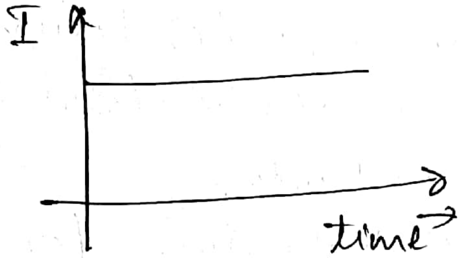
Asst. Professor,
Dept of E&C.

D.C CIRCUITS : A Direct Current always remains constant and does not vary with time. The D.C. current characterises the flow of Electric charge in one particular direction



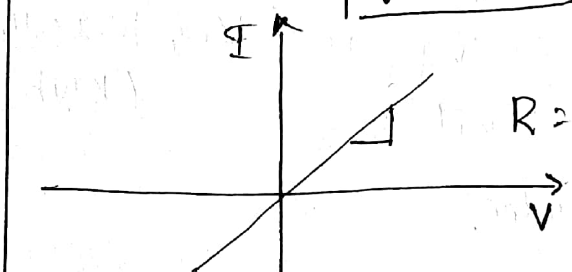
A D.C circuit consists of constant voltage sources, constant current sources and their interconnection with resistances only.
The study of D.C circuits necessiates the study of the various elements of an Electric circuit.

OHM'S LAW : At constant Temperature, the current flowing through any conductor is directly proportional to the potential difference between the two ends of the conductor.

$I \propto V$ at constant temperature

$I = \frac{V}{R}$

$\boxed{V = IR}$ $R \rightarrow$ constant, known as Resistance of the conductor.



$R = \frac{1}{\text{Slope}}$

$\text{Slope} = \frac{\Delta I}{\Delta V}$

graphical representation of Ohm's Law.

LIMITATIONS OF OHM'S LAW :

(i) Ohm's law does not hold good for Non-linear devices such as Zener diodes, Voltage regulators, etc.

(ii) Ohm's law does not hold good for Non-metallic Conductors such as Silicon carbide, Polymers, etc for such devices VI-relation is of the form
$V = KI^m$ where $K, m \rightarrow$ constants.

(iii) Ohm's law does not hold good for Arc lamps because of their Non-linear Characteristics.

ELECTRICAL ENERGY (W) :

It is the total amount of Electrical Workdone in an Electric Circuit.

$$W = \text{Power} \times \text{time} = VI \times t \text{ watt-sec}$$

$$W = \frac{V^2}{R} t = I^2 R t \text{ watt-sec}$$

NOTE : As the 'watt-sec' is a very small unit, Electrical Energy is measured in larger units i.e 'Kilo Watt Hour' (KWh)
The Practical Unit of energy is 'Kilo Watt Hour' (KWh) whose trade name is 'Unit'

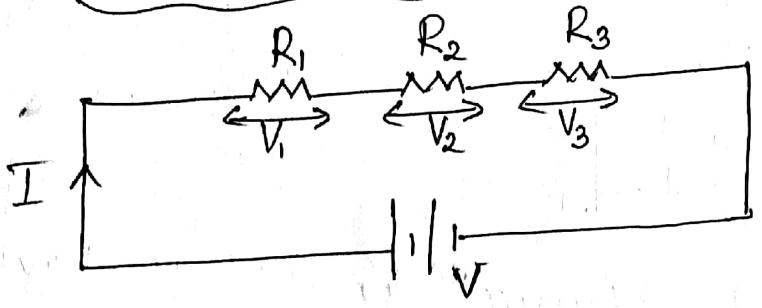
$$1 \text{ KWh} = 3.6 \times 10^6 \text{ joules.}$$

ELECTRICAL POWER (P) :- The Rate at which Electrical work is done in an Electric Circuit is called Electrical Power.

$$P = \frac{W}{t} = \frac{VI.t}{t}$$

$$P = VI = \frac{V^2}{R} = I^2R \text{ watts}$$

RESISTANCES IN SERIES (R_s) :



$$V = V_1 + V_2 + V_3$$

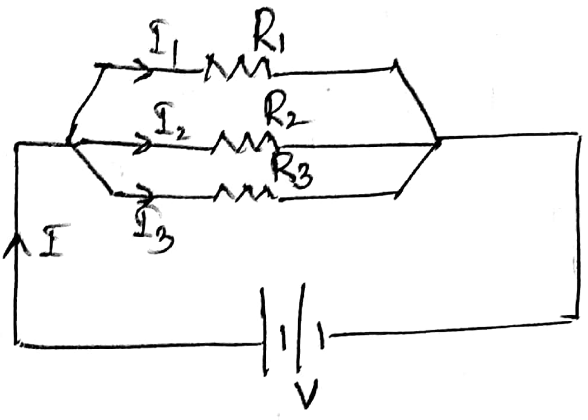
$$I R_s = IR_1 + IR_2 + IR_3$$

∴ Total Resistance $R_s = R_1 + R_2 + R_3$

If there are 'n' Resistances Connected in Series

$$R_s = R_1 + R_2 + R_3 + \ldots\ldots + R_n$$

RESISTANCES IN PARALLEL : (R_p)



$$I = I_1 + I_2 + I_3$$

$$\frac{V}{R_p} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$\therefore \quad \frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

If there are 2 Resistances connected in Parallel

$$R_p = \frac{R_1 R_2}{R_1 + R_2}$$

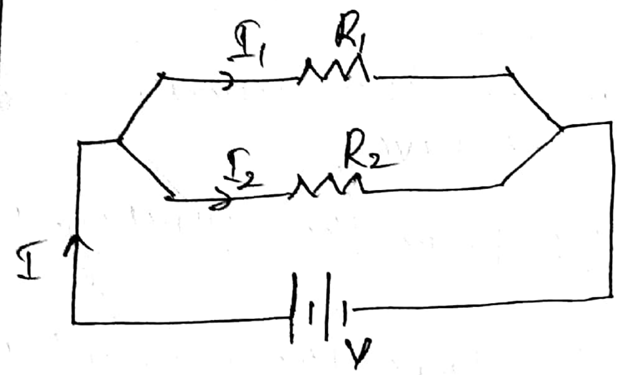
If there are 3 Resistances connected in parallel

$$R_p = \frac{R_1 R_2 R_3}{R_1 R_2 + R_2 R_3 + R_3 R_1}$$

If there are 'n' Resistances connected in parallel

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}$$

CURRENT IN A PARALLEL BRANCH :



$$I = I_1 + I_2 \quad \ldots\ldots (a)$$

As voltage across parallel combination is constant,

$$V = I_2 R_2 = I_1 R_1$$

$$\frac{I_2}{I_1} = \frac{R_1}{R_2}$$

$$\frac{I_2}{I_1} + 1 = \frac{R_1}{R_2} + 1$$

$$\frac{I_2 + I_1}{I_1} = \frac{R_1 + R_2}{R_2}$$

$$\frac{I}{I_1} = \frac{R_1 + R_2}{R_2}$$

On Re-arranging,

$$\therefore \boxed{I_1 = \frac{I R_2}{R_1 + R_2}}$$

Similarly $I_2 = \frac{I R_1}{R_1 + R_2}$

In general,

$$\text{Branch Current} = \frac{\text{Total Current} \times \text{The other Resistance}}{\text{Sum of the Two Resistances.}}$$

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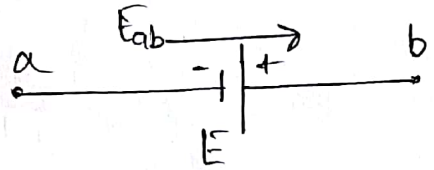
NOTE :

(i) Currents flowing towards the junction are are taken as '+ive'.

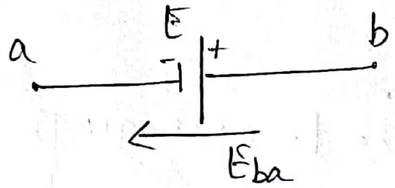
(ii) Currents flowing away from the junction are taken as -ive.

(iii) All the voltage rises are taken as '+ive' and all the voltage drops are taken as '-ive'.

(iv)

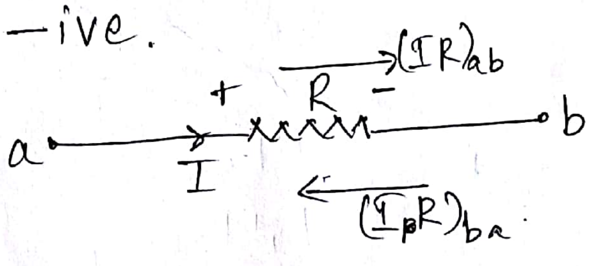


when the battery is traced from a to b, 'E_{ab}' is +ive.



when the battery is traced from b to a, 'E_{ba}' is -ive.

(v)



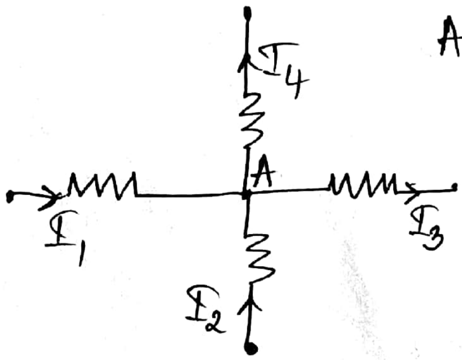
The voltage drop $(IR)_{ab}$ is -ive.
The voltage drop $(IR)_{ba}$ is +ive.

KIRCHOFFS LAWS : (i) Current law (ii) Voltage law.

(i) KIRCHOFFS CURRENT LAW (KCL) : The Algebraic Sum of all the Currents meeting at any junction of an Electrical Circuit is zero.

Mathematically, i.e $\sum I = 0$.

Eg:- Consider junction 'A' of an Electrical Circuit shown below.



According to Kirchoff's current law,

$$I_1 + I_2 - I_3 - I_4 = 0$$

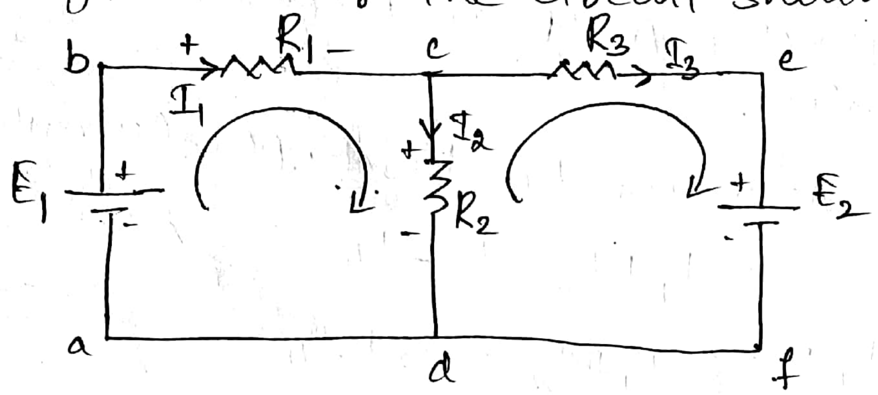
$$I_1 + I_2 = I_3 + I_4$$

KCL can also be stated as "At any junction of an Electric Circuit, the sum of all the Currents entering the junction is equal to the Sum of all the Currents leaving the junction"

KIRCHOFF'S VOLTAGE LAW (KVL) ; In any closed electrical circuit, the algebraic sum of all the EMFs and the Resistive drops is equal to zero.

Mathematically, i.e $\sum E + \sum IR = 0$.

Eg: Consider the circuit shown in fig below,



According to KVL,

for the closed loop abcda :

$$+E_1 - I_1 R_1 - I_2 R_2 = 0.$$

$$I_1 R_1 + I_2 R_2 = E_1$$

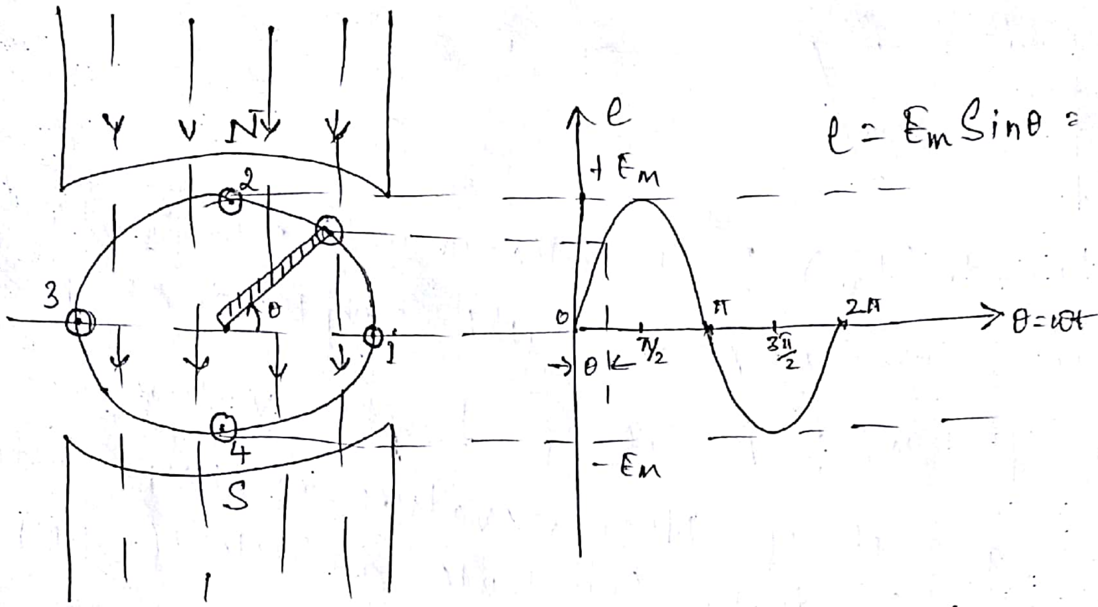
for the closed loop dcefd :

$$+I_2 R_2 - I_3 R_3 - E_2 = 0.$$

$$I_2 R_2 - I_3 R_3 = E_2$$

GENERATION OF A.C VOLTAGE :

$e = E_m \sin\theta = E_m \sin\omega t$



The EMF Induced in the conductor is given by

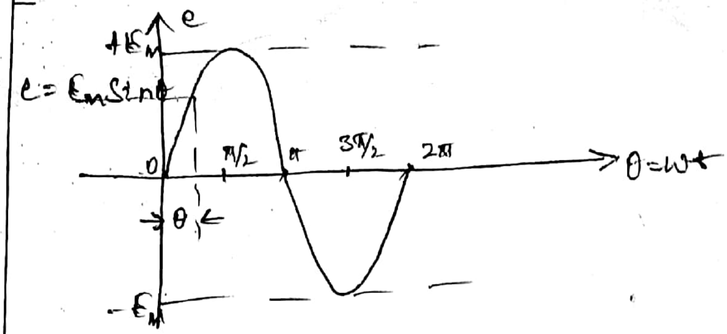
$e = Bl v \sin\theta = E_m \sin\omega t$ where, $l \rightarrow$ Length of the Conductor (m)
$B \rightarrow$ Flux density (wb/m^2)
$v \rightarrow$ Velocity
$\omega \rightarrow$ Angular Velocity.

* When the Conductor is rotating from Position 1 to 2 and 2 to 3 i.e from $\theta = 0$ to $\theta = \pi$, it is rotating under the influence of North pole & the direction of the Induced EMF is +ive.

* Similarly when the Conductor is rotating from Position 3 to 4 & 4 to 5 i.e from $\theta = \pi$ to $\theta = 2\pi$, it is rotating Under the influence of South pole & the direction of Induced EMF is -ive.

DEFINITIONS :

(i) Instantaneous Value : (e) The Value of EMF induced in the Conductor at any instant



(ii) <u>Amplitude (Em)</u> : The Maximum Value of EMF induced in the conductor is called amplitude.

(iii) <u>Cycle of EMF</u> : A Set of Positive values together with a Set of Negative values of EMF induced in the conductor Constitute a cycle of EMF induced.

(iv) <u>Frequency (f)</u> : It is defined as the number of cycles of EMF induced in the conductor per second.

(v) <u>Time Period (T)</u> : It is the time taken to complete One cycle of the EMF induced ($T = 1/f$)

<u>ADVANTAGES OF SINUSOIDAL WAVEFORMS</u> :

(i) Many Phenomena occuring in the nature are of Sinusoidal in nature <u>Eg</u>: Motion of a Pendulum, Vibration of Strings in Musical instruments, etc.

(ii) The Derivative & Integral of a Sinusoidal function is also Sinusoidal in nature. This makes the mathematical analysis of an Electrical Circuit much easier.

(iii) When the current in a capacitor or Inductor is sinusoidal in nature, the voltage across them is also sinusoidal. This is not true for other waveforms.

(iv) For any disturbance in the circuit, the shape of the sinusoidal waveform remains the same which is not true for other waveforms.

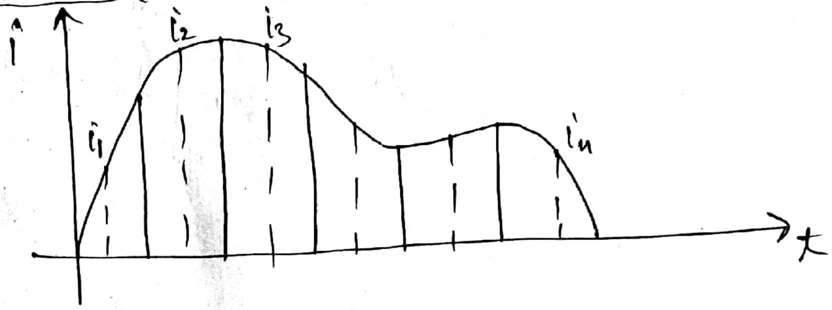
(V) When a three phase sinusoidal voltage is applied to the windings of a motor, it produces a revolving magnetic field, which has the capacity to do work. Most of the A.C motors used in Industrial or other applications work on this Principle.

EFFECTIVE VALUE OF AN ALTERNATING CURRENT (R.M.S VALUE)

Defn:

The effective or rms value of an Alternating current is equal to the steady current, which produces the same amount of heat as produced by the alternating current, when passed through the same resistance for the same time.

EFFECTIVE VALUE OF AN ALTERNATING CURRENT REPRESENTED BY ANY WAVEFORM :- [I or I_{rms}]



The wave from is divided into 'n' equal parts, each interval is equal to 't/n' seconds. Let $i_1, i_2 \ldots i_n$ be the mid-ordinates of these intervals.

Heat produced during first interval $= i_1^2 R\, t/n$

Heat produced -1- second interval $= i_2^2 R\, t/n$

⋮

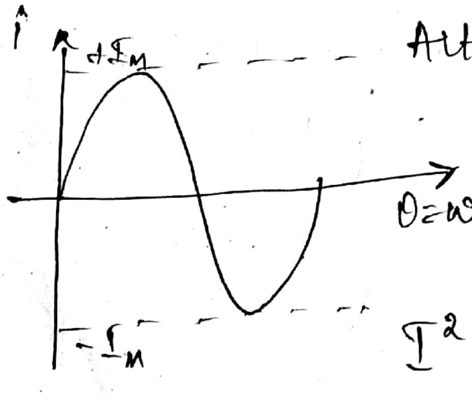
Heat produced during n^{th} interval $= i_n^2 R\, t/n$

∴ The total heat produced in 't' seconds } $H = \dfrac{(i_1^2 + i_2^2 + \ldots + i_n^2)Rt}{n}$

$$I^2 R t = \frac{(i_1^2 + i_2^2 + \ldots + i_n^2)Rt}{n}$$

Effective or RMS value of an Alternating Current } $I = \sqrt{\dfrac{i_1^2 + i_2^2 + \ldots + i_n^2}{n}}$

EFFECTIVE VALUE OF AN ALTERNATING CURRENT WHICH IS SINUSOIDALLY VARYING:



Alternating current } $i = I_m \sin\theta$

The effective value of current is

$$I^2 = \frac{1}{2\pi}\int_0^{2\pi} i^2 \cdot d\theta = \frac{1}{2\pi}\int_0^{2\pi} I_m^2 \sin^2\theta \cdot d\theta$$

$$I^2 = \frac{I_m^2}{2\pi}\int_0^{2\pi}\left(\frac{1-\cos 2\theta}{2}\right).d\theta = \frac{I_m^2}{4\pi}\left[\theta - \frac{\sin 2\theta}{2}\right]_0^{2\pi}$$

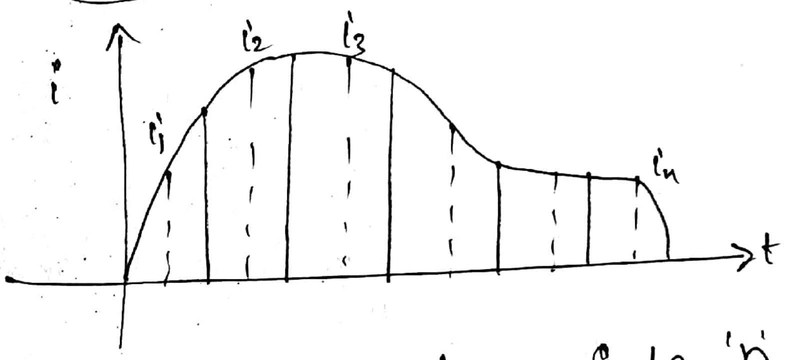
$$I^2 = \frac{I_m^2}{4\pi}\times\left[(2\pi - 0) - 0\right]$$

$$\boxed{I \text{ or } I_{rms} = \frac{I_m}{\sqrt{2}} = 0.707\, I_m}$$

AVERAGE VALUE OF AN ALTERNATING CURRENT (I_{av})

Defn: The Average value of an Alternating Current is equal to that Steady current, which transfers the same amount of charge, as transferred by the alternating current across the same circuit and in the same time.

AVERAGE VALUE OF AN ALTERNATING CURRENT REPRESENTED BY ANY WAVEFORM:



Divide the waveform into 'n' equal parts, so that duration of each interval is 't/n' seconds. Let 'q' be the charge transferred across the circuit in t sec.

Charge transferred during first interval = $i_1 \frac{t}{n}$

Charge transferred -||- second interval = $i_2 \frac{t}{n}$

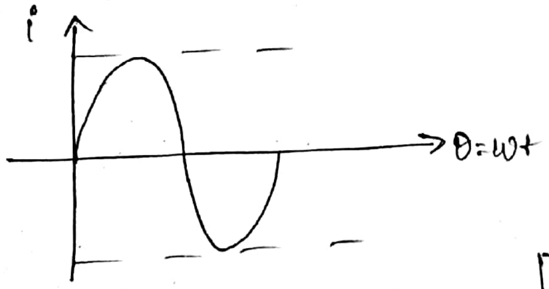
⋮

Charge transferred during n^{th} interval = $i_n \frac{t}{n}$

∴ The total charge transferred in 't' seconds } $q = I_{av} t = \frac{(i_1 + i_2 + \dots + i_n) t}{n}$

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

AVERAGE VALUE OF AN ALTERNATING CURRENT REPRESENTED BY A SINUSOIDAL WAVEFORM :



$$I_{av} = \frac{1}{\pi}\int_0^{\pi} i \, d\theta = \frac{1}{\pi}\int_0^{\pi} I_m \sin\theta \, d\theta$$

$$= \frac{I_m}{\pi}\left[-\cos\theta\right]_0^{\pi} = \frac{I_m}{\pi}\left[-1-(-1)\right]$$

$$I_{av} = \frac{2 I_m}{\pi} = 0.637 \, I_m$$

NOTE :- The Average value of an Alternating Current represented by a sine wave over one complete cycle is zero.

FORM FACTOR (K_f) :- The Form Factor of an Alternating quantity represented by a sinusoidal waveform is defined as the ratio of RMS value to its Average value.

$$\text{Form factor } K_f = \frac{\text{rms value}}{\text{Average value}} = \frac{I_{rms}}{I_{av}}$$

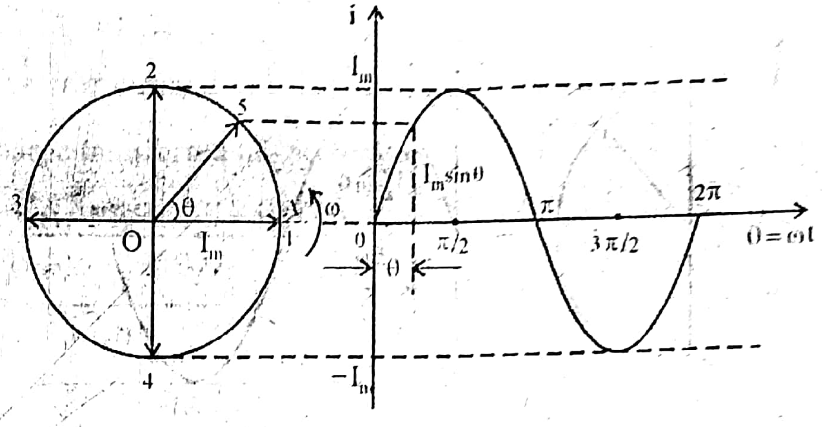
$$K_f = \frac{0.707 I_m}{0.637 I_m} = 1.11, \text{ for a sine wave.}$$

PEAK FACTOR (K_p) :- The Peak factor of an Alternating quantity represented by a sinusoidal waveform is defined as the ratio of Maximum value to its rms value.

$$\text{Peak Factor } K_p = \frac{\text{Maximum value}}{\text{rms value}} = \frac{I_m}{I_{rms}}$$

$$K_p = \frac{I_m}{0.707 I_m} = 1.414, \text{ for a sine wave.}$$

PHASE & PHASE - DIFFERENCE :



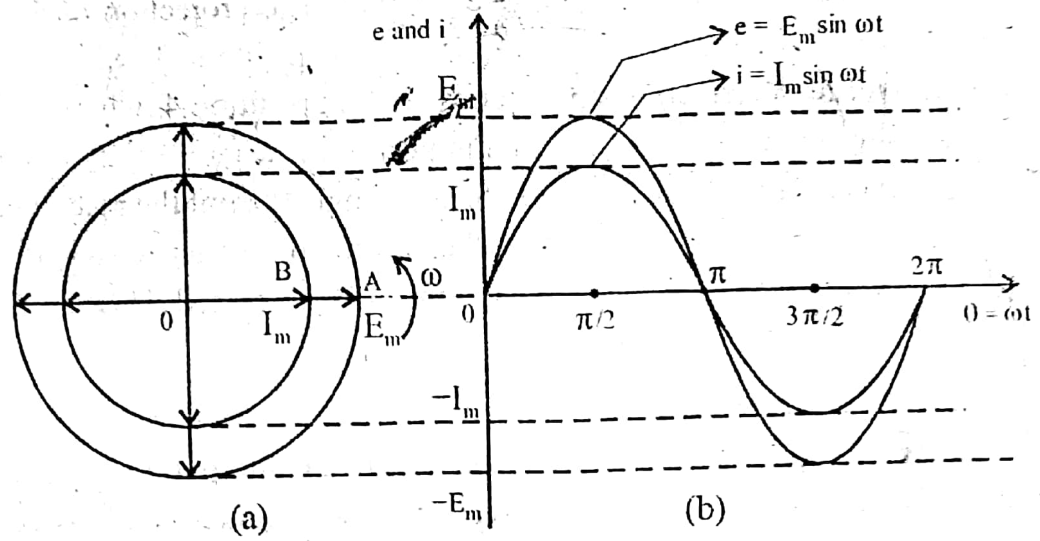
Defn : The phase of an Alternating quantity at any instant is the angle through which the Rotating Vector representing the alternating has rotated through, from the reference axis.

↳ At position-1, the phase is zero, At other instant, Say at position-5, the phase is 'θ'.

