heating, a voltage is applied across two electrodes and are separated from each other. At a certain airgap, an arc is established between two electrodes. The current flows from one electrode to another via airgap. Intense heat is generated in the airgap (about 3000 - 3500°c). Although high voltage is required to establish the arc but to maintain arc, low voltage is sufficient. This principle is used in arc furnace.

(a) **Direct arc heating:**

In this method, arc is established between two electrodes and the material to be heated (charge) is placed such that current passes thro' it

(b) **Indirect arc heating:**

In this method, arc is established between two electrodes and the heat produced due to arc is transmitted to the charge.

Characteristics of Electrodes

Electrodes suitable for arc funace must posses the following characteristics

(i) High electrical conductivity
(ii) Infusibility
(iii) Insolubility

(iv) Chemical Inertness

(v) Good Mechanical Strength.

vi) Resistant to thermal shock.

Types of Arc furnaces:

There are three types of arc furnaces viz

1. Direct arc furnace
2. Indirect arc furnace.
3. submerged arc furnace.

In direct arc furnace, arc is formed between Electrodes and charge, while indirect arc furnace, arc is formed between two electrodes and heat is transmitted to the charge by radiation.

1. Direct arc furnace:

In this furnace, arc is formed between two electrodes and the charge such that current passes thro' the charge. Very high temperature develops due to passing of current thro' the charge.

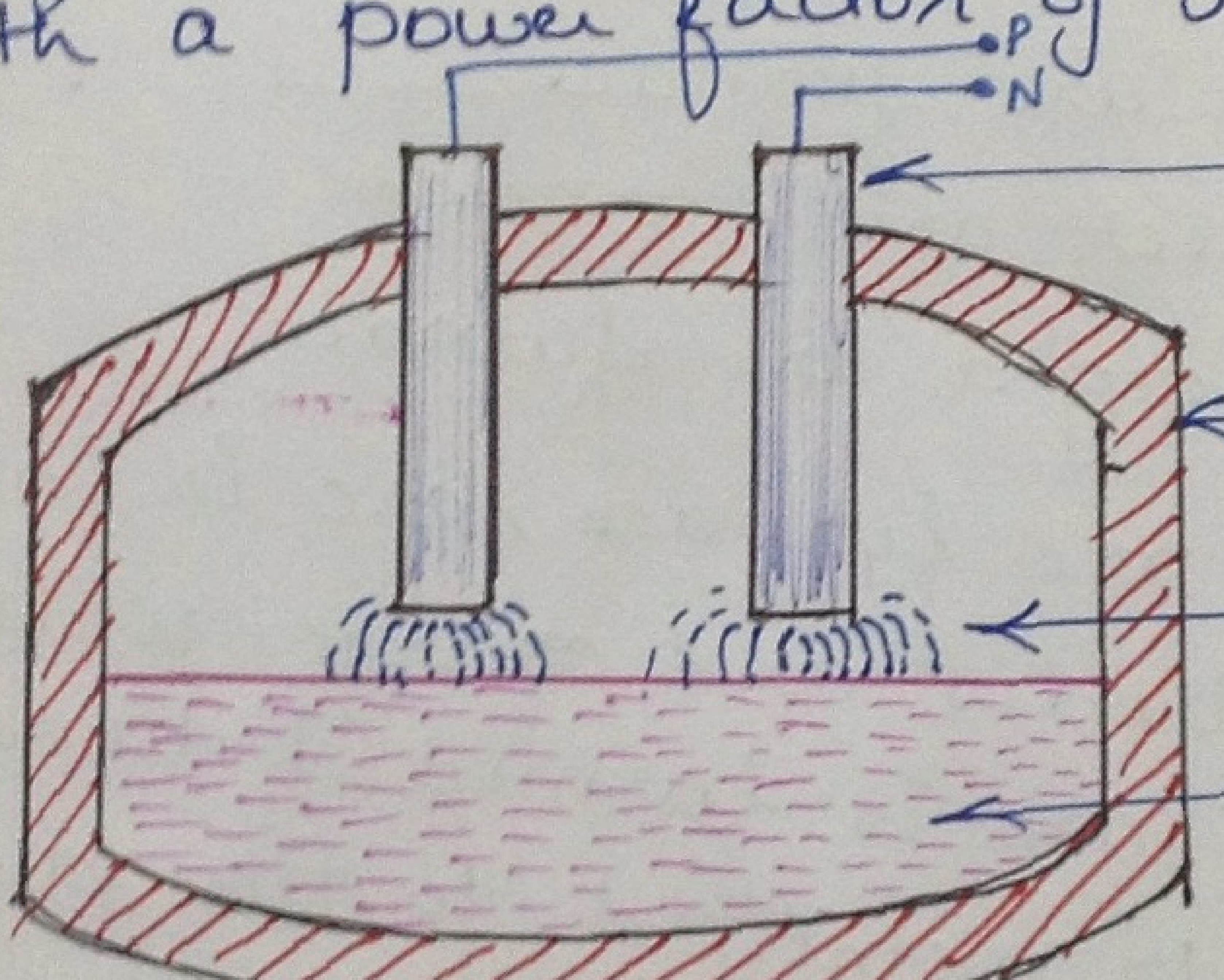
Furnace uses two electrodes for 1ϕ supply & three electrodes for 3ϕ supply is equilateral triangle formation.

↑ $R = \frac{\rho l}{a}$ ↑

The electrodes can be lowered or raised to obtain a desired length of arc. Longer the arc, lesser the Voltage required and lesser the heat input. Power supply is obtained thro' a tap changing T/F.

Due to low voltage required by arc, magnitude of current is very high.

Direct arc furnace is used for refining rather than for melting due to higher cost. The specific energy consumption is 1000 kWh/tonne with a power factor of 0.8 lag



The advantages of direct arc funace are given

(i) Self stirring of charge takes place due to passage of current thro' it.

(ii) Higher capacity

(iii) Higher temperature can be achieved.

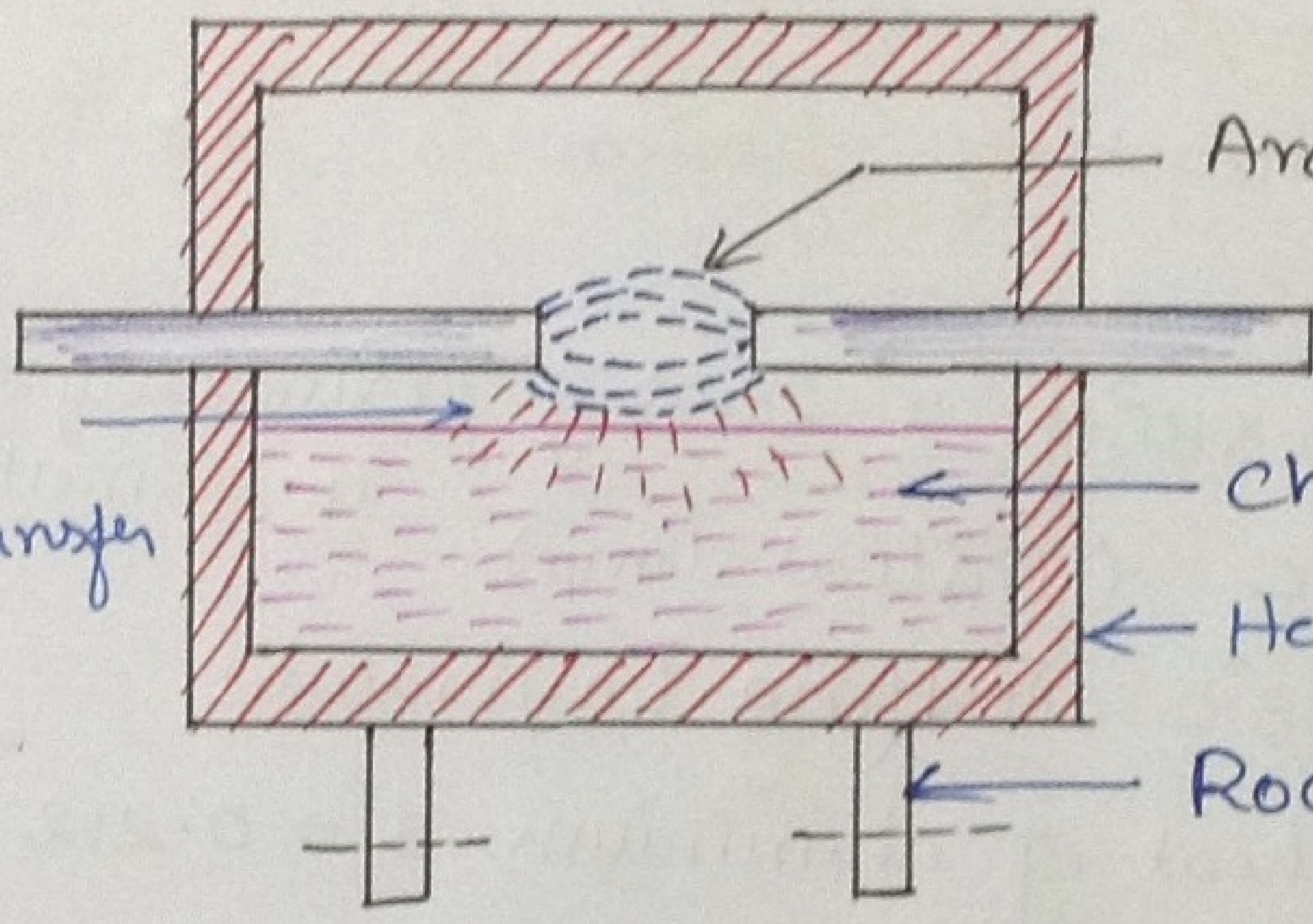
(iv) pure form of product can be obtained hence it is suitable for metal refining

