MODULE - 1.

DC CIRCUITS

A SCIENTIST AND AN ENGINEER.

A scientist is concerned with what happens in an electric system and will try to explain its mysteries.

An engineer accepts that electricity is there and seeks to make use of its properties without the need to fully understand them.

Study of electrical engineering can be categorised into four different parts. They are.

1. PRODUCTION 2. TRANSMISSION
3. APPLICATION 4. CONTROL

A BASIC ELECTRICAL SYSTEM :-

It consists of four parts namely.

1. SOURCE 2. TRANSMISSION SYSTEM.
3. CONTROL APPARATUS 4. LOAD.

Source :-

The main function of a source is to provide energy for the electrical system Ex: Generator, Battery or Socket outlet.

TRANSMISSION SYSTEM :- Ex: insulated wires.

The main function of a transmission system is to transfer the energy from the source to the load.

CONTROL APPARATUS :- Ex: Switch.

The main function of the control appratus is to control the flow of power from source to Load.

LOAD :- Ex: Lamps, heaters, Fan

The main function of the load is to absorb the electrical energy supplied by the source

ELECTRIC CIRCUIT

An electrical circuit is an interconnection of the various elements such as,

- VOLTAGE SOURCE
- CURRENT SOURCE
- RESISTORS
- INDUCTORS and
- CAPACITORS.

ELECTRICAL COMPONENTS :-

Electrical components can be basically classified into two categories.

1. ACTIVE COMPONENTS.
2. PASSIVE COMPONENTS.

ACTIVE COMPONENTS :-

Those devices or components which produce energy in the form of voltage or current are called as active components.

Ex :- Diodes, Transistors or SCR, Voltage or current source

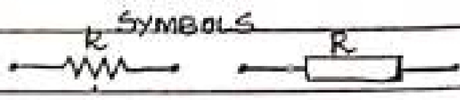
PASSIVE COMPONENTS :-

Those devices or components which store or maintain energy in the form of voltage or current are known as passive components.

Ex :- Resistor, Capacitor, Inductor

PASSIVE COMPONENTS :-

• RESISTOR AND RESISTANCE.

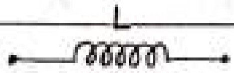


An electrical component which implements electrical resistance i.e the opposition to the flow of electrical current.

Applications :-

1. To reduce current flow
2. To Adjust signal levels, To bias active elements.
3. To terminate transmission lines.

Therefore electrical resistance of an electrical Conductor is a measure of the difficulty to pass an electric current through that conductor. The SI unit of electrical resistance is "OHMS (Ω)"

• INDUCTOR AND INDUCTANCE. 

An electrical component which resists the changes in electrical current passing through it. It is also called as a coil or a reactor. The energy will be stored in a magnetic field in the coil as long as the current flows.

Applications :-

- To block AC and allow DC to pass (chokes)
- In electronic filters to separate signals of different frequencies.
- Also used with capacitors to make tuned circuits

Therefore inductance is the property of an electrical conductor by which a change in current through it induces an electromotive force in both the conductor itself and in any nearby conductors by mutual inductance. The SI unit of electrical inductance is "HENRY (H)"

• CAPACITOR AND CAPACITANCE. 

An electrical component which stores electrical energy temporarily in an electric field formed between the two plates (in a dielectric medium)

Applications :-

- To block DC and allow AC to pass.
- To smooth the output of power supplies
- In tuned circuits.
- To stabilize voltage and Power flow.

Therefore capacitance is the ability of a body to store an electric charge. The SI unit is "FARAD"

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BASIC LAWS IN ELECTRICAL ENGINEERING.

A. OHM'S LAW.

It states that The current through a conductor between two points (Any passive element) is directly proportional to the Voltage across the two points

i.e $I \propto V$ ——— (1)

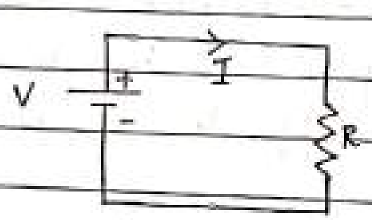
Now If we introduce a proportionality constant i.e the resistance 'R', then the mathematical equation for ohm's law, will be

$V = IR$ ——— (2)

NOTE :- The temperature is assumed to be constant also the diameter length of the material should be fixed. (or it should remain constant)

LIMITATIONS :-

1) It doesn't hold good for non-linear devices such as semiconductors and Zener diodes.
2) It is not applicable to non-metallic conductors such as silicon carbide
3) It cannot be applied to Arc Lamps.
4) It cannot be applied to unilateral networks.



$V \propto I$

$\therefore \frac{V}{I}$ = CONSTANT = R.

i.e $\boxed{V = IR}$

B. KIRCHHOFF'S LAWS.

Kirchhoff's Laws forms the fundemental principles which are used to write the circuit equations. These laws relate to the topology of the circuit.

- KIRCHHOFF'S CURRENT LAW:

It states that The algebriac sum of currents meeting at a junction in a circuit is Zero. In other words, The sum of currents entering a node will be equal to the sum of currents leaving the node.

i.e

Algebriac sum of current entering a node + Algebriac sum of current leaving a node = 0

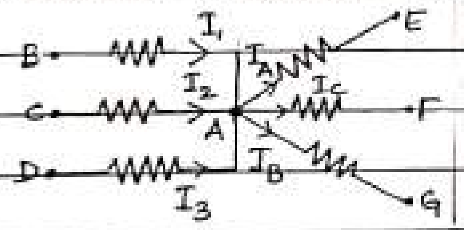
- KIRCHHOFF'S VOLTAGE LAW:

It states that "At any instant, In a closed loop/mesh/circuit, The algebriac sum of Voltage drops and the emf's will be zero

i.e.

Algebriac sum of emf's + Algebriac sum of voltage drops = 0.

KIRCHHOFF'S CURRENT LAW



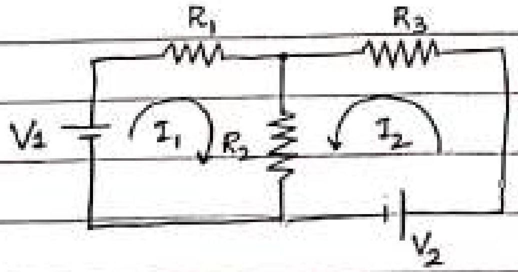
AT NODE A.

$I_1 + I_2 + I_3 = I_A + I_B + I_C$

i.e $I_1 + I_2 + I_3 - (I_A + I_B + I_C) = 0$

$I_1 + I_2 + I_3 - I_A - I_B - I_C = 0$ //

KIRCHHOFF'S VOLTAGE LAW



EMF'S = VOLTAGE DROPS

$V_1 = I_1R_1 + (I_1+I_2)R_2$ —— A

$V_2 = I_2R_3 + (I_1+I_2)R_2$ —— B.