↳ The phase of the Alternating quantity varies from 0 to 2π.

PHASE - DIFFERENCE : The Phase difference between two alternating quantities is the angle difference between the two rotating vectors, representing the two alternating quantities.

IN- PHASE :



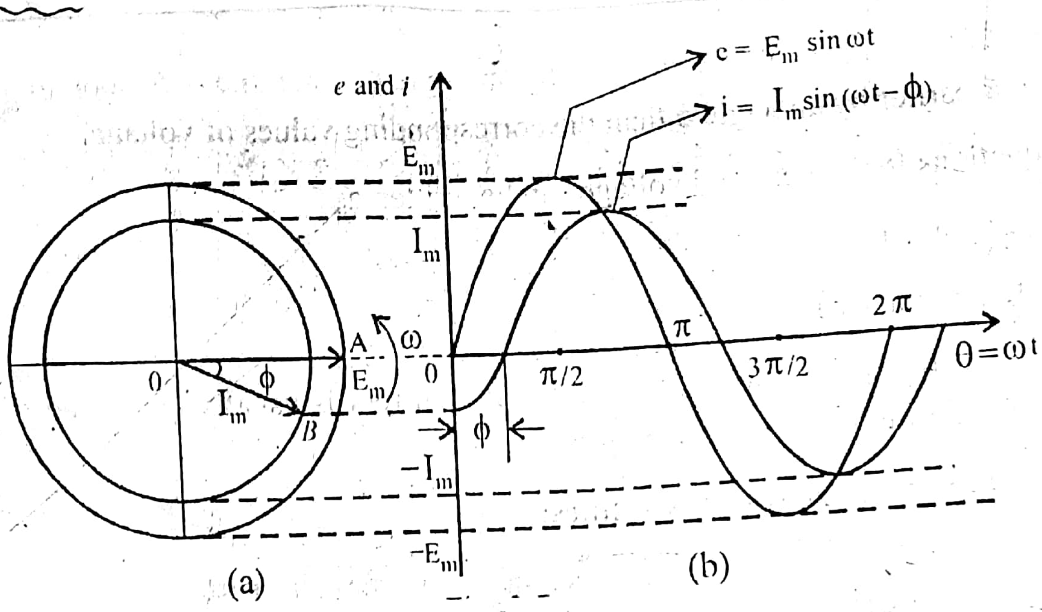
↳ Two Alternating quantities are said to be in phase with each other, when their corresponding values Occur at the same time.

↳ The voltage & current equations are,

$e = E_m \sin\omega t$

$i = I_m \sin\omega t.$

PHASE LAG :



(a) (b)

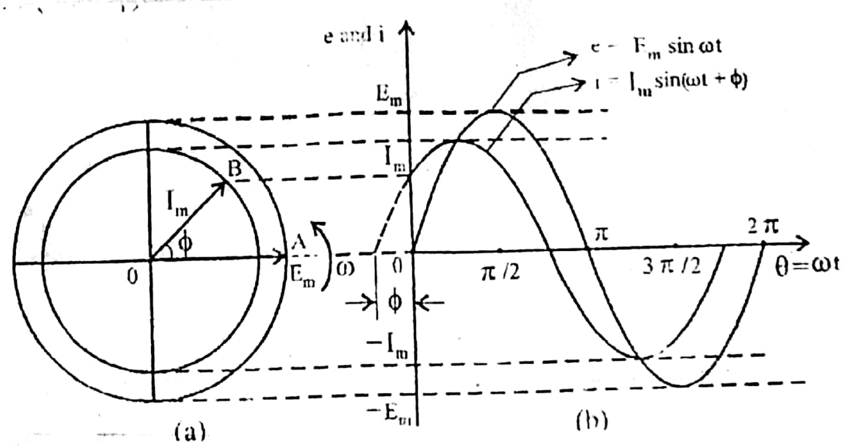
↳ The current is said to lag the voltage by an angle φ, when the corresponding values of current occur later by an angle φ, than the corresponding values of voltage.

↳ The current & voltage equns. are,

$e = E_m \sin\omega t$

$i = I_m \sin(\omega t - \phi)$.

PHASE - LEAD :



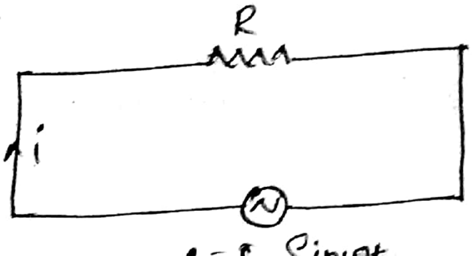
↳ The current is said to lead the voltage by an angle ϕ, when the corresponding values of current occur earlier by an angle ϕ than the corresponding values of voltage.

↳ The current & voltage eqns: are,

$$e = E_m \sin \omega t$$

$$i = I_m \sin(\omega t + \phi)$$

PURE RESISTANCE CIRCUIT (R) : By, Ohm's law



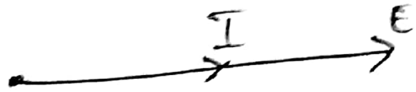
$i = \frac{e}{R}$

$i = \frac{E_m}{R} \sin\omega t = I_m \sin\omega t$

where $I_m = \frac{E_m}{R}$

↳ Comparing $e = E_m \sin\omega t$ & $i = I_m \sin\omega t$, the current is in phase with voltage.

↳ Vector representation,



Instantaneous Power } $P = ei = E_m \sin\omega t \cdot I_m \sin\omega t = E_m I_m \sin^2\omega t$

$P = \frac{E_m I_m}{2} [1 - \cos 2\omega t]$

$P = \frac{1}{2} E_m I_m - \frac{1}{2} E_m I_m \cos 2\omega t$.

The term $\frac{1}{2} E_m I_m \cos 2\omega t$ is a periodically varying quantity whose frequency is two times the frequency of the applied voltage & its Average value over a period is zero.

$\therefore P = \frac{1}{2} E_m I_m = \frac{E_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}}$

$\boxed{P = EI}$

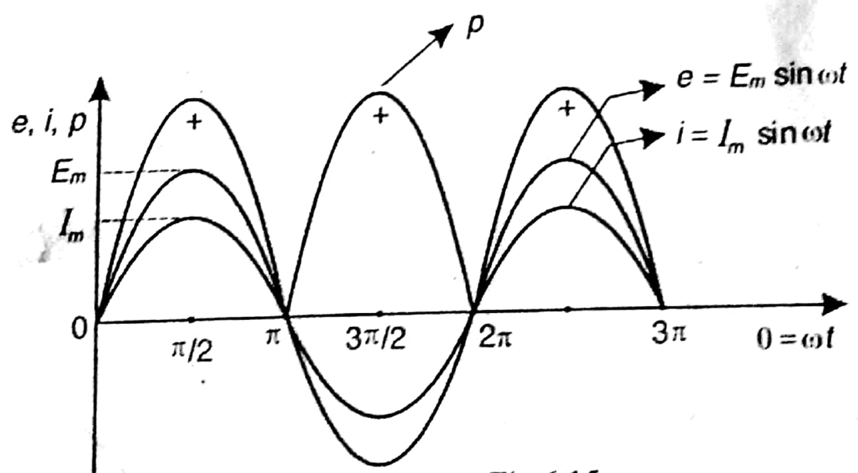


Fig.6.15

FORM FACTOR (K_f) : The form factor of an Alternating quantity represented by a Sinusoidal wave form is defined as the ratio of RMS value to its Average value.

$$\text{Form factor } K_f = \frac{\text{rms value}}{\text{Average value}} = \frac{I_{rms}}{I_{av}}$$

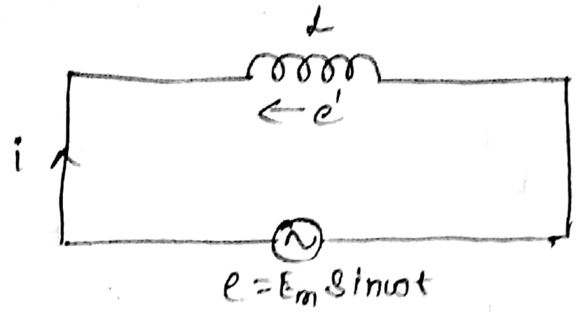
$$K_f = \frac{0.707\, I_m}{0.637\, I_m} = 1.11 \text{ for a Sine wave}$$

PEAK FACTOR (K_p) : The Peak factor of an Alternating quantity represented by a Sinusoidal wave form is defined as the ratio of its Maximum value to its rms value.

$$\text{Peak factor } K_p = \frac{\text{Maximum value}}{\text{rms value}} = \frac{I_m}{I_{rms}}$$

$$K_p = \frac{I_m}{0.707 I_m} = 1.414, \text{ for a Sine wave.}$$

PURE INDUCTANCE CIRCUIT (L) : An Alternating voltage $e = E_m \sin\omega t$ produces an alternating current i, which produces an alternating flux linking the coil, hence an EMF e' is induced in it, which opposes the applied voltage.



$\therefore e = E_m \sin\omega t$

$$e' = -L\frac{di}{dt} = -e \quad \therefore \boxed{e = L\frac{di}{dt}}$$

$$di = \frac{e}{L}dt = \frac{1}{L}E_m \sin\omega t \cdot dt$$

On Integration

$$i = \frac{E_m}{L}\int \sin\omega t \cdot dt$$

$$i = \frac{E_m}{\omega L}(-\cos\omega t)$$

$$i = \frac{E_m}{X_L}\sin(\omega t - \pi/2)$$

$$\boxed{i = I_m \sin(\omega t - \pi/2)}$$

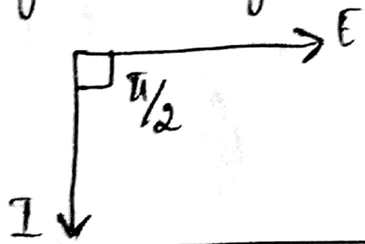
where, $I_m = \frac{E_m}{X_L}$

$X_L = \omega L = 2\pi f \cdot L$

$X_L \rightarrow$ Inductive reactance in ohms.

$\therefore$ Comparing $e = E_m \sin\omega t$ & $i = I_m \sin(\omega t - \pi/2)$, the current lags the voltage by an angle $\pi/2$.

↳ Vector representation



Instantaneous Power } $P = ei = E_m \sin\omega t . I_m \sin(\omega t - \pi/2)$

$= E_m I_m \sin\omega t . (-\cos 2\omega t)$

$$P = -\frac{1}{2} E_m I_m \sin 2\omega t$$

↳ The equation for 'P' is periodically varying & having a frequency two times the frequency of the applied voltage & whose average value is zero.

Hence the Power Consumed by Pure Inductance is zero ∴ $P = 0$

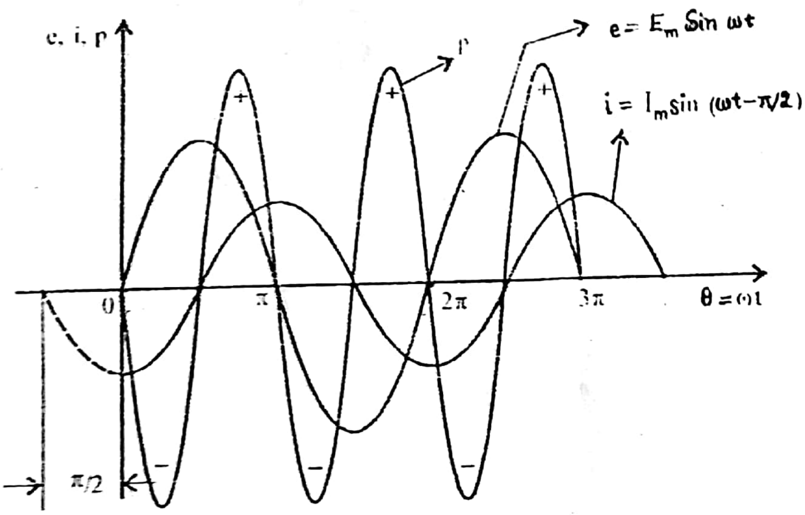
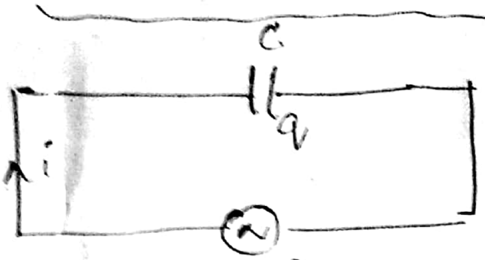


Fig.6.18

PURE CAPACITANCE CIRCUIT (C) : Consider a pure capacitance 'C' across which an Alternating voltage $e = E_m \sin\omega t$ is applied, due to which an alternating current flows.



$e = E_m \sin\omega t$

$$i = \frac{dq}{dt} = \frac{d[ce]}{dt} = C\,\frac{d[E_m \sin\omega t]}{dt}$$

$$= \omega C E_m \cos\omega t = \frac{E_m}{(1/\omega C)} \sin(\omega t + \pi/2) = \frac{E_m \sin(\omega t + \pi/2)}{X_c}$$

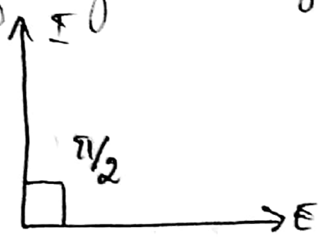
$$\boxed{i = I_m \sin(\omega t + \pi/2)}$$

where $I_m = \frac{E_m}{X_c}$ &

$X_c = \frac{1}{\omega C} = \frac{1}{2\pi f C}$ → capacitive reactance in ohms.

↳ Comparing $e = E_m \sin\omega t$ & $i = I_m \sin(\omega t + \pi/2)$, Current leads voltage by an angle $\pi/2$

↳ Vector Representation



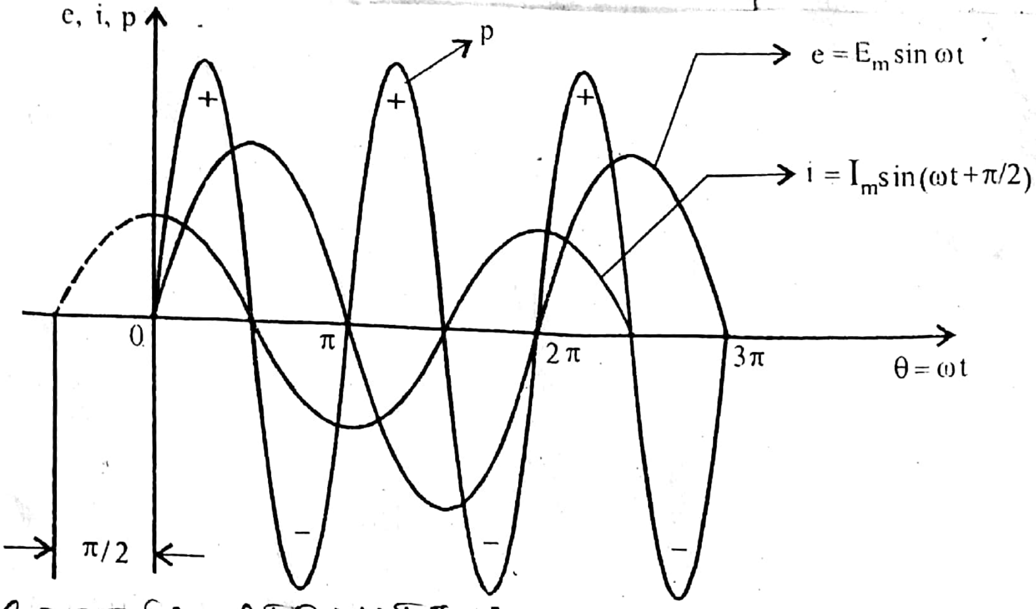
↳ Instantaneous Power $P = ei = E_m \sin\omega t \cdot I_m \sin(\omega t + \pi/2)$

$$= E_m I_m \sin\omega t \cdot \cos\omega t$$

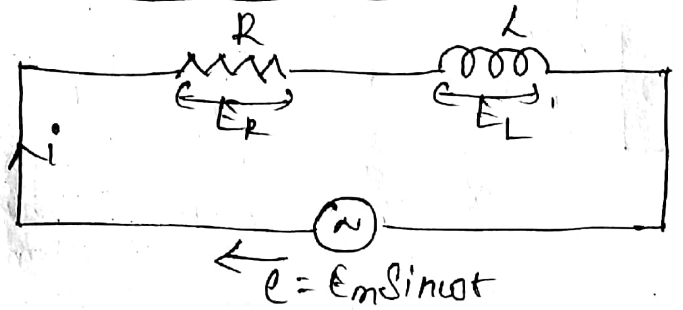
$$P = \frac{1}{2} E_m I_m \sin 2\omega t$$

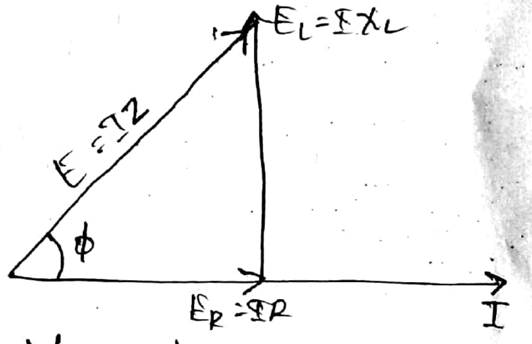
The equation for 'P' is periodically varying & having frequency two times the frequency of the applied voltage & whose Average value is zero.

Hence the Power consumed by pure Capacitance is zero $\therefore P = 0$



RL - SERIES CIRCUIT :-





Vector diagram

↳ From the Vector diagram

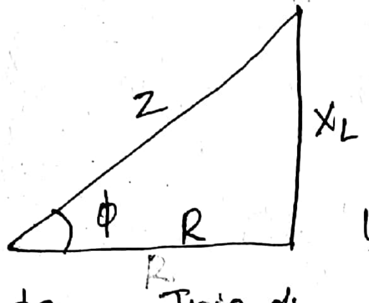
$E_R = IR$ → which is in phase with current.

$E_L = IX_L$ → which leads the current by 90°

$E = IZ$ → The vector sum of E_R & E_L

↳ $I = \frac{E}{Z}$ where $Z = \sqrt{R^2 + X_L^2}$

Z → Impedance of the circuit in Ohms.



Impedance Triangle

↳ Power factor angle } $\phi = \tan^{-1}\left(\frac{X_L}{R}\right)$

↳ Here the current lags the voltage by an angle ϕ i.e if $e = E_m \sin\omega t$ then $i = I_m \sin(\omega t - \phi)$

→ Instantaneous Power $p = e\,i = E_m \sin\omega t \cdot I_m \sin(\omega t - \phi)$

$$p = \frac{E_m I_m}{2}\left[\cos\phi - \cos(2\omega t - \phi)\right]$$

$$\therefore\ p = \frac{E_m I_m}{2}\cos\phi - \frac{E_m I_m}{2}\cos(2\omega t - \phi)$$

The second term is a periodically varying quantity whose frequency is two times the frequency of the applied voltage & its average value is zero.

$$\therefore\ P = \frac{1}{2} E_m I_m \cos\phi = \frac{E_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}} \times \cos\phi$$

$$\therefore\ \boxed{P = EI\cos\phi}$$

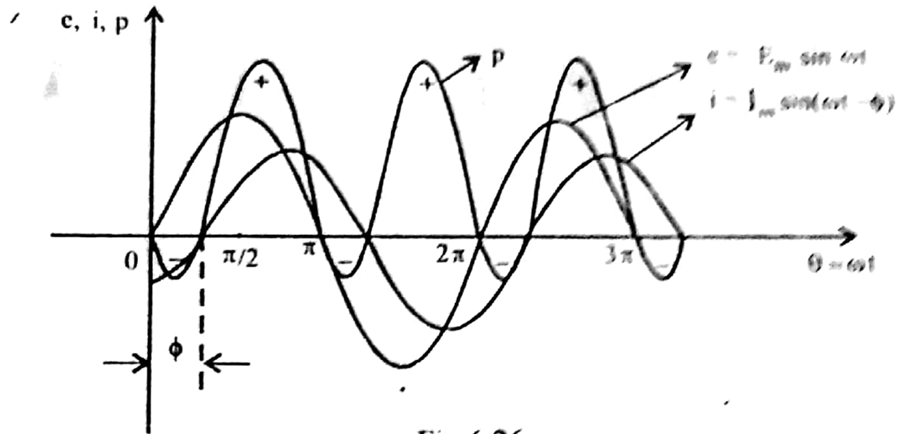
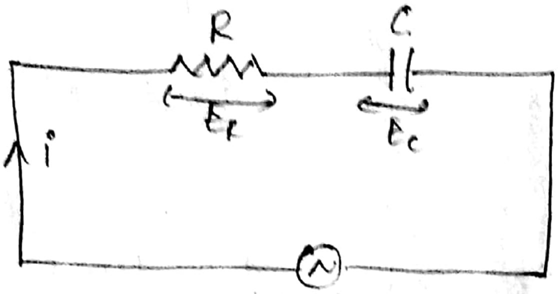
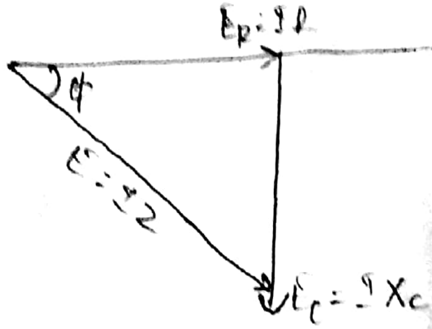


Fig.6.26

RC. SERIES CIRCUIT :



$e = E_m \sin\omega t$



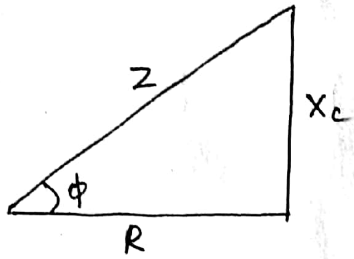
Vector diagram

From the Vector diagram

$E_R = IR$ → which is in phase with Current.

$E_C = IX_C$ → which lags the Current by 90°

$E = IZ$ → The Vector Sum of E_R & E_C.



Impedance Triangle

$I = \frac{E}{Z}$ where $Z = \sqrt{R^2 + X_C^2}$

Z → Impedance of the Circuit.

Power factor angle } $\phi = \tan^{-1}\left(\frac{X_C}{R}\right)$

↳ Here the Current leads the voltage by an angle 'ϕ' i.e if $e = E_m \sin\omega t$ then $i = I_m \sin(\omega t + \phi)$

↳ Instantaneous Power $P = e\,i = E_m \sin\omega t \cdot I_m \sin(\omega t + \phi)$

$= \frac{E_m I_m}{2}\left[\cos(-\phi) - \cos(2\omega t + \phi)\right]$

$\therefore P = \frac{1}{2} E_m I_m \cos\phi - \frac{1}{2} E_m I_m \cos(2\omega t + \phi)$

The Second term is a periodically varying quantity, whose frequency is two times the frequency of the applied voltage E, its average value is zero.

$\therefore P = \frac{1}{2} E_m I_m \cos\phi = \frac{E_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}} \times \cos\phi$

$\therefore$ $\boxed{P = EI \cos\phi}$

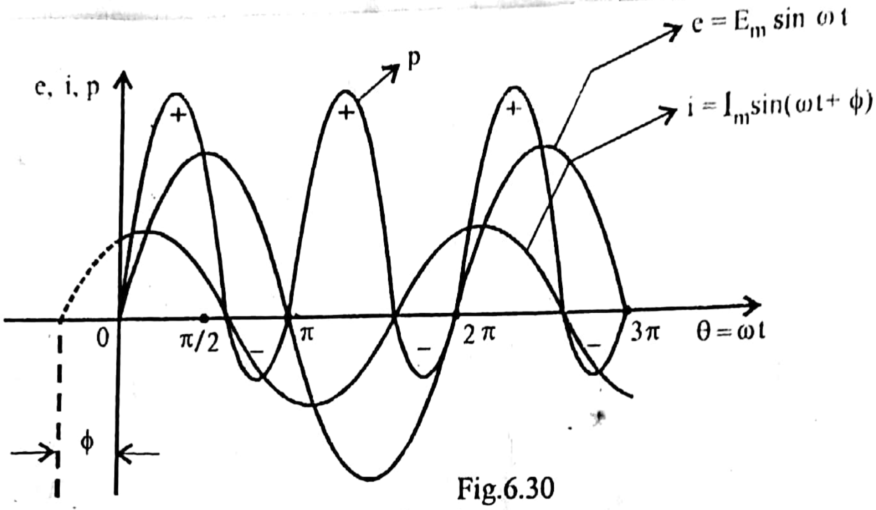
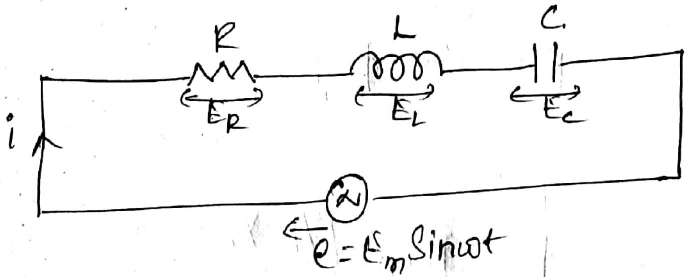


Fig.6.30

RLC - SERIES CIRCUIT :-



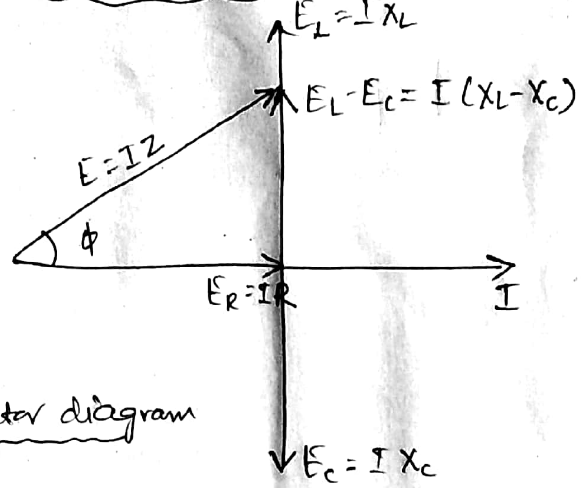
Three cases are discussed

(i) when $X_L > X_C$

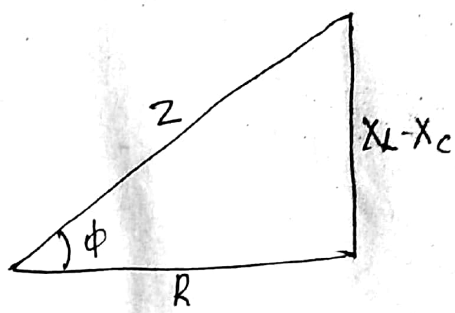
(ii) when $X_L < X_C$

(iii) when $X_L = X_C$

(i) when $X_L > X_C$:



Vector diagram



Impedance Triangle

↳ From the Vector diagram, the current lags the voltage by an angle 'ϕ'

$$I = \frac{E}{Z}$$

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

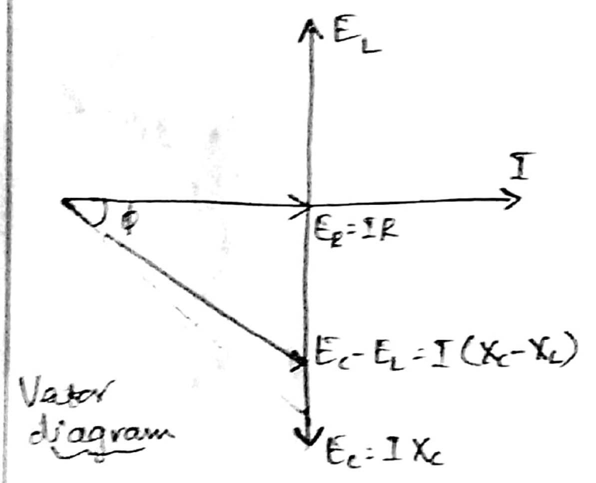
↳ The circuit is similar to an RL- Series circuit, i.e if $e = E_m \sin\omega t$ then $i = I_m \sin(\omega t - \phi)$

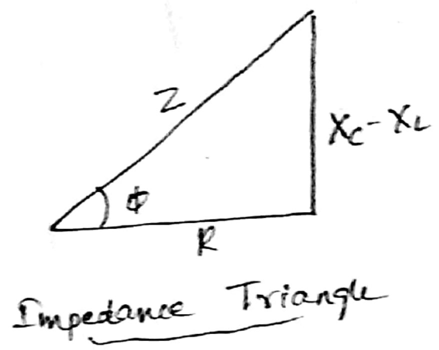
Hence $\boxed{P = EI\cos\phi}$

&

Power factor angle } $\phi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right)$

(ii) When $X_L < X_C$:





↳ From the vector diagram, current leads the voltage by an angle 'ϕ'

$$I = \frac{E}{Z}$$

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

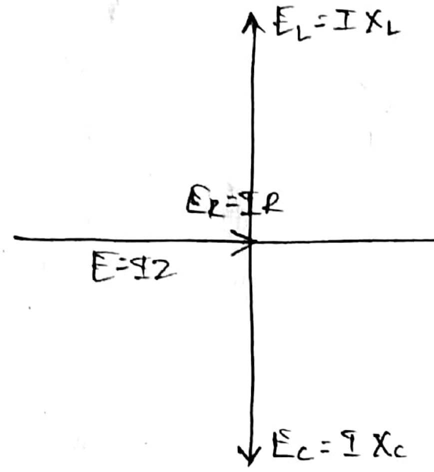
↳ ∴ The circuit is similar to an RC-Series Circuit, i.e if $e = E_m \sin \omega t$ then $i = I_m \sin(\omega t + \phi)$

Hence $\boxed{P = EI \cos\phi}$

&

Power factor angle } $\phi = \tan^{-1}\left(\frac{X_C - X_L}{R}\right)$

(iii) When $X_L = X_C$:- E_L & E_C get cancelled with each other i.e current is in phase with voltage & the circuit behaves as a pure resistance circuit



$\therefore Z = R$

i.e If $e = E_m \sin\omega t$ then $i = I_m \sin\omega t$

Hence $P = EI$

POWER FACTOR OF A CIRCUIT : Power factor of an A.C circuit is defined in 3-ways.