(v) Composition of product can be controlled.

Note: When an airgap is subjected to a HV, the air in the gap gets ionised under electrostatic field. This ionised air becomes a conducting medium & I flows thro' it in the form of spark. When spark persists for a longer duration, it is known as "arc". In order to establish an arc HV is required but once the arc is established, a small voltage is sufficient to maintain it. The arc established between two electrodes generate intense heat and temp can raise to 1000°c to 3500°c. This is the principle of arc furnaces.

2 Indirect arc furnace:

In this type of furnace, arc is formed between two electrodes above the charge and heat is transmitted to the charge by radiation.



Arc is formed by momentarily shorting the electrodes by bringing them closer and then separating them. Generally, two electrodes are used so that only 1ø supply is used. As the current does not flow thro' the charge, no automatic stirring action is obtained.

The furnace need to be rocked continuously so that heat is distributed uniformly. A rocking wheel arrangement is used to rock the furnace.

This furace is mainly used for melting of non-ferrous metals

Advantages:

1) Low production cost/ton.
(ii) power factor is high
(iii) Metal loss due to oxidation + Volatilisation is low
(iv) Castings of intricate design can be made

① A furnace consuming 5 kW take 15 mins to just melt 2.5 kg of aluminium. The initial temperature being 15°C. Find the efficiency of the furnace when the specific heat of aluminium is 0.212 cal/gm/°C. Melting point is 658°C and the latent heat of fusion is 32 J/gm

Given data:

$m = 2.5 \times 10^3 g = 2500 g$ (Quantity of aluminium to be melt)

$\theta_1 = 15°C$ (Initial temp)

$\theta_2 = 658°C$ (Melting temperature)

Specific heat of aluminium, $S = 0.212$ cal/gm/°C

Latent heat of fusion, $L = 32$ J/gm

$= 32 * 0.239$ cal/gm

$L = 7.648$ cal/gm

$\because 1J = 0.239$ calorie

Heat required to melt 2.5 kg of aluminium (ie) o/p

$H = m[S(\theta_2 - \theta_1) + L]$

$= 2500[0.212(658-15) + 7.648]$

$= 359910$ calories

$= 359910 * 4.184$

$H = 1505899.582 J$

1J = 0.239 calories

1 cal = 4.184 J

$1J = 2.78 \times 10^{-7}$ kWh

1 kWh = 3.6 MJ

$H = 1505899.582 * 2.78 * 10^{-7}$

$H = 0.4186$ kwh

Energy i/p $= 5 * \frac{15}{60}$

Energy i/p $= 1.25$ kwh.

∴ The Efficiency of the furnace, η

$$\eta = \frac{\text{Heat Required}}{\text{i/p power}}$$

$$= \frac{\text{o/p power}}{\text{i/p power}} = \frac{0.4186}{1.25}$$

$$= 0.33488 * 100$$

$\eta = 33.48\%$

② Estimate the efficiency of a high frequency Induction furnace which takes 10 min to melt 1.8 kg of aluminium. The input to the furnace being 5 kW and initial temperature 15°C.

specific heat of aluminium = 880 J/kg/°C

Melting point of aluminium = 660°C.

Latent heat of fusion of aluminium = 32 kJ/kg.

Solution:

$m = 1.8$ kg.

Initial temp, $\theta_1 = 15°C$.

Melting temp, $\theta_2 = 660°C$.

$S = 880$ J/kg/°C.

$L = 32$ kJ/kg

$= 32000$ J/kg.

Heat required to melt 1.8 kg of aluminium

$H = m[s(\theta_2 - \theta_1) + L]$

$= 1.8[880(660-15) + 32,000]$

$= 10,79,280$ J. $\quad \because 1$ KWh $= 3.6$ MJ

$= \frac{10,79,280}{3.6 \times 10^6}$

(ie) o/p energy

$H = 0.3$ kwh

Energy input $= 5 * \frac{10}{60}$

$= 0.8333$ kwh.

$\therefore$ Efficiency of furnace, $\eta = \frac{\text{o/p power}}{\text{i/p power}} \times 100$

$= \frac{0.3}{0.8333} \times 100$

$\eta = 36\%$.

Assign. Quest

(3) Calculate the time taken to melt 3 metric tonnes of steel in a 3ø arc furnace having the following data:

Current = 5000 A

Arc Voltage = 60 V

Resistance of transformer = 0.003 Ω

Reactance of transformer = 0.005 Ω

Melting point of steel = 1370°c

Initial Temperature of steel = 18°c.

Assume overall efficiency as 60 %

Given data: Specific heat = 444 J/Kg/°c.
Latent heat = 37.25 KJ/Kg.

$I = 5000\,A$. $R_A = 0.003\,\Omega$ $\theta_1 = 18°c$

$V_A = 60\,V$ $X_A = 0.005\,\Omega$ $\theta_2 = 1370°c$.