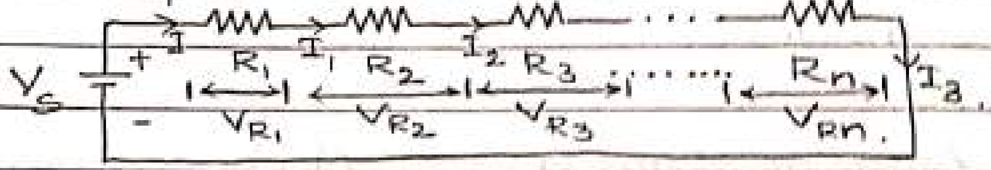
$\therefore$ $V_1 + V_2 = I_1R_1 + I_2R_3 + 2(I_1+I_2)R_2$ //

BASIC ELECTRICAL CIRCUITS.

1. SERIES CIRCUIT.

These are the circuits where 'n' number of resistors are connected in series.

For Example:- Consider the circuit shown



The above circuit shows the series circuit connection of resistors $R_1 \rightarrow R_n$.

Now branch voltages are given as.

V_1 for R_1, V_2 for R_2 and V_n for R_n and V_1, V_2, and V_n are different with respect to the resistor's value.

Therefore

$$V_s = V_1 + V_2 + V_3 - - - - V_n$$

Also the Equivalent/Effective resistance is given by $R = R_{eq} = R_{eff} = R_1 + R_2 + R_3 - - - - R_n$

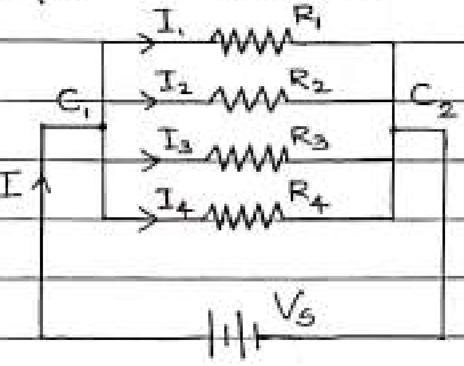
Also it has to be noted that the current will be the same in all parts of the circuit.

i.e $I = I_1 = I_2 = I_3 \cdots\cdots = I_n$.

2. PARALLEL CIRCUIT

These are the circuits where 'n' number of resistors are connected in such a way that one end of all resistors are connected to a common point and the other ends of all resistors are connected to another common point and the supply will be connected across the two common points.

For Example :- Consider the circuit shown.



The above circuit shows the parallel circuit connection of resistors $R_1 \rightarrow R_4$. As we can see that the resistors R_1 to R_4 are so connected that one end of each resistor is connected to C_1 and the other end to C_2.

It can be seen that At node 'C_1' the circuit is divided into '4' branches, Hence the current 'I' is divided into four different currents I_1, I_2, I_3, I_4

$$\therefore \quad I = I_1 + I_2 + I_3 + I_4$$

Also it has to be noted that, As all the resistors are connected accross the Supply 'V_S', The voltage accross each resistor will be the same.

i.e $\quad V_S = V_1 = V_2 = V_3 = V_4$

$$\boxed{\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}.}$$

AC FUNDEMENTALS :-

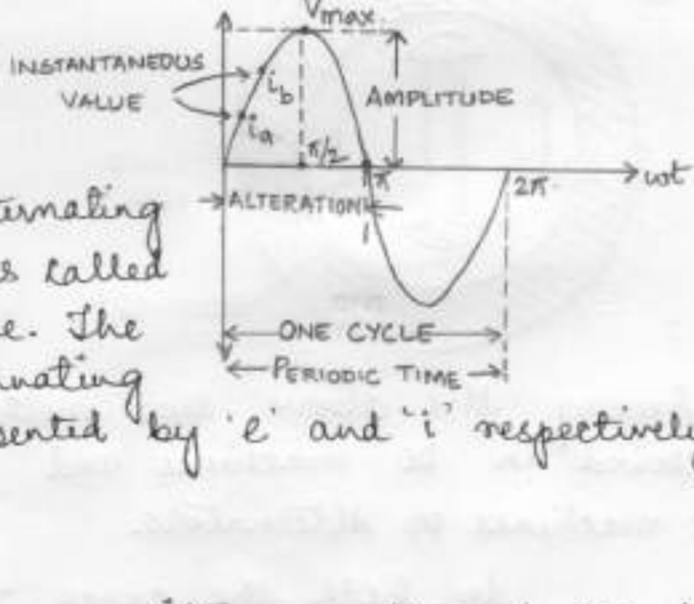
A) Terms frequently used while dealing with a.c. circuits

1. Alternating quantity :-

Any quantity which acts in alternate positive and negative directions, whose magnitude undergoes a definite series of changes in definite intervals of time, is knows as an alternating quantity. In an alternating quantity, The sequence of changes while in positive is identical with the sequence of changes while in negative.

2. Waveform :-

The graph between an alternating quantity and time is called waveform. when alternating quantity is depicted in Y-axis and time along X-axis. as shown in the figure below.



3. Instantaneous value :-

The Value of an alternating quantity at any instant is called as an instantaneous value. The instantaneous values of alternating voltage and current is represented by 'e' and 'i' respectively.

4. Alteration :-

when an alternating quantity goes through one half cycle, it completes an alteration.

5. Cycle :- when an alternating quantity completes one full cycle (set of +ve and -ve values), it completes one cycle.

6. Periodic Time :-

The time taken by an alternating quantity to complete one full cycle is known as periodic time and is denoted by 'T'

7. <u>Amplitude</u> :- ②

The maximum value (positive or negative) which an alternating quantity attains during one complete cycle is called Amplitude / Peak / Maximum value. The amplitude of alternating voltage is represented 'Em' and that of alternating current by 'Im'.

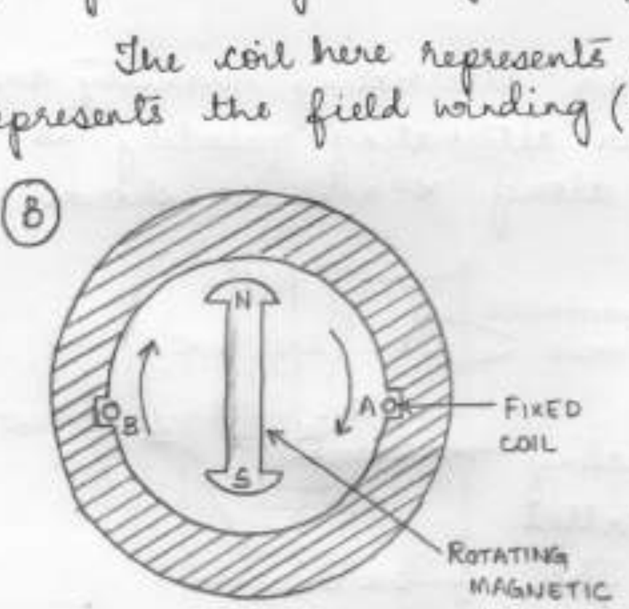
B) GENERATION OF SINUSOIDAL AC VOLTAGE.