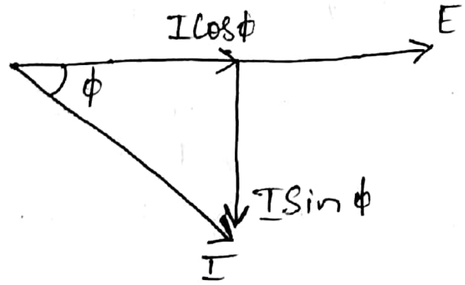
(i) $P.F = \cos\phi$ → Cosine of the angle between voltage & the current.

(ii) $P.F = \frac{R}{Z}$ → Ratio of Resistance to the Impedance of the circuit.

(iii) $P.F = \frac{P}{EI}$ → Ratio of Real power to the Apparent power.

The maximum value of Power factor is unity.

NOTE :



I Cosϕ → Inphase Component, which contributes to the Real power also known as "Real-component" or "Active Component" or "Wattfull Component"

I Sinϕ → The Quadrature component which does not contribute to Power consumed, also known as "Reactive component" or "Wattless Component"

$P = EI\cos\phi$ → Real Power in watts

$Q = EI\sin\phi$ → Reactive Power in Volt Amps

$S = EI$ → Apparent Power in Volt Amps.

PRACTICAL IMPORTANCE OF POWER FACTOR :

- The active power consumed by the load in an A.C circuit is given by $P = EI\cos\phi$. If the P.F of the load is small, the active power generated by an Alternator & the Active power transmitted & received by the consumer decreases.

- If the P.F is small, for transmitting a particular Power, the Current in the Transmission line increases & hence, the Copper losses (I^2R losses) will increase & the efficiency of Transmission decreases.

- Due to Low P.F, the current carrying capacity of the conductors has to be increased. Hence large sized conductors have to be used for transmission of Electrical power which involves larger investment.

- Hence, for the effective use of supplied energy, the supplying agencies insist on the customers to improve the P.F's of their loads to 0.85 to 0.90 by using static condensers across the load.

- The supplying agencies also give some incentive in the tariffs to the consumers for improving the P.F's of the loads.

THREE - PHASE CIRCUITS :

ADVANTAGES OF 3 - ϕ SYSTEMS :

(i) For the same capacity, a three apparatus costs less than a single phase apparatus.

(ii) The size of 3-ϕ apparatus is smaller in size than single phase apparatus of the same capacity & hence requires less material for construction.

(iii) For transmitting same amount of power over the same distance, under the same power loss, the amount of conductor material required is less in case of 3-ϕ system than in case of single phase system.

(iv) Three phase motors produce uniform torque whereas, the torque produced by single phase motors is pulsating.

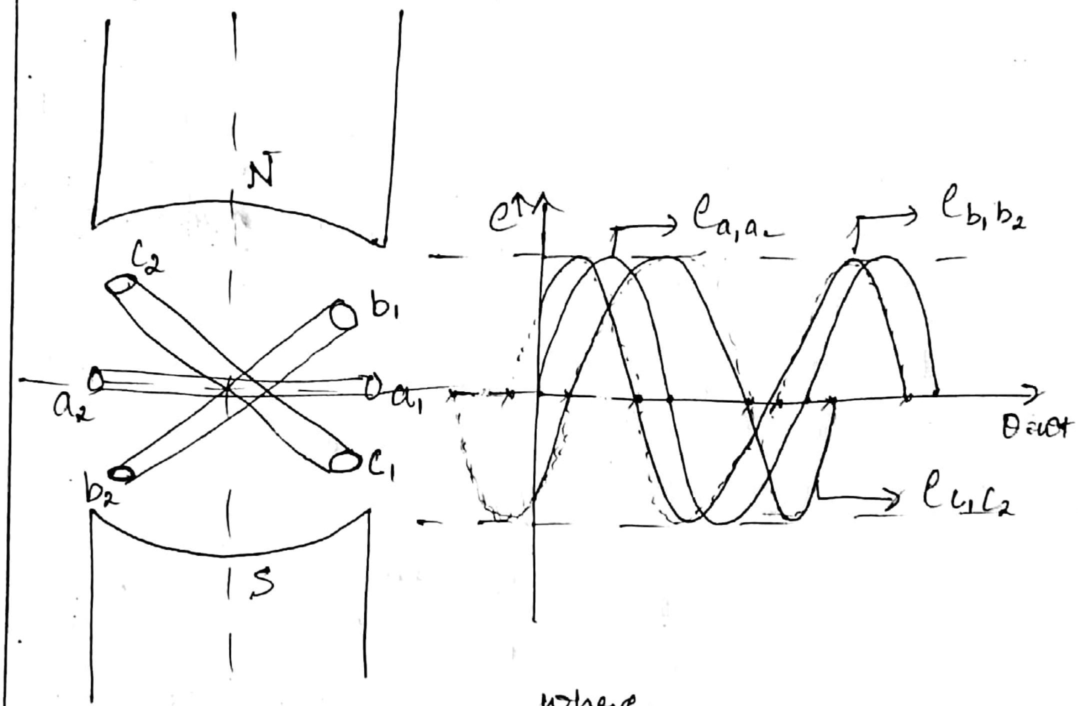
(v) Three phase motors are self starting whereas single phase motors are not self starting.

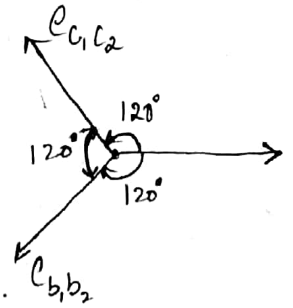
(vi) In case of 3-ϕ system, two different voltage can be obtained [line & phase] whereas only one voltage can be obtained in a single phase system.

(vii) The single phase generators in parallel give rise to harmonics, whereas 3-ϕ generators can be conveniently connected in parallel without giving rise to the generation of harmonics.

GENERATION OF 3-ϕ VOLTAGES :-

- In a 3-ϕ system, there are three equal voltages of same frequency displaced from one another by 120° electrically.
- These voltages are produced by a 3-ϕ generator which has 3-identical windings electrically displaced by 120°.





where,

$$e_{a_1a_2} = E_m \sin \omega t$$

$$e_{b_1b_2} = E_m \sin(\omega t - 120°)$$

$$e_{c_1c_2} = E_m \sin(\omega t - 240°)$$

- When these star connected or delta connected windings are rotated in a magnetic field, an EMF is induced in each of these windings.

↳ These EMFs are of same magnitude & frequency but are displaced by 120° from each other.

Explanation: when the 3-coils a_1a_2, b_1b_2 & c_1c_2 are rotated under the influence of a Magnetic field then three EMFs are induced $e_{a_1a_2}$, $e_{b_1b_2}$ & $e_{c_1c_2}$, which are displaced by 120° with each other.

PHASE SEQUENCE:- The phase sequence of the three phase supply is the order in which maximum values of the three phase voltages occurs

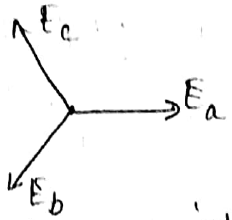


FIG:- Phase Sequence 'abc'

$E_a = E \angle 0^\circ$ V

$E_b = E \angle -120^\circ$ V

$E_c = E \angle +120^\circ$ V

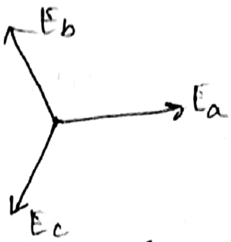


FIG:- Phase Sequence 'acb'.

$E_a = E \angle 0^\circ$ V

$E_c = E \angle 0^\circ$ V

$E_b = E \angle +120^\circ$ V

↳ In the above fig, Three phase voltages occur in the order abc, hence the phase sequence of the supply is abc.

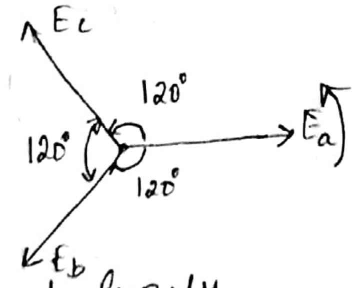
↳ By convention, RYB is considered positive & RBY is negative.

SIGNIFICANCE OF PHASE SEQUENCE :

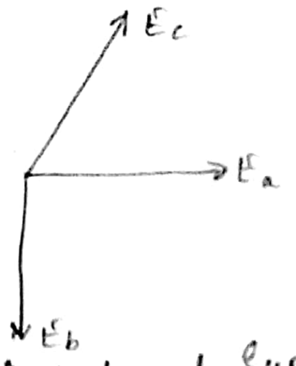
(i) When a three phase supply of a Particular Sequence is given to a Static three phase load, Certain currents flow through the lines & Phases of the load.
If the Phase Sequence is changed, then both magnitude & phase of the currents flowing in the lines & phases of the load will change.

(ii) If the load is a 3-phase Induction motor, when the sequence of the Supply is changed, not only the magnitudes & Phases of line current change, but the direction of rotation of the motor changes.

BALANCED THREE PHASE SUPPLY : A three phase supply is said to be Balanced, when all three voltages differ in phase by 120° w.r.t one another.
↳ The three phase supply is said to be Un-balanced, even if one of the above conditions is not satisfied.

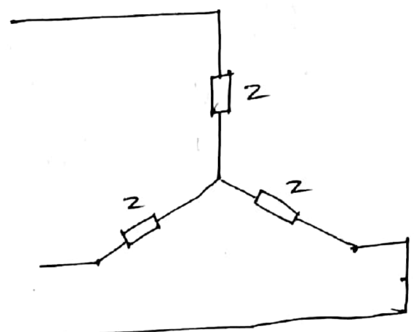


Balanced Supply

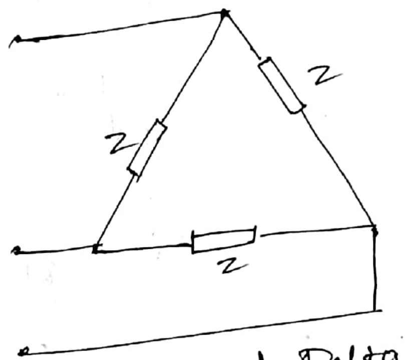


Un-balanced Supply.

BALANCED LOAD : A three phase load is said to be balanced, when impedances of all three phases are exactly the same.



3-ϕ Balanced Star Connected Load.



3-ϕ Balanced Delta connected load.

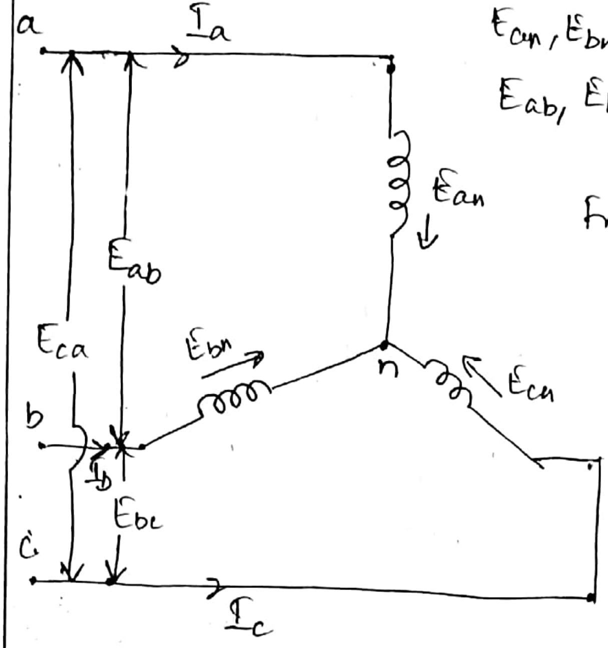
In a three phase Balanced Load, wheather Star or Delta connected the magnitudes of Phase Currents are the same but differ by 120° w.r.t each other, when a Balanced three phase supply is given.

THREE - PHASE CONNECTIONS : There are two types of three phase connections

(i) Star Connection.

(ii). Delta Connection.

(i) STAR CONNECTION (Y)



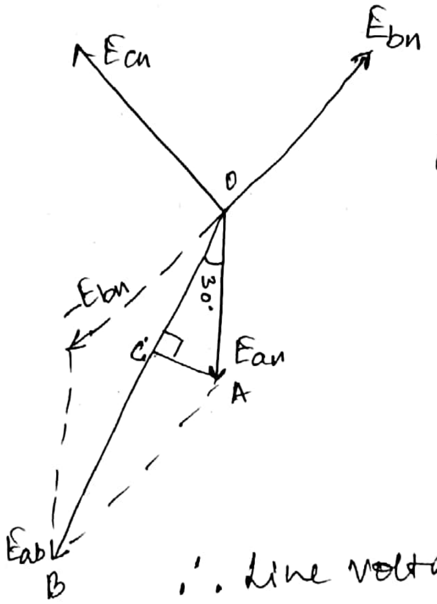
E_{an}, E_{bn} & $E_{cn} \rightarrow$ Phase Voltages $= E_{ph}$

E_{ab}, E_{bc} & $E_{ca} \rightarrow$ Line Voltages $= E_L$

From the circuit,

Line Current = Phase Current

$I_L = I_{ph}$



Draw a Perpendicular AC on OB,

From Δ^{le} AOC,

$$\cos 30^\circ = \frac{OC}{OA} = \frac{OB/2}{OA}$$

$$OB = 2 \times OA \times \cos 30^\circ$$

$$E_{ab} = 2 \times E_{an} \times \sqrt{3}/2$$

$$\boxed{E_L = \sqrt{3}\, E_{ph}}$$

$\therefore$ Line voltage $= \sqrt{3} \times$ Phase voltage.

↳ Power consumed by 3-phase circuit

$$P = 3 \times \text{Power in each phase}$$

$$= 3 \times E_{ph} I_{ph} \cos\phi = 3 \times \frac{E_L}{\sqrt{3}} \times I_L \times \cos\phi$$

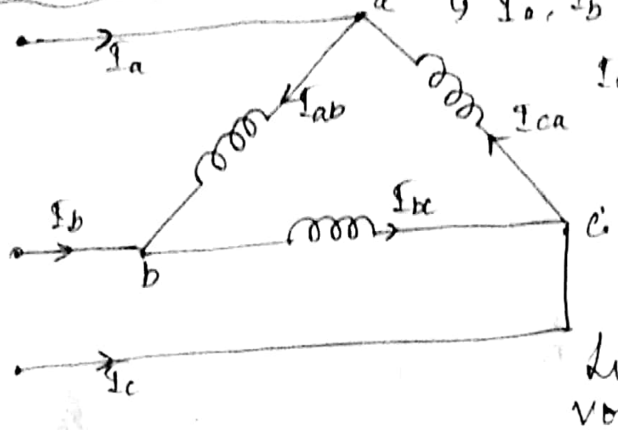
$$\boxed{P = \sqrt{3}\, E_L I_L \cos\phi}$$

where ϕ = Angle b/w E_{ph} & I_{ph}

DELTA CONNECTION (Δ) :

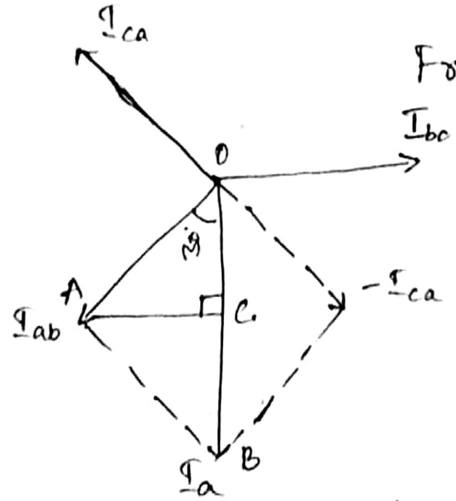
I_a, I_b & I_c → Line Currents } $= I_L$

I_{ab}, I_{bc} & I_{ca} → Phase currents } $= I_{ph}$



Line voltage } = phase voltage

$E_L = E_{ph}$



From Δ^le AOC,

$$\cos 30^\circ = \frac{OC}{OA} = \frac{OB/2}{OA}$$

$$OB = 2 \times OA \times \cos 30^\circ$$

$$I_a = 2 \times I_{ab} \times \frac{\sqrt{3}}{2}$$

$$\boxed{I_L = \sqrt{3}\, I_{ph}}$$

∴ Line current = $\sqrt{3}$ Phase current.

Power Consumed by 3-phase Circuit,

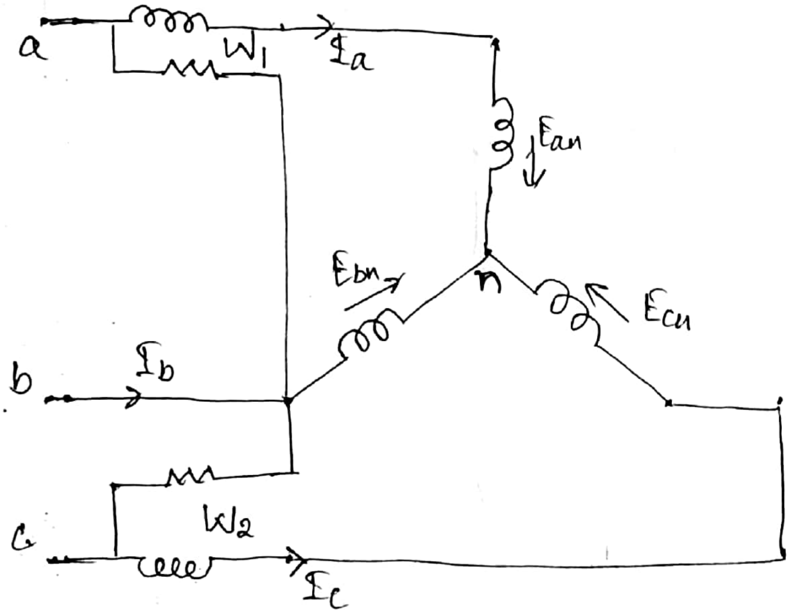
P = 3 × Power in each phase

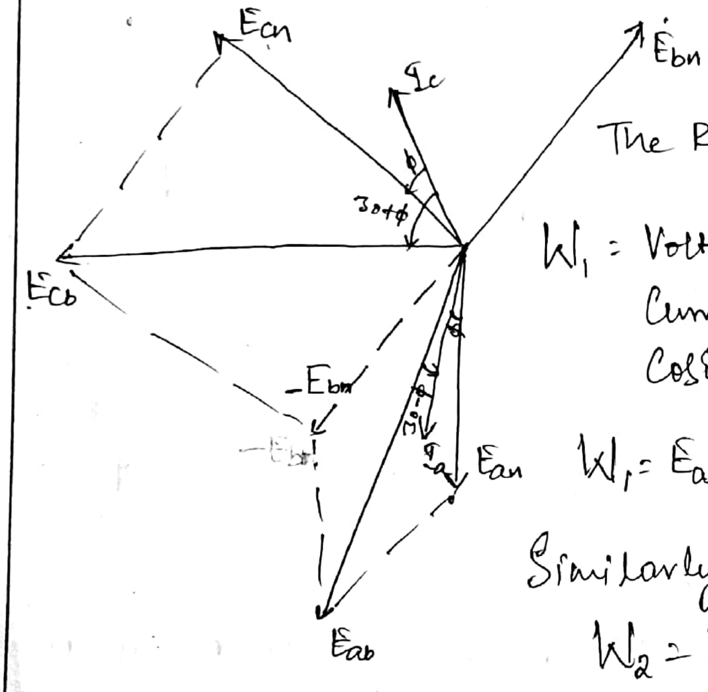
$$= 3 \times E_{ph} I_{ph} \cos\phi = 3 \times E_L \times \frac{I_L}{\sqrt{3}} \times \cos\phi$$

$$\boxed{P = \sqrt{3}\, E_L I_L \cos\phi}$$

where ϕ = Angle b/n E_{ph} & I_{ph}

MEASUREMENT OF POWER IN THREE PHASE CIRCUIT [TWO WATTMETER METHOD] :





The Reading of Wattmeter-1 is,

W_1 = Voltage across potential coil × Current through current coil × Cosine of angle b/n voltage & current.

$W_1 = E_{ab} I_a \cos\{\angle E_{ab} \text{ \& } \angle I_a\}$

Similarly,

$W_2 = E_{cb} I_c \cos\{\angle E_{cb} \text{ \& } \angle I_c\}$

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Assuming an Inductive load, I_a lags E_{an} by an angle ϕ. Hence the angle b/n E_{ab} & I_a is $(30-\phi)$

$$\therefore W_1 = E_{ab} I_a \cos(30-\phi)$$

$$W_1 = E_L I_L \cos(30-\phi) \quad \ldots\ldots (a)$$

Similarly, I_c lags E_{cn} by an angle ϕ, Hence the angle b/n E_{cb} & I_c is $(30+\phi)$.

$$\therefore W_2 = E_{cb} I_c \cos(30+\phi)$$

$$W_2 = E_L I_L \cos(30+\phi) \quad \ldots\ldots (b)$$

Adding equns. (a) & (b),

$$W_1 + W_2 = E_L I_L \left[\cos(30-\phi) + \cos(30+\phi)\right]$$

$$= E_L I_L \times 2 \cos 30 . \cos\phi$$

$$\therefore \boxed{W_1 + W_2 = \sqrt{3}\, E_L I_L \cos\phi = \text{Three phase Power.}}$$

Expression for Power factor (P.f) :

w.k.t $\quad W_1 = E_L I_L \cos(30-\phi)$

$\quad W_2 = E_L I_L \cos(30+\phi)$

$$W_1 - W_2 = E_L I_L \left[\cos(30-\phi) - \cos(30+\phi)\right]$$

$$= E_L I_L \times 2 \sin 30 . \sin\phi$$

$$\therefore W_1 - W_2 = E_L I_L \sin\phi \quad \ldots\ldots (a)$$

w.k.t $\quad W_1 + W_2 = \sqrt{3}\, E_L I_L \cos\phi \quad \ldots\ldots (b)$

$\frac{\text{equn } (a)}{\text{equn } (b)}$ is $\frac{W_1 - W_2}{W_1 + W_2} = \frac{\tan\phi}{\sqrt{3}}$

$$\tan\phi = \sqrt{3}\left[\frac{W_1 - W_2}{W_1 + W_2}\right]$$

$$\therefore \phi = \tan^{-1}\left\{\sqrt{3}\left[\frac{W_1 - W_2}{W_1 + W_2}\right]\right\}$$

$$\therefore P.f = \cos\phi = \cos\left[\tan^{-1}\left\{\sqrt{3}\left(\frac{W_1 - W_2}{W_1 + W_2}\right)\right\}\right]$$

EFFECT OF POWER FACTOR (P.f) ON WATTMETER READINGS (W_1 & W_2) :

Case (i) : when P.f = 1 i.e $\phi = 0°$

$W_1 = E_L I_L \cos(30-\phi) = E_L I_L \cos(30-0) = \sqrt{3}/2 \, E_L I_L$

$W_2 = E_L I_L \cos(30+\phi) = E_L I_L \cos(30+0) = \sqrt{3}/2 \, E_L I_L$

∴ The two Wattmeter readings are positive & equal.

Case (ii) : when P.f = 0.5 i.e $\phi = 60°$

$W_1 = E_L I_L \cos(30-\phi) = E_L I_L \cos(30-60) = \sqrt{3}/2 \, E_L I_L$

$W_2 = E_L I_L \cos(30+\phi) = E_L I_L \cos(30+60) = 0$

∴ One of the Wattmeter reads zero.

Case (iii) : when P.f = 0 i.e $\phi = 90°$

$W_1 = E_L I_L \cos(30-\phi) = E_L I_L \cos(30-90) = \frac{1}{2} E_L I_L$

$W_2 = E_L I_L \cos(30+\phi) = E_L I_L \cos(30+90) = -\frac{1}{2} E_L I_L$

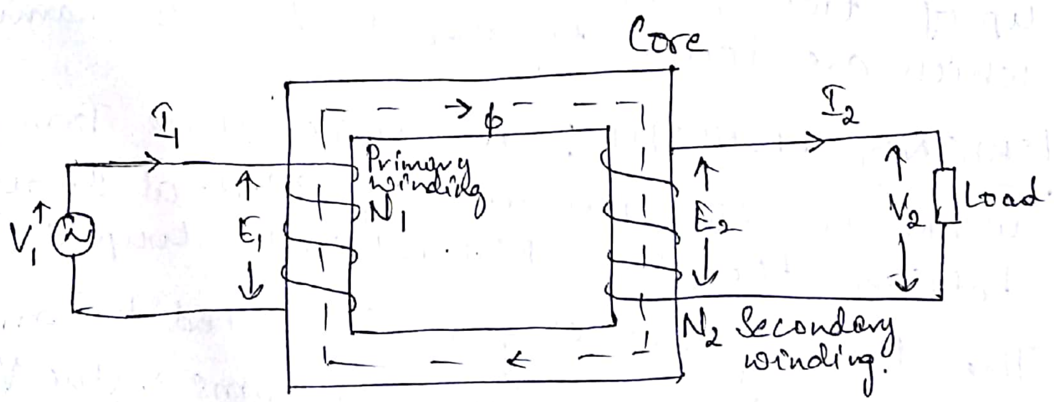
∴ One of the Wattmeter reads -ive. The pointer of the wattmeter kicks back & hence readings cannot be taken.

