

## **MODULE-I**

### **D.C NETWORKS**

#### **1.1 Kirchoff's Laws:-**

##### **1.1.1. Kirchoff's current law or point law (KCL)**

Statement:- In any electrical network, the algebraic sum of the currents meeting at a point is zero.

$$\Sigma I = 0 \dots \dots \dots \text{at a junction or node}$$

Assumption:- Incoming current = positive

Outgoing current = negative

##### **1.1.2. Kirchoff's voltage law or mesh law (KVL)**

Statement:- The algebraic sum of the products of currents and resistances in each of the conductors in any closed path (or mesh) in a network plus the algebraic sum of the emfs in that path is zero.

$$\Sigma IR + \Sigma emf = 0 \dots \dots \dots \text{round the mesh}$$

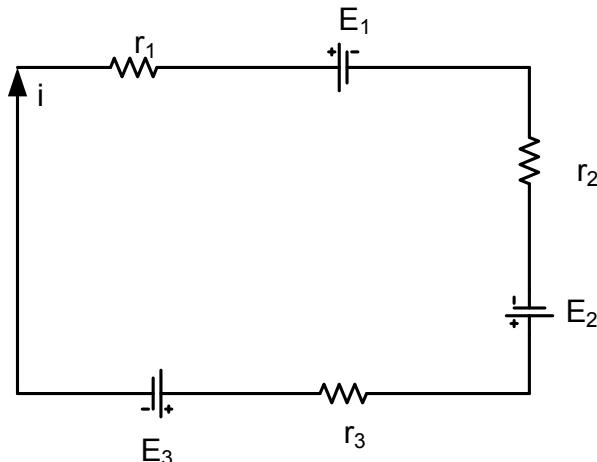
Assumption:- i) Rise in voltage (If we go from negative terminal of the battery to positive terminal) = positive

ii) Fall in voltage (If we go from positive terminal of the battery to negative terminal) = negative

iii) If we go through the resistor in the same direction as current then there is a fall in potential. Hence this voltage is taken as negative.

iv) If we go through the resistor against the direction of current then there is a rise in potential. Hence this voltage drop is taken as positive.

**Example:-** Write the loop equation for the given circuit below  
**(Supplementary exam 2004)**



Solution: Apply KVL to the loop,

$$\begin{aligned} -ir_1 - E_1 - ir_2 + E_2 - ir_3 - E_3 &= 0 \\ \Rightarrow E_1 - E_2 + E_3 &= -ir_1 - ir_2 - ir_3 \\ \Rightarrow E_1 - E_2 + E_3 &= -i(r_1 + r_2 + r_3) \end{aligned}$$

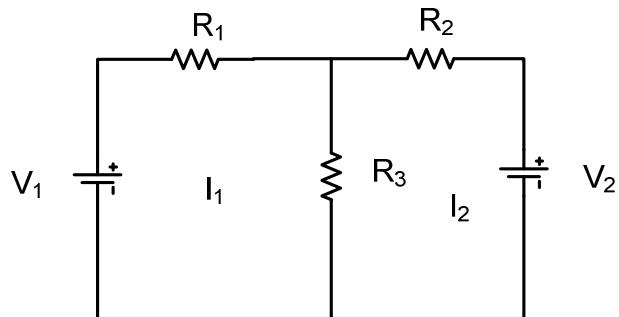
## 1.2. MAXWELL'S LOOP CURRENT METHOD (MESH ANALYSIS)

Statement:- This method determines branch currents and voltages across the elements of a network. The following process is followed in this method:-

- Here, instead of taking branch currents (as in Kirchoff's law) loop currents are taken which are assumed to flow in the clockwise direction.
- Branch currents can be found in terms of loop currents
- Sign conventions for the IR drops and battery emfs are the same as for Kirchoff's law.
- This method is easier if all the sources are given as voltage sources. If there is a current source present in a network then convert it into equivalent voltage source.

### Explanation:-

Consider a network as shown in Fig. below. It contains two meshes. Let  $I_1$  and  $I_2$  are the mesh currents of two meshes directed in clockwise.



Apply KVL to mesh-1,

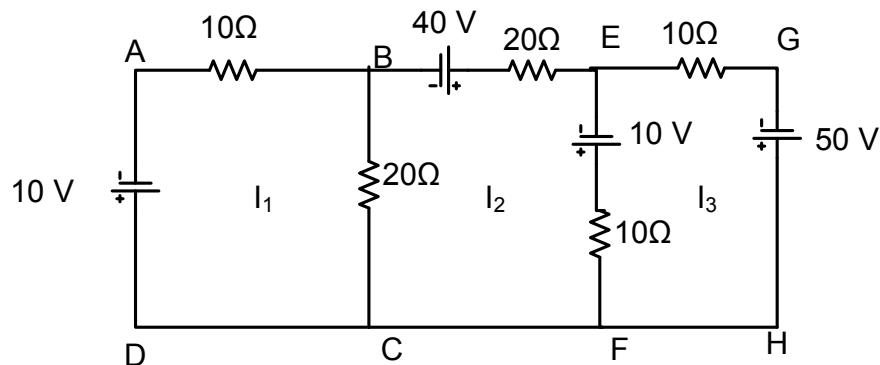
$$V_1 - I_1 R_1 - (I_1 - I_2) R_3 = 0$$

Apply KVL to mesh-2,

$$-I_2 R_2 - V_2 - (I_2 - I_1) R_3 = 0$$

When we consider mesh-1, the current  $I_1$  is greater than  $I_2$ . So, current through  $R_3$  is  $I_1 - I_2$ . Similarly, when we consider mesh-2, the current  $I_2$  is greater than  $I_1$ . So, current through  $R_3$  is  $I_2 - I_1$ .

**Example:** Find  $I_1$ ,  $I_2$  and  $I_3$  in the network shown in Fig below using loop current method



Solution:- For mesh ABCDA,

$$\begin{aligned} -I_1 \times 10 - (I_1 - I_2) \times 20 - 10 &= 0 \\ \Rightarrow 3I_1 - 2I_2 &= -1 \end{aligned} \quad (1)$$

For mesh BEFCB,

$$\begin{aligned} 40 - I_2 \times 20 + 10 - (I_2 - I_3) \times 10 - (I_2 - I_1) \times 20 &= 0 \\ \Rightarrow 2I_1 - 5I_2 + I_3 &= -5 \end{aligned} \quad (2)$$

For mesh EGHFE,

$$\begin{aligned} -10I_3 + 50 - (I_3 - I_2) \times 10 - 10 &= 0 \\ \Rightarrow I_2 - 2I_3 &= -4 \end{aligned} \quad (3)$$

Equation (2)  $\times 2 +$  Equation (3)

$$4I_1 - 9I_2 = -14 \quad (4)$$

Solving eq<sup>n</sup> (1) & eq<sup>n</sup> (4)

$$I_1 = 1 \text{ A}, I_2 = 2 \text{ A}, I_3 = 3 \text{ A}$$

### **1.3. NODAL ANALYSIS**

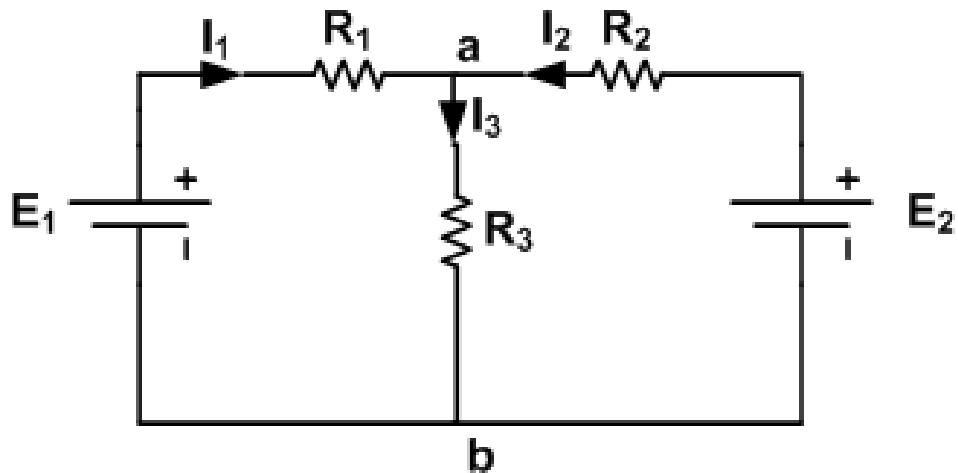
**Statement:-** This method determines branch currents in the circuit and also voltages at individual nodes.

The following steps are adopted in this method:-

- Identify all the nodes in the network.
- One of these nodes is taken as reference node in at zero potential
- The node voltages are measured w.r.t the reference node
- KCL to find current expression for each node
- This method is easier if all the current sources are present. If any voltage source is present, convert it to current source

- The number of simultaneous equations to be solved becomes  $(n-1)$  where ‘ $n$ ’ is the number of independent nodes.

**Explanation:-**



At node ‘a’       $I_1 + I_2 = I_3$

By ohms law,     $I_1 = \frac{E_1 - V_a}{R_1}, I_2 = \frac{E_2 - V_a}{R_2}, I_3 = \frac{V_a}{R_3}$

Therefore,         $V_a \left[ \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right] - \frac{E_1}{R_1} - \frac{E_2}{R_2} = 0$

or,                 $V_a \left[ \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right] - \frac{E_1}{R_1} - \frac{E_2}{R_2} = 0$

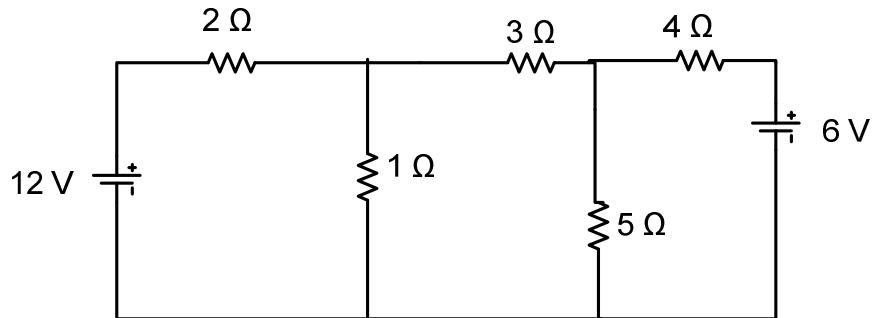
or,                 $V_a \left[ \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right] - \frac{E_1}{R_1} - \frac{E_2}{R_2} = 0$

Hence,

- Node voltage multiplied by sum of all the conductance connected to this node. This term is positive
- The node voltage at the other end of each branch (connected to this node) multiplied by conductance of this branch). This term is negative.

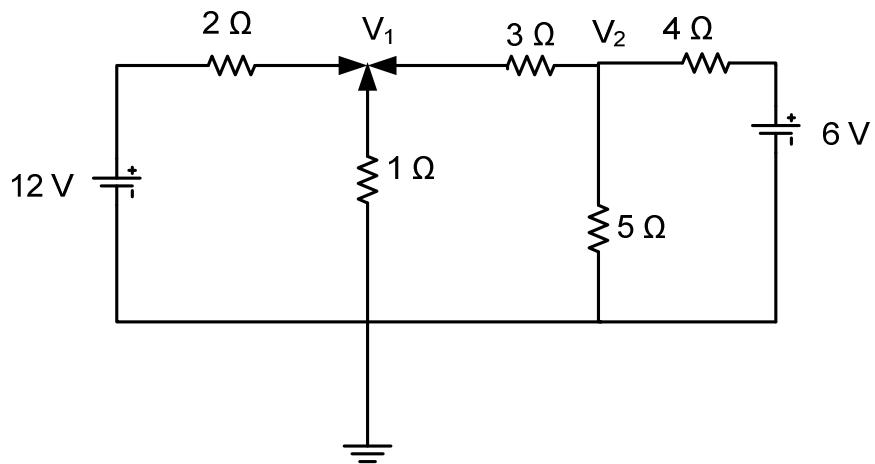
**Example:-** Use nodal analysis to find currents in the different branches of the circuit shown below.

(Supplementary Exam July- 2004)



Solution:-

Let  $V_1$  and  $V_2$  are the voltages of two nodes as shown in Fig below



Applying KCL to node-1, we get

$$\begin{aligned} \frac{12 - V_1}{2} + \frac{0 - V_1}{1} + \frac{V_2 - V_1}{3} &= 0 \\ \Rightarrow 36 - 3V_1 - 6V_1 + 2V_2 - 2V_1 &= 0 \\ \Rightarrow -11V_1 + 2V_2 &= 36 \dots\dots\dots(1) \end{aligned}$$

Again applying KCL to node-2, we get:-

$$\begin{aligned}\frac{V_1 - V_2}{3} + \frac{0 - V_2}{5} + \frac{6 - V_2}{4} &= 0 \\ \Rightarrow 20V_1 - 47V_2 + 90 &= 0 \\ \Rightarrow 20V_1 - 47V_2 &= -90 \dots\dots\dots\dots(2)\end{aligned}$$

Solving Eq (1) and (2) we get  $V_1 = 3.924$  Volt and  $V_2 = 3.584$  volt

$$\text{Current through } 2\Omega \text{ resistance} = \frac{12-V_1}{2} = \frac{12-3.924}{2} = 4.038 \text{ A}$$

$$\text{Current through } 1\Omega \text{ resistance} = \frac{0-V_1}{1} = -3.924 \text{ A}$$

$$\text{Current through } 3\Omega \text{ resistance} = \frac{V_1-V_2}{3} = 0.1133 \text{ A}$$

$$\text{Current through } 5\Omega \text{ resistance} = \frac{0-V_2}{5} = -0.7168 \text{ A}$$

$$\text{Current through } 4\Omega \text{ resistance} = \frac{6-V_2}{4} = 0.604 \text{ A}$$

As currents through  $1\Omega$  and  $5\Omega$  are negative, so actually their directions are opposite to the assumptions.

#### **1.4. STAR-DELTA CONVERSION**

**Need:-** Complicated networks can be simplified by successively replacing delta mesh to star equivalent system and vice-versa.

In delta network, three resistors are connected in delta fashion ( $\Delta$ ) and in star network three resistors are connected in wye (Y) fashion.

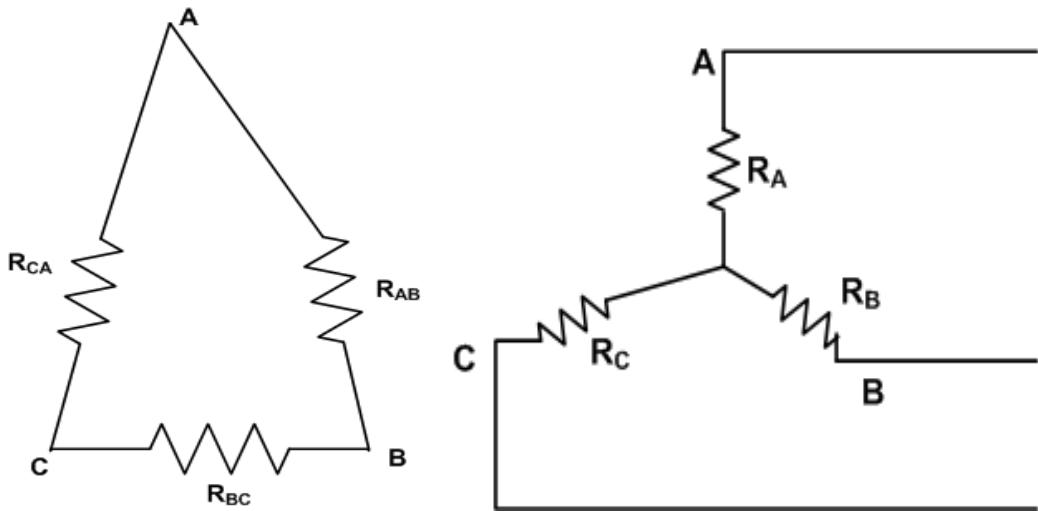


Fig. 1.4.1.

a) Delta connection

b) Star connection

1.4.1. **Delta to Star Conversion**:- From Fig. 1.4.1 (a),  $\Delta$  : Between A & B, there are two parallel paths.

$$\text{Resistance between terminal A \& B} = \frac{R_{AB}(R_{BC} + R_{CA})}{R_{AB} + R_{BC} + R_{CA}}$$

From Fig. 1.4.1 (b), STAR: Between A & B two series resistances are there  $R_A + R_B$ . So, terminal resistances have to be the same.

$$R_A + R_B = \frac{R_{AB}(R_{BC} + R_{CA})}{R_{AB} + R_{BC} + R_{CA}} \dots\dots\dots(1)$$

$$R_B + R_C = \frac{R_{BC}(R_{CA} + R_{AB})}{R_{AB} + R_{BC} + R_{CA}} \dots\dots\dots(2)$$

$$R_C + R_A = \frac{R_{CA}(R_{AB} + R_{BC})}{R_{AB} + R_{BC} + R_{CA}} \dots\dots\dots(3)$$

Eq {(1)-(2)}+(3) & Solving,-

$$R_A = \frac{R_{AB} \times R_{CA}}{R_{AB} + R_{BC} + R_{CA}} \dots\dots\dots(4)$$

$$R_B = \frac{R_{AB} \times R_{BC}}{R_{AB} + R_{BC} + R_{CA}} \dots\dots\dots(5)$$

$$R_C = \frac{R_{CA} \times R_{BC}}{R_{AB} + R_{BC} + R_{CA}} \dots \dots \dots \quad (6)$$

**Easy way to remember:-**

$$\text{Any arm of star connection} = \frac{\text{Product of two adjacent arms of delta}}{\text{sum of arms of delta}}$$

### **1.4.2. Star to Delta conversion**

Eq { (1) X (2) } + (2) X (3) + (3) X (1) & Simplifying,-

$$R_{AB} = \frac{R_A R_B + R_B R_C + R_C R_A}{R_C} = R_A + R_B + \frac{R_A R_B}{R_C}$$

$$R_{B|C} = R_B + R_C + \frac{R_B R_C}{R_A}$$

$$R_{CA} = R_C + R_A + \frac{R_C R_A}{R_B}$$

**Easy way to remember:-** *Resistance between two terminals of delta = sum of star resistance connected to those terminals + product of the same to resistance divided by the third resistance.*

**Example(delta to star):-** Convert the following Delta Resistive Network into an equivalent Star Network.

$$Q = \frac{AC}{A+B+C} = \frac{20 \times 80}{130} = 12.31\Omega$$

$$P = \frac{AB}{A+B+C} = \frac{20 \times 30}{130} = 4.61\Omega$$

$$R = \frac{BC}{A+B+C} = \frac{30 \times 80}{130} = 18.46\Omega$$

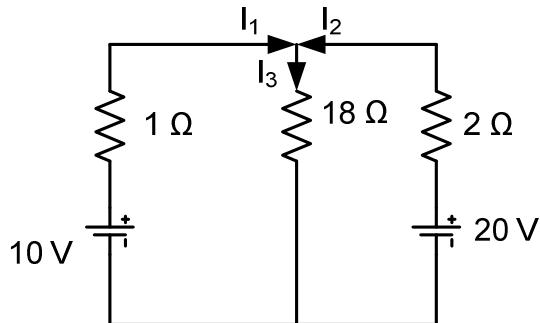
## NETWORK THEOREMS

- SUPERPOSITION THEOREM
- THEVENIN'S THEOREM
- NORTON'S THEOREM
- MAXIMUM POWER TRANSFER THEOREM

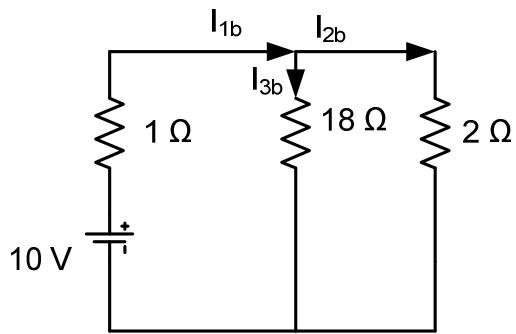
### 1. Superposition theorem

Statement:- In a network of linear resistances containing more than one generator (or source of emf), the current which flows at any point is the sum of all the currents which would flow at that point if each generator were considered separately and all the other generators replaced for the time being by resistances equal to their internal resistance.

**Example:-** By means of superposition theorem, calculate the currents in the network shown.



Step 1. Considering 10 V battery



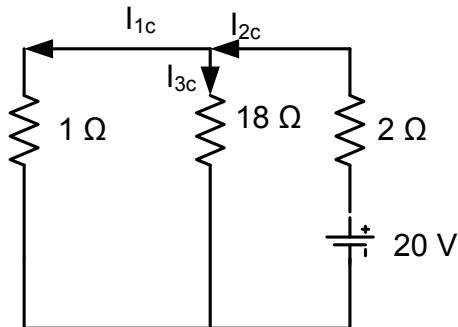
$$R_{eq} = \frac{2 \times 18}{2 + 18} + 1 = 2.8 \Omega$$

$$I_{1b} = \frac{10}{2.8} = 3.57 \text{ A}$$

$$I_{2b} = 3.57 \times \frac{18}{20} = 3.21 \text{ A}$$

$$I_{3b} = I_{1b} - I_{2b} = 0.36 \text{ A}$$

### Step 2. Considering 20 V battery



$$R_{eq} = \frac{1 \times 18}{1 + 18} + 2 = 2.95 \Omega$$

$$I_{2c} = \frac{20}{2.95} = 6.78 A$$

$$I_{1c} = 6.78 \times \frac{18}{19} = 6.42 A$$

$$I_{3b} = I_{2c} - I_{1c} = 0.36 A$$

### Step 3. Results

$$I_1 = I_{1b} - I_{1c} = 3.57 - 6.42 = -2.85 A$$

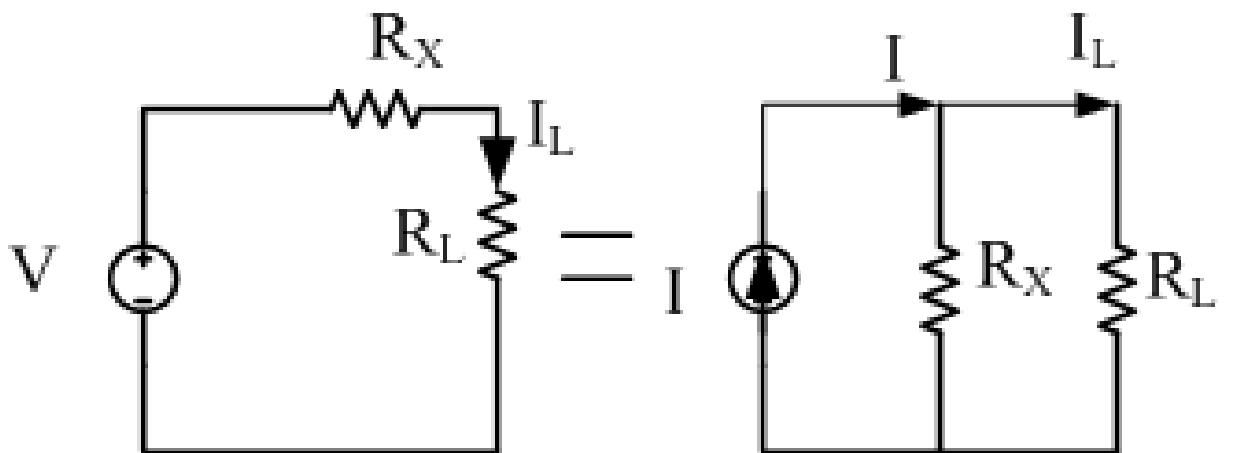
$$I_2 = I_{2c} - I_{2b} = 6.78 - 3.21 = 3.57 A$$

$$I_3 = I_{3b} + I_{3c} = 0.36 + 0.36 = 0.72 A$$

### 2. SOURCE CONVERSION:-

**Statement:** A voltage source (V) with a series resistance (R) can be converted to a current source ( $I=V/R$ ) with a parallel resistance (R) and vice-versa.

**Proof:-**



$$I_L = \frac{V}{R_X + R_L} \quad (1)$$

$$I_L = I \frac{R_X}{R_X + R_L} \quad (2)$$

From Eq. (1) & (2)

$$V = IR_X \quad (3)$$

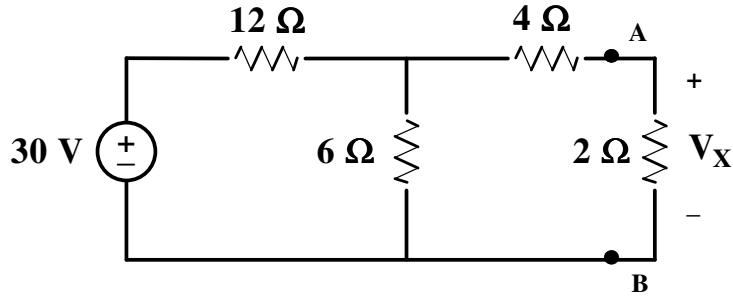
- **STATEMENT:** The two circuits are said to be electrically equivalent if they supply equal load currents with the same resistance connected across their terminals.
- voltage source having a voltage  $V$  and source resistance  $R_X$  can be replaced by  $I (= V/R_X)$  and a source resistance  $R_X$  in parallel with current source.
- Current source  $I$  and source resistance  $R_X$  can be replaced by a voltage source  $V (=IR_X)$  and a source resistance  $R_X$  in series with  $V$ .

### 3. THEVENIN'S THEOREM:-

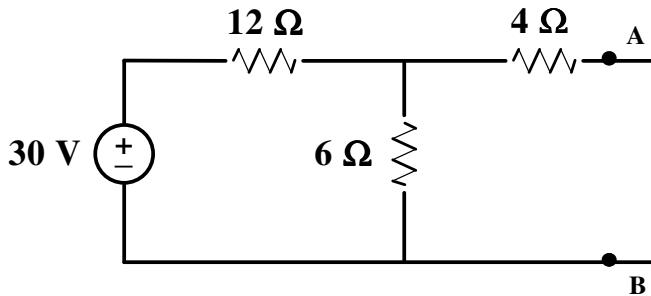
**Statement:-** Any pair of terminals  $AB$  of a linear active network may be replaced by an equivalent voltage source in series with an equivalent

resistance  $R_{th}$ . The value of  $V_{th}$  (called the Thevenin's voltage) is equal to potential difference between the terminals  $AB$  when they are open circuited, and  $R_{th}$  is the equivalent resistance looking into the network at  $AB$  with the independent active sources set to zero i.e with all the independent voltage sources short-circuited and all the independent current sources open-circuited.

Example:- Find  $V_x$  by first finding  $V_{TH}$  and  $R_{TH}$  to the left of A-B



Solution:- step1. First remove everything to the right of A-B.

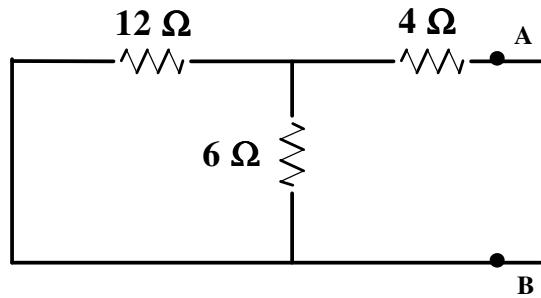


$$V_{AB} = \frac{(30)(6)}{6 + 12} = 10 V$$

Notice that there is no current flowing in the  $4 \Omega$  resistor (A-B) is open. Thus there can be no voltage across the resistor.

Step 2. To find  $R_{th}$

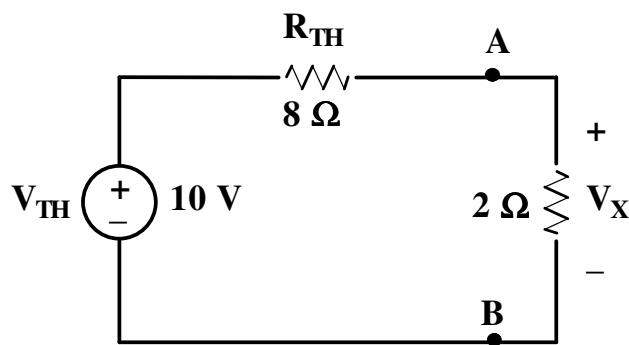
We now deactivate the sources to the left of A-B and find the resistance seen looking in these terminals.



$$R_{TH} = 12 \parallel 6 + 4 = 8 \Omega$$

Step 3. To find  $V_x$

After having found the Thevenin circuit, we connect this to the load in order to find  $V_x$ .



$$V_x = \frac{(10)(2)}{2+8} = 2V$$

#### 4. NORTON'S THEOREM:

**Statement:** Any two terminal linear active network (containing independent voltage and current sources), may be replaced by a constant current source  $I_N$  in parallel with a resistance  $R_N$ , where  $I_N$  is the current flowing through a short circuit placed across the terminals and  $R_N$  is the equivalent resistance of the network as seen from the two terminals with all sources replaced by their internal resistance.

**Example:** Find the Norton equivalent circuit to the left of terminals A-B for the network shown below. Connect the Norton equivalent circuit to the load and find the current in the  $50\ \Omega$  resistor.

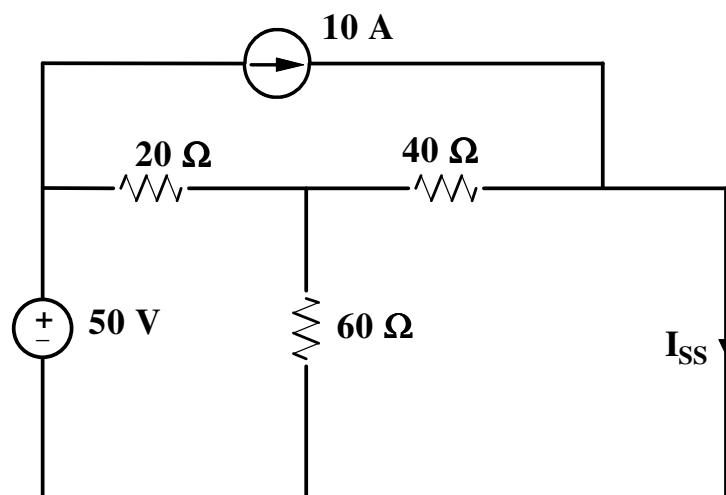
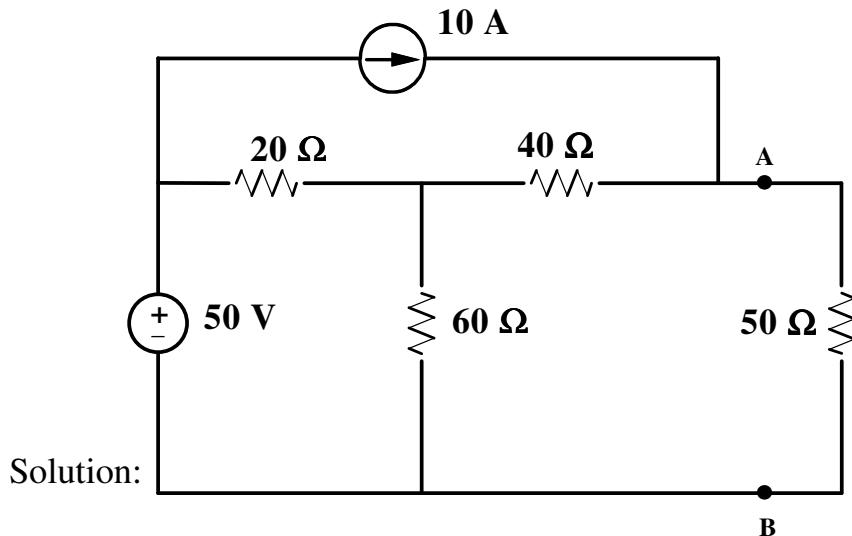
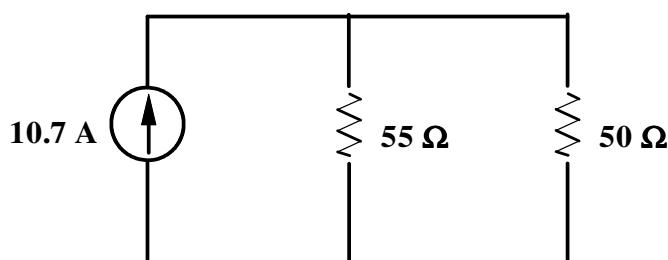


Fig. Circuit to find  $I_{NORTON}$

$$I_{ss} = 10.7\text{ A}$$

It can also be shown that by deactivating the sources, We find the resistance looking into terminals A-B is  $R_N = 55\ \Omega$

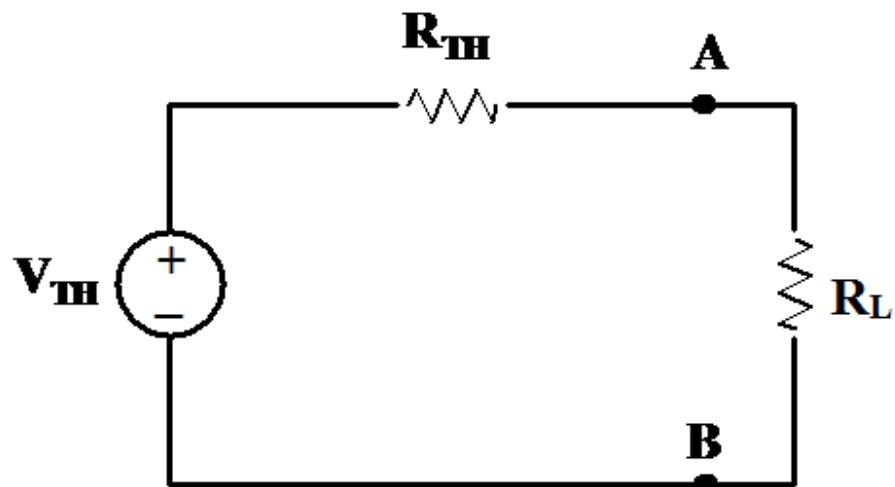
$R_N$  and  $R_{TH}$  will always be the same value for a given circuit. The Norton equivalent circuit tied to the load is shown below.



## 5. MAXIMUM POWER TRANSFER THEOREM:

- **Statement:** For any power source, the maximum power transferred from the power source to the load is when the resistance of the load  $R_L$  is equal to the equivalent or input resistance of the power source ( $R_{in} = R_{Th}$  or  $R_N$ ).
- The process used to make  $R_L = R_{in}$  is called impedance matching.

**Explanation:**



$$I = \frac{V_{Th}}{R_{Th} + R_L}$$

$$P_L = I^2 R_L = \frac{V_{Th}^2 R_L}{(R_{Th} + R_L)^2}$$

$$\text{For } P_L \text{ to be maximum, } \frac{dP_L}{dR_L} = 0$$

$$\text{Or, } R_L = R_{Th}$$

$$\text{So, Maximum power drawn by } R_L = I^2 R_L = \frac{V_{Th}^2 R_L}{(2R_L)^2} = \frac{V_{Th}^2}{4R_L}$$

$$\text{Power supplied by the source} = \frac{V_{Th}^2}{(R_{Th} + R_L)}$$

## TRANSIENTS

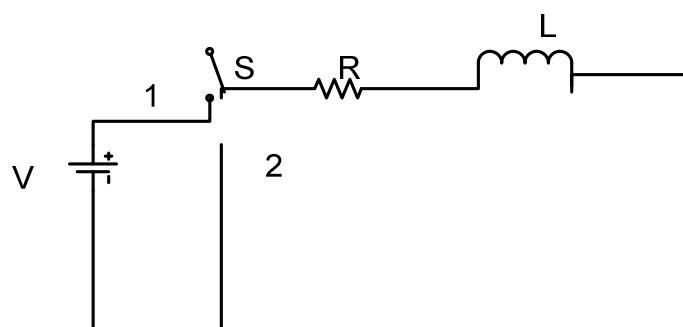
**Statement:** Sudden change in electrical circuit.

- Amplitude dies out and frequency is more
- Transient disturbances are produced whenever:-
  - An apparatus or circuit is suddenly connected to or disconnected from the supply.
  - A circuit is shorted
  - There is a sudden change in the applied voltage from one finite value to another.
  - *Transients are produced whenever different circuits are suddenly switched on or off from the supply voltage.*

Resultant current consists of two parts:-

- A final steady state or normal current
- A transient current superimposed on the steady state current
- Transient currents are not driven by any part of the applied voltage but are entirely associated with changes in the stored energy in inductors and capacitors.
- Since there is no stored energy in resistors, there are no transients in pure resistive circuit.

### Transient in R-L Series circuit:-



When Switch ‘S’ is connected to ‘1’,

$$V = R i + L \frac{di}{dt}$$

$$i = i_{ss} + i_{tr}$$

$$i_{ss} = \frac{V}{R}$$

$$i_{tr} = R i + L \frac{di}{dt} = 0$$

$$\frac{di}{dt} + \frac{R}{L} i = 0$$

$$\frac{di}{dt} = -\frac{R}{L} i$$

$$\frac{di}{i} = -\frac{R}{L} dt$$

$$\ln i = -\frac{R}{L} t; i_{tr} = K e^{-\frac{R}{L} t}$$

$$i_{ss} = \frac{V}{R}$$

$$i_{tr} = K e^{-\frac{R}{L} t}$$

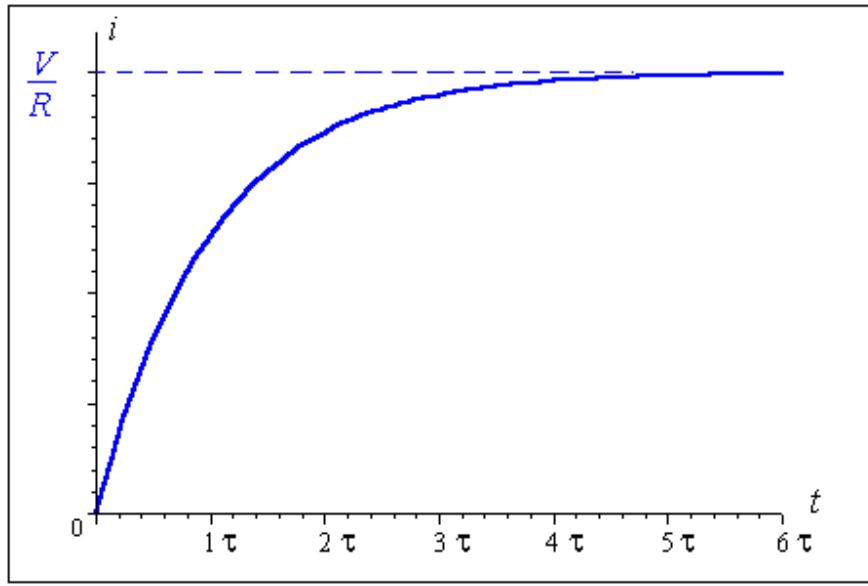
$$i = \frac{V}{R} + K e^{-\frac{R}{L} t}$$

At  $t=0, i=0$  So,

$$0 = \frac{V}{R} + K$$

$$K = -\frac{V}{R}$$

$$i = \frac{V}{R} \left( 1 - e^{-\frac{R}{L} t} \right)$$



$\lambda = \frac{L}{R}$  is called time constant and  $\frac{R}{L}$  is called damping coefficient of the circuit

$$V_R = iR = V \left( 1 - e^{-\frac{t}{\lambda}} \right)$$

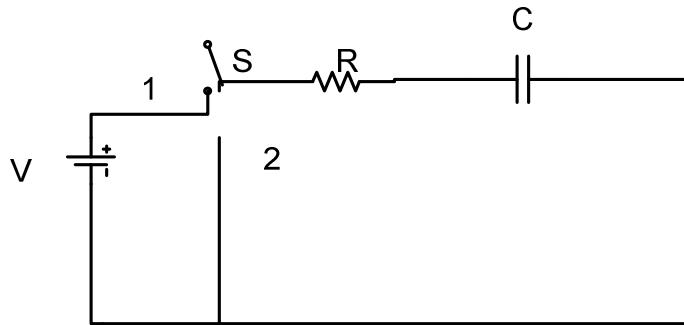
Emf of self inductance is  $-L \frac{di}{dt} = i_t R$

If  $t = \lambda$ , then  $i_t = I_0 e^{-1} = I_0 e^{-1} = I_0/e = I_0/2.718 = 0.37 I_0$

Hence, time period of a circuit is the time during which the transient current decrease to 0.37 of its initial value.