$m = 3$ metric tonnes $= 3000$ Kg $(3 * 1000)$

Energy required to melt 3 tonnes steel = H.

$$H = m[s(\theta_2 - \theta_1) + L]$$

$$= 3000[444(1370 - 18) + (37.25 \times 10^3)]$$

$$= 3000[(444 * 1352) + 37250]$$

$$= 3000[600288 + 37250]$$

$$= 1.9126 * 10^9 \text{ Joules.}$$

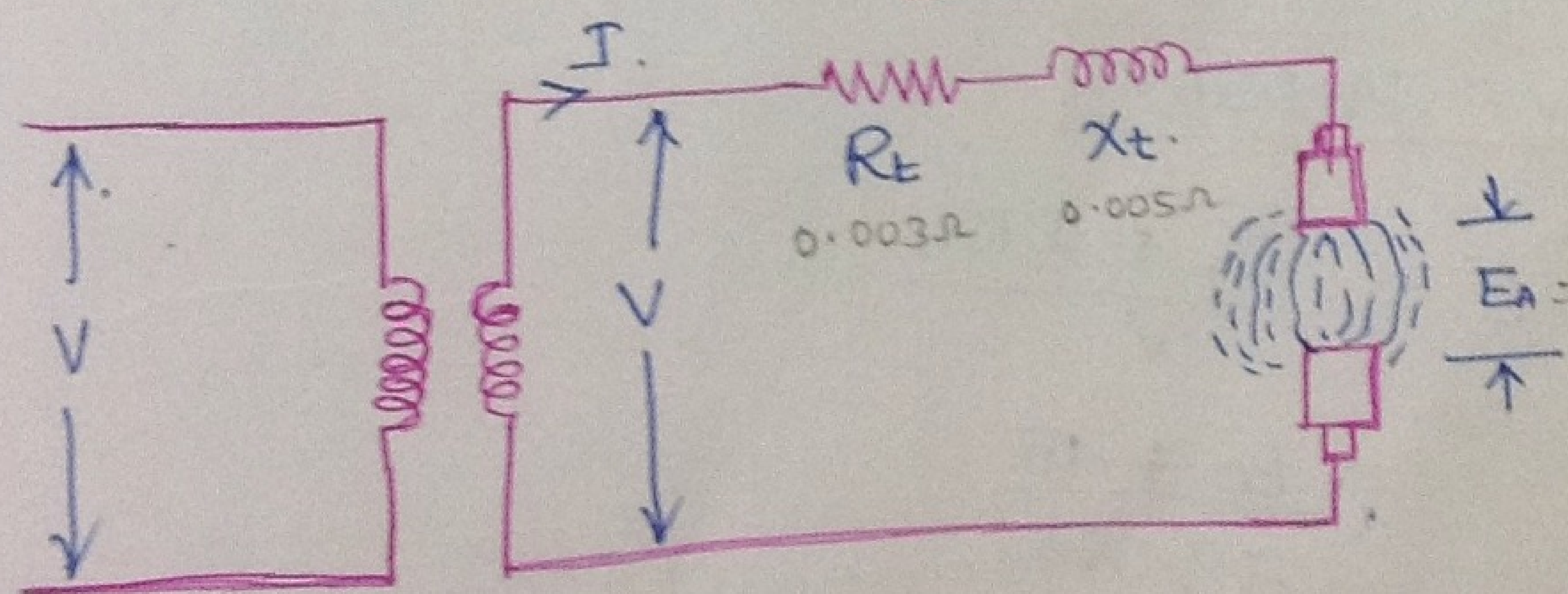
$$= 1.9126 * 10^9 * 2.78 * 10^{-7} \text{ KWh.}$$

$$\boxed{H = 531.70 \text{ KWh.}}$$

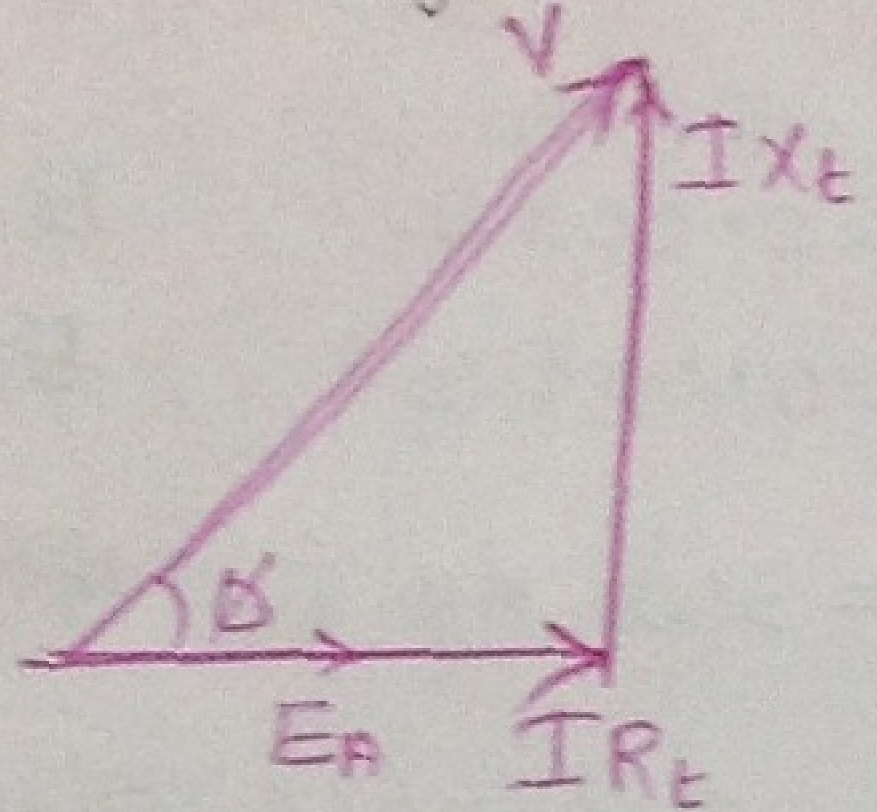
$1\,J = 2.78 \times 10^{-7}$ kWh

1 Kcal $= 1.162 \times 10^{-3}$ kWh.

The equivalent circuit of Arc - Furnance.



The phasor diagram is



Arc resistance / phase $= \frac{60}{5000} = 0.012\ \Omega$

Drop due to Resistance of Transformer $= IR_t$

$= 5000 * 0.003$

$= 15\ V$

Drop due to Reactance of T/f $= IX_t$

$= 5000 * 0.005$

$= 25\ V.$

From the phasor diagram,

$$V = \sqrt{(E_A + IR_t)^2 + (IX_t)^2}$$

$$= \sqrt{(60 + 15)^2 + (25)^2}$$

$$\boxed{V = 79.056\ V}$$

$$\cos\delta = \frac{E_A + IR_t}{V}$$

$$= \frac{60 + 15}{79.056}$$

$$\boxed{\cos\delta = 0.948 \text{ lag}}$$

Actual Heat required (Avg. o/p) $= \frac{H}{\eta}$

$= \frac{531.70}{0.6}$

$= 886.167$ kWh.

power input $= 3VI\cos\phi * 10^{-3}$ kW

$= 3 * 79.056 * 5000 * 0.948 * 10^{-3}$ kW

$= 1124.176$ kW

Then, the time required $= \frac{\text{Actual Heat required}}{\text{power input}}$

$= \frac{886.167}{1124.176}$

$= 0.788$ hour

Time = 47.28 Mins

Electrical $\eta = \frac{o/p}{i/p} =$

$= \frac{3 \times 60 \times 5000}{1124.176 \times 1000} \times 100$

$=$ ____

Pg-4.26

(4) Calculate the time taken (67.2 min) to melt 5 ton of steel (5000 kg, 5000×10^3 g) in 3ϕ arc furnace having the following data

Current $= 8{,}000$ A.

Arc Voltage $= 50$ V.

Latent heat $= 8.89$ kcal/kg (cal/g)

Initial temp $= 18°$C

Resistance $= 0.003\Omega$

Reactance $= 0.005\Omega$

Specific heat $= 0.12$ cal/g/°C

Melting point $= 1370°$C

The overall efficiency is 50%. Find also the p.f and the electrical efficiency of the furnace.

$H = M[S(\theta_2 - \theta_1) + L]$

$= 5000 \times 10^3 [0.12(1370 - 18) + 8.89]$

$= 855650 \times 10^3$ cal

$H = \frac{855650 \times 10^3}{0.239} = 3580125523$ J

$= 3580125523 \times 2.78 \times 10^{-7}$

$H = 995.2748$ kWh

$V = \sqrt{(E_A + IR_t)^2 + (IX_t)^2} = 84.119$ V

$\cos\phi = \frac{50 + 24}{84.119} = 0.8797$

i/p power $= 3 \times 84.119 \times 8000 \times 0.8797 \times 10^{-3}$

$= 1775.98$ kW

Actual heat reqd $= H/\eta = \frac{995.2748}{0.5} = 1990.54$ kWh

Time taken $= \frac{1990.54}{1775.98} = 1.12$ hours

$= 67.24$ Min

Electrical $\eta = \frac{3 \times 50 \times 8000}{1775.98 \times 1000} \times 100 = 67.56\%$

Assign...