TRANSFORMERS :

① Introduction : A Transformer is a Static Electrical device, which transfers Electrical power from One Electrical Circuit to the other, which are Magnetically Coupled together with or without change of Voltage & Current and without any change of Power & frequency.

↳ The Transformer is a Static apparatus & has no moving apparatus, hence there are no Mechanical losses. Hence the efficiency of a Transformer is very high of the order of 95 to 98%.

CONSTRUCTION :



A Single phase Transformer consists of 2-parts
(i) Windings.
(ii) Core.

↳ The windings are made of copper because they possess very small resistance. The winding which is connected to the supply is called primary winding & the one which is connected to the load is called secondary winding.
The primary winding has N_1 number of turns & secondary has N_2 number of turns.

↳ The core is made up of silicon steel which has high relative permeability & low hysteresis co-efficient. The core is laminated to reduce eddy current losses.
For small transformers each lamination is a single piece. For large transformers each section is made up of two or more sections of E, T or L shaped, which are joined together to form the lamination.

WORKING PRINCIPLE: A single phase transformer works on the principle of mutual induction between the two magnetically coupled coils.

↳ The primary winding is connected to an alternating voltage source of rms value V_1 volts, hence an alternating current I_1 flows through the primary winding & sets up an alternating flux 'ϕ' in the transformer core which links both primary & secondary winding. Therefore an EMF 'E_1' is induced in the primary winding & an EMF 'E_2' is induced in the secondary winding.

w.k.t $e_1 = -N_1 \frac{d\phi}{dt}$ & $e_2 = -N_2 \frac{d\phi}{dt}$

$$\therefore \frac{e_2}{e_1} = \frac{N_2}{N_1} = \frac{E_2}{E_1}$$

$$\therefore \frac{E_2}{E_1} = \frac{N_2}{N_1} = 'K' \text{ Transformation Ratio.}$$

Power i/p to the Primary winding = Power o/p from the Secondary winding.

$$E_1 I_1 = E_2 I_2$$

$$\therefore \frac{E_2}{E_1} = \frac{I_1}{I_2} = K$$

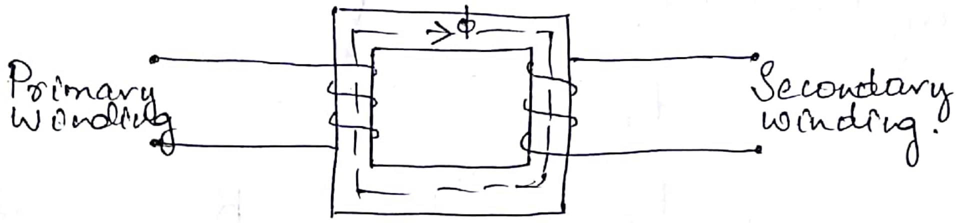
$$\therefore \boxed{\frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K}$$

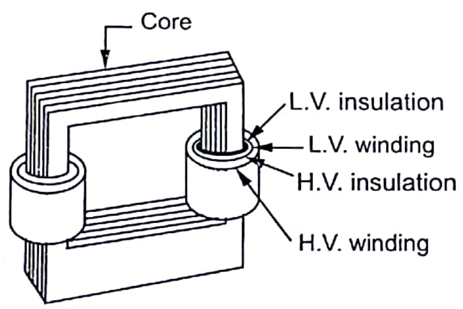
or

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

TYPES OF TRANSFORMERS : Depending on the way in which Primary & Secondary windings are wound on the Core, The Transformers are classified into two types (i) CORE TYPE
(ii) SHELL TYPE

(i) **CORE TYPE TRANSFORMERS** : The Primary & Secondary windings are connected on Seperate limbs to reduce the Leakage flux.



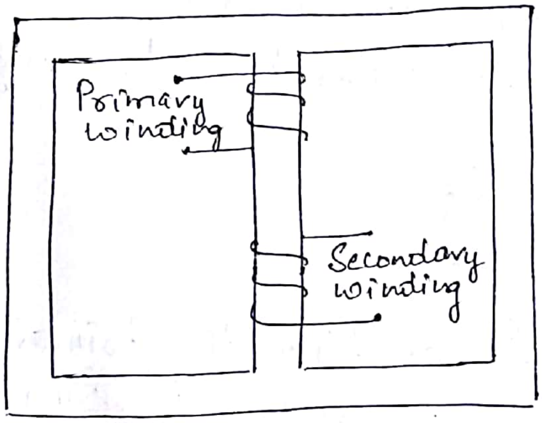


(b) Construction

↳ The Core may be Circular or Rectangular oval, In practice, One Half of the Primary winding & One half of the Secondary winding are placed Concentrically On One limb, the low voltage One nearer to the core.

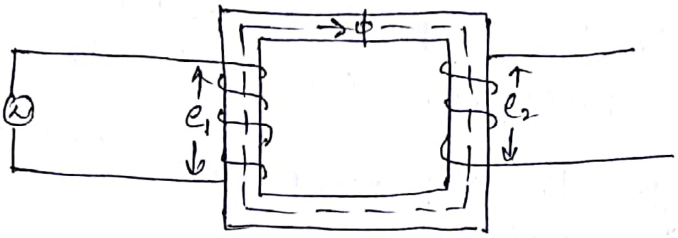
- The Core is always laminated to reduce the eddy current loss. For small sized Transformers the Core is Rectangular in Shape but for Large Size Transformers Cruciform Core is used.
- The core type Transformers are used to handle low & Medium voltages.

SHELL TYPE TRANSFORMERS : - The Primary and Secondary windings are located on central limb.



- The coils are wound as Multilayer disc type in the form of Pancake.
- Such Multilayer discs are insulated from each other by Paper.
- The core is rectangular in Shape & is laminated to reduce eddy current losses.
- The choice of core for shell type Transformer depends on Voltage rating, KVA rating, weight, Insulation Stress, Heat distribution etc.
- Shell type Transformers are used for handling very high voltages.

EMF Equation of a Transformer :



↳ When an Alternating voltage $V = V_m \sin\omega t$ of rms Value $V_1 = \frac{V_m}{\sqrt{2}}$ is applied to the Primary winding of the Transformer, the Alternating current produces an alternating flux 'ϕ', which links both Primary and Secondary winding.

w.k.t $\quad e_1 = -N_1 \frac{d\phi}{dt}$

$\phi = \phi_m \sin\omega t$. Since the Primary applied voltage is Sinusoidal.

$\therefore e_1 = -N \frac{d[\phi_m \sin\omega t]}{dt}$

$= -\omega N_1 \phi_m \cos\omega t$

$e_1 = 2\pi f N_1 \phi_M \sin(\omega t - 90^\circ)$ $\quad \{ -\cos\omega t = \sin(\omega t - 90^\circ) \}$

∴ The Magnitude of the Maximum value of Induced EMF in Primary winding is

$E_{m1} = 2\pi f N_1 \phi_M$

∴ The rms value of Induced EMF in the Primary winding is $\} \; E_1 = \frac{E_{m1}}{\sqrt{2}}$

$$E_1 = \frac{2\pi f N_1 \phi_m}{\sqrt{2}}$$

$$\therefore \boxed{E_1 = 4.44 f \phi_m N_1}$$

Similarly rms value of EMF induced in the secondary winding is

$$\boxed{E_2 = 4.44 f \phi_m N_2}$$

$$\therefore \frac{E_2}{E_1} = \frac{N_2}{N_1} = \text{'K' Transformation Ratio.}$$

or

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} \rightarrow$$ EMF induced per turn in both Primary & Secondary winding.

LOSSES IN A TRANSFORMER:- The losses that occur in a Transformer are

(i) Iron loss
(ii) Copper loss

(i) **IRON LOSS (W_i)** : It is called as core loss as it occurs in the core portion of the Transformer.

Iron loss is of 2-types,
(a) Eddy Current loss (W_e)
(b) Hysteresis loss (W_h)

(a) ↳ The Eddy Current loss (W_e) occurs due to flow of eddy currents in the laminations of the core.

↳ The Eddy currents are induced in the laminations because of the alternating flux produced by Primary winding links them.

↳ These eddy currents cause power loss in the core of the Transformer by heating up the core.

↳ The Eddy current loss is given by the 'Empirical formula'

$$W_e = \beta B_m^2 f^2 t^2 V \text{ watts}$$

where, W_e = Eddy current loss in watts

B_m = Maximum value of flux density in the core (Wb/m^2)

f = Supply frequency (Hz)

t = Thickness of the laminations (m)

V = Volume of the core (m^3)

β = A constant, which depends on the Magnetic material in the core.

NOTE: To keep the Eddy current loss as small as possible, the core is made of thin laminations of High Permeability magnetic material, such as Silicon Steel & they are insulated from one another by coating them with Varnish or an Oxide layer.

(b) Hysteresis loss : Since the flux in a Transformer core is alternating, therefore, power is required for the continuous reversal of the molecular magnets, which compose the core. This power is dissipated in the form of heat & is known as Hysteresis loss.

It is given by empirical formula,

$$W_h = \eta B_m^{1.6} f V \text{ watts}$$

where, W_h = Hysteresis loss in watts

B_m = Maximum value of Flux density (wb/m^2)

f = Supply frequency (Hz)

V = Volume of the Core (m^3)

η = A constant, which depends on the Magnetic Material in the Core.

IRON LOSS = EDDY CURRENT LOSS + HYSTERESIS LOSS

$$W_i = W_e + W_h$$

$$W_i = \left(\beta B_m^2 f^2 t^2 V + \eta B_m^{1.6} f V\right) \text{ watts.}$$

(ii) COPPER LOSS :- (W_{cu}) This loss is due to the Resistances R_1 & R_2 of the Primary & Secondary windings respectively.

∴ Total Copper loss = Copper loss in Primary + Copper loss in Secondary.

$$W_{cu} = I_1^2 R_1 + I_2^2 R_2 \text{ watts}$$

$$= I_1^2 R_1 + I_1^2 R_2'$$

$$W_{cu} = I_1^2 (R_1 + R_2') = I_1^2 R_{01}$$

or

$$W_{cu} = I_2^2 (R_2 + R_1') = I_2^2 R_{02}$$

The copper loss depends on the currents I_1 & I_2, which vary with load. Hence the copper loss in the Transformer is a variable loss.

EFFICINCY OF A TRANSFORMER : The efficiency of a Transformer at any load & Power factor is defined as the Ratio of the Power Output at the Secondary to the Power i/p at the Primary winding.

$$\text{Efficiency } \eta = \frac{\text{Power o/p in watts}}{\text{Power i/p in watts}}$$

Power I/p $= V_1 I_1 \cos\phi$

where, V_1 = Primary applied voltage
I_1 = Primary current.
$\cos\phi_1$ = Power factor of the Primary

$$\eta = \frac{\text{Input} - \text{losses}}{\text{Input}} = \frac{\text{Input} - \text{Copper loss} - \text{Iron loss}}{\text{Input}}$$

$$\eta = \frac{V_1 I_1 \cos\phi - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi}$$

$$\eta = 1 - \frac{I_1 R_{01}}{V_1 \cos\phi_1} - \frac{W_i}{V_1 I_1 \cos\phi}$$

Efficiency is Maximum, when $\frac{d\eta}{dI_1} = 0$

$$\frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 \cos\phi_1} + \frac{W_i}{V_1 I_1^2 \cos\phi_1} = 0$$

$$\frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1}$$

$$W_i = I_1^2 R_{01} = I_2^2 R_{02}$$

$\therefore W_i = W_{cu}$

i.e **Iron Loss = Copper Loss** is the Condition for Maximum efficiency of a Transformer

Consider, $W_i = I_2^2 R_{02}$

$$I_2 = \sqrt{\frac{W_i}{R_{02}}}$$

is the load current for which efficiency is maximum.

The KVA of the TRANSFORMER at which 'MAXIMUM EFFICIENCY' occurs is derived as follows:

Let, W_i = Iron loss of the Transformer.
W_{cu} = Full load copper loss.

w.k.t $W_{cu} \propto (\text{Full load KVA})^2$ ....(a)

Let, x = KVA o/p at which efficiency is maximum.

At x KVA, $W_i = W_{cu}$

$\therefore W_i \propto x^2$ ......(b)

Comparing equns (a) & (b)

$$\left(\frac{x}{\text{Full load KVA}}\right)^2 = \frac{W_i}{W_{cu}}$$

$$\therefore x = \text{Full-load KVA}\sqrt{\frac{W_i}{W_{cu}}} = \text{Full load KVA}\sqrt{\frac{\text{Iron loss}}{\text{Full load Cu-loss}}}$$

NOTE : The efficiency at any load & P.f is given by,

$$\eta_x = \frac{x \times KVA \times 1{,}000 \times P.f}{(x \times KVA \times 1{,}000 \times P.f) + (W_i) + (x^2 W_{cu})}$$

where, x = Load, expressed as a fraction of full load.

$x = 1$, for full load

&

$x = 1/2$, for Half full load.

DOMESTIC WIRING :-

SERVICE MAINS :-

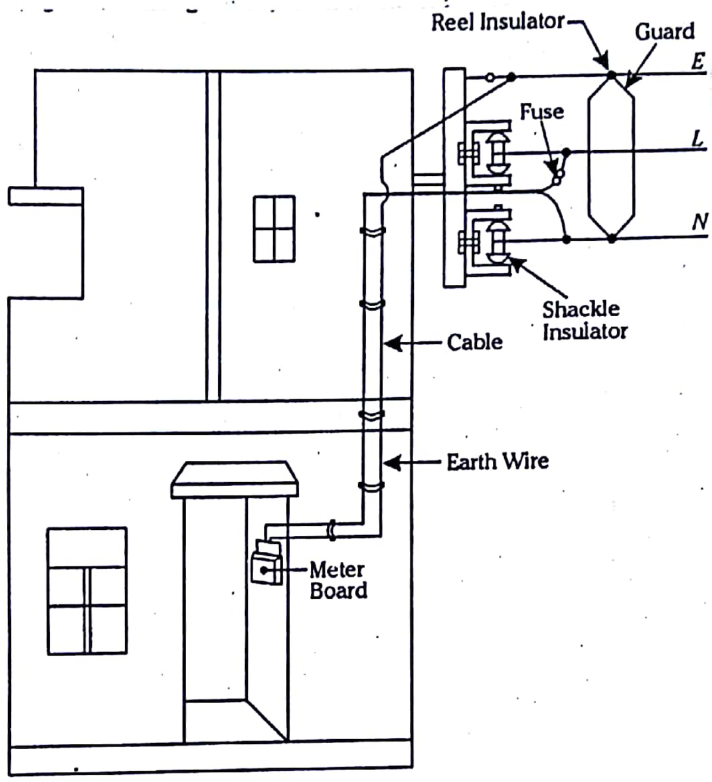


Fig. 3.81 : Service connections with PVC or weather proof cables

- Line bringing power from Suppliers distribution System to Consumer premises [energy meter] is called Service connection (or) Service main.
- Can be achieved by means of Underground Cables or by means of Overhead Conductors.
- Overhead with PVC Cables or Weather proof cables.

Construction : Bare conductors are run from the suppliers pole to shackle insulators fitted to brackets fixed on a cross arm, embedded into the wall of a two storeyed building at an appropriate height.

METER BOARD & DISTRIBUTION BOARD :-

↳ Meter board is connected to consumer internal wiring

↳ Supply authority has to charge the consumer for the electrical energy consumed. Hence it is connected to energy meter.

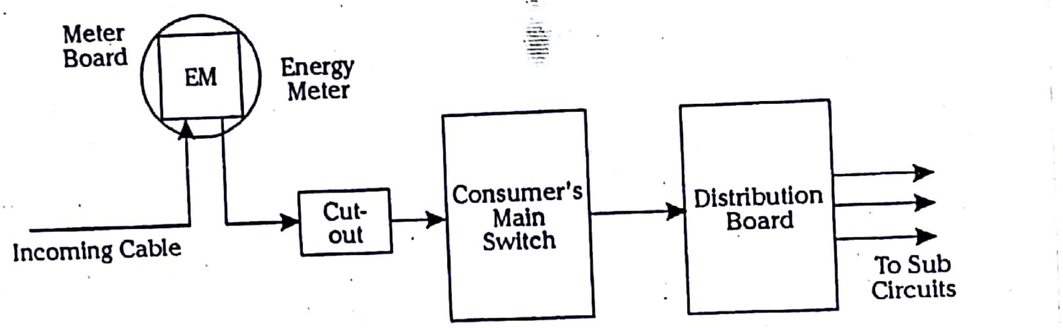


Fig. 3.82 : Block diagram of the meter board and the distribution board

↳ The cut-out contains a fuse wire so that if the consumer draws more current than the rated current of the meter, the fuse will blow off, thus preventing damage to the meter.

↳ The cut-out & meters are the supply authority's property.

↳ The energy meter should be installed at such a place where it is readily accessible to both the consumer & the supply authority.

- The energymeter should be provided with a protective covering enclosing it completely & a glass window through which readings can be taken.
- Fuses should be provided to interrupt any short circuit current that may occur.

The type of Wiring to be adopted for taking electrical connections from the Supply agency depends on various factors.

Important factors to be considered are,

(a) Durability
(b) Saftey
(c) Appearence
(d) Cost
(e) Accessebility
(f) Maintainance Cost.

(a) DURABILITY :- The type of wiring selected should be of Proper Specification so that, it is durable & does not give rise to problems quite often.

(b) SAFTEY :- Saftey is a very important factor in Selecting a wiring System & the wiring System must be fool proof from any electrical Shock.

(c) APPEARENCE :- The wiring System should enhance the appearence or atleast should be concealed.

(d) COST : Type of wiring System Selected should not eat much into the budget of the owner, Look for convinience rather than luxury in Selecting a Wiring System.

(e) ACCESSEBILITY : Various Switches & plugpoints must be easily accessible i.e near to the place where appliances are usually kept.

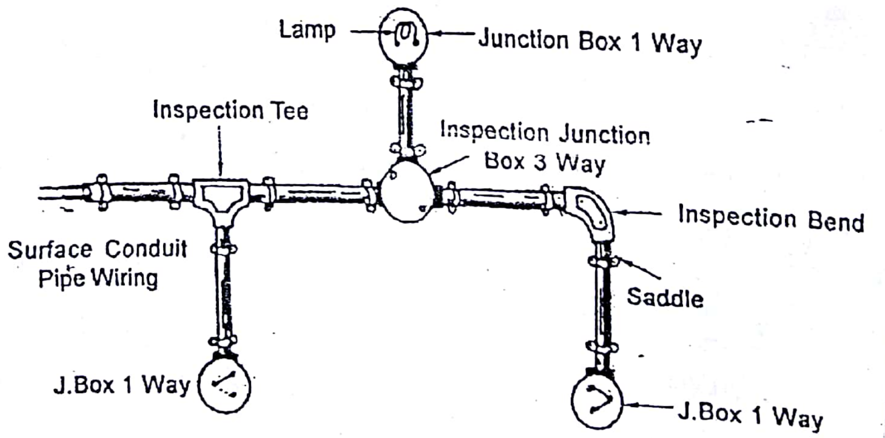
There must be provision for the extension of wiring system & Renewal if necessary.

(f) MAINTAINENCE COST :- Maintainance cost of the wiring system should be as minimum as possible.

SYSTEMS OF WIRING :- The following are the various systems of wirings.

(i) Cleat wiring.
(ii) Wooden casing & capping wiring.
(iii) conduit wiring — Surface conduit wiring. / Concealed conduit wiring
(iv) Lead sheathed or Metal sheathed wiring.

SURFACE CONDUIT WIRING : In this system of wiring, conduits are fixed on the surface of walls or ceilings by means of saddles, secured to wooden gutties with screws at an interval of 1m.



: Surface conduit wiring

↳ The VIR or PVC cables/wires are drawn by means of 18SWG GI wire. The Earth wire is fixed by means of earth clips

<u>CONCEALED CONDUIT WIRING</u> :- Here the conduits is buried under the wall or ceiling.

↳ PVC conduits are most popular because of their lower cost & require less time to install.

↳ The channels are provided in the wall before plastering & then conduit is fixed in the channels by means of clamps & hooks.

↳ The 18 SWG GI wire are drawn & covered by cement plastering to make it moisture proof.

	SURFACE CONDUIT WIRING	CONCEALED CONDUIT WIRING
(i)	The conduit/pipe is fixed on the wall.	The conduit/pipe is completely sunk into the RCC wall.
(ii)	It has Bad Appearence.	It is concealed & does not affect the appearence.
(iii)	It is cheaper	Comparitively it is costlier.
(iv)	It is ~~cheaper~~ not fully protected from Mechanical injury	It is fully protected from Mechanical injury.
(v)	It is fixed by means of Saddles	It is fixed by means of J-hooks.
(vi)	It uses Tees & Elbows	Only Bends are used.

TWO-WAY CONTROL OF LAMPS :

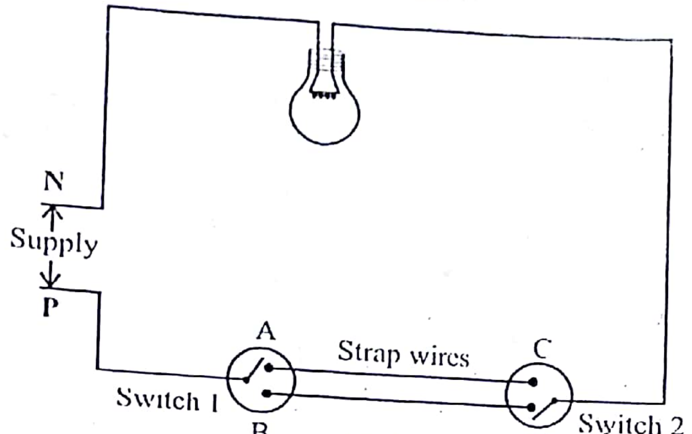


Fig.7.9

SWITCHING TABLE :

S.No.	Position of Switch 1	Position of Switch 2	Lamp ON or OFF
1	A	D	OFF
2	A	C	ON
3	B	C	OFF
4	B	D	ON

- The wires used b/n switches are called Strap wires.
- When the switch-1 is in position-A & switch-2 is in position-D, the lamp circuit is not closed & hence the lamp is OFF.
- When the switch-1 is changed to position-B, the lamp circuit is closed & hence lamp is ON.
- If the switch-2 is changed to position-C, again the lamp circuit is broken and the lamp is switched off.

THREE WAY CONTROL OF LAMPS : Sometimes in very big corridors, Godowns or Workshops, it may be necessary to control the lamps from three points.

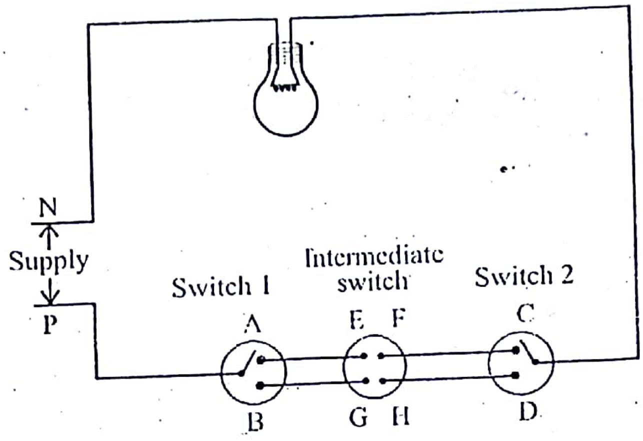


Fig.7.10

Sl No	Position of Switch-1	Position of Intermediate Switch	Position of Switch-2	Lamp ON or OFF
1	A	EF, GH	C	ON
2	A	EF, GH	D	OFF
3	B	EF, GH	C	OFF
4	B	EF, GH	D	ON
5	A	EH, GF	C	OFF
6	A	EH, GF	D	ON
7	B	EH, GF	C	ON
8	B	EH, GF	D	OFF

↳ When the Switches-1 & 2 are in position-A & B respectively, and the Intermediate Switch is in position of Straight connection i.e when EF & GH are connected, the lamp circuit is closed & hence the lamp glows (ON)

↳ Now if the Intermediate Switch is changed to position of cross connection i.e when EH & GF are connected, the lamp circuit is open & hence the lamp is Switched OFF.

↳ Now if the position of Switch-2 is changed from 'C' to 'D', the lamp circuit is closed & the lamp is Switched ON.

Thus the lamp can be controlled from 3-points.

EARTHING :- Earthing or Grounding is to connect the body of an Electrical equipment to the general mass of the earth by a wire of negligable resistance.

↳ Earthing brings the body of the equipment to zero potential & thus avoids Shocks to the personnel, incase the body of the equipment comes in contact with live wire.

↳ The Neutral of the Supply System is Solidly earthed to ensure that its potential is also zero.

NECESSITY OF EARTHING :- Earthing is necessary for the following reasons.

(a) To protect the Human being from dis-ability or death incase the human body comes in contact with the frame of any Electrical machinery, appliance or component which is electrically charged due to leakage current or fault.

(b) To maintain a constant line voltage.

(c) To protect tall buildings & structures from atmospheric lightening strikes.

(d) To protect all machines, fed from overhead lines, from atmospheric lightening.

(e) To serve as the return conductor for Telephone, Telegraph & Traction work.

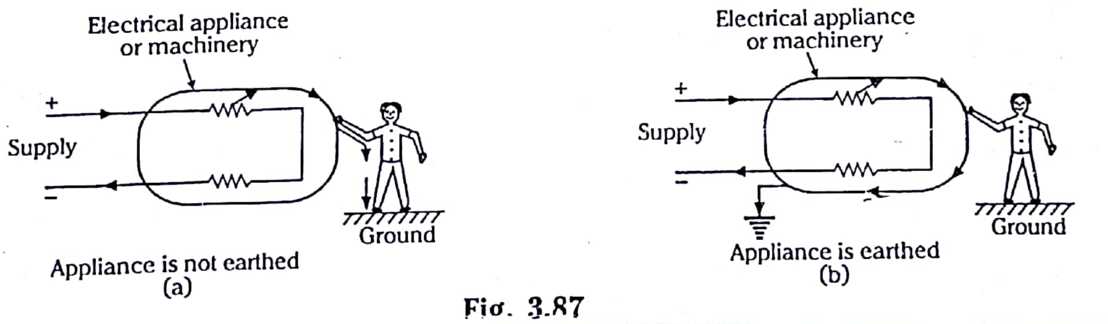


Fig. 3.87

TYPES OF EARTHING :- There are 2-types of earthing.

(i) Pipe earthing.

(ii) Plate earthing.