### Transient in R-C Series Circuit:

Consider an ac circuit containing a resistor of resistance  $R$  ohms and a capacitor of capacitance  $C$  farad across an a.c source of rms voltage  $V$  volts as shown in Fig. below:-



### Charging of RC

$$V = V_R + V_C$$

When switch is connected to '1' (charging):-

$$V = V_R + V_C$$

$$V = iR + \frac{1}{C} \int i dt$$

$$R \frac{di}{dt} + \frac{i}{C} = 0$$

$$\frac{di}{dt} + \frac{1}{RC}i = 0$$

$$i = K e^{\frac{-t}{RC}}$$

$$A t \quad t=0^+; i = I_0 e^{\frac{-t}{\tau}}$$

$$K = \frac{V}{R}; \text{ So, } i = \frac{V}{R} e^{\frac{-t}{RC}}$$

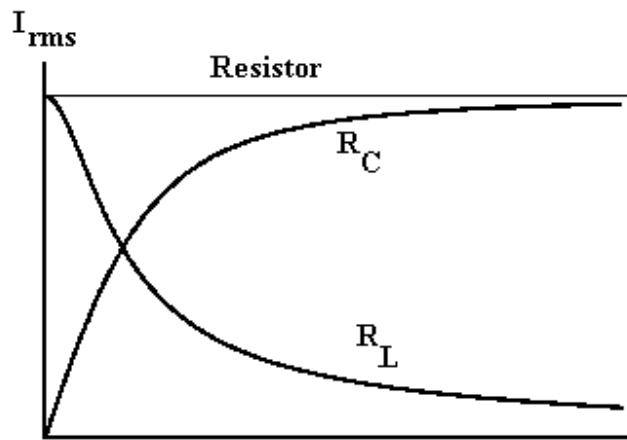
$$V_R = iR = I_0 e^{\frac{-t}{\tau}} R = V e^{\frac{-t}{\tau}}$$

$$V_C = \frac{1}{C} \int i dt = \frac{1}{C} \int_0^t I_0 e^{\frac{-t}{\tau}} dt$$

$$V_C = \frac{1}{C} I_0 (-\tau) \left[ \frac{-t}{\tau} \right]_0^t = \frac{1}{C} \frac{V}{R} (-R C)$$

$$V_C = -V \left( e^{\frac{-t}{\tau}} - e^0 \right)$$

$$V_C = V \left( 1 - e^{\frac{-t}{\tau}} \right)$$



### Discharging of RC

When connected to '2' in the Fig. above,

$$R i + \frac{1}{C} \int i d t = 0$$

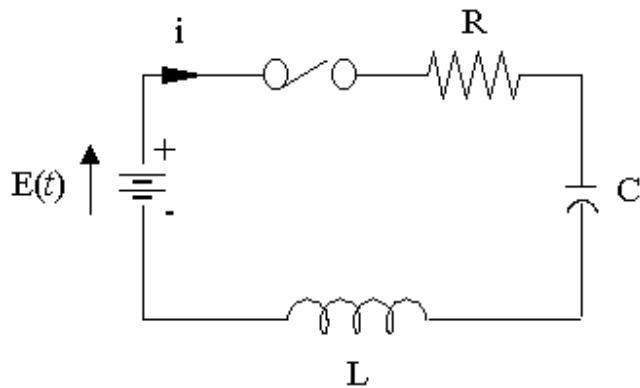
$$R \frac{d i}{d t} + \frac{i}{C} = 0$$

$$i = K e^{\frac{-t}{RC}}$$

At  $t = 0$ ;  $i = \frac{-V}{R}$  (voltage across capacitor starts discharging in opposite direction to the original current direction)

$$i = -I_0 e^{\frac{-t}{RC}} = -I_0 e^{\frac{-t}{\tau}}$$

## Transient in R-L-C Series Circuit



- Two types of energy:- Electromagnetic and electrostatic. So any sudden change in the conditions of the circuit involves redistribution of these two energies.
- Transient current produced due to this redistribution may be unidirectional and decaying oscillatory.

From the above Fig,

$$iR + L \frac{di}{dt} + \frac{1}{C} \int i dt = V$$

$$R \frac{di}{dt} + L \frac{d^2i}{dt^2} + \frac{i}{C} = 0$$

$$\frac{d^2i}{dt^2} + \frac{R}{L} \frac{di}{dt} + \frac{1}{LC} i = 0$$

$$\alpha \pm \beta = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$\alpha \pm \beta = \frac{\frac{-R}{L} \pm \sqrt{\left(\frac{R}{L}\right)^2 - \frac{4}{LC}}}{2}$$

$$\alpha \pm \beta = \frac{-R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

$$\alpha = \frac{-R}{2L} \quad \text{and} \quad \beta = \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

Solution of differential equation is:-

$$i = K_1 e^{P_1 t} + K_2 e^{P_2 t}$$

Roots are:  $\alpha + \beta = P_1$ ;  $\alpha - \beta = P_2$

$K_1$  &  $K_2$  depends on boundary condition

Case 1: High loss circuit:-  $\left(\frac{R}{2L}\right)^2 > \frac{1}{LC}$  i.e Overdamped

In this case,  $\beta$  is positive real quantity. Hence  $P_1$  and  $P_2$  are real but unequal.

$$\begin{aligned} i &= K_1 e^{\alpha t} e^{\beta t} + K_2 e^{\alpha t} e^{-\beta t} \\ i &= K_1 e^{\alpha t} e^{\beta t} + K_2 e^{\alpha t} e^{-\beta t} \\ i &= e^{\alpha t} \left[ K_1 e^{\beta t} + K_2 e^{-\beta t} \right] \end{aligned}$$

The expression of 'i' is over damped transient non-oscillatory current.

CASE 2:- Low-loss circuit:  $\left(\frac{R}{2L}\right)^2 < \frac{1}{LC}$  i.e Underdamped

In this case,  $\beta$  is imaginary. Hence roots are complex conjugate

$$\begin{aligned} P_1 &= \alpha + j\beta; P_2 = \alpha - j\beta \\ i &= K_1 e^{P_1 t} + K_2 e^{P_2 t} \\ i &= K_1 e^{(\alpha + j\beta)t} + K_2 e^{(\alpha - j\beta)t} \\ i &= K_1 e^{\alpha t} e^{j\beta t} + K_2 e^{\alpha t} e^{-j\beta t} \\ i &= e^{\alpha t} \left[ K_1 e^{j\beta t} + K_2 e^{-j\beta t} \right] \end{aligned}$$

The expression of 'i' is damped oscillatory

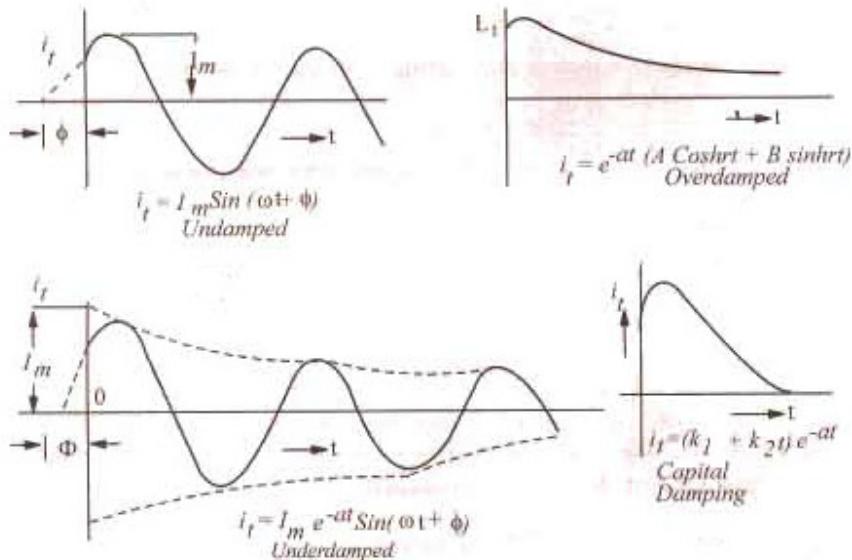
CASE 3:  $\left(\frac{R}{2L}\right)^2 = \frac{1}{LC}$  i.e Critical damping

In this case  $\beta = 0$ , Hence roots  $P_1$  &  $P_2$  are real and equal.

$$P_1 = \alpha + 0 = \alpha; P_2 = \alpha - 0 = \alpha$$

$$i = K_1 e^{\alpha t} + K_2 t e^{\alpha t}$$

The above expression is of critical damping because current is reduced to almost zero in the shortest possible time.



**Example:** A coil having a resistance of  $2\Omega$  and an inductance of  $1 \text{ H}$  is switched on to a  $10 \text{ V}$  D.C supply. Write down the expression of current  $i(t)$  in the coil as a function of time

$$\text{Ans: } R = 2\Omega, L = 1 \text{ H}, V = 10 \text{ V}$$

$$\text{Time constant } (\tau) = L/R = 1/2 = 0.5 \text{ sec}$$

$$\text{Steady current} = V/R = 10/2 = 5 \text{ A}$$

$$i(t) = \frac{V}{R} \left( 1 - e^{-\frac{t}{\tau}} \right)$$

$$i(t) = 5 \left( 1 - e^{-\frac{t}{0.5}} \right) \text{ A}$$

## **SINGLE PHASE A.C CIRCUIT**

### **Single phase EMF generation:**

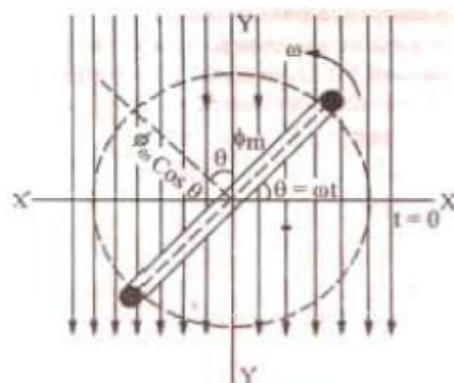
Alternating voltage may be generated

- 1) By rotating a coil in a magnetic field
  - 2) By rotating a magnetic field within a stationary coil

The value of voltage generated depends upon

- 1) No. of turns in the coil 2) field strength 3) speed

## **Equation of alternating voltage and current**



**N**= No. of turns in a coil

$\Phi_m$ = Maximum flux when coil coincides with X-axis

$\omega$  = angular speed (rad/sec) =  $2\pi f$

At  $\theta = \omega t$ ,  $\Phi = \text{flux component } \perp \text{ to the plane} = \Phi_m \cos \omega t$

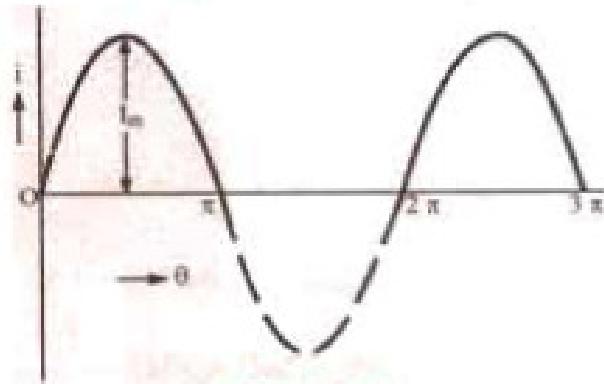
According to the Faraday's law of electromagnetic induction,

$$e = -N \frac{d\phi}{dt} = -N \frac{d}{dt} \phi_m \cos \omega t = \omega N \phi_m \sin \omega t \dots \dots \dots (1)$$

Now, e is maximum value of  $E_m$ , when  $\sin\theta = \sin 90^\circ = 1$ .

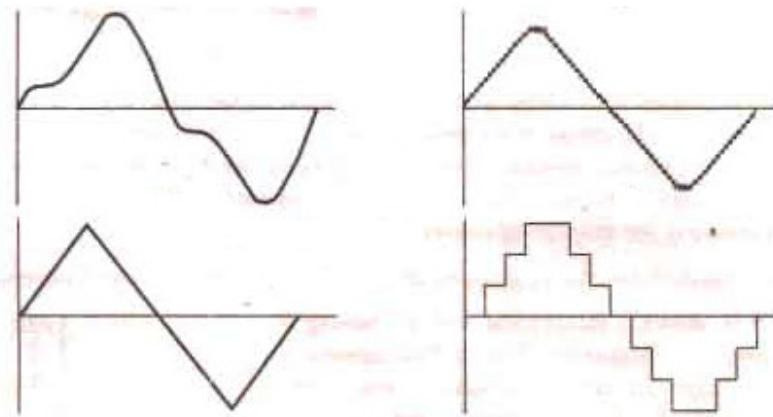
From Eq<sup>n</sup> (1) & (2),  $e = E_m \sin \omega t$  volt

Now, current (i) at any time in the coil is proportional to the induced emf (e) in the coil. Hence,  $i = I_m \sin \omega t$  amp



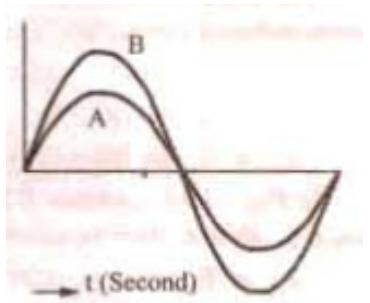
### A.C terms:

- Cycle:- A complete set of positive and negative values of an alternating quantity is known as cycle.



- Time period: The time taken by an alternating quantity to complete one cycle is called time T.
- Frequency: It is the number of cycles that occur in one second.  $f = 1/T$   
 $f = PN/120$  where, P= No. of poles, N= Speed in rpm
- Waveform: A curve which shows the variation of voltage and current w.r.t time or rotation.

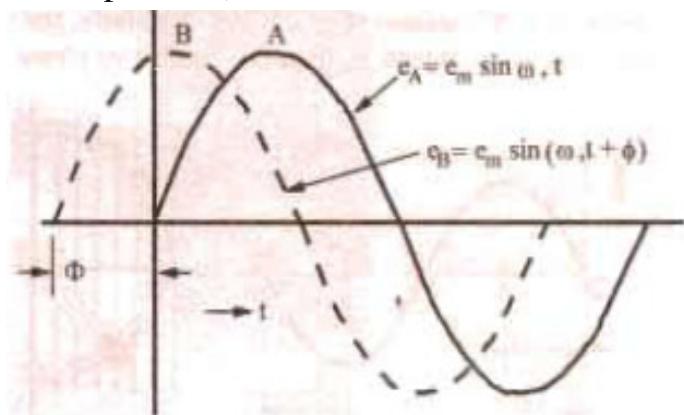
- Phase & Phase difference:



$$e_A = E_m \sin \omega t$$

In phase:  $e_B = E_m \sin \omega t$

Out of phase: i) B leads A



$$e_A = E_m \sin \omega t$$

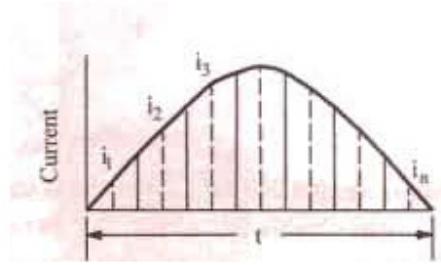
Phase difference  $\Phi$ .  $e_B = E_m \sin(\omega t + \alpha)$

ii) A leads B or B lags A

$$e_A = E_m \sin \omega t$$

$$e_B = E_m \sin(\omega t - \alpha)$$

## Root mean Square (RMS) or effective or virtual value of A.C:-



$$I_{rms} = \sqrt{\frac{i_1^2 + i_2^2 + \dots + i_n^2}{n}} = \text{Square root of the mean of square of the instantaneous currents}$$

- It is the square root of the average values of square of the alternating quantity over a time period.

$$I_{rms} = \sqrt{\frac{1}{T} \int_0^T i^2(\omega t) d(\omega t)}$$

## Average Value (or mean value):

- It is the arithmetic sum of all the instantaneous values divided by the number of values used to obtain the sum

$$I_{av} = \frac{i_1 + i_2 + \dots + i_n}{n}$$

$$I_{av} = \frac{1}{T} \int_0^T i(\omega t) d(\omega t)$$

**Form factor ( $K_f$ ):-** is the ratio of rms value to average value of an alternating quantity. ( $K_f = I_{rms}/I_{av}$ )

**Peak factor ( $K_a$ ) or crest factor:-** is the ratio of peak (or maximum) value to the rms value of alternating quantity ( $K_a = I_{max}/I_{rms}$ )

**Example:** An alternating current varying sinusoidally with a frequency of 50 Hz has an RMS value of 20 A. Write down the equation for the instantaneous value and find this value a) 0.0025 sec b) 0.0125 sec after passing through a positive maximum value. At what time, measured from a positive maximum value, will the instantaneous current be 14.14 A?

$$I_m = 20\sqrt{2} = 28.2 \text{ A}$$

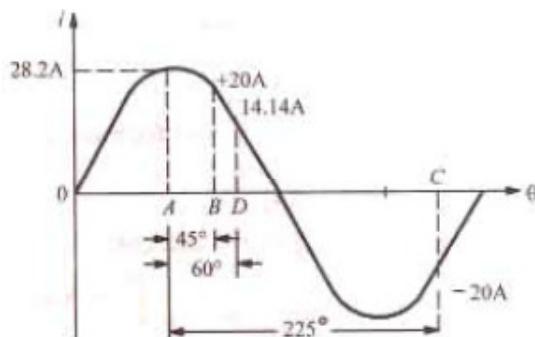
Ans:  $\omega = 2\pi \times 50 = 100\pi \text{ rad/s}$

The equation of the sinusoidal current wave with reference to point O as zero time point is

$$i = 28.2 \sin 100\pi t \text{ Ampere}$$

Since time values are given from point A where voltage has positive and maximum value, the equation may itself be referred to point A. In this case, equation becomes

$$i = 28.2 \cos 100\pi t$$



i) When  $t = 0.0025$  second

$$\begin{aligned} i &= 28.2 \cos 100\pi \times 0.0025 \dots \text{angle in radian} \\ &= 28.2 \cos 100 \times 180 \times 0.0025 \dots \text{angle in degrees} \\ &= 28.2 \cos 45^\circ = 20 \text{ A} \dots \text{point B} \end{aligned}$$

ii) When  $t = 0.0125$  sec

$$\begin{aligned} I &= 28.2 \cos 100 \times 180 \times 0.0125 \\ &= 28.2 \cos 225^\circ = 28.2 \times (-1/\sqrt{2}) \\ &= -20 \text{ A} \dots \text{point C} \end{aligned}$$

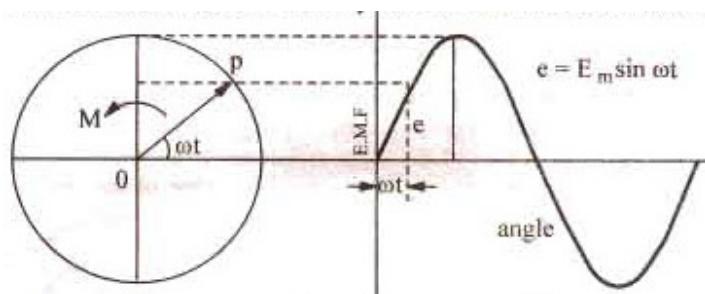
iii) Here  $i = 14.14 \text{ A}$

$$14.14 = 28.2 \cos 100 \times 180 t$$

$$\cos 100 \times 180 t = \frac{1}{2}$$

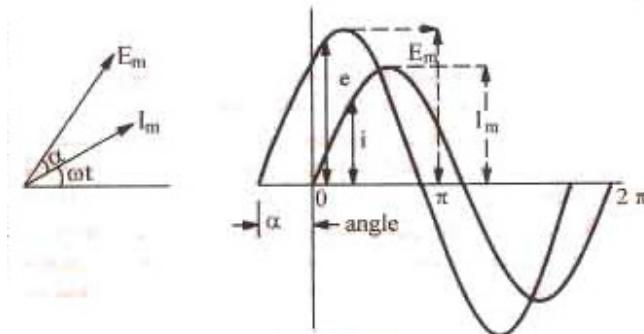
$$\text{Or, } 100 \times 180 t = \cos^{-1}(1/2) = 60^\circ, t=1/300 \text{ sec} \dots \dots \dots \text{point D}$$

### Phasor & Phasor diagram:



**Phasor:** Alternating quantities are vector (i.e having both magnitude and direction). Their instantaneous values are continuously changing so that they are represented by a rotating vector (or phasor). A phasor is a vector rotating at a constant angular velocity

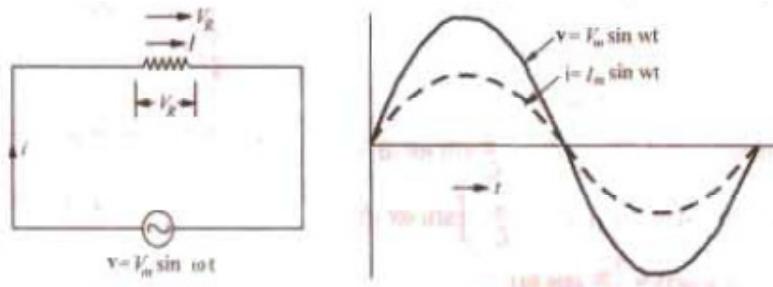
**Phasor diagram:** is one in which different alternating quantities of the same frequency are represented by phasors with their correct phase relationship



### **Points to remember:**

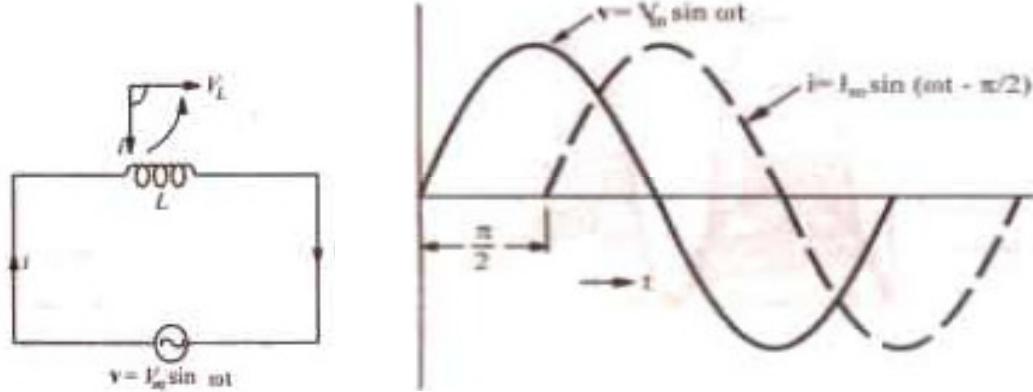
1. The angle between two phasors is the phase difference
2. Reference phasor is drawn horizontally
3. Phasors are drawn to represent rms values
4. Phasors are assumed to rotate in anticlockwise direction
5. Phasor diagram represents a “still position” of the phasors in one particular point

### A.C through pure ohmic resistance only



$$v = iR \text{ or } i = \frac{v}{R} = \frac{V_m}{R} \sin \omega t \text{ (in phase)}$$

### A.C through pure inductance only



$$v = L \frac{di}{dt} = V_m \sin \omega t$$

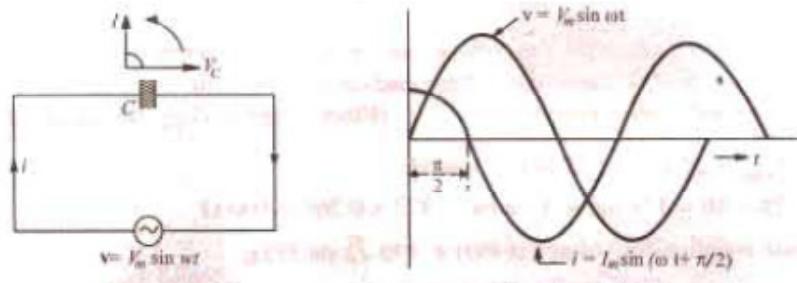
$$i = \frac{V_m}{L} \int \sin \omega t$$

$$i = -\frac{V_m}{\omega L} \cos \omega t$$

$$i = I_m \sin \left( \omega t - \frac{\pi}{2} \right) \quad (\text{current lags by } 90^\circ)$$

$$\omega L = 2\pi f L = X_L = \text{inductive reactance (in } \Omega \text{)}$$

## A.C through pure Capacitance only



$$\begin{aligned}
 i &= C \frac{dv}{dt} = C \frac{d}{dt}(V_m \sin \omega t) \\
 &= \omega C V_m \cos \omega t \\
 &= \omega C V_m \sin \left( \omega t + \frac{\pi}{2} \right) = \frac{V_m}{\omega C} \sin \left( \omega t + \frac{\pi}{2} \right) \\
 &= I_m \sin \left( \omega t + \frac{\pi}{2} \right) \quad (\text{current leads by } 90^\circ) \\
 \frac{1}{\omega C} &= X_C = \frac{1}{2\pi f C} = \text{capacitive reactance (in } \Omega \text{)}
 \end{aligned}$$

**'j' operator:**  $j$  is a operator which rotates a vector by  $90^\circ$  in anticlockwise direction

$$j^2 = -1 ; j = \sqrt{-1}$$

Note: 'i' is used for current hence 'j' is used to avoid confusion

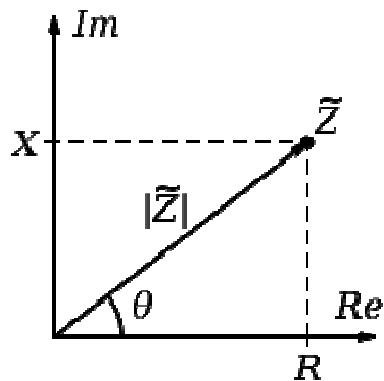
## Mathematical representation of vectors:

1. Rectangular or Cartesian form :-  $\vec{V} = a \pm jb$
2. Polar form :  $\vec{V} = V \angle \pm \theta$
3. Trigonometrical form :  $\vec{V} = V(\cos \theta \pm j \sin \theta)$
4. Exponential form :  $\vec{V} = V e^{\pm j \theta}$

**Note:** rectangular form is best suited for addition and subtraction & polar form is best suited for multiplication and division

### IMPEDANCE:

In quantitative terms, it is the complex ratio of the voltage to the current in an alternating current (AC) circuit. Impedance extends the concept of resistance to AC circuits, and possesses both magnitude and phase, unlike resistance, which has only magnitude. When a circuit is driven with direct current (DC), there is no distinction between impedance and resistance; the latter can be thought of as impedance with zero phase angle.



Where X=Total reactance of the network (Both inductive and capacitive)

R=Resistance of the network in ohm.

$\theta$ = Phasor angle in degree/Radian.

Note:

- I. If  $\theta = 0$  degree then the load is purely **Resistive**.
- II. If  $\theta = -90$  degree then the load is purely **inductive**. (lagging)
- III. If  $\theta = 90$  degree then the load is purely **capacitive**. (leading)

$$Z = R + jX$$

Where Z=impedance of the electrical network in ohm.

R=Resistance of the network in ohm.

X=Reactance of the electrical network in ohm.

### **Admittance:**

In electrical engineering, admittance is a measure of how easily a circuit or device will allow a current to flow. It is defined as the inverse of impedance. The SI unit of admittance is the siemens (symbol S).

Admittance is defined as:

$$Y = 1/Z$$

Where

Y is the admittance, measured in siemens

Z is the impedance, measured in ohms

The synonymous unit mho, and the symbol  $\mathfrak{U}$  (an upside-down uppercase omega  $\Omega$ ), are also in common use.

Resistance is a measure of the opposition of a circuit to the flow of a steady current, while impedance takes into account not only the resistance but also dynamic effects (known as reactance). Likewise, admittance is not only a measure of the ease with which a steady current can flow, but also the dynamic effects of the material's susceptance to polarization:

$$Y = G + j B$$

Where

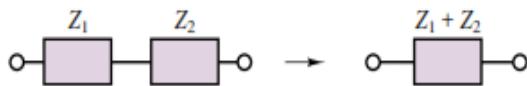
$Y$  is the admittance, measured in siemens.

$G$  is the conductance, measured in siemens.

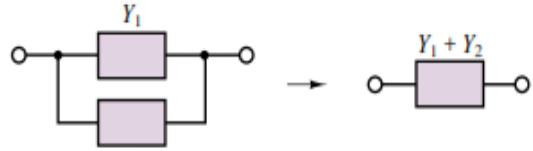
$B$  is the susceptance, measured in siemens.

### AC Equivalent Circuits:

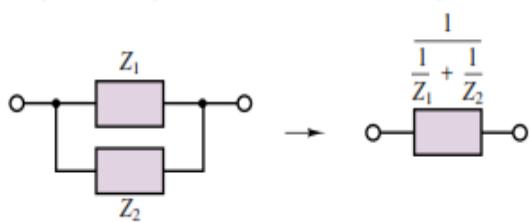
Impedances in series add:



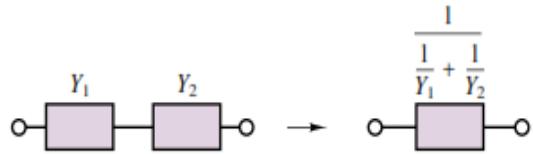
Admittances in parallel add:



Impedances in parallel behave like resistors in parallel:



Admittances in series behave like conductances in series:



1. Impedances in series add together to give the equivalent impedance while the admittance in parallel add together to give the equivalent admittance.
2. Impedances in parallel gives equivalent impedance by reciprocating the reciprocal sum of the impedances and to obtain the equivalent admittance in series same procedure has to be followed.

### Instantaneous and Average Power

The most general expressions for the voltage and current delivered to an arbitrary load are as follows:

$$v(t) = V \cos(\omega t - \theta_V)$$

$$i(t) = I \cos(\omega t - \theta_I)$$

Since the instantaneous power dissipated by a circuit element is given by the product of the instantaneous voltage and current, it is possible to obtain a general expression for the power dissipated by an AC circuit element:

$$p(t) = v(t)i(t) = V I \cos(\omega t) \cos(\omega t - \theta)$$

It can be further simplified with the aid of trigonometric identities to yield

$$p(t) = V I / 2 \cos(\theta) + V I / 2 \cos(2\omega t - \theta)$$

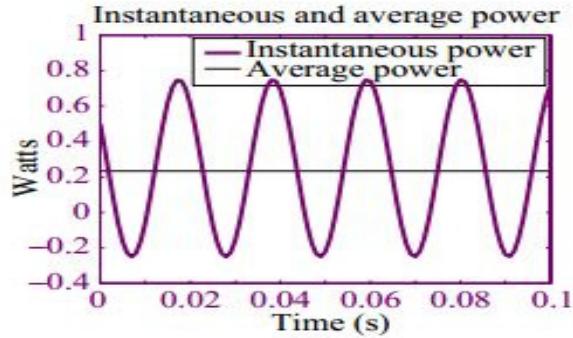
where  $\theta$  is the difference in phase between voltage and current

The average power corresponding to the voltage and current signal can be obtained by integrating the instantaneous power over one cycle of the sinusoidal signal. Let  $T = 2\pi/\omega$  represent one cycle of the sinusoidal signals. Then the average power,  $P_{av}$ , is given by the integral of the instantaneous power,

$p(t)$ , over one cycle:

$$\begin{aligned} P_{av} &= \frac{1}{T} \int_0^T p(t) dt \\ &= \frac{1}{T} \int_0^T \frac{VI}{2} \cos(\theta) dt + \frac{1}{T} \int_0^T \frac{VI}{2} \cos(2\omega t - \theta) dt \\ P_{av} &= \frac{VI}{2} \cos(\theta) \quad \text{Average power} \end{aligned}$$

since the second integral is equal to zero and  $\cos(\theta)$  is a constant.



In phasor notation, the current and voltage are given by

$$\mathbf{V}(j\omega) = V e^{j\psi}$$

$$\mathbf{I}(j\omega) = I e^{-j\theta}$$

impedance of the circuit element defined by the phasor voltage and current to be

$$Z = \frac{V}{I} e^{-j(\theta)} = |Z| e^{j\theta_Z}$$

The expression for the average power using phasor notation

$$P_{av} = \frac{1}{2} \frac{V^2}{|Z|} \cos \theta = \frac{1}{2} I^2 |Z| \cos \theta$$

### Power Factor

The phase angle of the load impedance plays a very important role in the absorption of power by load impedance. The average power dissipated by an AC load is dependent on the cosine of the angle of the impedance. To recognize the importance of this factor in AC power computations, the term  $\cos(\theta)$  is referred to as the power factor (pf). Note that the power factor is equal to 0 for a purely

inductive or capacitive load and equal to 1 for a purely resistive load; in every other case,  $0 < \text{pf} < 1$ . If the load has an inductive reactance, then  $\theta$  is positive and the current lags (or follows) the voltage. Thus, when  $\theta$  and  $Q$  are positive, the corresponding power factor is termed lagging. Conversely, a capacitive load will have a negative  $Q$ , and hence a negative  $\theta$ . This corresponds to a leading power factor, meaning that the load current leads the load voltage. A power factor close to unity signifies an efficient transfer of energy from the AC source to the load, while a small power factor corresponds to inefficient use of energy. Two equivalent expressions for the power factor are given in the following:

$$\text{pf} = \cos(\theta) = \frac{P_{\text{av}}}{\tilde{V}\tilde{I}} \quad \text{Power factor}$$

where  $\tilde{V}$  and  $\tilde{I}$  are the rms values of the load voltage and current.

## Complex Power

The expression for the instantaneous power may be further expanded to provide further insight into AC power. Using trigonometric identities, we obtain the

$$\begin{aligned} p(t) &= \frac{\tilde{V}^2}{|Z|} [\cos \theta + \cos \theta \cos(2\omega t) + \sin \theta \sin(2\omega t)] \\ &= \tilde{I}^2 |Z| [\cos \theta + \cos \theta \cos(2\omega t) + \sin \theta \sin(2\omega t)] \end{aligned}$$

following expressions:  $= \tilde{I}^2 |Z| \cos \theta (1 + \cos(2\omega t)) + \tilde{I}^2 |Z| \sin \theta \sin(2\omega t)$

Recalling the geometric interpretation of the impedance  $Z$

$$|Z| \cos \theta = R \text{ and } |Z| \sin \theta = X$$

are the resistive and reactive components of the load impedance, respectively. On the basis of this fact, it becomes possible to write the instantaneous power as:

$$\begin{aligned} p(t) &= \tilde{I}^2 R(1 + \cos(2\omega t)) + \tilde{I}^2 X \sin(2\omega t) \\ &= \tilde{I}^2 R + \tilde{I}^2 R \cos(2\omega t) + \tilde{I}^2 X \sin(2\omega t) \end{aligned}$$

Since  $P_{av}$  corresponds to the power absorbed by the load resistance, it is also called the real power, measured in units of watts (W). On the other hand,  $Q$  takes the name of reactive power, since it is associated with the load reactance. The units of  $Q$  are volt-amperes reactive, or VAR. Note that  $Q$  represents an exchange of energy between the source and the reactive part of the load; thus, no net power is gained or lost in the process, since the average reactive power is zero. In general, it is desirable to minimize the reactive power in a load.

The computation of AC power is greatly simplified by defining a fictitious but very useful quantity called the complex power,  $S$ :

$$S = \tilde{\mathbf{V}} \tilde{\mathbf{I}}^*$$

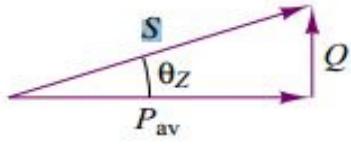
where the asterisk denotes the complex conjugate. You may easily verify that this definition leads to the convenient expression

$$S = \tilde{V} \tilde{I} \cos \theta + j \tilde{V} \tilde{I} \sin \theta = \tilde{I}^2 R + j \tilde{I}^2 X = \tilde{I}^2 Z$$

or

$$S = P_{av} + jQ$$

The complex power  $S$  may be interpreted graphically as a vector in the complex  $S$  plane



$$|S| = \sqrt{P_{av}^2 + Q^2} = \tilde{V} \cdot \tilde{I}$$

$$P_{av} = \tilde{V} \tilde{I} \cos \theta$$

$$Q = \tilde{V} \tilde{I} \sin \theta$$

The magnitude of  $S$ ,  $|S|$ , is measured in units of volt-amperes (VA) and is called apparent power, because this is the quantity one would compute by measuring the rms load voltage and currents without regard for the phase angle of the load. The complex power may also be expressed by the product of the square of the rms current through the load and the complex load impedance:

$$S = \tilde{I}^2 Z$$

or

$$\tilde{I}^2 R + j \tilde{I}^2 X = \tilde{I}^2 Z$$

or, equivalently, by the ratio of the square of the rms voltage across the load to the complex conjugate of the load impedance:

$$S = \frac{\tilde{V}^2}{Z^*}$$

## **Active, Reactive and Apparent Power**

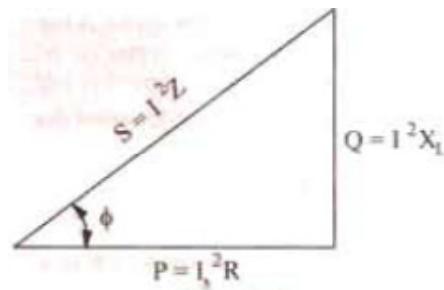


Fig. Power Triangle

$$S^2 = P^2 + Q^2$$

$$S = P + jQ$$

- **Apparent power, S**: is the product of rms values of the applied voltage and circuit current. It is also known as wattless (idle) component  
 $S=VI=IZx \quad I=I^2Z \quad \text{volt-amp}$
  - **Active power or true power, P**: is the power which actually dissipated in the circuit resistance. It is also known as wattful component of power.  
 $P=I^2R=I^2Z\cos\Phi=VI\cos\Phi \quad \text{watt}$
  - **Reactive power, Q**:- is the power developed in the reactance of the circuit.  
 $Q=I^2X=I^2Z\sin\Phi=VI\sin\Phi \quad \text{VAR}$

Example: In a particular R-L series circuit a voltage of 10 V at 50 Hz produces a current of 700 mA while the same voltage at 75 Hz produces 500 mA. What are the values of R and L in the circuit.

Ans. i)

$$Z = \sqrt{R^2 + (2\pi \times 50L)^2} = \sqrt{R^2 + 98696L^2}$$

$$V = IZ \text{ or } 10 = 700 \times 10^{-3} \sqrt{(R^2 + 98696L^2)}$$

$$\sqrt{(R^2 + 98696L^2)} = 10/700 \times 10^{-3} = 100/7$$

ii) In the second case

$$Z = \sqrt{R^2 + (2\pi \times 75L)^2} = \sqrt{R^2 + (222066L^2)}$$

$$10 = 500 \times 10^{-3} \sqrt{(R^2 + 222066L^2)}$$

$$\sqrt{(R^2 + 222066L^2)} = 20$$

subtracting eq(i) from eq(ii), we get

$$222066L^2 - 98696L^2 = 400 - (10000/49)$$

$$123370L^2 = 196$$

$$L = 0.0398 \text{ m} \quad H = 40 \text{ m}$$

Substituting this value of  $L$  in eq(ii), we get

$$R^2 + 222066(0.398)^2 = 400$$

$$R = 6.9 \Omega$$

## Introduction to resonance in series & parallel circuit

### **Resonance:**

**Definition:** An AC circuit is said to be in resonance when the circuit current is in phase with the applied voltage. So, the power factor of the circuit becomes unity at resonance and the impedance of the circuit consists of only resistance.

**Series Resonance:** In R-L-C series circuit, both  $X_L$  and  $X_C$  are frequency dependent. If we vary the supply frequency then the values of  $X_L$  and  $X_C$  varies. At a certain frequency called resonant frequency ( $f_r$ ),  $X_L$  becomes equal to  $X_C$  and series resonance occurs.

At series resonance,  $X_L = X_C$

$$2\pi f_r L = 1/2\pi f_r C$$

$$f_r = 1/2\pi\sqrt{LC}$$

Impedance of RLC series circuit is given by:

$$Z = \sqrt{R^2 + (X_L - X_C)^2} \quad (\text{Since, } X_L = X_C)$$

$$Z = \sqrt{R^2}$$

$$Z = R$$

$$\cos\phi = \frac{R}{Z} = \frac{R}{R} = 1$$

### Properties of series resonance:-

In series resonance,

- The circuit impedance Z is minimum and equal to the circuit resistance R.
- The circuit current  $I = V/Z = V/R$  and the current is maximum
- The power dissipated is maximum,  $P = V^2/R$
- Resonant frequency is  $f_r = 1/2\pi\sqrt{LC}$
- Voltage across inductor is equal and opposite to the voltage across capacitor
- Since power factor is 1, so zero phase difference. Circuit behaves as a purely resistive circuit.