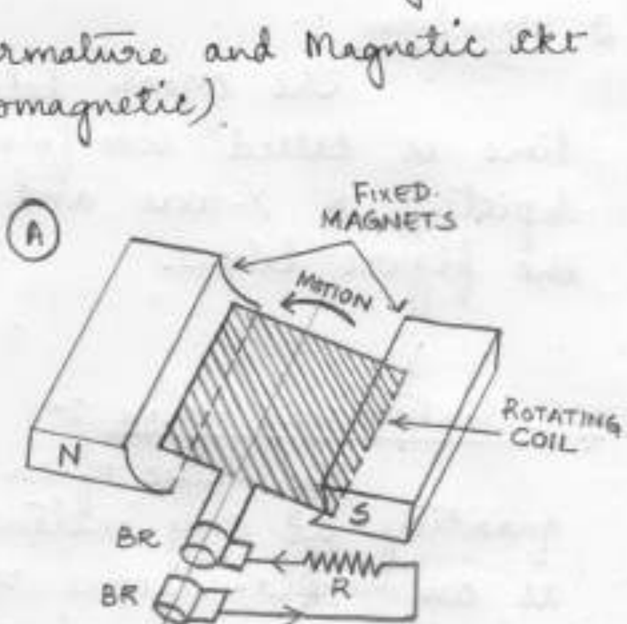
Alternating voltage may be generated

a) By rotating a coil in a magnetic field (Fig A)

b) By rotating a magnetic field within a stationary coil (Fig B)

The coil here represents the armature and Magnetic ckt represents the field winding (Electromagnetic)





Among the above two methods, method 'a' will be followed in DC machines and Method 'b' will be used in AC machines or Alternators.

In both the cases, The value of the alternating voltage generated depends upon

i) No of turns in the coil (N)

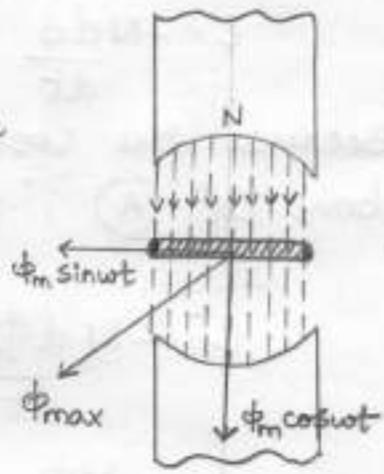
ii) The strength of the magnetic field

iii) The speed at which the coil or Magnetic field rotates.

The alternating voltage generated has regular changes in magnitude and direction. If a load is connected across the alternating voltage, An alternating current flows in the circuit.

c) Equation of alternating emf :-

Consider a rectangular coil of 'N' turns rotating in anticlockwise direction, with an angular velocity of 'ω' radians per second, in a uniform magnetic field as shown.



Assume that the plane of the coil is coincidence with the x-axis. At this instant maximum flux, ϕ_{max} links with the coil.

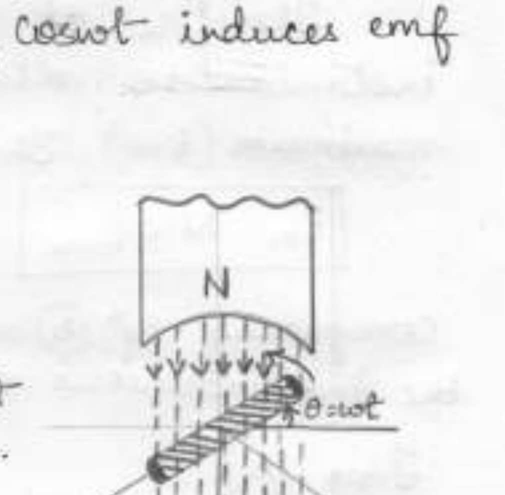
As and when the coil starts rotating, The flux linking with the coil also changes, and hence an emf is induced in the coil. (By Faraday's first law)

The maximum flux linking with the coil which is acting vertically downwards can be resolved into two components, which are perpendicular to each other. They are

- $\phi_{max} \sin\omega t$ parallel to the plane of the coil
- $\phi_{max} \cos\omega t$ perpendicular to the plane of the coil.

Out of the two components $\phi_{max} \cos\omega t$ induces emf in the coil.

Let us assume that the coil is rotating and has turned through an angle 'θ' in time 't' seconds. Obviously $\theta = \omega t$. When the coil is in this position, The cosine component of ϕ_{max} will induce an emf in the coil.



As per faraday's law, emf induced in a coil is given by.

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

where N = No of turns in the coil

$\frac{d\phi}{dt}$ = Rate of change of flux linking with the coil.

Now

$$e = -N\frac{d\phi}{dt} \quad \text{——— (A)}$$

Because the cosine component induces the emf, In the above eq^n (A), 'ϕ' is replaced by $\phi_{max} \cos\omega t$

$$e = -N\frac{d\phi_{max}\cos\omega t}{dt}$$

$$= -N\phi_{max}\frac{d\cos\omega t}{dt}$$

$$= -N\phi_{max}\omega\left[-\sin\omega t\right]$$

$$\boxed{e = N\phi_{max}\omega \sin\omega t} \text{ volts} \quad \text{——— (B)}$$

where 'e' represents the instantaneous voltage.

Consider the eq^n (B). The schematic and waveform shown below explains that '$\phi_{max}\sin\omega t$' term in eq^n (B) will be equal to 'ϕ_{max}' when $\theta = \omega t = 90°$

Therefore at $\theta = \omega t = 90°$, The instantaneous voltage 'e' will be maximum (E_m), Therefore

$$\boxed{E_m = N\omega\phi_{max}} \quad \text{——— (C)}$$

comparing eq^n (B) and (C) we can derive the relation between the Instantaneous voltage 'e' and Maximum voltage 'E_m'

from (B)

$$e = N\omega\phi_{max}\sin\omega t$$

from (C) $E_m = N\omega\phi_{max}$. Substituting eq^n (C) in eq^n (B)

$$\boxed{e = E_m \sin\omega t} \text{ volts}$$

$$e = E_m \sin\omega t = E_m \sin\theta = E_m \sin[2\pi f t] = E_m \sin\left[\frac{2\pi}{T}\cdot t\right]$$

D) Root-Mean-Square (R.m.s) Value of an alternating quantity (or) Effective value of an alternating quantity.

It is defined as "The DC current which when flowing through a given resistance for a given time produces the same amount of heat as produced by the alternating current, when flowing through the same resistor for the same time."

E) Expression for r.m.s value of an alternating quantity.

To get the r.m.s value of an alternating quantity the following steps have to be followed.

1. Calculate the square of all instantaneous values for the angle duration $0-\pi$ and find the area covered by each strip of the squared wave $[i^2 d\theta]$
2. Take the mean of all the strip areas "$i_0^2 d\theta_{0}$" upto "$i_n^2 d\theta_\pi$" from $[0 \rightarrow \pi \text{ radians}]$
3. Find out the square root of the mean of all strip

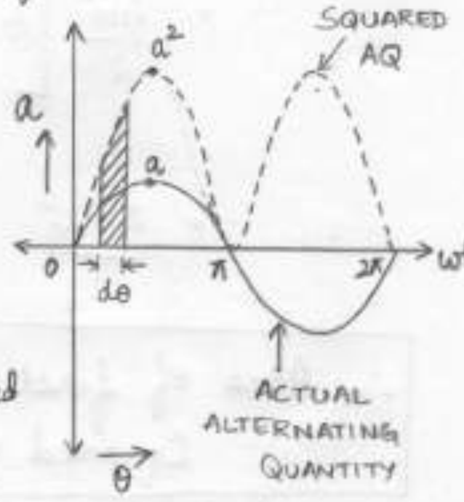
Derivation :-

Let us consider an alternating quantity 'A'. we Know that the instantaneous value of 'A' is given by

$$a = A_m \sin\theta$$

Let the quantity be represented by a sine wave as shown.