PIPE EARTHING :

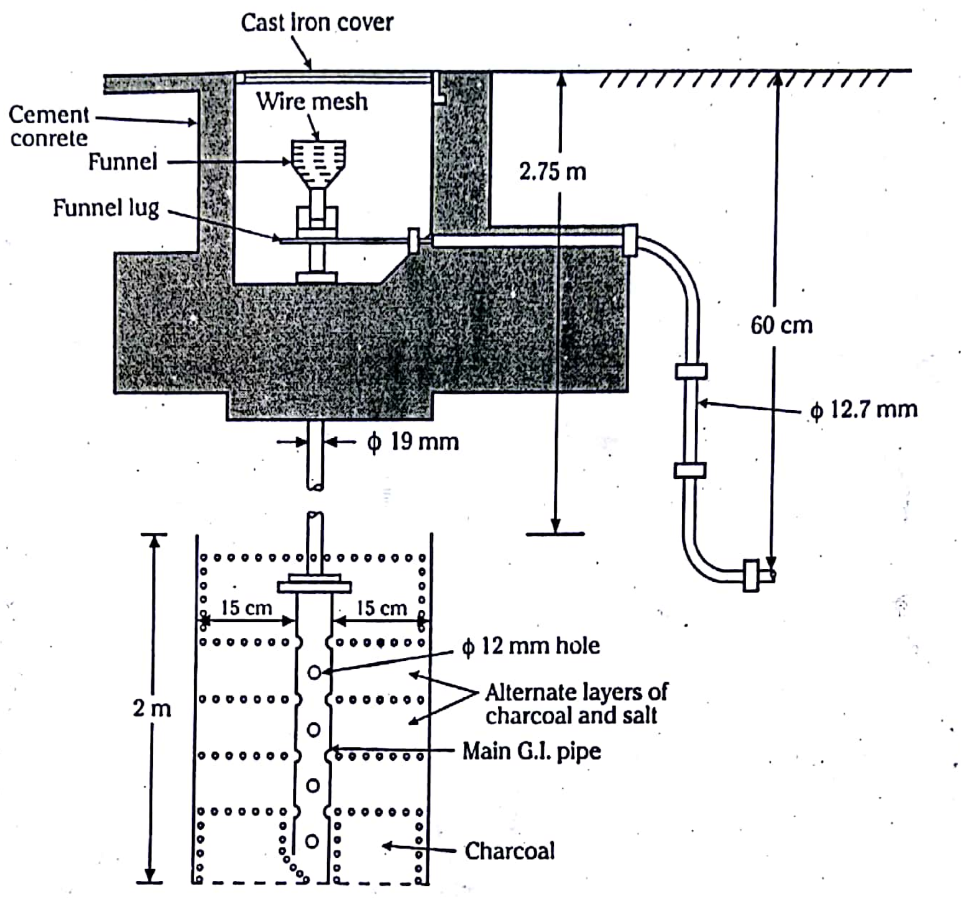


Fig. 3.89 Pipe Earthing

↳ A G.I pipe of 38mm diameter & 2m length is vertically embedded into the ground to serve as earth eletrode, the depth depending on the soil condition

↳ According to Indian Standard, the pipe should go down to a depth of 4.75m

↳ The pipe must be placed upright in wet ground. The pit area around the G.I pipe is filled with salt & charcol mixture for a distance of 15cm around pipe. This mixture improves the soil condition & efficiency of Earthing System.

↳ In Summer, the soil becomes dry in which case Salt water is poured through the funnel connected to the main G.I pipe through 19mm diameter pipe, to keep the soil wet.

↳ The Earthwire from the 19mm diameter G.I pipe should be carried in a conduit of G.I pipe of diameter 12.7mm at a depth of 60cm below the ground.

PLATE EARTHING :-

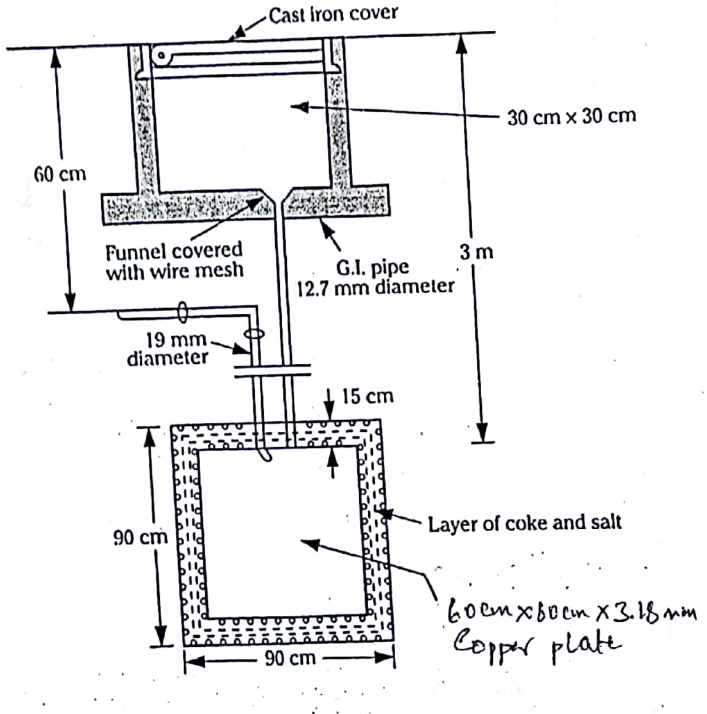


Plate Earthing

↳ A Copper plate of Size 60cm × 60cm × 3.18mm is used for the purpose of earthing. The plate is kept with its face vertical at a depth of 3m & it is so arranged that it is embedded in alternate layers of salt & charcoal, for a thickness of about 15cm.

↳ The nut & bolts must be made of copper for copper plate and of Galvanised Iron for G.I plate.

↳ The Earthwire is drawn through a G.I pipe of 19mm diameter, at about 60cm below the ground.

↳ The G.I pipe is fitted with a funnel on the top. To achieve effective earthing, salt water is poured periodically through the funnel.

PROTECTIVE DEVICES :

(1) **FUSE :** A fuse is a saftey device, a weak link connected in series with the circuit, which melts whenever the current in the circuit exceeds the value of the fuse provided, either due to overload or short circuit, thus opening the circuit & protecting other materials in the circuit.

Need for FUSE : If there is an overload or fault occurs, the conductor will carry a large current than normal current, this will cause overheating of conductor & damage to appliances & devices.

↳ Hence the need is felt for a built-in mechanism by which the entire installation is saved from possible damage, in the event of a short circuit or fault.

RATINGS :-

FUSING FACTOR : Fusing factor of a fuse is defined as the ratio of the 'Minimum fusing current' to the 'current rating' of the fuse element.

$$\text{Fusing Factor} = \frac{\text{Minimum fusing current}}{\text{current rating of the fusing element.}}$$

↳ The value of fusing factor is always more than 1.

MINIMUM FUSING CURRENT: This is the minimum value of current at which a fuse shall melt.

↳ The various factors on which the fusing current depends, are as follows. (i) Material of the fuse element.
(ii) Length.
(iii) Diameter.

↳ In practice an alloy of Tin & Lead is used as an ordinary fuse wire.

RATED CURRENT: It is the maximum current which a fuse can carry without any undue heating or melting.

MINIATURE CIRCUIT BREAKER (MCB):

[What is MCB? Explain its need & features?]

↳ A Miniature Circuit Breaker is an Electromechanical device, which makes the circuit in normal operation & disconnects the circuit under the abnormal condition when the current exceeds the preset value.

↳ MCB is a high fault capacity current limiting, trip free automatic switching device with thermal & magnetic operation to provide protection against overload & short circuit.

MCB has the following features :-

(i) Its operation is very fast & opens in less than one millisecond.

(ii) No tripping circuit is necessary & the operation is automatic.

(iii) Provides protection against overload & short circuit without noise, smoke & flame.

(iv) It can be ~~reset~~ reset very quickly after connecting the fault, just by switching a button.
No re-wiring is required.

(v) It cannot be reclosed if fault persists.

(vi) The Mechanical life is upto or more than One Lakh operating cycle.

Hence now a days MCB's are used rather than re-wirable fuse.

ELECTRIC SHOCK :- When a person comes in contact with live wire supplying electricity, he recieves a shock.
The severity of the shock received depends on the voltage of the wire & the body resistance of the person.

↳ The voltages used domestically are 230V for lighting & heating and 440V for running Induction motors. These voltages can give severe shocks & may cause death to the person.

↳ The Maximum current the human body can withstand is 30mA for not more than 25ms duration.

↳ The current flowing through the body of a person during shock depends on the Body Resistance (R_b)

(a) For a ~~wet~~ Dry body, $R_b = 1,00,000\,\Omega$

(b) For a Wet body, $R_b = 1,000\,\Omega$

PREVETION OF SHOCKS :- The following precautions may be taken by persons from getting Electric Shocks in home.

(i) Care must be taken to see that ground points are properly provided to all the sockets to which electrical appliances are connected.

(ii) Proper earthing has to be provided & periodically the Earthing resistance has to be checked to see that it does not exceed 3 to 5Ω

(iii) Cover all Electrical Sockets with plastic saftey caps.

(iv) Replace all worn chords & wiring.

(v) Never use an Electrical appliance like Radio or Iron ~~heat~~ near water.

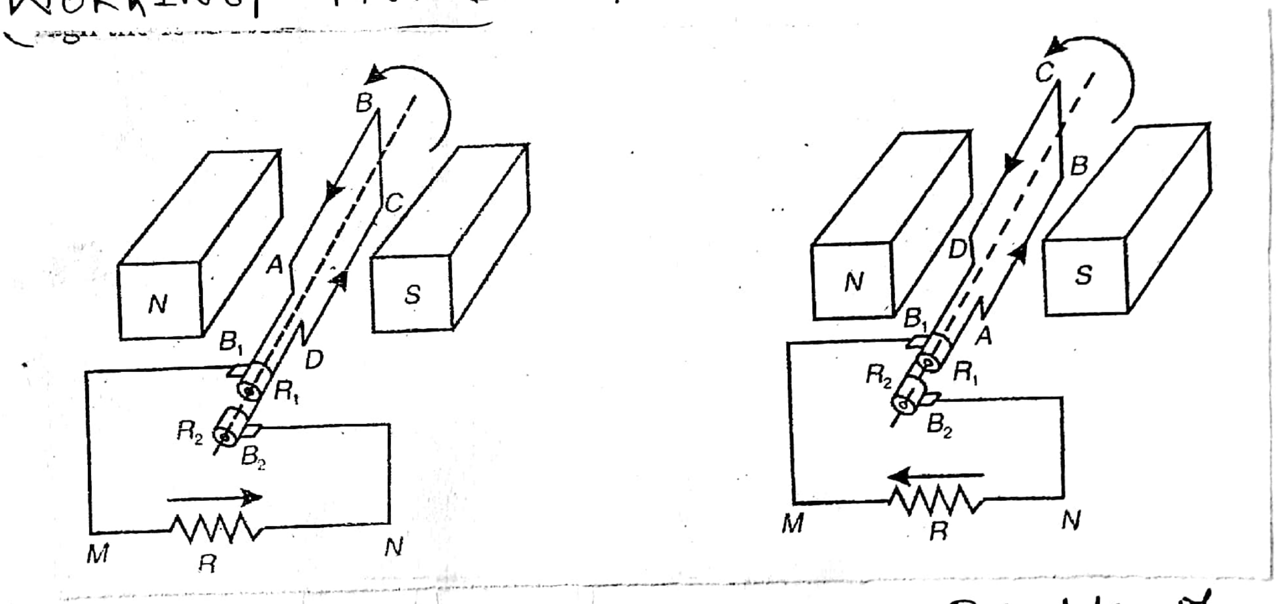
(vi) Do not touch Electrical appliances & switches with wet hands.

D.C GENERATORS :

INTRODUCTION : An Electrical Machine which Converts Mechanical energy into an Electrical energy is called an Eletric generator.

The D.C generators Convert Mechanical energy into D.C Electrical energy.

WORKING PRINCIPLE :-



- A D.C generator Works on the Principle of the nature of the Electromagnetic Induction, The Induced EMF is Dynamically induced EMF.
- The equn:- for the EMF Induced in each conductor is given by,

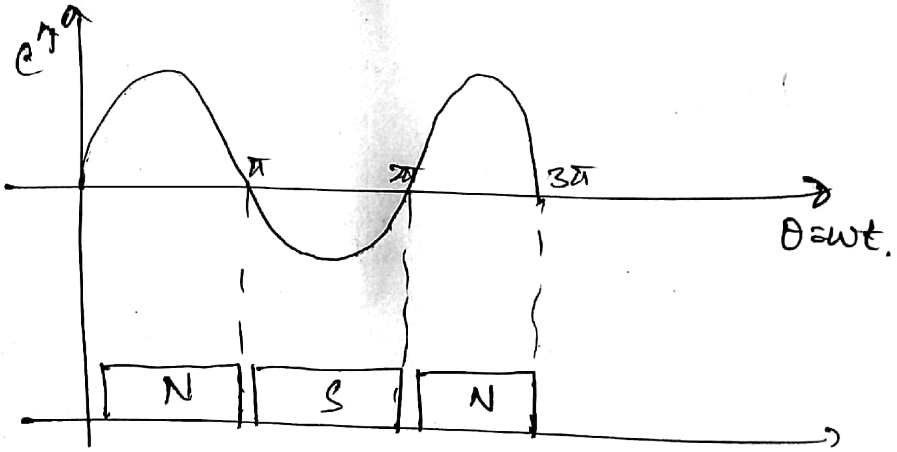
$$e = BlV\sin\theta = E_m\sin\theta$$

where B = Flux density produced by the poles in Wb/m^2 or Tesla.

l = Length of the Conductor in meters.
V = Velocity with which the Conductor is moving m/s.

Explanation: The two conductors are connected together to form a Coil ABCD.

During One revolution, each of the conductors Cut the flux from zero value to Maximum value & again zero value, when it is moving under a pole. ∴ The nature of the EMF induced in the conductor is Sinusoidal in nature, as shown in fig below.



CONSTRUCTION OF A D.C MACHINE :-

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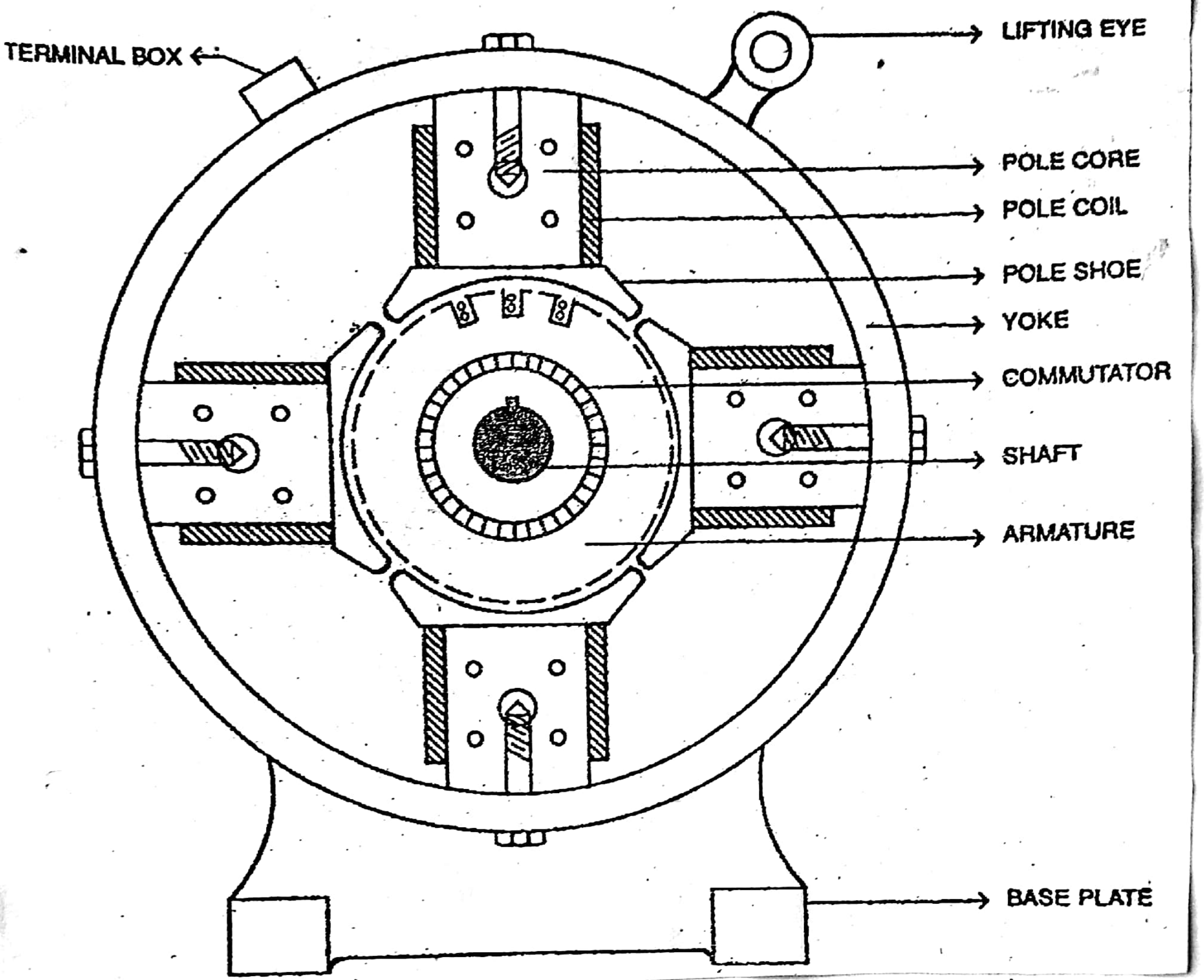


A D.C generator consists of 2-parts
1. Stationary part.
2. Rotating part.

Stationary Part consists of
(i) Yoke or Magnetic frame
(ii) Main pole along with Pole shoes & Pole coils
(iii) Base plate & Lifting eye.
(iv) Brush Box with Brushes.
(v) Terminal Box

Rotating part consists of
(i) Armature core & Armature Windings.
(ii) Commutators.
(iii) Shaft & Bearings.

YOKE (OR) MAGNETIC FRAME :

FUNCTIONS : It serves the purpose of outermost cover of a D.C machine, so that insulating materials get protected from harmful atmospheric elements like moisture, Dust & various gases like SO_2, Acidic fumes, etc.

↳ The Yoke supports the field system & forms a part of the magnetic circuit.

CHOICE OF MATERIAL : In order to reduce weight & to have better magnetic properties, yokes of large generators are made of cast steel & yokes of small generators are made of cast Iron as they are cheap.

MAIN POLES, POLE SHOES & POLE COILS :

(a) POLE CORE & POLE SHOES

(b) POLE COILS (OR) FIELD WINDINGS.

(a) POLE CORE & POLE SHOES

FUNCTIONS:

* Pole core carries the field windings necessary to produce the magnetic flux, required for the generation of EMF.
* Pole shoe directs the flux produced through airgap to armature core.
* Pole shoes are cylindrical shape so that the flux produced spreads out uniformly in the airgap & also it reduces the reluctance of the magnetic path because of larger area of cross section(a)

CHOICE OF MATERIAL: The main poles are made of an alloy steel of high relative permeability. The pole core is made of laminations of required shape & size, and are stamped to get a pole which is then bolted to the yoke.

(b) FIELD WINDING:

The field winding is wound on the pole core with a definite direction.

FUNCTIONS:

* To carry current due to which pole core, on which the field winding is placed, behaves as an electromagnet, producing necessary flux.

* Field winding is wound in such a direction that alternate 'N' and 'S' poles are formed. The total no. of poles is denoted as P.

CHOICE OF MATERIAL : Copper is the best material as it is a good conductor & has good pliability.

BRUSH BOX WITH BRUSHES :

FUNCTIONS :-

* Brushes are stationary & resting on the surface of the commutator.
* It collects current from commutator and makes it available to the stationary external circuit via Terminal box.

CHOICE OF MATERIAL :-

* Brushes are normally made up of soft material like carbon to avoid wear & tear of commutator.

ARMATURE CORE & ARMATURE WINDINGS :-

(a) ARMATURE CORE
(b) ARMATURE WINDING

(a) ARMATURE CORE :-

FUNCTIONS :

* Armature core is cylindrical in shape mounted on the shaft. It has uniformly cut slots on its outer periphery on which Armature windings are placed.
* Armature core has Air ducts which serve the purpose of cooling

CHOICE OF MATERIAL :
* It is madeup of silicon steel laminations to minimise the eddy current losses.

(b) ARMATURE WINDING :- The outer periphery of the Armature is cut into number of slots to hold the Armature windings.
There are 2-types of winding
LAP WINDING → which carries more current
WAVE WINDING → which carries less current.

CHOICE OF MATERIAL :- It is made up of a conducting material like copper.

COMMUTATOR :-

FUNCTIONS : Commutator collects the current from Armature Conductor and Converts Alternating Current into Direct Current (A.C to D.C)

CHOICE OF MATERIAL : It is cylindrical in Shape & is made up of Wedge shaped Segments of high conductivity Copper. These Segments are insulated from each other by a thin layer of insulating Mica.

SHAFT & BEARINGS :-

The Shaft of the D.C generator is rotated by a prime Mover, due to which the Armature rotates. For Small generators, roller bearings are used at both ends of the Shaft.

EMF equation of a D.C Generator:

Let, P = Number of Poles.

N = Speed of Armature in r.p.m

ϕ = Flux per pole in Webers.

Z = Total number of Armature Conductors.

A = Number of parallel paths.

The Flux cut by the Conductor in One revolution } $d\phi = P\phi$

Time take by the conductor to make one revolution } $dt = \frac{60}{N}$

∴ EMF Induced in One Conductor $\frac{d\phi}{dt} = \frac{P\phi}{\left(\frac{60}{N}\right)}$

$$\frac{d\phi}{dt} = \frac{PN\phi}{60} \text{ volts.}$$

∴ The EMF induced per parallel path } = EMF Induced per Conductor } × { Number of Conductors per parallel path

$$E_g = \frac{PN\phi}{60} \times \frac{Z}{A}$$

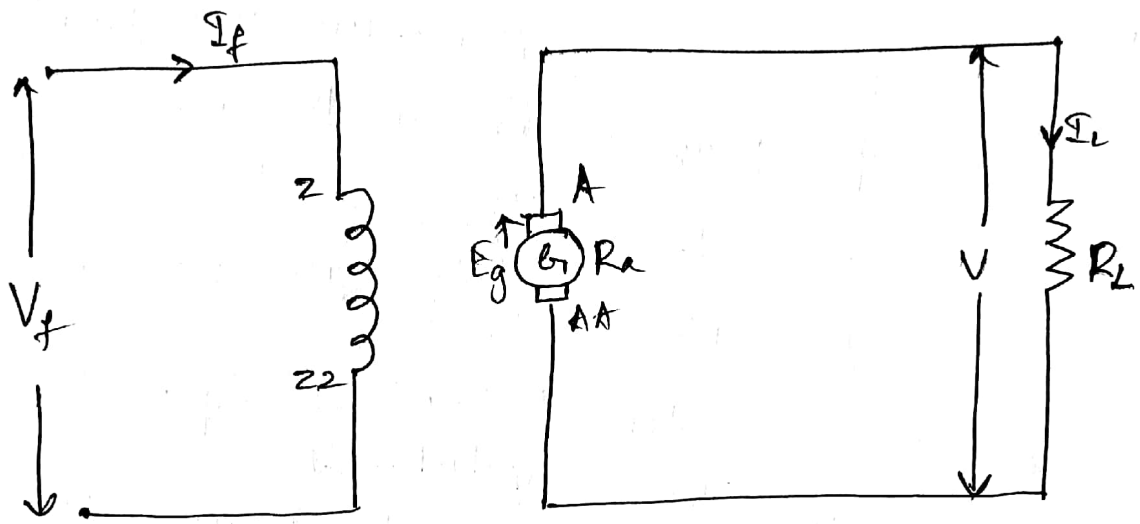
$$\boxed{E_g = \frac{PN\phi Z}{60A} \text{ volts}}$$

is called EMF eqn. of a D.C generator.

Case (i): For Lap Winding $A = P$, ∴ $E_g = \frac{N\phi Z}{60}$ volts

Case (ii): For Wave Winding $A = 2$, ∴ $E_g = \frac{PN\phi Z}{120}$ volts

NOTE: SYMBOLIC REPRESENTATION OF A DC GENERATOR :



↳ The Symbolic representation of a D.C generator with its Armature & Field windings is shown in fig above.

↳ The Field winding is connected to a D.C voltage Source of Voltage V_f, due to which a Constant Current of I_f Amps flows through the field winding. A Magnetic flux 'φ' is produced by field winding.

↳ When the Armature is rotated by means of Prime mover, the Armature Conductors cut the Magnetic flux & hence an EMF 'E_g' is generated.

↳ When a load Resistance R_L is connected across the terminals of the Generator, a load Current 'I_L' flows through it. 'V' is the Terminal voltage of the D.C generator.

* A & AA Represent positive & Negative terminals of Armature Respectively
* Z & ZZ Represent positive & Negative terminals of Field winding Respectively.

NOTE : The Terminal Voltage of the D.C generator is Slightly less than generated Voltage, because

(i) The Armature Conductors have a Small resistance known as Armature Resistance 'R_a' & hence a Small Voltage drop 'I_aR_a' due to Current flowing through the Armature Conductors.

(ii) The Current in the Armature sets up its own flux known as Armature flux, this opposes the main flux & hence the main flux gets Reduced & Hence the EMF induced in the D.C generator also gets reduced. This is known as Armature Reaction Drop (A.R.D)

(iii) The Contact b/n the Commutator & the Brushes has some Resistance known as Brush Contact Resistance. ∴ The Voltage in a D.C generator due to Brush contact resistance is two times the Voltage drop per brush.