**Example:** A series RLC circuit having a resistance of  $50\Omega$ , an inductance of  $500\text{ mH}$  and a capacitance of  $400\text{ }\mu\text{F}$ , is energized from a  $50\text{ Hz}$ ,  $230\text{ V}$ , AC supply. Find a) resonant frequency of the circuit b) peak current drawn by the circuit at  $50\text{ Hz}$  and c) peak current drawn by the circuit at resonant frequency

Ans.

$$\text{a)} f_0 = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{500\times10^{-3}\times400\times10^{-6}}} = 11.25\text{ Hz}$$

$$\text{b)} R = 50\Omega$$

$$X_L = \omega L = 2\pi \times 50 \times 500 \times 10^{-3} = 157\Omega$$

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi \times 50 \times 400 \times 10^{-6}} = 7.9\Omega$$

$$X = X_L - X_C = 157 - 7.9 = 149.1\Omega$$

$$Z = \sqrt{R^2 + X^2} = \sqrt{50^2 + 149.1^2} = 157.26\Omega$$

$$\text{Peak supply voltage, } V_m = \sqrt{2} \text{ V}_{\text{rms}} = \sqrt{2} (230) = 325.26\text{ V}$$

$$\text{Hence peak current at } 50\text{Hz } I_m = \frac{V_m}{Z} = \frac{325.26}{157.26} = 2.068$$

$$\text{c) At resonance, } Z_0 = R = 50\Omega$$

$$\text{So, peak current during resonance, } I_{m0} = \frac{V_m}{R} = \frac{325.26}{50} = 6.5025\text{A}$$

### Parallel resonance:

#### Points to remember:

- Net susceptance is zero, i.e  $1/X_C = X_L/Z^2$

$$X_L \times X_C = Z^2$$

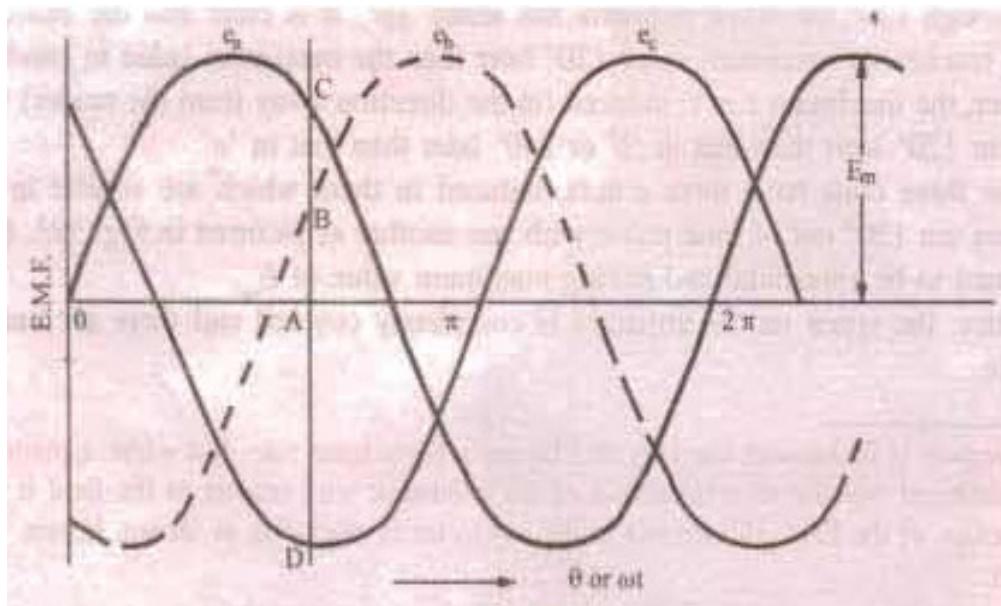
$$\text{Or } L/C = Z^2$$

- The admittance equals conductance
- Reactive or wattless component of line current is zero
- Dynamic impedance =  $L/CR\text{ }\Omega$

- Line current at resonance is minimum and  $V/L/CR$  but is in phase with the applied voltage
- Power factor of the circuit is unity

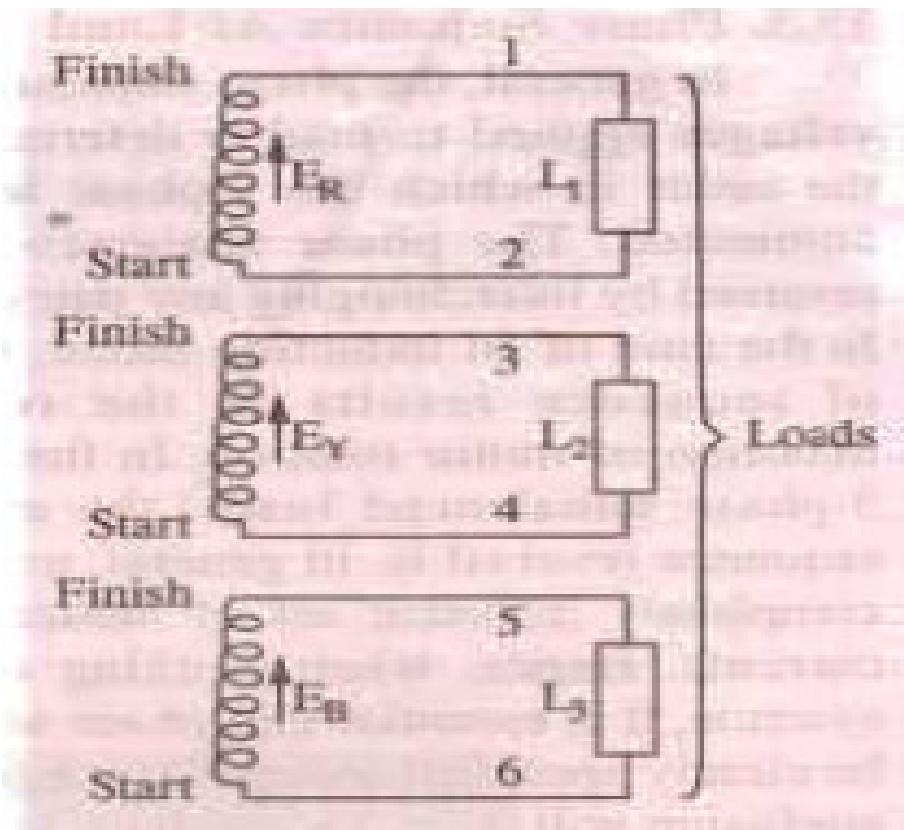
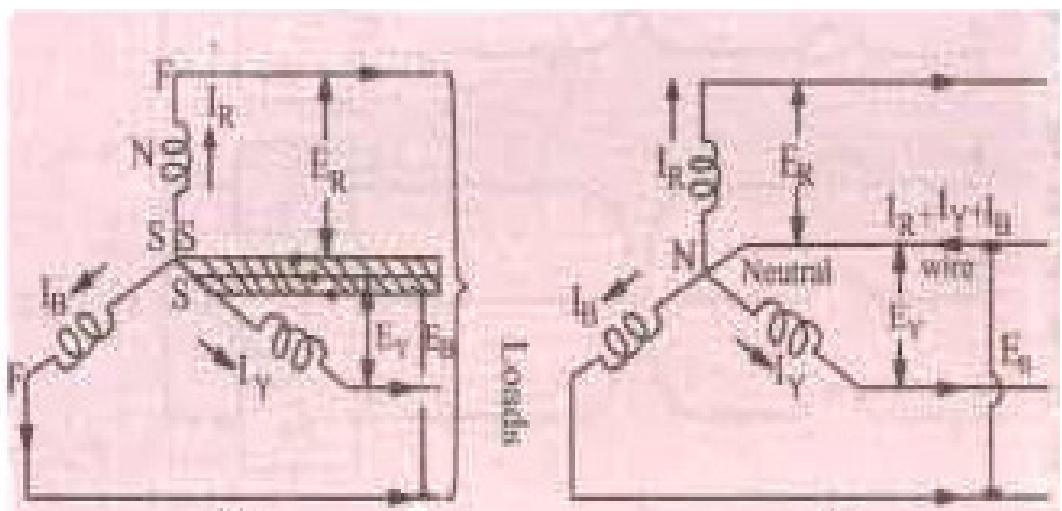
### THREE PHASE AC CIRCUIT

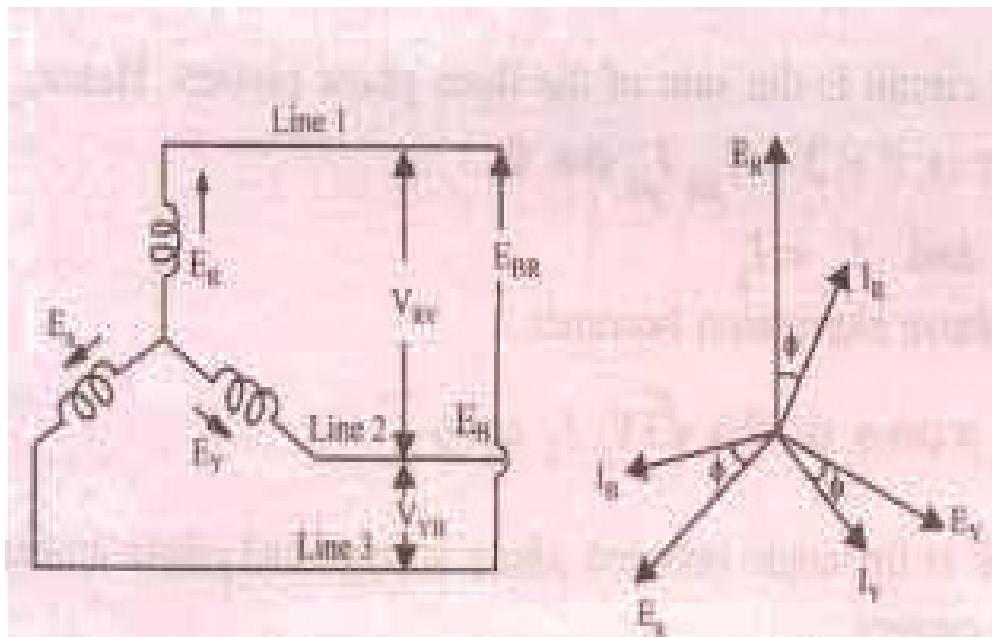
#### Three phase EMF Generation:-



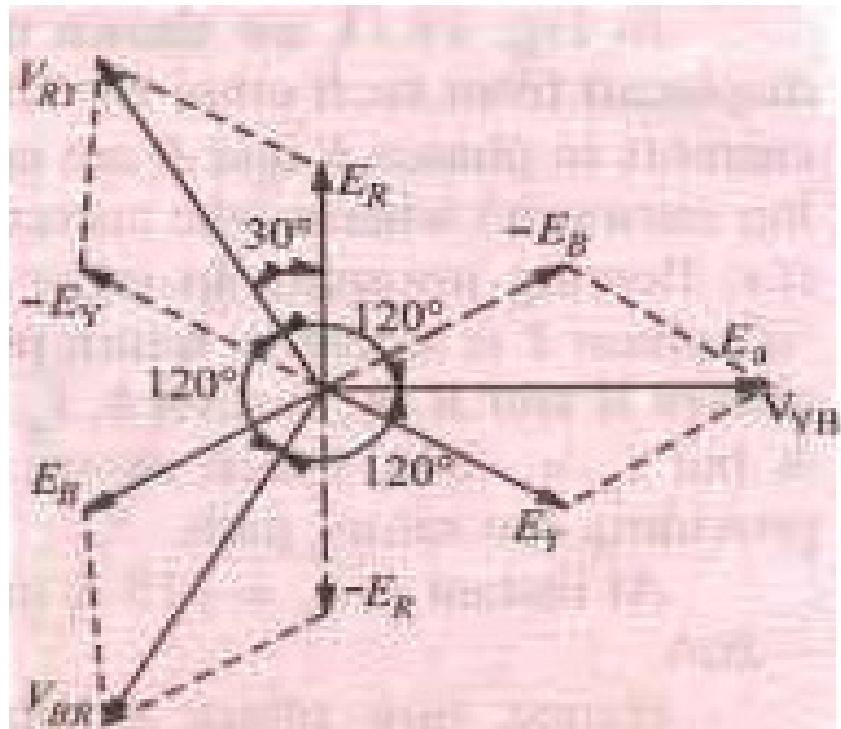
If the 3-coil windings  $W_1$ ,  $W_2$  and  $W_3$  arranged at  $120^\circ$  apart from each other on the same axis are rotated, then the emf induced in each of them will have a phase difference of  $120^\circ$ . In other words if the emf (or current) in one winding ( $w_1$ ) has a phase of  $0^\circ$ , then the second winding ( $w_2$ ) has a phase of  $120^\circ$  and the third ( $w_3$ ) has a phase of  $240^\circ$ .

### Star (Y) connection:-





Phasor diagram:-



Here,  $E_R$ ,  $E_Y$ ,  $E_B$  are phase voltages and  $V_{RY}$ ,  $V_{YB}$ ,  $V_{BR}$  are line voltages

$$\begin{aligned}
 V_{RY} &= \sqrt{E_R^2 + E_Y^2} + 2E_R E_Y \cos 60^\circ \\
 &= \sqrt{E_R^2 + E_R^2} + 2E_R E_R \cos 60^\circ \\
 &= \sqrt{3} E_R
 \end{aligned}$$

Hence,

- Line voltage =  $\sqrt{3} \times$  phase voltage
- Line current = phase current
- Line voltages are also  $120^\circ$  apart
- Line voltage are  $30^\circ$  ahead of respective phase voltages
- The angle between line voltage and line current is  $(30^\circ + \Phi)$

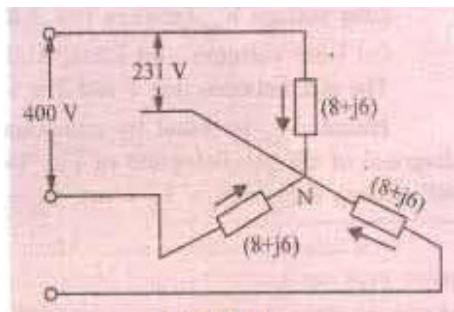
Power: Total power =  $3 \times$  phase power

$$\begin{aligned}
 &= 3 \times V_{ph} \times I_{ph} \times \cos \Phi \\
 &= \sqrt{3} V_L I_L \cos \Phi
 \end{aligned}$$

$\Phi$  is the angle between phase voltage and current

**Example:** A balanced star connected load of  $(8+j6)\Omega$  per phase is connected to a balanced 3-phase 400 V supply. Find the line current, power factor, power and total volt-amperes.

Ans.



$$Z_{ph} = \sqrt{8^2 + 6^2} = 10\Omega$$

$$V_{ph} = \frac{400}{\sqrt{3}} = 231 V$$

$$I_{ph} = \frac{V_{ph}}{Z_{ph}} = \frac{231}{10} = 23.1 A$$

(i)  $I_L = I_{ph} = 23.1 A$

(ii)  $p.f = \cos\Phi = \frac{R_{ph}}{Z_{ph}} = \frac{8}{10} = 0.8$  (lag)

(iii) Power  $P = \sqrt{3} V_L I_L \cos\Phi$

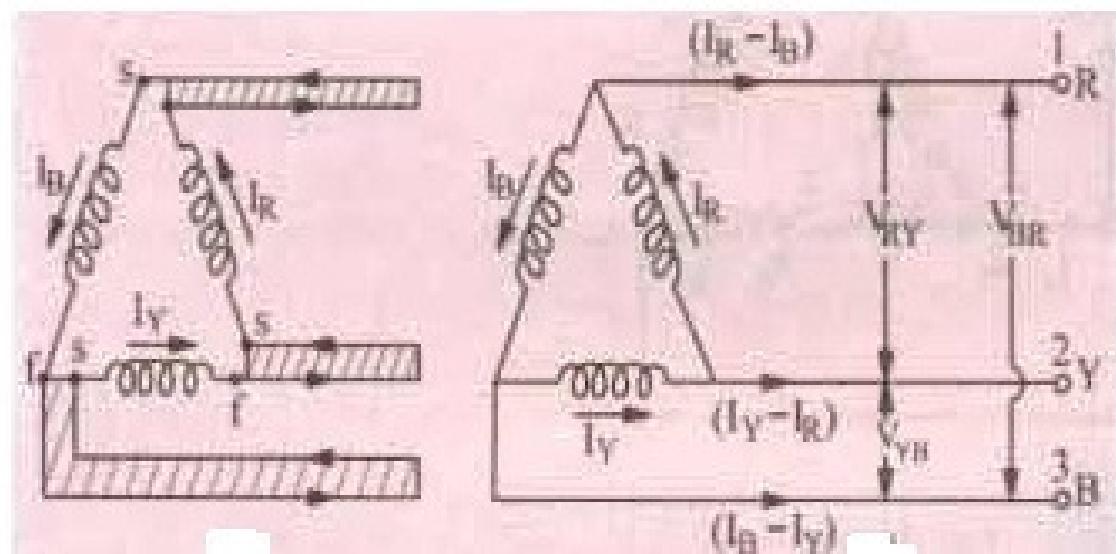
$$= \sqrt{3} \times 400 \times 23.1 \times 0.8$$

$$= 12,800 W \quad [\text{Also, } P = 3I_{ph}^2 R_{ph} = 3(23.1)^2 \times 8 = 12,800 W]$$

(iv) Total volt-amperes,

$$S = \sqrt{3} V_L I_L = \sqrt{3} \times 400 \times 23.1 = 16,000 VA$$

### Delta-connection:



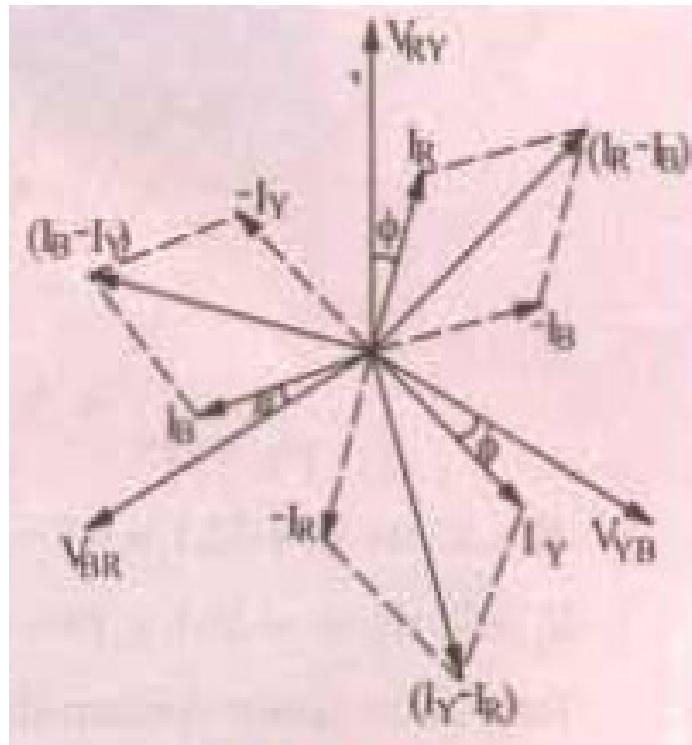


Fig. Phasor Diagram

$$I_L = I_R - I_B$$

$$I_L = \sqrt{I_R^2 + I_B^2 + 2I_R I_B \cos 60^\circ} = \sqrt{I_R^2 + I_R^2 + 2I_R I_R \cos 60^\circ} = \sqrt{3} I_R$$

Hence,

- Line current  $= \sqrt{3}$  phase current
- Line voltage = phase voltage
- Line currents are also  $120^\circ$  apart
- Line currents are  $30^\circ$  behind the respective phase currents
- Angle between line current and line voltage is  $30^\circ + \Phi$

Power: Total power =  $3 \times$  phase power

$$\begin{aligned}
 &= 3 \times V_{ph} I_{ph} \cos \Phi \\
 &= 3 \times V_L \times I_L / \sqrt{3} \times \cos \Phi \\
 &= \sqrt{3} V_L I_L \cos \Phi
 \end{aligned}$$

**Note:** For both star and delta system:

Active & True power =  $\sqrt{3} V_L I_L \cos\Phi$

Reactive power =  $\sqrt{3} V_L I_L \sin\Phi$

Apparent power =  $\sqrt{3} V_L I_L$

## **MODULE-II**

### **Magnetic Circuits:**

#### **The Magnetic Field and Faraday's Law:**

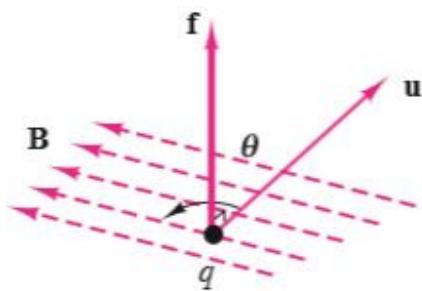
Magnetic fields are generated by electric charge in motion, and their effect is measured by the force they exert on a moving charge. As you may recall from previous physics courses, the vector force  $f$  exerted on a charge of  $q$  moving at velocity  $u$  in the presence of a magnetic field with flux density  $B$  is given by

$$f = qu \times B$$

Where the symbol  $\times$  denotes the (vector) cross product. If the charge is moving at a velocity  $u$  in a direction that makes an angle  $\theta$  with the magnetic field, then the magnitude of the force is given by

$$f = quB \sin \theta$$

and the direction of this force is at right angles with the plane formed by the vectors  $B$  and  $u$ .



The magnetic flux  $\phi$  is then defined as the integral of the flux density over some surface area.

$$\phi = \int_A B dA \text{ in webers}$$

$$\Rightarrow \phi = B \cdot A$$

**Faraday's law** states that a time-varying flux causes an induced electromotive force, or emf

$$e = -\frac{d\phi}{dt}$$

In practical applications, the size of the voltages induced by the changing magnetic field can be significantly increased if the conducting wire is coiled many times around, so as to multiply the area crossed by the magnetic flux lines many times over. For an N-turn coil with cross-sectional area A, for example, we have the emf

$$e = N \frac{d\phi}{dt}$$

When N-turn coil linking a certain amount of magnetic flux, then the flux linkage

$$\lambda = N \phi$$

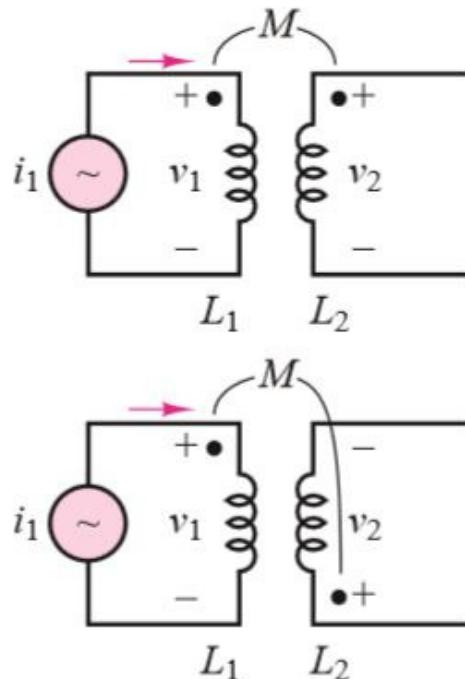
$$\Rightarrow e = \frac{d\lambda}{dt}$$

The relation between flux linkage and current is given by  $\lambda = Li$

so that the effect of a time-varying current was to induce a transformer voltage across an inductor coil, according to the expression  $v = L \frac{di}{dt}$

$L$  is the self-inductance which measures the voltage induced in a circuit by magnetic field generated by a current flowing in the same circuit.

## Self and mutual Inductance:



The figure shown above depicts a pair of coils one of which,  $L_1$  is excited by a current  $i_1$  and therefore develops a magnetic field and a resulting induced voltage  $v_1$ . The second coil,  $L_2$ , is not energized by a current, but links some of the flux generated by current  $i_1$  around  $L_1$  because of its close proximity to the first coil. The magnetic coupling between the coils established by virtue of their proximity is described by a quantity called mutual inductance and defined by the symbol  $M$ . The mutual inductance is defined by the equation

$$v_2 = M \frac{di_1}{dt}$$

The dots shown in the two drawings indicate the polarity of the coupling between the coils. If the dots are at the same end of the coils, the voltage induced in coil 2 by a current in coil 1 has the same polarity as the voltage induced by the same current in coil 1; otherwise, the voltages are in opposition, as shown in the lower part of Figure. Thus, the presence of such dots indicates that magnetic coupling is present between two coils. It should also be pointed out that if a current (and therefore a magnetic field) were present in the second coil, an additional voltage would be induced across coil 1. The voltage induced across a coil is, in general, equal to the sum of the voltages induced by self-inductance and mutual inductance.

As already discussed  $v = L \frac{di}{dt}$  with  $L$  constant

$$\text{then } e = N \frac{d\phi}{dt}$$

$$\text{the inductance is given by } L = \frac{N\phi}{i} = \frac{\lambda}{i}$$

This expression implies that the relationship between current and flux in a magnetic structure is linear, but due to the properties of ferromagnetic materials the flux-current relationship is nonlinear.

### **Ampere's Law:**

Ampere's law forms a counter part to Faraday's law. Both the laws explains the relationship between electricity and magnetism. Ampere's law states that the magnetic field intensity  $H$  in the vicinity of a conductor is related to the current carried by the conductor; thus Ampère's law establishes a dual relationship with Faraday's law.

In the previous section, we described the magnetic field in terms of its flux density  $B$  and flux  $\phi$ . To explain Ampère's law and the behaviour of magnetic materials, we need to define a relationship between the magnetic field intensity  $H$  and the flux density  $B$ . These quantities are related by

$$B = \mu H = \mu_r \mu_0 H \text{Wb/m}^2 \text{ or T}$$

where the parameter  $\mu$  is a scalar constant for a particular physical medium which is the permeability of the medium. The permeability of a material can be factored as the product of the permeability of freespace  $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$ , and the relative permeability  $\mu_r$ , which varies greatly according to the medium. For example, for air and for most electrical conductors and insulators,  $\mu_r$  is equal to 1. For ferromagnetic materials,  $\mu_r$  can take values in the hundreds or thousands. The size of  $\mu_r$  represents a measure of the magnetic properties of the material.

Ampère's law states that the integral of the vector magnetic field intensity  $H$  around a closed path is equal to the total current linked by the closed path  $i$ :

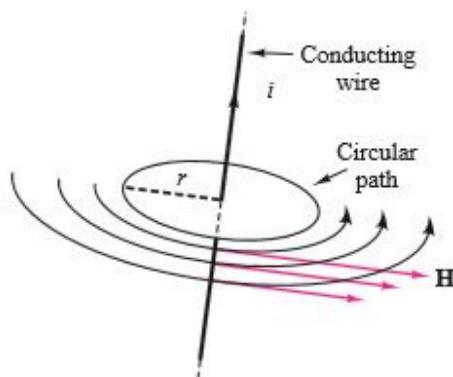
$$\oint H \cdot dl = \sum i$$

where  $dl$  is an increment in the direction of the closed path. If the path is in the same direction as the direction of the magnetic field, we can use scalar quantities to state that

$$\int H dl = \sum i$$

Direction of the magnetic field intensity  $H$  is determined by the familiar right-hand rule. This rule states that if the direction of current  $i$  points in the direction of the thumb of one's right hand, the resulting magnetic field encircles the conductor in the direction in which the other four fingers would encircle it.

By the right-hand rule, the current,  $i$ , generates a magnetic field intensity,  $H$ , in the direction shown.



Therefore for the closed-path integral becomes equal to  $H \cdot 2\pi r$ , since the path and the magnetic field are in the same direction, and the magnitude of the magnetic field intensity is given by

$$H = \frac{i}{2\pi r}$$

### **Magnetic circuit:**

To analyse the operation of electromagnetic devices the approximation is taken that a mean path for the magnetic flux and that the corresponding mean flux density is approximately constant over the cross-sectional area of the magnetic structure. When a coil is wound around a core with cross-sectional area  $A$  will have flux density as  $B = \frac{\phi}{A}$ , where area is assumed to be perpendicular to the direction of the flux lines. The field intensity obtained to be  $H = \frac{B}{\mu} = \frac{\phi}{A\mu}$

mmf of the coil can be represented by the product of magnetic field intensity and the length of the magnetic field

$$F = N.i = H.l$$

$$\Rightarrow F = \phi \frac{l}{\mu A}$$

The term  $\frac{l}{\mu A}$  is known as reluctance of magnetic circuit.

The relation between inductance and reluctance derived as

$$L = \frac{\lambda}{i} = \frac{N\phi}{i} = \frac{N}{i} \frac{Ni}{R} = \frac{N^2}{R} \text{ H}$$

In many magnetic structures and in rotating machines air gaps are very common.

The effect of air gap is to break the continuity of the high-permeability path for the flux, adding a high reluctance component to the equivalent circuit. The situation is analogous to adding a very large series resistance to a series electric circuit. In this case the basic concept of reluctance still applies, although now two different permeabilities must be taken into account.

Hence reluctance of the air gap is  $R_g = \frac{l_g}{\mu_0 A_g}$

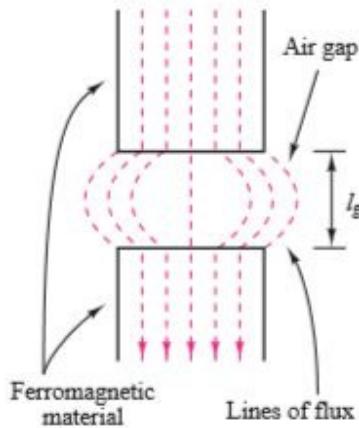
Where  $R_g$  = reluctance of air gap

$\mu_0$  = permeability

$A_g$  = cross-sectional area of the air-gap in the given structure

$l_g$  = length of air gap

$A_g$  is different from the other cross-sectional area of the structure because of the phenomenon known as Fringing as they cross an air gap.

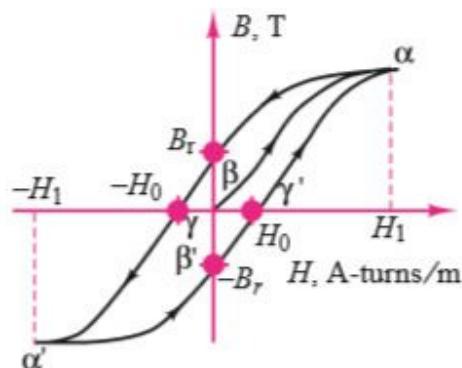


### Magnetic materials and B-H curves:

The relationship between the magnetic flux density  $B$  and the associated field intensity  $H$  is expressed by  $B = \mu H$ , where  $\mu$  = permeability of magnetic material.

From the above expression flux density increases in proportion to field intensity upto a saturation point reaches. But in general all magnetic material shows a nonlinear B-H curve, depending upon the value of permeability, which can be better explained by eddy currents and hysteresis. Eddy current caused by any time-varying flux in the core material. It will induce a voltage , and therefore current. The induced voltage will cause eddy current, which depends on the resistivity of the core. Hysteresis is another loss mechanism in magnetic materials. It shows a

complex behaviour related to the magnetization properties of the material which can be shown as



Here the core has been energized for some time ,with a field intensity of  $H_1$  A-turns/m. as the current decreases curve follow from the point  $\alpha$  to the point  $\beta$ . At this point mmf is zero to bring the flux density to zero ,mmf is further decreased until the field intensity reaches to  $-H_0$ . As mmf value is made more negative , the curve eventually reaches to the point  $\alpha'$ . The excitation current is now increased, the magnetization curve will follow the path  $\alpha' = \beta' = \gamma' = \alpha$ , and finally returns to the original point of B-H curve.

**Hysteresis loss:-** During the complete cycle, the magnets within the magnetic material try to align first in one way and then in reverse way. The tendency to turn around of elementary magnets give rise to mechanical stresses in the magnetic material, which in turn produces heat which is a waste form of energy. The

dissipated heat energy during the cycle of magnetization is given by the area within the hysteresis loop and is called hysteresis loss.

$$\text{Hysteresis power loss} = P_h = K f B_{\max}^x V$$

Where,  $K$  = Hysteresis coefficient

$f$  = frequency of magnetization

$V$  = volume of the material ( $\text{m}^3$ )

$B_{\max}$  = Maximum flux density ( $\text{wb}/\text{m}^2$ )

$x = 1.5-2.5$

- Steinmetz law:-  $P_h = \eta f B_{\max}^{1.6} V$

Where,  $\eta$  = Steinmetz constant or hysteresis coefficient

$f$  = frequency of magnetization

$V$  = volume of the material ( $\text{m}^3$ )

$B_{\max}$  = Maximum flux density ( $\text{wb}/\text{m}^2$ )

$B_m$  lies between 0.1 to 1.2  $\text{wb}/\text{m}^2$ , when  $B$  is not between 0.1

**Eddy current loss:** During the cycle of magnetization, the change in flux density induces an emf in the core of an electromagnet. The effect sets up small locally circulating currents called eddy currents. These currents are of no practical significance but produce heat which means some loss of energy. This loss of energy is called eddy current loss.

$$P_e = K_e t^2 f^2 V$$

## **Eddy current loss:-**

Where,  $K_e$ = Eddy current constant

$t$ = thickness of the lamination of the pole core and armature

$B$ = Flux density

$F$ = Frequency

$V$ = Volume of iron subject to change of flux

## **Points to Remember:**

- The eddy current loss can be minimized by using thin laminated cores.
- Use of laminations increase the resistance of eddy current path and thereby reduces its magnitude
- The hysteresis loss can be minimized by choosing the material having low hysteresis coefficient. e.g:- silicon steel:- 1.91
- The hysteresis and eddy current losses are together known as iron loss or core loss.
- For any machine ,  $B_m$  and  $f$  are also nearly constant. Hence these are also called constant loss.
- Hysteresis loss =  $xy(\text{area of } B/H \text{ loop})$   
where,  $x$  and  $y$  are scales of  $B$ &  $H$ .
- Unit of hysteresis loss is  $J/m^3/\text{cycle}$  or  $\text{watt}/m^3$

**Permeability:** Every substance possesses a certain power of conducting magnetic lines of force (iron is better conductor for magnetic lines of force than air). Permeability of a material is its conducting power for magnetic lines of force. It is the ratio of flux density (B) produced in a material to the magnetic field strength i.e

$$\mu = B/H$$

**Absolute & Relative Permeability:** For measuring relative permeability, vaccum or free space is chosen as the reference medium.

$$\text{Absolute permeability } \mu_0 = 4\pi \times 10^{-7} \text{ H/m}$$

Now, take any medium other than vaccum. If its relative permeability as compared to vaccum is  $\mu_r$ , then  $\mu = \mu_0 \mu_r$

In other words,  $\mu_r$  indicates the extent to which the given material is a better conductor of magnetic flux than air.

**Reluctance:** (S) is a measure of the opposition offered by a magnetic circuit to the setting up of flux.

$$S = MMF/\Phi, \quad S = l / (\mu_0 \mu_r A) \quad [\text{unit- AT/wb}]$$

**Example:** The hysteresis loop of an iron ring was found to have an area of  $10 \text{ cm}^2$  on a scale of  $1 \text{ cm} = 1000 \text{ AT/m}$  (X-axis);  $1 \text{ cm} = 0.2 \text{ wb/ m}^2$  (Y- axis). The ring

has a mean length of 100 cm and cross-sectional area of 5 cm. Compute the hysteresis loss in watts for a frequency of 50 Hz.

**Ans.** Area of hysteresis loop =  $10 \times 0.2 \times 1000 \text{ AT-wb/m}^3 = 2000 \text{ AT-wb/m}^3$

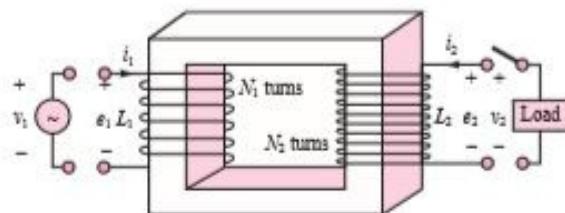
$$\text{Hysteresis loss} = 2000 \times 50 = 10,0000 \text{ J/m}^3/\text{s} [\text{f} = 50 \text{ cycle/s}]$$

$$\text{Volume} = 1 \times 5 \times 10^{-4} \text{ m}^3$$

$$\text{Hysteresis loss} = 100000 \times 1 \times 5 \times 10^{-4} \text{ W} = 50 \text{ W}$$

## TRANSFORMER

One of the more common magnetic structures in everyday applications is the transformer. An ideal transformer is a device that can step an AC voltage up or down by a fixed ratio, with a corresponding decrease and increase in current. A simple magnetic transformer is shown as below



Here coil  $L_1$  represents the input side of the transformer or primary winding of it, whereas the coil  $L_2$  is the output coil or secondary winding ; both winding are wound around the same magnetic structure. The operation of a transformer requires a time-varying current; if a time-varying voltage is applied to the primary

side of the transformer, a corresponding current will flow in L1; this current acts as an mmf and causes a (time-varying) flux in the structure. But the existence of a changing flux will induce an emf across the secondary coil! Without the need for a direct electrical connection ,the transformer can couple a source voltage at the primary to the load; the coupling occurs by means of the magnetic field acting on both coils. Thus, a transformer operates by converting electric energy to magnetic, and then back to electric energy. When a time-varying voltage source is connected to the input side, then by Faraday's law, a corresponding time-varying flux  $d\phi/dt$  is established in coil L1:

$$e_1 = N_1 \frac{d\phi}{dt} = v_1$$

Due to flux an emf induced across the secondary coil is

$$e_2 = N_2 \frac{d\phi}{dt} = v_2$$

So the relation between the input and output voltage is  $\frac{v_2}{v_1} = \frac{N_2}{N_1}$

As mmf in transformer remains same though out the core i.e.

$$i_1 N_1 = i_2 N_2$$

$$\frac{i_2}{i_1} = \frac{N_1}{N_2}$$

Here  $N_1$  and  $N_2$  are the primary and secondary turns, respectively. As the ideal transformer does not dissipate any power, since

$$v_1 i_1 = v_2 i_2$$

Another important performance characteristic of a transformer is its power efficiency

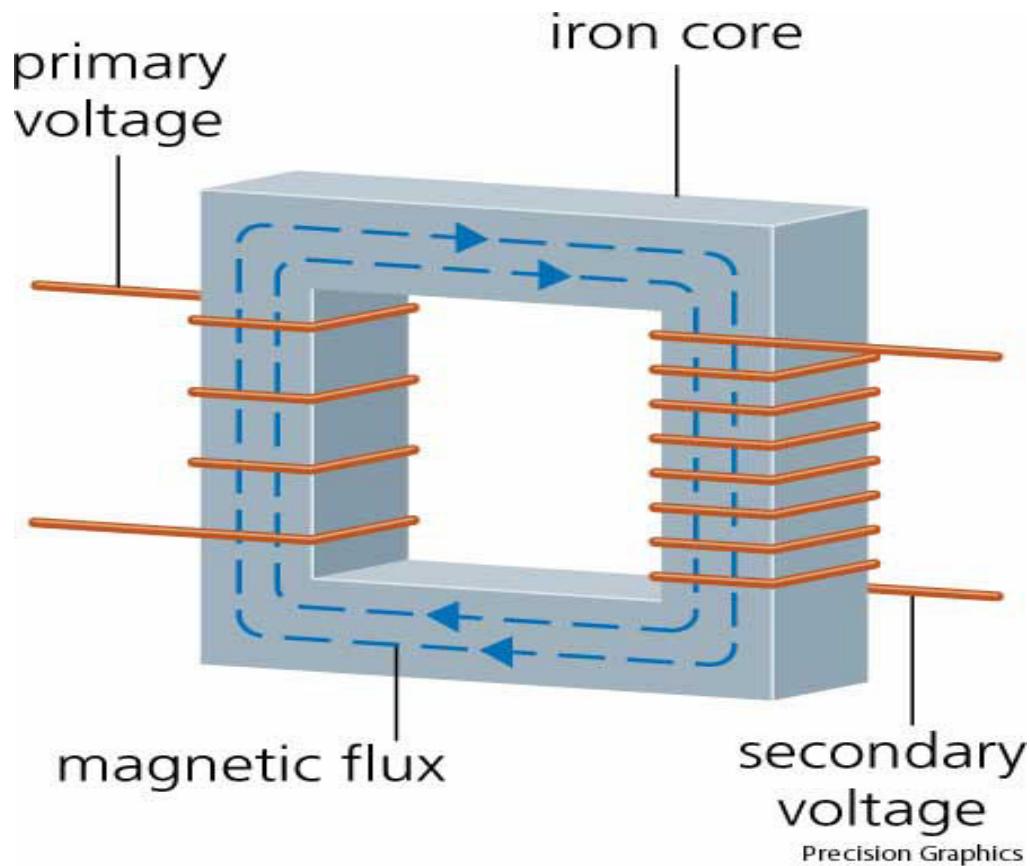
Power efficiency  $\eta = \text{Output power} / \text{Input power}$

**Definition:**

- It is a static device used for the purpose of transferring electrical energy from one circuit to another at same frequency but at different voltage (or current or both).
- It is used for raising or lowering the voltage of an a.c. supply with corresponding decrease or increase in current.
- It is an a.c. device

**Some more aspects of transformer:-**

It consists of two windings, primary and secondary wound on a common laminated magnetic core.



The winding connected to the a.c. source is called primary winding and one connected to the load is called secondary winding.

$V_1$  is applied to primary. Depending upon  $N_1 & N_2$ ,  $E_2$  is induced in the secondary. This  $E_2$  causes a secondary current  $I_2$ . Consequently terminal voltage  $V_2$  appears across the load.

If  $V_1 > V_2$ , it is called a step up transformer.

If  $V_1 < V_2$ , it is called a step down transformer.