Let us consider an elementary strip of thickness '$d\theta$' in the first half cycle of the squared wave represented by dotted lines.



The instantaneous value of this strip will be "a^2"

Therefore area of the strip $= a^2 d\theta$

Area of the first half cycle of squared wave $= \int_0^{\pi} a^2 d\theta$

But $a = A_m \sin\theta$

$$= \int_0^{\pi} (A_m \sin\theta)^2 . d\theta$$

$$= A_m^2 \int_0^{\pi} \sin^2\theta . d\theta$$

$$= A_m^2 \int_0^{\pi} \left[\frac{1-\cos 2\theta}{2}\right] . d\theta \qquad \because \sin^2\theta = \frac{1-\cos 2\theta}{2}$$

$$= \frac{A_m^2}{2} \int_0^{\pi} (1-\cos 2\theta) . d\theta$$

$$= \frac{A_m^2}{2} \left[\int_0^{\pi} 1 . d\theta - \int_0^{\pi} \cos 2\theta . d\theta\right]$$

$$= \frac{A_m^2}{2} \left[\theta - \frac{\sin 2\theta}{2}\right]_0^{\pi} = \frac{A_m^2}{2} \left[(\pi - 0) - (0 - 0)\right]$$

$$= \frac{\pi A_m^2}{2}$$

$\therefore$ Area of first half cycle of Squared wave $= \frac{\pi A_m^2}{2}$

Now $A_{rms} = \sqrt{\dfrac{\text{Area of first half cycle of squared wave}}{\text{Base (Total samples)}}}$

Here Total samples = π

$$\therefore \quad A_{rms} = \sqrt{\frac{0.5\pi A_m^2}{\pi}} = \sqrt{\frac{A_m^2}{2}}$$

$$A_{rms} = \frac{A_m}{\sqrt{2}} = 0.707 A_m$$

$$\therefore \quad \boxed{A_{rms} = 0.707 A_m} \text{ volts}$$

For current $I_{rms} = 0.707\, I_m$ amps

Voltage $V_{rms} = 0.707\, V_m$ volts.

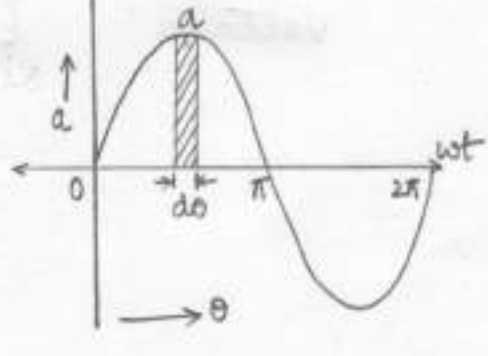
F) Average Value of an alternating quantity.

It is defined as "the arithmetical average of all the values of an alternating quantity over one cycle".

An alternating quantity is always represented by a sinusoidal wave which is symmetrical in nature. Therefore the positive half is exactly equal to the negative half. Therefore, the average value over the entire cycle is zero. Hence in this case the averge value is obtained by adding the instantaneous values of alternating quantity over one half cycle. consider alternating quantity 'A'

W.K.t $a = A_m \sin\theta$

Let us consider an elementary strip of thickness '$d\theta$' in the first half cycle as shown. The Mid-ordinate be 'e' the instantaneous value at $d\theta$.



∴ Area of the strip = $a.d\theta$

Total area covered by first half cycle = $\int_0^{\pi} a.d\theta$

But $a = A_m \sin\theta$

$$\therefore \quad = \int_0^{\pi} (A_m \sin\theta)\, d\theta$$

$$= A_m \int_0^{\pi} \sin\theta \, . \, d\theta$$

$$= A_m \left[-\cos\theta\right]_0^{\pi} = A_m\left[-\cos\pi + \cos 0\right] = \left[1 + 1\right] A_m$$

$$\boxed{\text{Area of one half cycle} = 2A_m}$$

$$\therefore \text{Average value} = \frac{\text{Area of one half cycle}}{\text{Base (Total samples)}}$$

$$A_{avg} = \frac{2A_m}{\pi} = 0.637\, A_m$$

$$\therefore \quad \boxed{A_{avg} = 0.637\, A_m}$$

For current $\quad I_{avg} = 0.637\, I_m$ amps.

Voltage $\quad E_{avg} = V_{avg} = 0.637\, V_m$ volts.

Single-phase A.C. Circuits

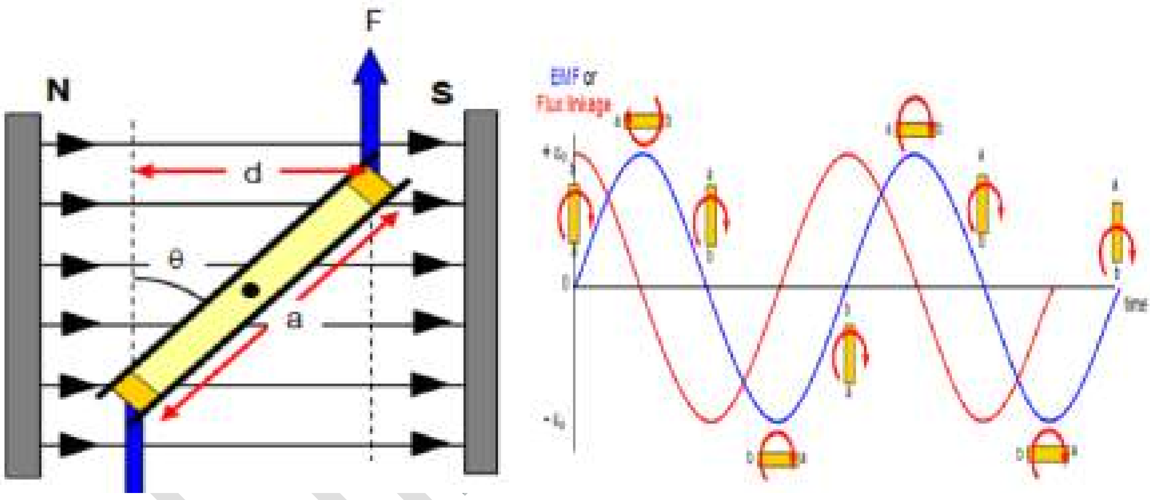
Syllabus: Generation of sinusoidal voltage, frequency of generated voltage, definition and numerical values of average value, root mean square value, form factor and peak factor of sinusoidally varying voltage and current, phasor representation of alternating quantities. Analysis, with phasor diagrams, of R, L, C, R-L, R-C and R-L-C circuits and, parallel and series- parallel circuits. Real power, reactive power, apparent power and power factor.