Generated EMF = Terminal Voltage + Armature Resistance Drop + Armature Reaction Drop + Brush Contact Resistance Drop

$$E_g = V + I_a R_a + A.R.D + B.C.D$$

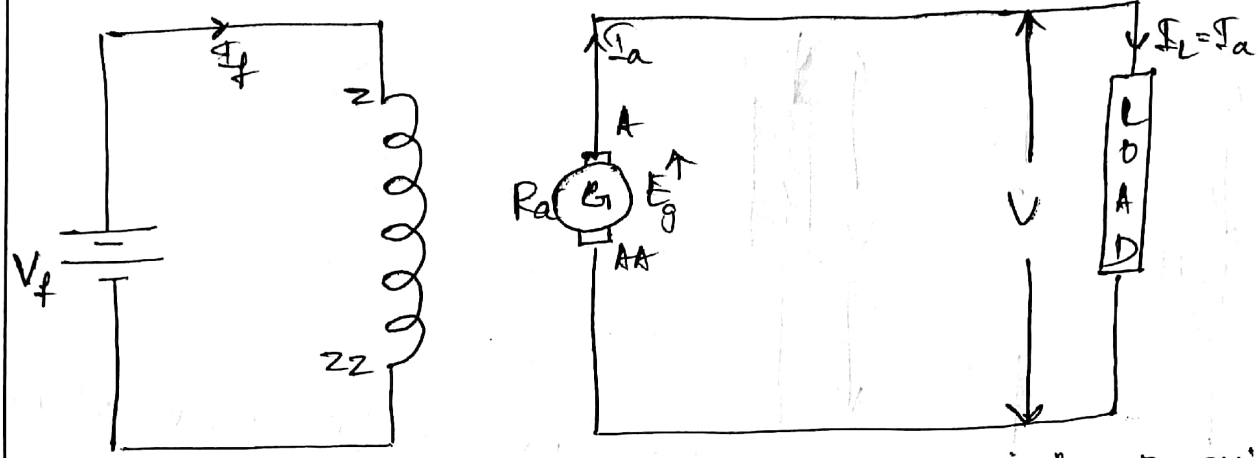
or

$$V = E_g - I_a R_a - A.R.D - B.C.D$$

TYPES OF GENERATORS :

- Self excited D.C generator
  - D.C Shunt generator
  - D.C Series generator
  - D.C Compound generator.
    - Cummulatively Compounded
      - Long Shunt
      - Short Shunt
    - Differentially compounded
      - Long Shunt
      - Short Shunt
- Seperately excited D.C generator

SEPERATELY EXCITED D.C GENERATOR :



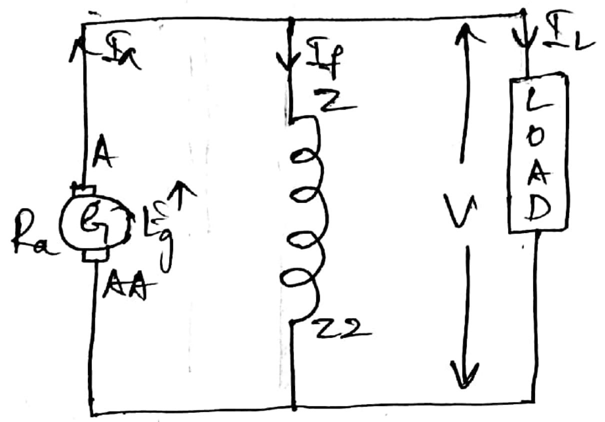
* The excitation to the field winding is provided by a Seperate D.C voltage 'V_f'. This Voltage drive a current I_f through the field winding due to which a Magnetic flux is produced.
* When the Armature is rotated by a Prime mover, the Armature conductors cut the Magnetic flux & hence an EMF 'E_g' is induced.
* When the load is connected across the Armature terminals, a Current I_L flows through the load.
* If 'V' is the Terminal Voltage of D.C generator, then $I_a = I_L$

&

$$V = E_g - I_a R_a - A.R.D - B.C.D$$

where, A.R.D → Armature Reaction Drop
B.C.D → Brush Contact Resistance Drop

SELF EXCITED D.C GENERATOR :



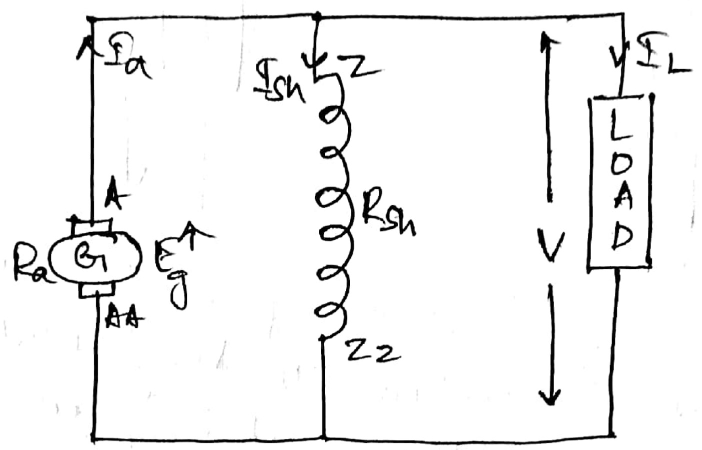
* The excitation to the field winding is provided by the generator itself.
* Here the Pole Cores have a residual flux ϕ_r, when the Armature is rotated by the Prime mover, the Armature Conductors Cut the residual flux & A Small amount of EMF is induced.
* This is Cummulative process, the increase of induced EMF & the increase of flux, help each other and the Terminal Voltage is builtup to its rated value.

$$I_a = I_L + I_f \quad \&$$

∴ Terminal Voltage } $V = E - I_a R_a - A.R.D - B.C.D$

where, A.R.D → Armature Reaction Drop
B.C.D → Brush Contact Drop.

D.C SHUNT GENERATOR :



* The Shunt field winding consists of a large number of thin turns of copper, So that its Resistance is quite high & I_{sh} is very Small.

* I_{sh} & hence the flux produced remains allmost Constant, irrespective of the load current, over operating range of the generator.

* It is called as Shunt generator because the field winding is connected across the Armature Terminals.

* From the circuit, $I_{sh} = \frac{V}{R_{sh}}$ where, R_{sh} = Resistance of Shunt field Winding.

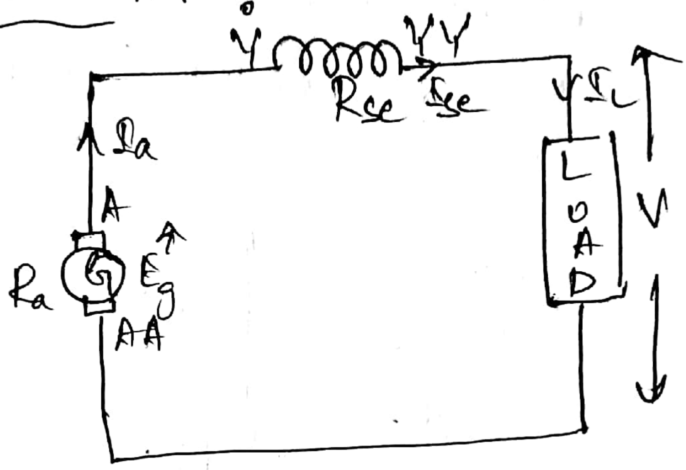
$$I_a = I_L + I_{sh}$$

Terminal Voltage $V = E_g - I_a R_a - A.R.D - B.C.D$ where,

A.R.D → Armature Reaction Drop.

B.C.D → Brush Contact Drop.

D.C SERIES GENERATOR :



- The Series field winding Consists of a few thick Copper turns, hence its resistance is very small.
- Whatever the Current flows through the load Same current flows through Armature & field winding.
- This is called Series generator, because the field winding is connected in Series with Armature.

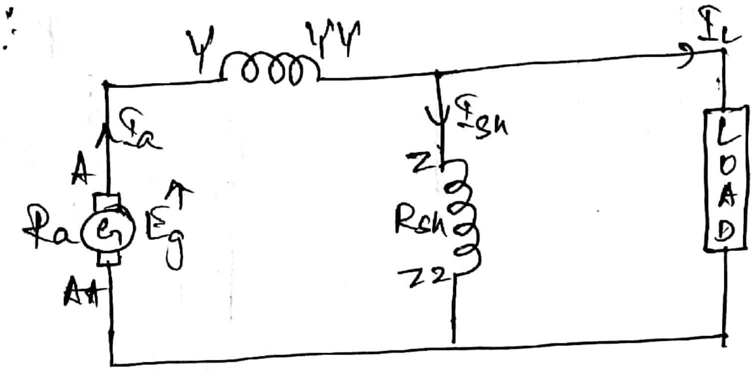
$$\therefore \; I_a = I_{se} = I_L$$

Terminal Voltage } $V = E - I_a (R_a + R_{se}) - A.R.D - B.C.D$

Where A.R.D = Armature Reaction Drop.
B.C.D = Brush Contact Drop.

COMMULATIVELY COMPOUNDED D.C GENERATORS:

(a) LONG SHUNT:



The Total flux $\phi = \phi_{sh} + \phi_{se}$

where, ϕ_{sh} = Flux produced by shunt field winding.

ϕ_{se} = Flux produced by series field winding.

$I_{sh} = \frac{V}{R_{sh}}$ & $I_a = I_L + I_{sh}$

Terminal Voltage $V = E - I_a(R_a + R_{se}) - A.R.D - B.C.D$

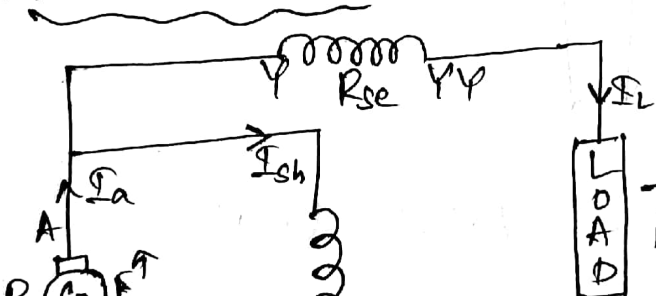
where A.R.D = Armature Reaction Drop

B.C.D = Brush Contact Drop

(b) SHORT SHUNT:

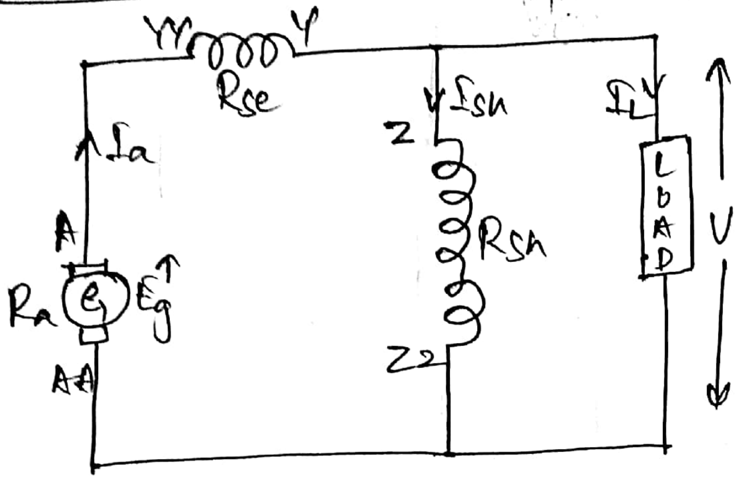
$I_{sh} = \frac{V + I_L R_{se}}{R_{sh}}$ & $I_a = I_L + I_{sh}$

Terminal Voltage $V = E - I_a R_a - A.R.D - B.C.D$



DIFFERENTIALLY COMPOUNDED D.C GENERATORS :-

(a) LONG SHUNT :-



Resultant Flux } $\phi = \phi_{sh} - \phi_{se}$

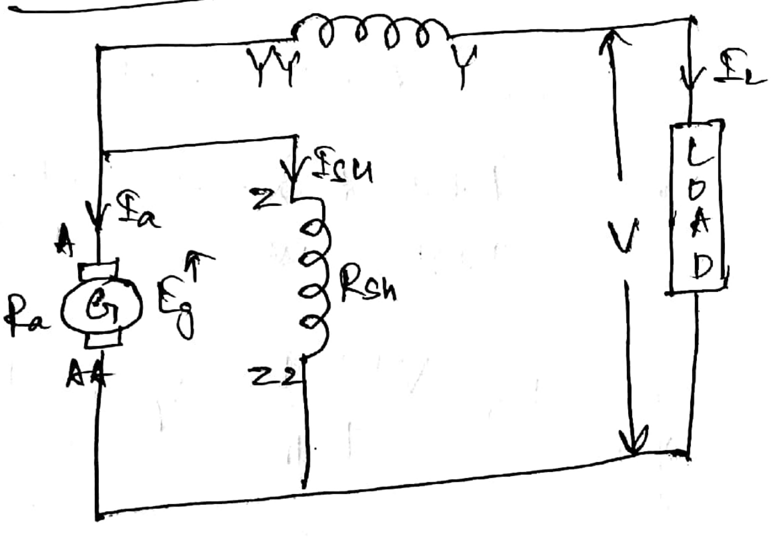
where, ϕ_{sh} = Flux produced by Shunt field winding.

ϕ_{se} = Flux produced by series field winding.

$$I_{sh} = \frac{V}{R_{sh}} \quad \& \quad I_a = I_L + I_{sh}$$

Terminal Voltage } $V = E_g - I_a(R_a + R_{se}) - A.R.D - B.C.D$

(b) SHORT SHUNT :-



$$I_{sh} = \frac{V + I_L R_{se}}{R_{sh}}$$

&

$$I_a = I_L + I_{sh}$$

Terminal Voltage } $V = E - I_a R_a - I_L R_{se} - A.R.D - B.C.D$

D.C MOTORS :

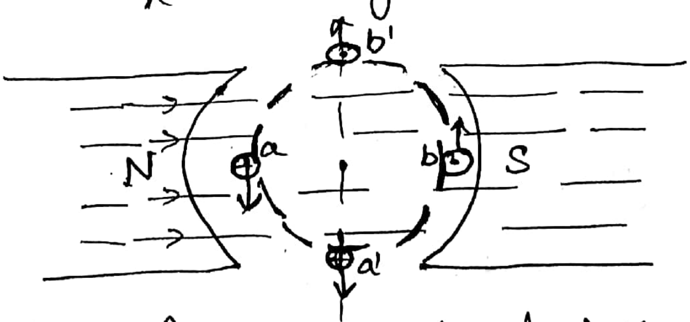
INTRODUCTION :- An Electrical Machine which converts Electrical energy into Mechanical energy is called an Electric Motor.

The D.C Motor converts D.C electrical energy into Mechanical energy

WORKING PRINCIPLE :- A D.C Motor works on the Principle that, "Whenever a Current carrying conductor is placed in a Magnetic field, it experiences a force (F)"

$$F = BIL \sin\theta \text{ Newtons}$$

where, F = Force experienced in Newtons.
B = Flux density of the Magnetic field.
I = Current flowing through the conductor.
l = Length of the conductor in meters



↳ All the Armature conductors mounted on the periphery of the Armature drum, get subjected to Mechanical force called Torque & the Armature of the Motor starts rotating.

↳ According to Fleming's left hand rule, the conductor 'a' experiences a force 'F' in Downward direction and the conductor 'b' experiences an equal force 'F' in the Upward direction. This constitute a Couple, tending to rotate the Armature in Anticlockwise direction.

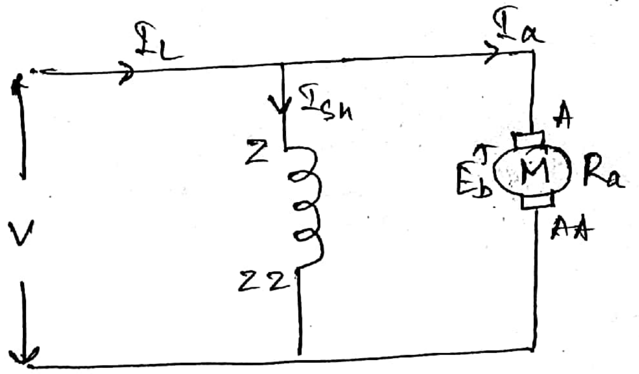
NOTE : Symbolic representation of a D.C Shunt motor.

'V' is the applied voltage, due to which a Current I_a flows through the Armature conductors.

I_L → Line Current &

I_{sh} → Current flowing in Shunt field winding

$$\therefore I_L = I_a + I_{sh}$$



Voltage 'V' has to Overcome.

(a) Back EMF
(b) Armature Resistance Drop
(c) Armature Reaction Drop
(d) Brush Contact Resistance Drop.

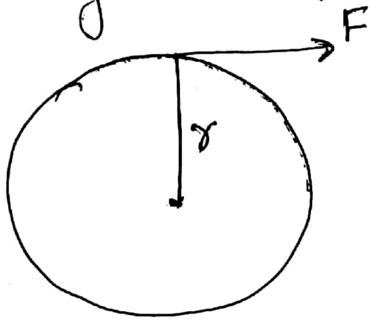
∴ Voltage eqn: of a D.C Motor is

$$V - E_b - I_a R_a - A.R.D - B.C.D = 0$$

(or)

$$V = E_b + I_a R_a + A.R.D + B.C.D$$

TORQUE EQUATION :- Consider the Armature of a D.C motor having radius 'r' & let 'F' be the tangential force acting on it.



Torque exerted on the Armature } $T_a = F \times r$ Nm ......(a)

Workdone by the force 'F' in One revolution } W = Force X Distance Covered in One revolution

$W = F \times 2\pi r$ watt sec

Power developed by the Armature } $P = F \times 2\pi r \times$ {Number of revolutions per second}

$= F \times 2\pi r \times \frac{N}{60}$

$= \frac{2\pi N}{60}(F \times r)$

$P = \frac{2\pi N T_a}{60}$ watts ...... (b)

The Electrical equivalent of Mechanical power } $P = E_b I_a$ ...... (c)

$\frac{2\pi N T_a}{60} = E_b I_a = \left(\frac{PN\phi Z}{60A}\right) I_a$

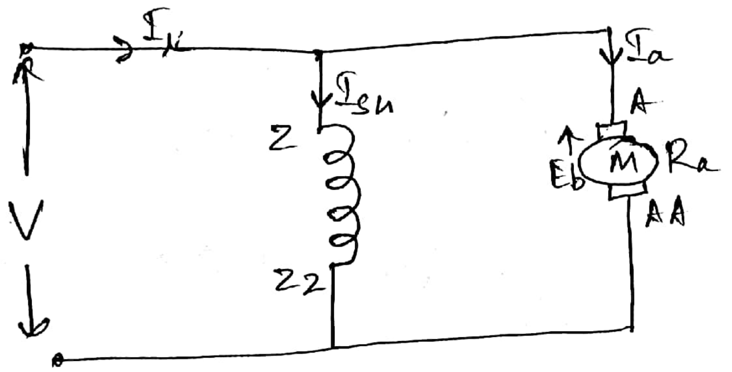
$\frac{2\pi N T_a}{60} = \left(\frac{PN\phi Z}{60A}\right) I_a$

$$T_a = \frac{1}{2\pi} \times \phi Z I_a \left(\frac{P}{A}\right) \text{ Nm}$$

(a)

$$T_a = 0.159\, \phi Z I_a \left(\frac{P}{A}\right) \text{ Nm}$$

(*) Show that the Mechanical power developed by a D.C. Shunt motor is maximum when the Back EMF is equal to half the applied voltage.



Let,

V = Applied voltage

E_b = Back EMF

I_a = Armature current

R_a = Resistance of Armature conductors

Voltage equn of D.C motor is,

$$V = E_b + I_a R_a$$

Multiplying both sides by I_a,

$$V I_a = E_b I_a + I_a^2 R_a$$

where, VI_a = Electrical Power i/p to the Armature [Armature i/p]

$I_a^2 R_a$ = Copper loss in the Armature.

$E_b I_a$ = Electrical equivalent of Mechanical power developed in the Armature including Iron & Mechanical losses. [Total Armature o/p]

Mechanical Power of the Motor } $P_m = VI_a - I_a^2 R_a$

For Maximum power to be developed } $\frac{dP_m}{dI_a} = 0.$

$$V - 2I_a R_a = 0$$

$I_a R_a = \frac{V}{2}$ Substitute in eqn (a)

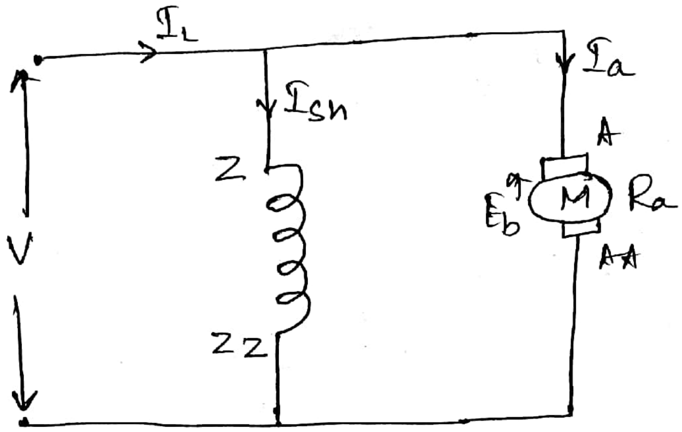
$$V = E_b + \frac{V}{2}$$

$$\therefore \boxed{E_b = \frac{V}{2}}$$

Thus the Mechanical Power developed by a Motor is maximum when the Back EMF is equal to half the applied voltage.

↳ This is purely Theoritical, In practice the current will be far greater than the normal current of the motor. Besides half the i/p power is wasted in the form of heat & other losses, bringing down the motor efficiency to less than 50%.

(*) Define Back EMF. Explain the Significance of Back EMF.



$$E_b = \frac{P N \phi Z}{60 A} \text{ volts}$$

→ As soon as the Armature of the D.C motor starts rotating, Dynamically Induced EMF (E_b) is produced in the Armature conductors. The direction of this induced EMF is found by Fleming's right hand rule such that it opposes the applied Voltage (V). This induced EMF is known as Back EMF (E_b)

SIGNIFICANCE: Due to presence of Back EMF (E_b) the D.C motor becomes self regulating machine i.e the motor is made to draw as much Armature current as is just sufficient to develop the Torque required by the load.

w.k.t $I_a = \frac{V - E_b}{R_a}$

→ When the load on the motor is decreased, the driving torque is excess of the requirement, so the Armature is accelerated.

As the Armature speed increases, the Back EMF E_b also increases & causes armature current to decrease. The motor will stop accelerating when the armature current is just sufficient to produce the reduced torque required by the load.

↳ When the load on the Motor is increased the Armature is slowed down.

As the Armature speed decreases, the Back EMF E_b also decreases & causes the Armature Current to increase. The motor will stop slowing down when the armature current is just sufficient to produce the ~~reduced~~ increased torque required by the load.

Speed of a DC Motor [Show that the speed of a DC motor is directly proportional to the Back EMF & inversely proportional to the Flux/pole]

Voltage equation of a D.C motor is,

$$V = E_b + I_a R_a$$

$$E_b = V - I_a R_a$$

$$\frac{PN\phi Z}{60A} = V - I_a R_a$$

$$\therefore N = \frac{V - I_a R_a}{\phi} \times \frac{60A}{PZ} \text{ rpm}$$

But $V - I_a R_a = E_b$

$$\therefore \quad N = \frac{E_b}{\phi} \times \frac{60A}{PZ}$$

For a particular machine P, Z & A are constants

$$N = k \frac{E_b}{\phi}$$

$$\boxed{N \propto \frac{E_b}{\phi}}$$

Thus Speed is directly proportional to Back EMF E_b & inversely proportional to flux ϕ.

For a Series Motor :-

Let N_1, I_{a1} & ϕ_1 be the speed, Armature Current & flux per pole in first case.

Let N_2, I_{a2} & ϕ_2 be the speed, Armature Current & Flux per pole in second case.

W.K.T $N_1 \propto \frac{E_{b1}}{\phi_1}$ where $E_{b1} = V - I_{a1} R_a$

&

$N_2 \propto \frac{E_{b2}}{\phi_2}$ where $E_{b2} = V - I_{a2} R_a$

$$\therefore \boxed{\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}}$$

Before Saturation of Magnetic poles Occur, $\phi \propto I_a$

$$\therefore \boxed{\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}}}$$

For a Shunt Motor :

w.k.t $\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$

here $\phi_1 = \phi_2$

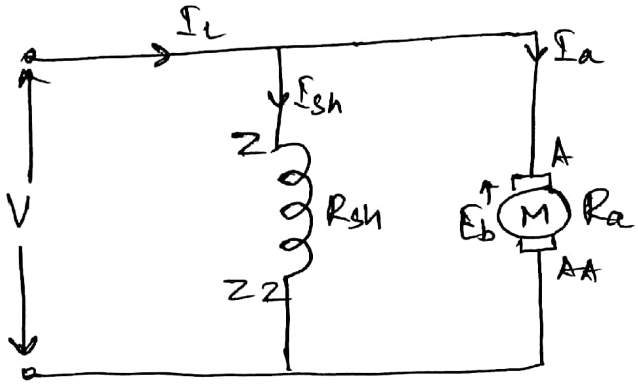
$$\therefore \boxed{\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}}$$

CLASSIFICATION OF D.C MOTORS :

- D.C Compound Motor
  - Cummulatively compounded D.C motor
    - Long Shunt
    - Short Shunt
  - Differentially compounded D.C motor
    - Long Shunt
    - Short Shunt
- D.C Shunt Motor
- D.C Series Motor

D.C SHUNT MOTOR :-

↳ In this type of motor, the shunt field winding is connected across the Armature.



↳ V is the applied voltage due to which a current I_L flows through the line, A current I_{sh} flows through the shunt field winding & current I_a through the armature conductors.

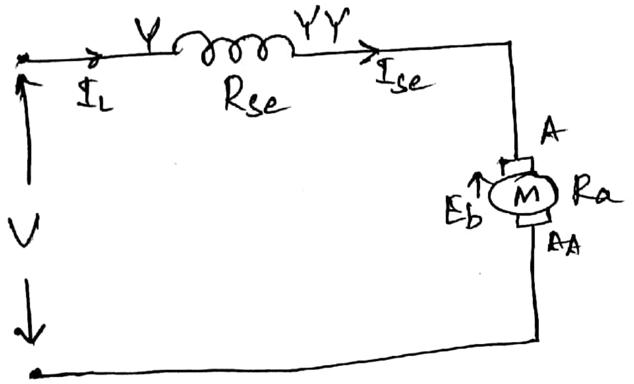
The shunt field current } $I_{sh} = \frac{V}{R_{sh}}$

The Armature Current } $I_a = I_L - I_{sh}$

The Back EMF $E_b = V - I_a R_a - A.R.D - B.C.D$

where, ARD = Armature Reaction Drop.
BCD = Brush Contact Resistance Drop.

D.C SERIES MOTOR :- In this type of motor, the series field winding is connected in series with Armature



↳ V is the applied voltage due to which a current I_1 flows through the line, the series field winding flows through the Armature Conductors. & through

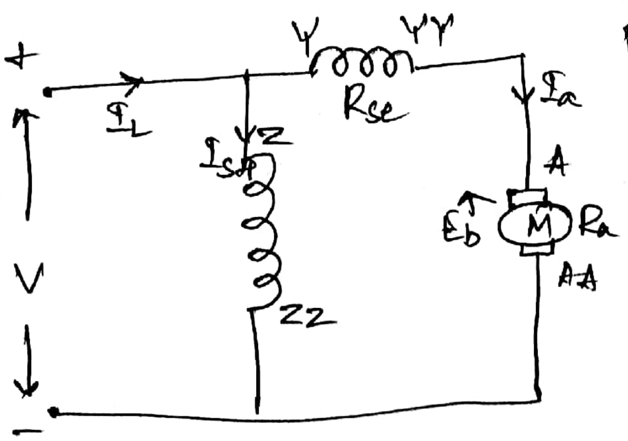
$$\therefore\ I_L = I_{se} = I_a$$

Back EMF $E_b = V - I_a(R_a + R_{se})$ - A.R.D - B.C.D

D.C COMPOUND MOTORS :-

(1) Cummulatively Compounded D.C motors

(i) **LONG SHUNT** :- If the Fluxes ϕ_{sh} produced by shunt field winding and ϕ_{se} produced by series field winding are in the same direction and are additive, then the motor is said to be Cummulatively compounded.



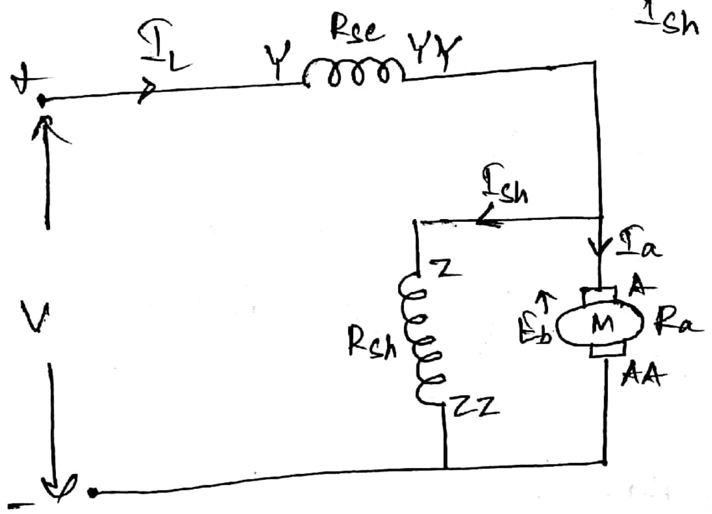
↳ For Cummulatively Compounded motors, the currents enter the positive terminals of the two field windings.

$$I_{sh} = \frac{V}{R_{sh}}$$

$$I_a = I_L - I_{sh}$$

$$E_b = V - I_a(R_a + R_{se}) - A.R.D - B.C.D$$

(ii) SHORT SHUNT :



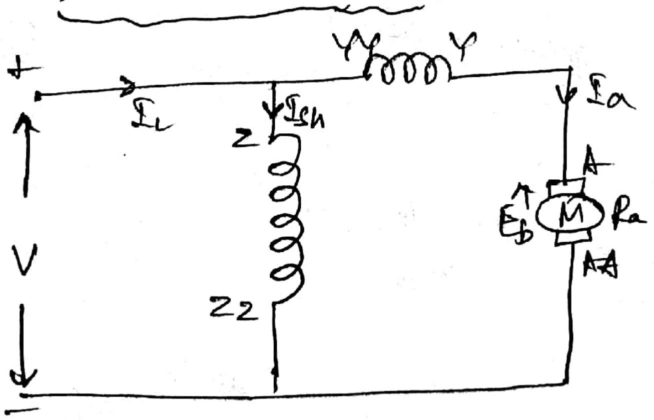
$$I_{sh} = \frac{V - I_L R_{se}}{R_{sh}}$$

$$I_a = I_L - I_{sh}$$

$$E_b = V - I_L R_{se} - I_a R_a - A.R.D - B.C.D$$

(2) Differentially Compounded D.C Motors

(i) LONG SHUNT : If the fluxes ϕ_{sh} & ϕ_{se} produced by shunt & series field winding oppose each other, the motor is said to be differentially compounded.