Two types - core type and shell type

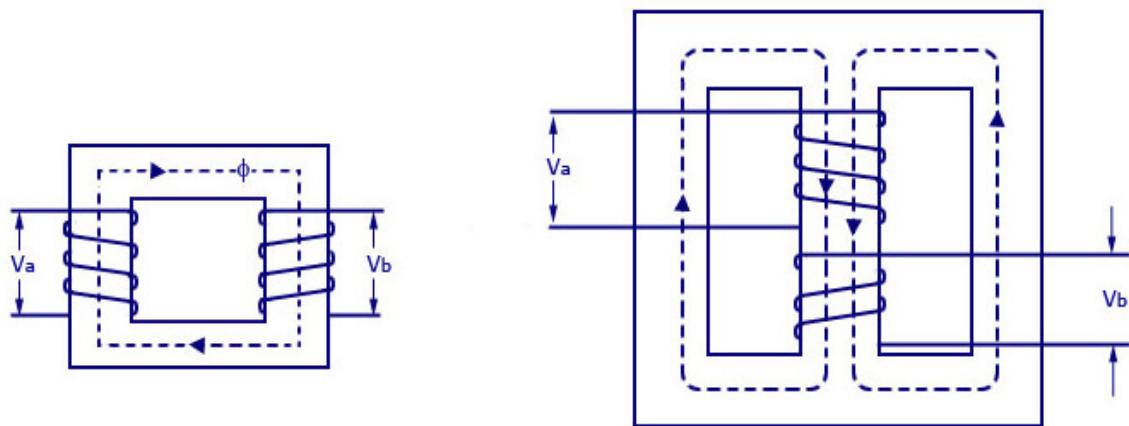
Core type: In core type the winding surrounds the steel core. The core consists of two vertical legs (limbs) with 2 horizontal sections called yokes.

To keep the leakage flux to a minimum , half of each winding is placed on each leg of core. The low voltage winding is placed adjacent to the steel core and high voltage winding is placed outside to reduce the insulating material required.

**Shell type:** In shell type transformer, steel core surrounds windings.LV and HV windings are wound over central lump.

Core type is used for high voltage and shell type is used for low voltage.

#### Core Type and Shell Type Transformer Winding



#### PRINCIPLE OF OPERATION

It is based on the principle of mutual induction i.e. whenever the amount of magnetic flux linked with the coil changes, an emf is induced in the coil.

Whenever alternating voltage  $V_1$  is applied to the primary winding,  $I_0$  (exciting current) flows which sets up  $\phi$  in magnetic core. This flux links with both windings and  $E_1$  &  $E_2$  are induced.

From Lenz's law,  $E_1 = -V_1$

If  $N_2 > N_1$  then  $E_2 > E_1$  and it becomes step up transformer

If  $N_2 < N_1$  then  $E_2 < E_1$  and it becomes step down transformer

Here  $E_2$  is in phase opposite to  $V_1$ .

If the secondary is open circuited, then the terminal voltage  $V_2$  at secondary is equal in magnitude and in phase with the induced emf at the secondary, i.e.  $E_2 = V_2$ .

## IDEAL TRANSFORMER

An imaginary transformer which has the following properties

1-Primary and secondary winding resistance are negligible, hence no resistive voltage drop.

2- leakage flux and leakage inductance are zero. There is no reactive voltage drop in the windings.

3- power transformer efficiency is 100% i.e. there are no hysteresis loss, eddy current loss or heat loss due to resistance.

4- permeability of the core is infinite so that it requires zero mmf to create flux in the core.

Power In the primary= power in the secondary .

$$E_1 I_1 = E_2 I_2$$

$$I_1 / I_2 = E_2 / E_1 = N_2 / N_1 = K = V_2 / V_1$$

1 – when transferring resistance or reactance from primary to secondary, multiply it by  $K^2$

2- when transferring resistance or reactance from secondary to primary, divide it by  $K^2$

3- Transferring voltage or current, only K is used.

- a) Any voltage V in primary becomes KV in secondary.
- b) Any voltage V in secondary becomes V/K in primary.
- c) Any current I in primary becomes I /K in secondary.
- d) Any current I in secondary becomes KI in primary.
- e) A resistance R in primary  $K^2R$  in secondary.
- f) A resistance R in secondary becomes  $R/K^2$ .

### EMF Equation:

$$\phi = \phi_m \sin \omega t$$

$$e_1 = -N_1 \frac{d\phi}{dt} = -N_1 \frac{d}{dt}(\phi_m \sin \omega t)$$

$$e_1 = -N_1 \omega \phi_m \cos \omega t = -N_1 \times 2\pi f \phi_m \cos \omega t$$

$$e_1 = N_1 2\pi f \phi_m \sin(\omega t - 90^\circ) \quad [E_{m1} = 2\pi f N_1 \phi_m]$$

$$\text{R.M.S value of } E_1 \text{ is: } E_1 = \frac{E_{m1}}{\sqrt{2}} = \frac{2\pi f N_1 \phi_m}{\sqrt{2}} = 4.44 f N_1 \phi_m$$

$$E_2 = 4.44 f N_2 \phi_m$$

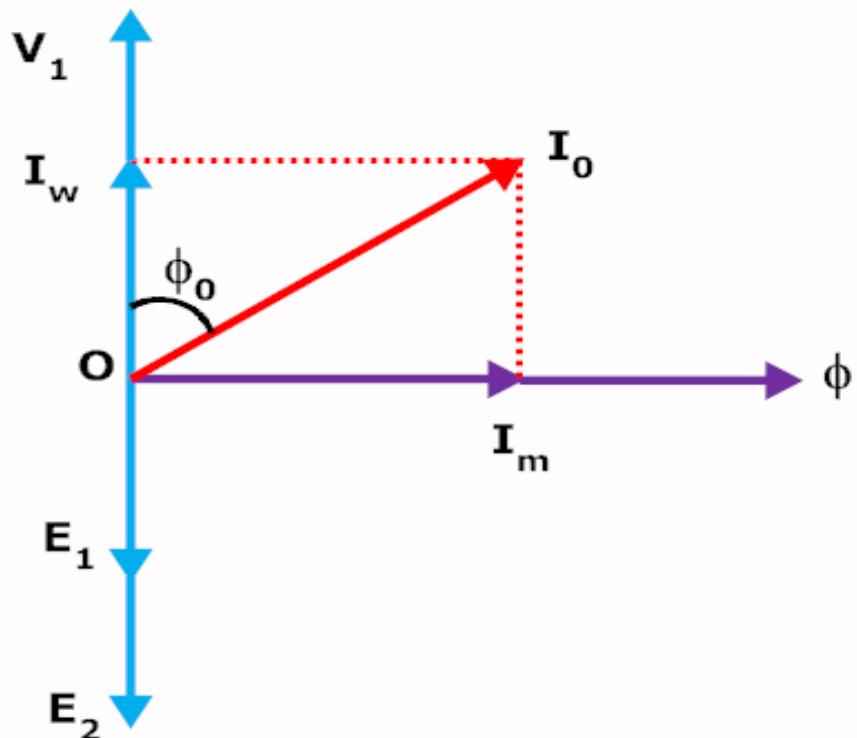
### Voltage Transformation Ratio:

$$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

- $N_2/N_1$  is known as voltage transformation ratio and represented by K.
- If  $N_2 > N_1$  or  $K > 1$  then step up transformer

- If  $N_1 > N_2$  or  $K < 1$  then step down transformer

### **Practical Transformer on no load:**



**Figure 4: Phasor diagram of practical transformer on no load**

- A transformer is said to be on no load if its primary winding is connected to AC supply and secondary is open. i.e secondary current is zero
- When an A.C voltage is applied to primary, a small current  $I_0$  flows in primary.
- $I_0 = N_0$ -load current

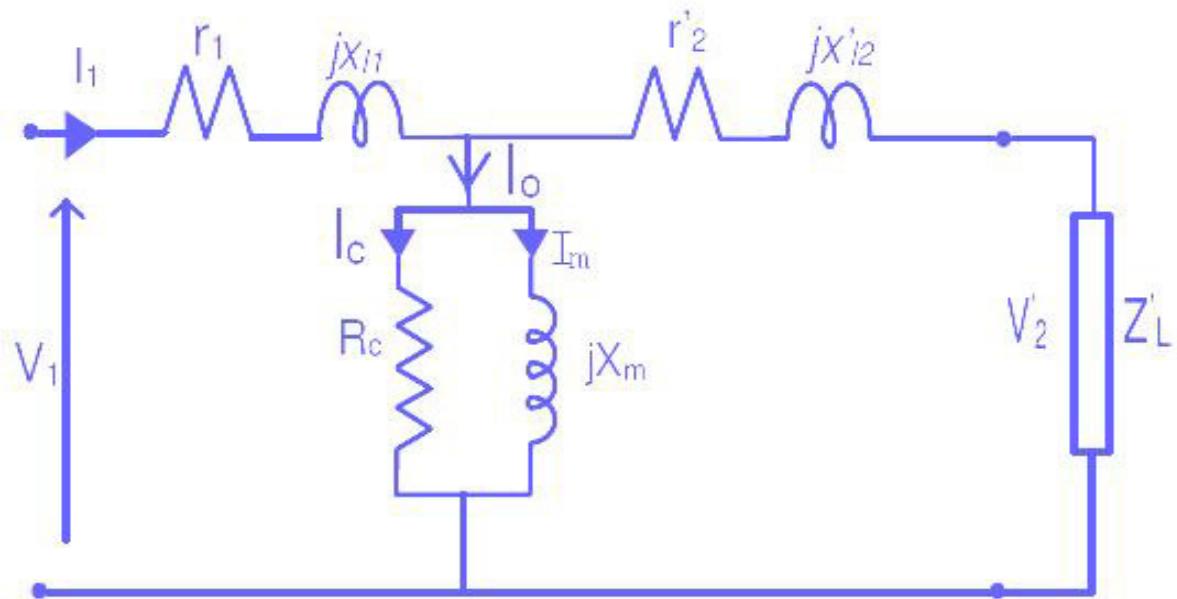
- $I_m$  = magnetizing current. It magnetizes the core and sets flux. So, in phase with it.
- $I_m$  is called the reactive or wattless component of no load current
- $I_w$  produces eddy current and hysteresis losses in the core and very small copper loss in primary. It is called active or wattful component of no load current.
- $I_w$  is in phase with the applied voltage ( $V_1$ ) at the primary.
- No load current  $I_0$  is small. So drops in  $R_1$  and  $X_1$  on primary side are very small. At no load  $V_1 = E_1$ .
- No load primary copper loss ( $I_0^2 R_1$ ) is very small. So, no load primary input power is equal to iron loss

$$I_w = I_0 \cos \phi_0, I_m = I_0 \sin \phi_0, I_0 = \sqrt{I_m^2 + I_w^2}$$

$$\text{No load power factor, } \cos \phi_0 = \frac{I_w}{I_0}$$

$$\text{No load input power (active power)} = V_1 I_0 \cos \phi_0,$$

$$\text{No load reactive power} = V_1 I_0 \sin \phi_0$$



(a)

- Winding resistance
- Leakage reactance
- Iron losses
- Depends on supply frequency,
- Maximum flux density in the core
- Volume of the core
- Impedance reflection and power transform:-

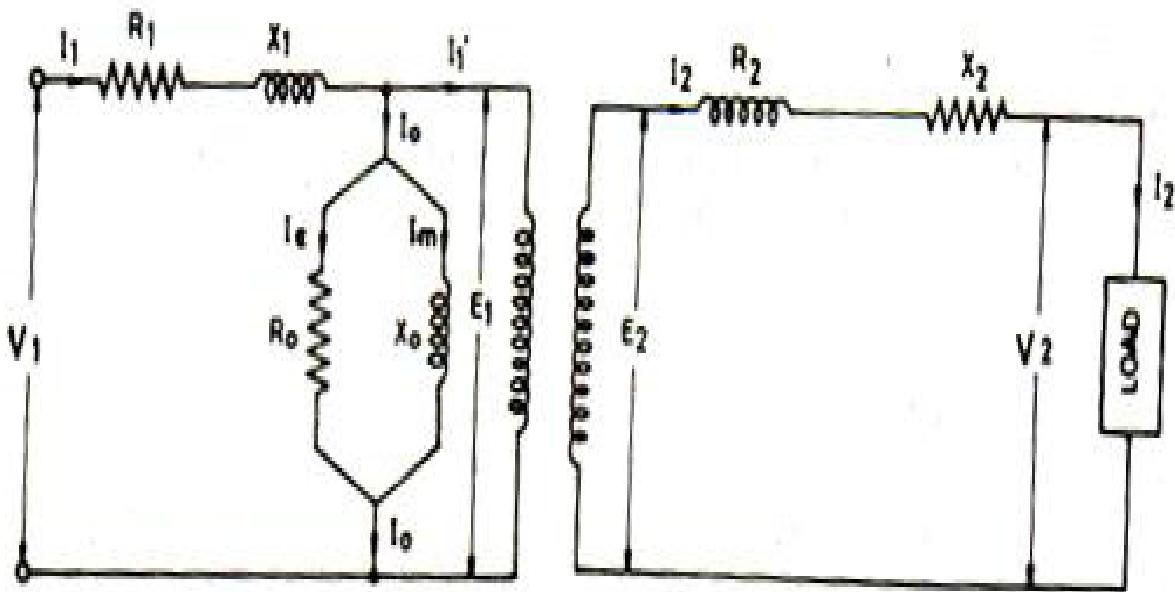
$$(I_p)^2 R_p = I_s^2 R_s$$

$$R_p = \left( \frac{I_s}{I_p} \right)^2 R_s \quad [\text{since, } N_p I_p = N_s I_s; \frac{I_p}{I_s} = \frac{N_s}{N_p} = K]$$

$$R_p = \frac{1}{K^2} R_s$$

$$\text{Similarly, } X_p = \frac{1}{K^2} X_s$$

### Equivalent Circuit of a loaded transformer:



**Example:** The primary winding of a single phase transformer is connected to a 220 V, 50 Hz supply. The secondary winding has 2000 turns. If the maximum value of the core flux is 0.003 wb, determine i) the number of turns on the primary winding ii) the secondary induced voltage

Ans.

$$E_1 = 220 \text{ V}, f = 50 \text{ Hz}$$

$$N_2 = 2000, \phi_m = 0.003 \text{ wb}$$

$$\text{i)} E_1 = 4.44 f \phi_m N_1$$

$$N_1 = \frac{E_1}{4.44 f \phi_m} = \frac{220}{4.44 \times 50 \times 0.003} = 330$$

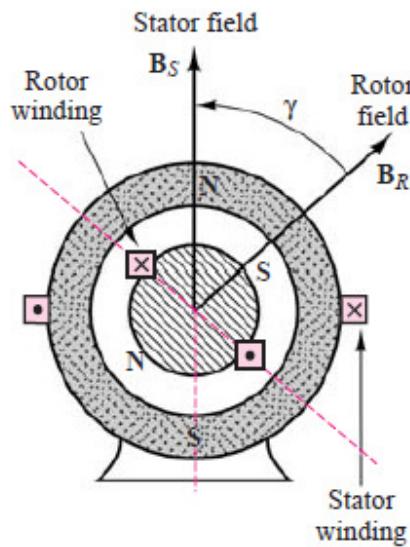
$$\text{ii)} E_2 = 4.44 f \phi_m N_2 = 4.44 \times 50 \times 0.003 \times 2000 = 1332$$

## **INTRODUCTION TO ELECTRIC MACHINES**

The operation of the three major classes of electric machines—DC, synchronous, and induction—first is described as intuitively as possible. The second part of the chapter is devoted to a discussion of the applications and selection criteria for the different classes of machines. The emphasis of this chapter is on explaining the properties of each type of machine, with its advantages and disadvantages with regard to other types; and on classifying these machines in terms of their performance characteristics and preferred field of application.

## **ROTATING ELECTRIC MACHINES**

The range of sizes and power ratings and the different physical features of rotating machines are such that the task of explaining the operation of rotating machines in a single chapter may appear formidable at first. Some features of rotating machines, however, are common to all such devices. This introductory section is aimed at explaining the common properties of all rotating electric machines. We begin our discussion with reference to Figure 14.1, in which a hypothetical rotating machine is depicted in a cross-sectional view. In the figure, a box with a cross inscribed in it indicates current flowing into the page, while a dot represents current out of the plane of the page.



**Figure 14.1** A rotating electric machine

In Figure 14.1, we identify a **stator**, of cylindrical shape, and a **rotor**, which, as the name indicates, rotates inside the stator, separated from the latter by means of an air gap. The rotor and stator each consist of a magnetic core, some electrical insulation, and the windings necessary to establish a magnetic flux (unless this is created by a permanent magnet). The rotor is mounted on a bearing-supported shaft, which can be connected to *mechanical loads* (if the machine is a motor) or to a *prime mover* (if the machine is a generator) by means of belts, pulleys, chains, or other mechanical couplings. The windings carry the electric currents that generate the magnetic fields and flow to the electrical loads, and also provide the closed loops in which voltages will be induced.

## BASIC CLASSIFICATION OF ELECTRIC MACHINES

An immediate distinction can be made between different types of windings characterized by the nature of the current they carry. If the current serves the sole

purpose of providing a magnetic field and is independent of the load, it is called a *magnetizing*, or excitation, current, and the winding is termed a **field winding**. Field currents are nearly always direct current (DC) and are of relatively low power, since their only purpose is to magnetize the core (recall the important role of high-permeability cores in generating large magnetic fluxes from relatively small currents). On the other hand, if the winding carries only the load current, it is called an **armature**. In DC and alternating-current (AC) synchronous machines, separate windings exist to carry field and armature currents. In the induction motor, the magnetizing and load currents flow in the same winding, called the *input winding*, or *primary*; the output winding is then called the *secondary*. As we shall see, this terminology, which is reminiscent of transformers, is particularly appropriate for induction motors.

It is also useful to classify electric machines in terms of their energy conversion characteristics. A machine acts as a **generator** if it converts mechanical energy from a prime mover, say, an internal combustion engine, to electrical form. Examples of generators are the large machines used in power generating plants, or the common automotive alternator. A machine is classified as a **motor** if it converts electrical energy to mechanical form. The latter class of machines is probably of more direct interest to you, because of its widespread application in engineering practice. Electric motors are used to provide forces and torques to generate motion in countless industrial applications. Machine tools, robots, punches, presses, mills, and propulsion systems for electric vehicles are but a few examples of the application of electric machines in engineering.

Note that in Figure 14.1 we have explicitly shown the direction of two magnetic fields: that of the rotor  $\mathbf{B}_R$  and that of the stator  $\mathbf{B}_S$ . Although these fields are generated by different means in different machines (e.g., permanent magnets, alternating currents, direct currents), the presence of these fields is what causes a rotating machine to turn and enables the generation of electric power. In particular, we see that in Figure 14.1 the north pole of the rotor field will seek to align itself with the south pole of the stator field. It is this magnetic attraction force that permits the generation of torque in an electric motor; conversely, a generator exploits the laws of electromagnetic induction to convert a changing magnetic field to an electric current. To simplify the discussion in later sections, we now introduce some basic concepts that apply to all rotating electric machines. Referring to Figure 14.2, we note that for all machines the force on a wire is given by the expression

$$\mathbf{f} = iw\mathbf{l} \times \mathbf{B}$$

Where  $iw$  is the current in the wire,  $\mathbf{l}$  is a vector along the direction of the wire, and  $\times$  denotes the cross product of two vectors. Then the torque for a multi-turn coil becomes

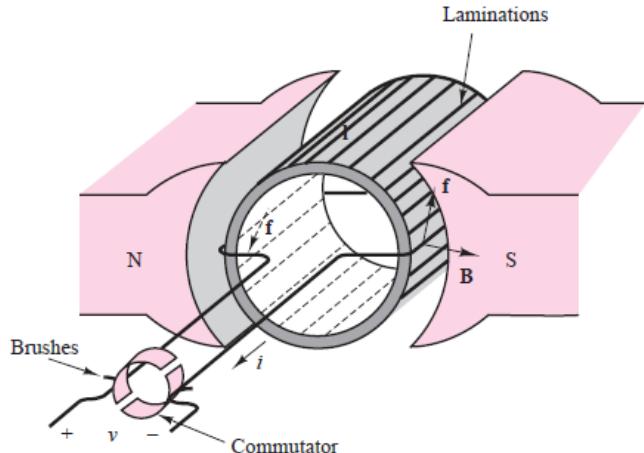
$$T = KBiwsin \alpha$$

Where

$B$  = magnetic flux density caused by stator field

$K$  = constant depending on coil geometry

$\alpha$  = angle between  $\mathbf{B}$  and normal to plane of coil



**Figure 14.2** Stator and rotor fields and the force acting on a rotating machine

In the hypothetical machine of Figure 14.2, there are two magnetic fields: one generated within the stator, the other within the rotor windings. Either (but not both) of these fields could be generated by a current or by a permanent magnet. Thus, we could replace the permanent-magnet stator of Figure 14.2 with a suitably arranged winding to generate a stator field in the same direction. If the stator were made of a toroidal coil of radius  $R$  (see Chapter 13), then the magnetic field of the stator would generate a flux density  $B$ , where

$$B = \mu H = \mu \frac{Ni}{2\pi R}$$

and where  $N$  is the number of turns and  $i$  is the coil current. The direction of the torque is always the direction determined by the rotor and stator fields as they seek to align to each other (i.e., counterclockwise in the diagram of Figure 14.1). It is important to note that Figure 14.2 is merely a general indication of the major features and characteristics of rotating machines. A variety of configurations exist, depending on whether each of the fields is generated by a current in a coil or by a

permanent magnet and whether the load and magnetizing currents are direct or alternating.

## **DC MACHINE**

### **FUNDAMENTAL:**

$$\text{Emf induced in coil} \quad e = -N \frac{d\Phi}{dt} \text{ volt}$$

$$\text{Emf induced in a conductor} \quad e = Blv \text{ volt}$$

$$\text{Force developed in a conductor} \quad F = BIL \text{ N}$$

$$\text{Electrical energy} \quad E_n = VIt \text{ Whour}$$

$$\text{Electrical power (Active)} \quad P=VI \text{ Watt}$$

$$\text{Resistance of conductor} \quad R=\rho l/a \text{ Ohm}$$

$$\text{Eqn. of current by Ohm's law, } I=V/R \text{ A}$$

$$\text{Magnetizing force, } H=NI/L \text{ AT/m}$$

$$\text{Flux density, } B=\Phi/A$$

$$\text{Electrical field intensity, } E=V/d \text{ V/m}$$

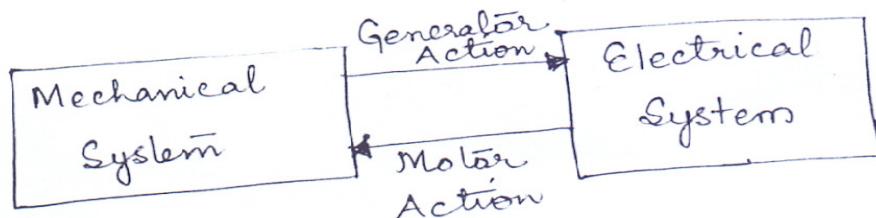
$$\text{Current density, } J=I/a \text{ A/m}^2$$

### **INTRODUCTION :**

DC machine is a device which converts mechanical energy into electrical energy and vice versa.

When the device acts as a generator (or dynamo), mechanical energy is converted into electrical energy.

On the other hand, when the device acts as a motor, electrical energy is converted into mechanical energy.



### ESSENTIAL FEATURES:

There is no real difference between a dc. motor and dc generator either from the point of view of the essential components or of the fundamental principles involved.

In the generator there is a conversion of mechanical to electrical energy while in the motor there is the reverse conversion of electrical to mechanical energy. The structure difference is merely one of the enclosure. Most generators work in sheltered situations e.g. in power stations and an open type of construction is thus possible, the advantage being that all the parts are in consequence, easily accessible. Motors often work in exposed

Situations, where there are dirt as damp, chemical fumes, explosive gases and so on, and it may therefore be necessary to enclose all the working parts.

## **CONSTRUCTION:**

### **STATOR**

Yoke/Frame

Field magnet  
(pole core & pole shoe)

Main field winding

Interpoles/commutating poles

Interpoles winding

### **ROTOR**

Armature core

Armature winding/ conductor

Commutator & Brushes

Shaft

Bearings

### **STATOR & ROTOR**

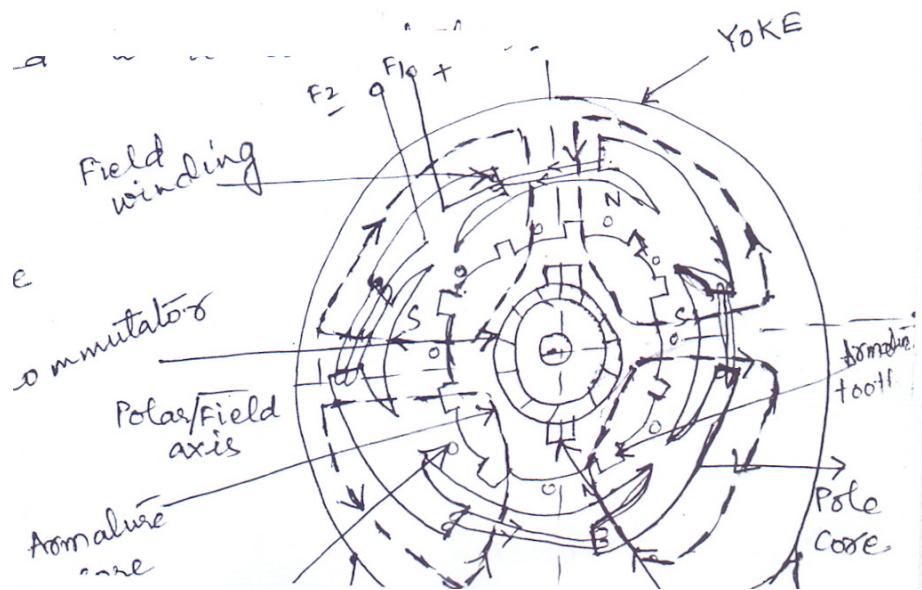
All conventional electrical machines consist of a stationary member called the stator separated by an air gap from a rotating member called rotor.

In d.c machines the stator usually consists of salient poles with coils wound round them so as to produce a magnetic field.

The rotor is familiarly called the armature and consists of a series of coils located in slots around its periphery and connected to a commutator.

### **Yoke/Frame**

Yoke is the outer frame dc m/c. It carries the magnetic flux provided by the pole and acts as a protecting shield for the entire machine. In small generators yokes are made of cast iron whereas in large machine cast sheet is used.



### Field magnet :

It is a strong permanent magnet (in case of a small dynamo) or an electromagnet (in case of large dynamo) of intense magnetic field.

Pole core & Pole shoe : The field magnet has two parts

Pole core (pole pieces)

Pole shoes.

Pole core is made of cast steel or cast iron with laminated pole shoes screwed on to the holes in the yoke.



Pole shoes spread out the flux in the air gap and reduce the reluctance of the magnetic path due to its large cross -section.

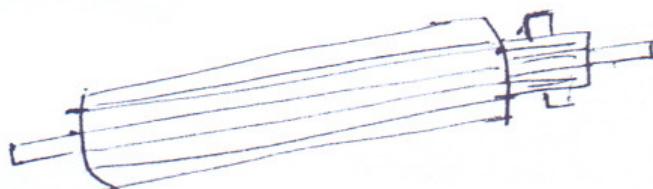
Poles shoes support the exciting coils.

Pole coils (field winding)

- It is otherwise known as exciting winding
- These are fine copper wire (or strip) wound around the pole pieces
- The flux produced by the winding is cut by the revolving armature

#### ARMATURE CORE:

- It houses armature coils in the slots. It is cylindrical or drum shaped.
- Armature is placed in between the two poles of field magnet and is rotated about its central axis mechanically (by a prime mover)



- It is usually made of circular sheet steel disc or laminations.

- Thickness of laminations is of the order of 0.5mm. Perforations exist in these laminations to provide axial flow of air through the armature for cooling purposes.
- Armature core is keyed to the shaft.
- During rotation it cuts the magnetic flux of the field magnets.
- It also provides a path of very low reluctance to the flux from north pole to south pole.

#### **ARMATURE WINDING:**

- It is made up of copper.
- It consists of large no. of insulated coils, each coil having one or more turns.
- Armature conductor are placed in armature slots.

#### **Commutator:**

- It converts the alternating current produced in the armature conductors into direct current.
- It consists of wedge shaped copper segments (Insulated from either side to form a ring. The number of segments of commutator equals the no. of armature coils.
- It facilitates the collection of current from the armature conductors.

#### **Brushes**

- They are fixed on the commutator by pressure springs.
- They are usually made of a high grade carbon or graphite and are in the shape of rectangular block.

- These are housed in a brush holder.
- They collect the current from the commutator and finally they pass on the EMF generated to load.

### Bearing

- The armature shaft is supported at the commutator end on ball or roller bearings which are packed in hard oil.
- They provide quieter operation, together with reduced wear and tear.
- Ball bearings are frequently employed for their reliability.
- Roller bearings are preferable for heavy duties.

### Interpoles

- In addition to the main poles, the dc machines are usually fitted with auxiliary poles placed between the main poles and they are called interpoles, the purpose of which is to provide better commutation.
- It minimizes sparking at the commutator.

### **Types of Armature Winding**

These are of two types : Lap winding

Wave winding

### Pole Pitch

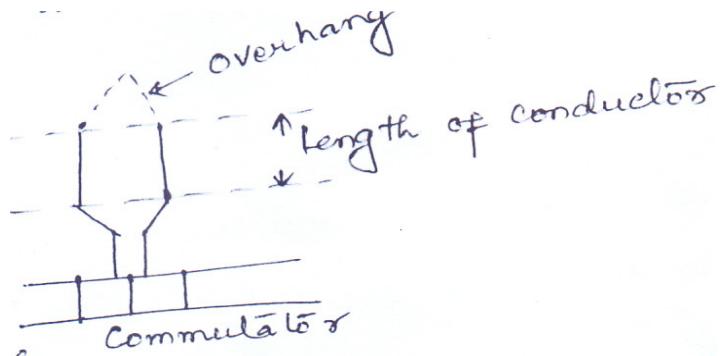
- It is defined as the no of armature conductors per pole.
- If there are 80 conductors and 8 poles, pole pitch is  $80/8 = 10$ .

## Conductor

- It is defined as the length of a wire lying the magnetic field as shown in fig1.

## Coil

- Two conductors with their end connections shown in fig1 from one coil.



- Coil may be single turn coil or multi-turn coil.
- End connections are called overhang.

## Coil Pitch

- It is defined as the distance between two sides of a coil in terms of armature slots.
- It is defined as the periphery of the armature between two sides of a coil.
- If the coil pitch is equal to the pole pitch, the winding is said to be full pitched, otherwise it is half-pitch

## Pitch:

It is defined as the distance between the second conductor one coil and the first conductor of the next coil as shown in fig.2 & 3.

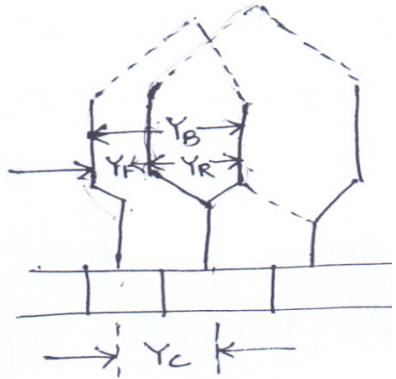


Fig.2. Lap wdg

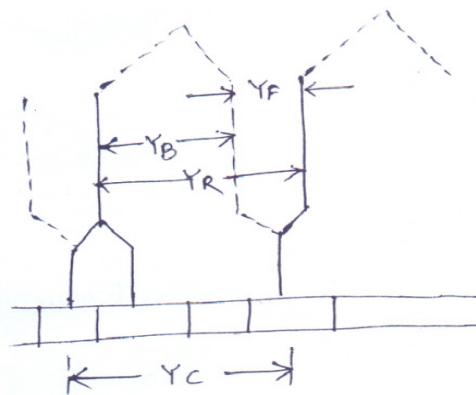


Fig.3. wave winding

### Back Pitch :

It is defined as the distance measured in terms of armature conductors that a coil advances on the back side of the armature as shown in fig.2 & 3.

### Resultant Pitch: ( $Y_R$ )

It is defined as the distance between the beginning of one coil and the beginning of the next coil or

$$\text{lap winding} \quad Y_R = Y_B - Y_F$$

$$\text{wave winding} \quad Y_R = Y_B + Y_F$$

### Coil Pitch ( $Y_c$ ):

It is defined as the distance between the beginning of one coil to the beginning of the next coil as shown in fig 2 & 3 for lap and wave winding respectively.

### Lap winding:

To get these type of winding following rules are commonly used: winding must be full pitched i.e.

$$Y_B + Y_F = \text{Pole Pitch}$$

1. To place the coil properly on the armatures, the front pitch as well as back pitch must be odd.
2. No. of commutator segment = no. of coils.
3. winding must close upon itself.
4.  $Y_c = \pm 1$

For Progressive or right handed winding

$$Y_F = Z/P - 1 \quad \text{and} \quad Y_B = Z/P + 1$$

For Retrogressive or left handed winding

$$Y_F = Z/P + 1 \quad \text{and} \quad Y_B = Z/P - 1$$

### Wave Winding:

1.  $Y_B$  &  $Y_F$  are odd and of opposite sign.
2.  $Y_B$  &  $Y_F$  are nearly equal to the pole pitch and differ by 2.
3.  $Y_C = (\text{No. of commutator bars } \pm 1) / \text{No. of pairs of pole}$

### Comparison:

Lap winding	Wave winding
No. of parallel paths = no. of poles	No. of parallel path = 2
No. of brushes sets = no. of poles	No. of brushes sets = 2
Used for high current & low voltage	Used for low current & high voltage

## **PRINCIPLE OF OPERATION OF DC GENERATOR:**

### **Principle:**

Faraday's law of electromagnetic induction according to which emf is induced in the conductors which drives the current through the conductor.

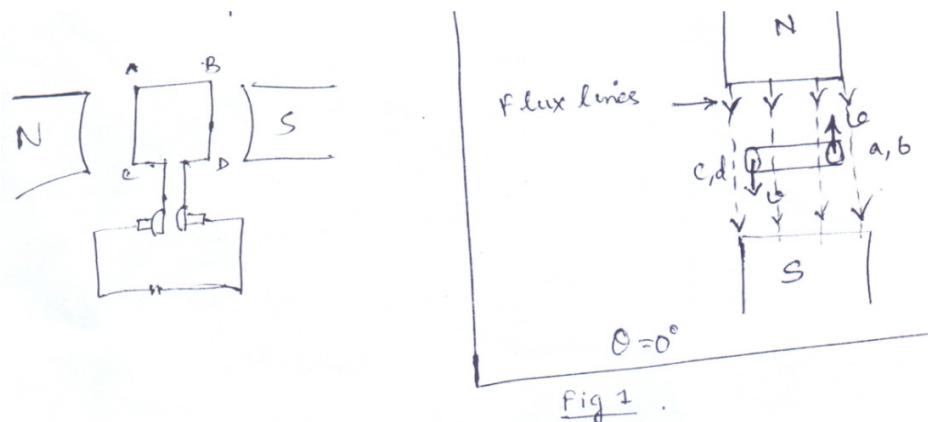
Fig below shows a single turn generator.

The coil is rotated in anticlockwise direction with the help of prime mover.

Fig. shows the different instants of the induced emf due to different positions of the coil.

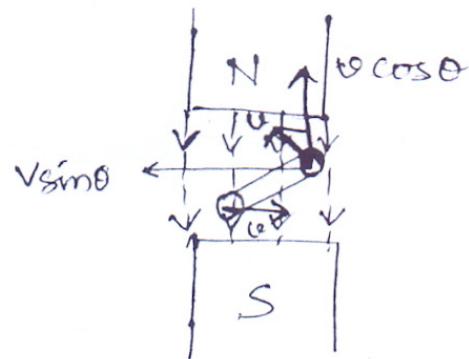
Magnetic field is produced either by a permanent magnet or an electromagnet energised by the DC supply.

When the angle  $\theta = 0^\circ$ , the coil is perpendicular to the magnetic field and the instantaneous component of velocity of conductors ab and cd is parallel to the magnetic field .



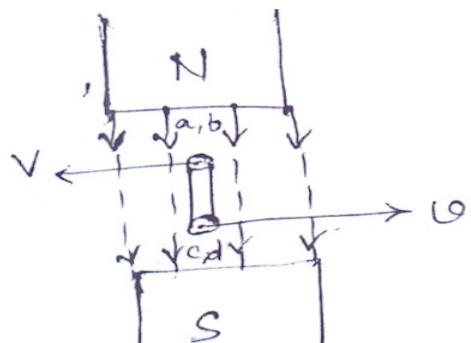
The flux linked with the coil is maximum but the rate of change of flux is minimum. Hence emf cannot be generated . Therefore current flows through the conductors.

When  $0 < \theta < 90^\circ$ , due to the rotation of the coil in the anticlockwise direction, the velocity of the conductor has two components that is  $v\sin\theta$  and  $v\cos\theta$ . Therefore the conductors will cut the flux due to  $v\sin\theta$ . Hence emf is induced in the conductors and current flows in the conductors.



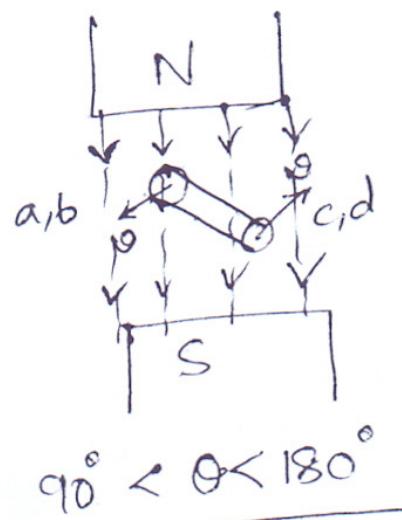
$$\underline{0^\circ < \theta < 90^\circ}$$

If when  $\theta = 90^\circ$ , coil is parallel to the magnetic field and the instantaneous component of velocity of conductors ab and cd is perpendicular to the magnetic field. The flux linked with the coil is minimum but the rate of change of flux is maximum. Hence emf generated is maximum. Therefore maximum current flows through the conductors.

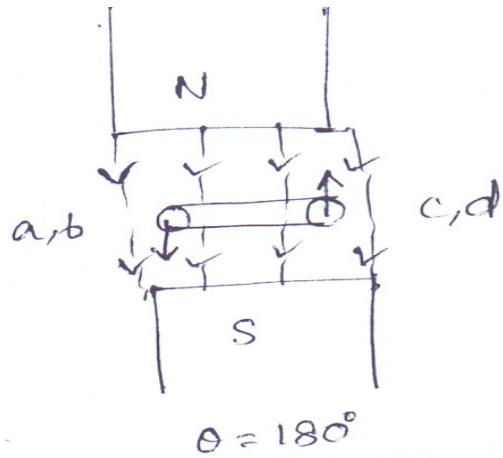


$$\theta = 90^\circ$$

When the coil rotates from  $\theta = 90^\circ$  to  $\theta = 180^\circ$  the components of velocity that is  $\sin \theta$  of conductors perpendicular to the field decreases and hence emf is induced in the conductor and current flow in the conductors.

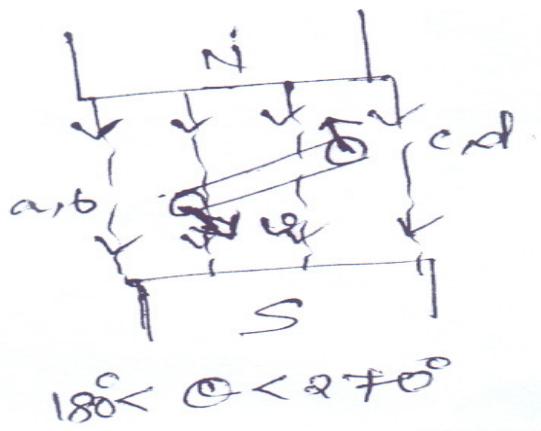


When  $\theta = 180^\circ$ , the coil is perpendicular to the magnetic field and the instantaneous components of velocity of conductors ab and cd is parallel to the magnetic field.

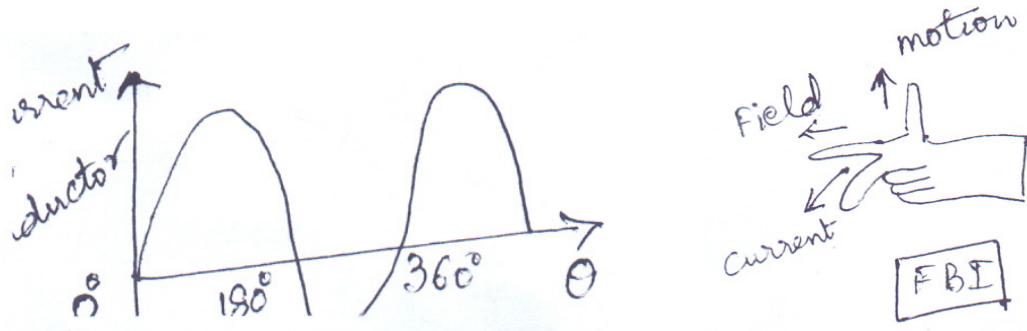


The flux linked with the coil is maximum but the rate of change of flux is minimum. Hence emf cannot be generated. Therefore the current flows through the conductor.