Introduction:

- An Alternating Current is one in which the magnitude and direction of an electrical quantity changes with respect to time.

Generation of sinusoidal voltage:

- Consider a rectangular coil of N turns placed in a uniform m gnetic field as shown in the figure.



- he coil is rotating in the anticlockwise direction at a uniform angular velocity of ω rad/sec.
- When the coil is in the vertical position, the flux linking the coil is zero because the plane of the coil is parallel to the direction of the magnetic field. Hence at this position, the emf induced in the coil is zero.
- When the coil moves by some angle in the anticlockwise direction, there is a rate of change of flux linking the coil and hence an emf is induced in the coil.
- When the coil reaches the horizontal position, the flux linking the coil is maximum, and hence the emf induced is also maximum.
- When the coil further moves in the anticlockwise direction, the emf induced in the coil reduces.
- Next when the coil comes to the vertical position, the emf induced becomes zero.
- After that the same cycle repeats and the emf is induced in the opposite direction.
- When the coil completes one complete revolution, one cycle of AC voltage is generated.
- An alternating quantity changes continuously in magnitude and alternates in direction at regular intervals of time.

Important terms associated with an alternating quantity are defined below.

1. Amplitude
   - It is the maximum value attained by an alternating quantity. Also called as maximum or peak value.

2. Time Period (T)
   - It is the Time Taken in seconds to complete one cycle of an alternating quantity.

3. Instantaneous Value
   - It is the value of the quantity at any instant.

4. Frequency (f)
   - It is the number of cycles that occur in one second. The unit for f equency is Hz or cycles/sec.
   - The relationship between frequency and time period can be de ived as follows.
   - Time taken to complete f cycles = 1 second
   - Time taken to complete 1 cycle = 1/f second

$$T = 1/f$$

5. Angular Frequency (ω)
   - Angular frequency is defined as the num er of radians covered in one second(ie the angle covered by the rotating coil).
   - The unit of angular frequency s rad/sec.
   - The component of flux acting along the plane of the coil does not induce any flux in the coil. Only the component acting perpendicular to the plane of the coil

i.e Φ_{max} cosωtd induces an emf in the coil.

$e = -N \quad \Phi_{max} \cos\omega t / dt$

$e = N\Phi_{max}\, \omega \sin$

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

<u>Advantages of AC system over DC system</u>

1. AC voltages can be efficiently stepped up/down using transformer.
2. AC motors are cheaper and simpler in construction than DC motors.
3. Switchgear for AC system is simpler than DC system.

Average Value

- The arithmetic average of all the values of an alternating quantity over one cycle is called its average value

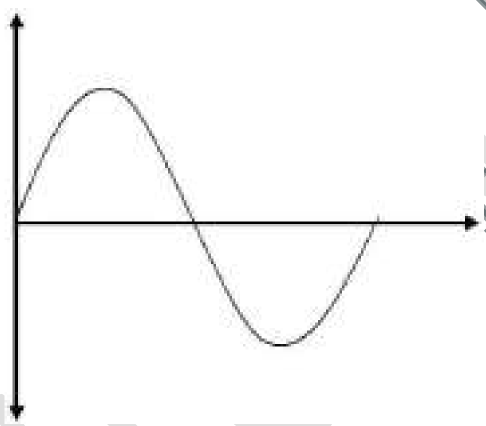
$$\text{Average value} = \frac{\text{Area under one cycle}}{\text{Base}}$$

- For Symmetrical waveforms, the average value calculated over one cycle becomes equal to zero because the positive area cancels the negative area.
- Hence for symmetrical waveforms, the average value is calculated for half cycle.

$$V_{av} = \frac{1}{2\pi}\int_0^{2\pi} v\,d(\omega t)$$

$$V_{av} = \frac{1}{\pi}\int_0^{\pi} v\,d(\omega t)$$

Average value of a sinusoidal current



$$i = I_m \sin \omega t$$

$${}_{av} = \frac{1}{\pi}\int_0^{\pi} i\,d(\omega t)$$

$${}_{av} = \frac{1}{\pi}\int_0^{\pi} I_m \sin \omega t\,d(\omega t)$$

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

Average value of a full wave rectifier output

$$i = I_m \sin \omega t$$

$${}_{av} = \frac{1}{\pi}\int_0^{\pi} i\,d(\omega t)$$

$$I_{av} = \frac{1}{\pi}\int_0^{\pi} I_m \sin \omega t d(\omega t)$$

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

Average value of a half wave rectifier output

$$i = I_m \sin \omega t$$

$$I_{av} = \frac{1}{2\pi}\int_0^{2\pi} i d(\omega t)$$

$$I_{av} = \frac{1}{2\pi}\int_0^{\pi} I_m \sin \omega t d(\omega t)$$

$$I_{av} = \frac{I_m}{\pi} = 0.318 I_m$$

RMS or Effective Value

- The effective or RMS value of an alternating quantity is that steady current (dc) which when flowing through a given resistance for a given time produces the same amount of heat produced by the alternating current flowing through the same resistance for the same time.

$$V_{rms} = \frac{1}{2\pi}\int_0^{2\pi} v d(\omega t)$$

RMS value of a sinusoidal current

$$i = I_m \sin \omega t$$

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

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2 \omega t d(\omega t)}$$

$$I_{rms} = \frac{I_m}{\sqrt{2}} = 0.707 I_m$$

Form Factor

The ratio of RMS value to the average value of an alternating quantity is known as Form Factor

$$FF = \frac{RMS\ Value}{Average\ Value}$$

Peak Factor or Crest Factor

The ratio of maximum value to the RMS value of an alte nating quantity is known as the peak factor

$$PF = \frac{MaximumValue}{RMSValue}$$

Phasor Representation

- An alternating quantity can be represented using

(i) Waveform

(ii) Equations

(iii) Phasor

- A sinusoidal alternating quantity can be represented by a rotating line called a **Phasor.**
- A phasor is a line of definite length rotating in anticlockwise direction at a constant angular velocity.

Phase

- Phase is defined as the fractional part of time period or cycle through which the quantity has advanced from the selected zero position of reference.

Phase Difference

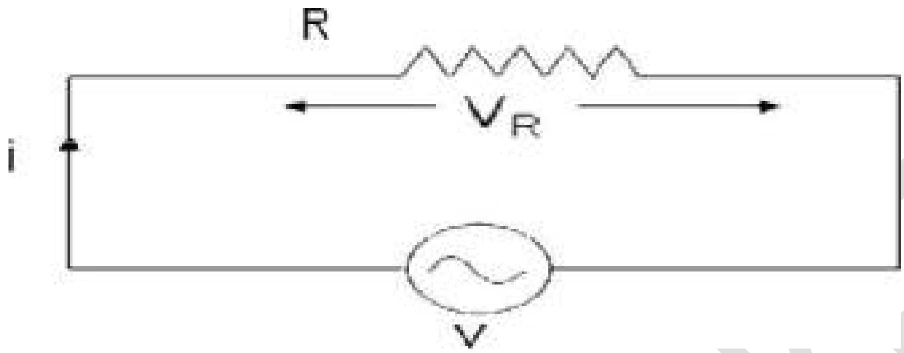
- When two alternating quantities of the same frequency have different zero points, they are said to have a phase difference. The angle between the zero points is the angle of phase difference.