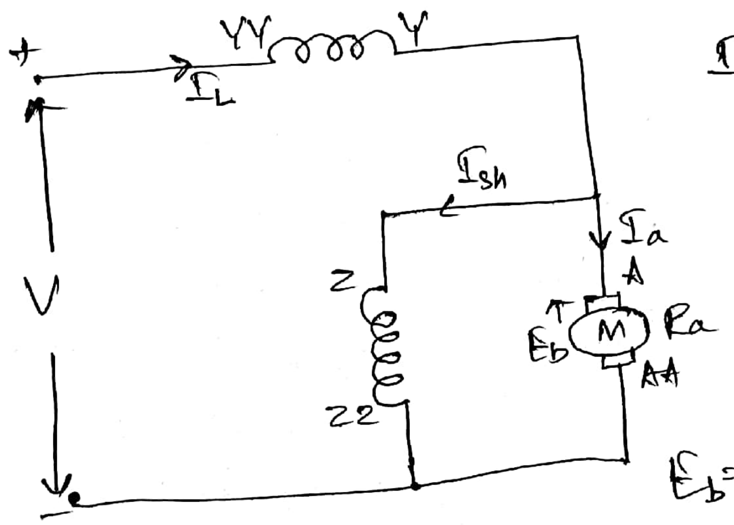
↳ In Differentially Compound Motors, the current through series field winding enter the Negative terminal & current through shunt field winding enter the positive terminal.

↳ $I_{sh} = \frac{V}{R_{sh}}$

$I_a = I_L - I_{sh}$ &

$E_b = V - I_a(R_a + R_{se}) - A.R.D - B.C.D$

SHORT SHUNT :-



$I_{sh} = \frac{V - I_L R_{se}}{R_{sh}}$

$I_a = I_L - I_{sh}$

&

$E_b = V - I_L R_{se} - I_a R_a - A.R.D - B.C.D$

CHARACTERISTICS OF D.C MOTORS: The 3-important characteristics of D.C motors are,

(i) T_a/I_a characteristic (or) Electrical characteristic

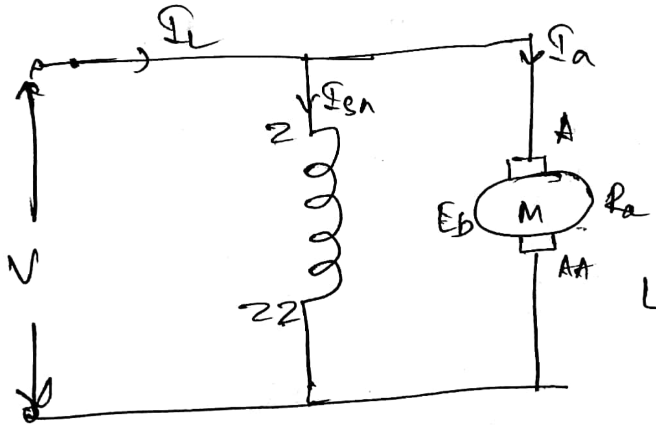
(ii) N/I_a characteristic

(iii) N/T_a characteristic (or) Mechanical characteristic

(1) CHARACTERISTICS OF D.C SHUNT MOTORS:

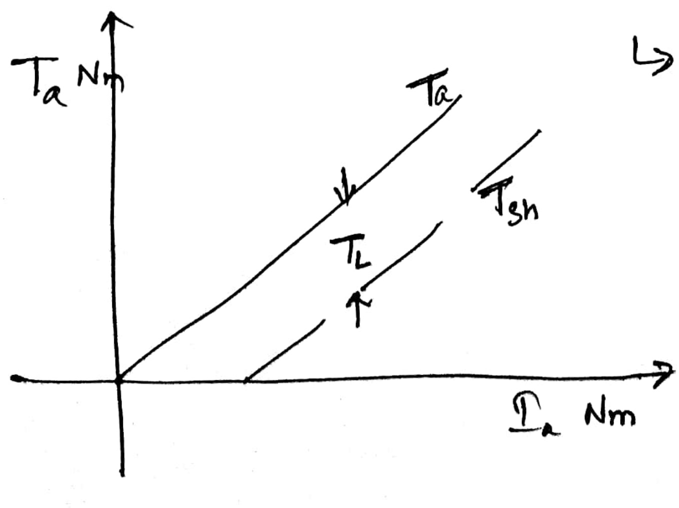
(i) T_a/I_a characteristic: w.k.t

$$T_a = 0.159\,\phi Z I_a \left(\frac{P}{A}\right)$$



↳ Shunt field current I_{sh} is constant ∴ ϕ is constant. Z, P & A are constants

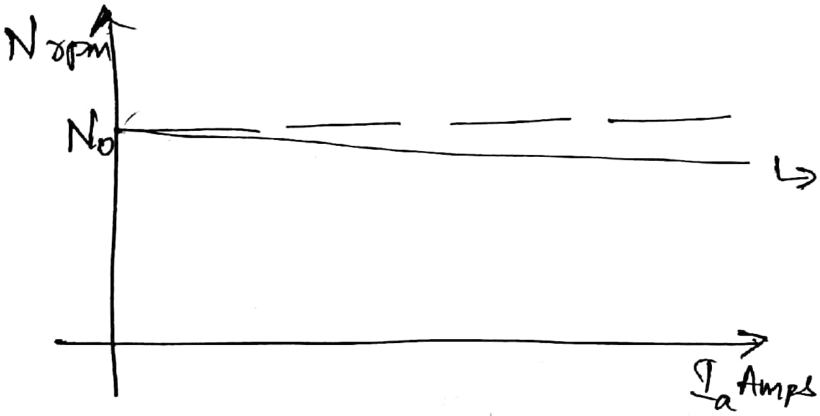
↳ ∴ $T_a \propto I_a$, Hence T_a/I_a characteristic is a straight line as shown.



↳ The shaft torque 'T_{sh}' is always less than Armature Torque 'T_a' due to Iron losses & Mechanical losses. (T_L)

∴ From T_a/I_a characteristic, We observe that a D.C Shunt motor has a Medium Starting Torque & hence does not suit where larger loads are to be started.

(ii) N/I_a Characteristic:



↳ w.k.t Back EMF, $E_b = \frac{PN\phi Z}{60A}$

$\therefore N \propto \frac{E_b}{\phi}$

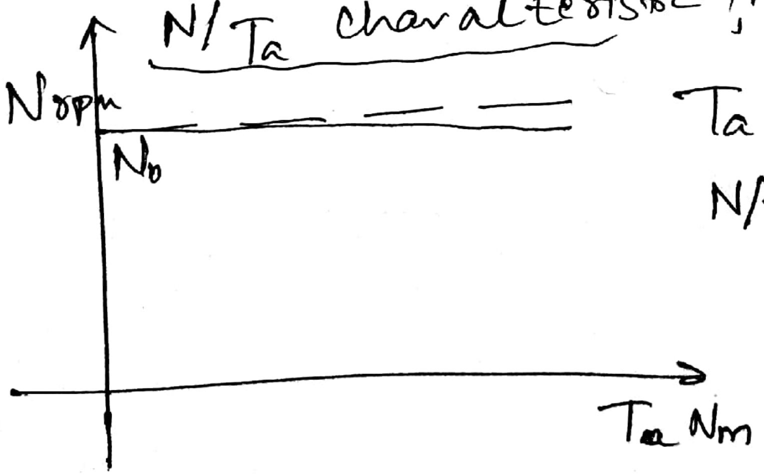
↳ For a D.C Shunt motor, ϕ is Constant

$\therefore N \propto E_b \propto V - I_a R_a$

↳ As I_a increases, $I_a R_a$ increases & hence the speed decreases. But the drop $I_a R_a$ is very small compared to V, Hence the decrease of speed as Armature current increases is also small.

↳ Hence, for all Practical purposes, A D.C Shunt motor is allmost a Constant speed motor.

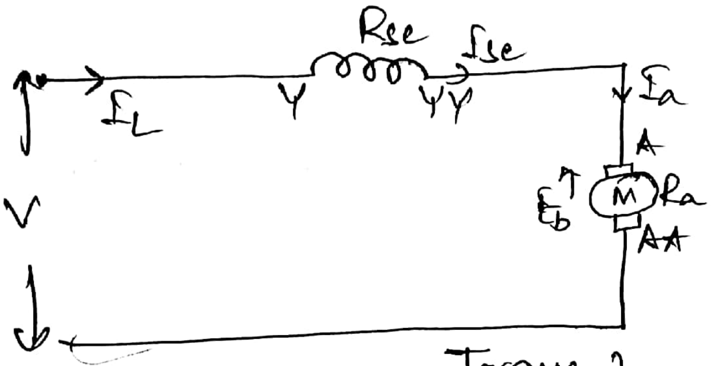
(iii) N/T_a characteristic :-



$T_a \propto I_a$ and hence N/T_a characteristic similar to N/I_a characteristic.

(2) CHARACTERISTICS OF D.C SERIES MOTORS :

(i) T_a / I_a characteristic :



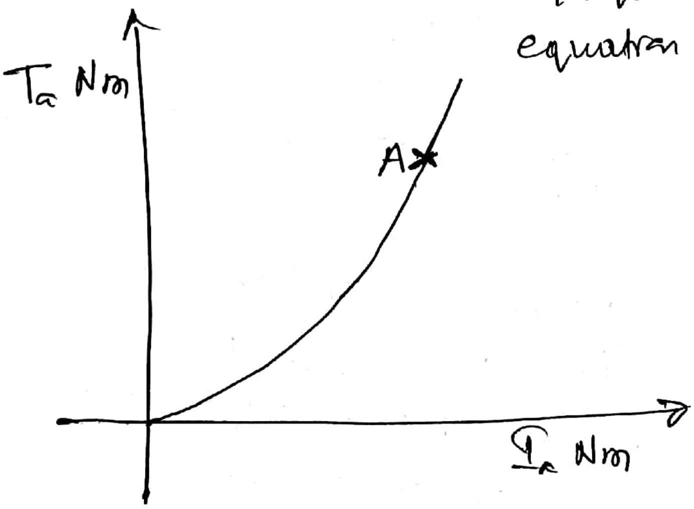
Torque equation } $T_a = 0.159\,\phi Z I_a \left(\frac{P}{A}\right)$

$T_a \propto \phi I_a$ but $\phi \propto I_a$

$\therefore$ $T_a \propto I_a^2$

After saturation, Flux remains constant

$\therefore$ $T_a \propto I_a$

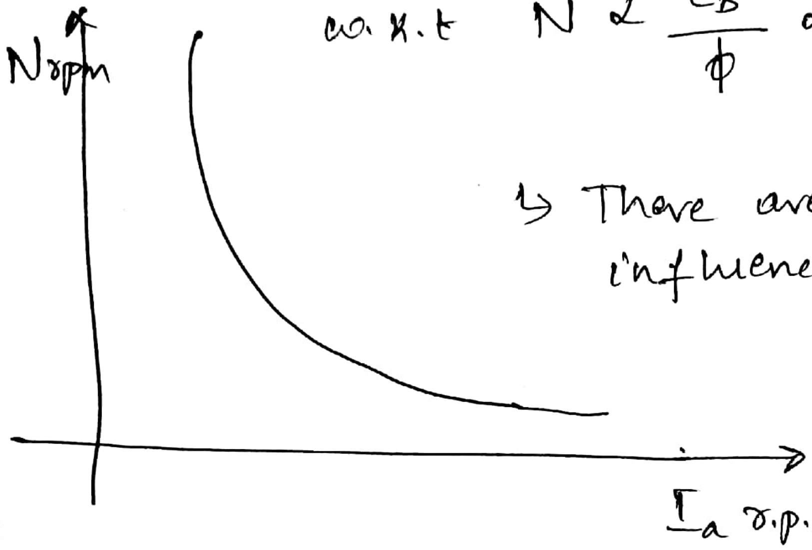


↳ from the characteristic : Upto point-A, $T_a \propto I_a^2$ & hence the curve is a parabola.

↳ Beyond point 'A', $T_a \propto I_a$ & hence the curve is a straight line.

↳ From this characteristic, We find that the starting Torque of a D.C Series motor is very high.

(ii) N/I_a Characteristic :



w.r.t $N \propto \frac{E_b}{\phi} \propto \frac{V - I_a(R_a + R_{se})}{\phi}$

↳ There are 2 factors which influence the speed of the motor

(i) $I_a(R_a + R_{se})$ increases & hence the speed decreases

(ii) The flux ϕ also increases due to which the speed decreases.

↳ The decrease of speed due to first factor is negligably small as compared to the decrease in speed due to second factor.

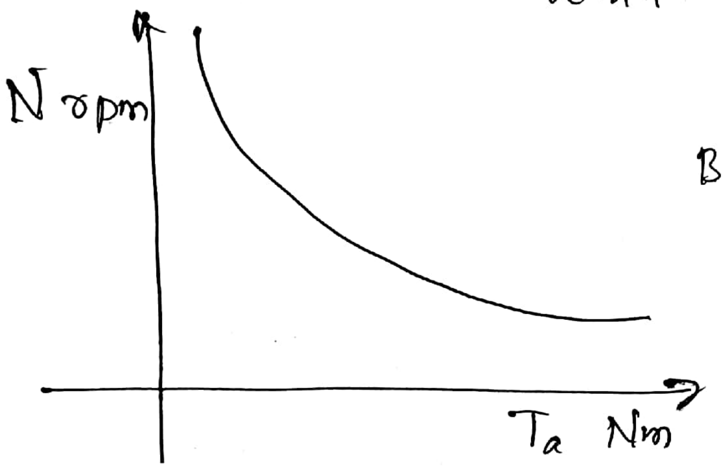
$\therefore N \propto \frac{1}{\phi}$ But $\phi \propto I_a$

$\therefore \boxed{N \propto \frac{1}{I_a}}$

↳ From the characteristic, As the load increases, the speed decreases over a wide range. Hence D.C series motor is a Variable speed motor.

NOTE :- At No load, I_a is very small, Hence if a D.C motor is started without any load on it, the speed is very high & it may run out of foundation due to Centrifugal forces. Hence, A D.C Series motor Should never be Started without load.

(iii) N/T_a Characteristic :-



W.K.T $T_a \propto I_a^2$

$I_a \propto \sqrt{T_a}$

But $N \propto \frac{1}{I_a}$

$\therefore N \propto \frac{1}{\sqrt{T_a}}$

1) For smaller values of Ta, 'N' is very large & for Higher value of Ta the speed decreases.

APPLICATIONS OF D.C MOTORS :

(1) SHUNT MOTORS

(i) Blowers & Fans
(ii) Centrifugal & Reciprocating pumps
(iii) Lathes, Drilling Machines & Milling machines.
(iv) Machine tools
(v) Boring Machines, Spinning & Weaving machines
(vi) For driving Constant Speed line Shafting

∴ Shunt motors are used when we need Medium Starting Torque & Constant Speed.

(2) SERIES MOTORS

(i) Traction purposes : Electric locomotives, Trolley cars, etc
(ii) Hoists & Cranes
(iii) Conveyors
(iv) Elevators

Series motors are used when we need very high starting Torque & Variable Speed.

MODULE 5(a)

TRANSFORMERS

Unit 5 (a): Single Phase Transformers:-

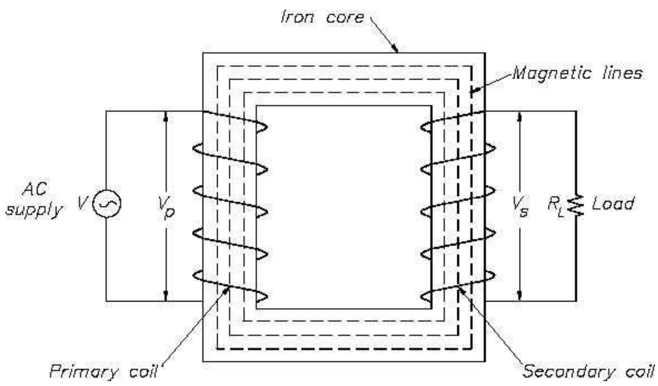
- Transformer is a static device which transfers electric energy from one electric circuit to another with the desired change in voltage and current levels without any change in power and frequency

CONSTRUCTION:

There are two basic parts of a transformer:

1) Magnetic core 2) winding

- The core of the transformer is either rectangular or square in size.
- The core is divided into i) Yoke ii)Limb
- Core is made up of silicon steel which has high permeability and low hysteresis co-efficient.
- The vertical portion on which the winding is wound is called Limb.
- The top and bottom horizontal portion is called Yoke.
- The core forms the magnetic circuit
- There are 2 windings i) Primary winding ii) Secondary winding which forms the Electric circuit. made up of conducting material like copper.
- The winding which is connected to the supply is called primary winding and having 'N_1' number of turns.
- The winding which is connected to a load is secondary winding and having 'N_2' number of turns.



TYPES OF TRANSFORMER:

Based on Construction the transformer are divided into:

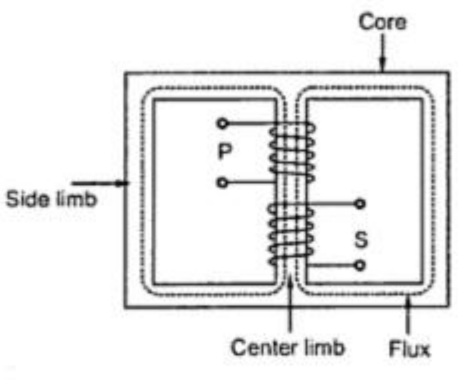
a) CORE TYPE b) SHELL TYPE.

Core type transformer:

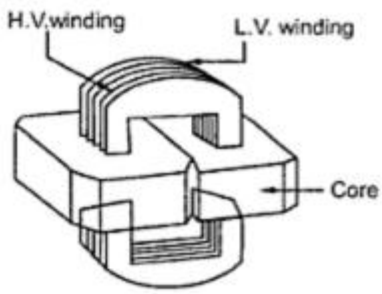
- the **fig.1** shows the core type of transformer.
- This type of transformer has a single magnetic circuit.
- The core has 2 limbs and windings encircled the core
- The primary and secondary windings are wound on two limbs of the core .
- The core is made of very thin laminations of high grade silicon steel material to reduce the eddy current loss and Hysteresis losses in the core.

Shell type transformer:

- The fig.2 shows the shell type of transformer.
- This type of transformer has a two magnetic circuit.
- The core has 3 limbs .
- The core surrounds the windings.
- The primary and secondary windings are wound on the central limb.
- The core is made of very thin laminations of high grade silicon steel material to reduce the eddy current loss and Hysteresis losses in the core.

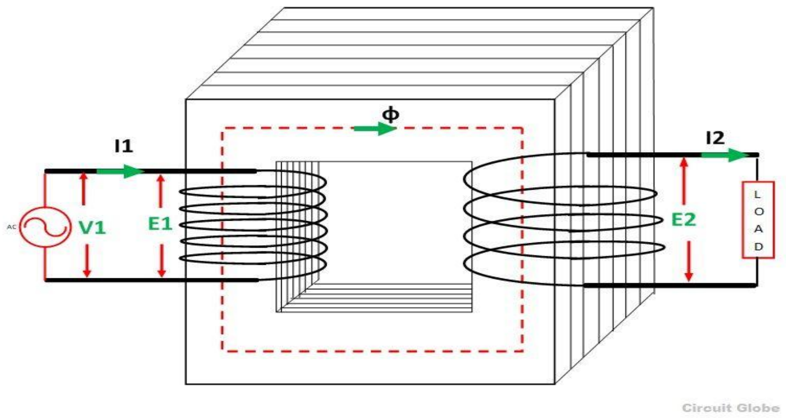


(a) Representation



(b) Construction

WORKING PRINCIPLE: - A transformer works on the principle of mutual induction between two magnetically coupled coils



- The fig shows the general arrangement of a transformer.
- An alternating voltage applied to Primary winding it circulates an alternating current.This current produces an alternating flux in the iron core which completes its path through common magnetic core as shown in dotted line in the above fig .
- This flux induces an Emf 'E1' in primary winding.
- The flux also links secondary winding and thereby induces an emf 'E2' in Secondary.
- Thus though there is no electrical contact between the two windings, an electrical energy gets transferred from primary to secondary.

EMF EQUATION:

Principle:- Whenever a coil is subjected to alternating flux, there will be an induced emf in it and is called the statically induced emf $e = \frac{Nd\phi}{dt}$

Let N_1, N_2 be the no. of turns of the primary and secondary windings, E_1, E_2 the induced emf in the primary and secondary coils. ϕ be the flux which is sinusoidal f be the frequency in Hz

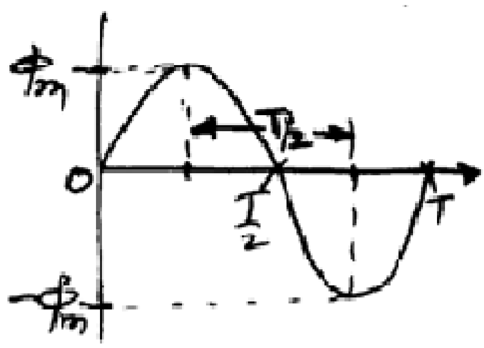


Figure showing the sinusoidal varying flux of peak value Φ_m.

Whenever a coil of N no- of tunes are linked by a time varying flux ϕ, the average emf induced in this coil is

$$e = \frac{Nd\phi}{dt}$$

As the flux is sinusoidal the change in flux from **$+\phi_m$ to $-\phi_m$** is $d\phi$ **= 2ϕ**m, and this change takes place in a duration dt = T/2 seconds.

The average induced emf in these N numbers of turns is

$E_{avg} = N.d\phi/dt = N.2\phi_m / (T/2) = 4\phi_m N/T = 4f\phi_m N$ volts (as f =1/T)

We know that the Form factor of a pure sine wave **F.F. = E_{rms}/E_{avg} = 1.11**

Therefore, **E_{rms} = 1.11 E_{avg}.**

= (1.11) ($4f\phi_m N$) = 4.44 $f\phi_m N$ volts.

In the primary coil**, N = N_1, E1 = $4.44f\phi_m N_1$ volts**

In the secondary coil, N = **N_2 , $E_2 = 4.44f\phi_m N_2$ volts**

LOSSES AND EFFICIENCY:

There are two types of power losses occur in a transformer

1) Iron loss 2) Copper loss

1) Iron Loss (P_i): This is the power loss that occurs in the iron part. This loss is due to the alternating frequency of the emf. Iron loss in further classified into two other losses.

a) Eddy current loss b) Hysteresis loss

The Iron losses are called as the constant losses.

a) Eddy current loss (We) :

- This power loss is due to the alternating flux linking the core, which will induced an emf , due to which a current called the eddy current is being circulated in the core.
- As there is some resistance in the core with this eddy current circulation converts into heat called the eddy current power loss.
- Eddy current loss is proportional to the square of the supply frequency.
- Eddy current loss can be minimized by using the core made of thin sheets of silicon steel material, and each lamination is coated with varnish insulation to suppress the path of the eddy currents.

b) Hysteresis loss (W_h): This is the loss in the iron core, due to the magnetic reversal of the flux in the core, which results in the form of heat in the core. This loss is directly proportional to the supply frequency.

- Hysteresis loss can be minimized by using the core material having high permeability.

Total Iron loss $P_i = W_e + W_h$

2) Copper loss or I^2R losses (Pcu) :
   - This is the power loss that occurs in the primary and secondary coils when the transformer is on load.
   - This power is wasted in the form of heat due to the resistance of the coils.
   - This loss is proportional to the sequence of the load hence it is called the Variable loss where as the Iron loss is called as the Constant loss as the supply voltage and frequency are constants

   Total losses of the transformer = $P_i + P_{cu}$

Efficiency: It is the ratio of the output power to the input power of a transformer

$$\eta = \frac{Output\ \ power}{Input\ \ power}$$

Input = Output + Total losses

= Output + Iron loss + Copper loss

Efficiency =

$$\eta = \frac{outputpower}{outputpower + Ironloss + copperloss}$$

$$= \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + Pi + Pcu}$$

Where, V_2 is the secondary (output) voltage, I_2 is the secondary (output) current and

cosΦ is the power factor of the load.

The transformers are normally specified with their ratings as KVA

Therefore,

$$\text{Efficiency} = \frac{(KVA)(10^3)\cos\Phi}{(KVA)(10^3)\cos\Phi + P_i + Pcu}$$

Since the copper loss varies as the square of the load the efficiency of the transformer at any desired load n is given by

$$\text{Efficiency} = \frac{n\,(KVA)(10^3)\cos\Phi}{n\,(KVA)(10^3)\cos\Phi + P_i + (n)^2\,Pcu}$$

where Pcu is the copper loss at full load

$Pcu = I^2R$ watts

CONDITION FOR MAXIMUM EFFICIENCY:

- In general for the efficiency to be maximum for any device the losses must be minimum.
- Between the iron and copper losses the iron loss is the fixed loss and the copper loss is the variable loss.
- When these two losses are equal and also minimum the efficiency will be maximum.