When  $180^\circ < \theta < 270^\circ$  due to rotation of the coil in the anticlockwise direction, the velocity of the conductors has two components that is  $v\sin\theta$  and  $v\cos\theta$  and the direction is opposite to the case when  $0^\circ < \theta < 90^\circ$ . Therefore the conductor have the flux due to  $v\sin\theta$ .

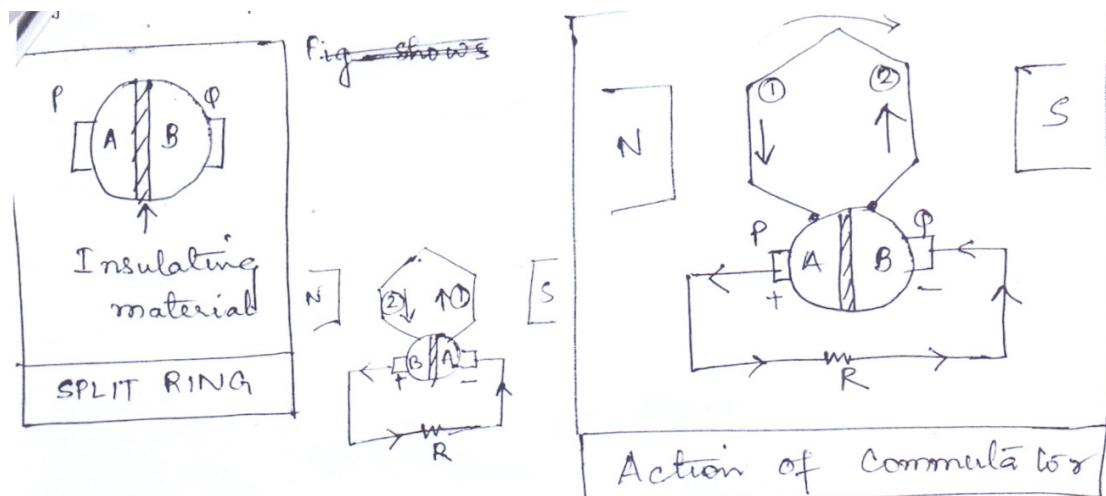


Hence emf is induced in the conductors in the direction opposite to the cases of  $0^0 < \theta < 90^0$  and current flows in the conductors in the direction opposite to the  $0^0 < \theta < 90^0$ . Similarly the other case till  $\theta = 360^0$ .



The direction of flow of current through the conductor can be found by Flemings right hand rule. To have a unidirectional current communicator is used.

Fig below shows a split ring where two segments A and B are separated by an insulating material. Let the conductor 1 be connected to segment A and conductor 2 be connected to segment B.

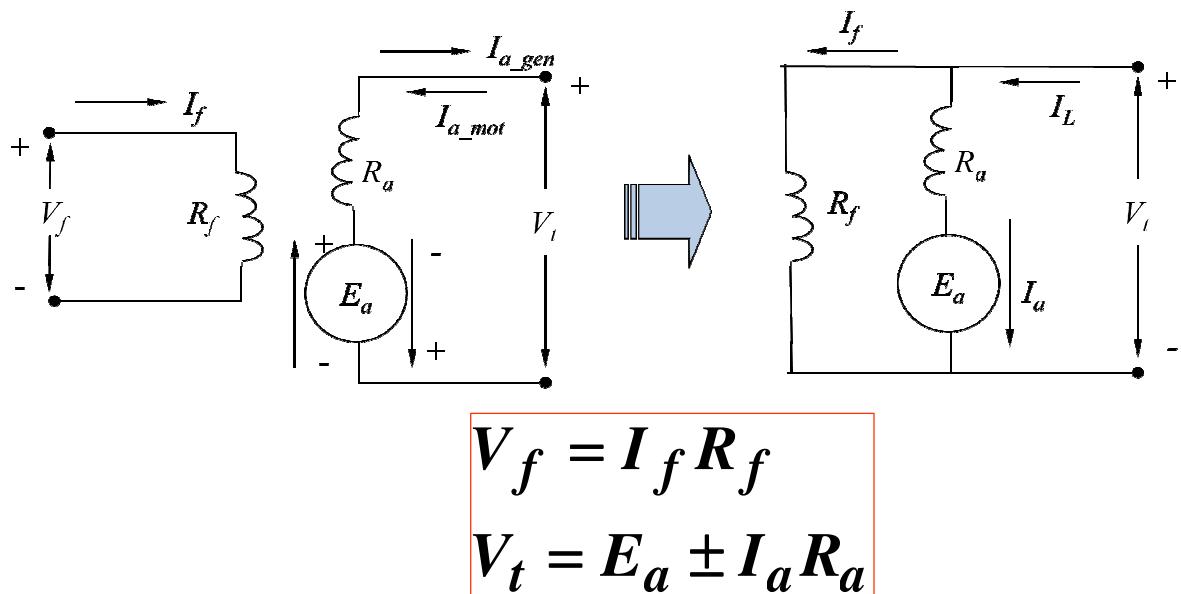


The conductor 1 carries current in the downward direction while the conductor 2 carries current in the upward direction and current through the resistance R flows

from P to Q. After one half of rotation, conductor 1 and 2 come under the influence of south and north pole respectively.

The split ring is mounted on the shaft and it rotates with the armature. The split ring will reverse this positions with the reversing of the position of the conductors, but the direction of current flow through the conductor remains unaltered because the P & Q are stationary.

### Equivalent circuit of a DC Machine



### Generated EMF and Electromagnetic Torque

$$V_f = I_f R_f$$

$$V_t = E_a \pm I_a R_a$$

Motor:  $V_t > E_a$

Generator:  $V_t > E_a$

Voltage generated in the armature circuit due the flux of the stator field current:

$$E_a = K_a \phi_d \omega_m$$

$K_a$ : design constant

Electromagnetic torque:

$$T_e = K_a \phi_d I_a$$

$$P_{em} = E_a I_a = T_e \omega_m$$

## Types of DC Machines

Both the armature and field circuits carry direct current in the case of a DC machine.

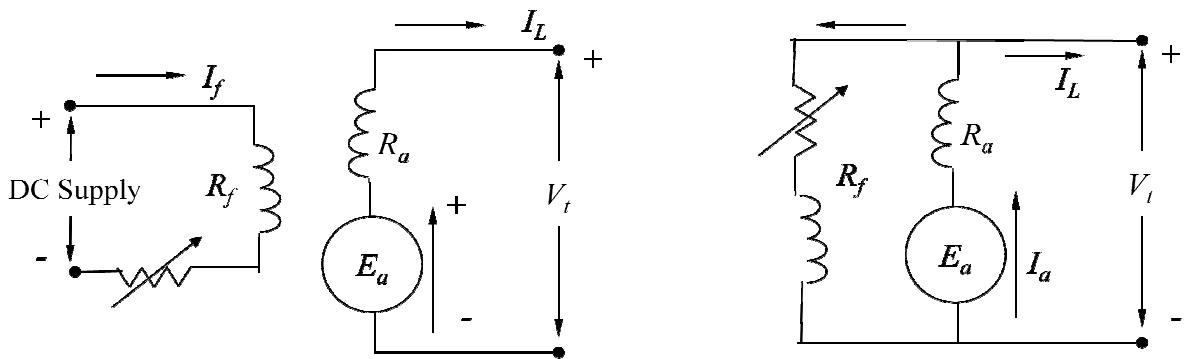
Self-excited DC machine: when a machine supplies its own excitation of the field windings. In this machine, residual magnetism must be present in the ferromagnetic circuit of the machine in order to start the self-excitation process.

Separately-excited DC machine: The field windings may be separately excited from an eternal DC source.

Shunt Machine: armature and field circuits are connected in parallel. Shunt generator can be separately-excited or self-excited.

Series Machine: armature and field circuits are connected in series.

## Separately-Excited and Self-Excited DC Generators



**Example:** A 100-kW, 250-V DC shunt generator has an armature resistance of 0.05 W and field circuit resistance of 60 W. With the generator operating at rated voltage, determine the induced voltage at (a) full load, and (b) half-full load.

Ans. (a) At full load,

$$V_t = E_a - I_a R_a$$

$$I_f = 250 / 60 = 4.17 \text{ A}$$

$$I_{L\_FL} = 100,000 / 250 = 400 \text{ A}$$

$$I_a = I_{L\_FL} + I_f = 400 + 4.17 = 404.17 \text{ A}$$

$$E_a = V_t + I_a R_a = 250 + 404.17 * 0.05 = 270.2 \text{ V}$$

(b) At half load,

$$I_f = 250 / 60 = 4.17 \text{ A}$$

$$I_{L\_HL} = 50,000 / 250 = 200 \text{ A}$$

$$I_a = I_{L\_HL} + I_f = 200 + 4.17 = 204.17 \text{ A}$$

$$E_a = V_t + I_a R_a = 250 + 204.17 * 0.05 = 260.2 \text{ V}$$

## **MODULE-III (10 HOURS)**

### **AC MACHINES**

AC machines have large advantages over DC machines. They are,

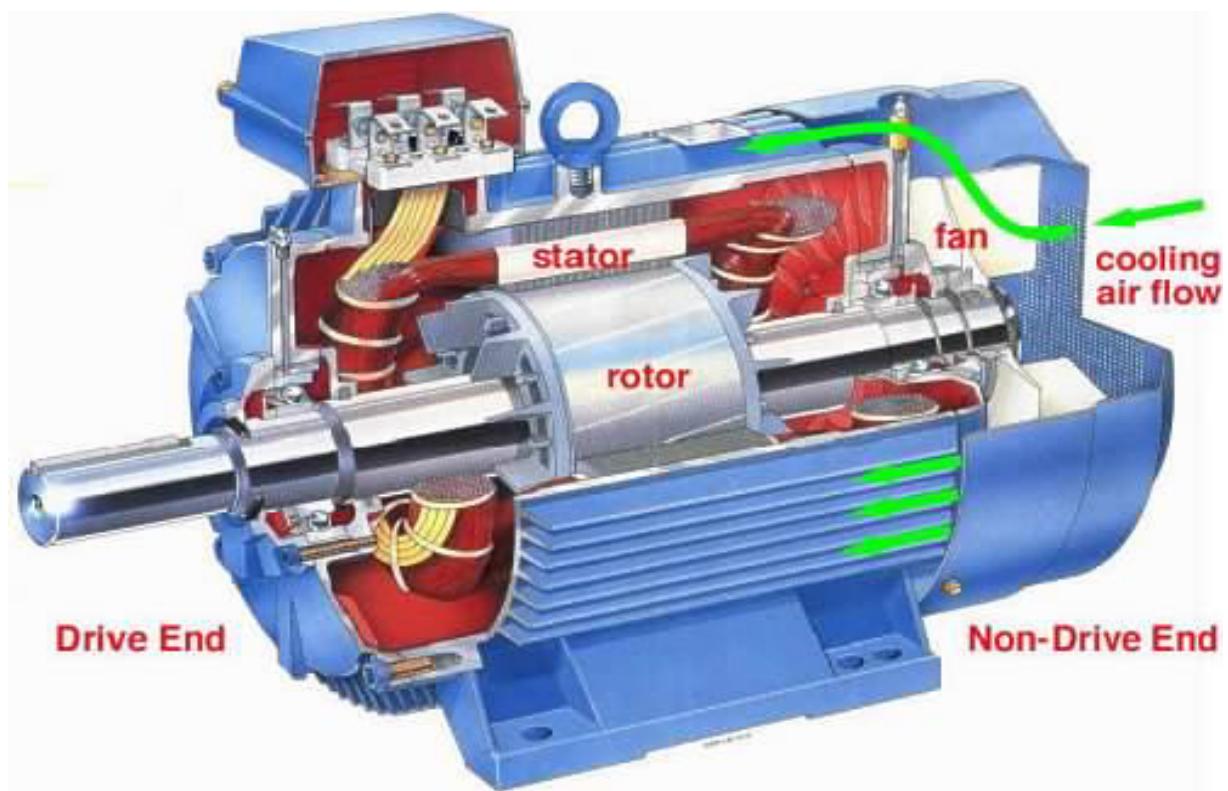
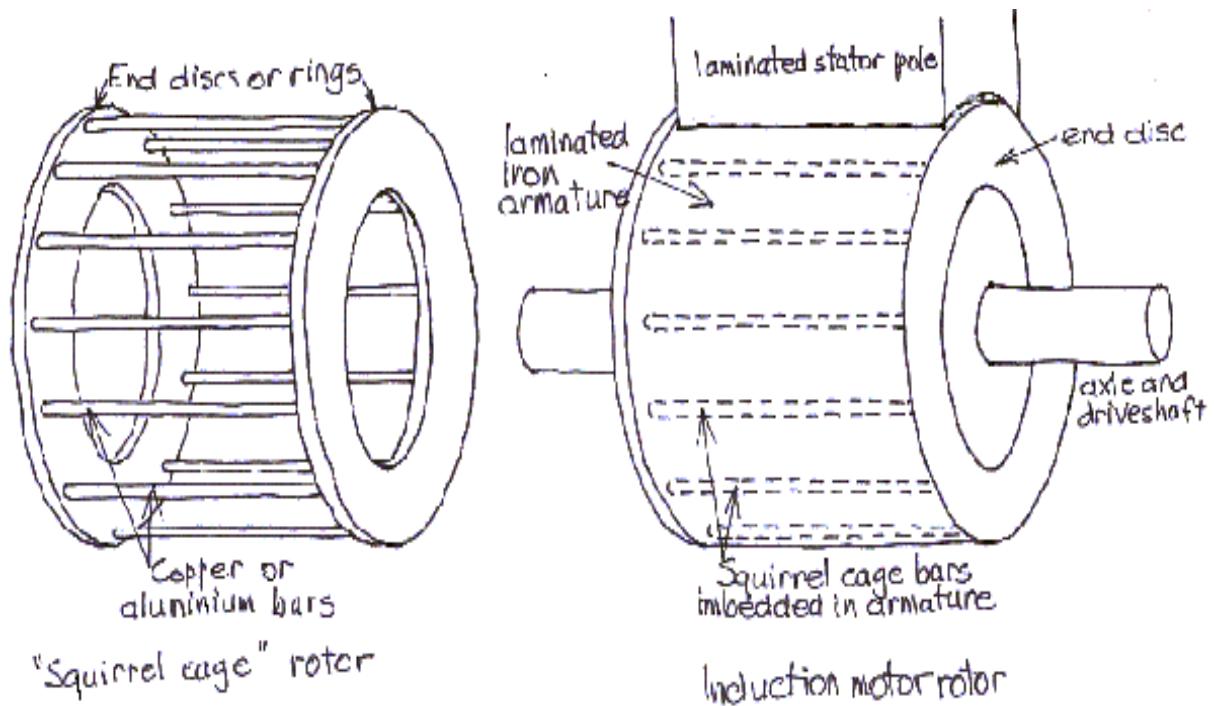
- Since basic generation of electricity is in the form of AC voltage, no converting device is necessary.
- Suitable for large ratings (upto more than 500 MW)
- Cost of an AC machine for same power and voltage rating is less than that of DC machines
- Since transformers are used in AC only, AC generation is must for commercial purpose operation.

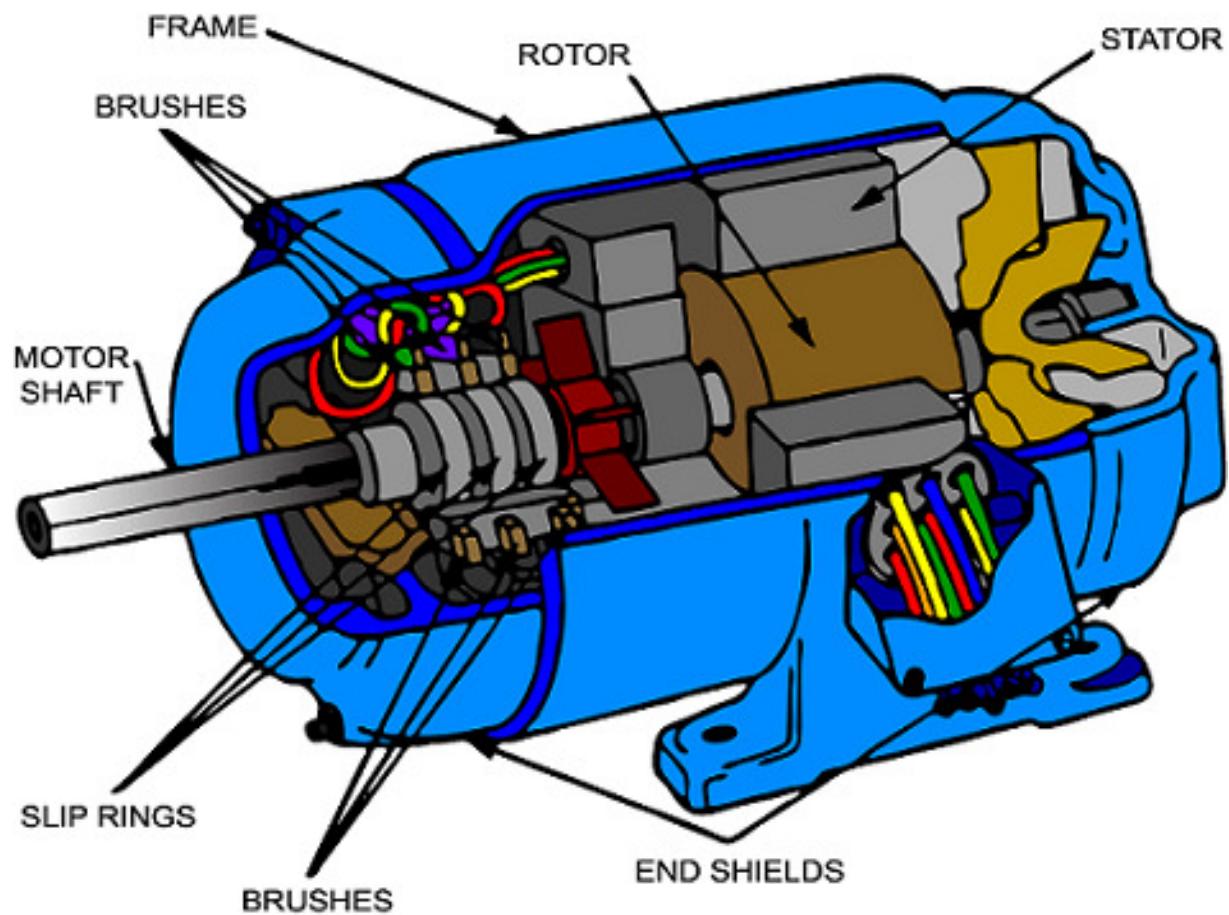
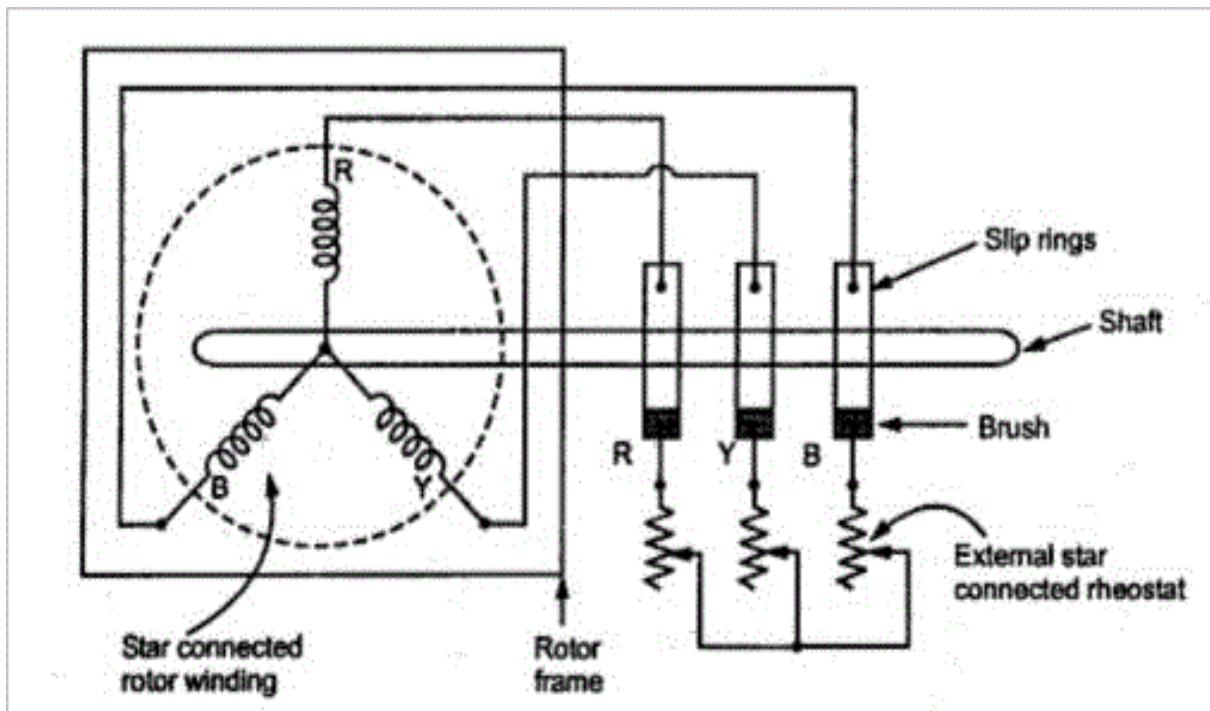
AC machines are broadly classified as:-

- Synchronous machine
  - Operates at constant speed and constant frequencies under steady state condition
  - Generator known as alternator
  - Faradays laws of electromagnetic induction
  - Does not have commutator
  - EMF is generated from mutual interaction between conductors and magnetic flux.
- Asynchronous machine
  - Operates with variable speed
  - Induction machine
  - Induction motor application in air conditioning, industrial use (rolling mills)
  - Induction generator application in wind generating system :- convert wind energy to electrical energy at constant frequency irrespective of wind speed

## **Three phase Induction Motor:**

- Three-phase induction motors are the most common and frequently encountered machines in industry
  - simple design, rugged, low-price, easy maintenance
  - wide range of power ratings: fractional horsepower to 10 MW
  - run essentially as constant speed from no-load to full load
  - Its speed depends on the frequency of the power source
- Construction:-
  - **Stator** :- three phase winding in star or delta
  - **Rotor** :-
  - ✓ **Squirrel cage rotor**
    - rotor windings are shorted internally
  - ✓ **Slip ring or phase wound rotor**
    - rotor windings are short circuited externally through three slip rings
  - Rotor windings are short circuited
  - Slip (S) :- difference between the speed of rotor (N) and the speed of rotating magnetic field (Ns). It is expressed in % as:
- $$S = [(Ns - N)/Ns] \times 100$$
- Slip varies from syn. Speed (Ns) to 1 (When the rotor is at rest)





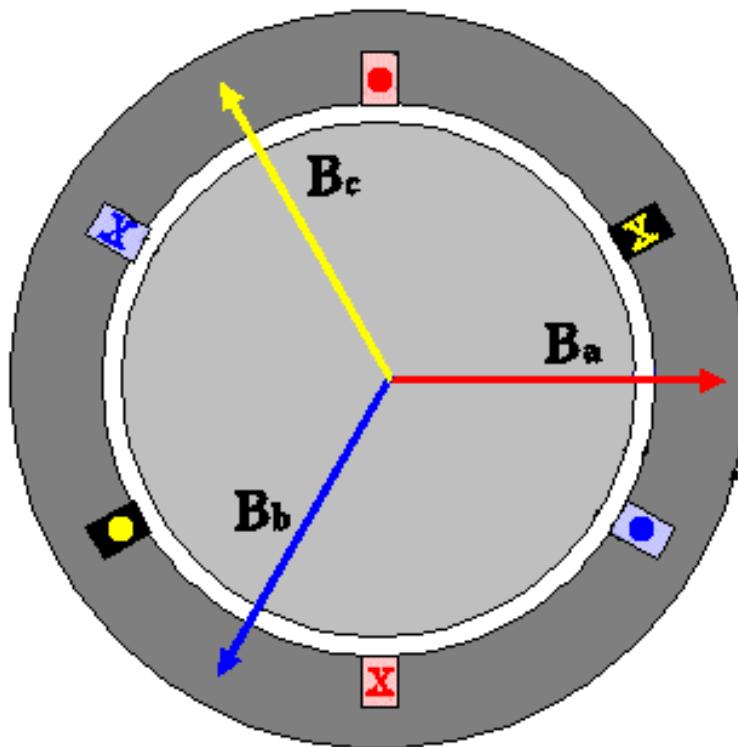
## Rotating Magnetic Field

- Balanced three phase windings, i.e. mechanically displaced 120 degrees from each other, fed by balanced three phase source
- A rotating magnetic field with constant magnitude is produced, rotating with a speed

$$n_{sync} = \frac{120f_e}{P} \text{ rpm}$$

Where  $f_e$  is the supply frequency and

$P$  is the no. of poles and  $n_{sync}$  is called the synchronous speed in  $rpm$  (revolutions per minute)



### **Principle of operation:**

- This rotating magnetic field cuts the rotor windings and produces an induced voltage in the rotor windings
- Due to the fact that the rotor windings are short circuited, for both squirrel cage and wound-rotor, and induced current flows in the rotor windings
- The rotor current produces another magnetic field

A torque is produced as a result of the interaction of those two magnetic fields

$$\tau_{ind} = k B_R \times B_s$$

Where  $\tau_{ind}$  is the induced torque and  $B_R$  and  $B_s$  are the magnetic flux densities of the rotor and the stator respectively

**Slip:** The difference between synchronous speed  $N_s$  and actual speed  $N$  of the rotor is known as slip.

$$\% \text{ Slip} = \frac{N_s - N}{N_s} \times 100\%$$

Sometimes,  $N_s - N$  is called slip speed

**Frequency of rotor ( $f'$ ):**

$$\begin{aligned} N_s - N &= \frac{120 f'}{P} \\ N_s &= \frac{120 f}{P} \\ \frac{N_s - N}{N_s} &= \frac{f'}{f} \\ f' &= sf \end{aligned}$$

**Torque Equation:**

$$T_{EM} = \frac{60}{2\pi N_s} * \text{rotor .input}$$

Unit- synchronous watt

## TORQUE- SLIP OR TORQUE-SPEED CHARACTERISTICS

$$T_{EM} = \frac{180}{2\pi N_s} * \frac{SE_2^2 R_2}{R_2^2 + (SX_2)^2}$$

For a constant supply voltage, E2 is also constant. So we can write torque equation as:-

$$T \propto \frac{SR_2}{R_2^2 + (SX_2)^2}$$

As R2 is constant.

### 1) HIGH SLIP REGION –

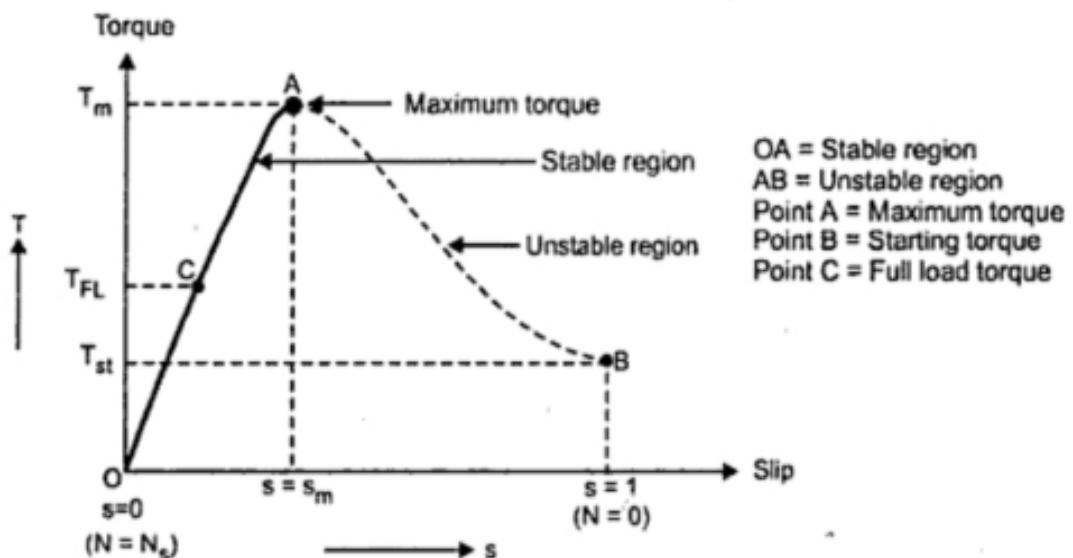
Here S is high

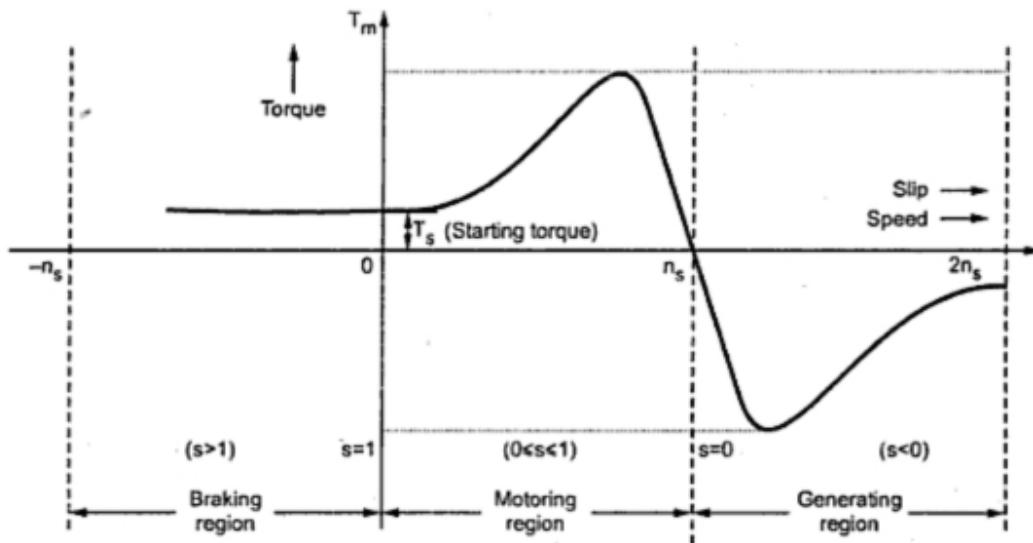
So,

$$T \propto \frac{SR_2}{(SX_2)^2} \propto \frac{1}{S}$$

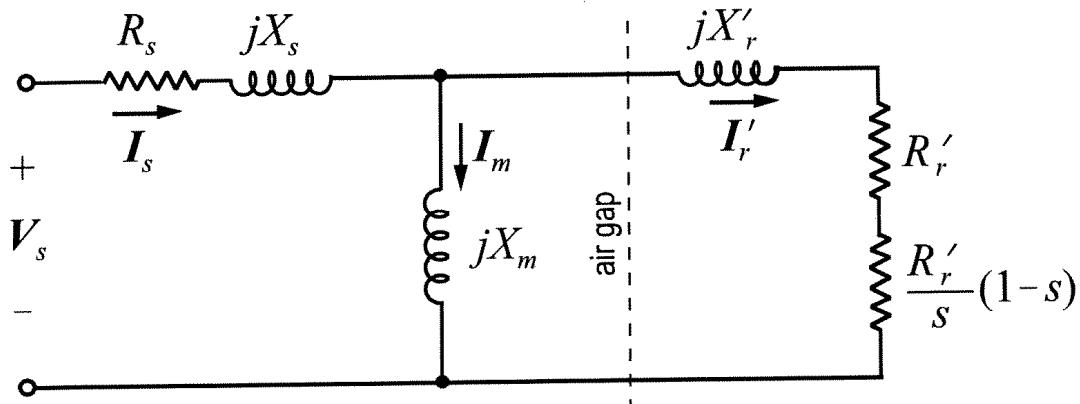
As R2 and X2 are constants

$$T_{Full\ Load} < T_M$$





## EQUIVALENT CIRCUIT



### Introduction to 1-phase induction motor:

- Used for domestic application
- 1-phase IM are fractional KW motors
  - Rotor – squirrel cage
  - Stator – distributed

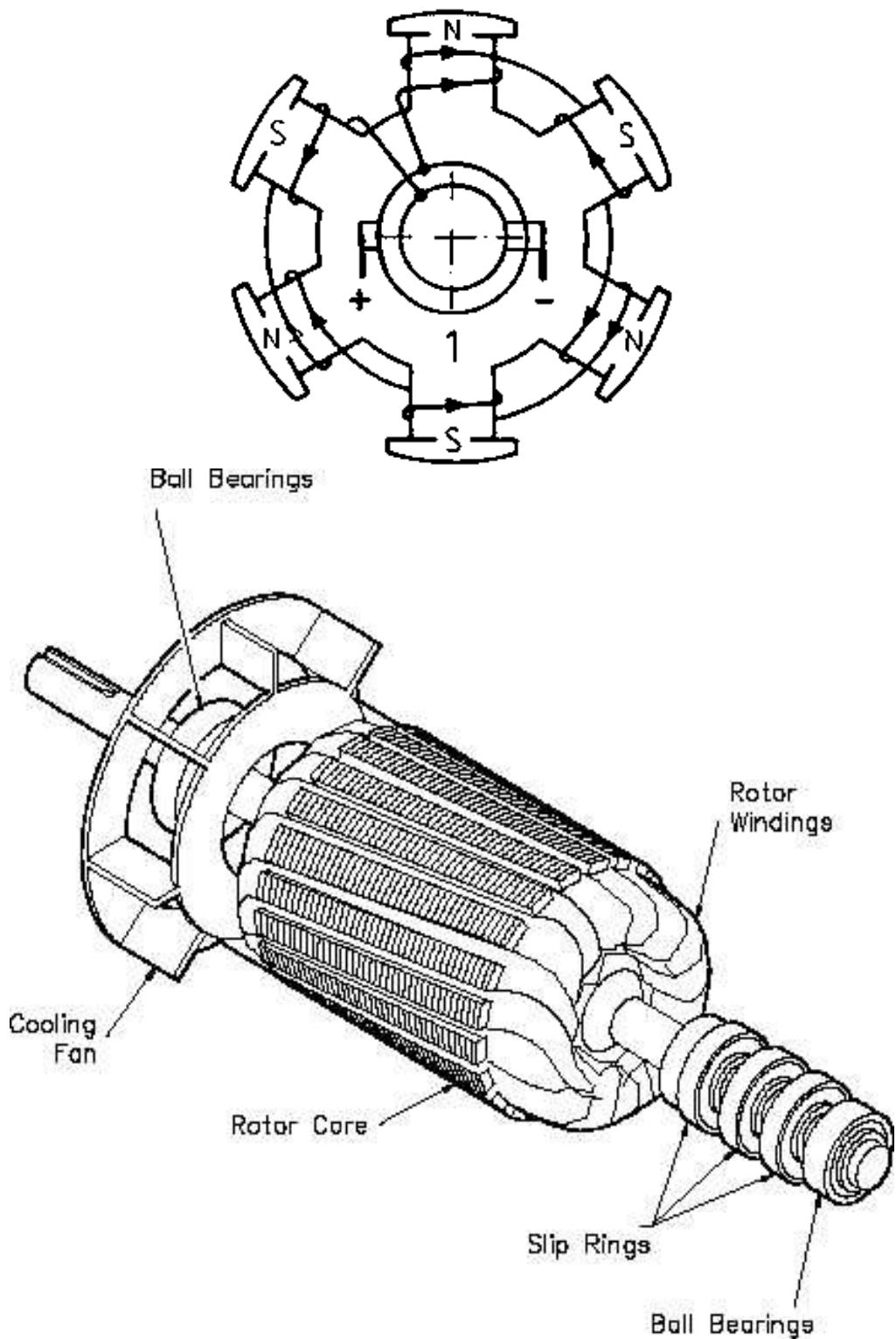
### Types of 1-phase IM:

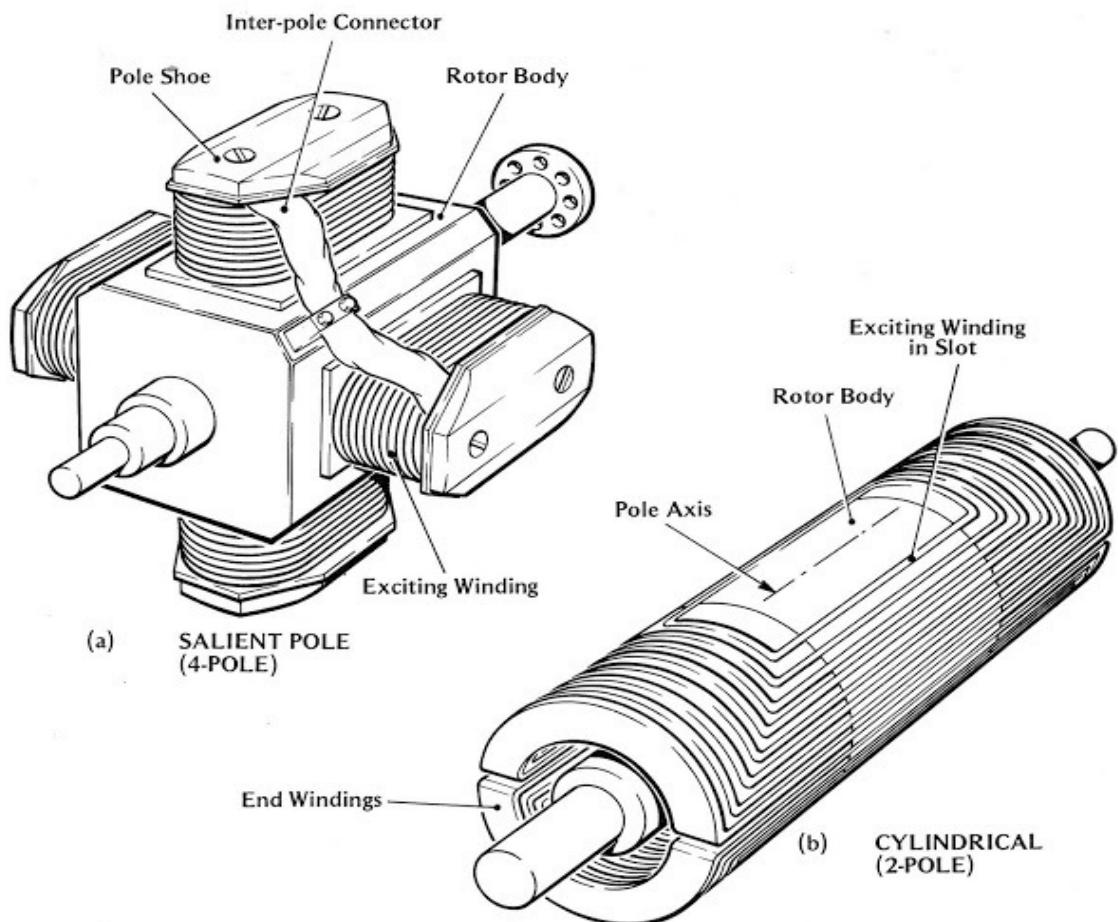
- Resistance split phase IM
- Capacitor split phase IM
  - Capacitor start IM