(6) A furnace consuming 5 kW take 15 mins to just melt 2.5 kg of Aluminium. The initial temperature being 15°c. Find the efficiency of the furnace when the specific heat of aluminium is 0.212 cal/g Melting point is 658°c and latent heat of fusion is 320 J/gm.

[1 Joule = 0.239 calories]

Given data:

$m = 2.5\ kg$

$= 2.5 \times 10^3 g$

$m = 2500 g.$

Initial temperature, $\theta_1 = 15°c$

Melting temperature, $\theta_2 = 658°c$

Sp. heat of aluminium, $S = 0.212$ cal/gm/°c

latent heat of fusion, $L = 320$ J/gm

$L = 76.48$ cal/gm.

To find:

Efficiency, η

[1 J = 0.239 cal

320 J/gm = x calories/gm

⇒ x = 320 × 0.239

x = 76.48 cal/gm]

Formulae:

$$\eta = \frac{O/P\ Power}{I/P\ Power}$$

Solution:

O/P Power is the heat required to melt the 2.5 kg of aluminium.

$$H = m[s(\theta_2 - \theta_1) + L]$$

O/P Power, $H = 2500[0.212(658 - 15) + 76.48]$

O/P Power = 531990 calories

⇒ **O/P power = 2225899.58 Joules**

$$\left[\begin{array}{l} 1\,J = 0.239\,cal \\ x\,J = 531990\,cal \\ \Rightarrow x = \frac{531990 \times 1}{0.239} \end{array}\right]$$

$$\left[\begin{array}{l} 1\,J = 2.78 \times 10^{-7}\,kwhr \\ 2225899.58\,J = x\,kwhr \\ x = 0.6188\,kwhr \end{array}\right]$$

⇒ **O/P Power = 0.6188 kwhr**

Given:

I/P Power = 5 kw for 15 mins.

⇒ I/P Power = 5×15/60 kwhr = 1.25 kwh

I/P Power = 1.25 kwh.

$$\eta = \frac{O/P\ Power}{I/P\ Power} = \frac{0.6188}{1.25} \Rightarrow \eta = 0.49504$$

% η = 49.504 %

(6) In a 3ø arc furnace to melt 10 tonne steel in 2 hours, estimate the average input to the furnace, if overall efficiency is 50%. If the current input is 9,000 A with the above KW input and the resistance and reactance of furnace leads (including transformer) are 0.003 Ω and 0.005 Ω respectively estimate the arc voltage and total KVA taken from the supply.

Specific heat of steel = $444 \, J \, kg^{-1} \, °c^{-1}$

Latent heat of fusion of steel = 37.25 kJ/kg

Melting point of steel = 1,370°c.

Solution: Assume: Initial temp of steel = 20°c

Energy required to melt 10 tonne steel

$$H = m[s(\theta_2 - \theta_1) + L]$$

$$= 10{,}000[444(1{,}370 - 20) + 37{,}250] \, J$$

$$= 6{,}366.5 \times 10^6 \, J$$

$$= \frac{6366.5 \times 10^6}{3.6 \times 10^6} \, kwh$$

$$\boxed{H = 1{,}768.5 \, kwh.}$$

Time taken in melting of steel = 2 hours.

$$\text{Average o/p} = \frac{\text{Total energy required in kwh}}{\text{Time of melting in hours}}$$

$$= \frac{1768.5}{2}$$

$$= 884.25 \, kw$$

$$\text{Average input} = \frac{\text{Average output}}{\text{Overall efficiency}}$$

$$= \frac{884.25}{0.5} = 1768.5 \text{ KW}$$

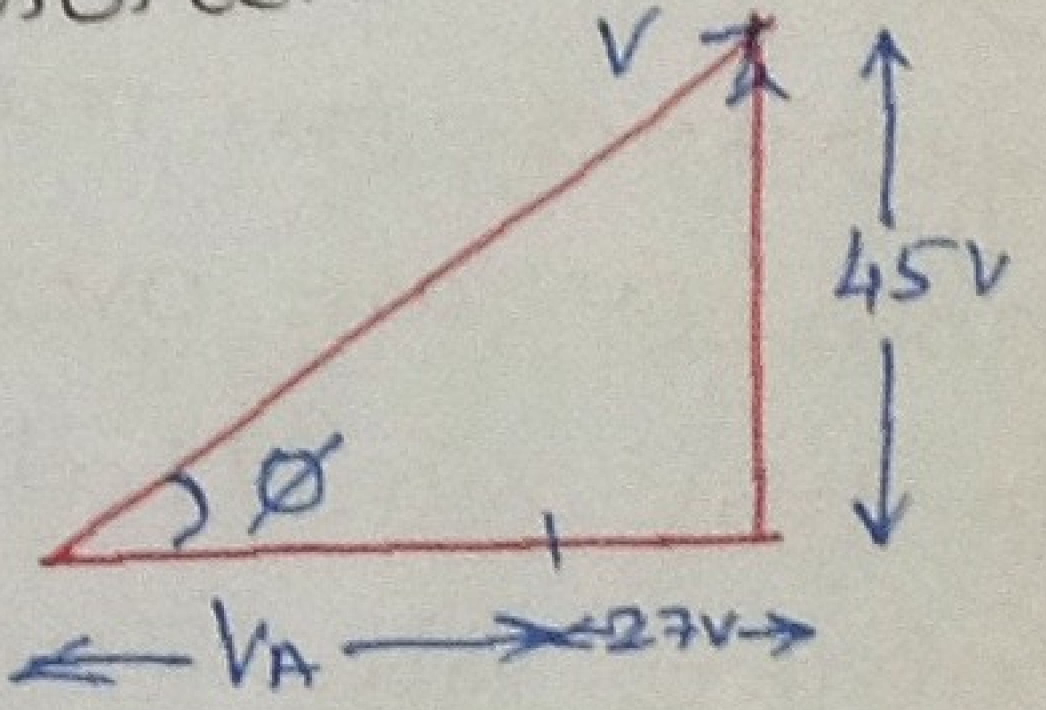
Current input, $I = 9000$ A.

Voltage drop due to resistance (including T/F) $= 9{,}000 \times 0.003$
$= 27$ V

Voltage drop due to reactance $= 9{,}000 \times 0.005$
$= 45$ V.

Let the arc drop the V_A volts, resistive in nature

From fig



O.C phase voltage of T/F sec

$$= \sqrt{(V_A+27)^2 + (45)^2} \text{ V}$$

& p.f (cos ø) $= \dfrac{V_A+27}{\sqrt{(V_A+27)^2+(45)^2}}$.