In Phase

- Two waveforms are said to be in phase, when the phase difference between them is zero. That is the zero points of both the waveforms are same.

- The waveform, phasor and equation representation of two sinusoidal quantities which are in phase is as shown. The figure shows that the voltage and current are in phase.

AC circuit with a pure resistance



Consider an AC circuit with a pure resistance R as shown in the figu e. The lternating voltage v is given by

$$v = V_m \sin \omega t \text{ ---------- (1)}$$

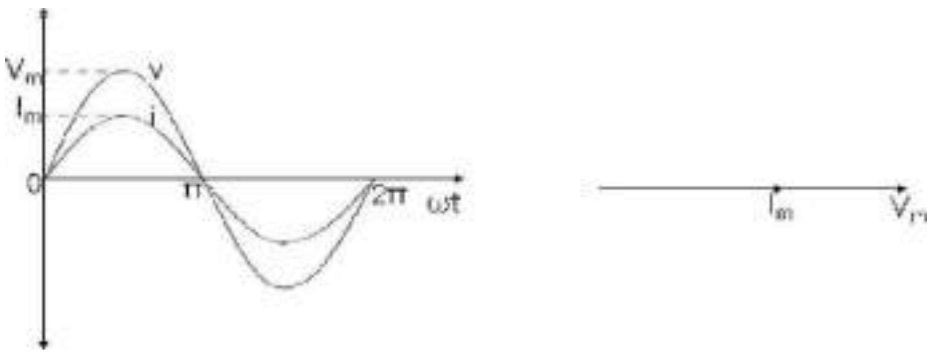
The current flowing in the circuit is i. The voltage across the resistor is given as V_R which is the same as v.
Using ohms law, we can write the follow ng relat ons

$$i = \frac{v}{R} = \frac{V_m \sin \omega t}{R}$$

$$i = I_m \sin \omega t \qquad (2)$$

Where $I_m = \frac{V_m}{R}$

From equation (1) and (2) we conclude that in a pure resistive circuit, the voltage and current are in phase. Hence the voltage and current waveforms and phasor can be drawn as below.



Instantaneous power

The instantaneous power in the above circuit can be derived as follows

$$p = vi$$

$$p = (V_m \sin \omega t)(I_m \sin \omega t)$$

$$p = V_m I_m \sin^2 \omega t$$

$$p = \frac{V_m I_m}{2}(1 - \cos 2\omega t)$$

$$p = \frac{V_m I_m}{2} - \frac{V_m I_m}{2} \cos 2\omega t$$

The instantaneous power consists of two terms. The fi st te m is c lled s the constant power term and the second term is called as the fluctuating power te m.

Average power

From the instantaneous power we can f nd the average power over one cycle as follows

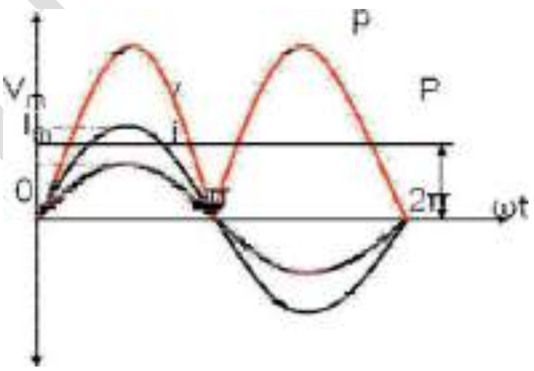
$$P = \frac{1}{2\pi} \int_0^{2\pi} \frac{V_m I_m}{2} - \frac{V_m I_m}{2} \cos 2\omega t \, d\omega t$$

$$P = \frac{V_m I_m}{2} - \frac{1}{2\pi} \int_0^{2\pi} \frac{V_m I_m}{2} \cos 2\omega t \, d\omega t$$

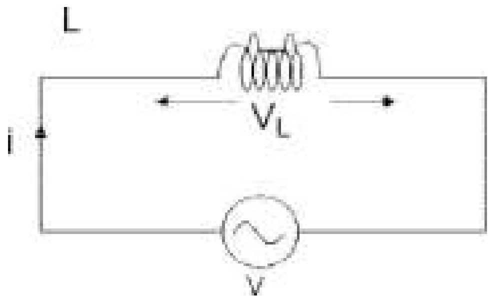
$$P = \frac{V_m I_m}{2} = \frac{V_m}{\sqrt{2}} \frac{I_m}{\sqrt{2}}$$

$$P = V.I$$

As seen above the average power is the product of the rms voltage and the rms current.



AC circuit with a pure inductance



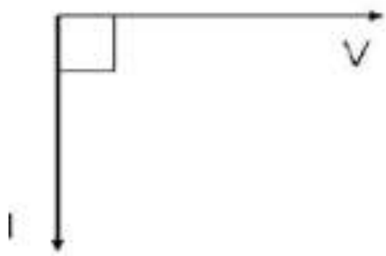
Consider an AC circuit with a pure inductance L as shown in the figu e. The alte nating voltage v is given by

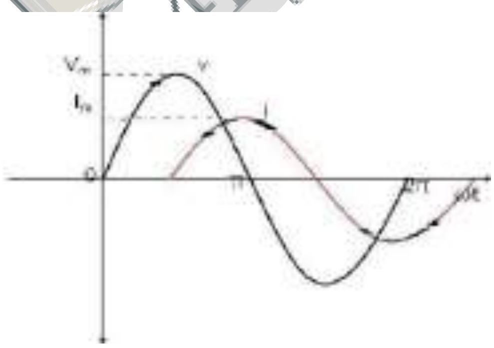
$$v = V_m \sin \omega t \quad \text{----------} \ (1)$$

The current flowing in the circuit is i. The voltage ac oss the inductor is given as V_L which is the same as v.

We can find the current through the inductor as follows

From equation (1) and (2) we observe that n a pure nductive circuit, the current lags behind the voltage by 90^o. Hence the voltage and current waveforms and phasors can be drawn as below.