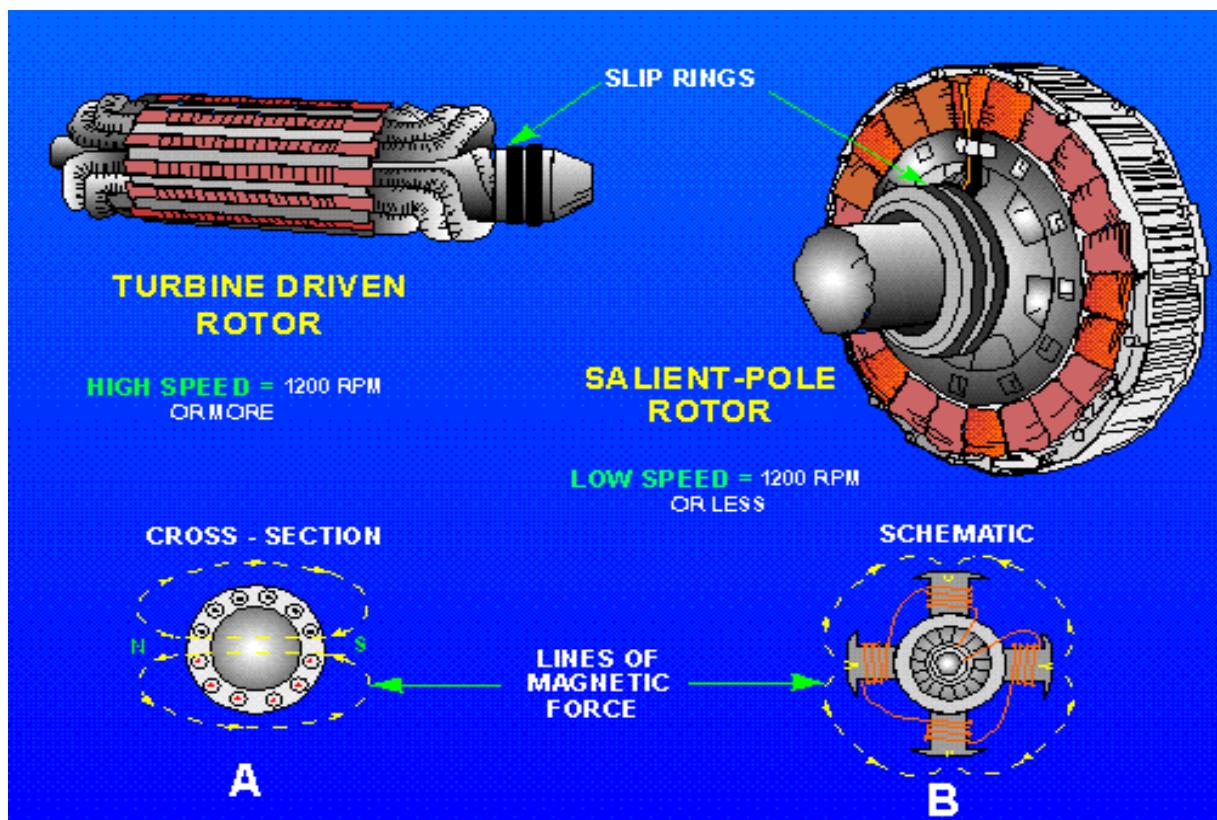
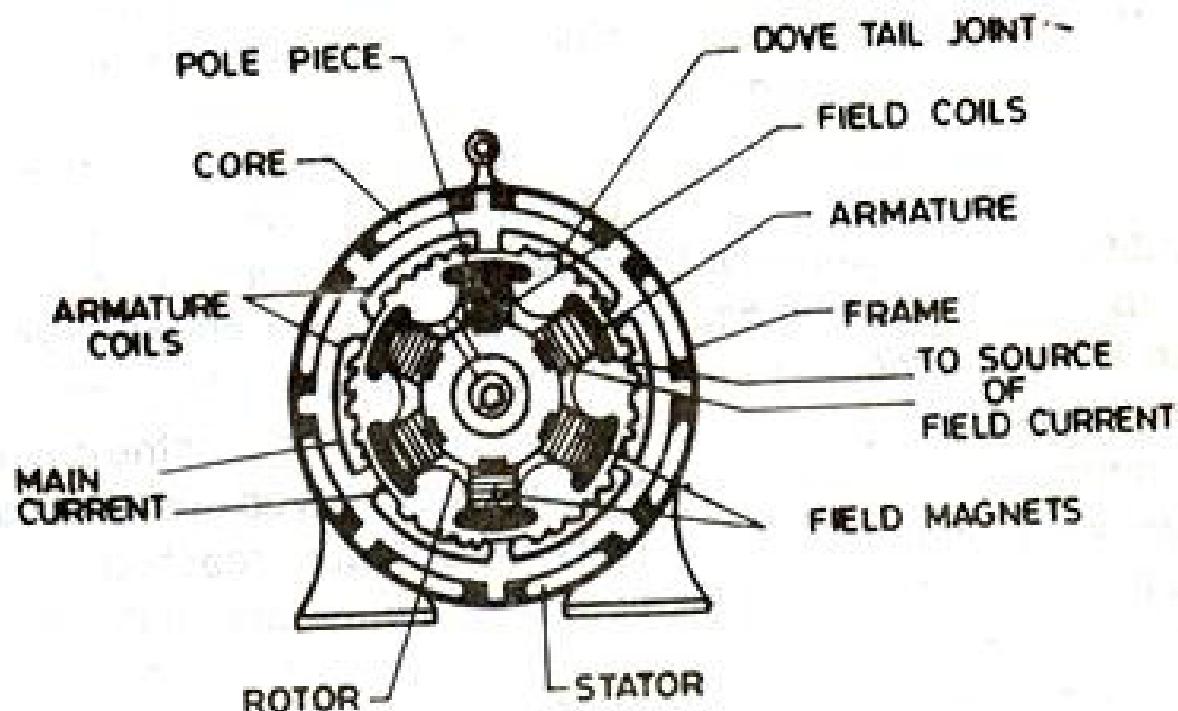
- Capacitor start capacitor run IM
- Capacitor run IM

### **Synchronous Machine Construction:**

- Field :- carrying a DC excited winding
  - Armature : three phase winding in which emf is generated
  - Armature stationary and rotating field structure
  - Armature winding is built of sheet-steel laminations having slots on its inner periphery
  - Three phase winding is placed in these slots and serves as armature winding.
  - connected in star
  - Field is connected to an external source through slip rings and brushes or else receives excitation from rotating bodies
  - Damper bars on the rotor :- damps the oscillations due to transients
  - Depending on rotor construction:-
  - Round rotor type
  - High speed machine such as turbine generators
  - Salient pole type
- Low speed such as water wheel generator







### **Frequency of output voltage:**

Let  $P$  = no of rotor poles

$N$  = Speed of the rotor in rpm

Number of cycles generated in one revolution =  $P/2$

Time taken for one revolution =  $60/N$  seconds

In  $60/N$  sec, no. of cycles =  $P/2$

In 1 sec, no. of cycles generated =  $P/2/60/N = PN/120$

So, frequency ( $f$ ) =  $PN/120$  Hz

### **Emf equation:**

Let  $P$  = no of poles

$N$  = speed in rpm

$T_{ph}$  = no of concentric turns

$K_d$  = distribution factor

$\Phi$  = flux produced per pole in weber

In one revolution flux cut by one armature conductor =  $\Phi P = d\Phi$

Time taken for one revolution =  $60/N$  sec =  $dt$

Therefore average emf induced in the conductor is given by

$$e = d\Phi/dt = \Phi P/60/N = \Phi PN/60 = 2\Phi PN/120$$

$e = 2\Phi f$  volts

therefore,  $f = PN/120$

For a sinusoidal ac voltage,

rms value = average value  $\times$  form factor

The value of form factor is 1.11 in case of sinusoidal a.c

Rms value of induced emf per conductor =  $1.11 \times e$

$$= (1.11) \times (2\Phi f)$$

$$= 2.22 \Phi f \text{ volts}$$

Emf per turn =  $2 \times 2.22\Phi f = 4.44\Phi f$  volts (Two conductors constitute one turn)

Therefore, Induced emf per phase = emf per turn x no of turns per phase =  $4.44 \Phi f T_{ph}$  volts

In practice, the stator winding is distributed. So, the actual induced emf will be slightly less than the calculated value and the induced emf per phase is multiplied by a factor  $K_d$ , known as distribution factor. (Generally  $K_d$  varies from 0.96 to 0.98).

## Synchronous Motor

### Salient features:

- It is not self starting
- It rotates at constant speed irrespective of the load torque
- Speed at which it rotates is synchronous speed ( $N_s = NP/120$  rpm)
- Draws current from the supply at any power factor (lagging, leading and unity)
- Needs both 3- $\phi$  AC supply (stator) and DC supply (rotor)
- Costlier

### Starting of synchronous Motor:

A synchronous motor is not self starting. It can be started by the following two methods:

1. Starting with the help of an external prime mover
2. Starting with the help of damper windings

### Motor starting with external prime mover:

In this method an external motor drives the synchronous motor and brings it to synchronous speed. The synchronous machine is then synchronized with the busbar as a synchronous generator. The prime mover is then disconnected. Once in parallel, the synchronous machine will work as a motor. Now the load can be connected to the synchronous motor. Since load is not connected to the synchronous motor before synchronizing, the starting motor has to overcome the inertia of the synchronous motor at no load. Therefore the rating of the starting

motor is much smaller than the rating of the synchronous motor. At present most large synchronous motors are provided with brushless excitation systems mounted on their shafts. These excitors are used as starting motors.

### **Motor starting with damper winding:**

It is the most widely used method. A damper winding consists of heavy copper bars inserted in slots of the pole faces of the rotor. These bars are short-circuited by end rings at both ends of the rotor. Thus, these short-circuited bars form a squirrel cage winding. When a three phase supply is connected to the stator, the synchronous motor with damper winding will start as a three-phase induction motor. As the motor approaches synchronous speed, the dc excitation is applied to the field windings. The rotor will then pull into step with the stator magnetic field.

**Hunting:** The phenomenon of oscillation of the rotor about its final equilibrium position is called hunting. The term hunting is used to signify that after sudden application of load, the rotor attempts to search for or hunt for its new equilibrium space position. Hunting occurs not only in synchronous motors but also in the synchronous generators upon the abrupt change in loading. Hunting leads to loss of synchronism, variation of supply voltage producing undesirable lamp flicker, increases the possibility of resonance, develops mechanical stress in the rotor shaft, and increases the losses and the temperature of the machine. Hunting can be reduced by using damper winding, using flywheel, by designing with suitable synchronizing power coefficients.

### **Application of synchronous motor:**

- In constant speed application
- Used as high power and high speed compressors, blowers, induced and forced draft fans, mainline traction, servo drives etc
- Used in power transmission systems to regulate line voltage
- Used to improve overall power factor of the plant

### Solved Question:

**Q1.** A dc shunt generator generates an emf of 520 V at a speed of 1200 rpm. It has 2000 armature conductors and flux per pole is 0.013 wb. The armature winding has 4 parallel paths. i) Determine the number of poles ii) Find the generated voltage, if the armature winding is wave connected

(1<sup>st</sup> Semester 2004)

**Solution.** Given:  $E = 520$  V,  $N = 1200$  rpm,  $Z = 2000$ ,  $\Phi = 0.013$  wb,  $A = 4$

i)  $E = P\PhiZN/60A$

$$\Rightarrow P = 60 AE/\PhiZN = 60 \times 4 \times 520/0.013 \times 2000 \times 1200 = 4$$

ii)  $E = P\PhiZN/60A = 4 \times 0.013 \times 2000 \times 1200 / 60 \times 2 = 1040$  volts

**Q2.** A DC shunt motor develops 200 V on no load, while running at 1200 rpm. If the machine has 4 poles and 100 lap wound armature conductors, calculate the flux per pole. Also calculate the shunt field current if the resistance of the shunt field is 200 ohms.

(1<sup>st</sup> Semester 2009)

**Solution:** Given:  $E_b = 200$  volts,  $N = 1200$  rpm,  $P = 4$ ,  $Z = 100$ ,  $A = P = 4$ ,  $R_{sh} = 200 \Omega$

Therefore, Flux per pole ( $\Phi$ ) =  $60 A E_b/ZNP = 60 \times 4 \times 200 / 100 \times 1200 \times 4 = 0.1$  wb

Neglecting armature resistance supply voltage,  $V = E_b = 200$  volts

Shunt field current  $I_{sh} = V / R_{sh} = 200 / 200 = 1$  A

**Q3.** A 3 phase, 50 Hz induction motor has 8 poles. If the full load slip is 2.5%, determine i) synchronous speed ii) Rotor speed iii) Frequency of the rotor current

(Supplementary Exam 2004)

**Solution:** Given:  $f = 50$  Hz, Pole (P) = 8, Full load slip = 0.025

i) Synchronous speed,  $N_s = 120 f/P = 120 \times 50/8 = 750$  rpm

ii) Rotor speed,  $N = N_s(1-S) = 750(1-0.025) = 731.25$  rpm

iii) Frequency of the rotor current  $f' = sf = 0.025 \times 50 = 1.25$  Hz

## **MODULE-IV (10 HOURS)**

### **Electrical Measuring Instruments:-**

The instruments in the broadest sense may be divided into two main classes:-

- Absolute instrument
- Secondary instrument

#### **Absolute instruments:-**

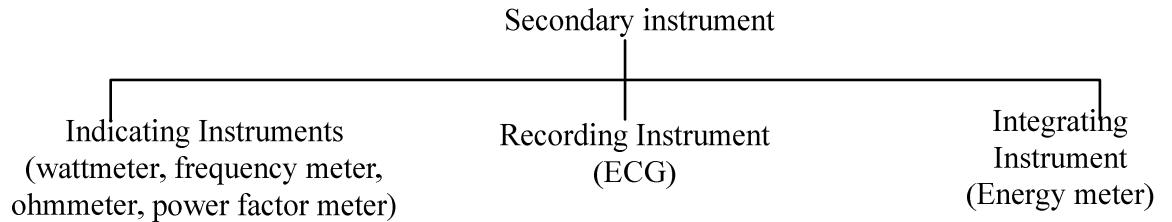
- These are the instrument which indicate the value of quantity being measured in terms of the deflection of the needle and a constant
- No calibration is needed as no comparison is required

Example: 1. Tangent Galvanometer (measure current in terms of angle of deflection, radius, no. of turns, horizontal component of magnetic field).

#### **2. Rayleigh current balance**

#### **Secondary instrument:-**

- These instruments are calibrated by comparison with absolute instrument.
- The magnitude of the quantity can be read directly from the calibrated scale.
- All most all the instruments in general use such as ammeter, voltmeter, wattmeter, watt-hour meter, frequency meter and power factor meter etc belong to this class.



- **Indicating instrument:** They can measure or indicate the instantaneous value of an electrical quantity being measured at the time by the help of pointer moving over a calibrated dial.
- **Recording instrument:** These instruments are those which instead of indicating by pointer or scale give a continuous record of the variation of the electrical quantity over a selected period of time. The moving system carries a ink pen which rests lightly on a chart or graph and moving uniformly to record variations.
- **Integrating instrument:** These instruments measure and read the total amount of energy supplied to a circuit in a given time.

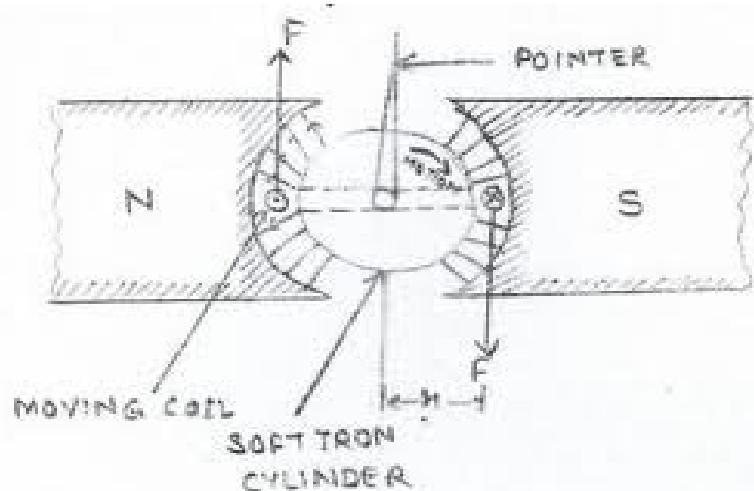
### Indicating instrument

It consist essential systems:-

- A deflecting system – which provides the necessary deflecting torque
- A controlling system- which offers the necessary restoring torque
- A damping system- which helps the pointer to come quickly to the deflected position.

## PMMC Instruments

These instruments are used either as ammeters or voltmeters and are suitable for dc network only. PMMC instruments work on the principle that, when a current carrying conductor is placed in a magnetic field, a mechanical force acts on the conductor. The current carrying coil, placed in magnetic field is attached to the moving system. With the movement of the coil, the pointer moves over the scale to indicate the electrical quantity being measured. This type of movement is known as D' Arsenoval movement.



It consists of a light rectangular coil of many turns of fine wire wound on an aluminum former inside which is an iron core as shown in fig. The coil is delicately pivoted upon jewel bearings and is mounted between the poles of a permanent horse shoe magnet. Two soft-iron pole pieces are attached to these poles to concentrate the magnetic field. The current is led in to and out of the coils by means of two control hair-springs, one above and other below the coil. These springs also provide the controlling torque. The damping torque is provided by

eddy currents induced in the aluminum former as the coil moves from one position to another.

### **Working:-**

When the instrument is connected in the circuit to measure current or voltage, the operating current flows through the coil. Since the current carrying coil is placed in the magnetic field of the permanent magnet, a mechanical torque acts on it. As a result of this torque, the pointer attached to the moving system moves in clockwise direction over the graduated scale to indicate the value of current or voltage being measured. This type of instruments can be used to measure direct current only. This is because, since the direction of the field of permanent magnet is same, the deflecting torque also gets reversed, when the current in the coil reverses. Consequently, the pointer will try to deflect below zero. Deflection in the reverse direction can be prevented by a “stop” spring.

### **Deflecting torque equation:-**

The magnetic field in the air gap is radial due to the presence of soft iron core. Thus, the conductors of the coil will move at right angles to the field. When the current is passed through the coil, forces act on its both sides which produce the deflecting torque.

Let       $B$  = flux density,  $\text{Wb}/\text{m}^2$

$l$  = length or depth of coil, m

$b$  = breadth of the coil.

$N$  = no. of turns of the coil.

If a current of ' $I$ ' Amperes flows in the coil, then the force acting on each coil side is given by,

    Force on each coil side,  $F = BIIN$  Newtons.

Deflecting torque,  $T_d = \text{Force} \times \text{perpendicular distance}$

$$= (BIIN) \times b$$

$T_d = BINA$  Newton metre.

Where,  $A = l \times b$ , the area of the coil in  $\text{m}^2$ .

    Thus,  $T_d \propto I$

The instrument is spring controlled so that,  $T_c \propto \theta$

The pointer will come to rest at a position, where  $T_d = T_c$

Therefore,  $\theta \propto I$

Thus, the deflection is directly proportional to the operating current. Hence, such instruments have uniform scale.

### **Advantages:-**

- a) Uniform scale.i.e, evenly divided scale.
- b) Very effective eddy current damping.
- c) High efficiency.
- d) Require little power for their operation.
- e) No hysteresis loss (as the magnetic field is constant).
- f) External stray fields have little effects on the readings (as the operating magnetic field is very strong).
- g) Very accurate and reliable.

### **Disadvantages:-**

- a) Cannot be used for ac measurements.
- b) More expensive (about 50%) than the moving iron instruments because of their accurate design.
- c) Some errors are caused due to variations (with time or temperature) either in the strength of permanent magnet or in the control spring.

### **Applications:-**

- a) In the measurement of direct currents and voltages.
- b) In dc galvanometers to detect small currents.
- c) In Ballistic galvanometers used for measuring changes of magnetic flux linkages

## **EXTENSION RANGE**

Shunts are used for the extension of range of ammeters. So a good shunt should have the following properties:-

- 1- The temperature coefficient of shunt should be low.
  - 2- Resistance of shunt should not vary with time.
  - 3- They should carry current without excessive temperature rise
  - 4- They should have thermal electromotive force with copper
- \* ‘Manganin’ is used for DC shunt and ‘Constantan’ as AC shunt.

**Ammeter:-** PMMC is used as indicating device. The current capacity of PMMC is small.

It is impractical to construct a PMMC coil, which can carry a current greater than 100 mA. Therefore a shunt is required for measurement of large currents.

$R_m$  = Internal resistance of movement (coil) in  $\Omega$

$R_{sh}$  = Resistance of shunt in  $\Omega$

$I_m = I_{fs}$  = Full scale deflection current of movement in Amperes

$I_{sh}$  = Shunt current in Amperes

$I$  = Current to be measured in Amperes

Since the shunt resistance is in parallel with the meter movement, the voltage drop across shunt and movement must be same.

$$I_{sh}R_{sh} = I_m R_m$$

$$\text{As } I_{sh} = I - I_m$$

$$(I - I_m)R_{sh} = I_m R_m$$

$$R_m/R_{sh} = (I - I_m)/I_m$$

$$R_m/R_{sh} = I/I_m - 1$$

$$I/I_m = 1 + R_m/R_{sh}$$

$$I = I_m(1 + R_m/R_{sh})$$

$I/I_m$  is known as multiplying power of shunt.

**Voltmeter:** For measurement of voltage a series resistor or a multiplier is required for extension of range.

$I_m$  = Full Scale Deflection current of movement in Ampere

$V_m$  = Full Scale Deflection Voltage in Volts

$R_m$  = Internal resistance of movement

$R_{se}$  = Multiplier resistance

$V$  = Full range voltage of instrument

$$V = I_m(R_m + R_{se})$$

$$V = V_m/R_m(R_m + R_{se})$$

$$V=V_m(1+R_{se}/R_m)$$

## MOVING IRON INSTRUMENT:

M.I instruments are mainly used for the measurement of alternating currents and voltages, though it can also be used for D.C measurements.

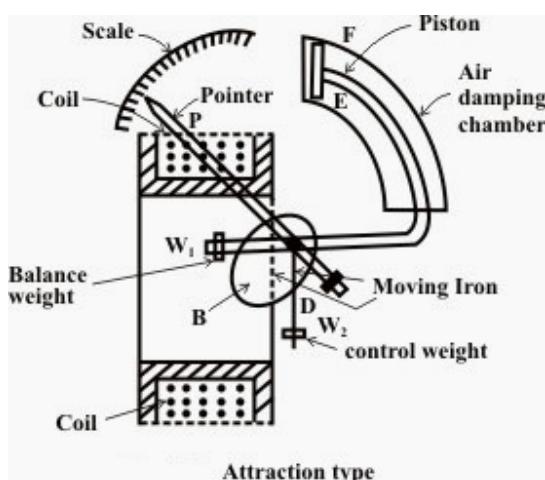
The general principle of a M.I instrument can be explained under;

Let a plate or vane of soft iron or of high permeability steel forms the moving element of the system. The iron vane is situated so as, it can move in a magnetic field produced by a stationary coil. The coil is excited by the current or voltage under measurement. When the coil is excited, it becomes an electromagnet and the iron vane moves in such a way so as to increase the flux of the electromagnet. Thus, the vane tries to occupy a position of minimum reluctance. Thus, the force produced is always in such a direction so as to increase the inductance of the coil.

There are two types of Moving- iron instruments.

### i. Attraction type:

In this type of instrument, a single soft iron vane (moving iron) is mounted on the spindle, and is attracted towards the coil when operating current flows through it.



### **Deflecting torque equation:**

Consider a small increment in current supplied to the coil of the instrument. Due to this current, let  $d\theta$  be the deflection under the deflecting torque  $T_d$ . Due to such deflection, some mechanical work will be done.

$$\text{Mechanical work} = T_d d\theta$$

Let  $I$  = Initial current

$L$ = instrument inductance because of the magnetic field.

$\theta$ = deflection

$d\theta$ =change in deflection

$dI$ =increase in current

$dL$ = change in inductance

The emf induced in the coil given by

$$e = d/dt(LI)$$

$$= IdL/dt + Ldi/dt$$

Multiplying  $Idt$  both side

$$eIdt = I^2dL + LIdt \quad (eIdt \text{ is the total energy supplied to the MI instrument})$$

the stored energy increases from

$$\frac{1}{2}LI^2 \rightarrow \frac{1}{2}(L+dL)(I+dI)^2$$

Hence change in stored energy,

$$\frac{1}{2}(L+dL)(I+dI)^2 - \frac{1}{2}LI^2 = \frac{1}{2}I^2dL + LIdI \quad (\text{neglecting the higher order terms })$$

The energy supplied is nothing but stored energy plus work done for deflection.

$$eIdt = I^2dL + LIdI$$

$$I^2dl + LIdI = \frac{1}{2}I^2dL + LIdI + T_d d\theta$$

$$T_d = \frac{1}{2} I^2 \frac{dL}{d\theta}$$

The controlling torque is given by

$$T_c = k\theta$$

At steady state condition,

$$\theta = \frac{1}{2k} I^2 \frac{dL}{d\theta}$$

Since the deflection is proportional to the square of coil current, the scale of such instruments is non-uniform (being crowded in the beginning and spread out near the finishing end of the scale).

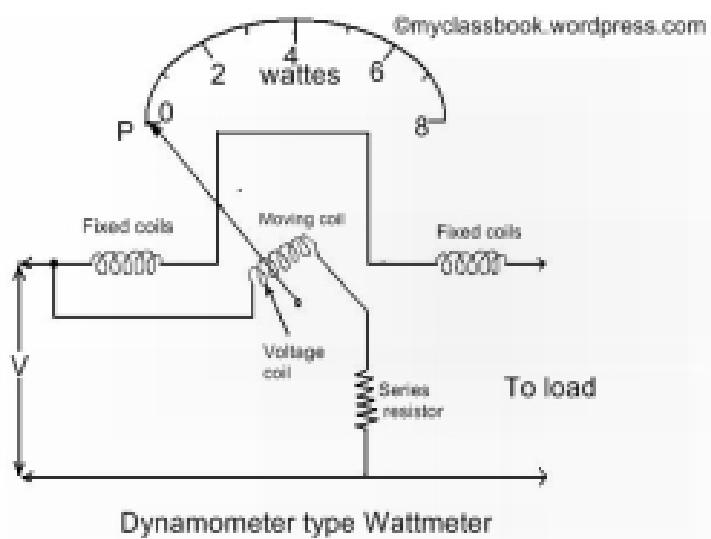
### **ii. Repulsion type:-**

In this two soft iron vanes are used; one fixed and attached the stationary coil, while the other is movable (moving iron), and mounted on the spindle of the instrument. When operating current flows through the coil, the two vanes are magnetised, developing similar polarity at the same ends. Consequently, repulsion takes place between the vanes and the movable vane causes the pointer to move over the scale. Thus, the deflection is proportional to the square of the coil current. The scale of the instrument is non-uniform; being crowded in the beginning and spread out near the finish end of the scale. However, the non-linearity of the scale can be corrected to some extent by the accurate shaping and positioning of the iron vanes in relation to the operating coil.

### **DYNAMOMETER TYPE WATTMETER:**

Electric power is the rate of doing work. It is expressed in Watts. The higher units of power used in practice include kilowatts, megawatts, etc.  $P_{\text{watt}} = VI \cos \phi$ , i.e., a power of one watt is said to be expended when a source of one volt passes a current of one ampere through a load resistance/ impedance of one ohm at unity power factor. The power measurements are made with the help of a wattmeter.

Wattmeter is an indicating deflecting type of instrument used in laboratories for measurement of power in various ranges. A wattmeter consists of two coils as shown in the schematic representative figure.



**Current coil (CC):** connected in series with circuit and carries the load current. It is designed such that it is wound with 2 to 3 turns of thick wire and hence it has a very low resistance.

**Voltage or Pressure or Potential coil (PC):** connected across the load circuit and hence carries a current proportional to the load current. The total load voltage appears across the PC. It is designed such that it is wound with several turns of thin wire. Wattmeter Connections hence it has a very high resistance. The wattmeter can be a UPF meter or LPF meter depending on the type of the load connected in the measuring circuit. For power measurements in AC circuits, the wattmeter is widely adopted. In principle and construction, it is a combination of those applicable for an ammeter and a voltmeter.

An electrodynamometer wattmeter consists of two fixed coils and a moving coil as shown in figure. The fixed coils are connected in series with the load and hence carry the load current. These fixed coils form the current coil of the wattmeter. The moving coil is connected across the load and hence carries a current proportional to the voltage across the load. A highly non-inductive resistance is put in series with the moving coil to limit the current to a small value. The moving coil forms the potential coil of the wattmeter.

The fixed coils are wound with heavy wire of minimum number of turns. The fixed coils embrace the moving coil. Spring control is used for movement and damping is by air. The deflecting torque is proportional to the product of the currents in the two coils. These watt meters can be used for both DC and AC measurements. Since the deflection is proportional to the average power and the spring control torque is proportional to the deflection, the scale is uniform. The meter is free from waveform errors. However, they are more expensive.

### **Expression for the deflection torque:**

Let  $i_c, i_p$  : Current in the fixed and moving coils respectively,

M : Mutual inductance between the two coils,

$\theta$  : Steady final deflection of the instrument,

K: Spring constant,

V, I : RMS values of voltage and current in the measuring circuit and

$R_p$  : Pressure coil resistance

Instantaneous voltage across pressure coil,  $v = \sqrt{2} V \sin \omega t$

Instantaneous current in the pressure coil,  $i_p = \sqrt{2} V/R_p \sin \omega t = \sqrt{2} I_p \sin \omega t$

Instantaneous current in the current coil,  $i_c = \sqrt{2} I \sin (\omega t - \phi)$

Instantaneous torque is given by:  $T_i = i_c i_p ( dM / d\theta )$

$$= [\sqrt{2} I \sin (\omega t - \phi)] [\sqrt{2} I_p \sin \omega t] (dM / d\theta)$$

$$\begin{aligned}
 \text{Average deflecting torque, } T_d &= (1/T) \int T_i d\omega t \\
 &= (1/T) \int I_p I [\cos \phi - \cos (2\omega t - \phi)] (dM/d\theta) d\omega t \\
 &= (VI/R_p) \cos \phi (dM/d\theta)
 \end{aligned}$$

Since the controlling torque,  $T_c = K\theta$ , we have at balance of the moving pointer,  
 $T_d = T_c$ ,

$$\text{So that, } \theta = [VI \cos \phi / (KR_p)] (dM/d\theta) = (K' dM/d\theta) P$$

Where  $K' = KR_p$  and  $P$  is the power consumption. Thus the deflection of the wattmeter is found to be the direct indication of the power being consumed in the load circuit.

Advantages:-

1.  $\theta \propto$  Power, the scale is uniform

2. High degree of accuracy
3. It can be used for both AC and DC circuits
4. Free from hysteresis & eddy current loss

Disadvantages:

1. Inductance of voltage coil at low power factor causes serious error

2. Reading may be affected by stray magnetic field acting on moving coil

Error:-

1. Due to pressure coil inductance

2. Due to connection
3. Due to temperature variation
4. Due to mutual inductance of current coil & pressure coil

### **Induction Type Energymeter**

Induction type energy meters are most commonly form of an A. c. KWh meter used to measure the energy consumed in any a.c. circuit in a prescribed period when supply voltage and frequency are constant, in day today life & in industrial installation. Energy meter is an integrating instrument which measure the total

quantity of electrical energy supplied to the circuit in a given period. These meters measure electrical energy in Kilowatt hours.

**Construction:** An Induction type single phase energy meter, has following main parts of the operating mechanism:

1. Driving System
2. Moving System
3. Braking System
4. Registering System
5. Compensating devices

**DRIVING SYSTEM** develops torque to rotate the moving system. It consists of two electromagnets one is formed by current coil & other one is by voltage coil or pressure coil.

**MOVING SYSTEM** essentially consists of an aluminum mounted on the spindle which is supported by Pivot-jewel Bearing system. Since there is not control spring, the disc makes continuous revolution under the action the deflecting torque.

**BRAKING SYSTEM** consists of a permanent magnet of C shaped covering a part of rotating disc to provide braking torque. By changing the position of breaking magnet, the Flux linkage with the disc can be changed, this torque is opposite to driving torque.

**REGISTERING SYSTEM** keeps the record of energy consumed by load through worm wheel or pinion gear mounted with spindle of moving disc.

**COMPENSATING DEVICES:** lag adjuster or phase compensator, friction compensator or low load adjustment.

## WORKING

When the energy meter is connected in the circuit, the current coil carries the load current and the pressure coil carries the current proportional to the supply voltage. The magnetic field produced by the SERIES magnet (series coil) is in phase with the line current & the magnetic field produced by the shunt magnet (pressure coil) is in quadrature with the applied voltage (since the coil is highly inductive). Thus, a phase difference exists between the fluxes produced by the two coils. This sets up a rotating field which interacts with the disc and produces a driving torque and, thus, disc starts rotating. The number of revolutions made by the disc depends upon the energy passing through the meter. The spindle is geared to the recording mechanism so that electrical energy consumed in the circuit is directly registered in KWh. The speed of the disc is adjusted by adjusting the position of the breaking magnet. For example, if the energy meter registers less energy than the energy actually consumed in the circuit, then the speed of disc has to be increased which is obtained by shifting the magnet nearer to the centre of the Disc and vice-versa.

At constant angular speed the power  $VI\cos\phi$  is proportional to the angular speed in r.p.s. We calibrate w and energy meter by time test.

Let K be the meter constant of energy meter, which is the number of revolution per KWh energy consumption. When connected to measure energy, if disc makes R number of revolution in t seconds. Then the reading of energy meter is:

$$Et = R/K$$

Let KW= Power in Kilowatt from wattmeter reading.

R= No. of revolution made by disc in 't' Sec.

$$K = \frac{\text{revolution}}{\text{KWh}}$$

$$\text{Energy recorded by meter under test } (Et) = \frac{R}{K} KWh$$

Let the wattmeter reading be KW watts of energy calculated from the wattmeter & stop watch is given by

$$\text{Energy consumed by wattmeter } (Es) = \frac{Kw \times t}{3600}$$

$$\begin{aligned}\text{Percentage Error} &= \left[ \frac{\frac{R}{K} - \frac{Kw \times t}{3600}}{\frac{Kw \times t}{3600}} \right] \times 100 \\ &= \left[ \frac{Et - Es}{Es} \right] \times 100\end{aligned}$$

### **Sources of error**

- Phase angle error occurs when the phase difference between pressure coil flux and supply voltage V is less than 90° - lag adjuster
- The frictional error are prominent at the bearing at light load – by changing the angle of inclination of friction compensator
- Negligible error due to voltage and frequency variation
- Error is small due to temperature variation

**Creeping:** It is sometimes observed that a meter rotates slowly even when there is no load in the circuit. This is called creeping or shunt running

**Anticreep devices:** 1. Two small holes in the rotor disc at diametrically opposite points  
 2. Radial slots are cut in the edge of the disc  
 3. A short iron wire or tongue is stuck to the surface of disc

## **POWER SUPPLY SYSTEMS**

### **Hydro Power plant**

Potential energy is the energy which a substance has due to its position or state. The water behind a dam has potential energy because of its position. The water can fall from this position and exert a force over a distance and therefore do work. In a Hydro-electric power plant the force is used to drive a turbine, which in turn drives the electric generator. Because gravity provides the force which makes the water fall, the energy stored in the water is called gravitational potential energy.

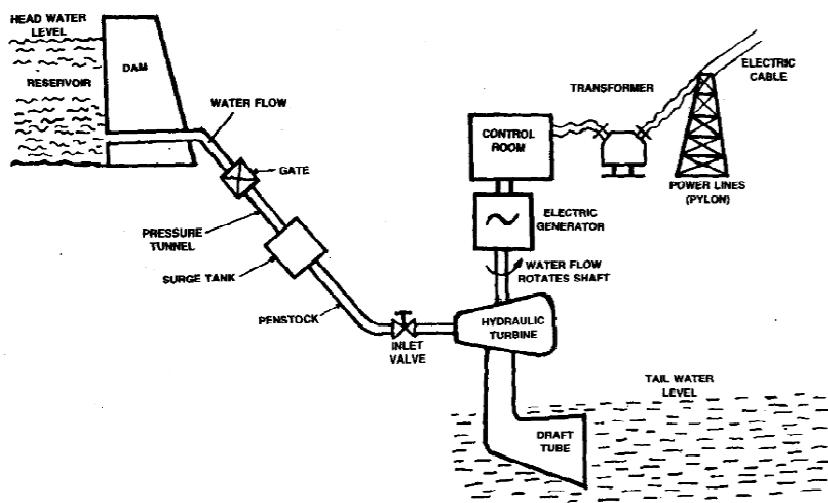
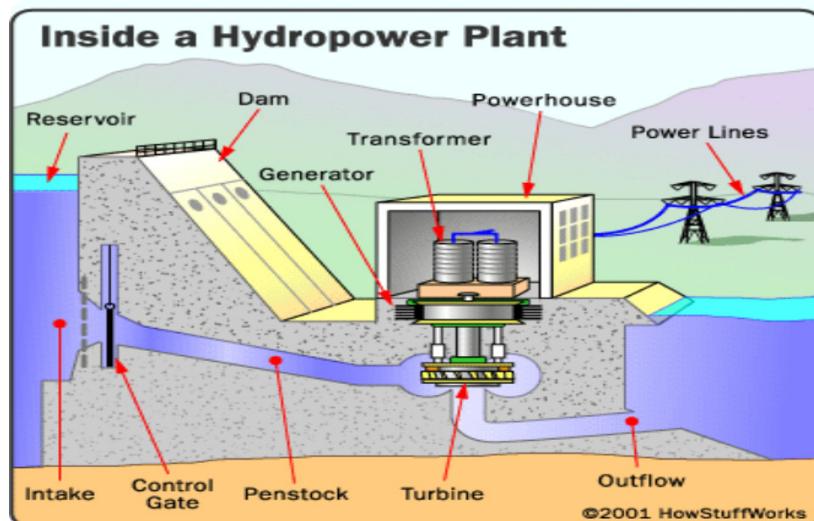


FIG. 3.6: LAYOUT OF HYDRO-ELECTRIC POWER PLANT

### Layout of Hydro electric power plant

In a reservoir the water collected from the catchment area is stored behind a dam. Catchment area gets its water from rain and streams. The level of water surface in the reservoir is called Head water level. Continuous availability of water is a basic necessity for a hydro-electric power plant.

Dam : The purpose of the dam is to store the water and to regulate the out going flow of water. The dam helps to store all the incoming water. It also helps to increase the head of the water. In order to generate a required quantity of power it is necessary that a sufficient head is available.

Spillway: Excess accumulation of water endangers the stability of dam construction. Also in order to avoid the over flow of water out of the dam especially during rainy season's spillways are provided. This prevents the rise of water level in the dam. Spillways are passages which allow the excess water to flow to a storage area away from the dam.

Gate : A gate is used to regulate or control the flow of water from the dam.

Pressure tunnel: It is a passage that carries water from the reservoir to the surge tank.

Surge tank: A Surge tank is a small reservoir or tank in which the water level rises or falls due to sudden changes in pressure.

Purpose of surge tank:

- To serve as a supply tank to the turbine when the water in the pipe is accelerated during increased load conditions and as a storage tank when the water is decelerating during reduced load conditions.

- To reduce the distance between the free water surface in the dam and the turbine, thereby reducing the water-hammer effect on penstock and also protect the upstream tunnel from high pressure rise.

Water-hammer effect :

- The water hammer is defined as the change in pressure rapidly above or below normal pressure caused by sudden change in the rate of water flow through the pipe, according to the demand of prime mover i.e. turbine.

**Penstock:** Penstock is a closed pipe of steel or concrete for supplying water under pressure to the turbine.

**Inlet valve :** Water from the penstock flows to the turbine through the inlet valve. The valve may be partially closed or open thereby regulating the pressure of water flowing to the turbine.

**Hydraulic turbine (Prime mover) :** The hydraulic turbine converts the energy of water into mechanical energy. The mechanical energy (rotation) available on the turbine shaft is coupled to the shaft of an electric generator and electricity is produced. The water after performing the work on turbine blades is discharged through the draft tube.

The prime movers which are in common use are Pelton wheel, Francis turbine and Kaplan turbine.

**Draft tube:** It is connected to the outlet of the turbine. It allows the turbine to be placed above the tail water level. Tail water level is the water level after the discharge from the turbine. The discharged water is sent to the river, thus the level of the river is the tail water level.

**Electric generator, Step-up transformer and Pylon :** As the water rushes through the turbine, it spins the turbine shaft, which is coupled to the electric generator. The generator has a rotating electromagnet called a rotor and a stationary part called a stator. The rotor creates a magnetic field that produces an electric charge in the stator. The charge is transmitted as electricity. The step-up transformer increases the voltage of the current coming from the stator. The electricity is distributed through power lines also called as pylon.

Hydro –electric power plants are usually classified according to the available head of water.

- High head power plants : Head of water is more than 500 metres. The turbine used in such plants is Pelton wheel.
- Medium head power plants : Head of water ranges from 80 to 500 metres. The turbine used in such plants is Francis turbine.
- Low head power plants : Head of water ranges from 1.5 to 80 metres. The turbine used in such plants is Kaplan turbine and Francis turbine.

**Advantages of hydel power plant :**

- Water is a renewable energy source.
- Maintenance and operation charges are very low.
- The efficiency of the plant does not change with age.
- In addition to power generation, hydro-electric power plants are also useful for flood control, irrigation purposes, fishery and recreation.
- Have a longer life(100 to 125 years) as they operate at atmospheric temperature.
- Water stored in the hydro-electric power plants can also be used for domestic water supply.

- Since hydro-electric power plants run at low speeds(300 to 400 rpm) there is no requirement of special alloy steel construction materials or specialised mechanical maintenance.