Total input power = 3 × current drawn/ph × Sec phase voltage × pf

$$1768.5 \times 1000 = 3 \times 9000 \times \sqrt{(V_A+27)^2+45^2} \times \frac{V_A+27}{\sqrt{(V_A+27)^2+45^2}}$$

$$1768.5 \times 1000 = 3 \times 9000 \times (V_A+27)$$

$$V_A + 27 = \frac{1768.5 \times 1000}{3 \times 9000}$$

$$V_A + 27 = 65.5 \text{ V}$$

$$V_A = 65.5 - 27$$

Arc voltage, $V_A = 38.5$ V

Unit 4 – ENERGY CONSERVATION AND ITS IMPORTANCE

SALIENT FEATURES OF THE ENERGY CONSERVATION ACT 2001:

The Act empowers the Central Government and State Governments to:

1. Specify energy consumption standards for notified equipment and appliances; direct mandatory display of label on notified equipment and appliances prohibit manufacture, sale, purchase and import of notified equipment and appliances not conforming to energy consumption standards;
2. Notify energy intensive industries, other establishments, and commercial buildings a sdesignated consumers;
3. Establish and prescribe energy consumption norms and standards for designated consumers;
4. Prescribe energy conservation building codes for efficient use of energy and its conservation in new commercial buildings having a connected load of 500 kW or a contract demand of 600 kVA and above;

DIRECT DESIGNATED CONSUMERS TO -

1. Designate or appoint certified energy manager in charge of activities for efficient use of energy and its conservation;
2. Get an energy audit conducted by an accredited energy auditor in the specified manner and interval of time;
3. Furnish information with regard to energy consumed and action taken on the recommendation of the accredited energy auditor to the designed agency;
4. Comply with energy consumption norms and standards;
5. Prepare and implement schemes for efficient use of energy and its conservation if the prescribed energy consumption norms and standards are not fulfilled, get energy audit of the building conducted by an accredited energy auditor in this specified manner and intervals of time;

STATE GOVERNMENTS MAY –

1. Amend the energy conservation building codes prepared by the Central Government to suit regional and local climatic conditions;

2. Direct every owners or occupier of a new commercial building or building complex being a designated consumer to comply with the provisions of energy conservation building codes;
3. Direct, if considered necessary for efficient use of energy and its conservation, any designated consumer to get energy audit conducted by an accredited energy auditor in such manner and at such intervals of time as may be specified;

B. ESTABLISHMENT OF BUREAU OF ENERGY EFFICIENCY:

Bureau of Energy Efficiency has been established with effect from 1st March, 2002 by merging the erstwhile Energy Management Centre, a society under the Ministry of Power. The Bureau would be responsible for spearheading the improvement of energy efficiency of the economy through various regulatory and promotional instruments.

The mission of the Bureau of Energy Efficiency is to develop policy and strategies with a thrust on self-regulation and market principles, within the overall framework of the Energy Conservation Act, 2001 with the primary objective of reducing energy intensity of the Indian economy. This will be achieved with active participation of all stake holders, resulting in accelerated and sustained adoption of energy efficiency in all sectors of the economy.

The primary objective of BEE is to reduce energy intensity in the Indian economy through adoption of result oriented approach. The broad objectives of the BEE are:

1. To assume leadership and provide policy framework and direction to national energy efficiency and conservation efforts and programmes;
2. To coordinate policies and programmes on efficient use of energy and its conservation with the involvement of stake holders;
3. To establish systems and procedures to measure, monitor and verify energy efficiency results in individual sectors as well as at national level;
4. To leverage multi-lateral, bi-lateral and private sector support in implementation of the Energy Conservation Act and programmes for efficient use of energy and its conservation;
5. To demonstrate energy efficiency delivery mechanisms, through private-public partnership,

6. To plan, manage and implement energy conservation programmes as envisaged in the Energy Conservation Act.

The Director-General is the chief executive officer of the Bureau of Energy Efficiency. The general superintendence, direction and management of the affairs of BEE is vested in the Governing Council having up to 26 members. The Governing Council is headed by Union Minister of Power and consists of Secretaries of various line Ministries, heads of various technical agencies under the Ministries, members representing industry, equipment and appliance manufacturers, architects, and consumers, and members from each of the five power regions representing the states of the region. The Director – General of the Bureau is the ex-officio member-secretary of the Governing Council.

BEE has been given a corpus fund of Rs. 50 Crore for setting up of the Central Energy Conservation Fund for meeting the expenses relating to the salaries, allowances and other remuneration of the officers and employees of the Bureau and to meet the expenses of the Bureau in discharge of its functions as well as on objects and for purposes authorized by the Act. It has also been authorised to collect appropriate fees in discharge of functions assigned to it and raise funds from other sources. BEE may become self-sufficient in a period of 5-7 years.

C. Functions of BEE:

The functions of BEE can be classified as regulatory functions being recommendatory body to the Central Government in implementing the provisions of the Energy Conservation Act and facilitation, market development and market transformation functions such as:

1. Arrange and organize training of personnel and specialists in the techniques for efficient use of energy and its conservation;
2. Develop testing and certification procedures and promote testing facilities;
3. Strengthen consultancy services;
4. Create awareness and disseminate information;
5. Promote research and development;
6. Formulate and facilitate implementation of pilot projects and demonstration projects;
7. Promote use of energy efficient processes, equipment, devices and systems;

8. Take steps to encourage preferential treatment for use of energy efficient equipment or appliances;
9. Promote innovative financing of energy efficiency projects;
10. Give financial assistance to institutions for promoting efficient use of energy and its conservation;
11. Prepare educational curriculum on efficient use of energy and its conservation
12. Implement international co-operation programmes relating to efficient use of energy and its conservation.

D. Action plan of BEE:

During the three year period 4/2004 – 3/2007 BEE shall primarily focus on 9 thrust areas. In addition, it shall also attend to ongoing programmes and such other programmes as are considered essential for promoting the objectives of the Act. In the following sections, the background, legislative mandate, approach, role of BEE for 8 thrust areas are described. Further more three-year target indicators as well as monitoring indicators have been set. Monitoring indicators were used in cases where BEE has little control over compliance or incases of difficulties to quantify a target.

REVIEW OF INDUSTRIAL ENERGY CONSERVATION:

Energy conservation is that the practice of decreasing the amount of energy used for constant quality and quantity of output. It should be achieved through economical energy use, in which case energy use is decreased whereas achieving an identical outcome, or by reduced consumption of energy services.

Background:

The Energy Conservation Act 2001, provides for the efficient use of energy and its conservation in India. The Government of India set up a Bureau of Energy Efficiency (BEE) under the provisions of the Energy Conservation Act. The mission of the BEE is to assist in developing policies and strategies with a thrust on self-regulation and market principles within the overall framework of the Energy Conservation Act with the primary objective of reducing the energy intensity of the Indian economy. The BEE coordinates with Designated Consumers, designated agencies, and other organizations and recognizes, identifies, and utilizes the existing resources and infrastructure, in performing the functions assigned to it under the Energy Conservation Act. In addition to providing regulatory and promotional functions of the Bureau, the act also provides a list of energy-intensive industries and other establishments specified as Designated Consumers.

One of the flagship programmes of Bureau of Energy Efficiency is Perform, Achieve and Trade (PAT) scheme aimed towards enhancing energy efficiency in Indian industrial sector in general and Designated Consumers (DCs) in particular. The PAT scheme was formed under the National Mission for Enhanced Energy Efficiency (NMEEE). The NMEEE is one of the eight national missions under the National Action Plan on Climate Change (NAPCC) launched by the Government of India in the year 2008.

The Bureau has envisaged that the smooth implementation of PAT scheme can be enhanced and strengthened by formulating and making available a suitable Energy Conservation Guidelines (EC Guidelines) for the targeted industry sub-sectors. Japan is one of the pioneers in implementing energy efficiency at the global level. As part of their energy efficiency efforts, the Government of Japan had introduced EC guidelines to support industries to improve energy performance. Looking at their success, the Government of India, on similar lines, has also prepared EC Guidelines for different categories of industries operating in India.

<u>Different categories of industries covered under the Energy Conservation Guidelines:</u>

Category-A

Designated Consumers covered under PAT scheme but limited to the following industries:

(1) Aluminium

(2) Cement

(3) Chlor-alkali

(4) Fertilizers

(5) Iron and Steel

(6) Petrochemicals

(7) Petroleum refineries

(8) Pulp and Paper

(9) Textile

(10) Thermal Power Stations.

Category-B

Large industries with energy consumption of less than the existing minimum threshold limits for Designated Consumers.

Category-C

Small-scale enterprises with energy costs accounting for more than 30% of the total production cost but limited to the following SME sectors:

(1) Glass

(2) Foundry

(3) Forging

(4) Ceramics

(5) Dairy

(6) Textile Industries.