Inductive reactance

The inductive reactance X_L is given as

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

$$I_m = \frac{V_m}{X_L}$$

It is equivalent to resistance in a resistive circuit. The unit is ohms ( )

Instantaneous power

The instantaneous power in the above circuit can be derived as follows

$$P = vi$$
$$= (V_m \sin \omega t)(I_m \sin(\omega t - \pi/2))$$
$$= -V_m I_m \sin \omega t \cos \omega t$$
$$= -\frac{V_m I_m}{2} \sin 2\omega t$$

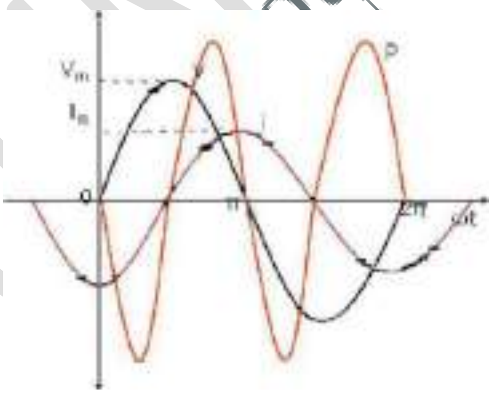
Average power

From the instantaneous power we can find the average power over one cycle as follows

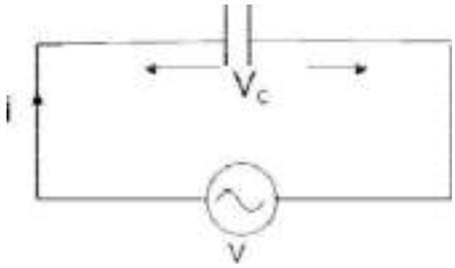
$$P = \frac{1}{2\pi}\int_0^{2\pi} -\frac{V_m I_m}{2} \sin 2\omega t \, d\omega t$$
$$P = 0$$

The average power in a pure inductive c rcu t s zero. Or in other words, the power consumed by a pure inductance is zero.

The voltage, current and power waveforms of a purely inductive circuit is as shown in the figure.



AC circuit with a pure capacitance



$$q = Cv$$

$$q = CV_m \sin \omega t$$

$$i = \frac{dq}{dt}$$

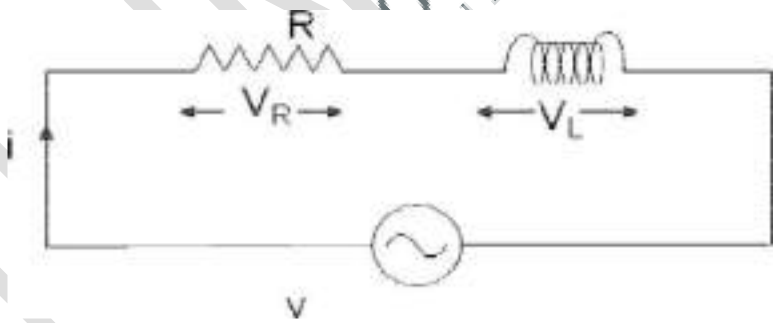
$$i = CV_m\omega \cos \omega t$$

$$i = \omega CV_m \sin(\omega t + \pi / 2)$$

$$i = I_m \sin(\omega t + \pi / 2)$$ --------------------(2)

Where $I_m = \omega CV_m$

R-L Series circuit



Consider an AC circuit with a resistance R and an inductance L connected in series as shown in the figure. The alternating voltage v is given by

$$v = V_m \sin \omega t$$

The current flowing in the circuit is i. The voltage across the resistor is V_R and that across the inductor is V_L.

V_R=IR is in phase with I

V_L=IX_L leads current by 90 degrees

With the above information, the phasor diagram can be drawn as shown.

The current I is taken as the reference phasor. The voltage V_R is in phase with I and the voltage V_L leads the current by 90^o. The resultant voltage V can be drawn as shown in the figure. From the phasor diagram we observe that the voltage leads the current by an angle Φ or in other words the current lags behind the voltage by an angle Φ.

From the phasor diagram, the expressions for the resultant voltage V and the angle Φ can be derived as follows.

$$V = \sqrt{V_R^2 + V_L^2}$$

$$V_R = IR$$

$$V_L = IX_L$$

$$V = \sqrt{(IR)^2 + (IX_L)^2}$$

$$V = I\sqrt{R^2 + X_L^2}$$

$$V = IZ$$

Where impedance

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

The impedance in an AC circuit is similar to a resistance in a DC circuit. The unit for impedance is ohms ( ).

Instantaneous power

The instantaneous power in an RL series circuit can be derived as follows

$$p = vi$$

$$p = (\ _m \sin \omega t)(I_m \sin(\omega t - \Phi))$$

$$p = \frac{_m I_m}{2}\cos\Phi - \frac{V_m I_m}{2}\cos(2\omega t - \Phi)$$

The instantaneous power consists of two terms. The first term is called as the constant power term and the second term is called as the fluctuating power term.

Average power

From the instantaneous power we can find the average power over one cycle as follows

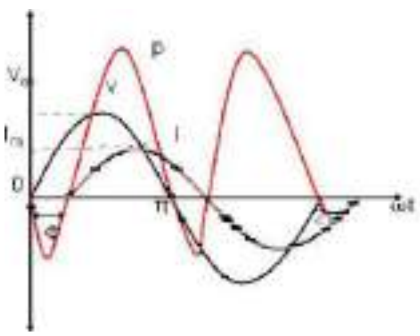
$$P = \frac{1}{2\pi}\int_0^{2\pi}\frac{V_m I_m}{2}\cos\Phi - \frac{V_m I_m}{2}\cos(2\omega t - \Phi)\ d\omega t$$

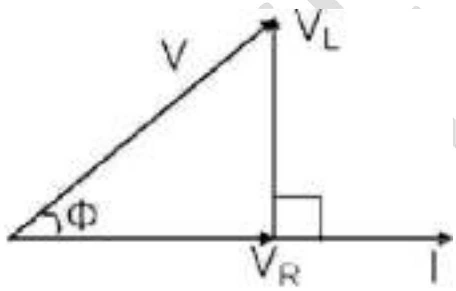
$$P = \frac{V_m I_m}{2}\cos\Phi$$

$$P = \frac{V_m}{\sqrt{2}}\frac{I_m}{\sqrt{2}}\cos\Phi$$

$$P = VI\cos\Phi$$

The voltage, current and power waveforms of a RL series circuit is as shown in the figure.





As seen from the power waveform, the instantaneous power is alternately positive and negative. When the power is positive, the power flows from the source to the load and when the power in negative, the power flows from the load to the source. The positive power is not equal to the negative power and hence the average power in the circuit is not equal to zero.

From the phasor diagram,

$$P = (IZ)\cdot I\cdot\frac{R}{Z}$$

$$P = I^2 R$$

Hence the power in an RL series circuit is consumed only in the resistance.
The inductance does not consume any power.

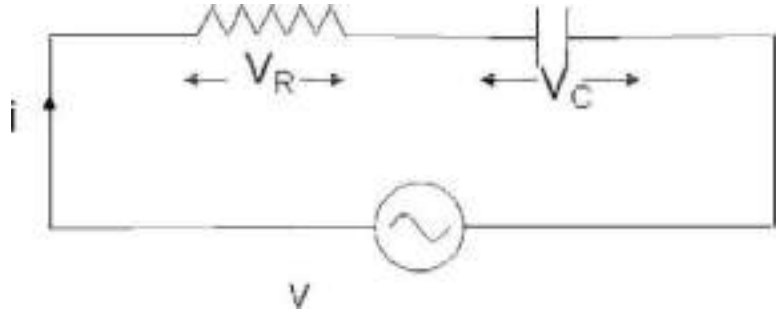
Power Factor

The power factor in an AC circuit is defined as the cosine of the angle between voltage and current ie cosΦ

$$P = VI\cos\Phi$$

The power in an AC circuit is equal to the product of voltage, current and power factor

R-C Series circuit



Consider an AC circuit with a resistance R and a capacitance C connected in se ies as shown in the figure. The alternating voltage v is given by

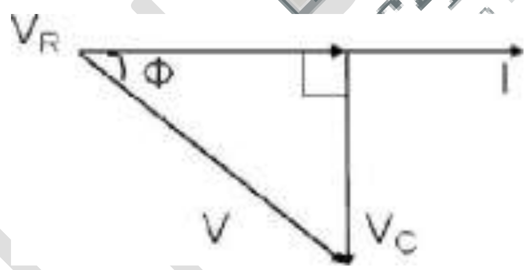
$$v = V_m \sin \omega t$$

The current flowing in the circuit is i. The voltage ac oss the esistor is V_R and that across the capacitor is V_C.