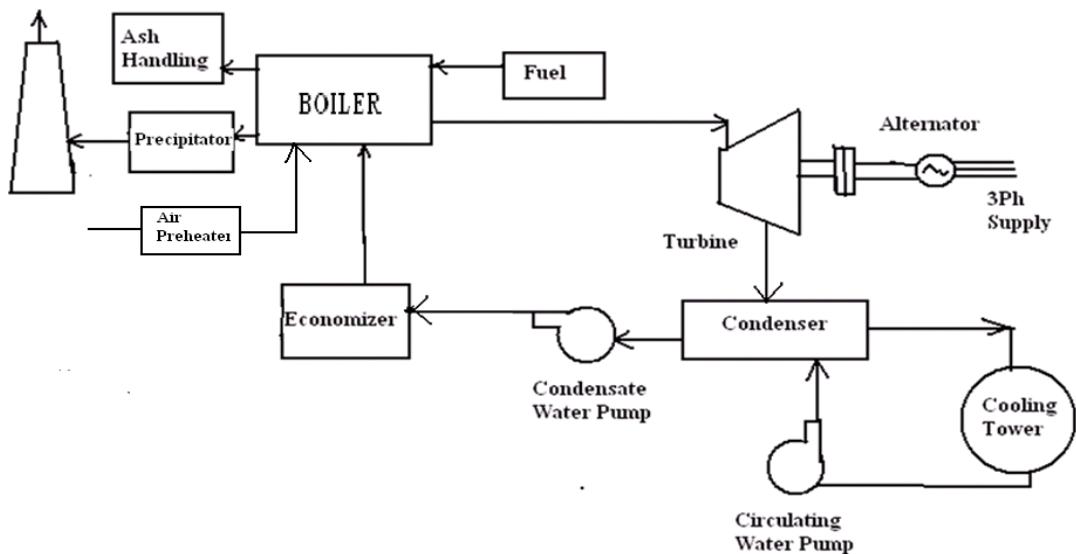
Disadvantages of hydel power plant :

- The initial cost of the plant is very high.
- Since they are located far away from the load centre, cost of transmission lines and transmission losses will be more.
- During drought season the power production may be reduced or even stopped due to insufficient water in the reservoir.
- Water in the reservoir is lost by evaporation

### **Thermal Power Plant:**

A Thermal Power Plant converts the heat energy of coal into electrical energy. Coal is burnt in a boiler which converts water into steam. The expansion of steam in turbine produces mechanical power which drives the alternator coupled to the turbine. Thermal Power Plants contribute maximum to the generation of Power for any country . Thermal Power Plants constitute 75.43% of the total installed captive and non-captive power generation in India. In thermal generating stations coal, oil, natural gas etc. are employed as primary sources of energy.

### **General Layout of Thermal Power Station:**



### Main and Auxiliary equipments

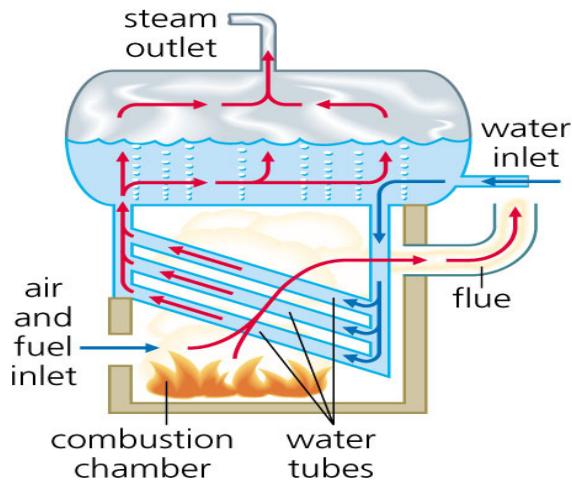
1. Coal handling plant: The function of coal handling plant is automatic feeding of coal to the boiler furnace. A thermal power plant burns enormous amounts of coal. A 200 MW plant may require around 2000 tons of coal daily.
2. Pulverizing plant: In modern thermal power plant , coal is pulverised i.e. ground to dust like size and carried to the furnace in a stream of hot air. Pulverising is a means of exposing a large surface area to the action of oxygen and consequently helping combustion.

Pulverising mills are further classified as:

- ✓ Contact mill
- ✓ Ball mill
- ✓ Impact mill

3. Draft fans The circulation of air is caused by a difference in pressure, known as Draft. Draft is a differential pressure b/w atmosphere and inside the boiler. It is necessary to cause the flow of gases through boiler setting. It may be Natural draft and Mechanical draft

#### 4. Boiler



A boiler or steam generator is a closed vessel in which water under pressure, is converted into steam. It is one of the major components of a thermal power plant. Always designed to absorb maximum amount of heat released in the process of combustion. Boilers are of two types-

- ✓ Fire tube boiler
- ✓ Water tube boiler

#### 5. Ash handling plant

The percentage of ash in coal varies from 5% in good quality coal to about 40% in poor quality coal. Power plants generally use poor quality of coal, thus amount of ash produced by it is pretty large. A modern 2000MW plant produces about 5000 tons of ash daily. The stations use some conveyor arrangement to carry ash to dump sites directly or for carrying and loading it to trucks and wagons which transport it to the site of disposal

## 6. Turbine

A steam turbine converts heat energy of steam into mechanical energy and drives the generator. It uses the principle that steam when issuing from a small opening attains a high velocity. This velocity attained during expansion depends on the initial and final heat content of the steam. This difference b/w initial and final heat content represents the heat energy converted into kinetic energy.

These are of two types :-

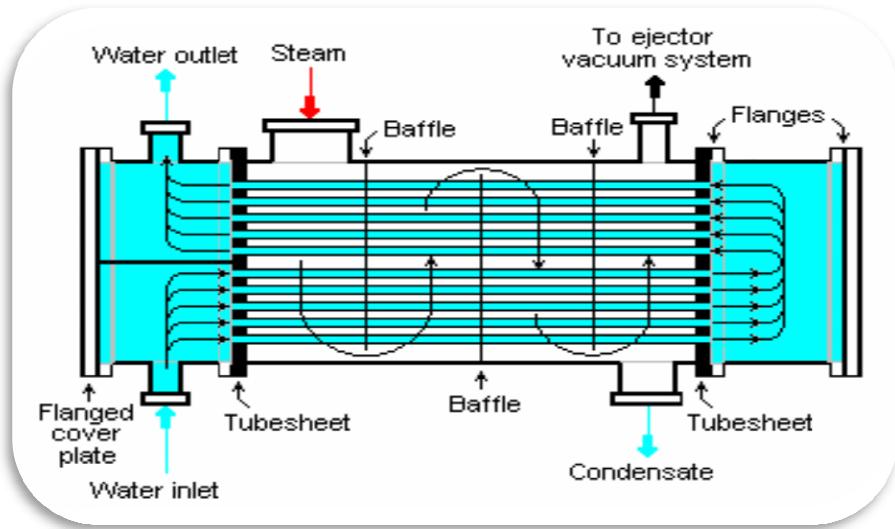
- ✓ Impulse turbine
- ✓ Reaction turbine

## 7. Condenser

Steam after rotating steam turbine comes to condenser. Condenser refers here to the shell and tube heat exchanger (or surface condenser) installed at the outlet of every steam turbine in Thermal power stations of utility companies generally.

- ❖ These condensers are heat exchangers which convert steam from its gaseous to its liquid state, also known as phase transition.
- ❖ In so doing, the latent heat of steam is given out inside the condenser. Where water is in short supply an air cooled condenser is often used.
- ❖ An air cooled condenser is however significantly more expensive and cannot achieve as low a steam turbine backpressure (and therefore less efficient) as a surface condenser.

The purpose is to condense the outlet (or exhaust) steam from steam turbine to obtain maximum efficiency and also to get the condensed steam in the form of pure water, otherwise known as condensate, back to steam generator or (boiler) as boiler feed water.



## 8. Cooling towers and ponds

A condenser needs huge quantity of water to condense the steam. Typically a 2000MW plant needs about 1500MGallon of water. Most plants use a closed cooling system where warm water coming from condenser is cooled and reused. Small plants use spray ponds and medium and large plants use cooling towers. Cooling tower is a steel or concrete hyperbolic structure having a reservoir at the base for storage of cooled water. Height of the cooling tower may be 150 m or so and diameter at the base is 150 m.

## 9. Feed water heater

Advantages of heating water before feeding back to the boiler:-

- Feed water heating improves overall plant efficiency.
- The dissolved oxygen and carbon dioxide which would otherwise cause boiler corrosion are removed in feed water heater
- Thermal stresses due to cold water entering the boiler drum are avoided.
- Quantity of steam produced by the boiler is increased.
- Some other impurities carried by the steam and condensate, due to corrosion of boiler and condensers are precipitated outside the boiler.

## 10. Economiser

Flue gases coming out of the boiler carry lot of heat. An economiser extracts a part of this heat from flue gases and uses it for heating feed water. This use of economiser results in saving coal consumption and higher boiler efficiency.

## 11. Superheater and Reheater

Superheater is a component of a steam-generating unit in which steam, after it has left the boiler drum, is heated above its saturation temperature. The amount of superheat added to the steam is influenced by the location, arrangement, and amount of super heater surface installed, as well as the rating of the boiler. The super heater may consist of one or more stages of tube banks arranged to effectively transfer heat from the products of combustion. Super heaters are classified as convection , radiant or combination of these.

Some of the heat of superheated steam is used to rotate the turbine where it loses some of its energy. Reheater is also steam boiler component in which heat is added to this intermediate-pressure steam, which has given up some of its energy in expansion through the high-pressure turbine. The steam after reheating is used to rotate the second steam turbine where the heat is converted to mechanical energy. This mechanical energy is used to run the alternator, which is coupled to turbine , there by generating electrical energy.

## 12. Air preheater

After flue gases leave economiser, some further heat can be extracted from them and used to heat incoming heat. Cooling of flue gases by 20 degree centigrade increases the plant efficiency by 1%.

Air preheaters may be of three types

- ❖ Plate type
- ❖ Tubular type
- ❖ Regenerative type

### **Nuclear Power Plant:**

A nuclear power plant works in a similar way as a thermal power plant. The difference between the two is in the fuel they use to heat the water in the boiler (steam generator). Inside a nuclear power station, energy is released by nuclear fission in the core of the reactor. 1 kg of Uranium  $U^{235}$  can produce as much energy as the burning of 4500 tonnes of high grade variety of coal or 2000 tonnes of oil.

### **Chain Reaction**

Uranium exists as an isotope in the form of  $U^{235}$  which is unstable. When the nucleus of an atom of Uranium is split, the neutrons released hit other atoms and split them in turn. More energy is released each time another atom splits. This is called a chain reaction.

### **Nuclear fission:**

It is a process of splitting up of nucleus of fissionable material like uranium into two or more fragments with release of enormous amount of energy. The nucleus of  $U^{235}$  is bombarded with high energy neutrons



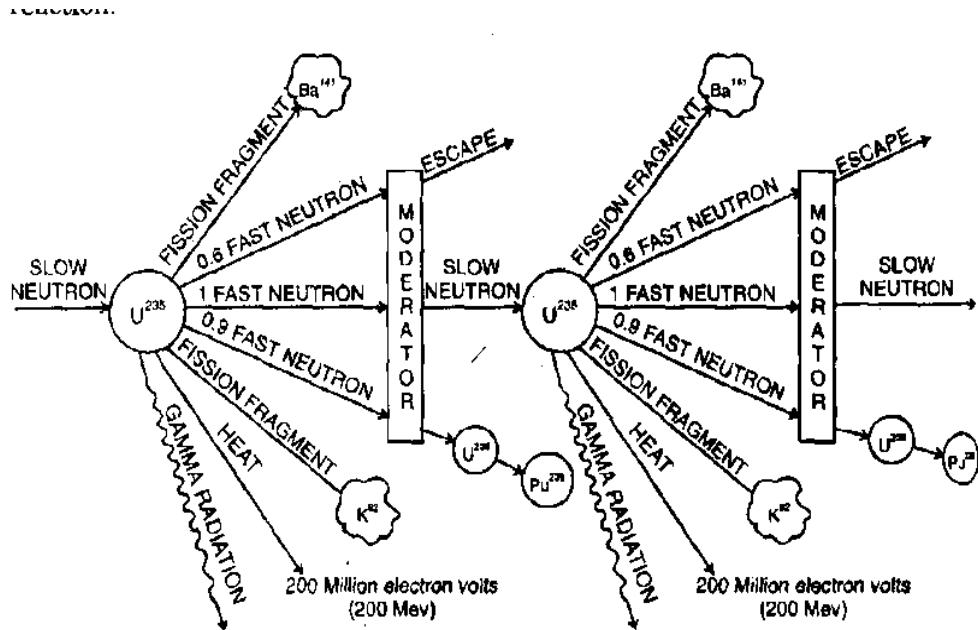
The neutrons produced are very fast and can be made to fission other nuclei of  $\text{U}^{235}$ , thus setting up a chain reaction. Out of 2.5 neutrons released one neutron is used to sustain the chain reaction.

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ joule.}$$

$$1 \text{ MeV} = 10^6 \text{ eV}$$

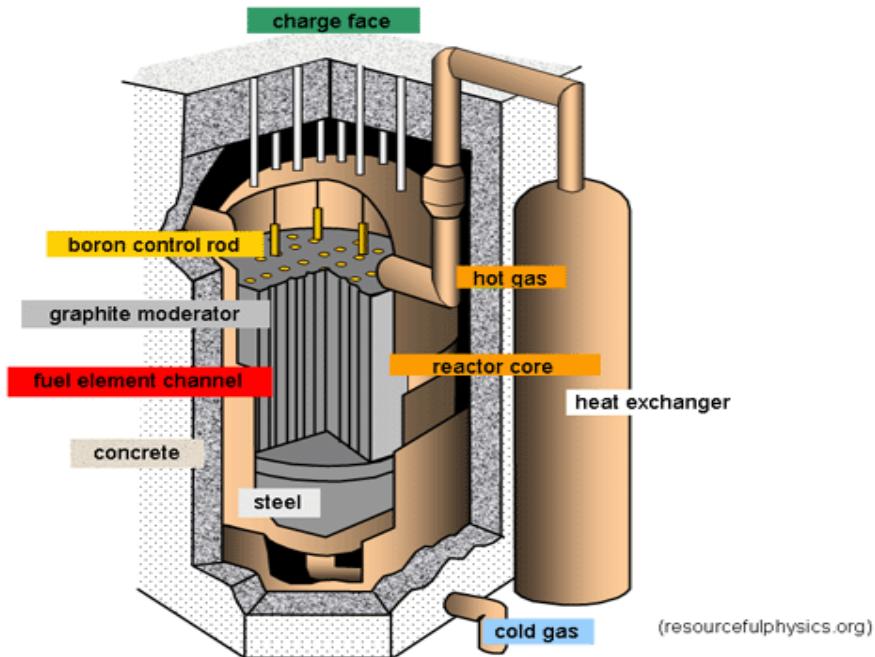
$\text{U}^{235}$  splits into two fragments ( $\text{Ba}^{141}$  &  $\text{K}^{92}$ ) of approximately equal size.

About 2.5 neutrons are released. 1 neutron is used to sustain the chain reaction. 0.9 neutrons is absorbed by  $\text{U}^{238}$  and becomes  $\text{Pu}^{239}$ . The remaining 0.6 neutrons escapes from the reactor. The neutrons produced move at a very high velocity of  $1.5 \times 10^7 \text{ m/sec}$  and fission other nucleus of  $\text{U}^{235}$ . Thus fission process and release of neutrons take place continuously throughout the remaining material. A large amount of energy(200 Million electron volts, Mev) is produced. Moderators are provided to slow down the neutrons from the high velocities but not to absorb them.



**Fig. 3.7: CONTROLLED CHAIN REACTION IN A NUCLEAR REACTOR**

Principal parts of a nuclear reactor:



(resourcefulphysics.org)

**Core:** Here the nuclear fission process takes place.

**Moderator:** This reduces the speed of fast moving neutrons. Most moderators are graphite, water or heavy water.

**Control rods:** Control rods limit the number of fuel atoms that can split. They are made of boron or cadmium which absorbs neutrons

**Coolant:** They carry the intense heat generated. Water is used as a coolant, some reactors use liquid sodium as a coolant.

**Fuel :** The fuel used for nuclear fission is U235 isotope.

**Radiation shield :** To protect the people working from radiation and (thermal shielding) radiation fragments.

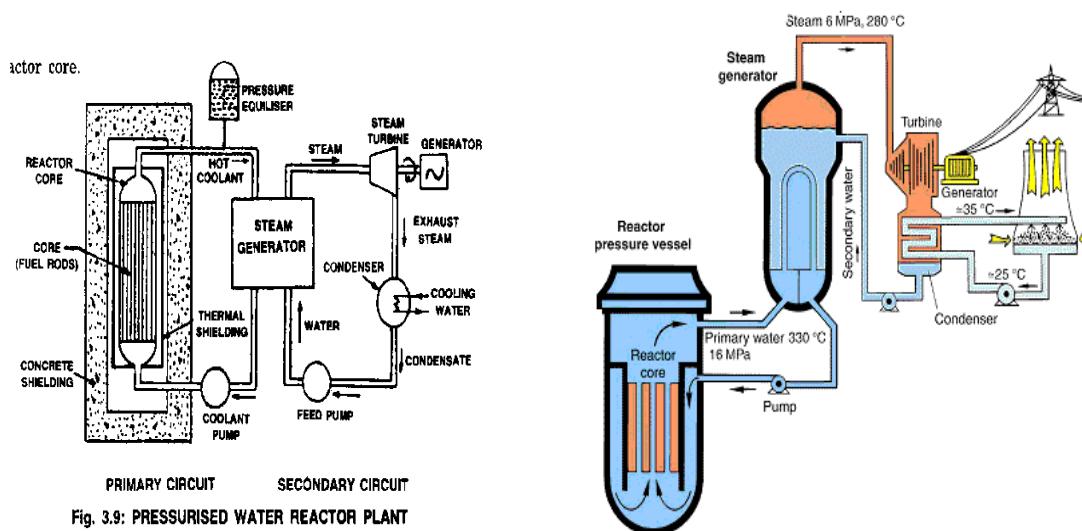
**Types of Nuclear power plant:**

\* Pressurised Water Reactor (PWR)

\* Boiling Water Reactor (BWR)

### Pressurised Water Reactor (PWR)

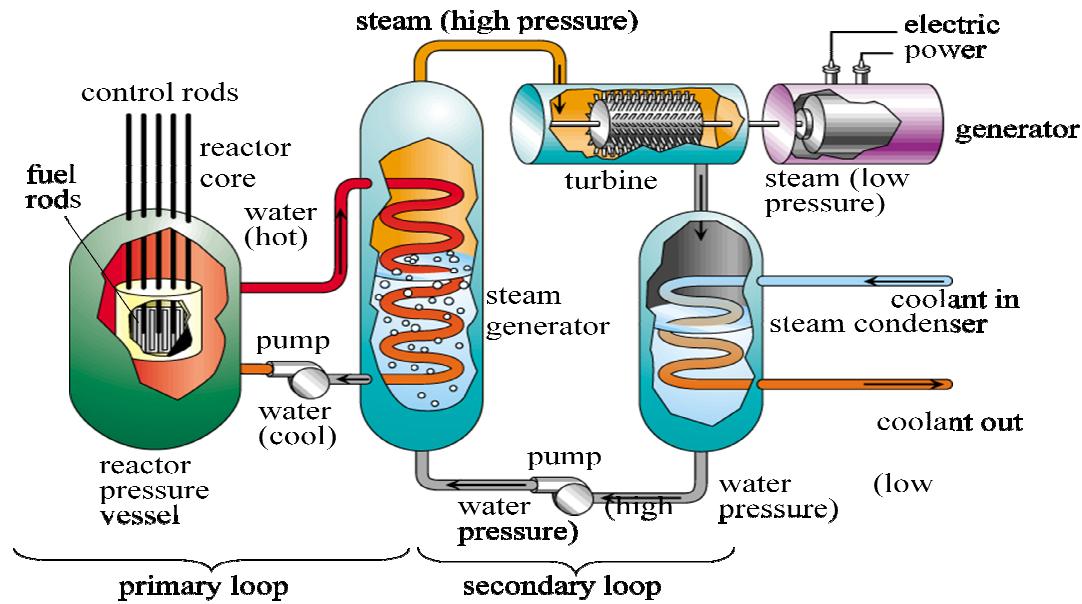
Heat is produced in the reactor due to nuclear fission and there is a chain reaction. The heat generated in the reactor is carried away by the coolant (water or heavy water) circulated through the core. The purpose of the pressure equalizer is to maintain a constant pressure of  $14 \text{ MN/m}^2$ . This enables water to carry more heat from the reactor. The purpose of the coolant pump is to pump coolant water under pressure into the reactor core.



The steam generator is a heat exchanger where the heat from the coolant is transferred on to the water that circulates through the steam generator. As the water passes through the steam generator it gets converted into steam. The steam produced in the steam generator is sent to the turbine. The turbine blades rotate. The turbine shaft is coupled to a generator and electricity is produced. After the steam performing the work on the turbine blades by expansion, it comes out of the

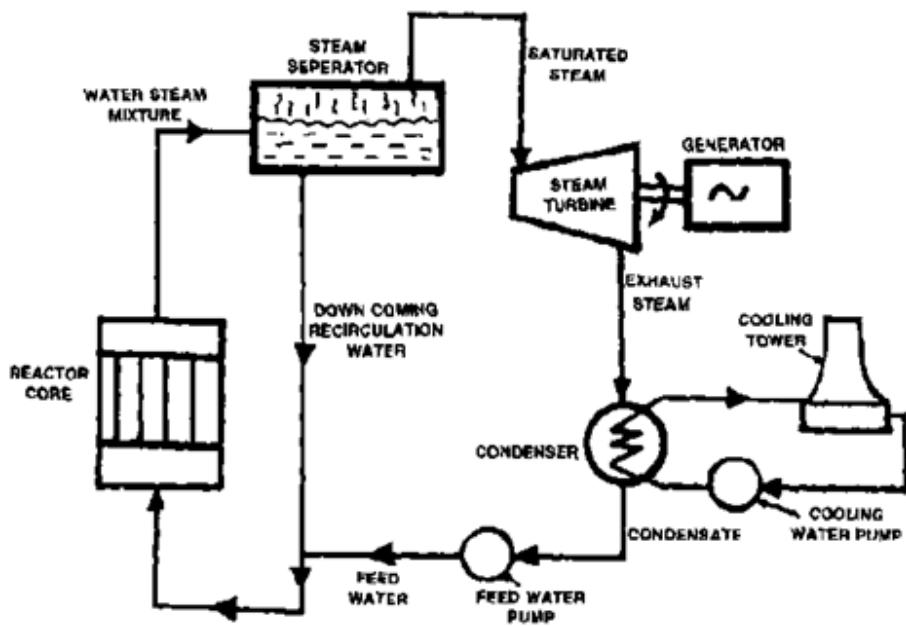
turbine as wet steam. This is converted back into water by circulating cold water around the condenser tubes. The feed pump pumps back the condensed water into the steam generator.

### Schematic diagram of a nuclear power plant with PWR



Boiling Water Reactor (BWR)

The water is circulated through the reactor where it converts to water steam mixture. The steam gets collected above the steam separator. This steam is expanded in the turbine which turns the turbine shaft. The expanded steam coming out of the turbine is condensed and is pumped back as feed water by the feed water pump into the reactor core. Also the down coming recirculation water from the steam separator is fed back to the reactor core.



**Fig. : BOILING WATER REACTOR PLANT**

➤ Advantages of Nuclear power plant:

Space required is less when compared with other power plants.

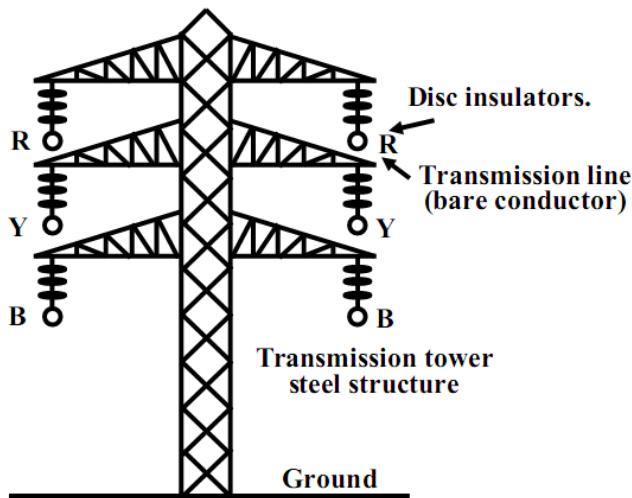
Nuclear power plant is the only source which can meet the increasing demand of electricity at a reasonable cost. A nuclear power plant uses much less fuel than a fossil-fuel plant.

➤ Disadvantages of Nuclear power plant:

Radioactive wastes must be disposed carefully, otherwise it will adversely affect the health of workers and the environment as a whole. Maintenance cost of the plant is high.

## Transmission of power

The huge amount of power generated in a power station (hundreds of MW) is to be transported over a long distance (hundreds of kilometers) to load centers to cater power to consumers with the help of transmission line and transmission towers as shown in figure.



To give an idea, let us consider a generating station producing 120 MW power and we want to transmit it over a large distance. Let the voltage generated (line to line) at the alternator be 10 kV. Then to transmit 120 MW of power at 10 kV, current in the transmission line can be easily calculated by using power formula circuit (which you will learn in the lesson on A.C circuit analysis) for 3-phases follows:

$$I = \frac{P}{\sqrt{3}V_L \cos \theta}$$

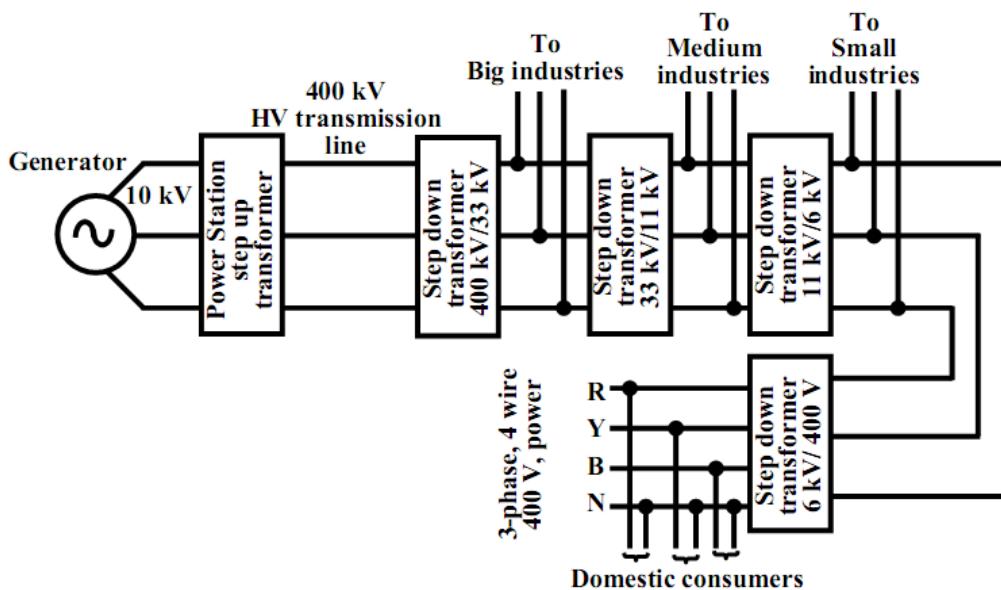
where  $\cos \theta$  is the power factor

$$= \frac{120 \times 10^6}{\sqrt{3} \times 10 \times 10^3 \times 0.8}$$
$$= 8660 \text{ Amp}$$

Instead of choosing 10 kV transmission voltage, if transmission voltage were chosen to be 400 kV, current value in the line would have been only 261.5 A. So sectional area of the transmission line (copper conductor) will now be much smaller compared to 10 kV transmission voltage. In other words the cost of conductor will be greatly reduced if power is transmitted at higher and higher transmission voltage. The use of higher voltage (hence lower current in the line) reduces voltage drop in the line resistance and reactance. Also transmission losses are reduced. Standard transmission voltages used are 132 kV or 220 kV or 400 kV or 765 kV depending upon how long the transmission lines are. Therefore, after the generator we must have a step up transformer to change the generated voltage (say 10 kV) to desired transmission voltage (say 400 kV) before transmitting it over a long distance with the help of transmission lines supported at regular intervals by transmission towers. It should be noted that while magnitude of current decides the cost of copper, level of voltage decides the cost of insulators. The idea is, in a spree to reduce the cost of copper one can not indefinitely increase the level of transmission voltage as cost of insulators will offset the reduction copper cost. At the load centers voltage level should be brought down at suitable values for supplying different types of consumers. Consumers may be (1) big industries, such as steel plants, (2) medium and small industries and (3) offices and domestic consumers. Electricity is purchased by different consumers at different voltage level. For example big industries may purchase power at 132 kV, medium and big industries purchase power at 33 kV or 11 kV and domestic consumers at rather low voltage of 230V, single phase. Thus we see that 400 kV transmission voltage is to be brought down to different voltage levels before finally delivering power to different consumers. To do this we require obviously step down transformers.

## Substations

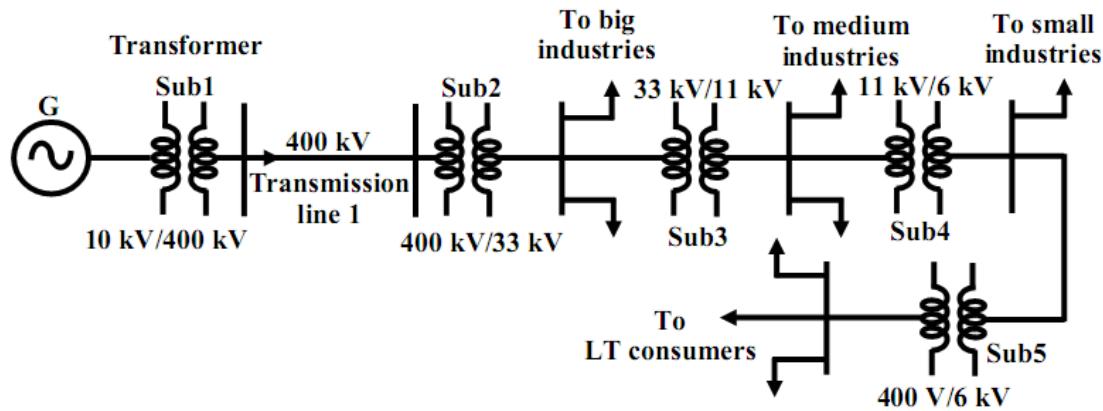
Substations are the places where the level of voltage undergoes change with the help of transformers. Apart from transformers a substation will house switches (called circuit breakers), meters, relays for protection and other control equipment. Broadly speaking, a big substation will receive power through incoming lines at some voltage (say 400 kV) changes level of voltage (say to 132 kV) using a transformer and then directs it outwards through outgoing lines. Pictorially such a typical power system is shown in figure in a short of block diagram. At the lowest voltage level of 400 V, generally 3-phase, 4-wire system is adopted for domestic connections. The fourth wire is called the neutral wire (N) which is taken out from the common point of the star connected secondary of the 6 kV/400 V distribution transformer.



Single line representation of power system:

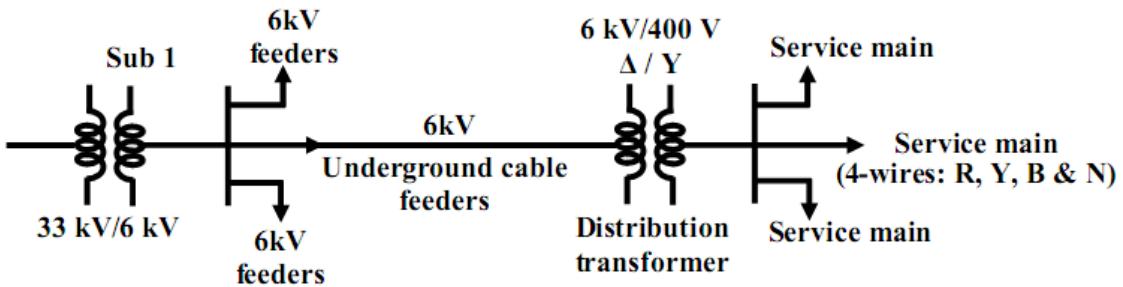
Trying to represent a practical power system where a lot of interconnections between several generating stations involving a large number of transformers

using three lines corresponding to R, Y and B phase will become unnecessary clumsy and complicated. To avoid this, a single line along with some symbolical representations for generator, transformers substation buses are used to represent a power system rather neatly. For example, the system shown in above with three lines will be simplified to below figure using single line.



## Distribution system

Till now we have learnt how power at somewhat high voltage (say 33 kV) is received in a substation situated near load center (a big city). The loads of a big city are primarily residential complexes, offices, schools, hotels, street lighting etc. These types of consumers are called LT (low tension) consumers. Apart from this there may be medium and small scale industries located in the outskirts of the city. LT consumers are to be supplied with single phase, 220 V, 40 Hz. We shall discuss here how this is achieved in the substation receiving power at 33 kV. The scheme is shown in figure.



Power received at a 33 kV substation is first stepped down to 6 kV and with the help of underground cables (called feeder lines), power flow is directed to different directions of the city. At the last level, step down transformers are used to step down the voltage from 6 kV to 400 V. These transformers are called distribution transformers with 400 V, star connected secondary. You must have noticed such transformers mounted on poles in cities beside the roads. These are called pole mounted substations. From the secondary of these transformers 4 terminals (R, Y, B and N) come out. N is called the neutral and taken out from the common point of star connected secondary. Voltage between any two phases (i.e., R-Y, Y-B and B-R) is 400 V and between any phase and neutral is 230 V (=400/3). Residential buildings are supplied with single phase 230V, 50Hz. So individual are to be supplied with any one of the phases and neutral. Supply authority tries to see that the loads remain evenly balanced among the phases as far as possible. Which means roughly one third of the consumers will be supplied from R-N, next one third from Y-N and the remaining one third from B-N. The distribution of power from the pole mounted substation can be done either by (1) overhead lines (bare conductors) or by (2) underground cables. Use of overhead lines although cheap, is often accident prone and also theft of power by hooking from the lines takes place. Although costly, in big cities and thickly populated areas underground cables for distribution of power, are used.

## Electric Heating

Electric heating is any process in which electrical energy is converted to heat. Common applications include heating of buildings, cooking, and industrial processes .An electric heater is an electrical appliance that converts electrical energy into heat. The heating element inside every electric heater is simply an electrical resistor, and works on the principle of Joule heating: an electric current through a resistor converts electrical energy into heat energy. Alternatively, a heat pump uses an electric motor to drive a refrigeration cycle, drawing heat from a source such as the ground or outside air and directing it into the space to be warmed.

## Dielectric Heating

Dielectric heating (also known as electronic heating, RF heating, high-frequency heating) is the process in which radiowave or microwave electromagnetic radiation heats a dielectric material. This heating is caused by dipole rotation.

## Direct Resistance Heating

Direct resistance heating offers manufacturers precise control and directed heat for applications such as preheating billets for forging, producing unique hardening patterns on metals, selectively heating forging dies and maintaining solutions at constant temperature. Direct resistance heating works only for electrically conductive workpieces. Direct resistance heating may well be the simplest and most economical method for through heating or heat treating workpieces of the appropriate material and geometry.

By generating heat within the workpiece rather than in a furnace, direct resistance heating offers a number of benefits over fuel-fired furnaces including:

### Rapid startup and heating

- \* Higher production rates
- \* Ease of automation
- \* Reduced metal scale
- \* Cleaner working environment
- \* Reduced floor space requirements, and
- \* Lower maintenance

The major metalworking applications of direct resistance heating are heating prior to forming, heat treating, and seam welding. Glass melting is the major nonmetals application. Other, less common, uses include heating concrete to accelerate setting, producing silicon carbide, and remelting metals in electroslag. A direct resistance heating electrical furnace of the type in which a bed of electrically conductive elements are located between two spaced electrodes in the furnace, and a method of controlling the operation of same, are provided. The furnace is of the type having a generally tubular heating chamber with a pair of spaced electrodes associated therewith and conveniently located one at each end of the tubular heating chamber. The furnace has feed or discharge control means and the rate of feed or discharge is controlled according to the electrical resistance or current flow between the electrodes. No temperature measurement is required to control the furnace operation.

### Indirect resistance heating

Indirect resistance heating furnaces are easy to control, and operate over a wide temperature range. In addition to heating metals, they are used for melting glass, sintering ceramics, and curing coatings. The number of applications continues to grow as technological developments broaden the operating temperature range of

indirect-resistance furnaces, and the demand for automatic process control increases.

Indirect resistance heating involves passing an electric current through a resistance heating element that transfers heat to the material by radiation, convection or conduction. Indirect-resistance heating can be accomplished by placing material into a well-insulated furnace with resistance heating elements in the walls. The inside surface of the furnace is lined with heat-resisting brick, ceramic, or fiber batting. The atmosphere may be air, inert gas, or a vacuum, depending on the requirements of the application.

In the heating process, an electric current is directed through the heating elements where it is dissipated as heat. The thermal energy is transferred to the part by convection, radiation and/or conduction. Below about 1250 F, heat transfer to the work piece is primarily by convection, sometimes with the aid of fans, as in "Forced" convection furnaces. Radiation is the major mode of heat transfer at temperatures above about 1250°F and in vacuum furnaces where there is no atmosphere to support convection.

Indirect resistance heating can also be done with encased resistance heaters. An encased resistance heater consists of an electric wire or ribbon resistance element surrounded by an electrical insulator enclosed in an outer envelope. The outer covering provides mechanical and chemical protection. The heater is placed on or in the solid or liquid to be heated. Heat generated by current flow through the resistance element is transferred to the work piece by conduction and convection (in liquid heating). These heaters almost always use line frequency, but they can be designed to operate at whatever voltage a plant has available.

## Induction heating

Induction heating is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction, where eddy currents are generated within the metal and resistance leads to Joule heating of the metal. An induction heater (for any process) consists of an electromagnet, through which a high-frequency alternating current (AC) is passed. Heat may also be generated by magnetic hysteresis losses in materials that have significant relative permeability. The frequency of AC used depends on the object size, material type, coupling (between the work coil and the object to be heated) and the penetration depth.

## Applications of Induction Heating

- Induction furnace
- Induction welding
- Induction cooking
- Induction brazing
- Induction sealing
- Heating to fit
- Heat treatment

## Advantages of Induction Heating

- Optimized Consistency
- Maximized Productivity
- Improved Product Quality
- Extended Fixture Life
- Environmentally Sound
- Reduced Energy Consumption

### Arc Heating:

The heating of a material by the heat energy from an electric arc, which has a very high temperature and very high concentration of heat energy. Also known as electric-arc heating.

### Infra-red heating:

An infrared heater is a body with a higher temperature which transfers energy to a body with a lower temperature through electromagnetic radiation. Depending on the temperature of the emitting body, the wavelength of the infrared radiation ranges from 780 nm to 1 mm. The relationship between temperature and wavelength is expressed by the Wien's displacement law.

No contact or medium between the two bodies is needed for the energy transfer. A rough classification of infrared heaters is connected to wavelength bands of major emission of the energy: short wave or near infrared for the range from 780 nm to 1400 nm, these emitters are also named bright because still some visible light with glare is emitted; medium infrared for the range between 1400 nm and 3000 nm; far infrared or dark emitters for everything above 3000 nm.

## **Electric welding**

Electrical arc welding is the procedure used to join two metal parts, taking advantage of the heat developed by the electric arc that forms between an electrode (metal filler) and the material to be welded. The welding arc may be powered by an alternating current generator machine (welder). This welding machine is basically a single-phase static transformer suitable for melting RUTILE (sliding) acid electrodes. Alkaline electrodes may also be melted by alternating current if the

secondary open-circuit voltage is greater than 70 V. The welding current is continuously regulated (magnetic dispersion) by turning the hand wheel on the outside of the machine, which makes it possible to select the current value, indicated on a special graded scale, with the utmost precision. To prevent the service capacities from being exceeded, all of the machines are fitted with an automatic overload protection which cuts off the power supply (intermittent use) in the event of an overload.

### Arc Welding:

Arc welding uses a welding power supply to create an electric arc between an electrode and the base material to melt the metals at the welding point. They can use either direct (DC) or alternating (AC) current, and consumable or non-consumable electrodes. The welding region is sometimes protected by some type of inert or semi-inert gas, known as a shielding gas, and/or an evaporating filler material. The process of arc welding is widely used because of its low capital and running costs.

### Radiation Welding

A process for welding metal sections in which at least two metal work pieces are welded together across a contact area using corpuscular radiation beams to heat the metal in the respective work pieces adjacent said contact area and form a welded joint.

A space is formed in the work piece in the region of the contact area, the space being positioned within said area in a location in which the corpuscular radiation beams utilized for welding dissipate. A metal tube filled with a corpuscular radiation sink material is placed in said space. Said tube completely fills said

space. Corpuscular radiation beams are directed from opposed sides of said joint to weld said work pieces together.