Category-D

Medium enterprises with energy costs accounting for 10% to 30% of the total production costs but limited to the following sectors

(1) Brick

(2) Hand tools

(3) Food

(4) Limestone industries.

Category-E

Micro industries with material costs more significant than energy costs

SMEs – Small and Medium Sized Enterprises

OBJECTIVES OF ENERGY CONSERVATION GUIDELINES FOR INDUSTRIES:

The overall objective of the Energy Conservation Guidelines for large industries and SMEs is to guide the management and operators in large industries and Small and Medium Sized Enterprises to manage energy consumption by standardizing the energy performance values of various energy- consuming equipment and systems deployed for the manufacturing process. One of the important components under the overarching framework of the EC Guidelines is the benchmarking of standard energy performance values and a procedure for establishing target energy performance values for major energy consuming equipment, such as boiler, furnace, thermic fluid heater, waste heat recovery (WHR) equipment, motor, etc.

The objective of this document is to provide Energy Conservation guidelines to large industries that are covered as Designated Consumers under PAT mechanism of the Energy Conservation Act 2001, but limited to the list as provided in Section 1, hereafter termed as Category-A industries.

METHODOLOGY:

Activities followed for preparation of Energy Conservation Guidelines:

A review of the EC Guidelines pertaining to industries in Japan was carried out to draw a blueprint of the EC Guidelines applicable for Indian industries. Relevant secondary data from different industries were collated through a questionnaire survey and field visits.

Other sources of secondary data include

(1) Performance audits and sectoral study report
(2) Original equipment manufacturers
(3) Industries
(4) Sectoral experts
(5) Stakeholder consultations with industries and industry associations
(6) Secondary sources such as relevant websites.

Interactions with industry personnel and industry associations were carried out to understand key operating parameters in different utilities. Further discussions were held with OEMs and sectoral experts in India and Japan to ascertain the relevant secondary data collated for the different utilities.

A detailed data analysis of the relevant parameters of the various utilities Industries were carried out using statistical tools to benchmark key opera parameters as 'standard value' and 'target value'. These parameters include air ratio, flue gas temperature, surface temperature, level of WHR, efficiency of motors, efficiency of fans, corrected target power factor of electrical equipment, lighting power density, etc. The average values and standard deviations of the data samples of similar groupings were arrived at through data analysis. The collated data were sanitized to exclude extremely high or low values for the purpose of analysis.

In preparing the EC Guidelines, the existing technology standards and various industry sub-sectors in India were considered. The draft EC Guidelines presented in a stakeholder workshop in which representatives from industries, industry associations, original equipment suppliers, sectoral experts, etc., participated and provided their inputs. The revised EC Guidelines were again presented in a second stakeholder workshop to ensure synergy with the industry. With these inputs, the EC Guidelines were finalized for Category-A industries.

The 'standard values' of an energy-consuming utility include optimum performance values, which are achieved by the industry under daily routine operations; the 'target values' of the utility represent better performance values than the standard values.

These values focus essentially on those benchmarks which shall guide the industry to improve the performance of the existing facilities, new installations, and retrofits in the existing facilities.

An empirical equation was considered to arrive at standard values and target values using the average and standard deviation of the data samples.

ENERGY CONSERVATION IN ELECTRICAL INDUSTRIES

Conversion of Heat to Electricity:

The thermal power plants use solid, liquid, and gaseous fuels for generating electricity. The generated electricity is either supplied to the grid or used as captive power. The power generation may be based on steam turbine, gas turbine, diesel engine, gas engine, etc.

Power-Generation Utilities

Standard Components

(1) Management and control

A. A thermal power plant, which is used either for public distribution or dedicated captive power generation utility, shall be operated efficiently, which shall be described in the EM Manual. Further, multiple power-generation facilities operating in parallel shall be managed to ensure a proper load distribution within the utilities and improve the overall efficiency which shall be described in the EM Manual.

B. The power generation plant shall take into consideration typical characteristics of each generation utility for determining load distribution while ensuring an overall efficient operation.

(2) Measurement and recording

A. The DC shall periodically measure the overall performance of power generation utility and shall record the results according to the instructions, which shall be described in the EM Manual.

(3) Maintenance and inspection

A. The DC shall be periodically inspected and maintained to ensure a trouble-free and smooth operation and achieve the highest possible energy efficiency. Details of maintenance and inspection shall be described in the EM Manual.

(4) Necessary measures when installing new facilities

A. The DC shall select and install a new power-generation utility of optim capacity considering the existing power requirements and considering the fut trends of power demands for captive power generation.

B. The design net heat rate of the newly installed power-generating utility at the receiving end shall not be significantly higher than the average level of the existing thermal power generation utilities.

Target Components

A. The DC shall install state-of-the-art on-line measurements and recording equipment to measure and control key operating parameters.

Cogeneration Utilities

Standards Components

(1) Management and control

A. The DC shall manage and operate equipment used in cogeneration facilities (e.g boilers, gas turbines, steam turbines, gas engines, and diesel engines) to achieve optimum energy efficiency under variable load conditions, which shall be described in the EM Manual.

B. The DC shall consider characteristics of different facilities to determine an optimum load distribution to respond to load variations for achieving the highest energy efficiency.

C. For cogeneration utilities with back pressure or extraction-type turbines, the industry shall control minimum allowable values of back pressure or bleeder pressure according to the instructions concerning the values, which shall be described in the EM Manual.

(2) Measurement and recording

A. The key parameters that influence the overall efficiency of equipment (e.g., boilers, gas turbines, steam turbines, gas engines, and diesel engines) shall be periodically measured and recorded according to the instructions concerning measurements and records of such parameters, which shall be described in the EM Manual.

B. In case of cogeneration utilities operated under low pressure, which is close to the minimum allowable limit for back pressure or extraction turbine, the facilities shall periodically measure and record the operating parameters, which shall be described in the EM Manual. These key parameters, which shall be measured and recorded, include operational time, inlet/outlet pressure, back or extraction pressure, and quantity of steam used, etc.

(3) Maintenance and inspection

A. Cogeneration utilities shall be periodically maintained and inspected in a way that maintains the highest level of overall efficiency, which shall be described in the EM Manual.

(4) Necessary measures when installing new facilities

A. The DC shall thoroughly analyse the actual use and future trends of heat and power demands and the availability of exhaust heat while selecting and installing a new cogeneration utility of optimum capacity. Historical data recorded for a period of one year or more shall be used for this purpose.

Target Components

A. The DC shall consider installing new cogeneration utility in case of large quantity of steam/ hot water demand and the continuous availability of exhaust heat throughout the year.

B. The DC shall explore modifying the existing operating conditions of extraction/back pressure turbine if it helps in improving the overall performance of the utility while ensuring the services.

Prevention of Energy Loss Due to Heat Radiation and Electric Resistance

Thermal energy and electrical energy are commonly used in various industrial processes. Radiation loss takes place in high temperature zones, which is controlled by better insulation on the surface and reducing openings. Electrical losses occur in various distribution lines connecting electrical utilities, such as resistance heating systems, cables, transformers, motors, etc.

Standards Components

(1) Management and control

A. The DC shall undertake thermal insulation work on different systems such as steam and condensate pipes, ducts, equipment, etc., which are used for transporting heat media, process fluid for heating, etc. (hereafter, "heat-using equipment") according to the industrial standard practices for thermal insulation works and equivalent standards.

B. The existing industrial furnaces shall be thermally insulated to improve the insulation performance to maintain external surface temperature based on the standard value as listed in table 5.4. The external surface temperature for the boiler shall be maintained as per Note (2) provided in table 5.4.

(2) Measurement and recording

A. The DC shall periodically measure all key parameters of surfaces to keep track and reduce heat losses. These parameters include the temperature of external surfaces of furnace, heated object temperature, mass of the object and waste gas temperature, etc. The results shall be analysed, heat losses shall be quantified, and the heat balance shall be prepared, which shall be described in the EM Manual.