- The load current at which the efficiency attains maximum value is denoted as I_{2m} and maximum efficiency is denoted as η_{max}.
- The efficiency is a function of load i.e. load current I_2 assuming $\cos\phi_2$ constant. The secondary terminal voltage V_2 is also assumed constant.
- So for maximum efficiency,

$$\frac{d\eta}{dI_2} = 0 \quad \text{while} \quad \eta = \frac{V_2\,I_2\,\cos\phi_2}{V_2\,I_2\,\cos\phi_2 + P_i + I_2^2\,R_{2e}}$$

$$\therefore \quad \frac{d\eta}{dI_2} = \frac{d}{dI_2}\left[\frac{V_2\,I_2\,\cos\phi_2}{V_2\,I_2\,\cos\phi_2 + P_i + I_2^2\,R_{2e}}\right] = 0$$

$$\therefore (V_2\,I_2\,\cos\phi_2 + P_i + I_2^2\,R_{2e})(V_2\cos\phi_2) - (V_2\,I_2\,\cos\phi_2)(V_2\cos\phi_2 + 2I_2\,R_{2e}) = 0$$

- Cancelling $(V_2\cos\phi_2)$ from both the terms we get,

$$V_2\,I_2\,\cos\phi_2 + P_i + I_2^2\,R_{2e} - V_2\,I_2\,\cos\phi_2 - 2\,I_2^2\,R_{2e} = 0 \quad \text{i.e.} \quad P_i - I_2^2\,R_{2e} = 0$$

$$\therefore \quad \boxed{P_i = I_2^2\,R_{2e} = P_{Cu}}$$

So condition to achieve maximum efficiency is that,

Copper losses = Iron losses i.e. $P_i = P_{Cu}$

Therefore the condition for maximum efficiency in a transformer is

Iron loss = Copper loss (whichever is minimum)

****

Problems

1. Find the number of turns on the primary & secondary side of a 440/230 V, 50 Hz single phase transformer, if the net area of cross section of the core is 30 cm^2& the maximum flux density is 1 Wb/m^2
2. A single phase transformer working at 0.8 p.f. has an efficiency 945 at both three fourth full load & full load of 600kW. Determine the eefficiency at half full-load, unity power factor.
3. A 600 kVA, 1 phase transformer has an efficiency of 92% both at full load & half load upf. Determine its efficiency at 75% full load 0.9 p.f.
4. A 50 kVA, 400/200 V, single phase transformer has an efficiency of 98% at full load & 0.8 p.f., while its efficiency is 96.9% at 25% of full load & unity power factor. Determine the iron & full load copper losses & voltage regulation, if the terminal voltage on full load is 195 V.
5. A transformer is rated at 100 kVA. At full load its copper loss is 1200W & its iron loss is 960W. calculate (i) the efficiency at full, upf (ii) the efficiency at half load, 0.9 p.f (iii) the load kVA at which maximum efficiency will occur.
6. The maximum efficiency at full load & upf of a single phase, 25 kVA, 500/1000 V, 50 Hz, transformer is 98%. Determine its efficiency at (i) 75% load, 0.9 p.f. (ii) 50% load, 0.8 p.f. (iii) 25% load, 0.6 p.f.
7. A single phase has 1000 turns on its primary & 400 turns on the secondary. An A.C voltage of 1250 V, 50 Hz is applied to its primary side with the secondary open circuited. Calculate the secondary emf, maximum value of flux density, given that the effective cross sectional area of core is 60 cm^2
8. A 250 kVA, 1 phase transformer has 98.135% efficiency at full load & 0.8 lagging p.f. The efficiency at half load & 0.8 lagging p.f. is 97.751%. calculate the iron loss & full load copper loss.
9. The primary winding of a transformer is connected to a 240 V, 50 Hz supply. The secondary winding has 1500 turns. If the maximum value of the core flux is 0.00207 Wb, determine the secondary emf, number of turns on primary, cross sectional area of the core if the flux density has a maximum value of 0.465 Tesla.
10. A 40 kVA single phase transformer has core loss of 450 W & full load copper loss of 850 W. if the p.f. of the load is 0.8, calculate , (i) full load efficiency (ii) load corresponding to maximum efficiency (iii) maximum efficiency at upf.

Unit 5 (b):

Induction Motors:-

- The asynchronous motors or the induction motors are most widely used ac motors in industry.
- They convert electrical energy in AC form into mechanical energy.
- They work on the principle of electromagnetic induction.
- They are simple and rugged in construction, quite economical with good operating characteristics and efficiency, requiring minimum maintenance, but have a low starting torque.
- They run at practically constant speed from no load to full load condition.
- The 3 - phase induction motors are self starting while the single phase motors are not self starting as they produce equal and opposite torques (zero resultant torque) making the rotor stationary.
- The speed of the squirrel cage induction motor cannot be varied easily.

CLASSIFICATION:

They are basically classified into two types based on the rotor construction

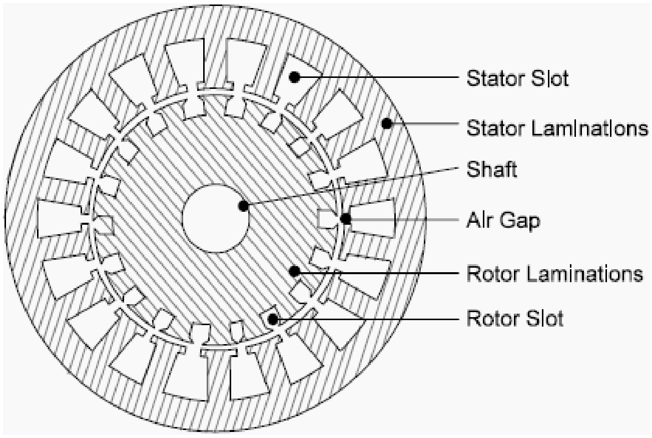
1. Squirrel cage motor
2. Slip ring motor or phase wound motor

CONSTRUCTION

- Induction motor consists of two parts (1) stator (2) rotor

1. Stator

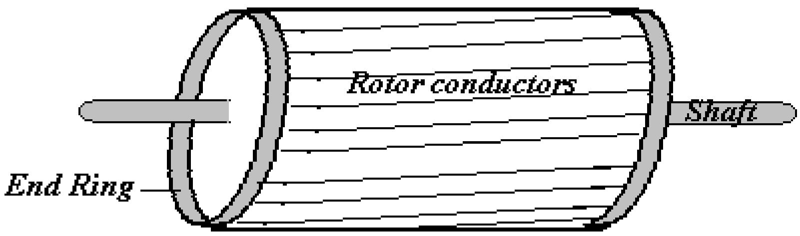
- It is the stationary part of the motor supporting the entire motor assembly.
- This outer frame is made up of a single piece of cast iron in case of small machines.
- In case of larger machines they are fabricated in sections of steel and bolted together.
- The core is made of thin laminations of silicon steel and flash enameled to reduce eddy current and hysteresis losses.
- Slots are evenly spaced on the inner periphery of the laminations.
- Conductors insulated from each other are placed in these slots and are connected to form a balanced 3 - phase star or delta connected stator circuit.
- Depending on the desired speed the stator winding is wound for the required number of poles. Greater the speed lesser is the number of poles.



2. Rotor

1. **Squirrel cage motor :**

- Squirrel cage rotors are widely used because of their ruggedness.
- The rotor consists of hollow laminated core with parallel slots provided on the outer periphery.
- The rotor conductors are solid bars of copper, aluminum or their alloys.
- The bars are inserted from the ends into the semi-enclosed slots and are brazed to the thick short circuited end rings.
- This sort of construction resembles a squirrel cage hence the name "squirrel cage induction motor".
- The rotor conductors being permanently short circuited prevent the addition of any external resistance to the rotor circuit to improve the inherent low starting torque.
- The rotor bars are not placed parallel to each other but are slightly skewed which reduces the magnetic hum and prevents cogging of the rotor and the stator teeth.

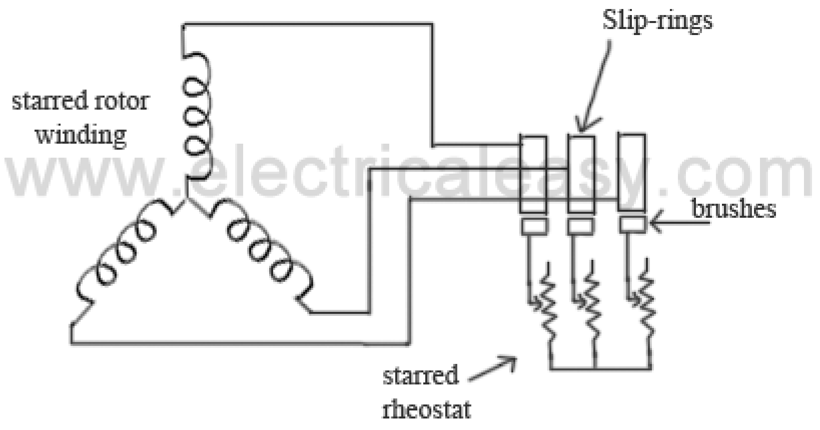


Squirrel cage induction rotor

2. **Slip ring motor or phase wound motor**

- The rotor in case of a phase wound/ slip ring motor has a 3-phase double layer distributed winding made up of coils, similar to that of an alternator.
- The rotor winding is usually star connected and is wound to the number of stator poles.

- The terminals are brought out and connected to three slip rings mounted on the rotor shaft with the brushes resting on the slip rings.
- The brushes are externally connected to the star connected rheostat in case a higher starting torque and modification in the speed torque characteristics are required.
- Under normal running conditions all the slip rings are automatically short circuited by a metal collar provided on the shaft and the condition is similar to that of a cage rotor.
- Provision is made to lift the brushes to reduce the frictional losses. The slip ring and the enclosures are made of phosphor bronze.



Phase wound rotor connections

- In both the type of motors the shaft and bearings (ball and roller) are designed for trouble free operation.
- Fans are provided on the shaft for effective circulation of air.
- The insulated (mica and varnish) stator and rotor windings are rigidly braced to withstand the short circuit forces and heavy centrifugal forces respectively. .
- Care is taken to maintain a uniform air gap between the stator and the rotor.

Comparison of the squirrel cage and slip ring rotors

The cage rotor has the following advantages:

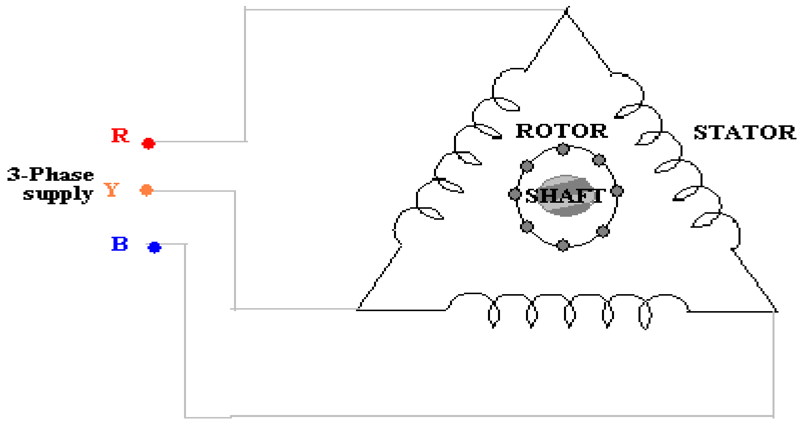
1. Rugged in construction and economical.
2. Has a slightly higher efficiency and better power factor than slip ring motor.
3. The absence of slip rings and brushes eliminate the risk of sparking which helps in a totally enclosed fan cooled (TEFC) construction.

The advantages of the slip ring rotor are:

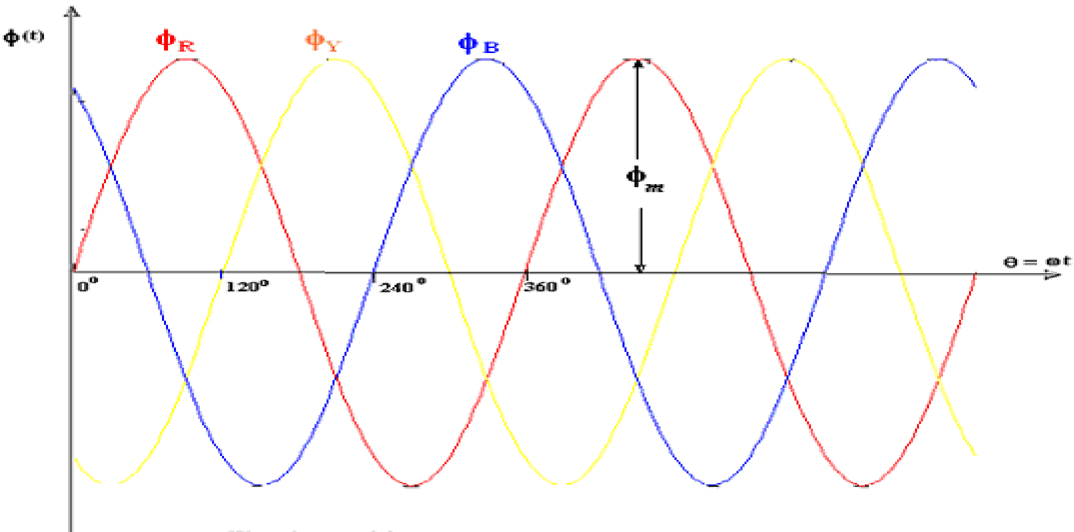
1. The starting torque is much higher and the starting current much lower when compared to a cage motor with the inclusion of external resistance.
2. The speed can be varied by means of solid state switching

ROTATING MAGNETIC FIELD

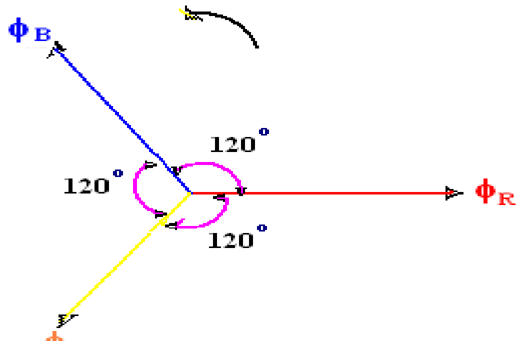
Consider a 3- phase induction motor whose stator windings mutually displaced from each other by 120° are connected in delta and energized by a 3- phase supply.



. The currents flowing in each phase will set up a flux in the respective phases as shown.



Waveforms of the flux in three phases



Phase Sequence RYB - Positive

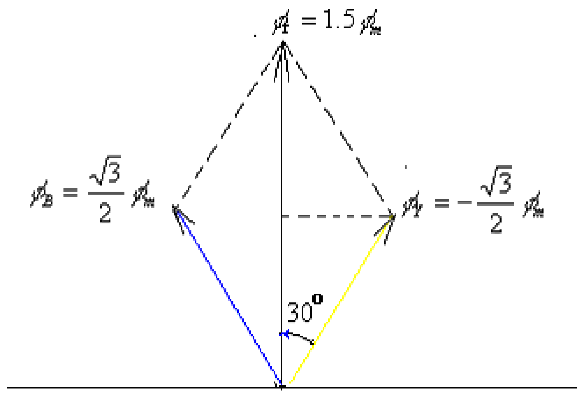
The corresponding phase fluxes can be represented by the following equations

$$\Phi_R = \Phi_m \sin \omega t = \Phi_m \sin \theta$$
$$\Phi_Y = \Phi_m \sin(\omega t - 120°)$$
$$\Phi_Y = \Phi_m \sin(\theta - 120°)$$

$$\Phi_B = \Phi_m \sin(\omega t - 240°)$$
$$\Phi_B = \Phi_m \sin(\theta - 240°)$$

The resultant flux at any instant is given by the vector sum of the flux in each of the phases.

(i) When $\theta = 0^\circ$, from the flux waveform diagram ,we have



Resultant flux at θ = 0°

$$\phi_R = 0$$

$$\phi_Y = \phi_{km} \sin(-120^\circ) = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = \phi_m \sin(-240^\circ) = \frac{\sqrt{3}}{2}\phi_m$$

The resultant flux ϕ_r is given by,

$$\phi_r = 2 * \frac{\sqrt{3}}{2}\phi_m \cos(30^\circ) = 1..5\phi_m$$

$$\phi_B = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_Y = -\frac{\sqrt{3}}{2}\phi_m$$

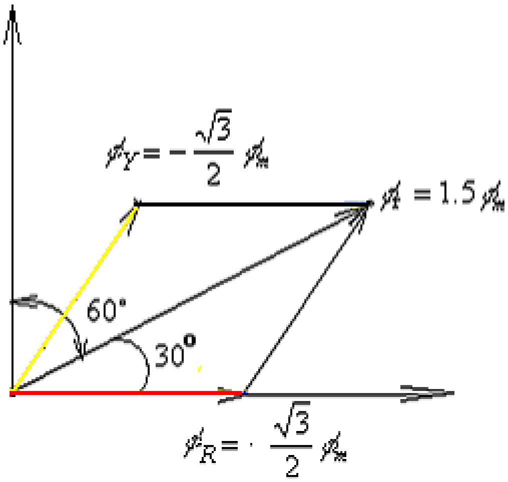
$$\phi_r = 1.5\phi_m$$

(ii) *When* $\theta = 60^o$

$$\phi_R = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_Y = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = 0$$



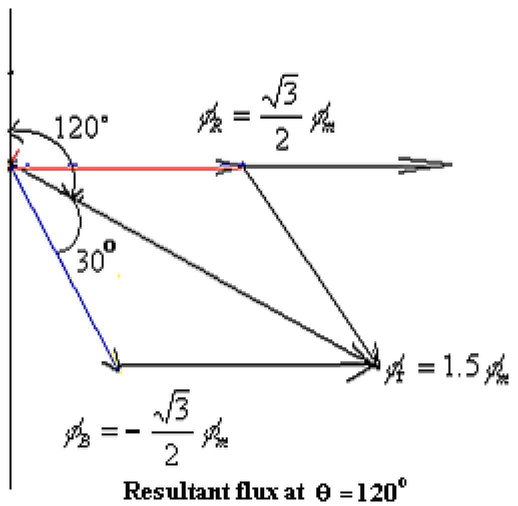
Resultant flux at θ = 60°

(iii) *When* $\theta = 120^\circ$

$$\phi_R = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_Y = 0$$

$$\phi_B = -\frac{\sqrt{3}}{2}\phi_m$$



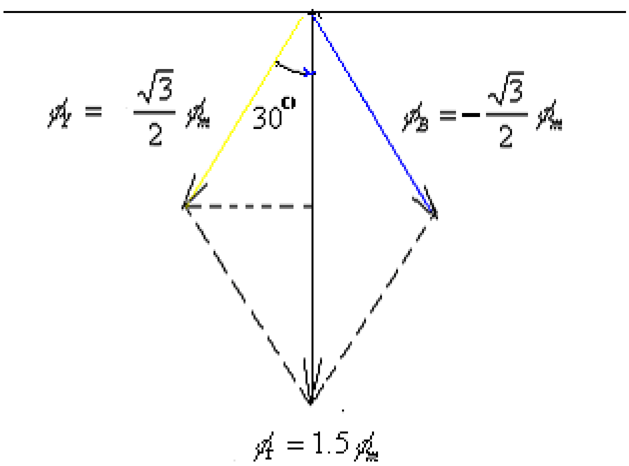
Resultant flux at θ = 120°

(iv) *When* $\theta = 180^\circ$

$$\phi_R = 0;$$

$$\phi_Y = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = -\frac{\sqrt{3}}{2}\phi$$



Resultant flux at θ = 180°

From the above discussion it is very clear that when the stator of a 3-phase induction motor is energized, a magnetic field of constant magnitude (1.5 φ_m) rotating at synchronous speed

(N_s) with respect to stator winding is produced.

WORKING PRINCIPLE:

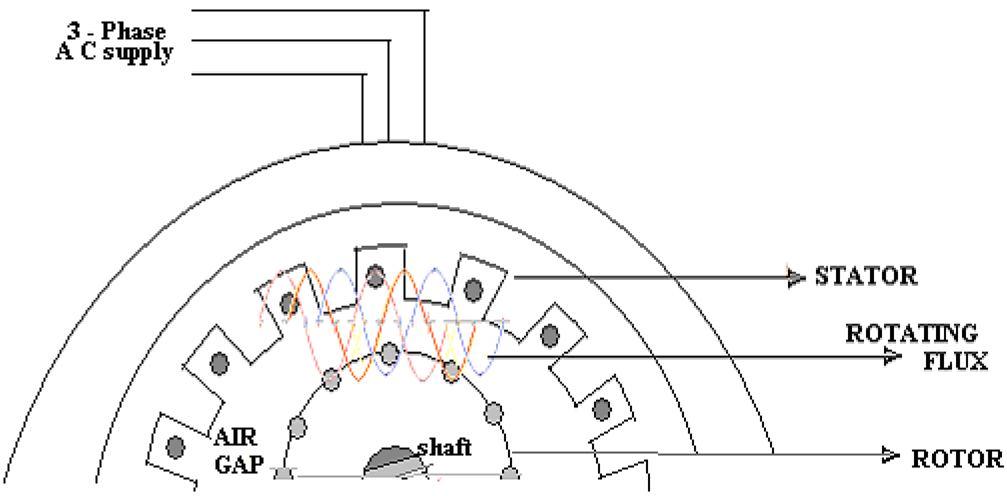
- When a 3-Φ supply is given to the stator winding a magnetic field of constant magnitude 1.5Φm and rotating with the synchronous speed Ns is produced.
- This rotating speed sweeps across the conductors and hence an emf is induced in rotor conductors.
- According to lenz's law, the direction of the induced emf is such as to oppose the very cause producing it. The cause is the relative speed between the rotating magnetic field and static stator
- Since rotor conductors are short circuited by themselves, the induced emf sets up the current in rotor conductors in such a direction to produce torque, which rotates the rotor in same direction as the magnetic field.
- But as the speed of the rotor is in the same direction of rotating magnetic field , the relative speed decreases.
- The speed of the rotor gradually increases and tries to catch up the speed of rotating magnetic field . But if it catches up the speed , then the relative speed becomes zero and hence , no emf will be induced in the rotor conductors hence the torque becomes zero hence motor stops . thus rotor will not be able to catch the speed of the magnetic field ,but rotates at a speed slightly lesser than the synchronous speed.

Consider a 3- phase stator winding energized from a 3 phase supply. As explained earlier a rotating magnetic field is produced running at a synchronous speed N_S

$$N_S = \frac{120\,f}{P}$$

Where f = supply frequency

P = Number of stator poles



CONCEPT OF SLIP (*S*):

- According to Lenz's law, the direction of rotor current will be such that they tend to oppose the cause producing it.
- The cause producing the rotor current is the relative speed between the rotating field and the stationary rotor.
- Hence, to reduce this relative speed, the rotor starts running in the same direction as that of stator field and tries to catch it.
- In practice the rotor can never reach the speed of the rotating magnetic field produced by the stator.
- This is because if rotor speed equals the synchronous speed, then there is no relative speed between the rotating magnetic field and the rotor.
- This makes the rotor current zero and hence no torque is produced and the rotor will tend to remain stationary.
- In practice, windage and friction losses cause the rotor to slow down. Hence, the rotor speed (N) is always less than the stator field speed (N_S).
- Thus the induction motor cannot run with ZERO SLIP. The frequency of the rotor current $f_r = sf$.
- The difference between the synchronous speed (N_S) of the rotating stator field and the actual rotor speed (N) is called the **slip speed.**
- Slip speed = $N_S - N$ depends upon the load on the motor

$$\% \text{ Slip } (s) = \frac{N_S - N}{N_S} * 100$$

Note: In an induction motor the slip value ranges from 2% to 4%

APPLICATIONS OF INDUCTION MOTORS:

Squirrel cage induction motor

- Squirrel cage induction motors are simple and rugged in construction, are relatively cheap and require little maintenance.
- Hence, squirrel cage induction motors are preferred in most of the industrial applications such as in

  i) Lathes
  ii) Drilling machines
  iii) Agricultural and industrial pumps
  iv) Industrial drives.

Slip ring induction motors

- Slip ring induction motors when compared to squirrel cage motors have high starting torque, smooth acceleration under heavy loads, adjustable speed and good running characteristics.

They are used in

i) Lifts
ii) Cranes
iii) Conveyors , etc.,

Necessity of starters for 3 phase induction motor

- When a 3- phase motor of higher rating is switched on directly from the mains it draws a starting current of about 4 -7 times the full load (depending upon on the design) current.
- This will cause a drop in the voltage affecting the performance of other loads connected to the mains.
- Hence starters are used to limit the initial current drawn by the 3 phase induction motors.
- The starting current is limited by applying reduced voltage in case of squirrel cage type induction motor and by increasing the impedance of the motor circuit in case of slip ring type induction motor.
- This can be achieved by the following methods.

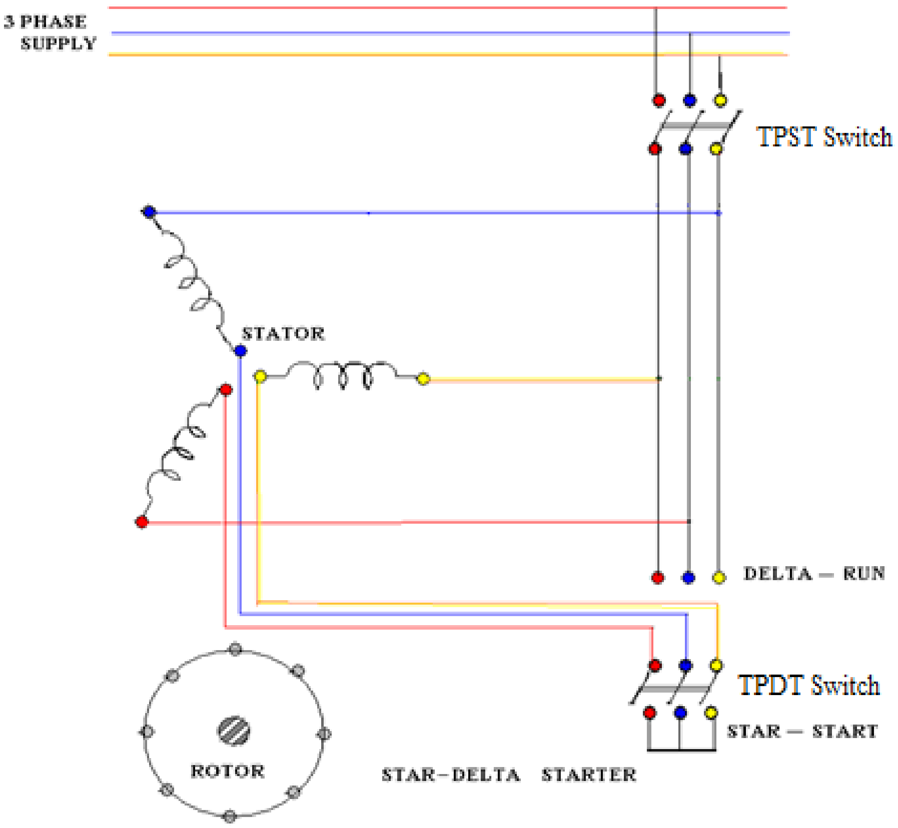
1. Star –delta starter

2. Auto transformer starter

3. Soft starter

Star delta starter

- This is the cheapest starter of all.
- It uses TPDT [Triple pole double through switch] which connects the stator winding in star and in delta during normal running conditions.
- Hence this starter is suitable only for those motors designed to run with the delta connected stator winding.
- The two ends of each phase of the stator winding are drawn out and connected to the starter terminals as shown in the following figure.



Initially when the TPDT Switch is in start position, the stator winding gets connected in star, hence phase voltage gets reduced by a factor of $1/\sqrt{3}$. Due to this starting current also gets reduced by a factor of $1/\sqrt{3}$.

When motor attains 50% to 60% of normal speed, the TPDT switch is thrown in the run position. Hence, the stator winding now gets connected in delta and each phase of the winding gets the rated voltage.

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Problems

1. The frequency of the emf in the stator of a 4 pole induction motor is 50 Hz, & that in the rotor is 1.5 Hz. What is its slip, & at what speed is the motor running?
2. A 4 pole, 3 phase, 50 Hz induction motor runs at a speed of 1470 rpm. Find the frequency of the induced emf in the rotor under this condition
3. A 10 pole induction motor is supplied by a 6 pole alternator which is driven at 1200 rpm. If the motor runs with a slip of 3% , what is its speed?
4. A 3-phase, 6 pole, 50 Hz induction motor has a slip of 1% at no load, & 3% at full load. Determine synchronous speed, no-load speed, full-load speed, frequency of rotor current at stand still & frequency of rotor current at full load.
5. An 8 pole alternator runs at 750 rpm & supplies power to a 6 pole, 3 phase induction motor which runs at 970 rpm. What is the slip of induction motor?
6. If the electromotive force in the stator of an 8 pole induction motor has a frequency of 50 Hz & that in the rotor 1.5 Hz, at what speed is the motor running & what is the slip?
7. A 6 pole, 3 phase, star connected alternator has an armature with 90 slots & 10 conductors/slot. It revolves at 1000 rpm. The flux/pole is 0.05 Wb. Calculate the emf generated/phase, if the winding factor is 0.97 & all conductors in each phase are in series.
8. A 6 pole induction motor supplies from a 3 phase, 50 Hz supply has a rotor frequency of 2.3 Hz. Calculate the %slip & the speed of the motor.