#### Resistance Welding:

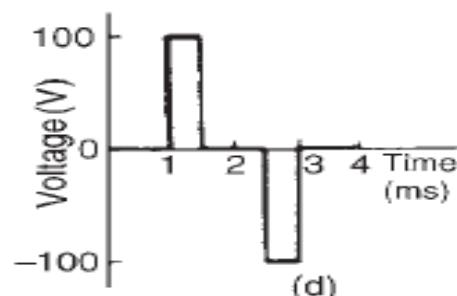
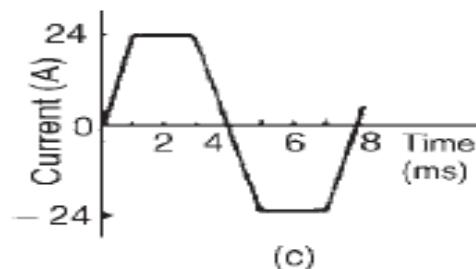
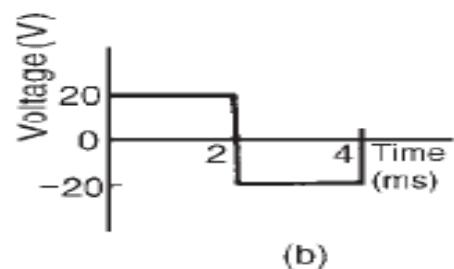
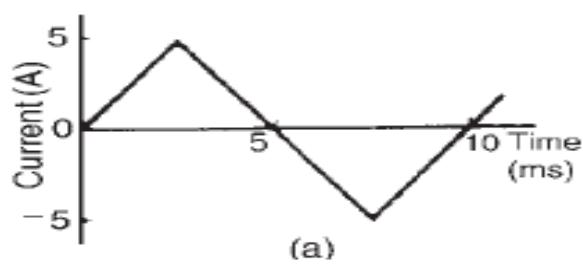
Resistance welding refers to a group of welding processes such as spot and seam welding that produce coalescence of faying surfaces where heat to form the weld is generated by the resistance of the welding current through the workpieces. Some factors influencing heat or welding temperatures are the proportions of the workpieces, the electrode materials, electrode geometry, electrode pressing force, weld current and weld time, etc.

Small pools of molten metal are formed at the point of most electrical resistance (the connecting surfaces) as a high current (100–100 000 A) is passed through the metal. In general, resistance welding methods are efficient and cause little pollution, but their applications are limited to relatively thin materials and the equipment cost can be high.

#### Question Bank

Q.1 For the waveforms shown in Figure 1 determine for each (i) the frequency (ii) the average value over half a cycle (iii) the rms value (iv) the form factor (v) the peak factor.

[**(a)** (i) **100 Hz** (ii) **2.50 A** (iii) **2.88 A** (iv) **1.15** (v) **1.74** **(b)** (i) **250 Hz** (ii) **20 V** (iii) **20 V** (iv) **1.0** (v) **1.0** **(c)** (i) **125 Hz** (ii) **18 A** (iii) **19.56 A** (iv) **1.09** (v) **1.23** **(d)** (i) **250 Hz** (ii) **25 V** (iii) **50 V** (iv) **2.0** (v) **2.0**]



**Figure:1**

Q.2 An alternating voltage  $v$  has a periodic time of 20 ms and a maximum value of 200 V. When time  $t = 0$ ,  $v = -75$  volts. Deduce a sinusoidal expression for  $v$  and sketch one cycle of the voltage showing important points. [ $v = 200 \sin(100t - 0.384)$ ]

Q.3 The instantaneous values of two alternating voltages are given by  $v_1 = 5 \sin \omega t$  and  $v_2 = 8 \sin(\omega t - \pi/6)$ . Obtain expressions for (a)  $v_1 + v_2$  and (b)  $v_1 - v_2$  [(a)  $v_1 + v_2 = 12.58 \sin(\omega t - 0.325) \text{ V}$  (b)  $v_1 - v_2 = 4.44 \sin(\omega t + 2.02) \text{ V}$ ]

Q.4 An alternating voltage is triangular in shape, rising at a constant rate to a maximum of 300 V in 8 ms and then falling to zero at a constant rate in 4 ms. The negative half cycle is identical in shape to the positive half cycle. Calculate (a) the mean voltage over half a cycle, and (b) the r.m.s voltage [(a) **150 V** (b) **170 V**]

Q.5 Determine, either by plotting graphs and adding ordinates at intervals, or by calculation, the following periodic functions in the form  $v = V_m \sin(\omega t)$

- (a)  $10 \sin \omega t + 4 \sin(\omega t + \pi/4)$  [**13.14 sin( $\omega t + 0.217$ )**]
- (b)  $80 \sin(\omega t + \pi/3) + 50 \sin(\omega t - \pi/6)$  [**94.34 sin( $\omega t + 0.489$ )**]
- (c)  $100 \sin(\omega t) - 70 \sin(\omega t - \pi/3)$  [**88.88 sin( $\omega t + 0.751$ )**]

Q.6. A coil of inductance 0.1 H and negligible resistance is connected in series with a  $25 \Omega$  resistor. The circuit is energized from a 230 V, 50 Hz source. Calculate: (a) the current in the circuit; (b) the p.d. across the coil; (c) the p.d. across the resistor; (d) the phase angle of the circuit. Draw to scale a phasor diagram representing the current and the component voltages. [**6.23 A, 196 V, 156 V, 51.5°**]

Q.7. A coil connected to a 230 V, 50 Hz sinusoidal supply takes a current of 10 A at a phase angle of  $30^\circ$ . Calculate the resistance and inductance of, and the power taken by, the coil. Draw, for one half-cycle, curves of voltage and current, and deduce and plot the power curve. Comment on the power curve. [**21.65 Ω, 39.8 mH, 2165 W**]

Q.8. A  $15 \Omega$  non-reactive resistor is connected in series with a coil of inductance 0.08 H and negligible resistance. The combined circuit is connected to a 240 V, 50

Hz supply. Calculate: (a) the reactance of the coil; (b) the impedance of the circuit; (c) the current in the circuit; (d) the power factor of the circuit; (e) the active power absorbed by the circuit. [25.1  $\Omega$ , 29.3  $\Omega$ , 8.19 A, 0.512, 1008 W]

Q.9. The potential difference measured across a coil is 20 V when a direct current of 2 A is passed through it. With an alternating current of 2 A at 40 Hz, the p.d. across the coil is 140 V. If the coil is connected to a 230 V, 50 Hz supply, calculate: (a) the current; (b) the active power; (c) the power factor. [2.64 A, 69.7 W, 0.115]

Q.10. A non-inductive load takes a current of 15 A at 125 V. An inductor is then connected in series in order that the same current shall be supplied from 240 V, 50 Hz mains. Ignore the resistance of the inductor and calculate: (a) the inductance of the inductor; (b) the impedance of the circuit; (c) the phase difference between the current and the applied voltage. Assume the waveform to be sinusoidal. [ 43.5 mH, 16  $\Omega$ , 58.6°]

Q.11. A series a.c. circuit, ABCD, consists of a resistor AB, an inductor BC, of resistance  $R$  and inductance  $L$ , and a resistor CD. When a current of 6.5 A flows through the circuit, the voltage drops across various points are:  $V_{AB} = 65$  V;  $V_{BC} = 124$  V;  $V_{AC} = 149$  V. The supply voltage is 220 V at 50 Hz. Draw a phasor diagram to scale showing all the resistive and reactive volt drops and, from the diagram, determine: (a) the volt drop  $V_{BD}$  and the phase angle between it and the current; (b) the resistance and inductance of the inductor. [ 170 V, 46°; 3.07  $\Omega$ , 60 mH]

Q.12. A coil takes a current of 10.0 A and dissipates 1410 W when connected to a 230 V, 50 Hz sinusoidal supply. When another coil is connected in parallel with it, the total current taken from the supply is 20.0 A at a power factor of 0.866.

Determine the current and the overall power factor when the coils are connected in series across the same supply. [5.34 A, 0.857]

Q.13. When a steel-cored reactor and a non-reactive resistor are connected in series to a 150 V a.c. supply, a current of 3.75 A flows in the circuit. The potential differences across the reactor and across the resistor are then observed to be 120 V and 60 V respectively. If the d.c. resistance of the reactor is  $4.5\ \Omega$ , determine the core loss in the reactor and calculate its equivalent series resistance. [77.5 W, 5.5  $\Omega$ ]

Q14. A  $30\Omega$  resistor is connected in parallel with a pure inductance of  $3\text{mH}$  across a 110V, 2kHz supply. Calculate (a) the current in each branch, (b) the circuit current, (c) the circuit phase angle, (d) the circuit impedance, (e) the power consumed, and (f) the circuit power factor.

[**(a)  $IR=3.67\text{A}$ ,  $IL =2.92\text{A}$  (b)  $4.69\text{A}$  (c)  $38.51^\circ$  lagging (d)  $23.45\Omega$  (e)  $404\text{W}$  (f)  $0.782$  lagging**]

Q15. A  $40\Omega$ resistance is connected in parallel with a coil of inductance  $L$  and negligible resistance across a 200V, 50Hz supply and the supply current is found to be 8A. Sketch a phasor diagram and determine the inductance of the coil. [**102mH**]

Q16. A  $1500\text{nF}$  capacitor is connected in parallel with a  $16\Omega$  resistor across a 10V, 10 kHz supply. Calculate (a) the current in each branch, (b) the supply current, (c) the circuit phase angle, (d) the circuit impedance, (e) the power consumed, (f) the apparent power, and (g) the circuit power factor. Sketch the phasor diagram. [**(a)  $IR=0.625\text{A}$ ,  $IC =0.943\text{A}$  (b)  $1.131\text{A}$  (c)  $56.46^\circ$  leading (d)  $8.84\Omega$  (e)  $6.25\text{W}$  (f )  $11.31\text{VA}$  (g)  $0.553$  leading**]

Q.17. A capacitor  $C$  is connected in parallel with a resistance  $R$  across a 60V, 100Hz supply. The supply current is 0.6A at a power factor of 0.8 leading. Calculate the values of  $R$  and  $C$ . [ **$R=125\Omega$ ,  $C =9.55\mu\text{F}$** ]

Q.18. A 75 ft resistance is connected in parallel with a  $10 \text{ } /j\text{F}$  capacitance. Determine an equivalent series RC circuit such that the two circuits have the same impedance at an angular frequency of 1000 rad/s. [R = 48  $\Omega$ , C = 27.8  $\mu\text{F}$ ]

Q.19. An inductive coil has resistance 30  $\Omega$ , but the inductance is unknown. The coil is connected in parallel with a 100- $\Omega$  resistor, and the combination, when connected across a 100-V, 60-Hz source, draws 400 W. Determine the value of the inductance. [26.53 mH]

Q.20. A parallel RL circuit consumes 480 W at 120 V and has a lagging power factor of 0.8. It is desired to make the power factor unity by connecting a capacitance in parallel with the RL circuit. If the source frequency is 60 Hz, find the value of the required capacitance. [66.3  $\mu\text{F}$ ]

8 A 31.8  $\mu\text{F}$  capacitor, a 127.5 mH inductor of resistance 30  $\Omega$  and a 100  $\Omega$  resistor are all connected in parallel to a 200 V, 50 Hz supply. Calculate the current in each branch. Draw a phasor diagram to scale to show these currents. Find the total current and its phase angle by drawing or otherwise. [2 A, 4 A, 2 A, 4.56 A]

Q.21. A 200 V, 50 Hz sinusoidal supply is connected to a parallel network comprising three branches A, B and C, as follows: A, a coil of resistance 3  $\Omega$  and inductive reactance 4  $\Omega$ ; B, a series circuit of resistance 4  $\Omega$  and capacitive reactance 3  $\Omega$ ; C, a capacitor. Given that the power factor of the combined circuit is unity, find: (a) the capacitance of the capacitor in microfarads; (b) the current taken from the supply. [127.4  $\mu\text{F}$ , 56 A]

Q.22. Two circuits, A and B, are connected in parallel to a 115 V, 50 Hz supply. The total current taken by the combination is 10 A at unity power factor. Circuit A consists of a 10  $\Omega$  resistor and a 200  $\mu\text{F}$  capacitor connected in series; circuit B consists of a resistor and an inductive reactor in series. Determine the following

data for circuit B: (a) the current; (b) the impedance; (c) the resistance; (d) the reactance. [8.5 A, 13.53 Ω, 10.74 Ω, 8.25 Ω]

Q.23. A parallel network consists of two branches A and B. Branch A has a resistance of 10 Ω and an inductance of 0.1 H in series. Branch B has a resistance of 20 Ω and a capacitance of 100 μF in series. The network is connected to a single-phase supply of 230 V at 50 Hz. Calculate the magnitude and phase angle of the current taken from the supply. Verify your answers by measurement from a phasor diagram drawn to scale. [6.05 A, 15.2° lagging]

Q.24. A coil has an inductance of 1.2 H and a resistance of 40 Ω and is connected to a 200 V, d.c. supply. Draw the current/time characteristic and hence determine the value of the current flowing 60 ms after connecting the coil to the supply. [4.3 A]

Q.25. A 25 V d.c. supply is connected to a coil of inductance 1 H and resistance 5 Ω. Determine the value of the current flowing 100 ms after being connected to the supply. [2 A]

Q.26. An inductor has a resistance of 20 Ω and an inductance of 4 H. It is connected to a 50 V d.c. supply. By drawing the appropriate characteristic find (a) the value of current flowing after 0.1 s and (b) the time for the current to grow to 1.5 A. [(a) 1 A (b) 0.18 s]

Q.27. The field winding of a 200 V d.c. machine has a resistance of 20 Ω and an inductance of 500 mH. Calculate: (a) the time constant of the field winding, (b) the value of current flow one time-constant after being connected to the supply, and (c) the current flowing 50 ms after the supply has been switched on. [(a) 25 ms (b) 6.32 A (c) 8.65 A]

Q.28. A circuit consists of a 200 Ω non-reactive resistor in parallel with a coil of 4 H inductance and 100 Ω resistance. If this circuit is switched across a 100 V d.c.

supply for a period of 0.06 s and then switched off, calculate the current in the coil 0.012 s after the instant of switching off. What is the maximum p.d. across the coil? [0.316 A, 155.5 V]

Q.29. The field winding of a d.c. machine has an inductance of 10 H and takes a final current of 2 A when connected to a 200 V d.c. supply. Calculate: (a) the initial rate of growth of current; (b) the time constant; and (c) the current when the rate of growth is 5 A/s. [21. 20 A/s, 0.1 s, 1.5 A]

Q.30. A 200 V d.c. supply is suddenly switched across a relay coil which has a time constant of 3 ms. If the current in the coil reaches 0.2 A after 3 ms, determine the final steady value of the current and the resistance and inductance of the coil. Calculate the energy stored in the magnetic field when the current has reached its final steady value. [0.316 A, 632 Ω 1.896 H, 94.6 mJ]

Q.31. A coil of inductance 4 H and resistance 80 Ω is in parallel with a 200 Ω resistor of negligible inductance across a 200 V d.c. supply. The switch connecting these to the supply is then opened, the coil and resistor remaining connected together. State, in each case, for an instant immediately before and for one immediately after the opening of the switch: (a) the current through the resistor; (b) the current through the coil; (c) the e.m.f. induced in the coil; and (d) the voltage across the coil. [1 A, 2.5 A, 0, 200 V; 2.5 A, 2.5 A, 700 V, 500 V]

### Transients in series connected C –R circuits

Q.32. An uncharged capacitor of 0.2 μF is connected to a 100 V, d.c. supply through a resistor of 100 kΩ Determine, either graphically or by calculation the capacitor voltage 10 ms after the voltage has been applied. [39.35 V]

Q.33. A circuit consists of an uncharged capacitor connected in series with a 50 kΩ resistor and has a time constant of 15 ms. Determine either graphically or by calculation (a) the capacitance of the capacitor and (b) the voltage drop across the

resistor 5 ms after connecting the circuit to a 20 V, d.c. supply. [(a) **0.3  $\mu$ F**, (b) **14.33 V**]

### (Poly Phase System & Power factor Improvement)

#### Star / Delta Connection

Q.1. Three loads, each of resistance  $50 \Omega$  are connected in star to a 400 V, 3-phase supply. Determine (a) the phase voltage, (b) the phase current and (c) the line current. [(a) **231 V** (b) **4.62 A** (c) **4.62 A**]

Q.2. If the loads in question 1 are connected in delta to the same supply determine (a) the phase voltage, (b) the phase current and (c) the line current. [(a) **400 V** (b) **8 A** (c) **13.86 A**]

Q.3. A star-connected load consists of three identical coils, each of inductance 159.2 mH and resistance  $50 \Omega$ . If the supply frequency is 50 Hz and the line current is 3 A determine (a) the phase voltage and (b) the line voltage. [(a) **212 V** (b) **367 V**]

Q.4. Three identical capacitors are connected (a) in star, (b) in delta to a 400 V, 50 Hz, 3-phase supply. If the line current is 12 A determine in each case the capacitance of each of the capacitors. [(a) **165.4  $\mu$ F** (b) **55.13  $\square$ F**]

Q.5. Three coils each having resistance  $6 \Omega$  and inductance L H are connected (a) in star and (b) in delta, to a 415 V, 50 Hz, 3-phase supply. If the line current is 30 A, find for each connection the value of L. [(a) **16.78 mH** (b) **73.84 mH**]

Q.6. A 400 V, 3-phase, 4 wire, star-connected system supplies three resistive loads of 15 kW, 20 kW and 25 kW in the red, yellow and blue phases respectively. Determine the current flowing in each of the four conductors. [**IR = 64.95 A, IY = 86.60 A IB = 108.25 A, IN = 37.50 A**]

Q.7. A 3-phase, star-connected alternator delivers a line current of 65 A to a balanced delta-connected load at a line voltage of 380 V. Calculate (a) the phase

voltage of the alternator, (b) the alternator phase current and (c) the load phase current. [(a) **219.4 V** (b) **65 A** (c) **37.53 A**]

Q.8. A three-phase, 400 V, star-connected motor has an output of 50 kW, with an efficiency of 90 per cent and a power factor of 0.85. Calculate the line current. Sketch a phasor diagram showing the voltages and currents. If the motor windings were connected in mesh, what would be the correct voltage of a three phase supply suitable for the motor? [**90.8 A, 240 V**]

Q.9. A three-phase, 400 V system has the following load connected in delta: between the red and yellow lines, a non-reactive resistor of  $100\ \Omega$ ; between the yellow and blue lines, a coil having a reactance of  $60\ \Omega$  and negligible resistance; between the blue and red lines, a loss-free capacitor having a reactance of  $130\ \Omega$ . Calculate: (a) the phase currents; (b) the line currents. Assume the phase sequence to be R-Y, Y-B and B-R. Also, draw the complete phasor diagram. [**4.00 A, 6.67 A, 3.08 A, 6.85 A, 10.33 A, 5.8 A**]

Q.10. A factory has the following load with power factor of 0.9 lagging in each phase. Red phase 40 A, yellow phase 50 A and blue phase 60 A. If the supply is 400 V, three phase, four-wire, calculate the current in the neutral and the total active power. Draw a phasor diagram for phase and line quantities. Assume that, relative to the current in the red phase, the current in the yellow phase lags by  $120^\circ$  and that in the blue phase leads by  $120^\circ$ . [**17.3 A, 31.2 kW**]

### Three Phase Power

Q.1. Determine the total power dissipated by three  $20\ \Omega$  resistors when connected (a) in star and (b) in delta to a 440 V, 3-phase supply. [(a) **9.68 kW** (b) **29.04 kW**]

Q.2. 10 A balanced delta-connected load has a line voltage of 400 V, a line current of 8 A and a lagging power factor of 0.94. Draw a complete phasor diagram of the load. What is the total power dissipated by the load? [**5.21 kW**]

Q.3. Three inductive loads, each of resistance  $4 \Omega$  and reactance  $9 \Omega$  are connected in delta. When connected to a 3-phase supply the loads consume 1.2 kW. Calculate (a) the power factor of the load, (b) the phase current, (c) the line current and (d) the supply voltage. [(a) **0.406** (b) **10 A** (c) **17.32 A** (d) **98.49 V**]

Q.4. The input voltage, current and power to a motor is measured as 415 V, 16.4 A and 6 kW respectively. Determine the power factor of the system. [**0.509**]

Q.5. A 440 V, 3-phase a.c. motor has a power output of 11.25 kW and operates at a power factor of 0.8 lagging and with an efficiency of 84%. If the motor is delta connected determine (a) the power input, (b) the line current and (c) the phase current. [(a) **13.39 kW** (b) **21.96 A** (c) **12.68 A**]

Q. 6. Two wattmeters are connected to measure the input power to a balanced 3-phase load. If the wattmeter readings are 9.3 kW and 5.4 kW determine (a) the total output power, and (b) the load power factor. [(a) **14.7 kW** (b) **0.909**]

Q.7. 8 kW is found by the two-wattmeter method to be the power input to a 3-phase motor. Determine the reading of each wattmeter if the power factor of the system is 0.85. [**5.431 kW, 2.569 kW**]

Q.8. Three similar coils, each having a resistance of  $4.0 \Omega$  and an inductive reactance of  $3.46 \Omega$  are connected (a) in star and (b) in delta across a 400 V, 3-phase supply. Calculate for each connection the readings on each of two wattmeters connected to measure the power by the two-wattmeter method. [(a) **17.15 kW, 5.73 kW** (b) **51.46 kW, 17.18 kW**]

Q.9. A 3-phase, star-connected alternator supplies a delta connected load, each phase of which has a resistance of  $15 \Omega$  and inductive reactance  $20 \Omega$ . If the line voltage is 400 V, calculate (a) the current supplied by the alternator and (b) the output power and kVA rating of the alternator, neglecting any losses in the line between the alternator and the load. [(a) **27.71 A** (b) **11.52 kW, 19.2 kVA**]

Q.10. Each phase of a delta-connected load comprises a resistance of  $40\ \Omega$  and a  $40\ \mu F$  capacitor in series. Determine, when connected to a 415 V, 50 Hz, 3-phase supply (a) the phase current, (b) the line current, (c) the total power dissipated, and (d) the kVA rating of the load. [(a) 4.66 A (b) 8.07 A (c) 2.605 kW (d) 5.80 kVA]

Q.11. Three  $24\ \mu F$  capacitors are connected in star across a 400 V, 50 Hz, 3-phase supply. What value of capacitance must be connected in delta in order to take the same line current? [8  $\mu F$ ]

### **Power factor improvement**

Q.1. A 415 V alternator is supplying a load of 55 kW at a power factor of 0.65 lagging. Calculate (a) the kVA loading and (b) the current taken from the alternator. (c) If the power factor is now raised to unity find the new kVA loading.  
[(a) 84.6 kVA (b) 203.9 A (c) 84.6 kVA]

Q.2. A single phase motor takes 30 A at a power factor of 0.65 lagging from a 240 V, 50 Hz supply. Determine (a) the current taken by the capacitor connected in parallel to correct the power factor to unity, and (b) the value of the supply current after power factor correction. [(a) 22.80 A (b) 19.5 A]

Q.3. A motor has an output of 6 kW, an efficiency of 75% and a power factor of 0.64 lagging when operated from a 250 V, 60 Hz supply. It is required to raise the power factor to 0.925 lagging by connecting a capacitor in parallel with the motor. Determine (a) the current taken by the motor, (b) the supply current after power factor correction, (c) the current taken by the capacitor, (d) the capacitance of the capacitor and (e) the kvar rating of the capacitor. [(a) 50 A (b) 34.59 A (c) 25.28 A (d) 268.2  $\mu F$  (e) 6.32 kvar]

Q.4. A 200 V, 50 Hz single-phase supply feeds the following loads: (i) fluorescent lamps taking a current of 8 A at a power factor of 0.9 leading, (ii) incandescent

lamps taking a current of 6 A at unity power factor, (iii) a motor taking a current of 12 A at a power factor of 0.65 lagging. Determine the total current taken from the supply and the overall power factor. Find also the value of a static capacitor connected in parallel with the loads to improve the overall power factor to 0.98 lagging. [21.74 A, 0.966 lagging, 21.68  $\mu$ F]

### (Magnetic Circuits & Transformers)

*Data of B/H, when not given in question, should be taken from Fig. 1.*

Q.1 A mild steel ring has a mean circumference of 500 mm and a uniform cross-sectional area of 300 mm<sup>2</sup>. Calculate the m.m.f. required to produce a flux of 500  $\mu$ Wb. An airgap, 1.0 mm in length, is now cut in the ring. Determine the flux produced if the m.m.f. remains constant. Assume the relative permeability of the mild steel to remain constant at 220. [ **3000 A, 346  $\mu$ Wb**]

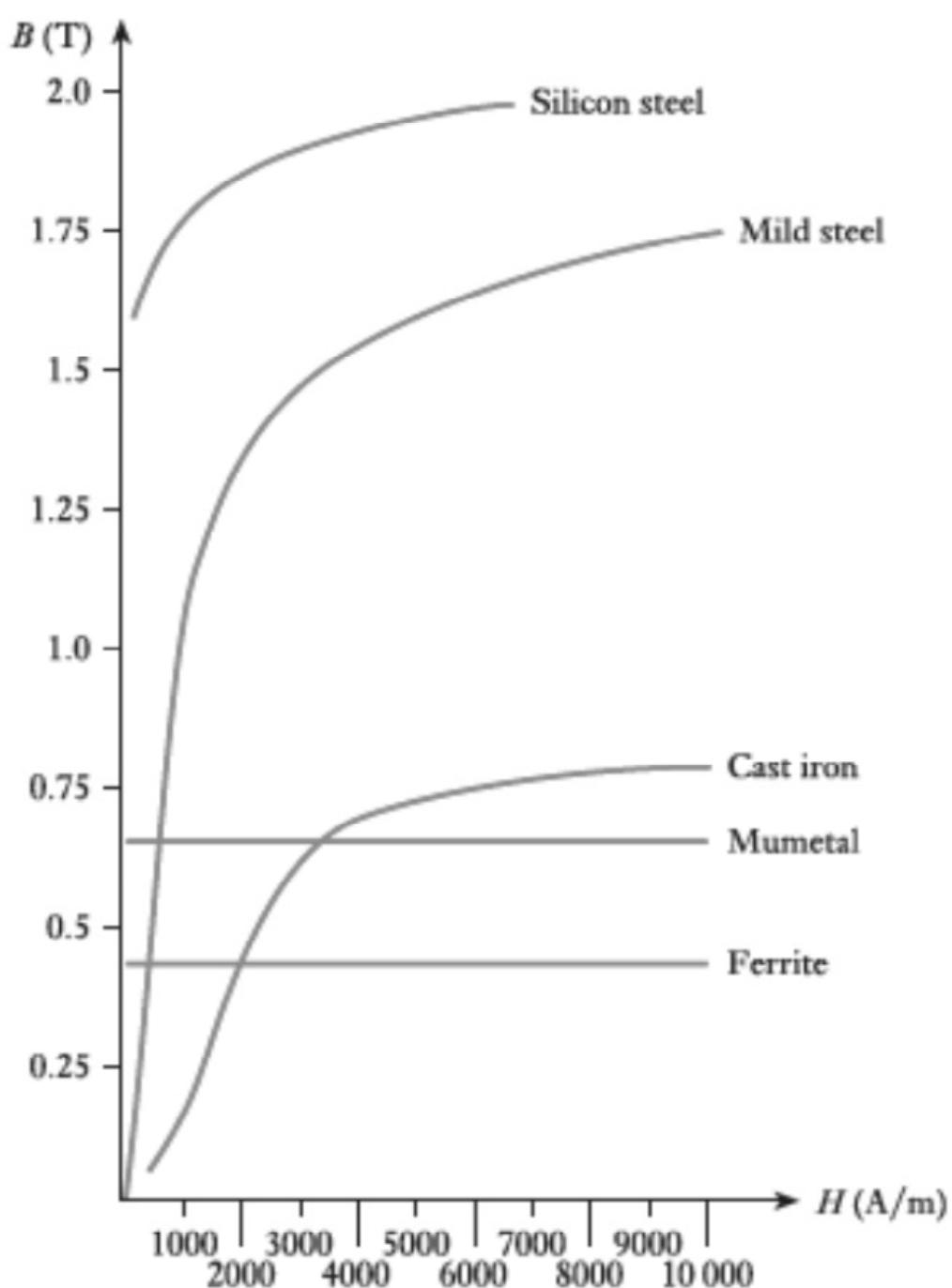


Figure:1

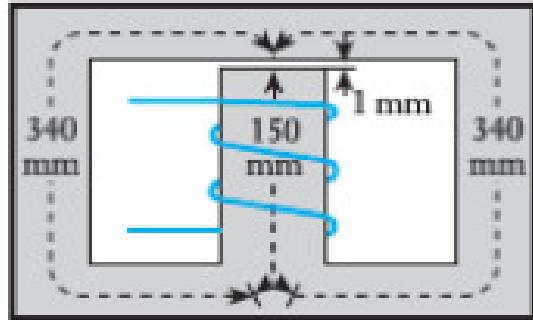


Figure:2

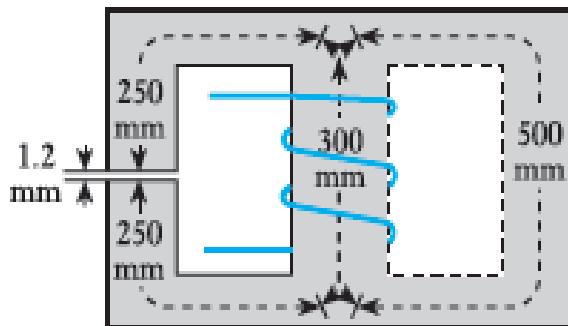


Figure:3

Q.2 A certain magnetic circuit may be regarded as consisting of three parts, A, B and C in series, each one of which has a uniform cross-sectional area. Part A has a length of 300 mm and a cross-sectional area of 450 mm<sup>2</sup>. Part B has a length of 120 mm and a cross-sectional area of 300 mm<sup>2</sup>. Part C is an airgap 1.0 mm in length and of cross-sectional area 350 mm<sup>2</sup>. Neglecting magnetic leakage and fringing, determine the m.m.f. necessary to produce a flux of 0.35 mWb in the airgap. The magnetic characteristic for parts A and B is given by:

$H$  (A/m) 400 560 800 1280 1800

$B$  (T) 0.7 0.85 1.0 1.15 1.25 [1100 A]

Q.3 A magnetic circuit made of silicon steel is arranged as in Fig. 2. The centre limb has a cross-sectional area of 800 mm<sup>2</sup> and each of the side limbs has a cross-sectional area of 500 mm<sup>2</sup>. Calculate the m.m.f. required to produce a flux of

1 mWb in the centre limb, assuming the magnetic leakage to be negligible. [1015 A]

Q.4 A magnetic core made of mild steel has the dimensions shown in Fig. 3. There is an airgap 1.2 mm long in one side limb and a coil of 400 turns is wound on the centre limb. The cross-sectional area of the centre limb is 1600 mm<sup>2</sup> and that of each side limb is 1000 mm<sup>2</sup>. Calculate the exciting current required to produce a flux of 1000 µWb in the airgap. Neglect any magnetic leakage and fringing. [5.85 A]

Q.5 The design requirements of an 11 000 V/400 V, 50 Hz, single-phase, core-type transformer are: approximate e.m.f./turn, 15 V; maximum flux density, 1.5 T. Find a suitable number of primary and secondary turns, and the net cross-sectional area of the core. [27 turns, 742 turns, 44 500 mm<sup>2</sup>]

Q.6 The primary winding of a single-phase transformer is connected to a 230 V, 50 Hz supply. The secondary winding has 1500 turns. If the maximum value of the core flux is 0.002 07 Wb, determine: (a) the number of turns on the primary winding; (b) the secondary induced voltage; (c) the net cross-sectional core area if the flux density has a maximum value of 0.465 T. [523, 688 V, 4450 mm<sup>2</sup>]

Q.7 The primary of a certain transformer takes 1 A at a power factor of 0.4 when connected across a 230 V, 50 Hz supply and the secondary is on open circuit. The number of turns on the primary is twice that on the secondary. A load taking 50 A at a lagging power factor of 0.8 is now connected across the secondary. Sketch, and explain briefly, the phasor diagram for this condition, neglecting voltage drops in the transformer. What is now the value of the primary current? [25.9 A]

Q.8 A 3300 V/230 V, single-phase transformer, on no load, takes 2 A at power factor 0.25. Determine graphically, or otherwise, the primary current and power

factor when the transformer is supplying a load of 60 A at power factor 0.9 leading. [4.26 A, 1.0]

Q.9 A transformer has 600 primary turns and 150 secondary turns. The primary and secondary resistances are  $0.25 \Omega$  and  $0.01 \Omega$  respectively and the corresponding leakage reactances are  $1.0 \Omega$  and  $0.04 \Omega$  respectively. Determine (a) the equivalent resistance referred to the primary winding, (b) the equivalent reactance referred to the primary winding, (c) the equivalent impedance referred to the primary winding, and (d) the phase angle of the impedance. [0.41Ω, 1.64Ω, 1.69Ω, 75.96°]

Q.10 The output stage of an amplifier has an output resistance of  $112 \Omega$ . Calculate the optimum turns ratio of a transformer which would match a load resistance of  $7 \Omega$  to the output resistance of the amplifier. [4:1]

Q.11 Determine the optimum value of load resistance for maximum power transfer if the load is connected to an amplifier of output resistance  $150 \Omega$  through a transformer with a turns ratio of 5:1. [6Ω]

Q.12 A single-phase, 220 V/1760 V ideal transformer is supplied from a 220 V source through a cable of resistance  $2 \Omega$ . If the load across the secondary winding is  $1.28 \text{ k}\Omega$  determine (a) the primary current flowing and (b) the power dissipated in the load resistor. [10A, 2 KW]

Q.13 An a.c. source of 24 V and internal resistance  $15 \text{ k}\Omega$  is matched to a load by a 25:1 ideal transformer. Determine (a) the value of the load resistance and (b) the power dissipated in the load. [24Ω, 9.6 mW]

Q.14 A load of resistance  $768 \Omega$  is to be matched to an amplifier which has an effective output resistance of  $12 \Omega$ . Determine the turn ratio of the coupling transformer. [1:8]

Q.15 An a.c. source of 20 V and internal resistance 20 k $\Omega$  is matched to a load by a 16:1 single-phase transformer. Determine (a) the value of the load resistance and (b) the power dissipated in the load. [(a) **78.13  $\Omega$**  (b) **5 mW**]

### (Rotating Machines)

Q.1 A 24-coil, 2-pole DC generator has 16 turns per coil in its armature winding. The field excitation is 0.05 Wb per pole, and the armature angular velocity is 180 rad/s. Find the machine constant and the total induced voltage. [ $ka = 5.1$ ;  $E_b = 45.9$  V]

Q.2 A 1,000-kW, 1,000-V, 2,400-rev/min separately excited DC generator has an armature circuit resistance of 0.04  $\Omega$ . The flux per pole is 0.4 Wb. Find: (a) the induced voltage; (b) the machine constant; and (c) the torque developed at the rated conditions. [(a)  **$E_b = 1,040$  V**; (b)  **$ka = 10.34$** ; (c)  **$T = 4,138$  N-m**]

Q.3 A 100-kW, 250-V shunt generator has a field circuit resistance of 50  $\Omega$  and an armature circuit resistance of 0.05  $\Omega$ . Find: (a) the full-load line current flowing to the load; (b) the field current; (c) the armature current; and (d) the full-load generator voltage. [(a) **400 A**; (b) **5 A**; (c) **405 A**; (d) **270.25 V**]

Q.4 A series motor draws a current of 25 A and develops a torque of 100 N-m. Find: (a) the torque when the current rises to 30 A if the field is unsaturated; and (b) the torque when the current rises to 30 A and the increase in current produces a 10 percent increase in flux. [(a) **144 N-m**; (b) **132 N-m**]

Q.5 A 200-V DC shunt motor draws 10 A at 1,800 rev/min. The armature circuit resistance is 0.15  $\Omega$  and the field winding resistance is 350  $\Omega$ . What is the torque developed by the motor? [ **$T = 9.93$  N-m**]

Q.6 A 4-pole, wave-connected armature of a d.c. machine has 750 conductors and is driven at 720 rev/min. If the useful flux per pole is 15 mWb, determine the generated e.m.f. [**270 volts**]

Q.7 A 6-pole generator has a lap-wound armature with 40 slots with 20 conductors per slot. The flux per pole is 25 mWb. Calculate the speed at which the machine must be driven to generate an e.m.f. of 300 V. [15 rev/s or 900 rev/min]

Q.8 A 4-pole armature of a d.c. machine has 1000 conductors and a flux per pole of 20 mWb. Determine the e.m.f. generated when running at 600 rev/min when the armature is (a) wave-wound, (b) lap-wound. [(a) 400 volts (b) 200 volts]

Q.9 A d.c. generator running at 25 rev/s generates an e.m.f. of 150 V. Determine the percentage increase in the flux per pole required to generate 180 V at 20 rev/s. [50%]

Q.10 A shunt generator supplies a 50 kW load at 400 V through cables of resistance 0.2 Ω. If the field winding resistance is 50 Ω and the armature resistance is 0.05 Ω, determine (a) the terminal voltage, (b) the e.m.f. generated in the armature. [(a) 425 volts (b) 431.68 volts]

Q.11 A short-shunt compound generator supplies 50 A at 300 V. If the field resistance is 30 Ω, the series resistance 0.03 Ω and the armature resistance 0.05 Ω, determine the e.m.f. generated. [304.5 volts]

Q.12 A d.c. generator has a generated e.m.f. of 210 V when running at 700 rev/min and the flux per pole is 120 mWb. Determine the generated e.m.f. (a) at 1050 rev/min, assuming the flux remains constant, (b) if the flux is reduced by one-sixth at constant speed, and (c) at a speed of 1155 rev/min and a flux of 132 mWb. [(a) 315 V (b) 175 V (c) 381.2 V]

Q.13 A 250 V d.c. shunt-wound generator has an armature resistance of 0.1 Ω. Determine the generated e.m.f. when the generator is supplying 50 kW, neglecting the field current of the generator. [270 V] EEEE Department Silicon Institute of Technology Bhubaneswar Basic Electrical Engineering Tutorial 14

Q.14 A d.c. motor operates from a 350 V supply. If the armature resistance is  $0.4\ \Omega$  determine the back e.m.f. when the armature current is 60 A. [326 volts]

Q.15 The armature of a d.c. machine has a resistance of  $0.5\ \Omega$  and is connected to a 200 V supply. Calculate the e.m.f. generated when it is running (a) as a motor taking 50 A and (b) as a generator giving 70 A. [(a) 175 volts (b) 235 volts]

Q.15 Determine the generated e.m.f. of a d.c. machine if the armature resistance is  $0.1\ \Omega$  and it (a) is running as a motor connected to a 230 V supply, the armature current being 60 A, and (b) is running as a generator with a terminal voltage of 230 V, the armature current being 80 A. [(a) 224 V (b) 238 V]

Q.16 The shaft torque required to drive a d.c. generator is 18.7 Nm when it is running at 1250 rev/min. If its efficiency is 87% under these conditions and the armature current is 17.3 A, determine the voltage at the terminals of the generator. [123.1 V]

Q.17 A 220 V, d.c. generator supplies a load of 37.5 A and runs at 1550 rev/min. Determine the shaft torque of the diesel motor driving the generator, if the generator efficiency is 78%. [65.2 Nm]

Q.18 A 4-pole d.c. motor has a wave-wound armature with 800 conductors. The useful flux per pole is 20 mWb. Calculate the torque exerted when a current of 40 A flows in each armature conductor. [203.7 Nm]

Q.19 Calculate the torque developed by a 240 V d.c. motor whose armature current is 50 A, armature resistance is  $0.6\ \Omega$  and is running at 10 rev/s. [167.1 Nm]

Q.20 An 8-pole lap-wound d.c. motor has a 200 V supply. The armature has 800 conductors and a resistance of  $0.8\ \Omega$ . If the useful flux per pole is 40 mWb and the armature current is 30 A, calculate (a) the speed and (b) the torque developed.

[(a) 5.5 rev/s or 330 rev/min (b) 152.8 Nm]

Q.21 A 240 V shunt motor takes a total current of 80 A. If the field winding resistance is  $120\ \Omega$  and the armature resistance is  $0.4\ \Omega$ , determine (a) the current in the armature, and (b) the back e.m.f. [(a) **78 A** (b) **208.8 V**]

Q.22 A d.c. motor has a speed of 900 rev/min when connected to a 460 V supply. Find the approximate value of the speed of the motor when connected to a 200 V supply, assuming the flux decreases by 30% and neglecting the armature volt drop. [559 rev/min]

Q.23 A 350 V shunt motor runs at its normal speed of 12 rev/s when the armature current is 90 A. The resistance of the armature is  $0.3\ \Omega$ . (a) Find the speed when the current is 45 A and a resistance of  $0.4\ \Omega$  is connected in series with the armature, the shunt field remaining constant. (b) Find the speed when the current is 45 A and the shunt field is reduced to 75% of its normal value by increasing resistance in the field circuit. [(a) **11.83 rev/s** (b) **16.67 rev/s**]

Q.24 A series motor runs at 900 rev/min when the voltage is 420 V and the current is 40 A. The armature resistance is  $0.3\ \Omega$  and the series field resistance is  $0.2\ \Omega$ . Calculate the resistance to be connected in series to reduce the speed to 720 rev/min with the same current. [**2 Ω**]

Q.25 A 320 V series motor takes 80 A and runs at 1080 rev/min at full load. The armature resistance is  $0.2\ \Omega$  and the series winding resistance is  $0.05\ \Omega$ . Assuming the flux is proportional to the field current, calculate the speed when developing full-load torque, but with a  $0.15\ \Omega$  diverter in parallel with the field winding. [**1239 rev/min**]