(3) Maintenance and inspection

A. Heat-using equipment shall be periodically inspected to maintain proper insulation to reduce heat losses according to the instructions concerning maintenance and inspection of the measures (e.g., insulation work), which shall be described in the EM Manual.

B. Steam traps shall be periodically maintained and inspected to prevent steam leaks and clogging caused by the malfunctioning of traps. The maintenance and inspection of the steam traps shall be detailed in the EM Manual.

(4) Necessary measures when installing new facilities

A. While installing a new heat-using utility, actions to improve thermal insulation shall be undertaken. These include employing optimum thickness of insulation, selecting low thermal conductivity material, multi-layer insulation, etc.

B. The DC shall minimize heat losses through radiation and air ingression by adopting suitable measures. These include minimum openings, proper sealing. double doors, air curtains, etc.

C. The DC shall reduce the heat radiation area by transporting heat media through a streamlined pipe route.

D. For a batch operated furnace with an operating temperature more than 1000°C, the utility shall apply veneering on interior surfaces.

Target Components

A. The DC shall examine the potential measures such as low thermal mass furniture and better insulation for bodies, bases, fixtures, and equipment used in handling hot materials to minimize heat losses. It includes boilers, furnaces, steam system, condensate recovery system, etc.

B. The industrial furnace shall be provided with optimum insulation using compatible material to reduce heat losses from the surfaces. The surface temperature of an industrial furnace shall be maintained as specified in table 5.4 as the target value.

C. For batch type furnaces operating with an internal temperature of more than 600°C, the utility shall consider insulation based on the temperatures listed in table 5.4 as the target value.

D. The DC shall examine various measures to improve thermal insulation of heat- using facilities. These shall include higher thickness of insulation, selecting low thermal conductivity insulating materials, veneering on internal surfaces, etc.

E. The DC shall minimize heat losses through dissipation and air leakage by adopting appropriate measures. These measures include reduced openings, improved sealing, double doors, air curtains, etc.

F. The DC shall examine the existing thermal sealing and undertake measures in heat-using facilities to prevent leakage of heat media from locations like rotating parts, joints, etc.

G. The DC shall also examine use of improved streamlined pipe route for transporting heat media to reduce heat radiations.

H. The DC shall examine methods such as covering of open-type facilities, steam using facilities and transport facilities which use high-temperature materials reduce heat losses, except in cases wherein it is required to cool the facilities while transportation.

PREVENTION OF ELECTRICITY LOSS DUE TO ELECTRIC RESISTANCE

Standards Components

(1) Management and control

A The DC shall manage and operate electrical systems such as transformers and umpable power supply systems to achieve the highest efficiency and minimine energy losses, which shall be described in the EM Manual. It shall ensure efficient operation ever during part-load conditions. The DC shall further adjust the number of units (transformers or uninterruptible power supply systems) in operation for optimum load allocation as per power requirements of various sections

B. The DC shall undertake actions to reduce distribution losses in power-receiving and transforming utilities. These actions shall include shorter distribution lines, proper current-carrying capacity of conductors, and an appropriate distribution voltage, etc., which shall be described in the EM Manual.

C. Operating practices to control starting or stopping of capacitors in line with the operation of the equipment in which they are installed shall be described in the EM Manual

D. The DC shall distribute single-phase loads in such a way that there is no current imbalance in the three-phase distribution system, which shall be described in EM Manual.

E. The utility shall be equipped with phase-protection relay/ single phasing preventer to avoid motor burn outs

F. The equipment that use electricity (hereafter, electricity-using utility') shall be managed and controlled according to the instructions concerning standard operating practices of the utility, which shall be described in the EM Manual.

G. The DC shall manage and control current flow to electricity-using facilities to minimise electrical losses which shall be described in the EM Manual.

(2) Measurement and recording

A. The DC shall periodically measure and record parameters that are required to reduce electricity losses, which shall be described in the EM Manual. Some of the parameters shall include electricity consumption and voltage, current and power factor in power-receiving and transforming equipment etc.

(3) Maintenance and inspection

A. The DC shall undertake preventive maintenance and routine inspection of electrical equipment (power-receiving and transforming equipment, and power distribution equipment), which shall be described in the EM Manual.

(4) Necessary measures when installing new facilities

A. While installing new equipment for power-receiving and distribution equipment, the DC shall select suitable capacity and highly efficient equipment to achieve the overall energy efficiency.

Target Components

A. The DC shall examine the improvements of the power factor at the receiving end by installing measures, such as automatic power factor controller, capacitor banks, etc., in the distribution facilities as shown as the target value in Table 5.5.
B. The DC shall install advanced management systems such as Supervisory Control and Data Acquisition (SCADA), which shall be integrated with each of the electricity-using utility towards automatic monitoring and recording of all key operating parameters.

Table 5.5. Target Power Factor

Load Type	Target Power Factor
Induction motor	0.95
Distribution system	0.99
Induction furnace	0.95

Welding machine	0.90 and above
DC drives	0.90 and above
Fluorescent lamp	0.95 and above

CONVERSION OF ELECTRICITY TO MOTOR POWER, HEAT AND LIGHT
Electric motors are widely used in industries for various loads, such as fans, blowers, pumps, compressors, conveyors, etc. A wide range of capacities of motors are used for these applications.

Further, electricity is used for heating and melting applications in furnaces and various types of industrial lighting.

Facilities Using Motors and Heaters

Standards Components

(1) Management and control

A. The DC shall stop motor driven equipment when not in use or during idle operation, which shall be described in the EM Manual. It shall consider the energy losses during idle run period versus energy consumption during initial start-up.

B. Parallel operation of multiple motors shall be managed in a way to achieve high efficiency of the motors, which shall be described in the EM Manual. Suitable load allocation during parallel operation of multiple motors shall be implemented during partial load conditions to maintain higher efficiency under varying load conditions.

C. The DC shall review the current use, end pressure and discharge rate of fluid machines (e.g., pumps, fans, blowers, compressors, etc.), and manage to reduce the load of the connected electric motors according to the instructions which shall be described in the EM Manual. The instructions may include the number of operating units, speed reduction, pipe layout and dimensions, impeller size, etc.. to cater to the variable load conditions.

D. The DC shall adopt measures in electric heating utilities (e.g., induction furnaces, arc furnaces, and resistance furnaces) to enhance the efficiency, which shall be provided in the EM Manual. The measures include loading pattern, reducing idle operation, better insulation, installation of the WHR system, etc., as applicable.

E. The electrolytic facilities shall use electrodes of a suitable size, shape, and characteristics, and shall be managed to attain high efficiency, which shall be described in the EM Manual. The instructions include distance between electrodes, concentration of electrolytes, and contact resistance of conductors.

F. The DC shall manage use of electricity in different types of electricity-using utilities (e.g., motor driven utilities, electric heating utilities, etc.) with a view to reduce electrical losses (e.g., voltage or current losses), which shall be described in the EM Manuai.

(2) Measurement and recording

A. The DC shall measure such parameters of electricity-using equipment and record the results which will be necessary to reduce electrical losses, which shall be described in the EM Manual.

(3) Maintenance and inspection

A. The motor-driven equipment shall be periodically inspected and maintained to reduce mechanical losses occurring in electric motors, power transmission units, and machines that apply loads to the motors, which shall be described in the EM Manual.

B. The motor-driven utility shall be periodically invited and maintained se different fluid machines (eg, pumps, Fans, Blowers, and compressors to prevent leakages and reduce resistance of pipes and dots, which shall be described in the EM Manual.

C. The DC shall reduce electric resistance losses in electric-heating equipment and electrolytic equipment through periodic instance and inspection of wire connections, contacts of switch, one which shall be described in the EM Manual

(4) Necessary measures when installing new facilities

A. The DC shall install and use efficient motors of suitable sizes

B. The DC shall install motors with compatible configurations to meet applications with large fluctuations of loads.

Target Components
A. The DC shall install and use high-energy efficient motors

B. The industry shall install energy-saving measures such as VFD in a applied utility with large load fluctuations.

C. The DC shall examine different heating methods (combustion of fuel, steam, fe air, thermic fluids, electric heating, etc.) for the selection of electric heating. It shall consider parameters, such as heat load, temperature range and energy costs for comparison.

PUMPS AND PUMPING SYSTEM

Pumps are used for a wide range of applications to transfer fluids through mechanical action. According to the basic operating principle, pumps can be classified as either dynamic pumps or positive displacement pumps. Dynamic pumps further classified into centrifugal pumps and special-effect pumps. Positive displacement pumps are classified into rotary pumps and reciprocating pumps Centrifugal pumps account for the major share of electricity consumption in the industrial sector.

Some of the centrifugal pumps used by the industry include: (1) mono-block pumps, (2) end-suction pumps, (3) split-case pumps, and (4) multistage pumps. The guideline covers centrifugal pumps, boiler feed water pumps (BFP), and vertical turbine pumps.

Standard Components

(1) Management and control

A. The DC shall use 'characteristic curves' provided by the manufacturer for the monitoring and control of pump operation. The pump(s) shall be operated close to 'Best Operating Point' (BOP) as specified by the pump manufacturer.

B. The DC shall use pumps with highest efficiency to meet the base load when multiple pumps are in operation.

C. In case of the DC using multi-pumps, it shall manage and control the loading of pump in such a way that it achieves the highest possible loading near the BOP in respective characteristic curve.

D. The DC shall ensure optimum loading of pumps during the entire range of operation both during full load and part load while operating multiple pumps in parallel, which shall be provided in the EM Manual.

E. The DC shall manage the piping network of the pumping system and the control operating parameters, such as flow rate, pressure, and temperature, which shall be provided in the EM Manual.

F. The DC shall maintain a minimum Net Positive Suction Head (NPSH) of pumps as prescribed by the manufacturer

(2) Measurement and recording

A. The DC shall measure and record key operating parameters such as the total differential head, flow rate and power consumption to evaluate efficiency of pumps which shall be described in EM Manual. It shall use on-line monitoring for centralized large system and periodical measurement for decentralised smaller pumps.

(3) Maintenance and inspection

A. The DC shall undertake routine/scheduled overhauling of pumps according to the instructions provided by the manufacturers, which shall be described in the EM Manual.

B. The DC shall maintain and inspect parameters, such as speed of motor, body temperature in pump ends, and vibration on a periodical basis, which shall be described in the EM Manual.

C. The DC shall undertake corrective maintenance in case of a significant drop in the total differential head observed in the pumping system.

D. The DC shall ensure a dynamic balancing of pump assembly after each overhauling.

(4) Necessary measures when installing new facilities

A. The DC shall select correct capacity of pump with energy efficient systems such as IE3 motor or permanent magnet synchronous motor, variable frequency drives (VFD), cogged v-belts for belt driven systems, etc., while considering existing demand and immediate future expansion plans.

B. The DC shall undertake water balance of the plant to assess the total pumping capacity.

C. The DC shall undertake the dynamic balancing of pump assembly during installation.

D. The DC shall optimize the number of stages available in a multi-stage pump (eg boiler feedwater pump) in case of availability of the head margins. E. The DC shall design and install a pumping network with minimum system resistance using seamless pipes, which shall be described in the EM Manual. F. The DC shall use a booster for small loads requiring higher pressures.

Target Components

A. The DC shall select and install most efficient pumps while matching the BOP with system parameters, considering both the existing requirements and the immediate expansion plans.

B. The DC shall install a proper size of suction valve as recommended by the B manufacturers.

C. The DC shall further include measures, such as correct sizing, seamless or fibre-reinforced plastic (FRP) pipe, better layout, plugging off leakages, application of improved insulation (hot and cold media), and the regular maintenance and installation of the appropriate measurement systems for pressure and flow, both at the source and points of usage.

AIR COMPRESSORS AND COMPRESSED AIR NETWORK

Air compressors are used in industries for a variety of applications to meet process requirements, operate pneumatic tools and meet instrumentation needs. These are mechanical devices used to compress and pressurize air. The centralised compressor air network consists of compressor(s), filter, after cooler, dryer, intelligent electronic control system, receiver tank (s), distribution piping, air cylinder, nozzle, ejector, etc.

The pressurized air is transferred to various points of usage either directly or through receiver tanks.

The compressors can be classified into

(1) positive displacement compressor and

(2) dynamic compressor.

Standard Components

(1) Management and control

A. The DC shall ensure the drawing of clean, cool, and dry air by compressors for optimum performance. It shall manage and control operations as per the instructions provided in the EM Manual in the compressed air system.

B. The DC shall use a suitable size of air compressors to meet the plant demands.

C. The DC shall pre-set a minimum possible generation pressure to optimise system performance, which shall be explained in the EM Manual.

D. The DC shall install receiver tanks with sufficient capacities for storing compressed air to eater to load demands and fluctuations.

E. The DC shall use dedicated air compressors to meet exclusive high or low- pressure demands.

F. In case of operation of multiple air compressors, the DC shall use the most efficient compressors to meet the base load.

(2) Measurement and recording

A. The DC shall undertake an on-line monitoring of pressure and air flow at the downstream of compressor and the power consumption of individual compressors to assess the performance, ie., Specific Power Consumption (SPC) which shall be described in the EM Manual

(3) Maintenance and inspection

A. The DC shall inspect and clean air filters on a weekly basis. The replacement of air filters shall be based on suction air conditions.

B. The DC shall undertake an overhauling of air compressors on a periodical basis, as is recommended by the manufacturer.

C. The DC shall avoid moisture carryover by compressed air. It shall drain the moisture accumulated on a regular basis.

D. The DC shall conduct leakage tests and plug off the compressed air leakages, which shall be described in the EM Manual.

(4) Necessary measures when installing new facilities

A. The DC shall undertake demand assessments of compressed air to select a suitable compressed air system based on the existing requirements as well as considering the immediate expansion plans. This includes energy-efficient systems, such as a inbuilt VFD, motor with permanent magnet, inverter type air compressor, etc.

B. The DC shall select and install air compressors with the lowest SPC while meeting the compressed air demands.

C. The DC shall install air compressor in a direction that a hermetically closed room or intake of contaminated air (oil, gas, etc.) is avoided.

D. The DC shall design and install a compressed air network with a minimum pressure drop. It shall use seamless metallic pipes or 'fiber reinforced plastic’ (FRP) pipe for compressed air lines, which shall be described in the EM Manual

E. The DC shall install intelligent electronic control systems to minimise energy consumption and reduce loss of compressed air. It shall also include an auto drain system for moisture removal.

F. The DC shall locate air compressors in such a way that it reduces the piping length and minimises line-pressure losses.

G. The DC shall meet fluctuations in compressed air demands using VFD-enabled screw air compressors. In case of a multiple air compressors system, the DC shall use one-inverter type air compressor with a suitable pressure setting to meet the variable load conditions while the other air compressors shall be used in continuous operation to cater to the base load.

H. The DC shall use centrifugal compressors for meeting a high volume with low pressure applications, wherever feasible.

I. The DC shall install air dryers in the distribution line which supplies to dry air usage points only, e.g., instrumentation air.

J. The DC shall ensure the proper location of air compressors and the quality of suction air as per the recommendation of the manufacturers, which shall be described in the EM Manual.

Target Components

A. The DC shall undertake demand assessment of compressed air at plant level to select and install a suitable compressed air system.

B. The DC shall avoid installing oversized air compressors, which may lead to inefficiencies.

C. The DC shall undertake the necessary measures such that the overall leakage from the compressed air network shall remain less than 10% of the total compressed air generation.

D. The DC shall optimise a compressed air system using a ring-frame network and avoiding unnecessary bends, redundant pipes, valves, etc.