V_R=IR is in phase with I

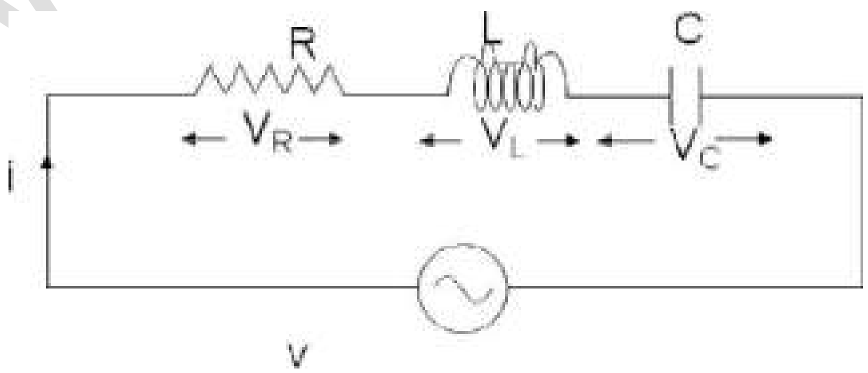
V_C=IX_C lags behind the current by 90 degrees

With the above information, the phasor diagram can be drawn as shown.



The current I is taken as the reference phasor. The voltage V_R is in phase with I and the voltage $_C$ lags behind the current by 90°. The resultant voltage V can be drawn as shown in the figure. From the phasor diagram we observe that the voltage lags behind the current by an angle Φ or in other words the current leads the voltage by an angle Φ.

R-L-C Series circuit



Consider an AC circuit with a resistance R, an inductance L and a capacitance C connected in series as shown in the figure. The alternating voltage v is given by

$$v = V_m \sin \omega t$$

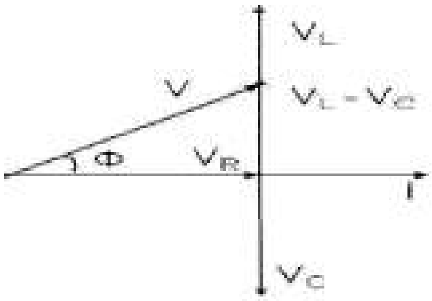
The current flowing in the circuit is i. The voltage across the resistor is V_R, the voltage across the inductor is V_L and that across the capacitor is V_C.

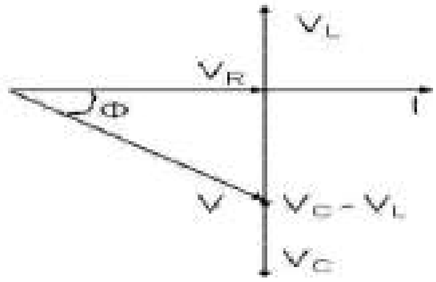
V_R=IR is in phase with I

V_L=IX_L leads the current by 90 degrees

V_C=IX_C lags behind the current by 90 degrees

With the above information, the phasor diagram can be drawn as shown. The current I is taken as the reference phasor. The voltage V_R is in ph se with I, the voltage V_L leads the current by 90° and the voltage V_C lags behind the current by 90°. There re two cases that can occur V_L>V_C and V_L<V_C depending on the values of X L nd X_C. And hence there are two possible phasor diagrams. The phasor V_L-V_C or V_C-V_L is d awn and then the resultant voltage V is drawn.





Numerical:

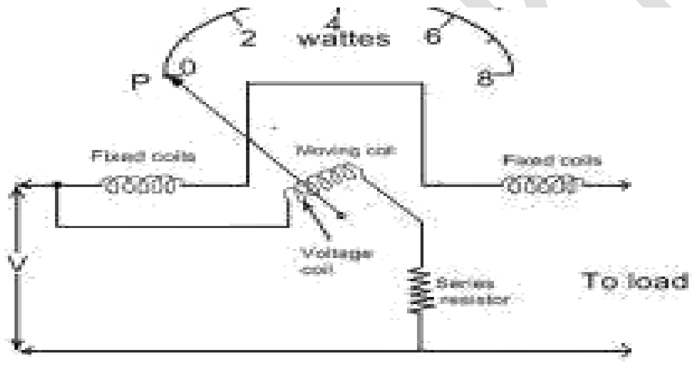
1. wo impedances Z_1=(10+j15) & Z_2=(5-j8) are connected in parallel across a voltage source. If the total current drawn is 10A, calculate currents in Z_1& Z_2 and power factor of the circuit.
2. A circuit consists of resistance 10 ohm, an inductance of 16mH & a capacitance of 150µF connected in series. A supply of 100V at 50Hz is given to the circuit. Find the current, power factor & power consumes by the circuit..
3. A parallel circuit comprises of a resistor of 20 ohm in series with an inductive reactance of 15 ohm in one branch & a resistor of 30 ohm in series with a capacitive reactance of 20 ohm in the other branch. Determine the current & power dissipated in each branch of the circuit if the total current drawn by the parallel circuit is $10\angle -30^0$ Amps
4. Two circuits A & B are connected in parallel across 200V, 50Hz supply. Circuit A consists of 10 ohm resistance & 0.12H inductance in series while circuit B consists of 20 ohm resistance in series with 40µF capacitance. Calculate (i) Current in each branch (ii) Total power factor (iii) Draw phasor diagram.

5. A 60 ohm resistor is connected in parallel with an inductive reactance of 80 ohm to a 240V, 50Hz supply. Calculate (i) the current through the resistor & inductor, (ii) the supply current, (iii) the circuit phase angle; (iv) draw the phasor diagram.
6. An inductor coil is connected to supply of 250V at 50Hz & takes a current of 5A. The coil dissipates 750W. Calculate power factor, resistance, & inductance of the coil.
7. Impedance in parallel with a 100μF capacitor is connected across a 200V, 50Hz supply. The coil takes a current of 4A & power loss in the coil is 600W. Calculate (i) resistance of the coil (ii) inductance of the coil (iii) the power factor of the circuit.

Measuring *Instruments*:

Syllabus: Construction and Principle of operation of dynamometer type wattmeter and single phase induction type energy meter.

Electrodynamometer Type Wattmeter:



Dynamometer type Wattmeter

Construction:

It consists of the following parts:

Moving coil - Moving coil moves the pointer with the help of spring control instrument In electrodynamometer type wattmeter, moving coil works as pressure coil. Hence moving coil is connected across the voltage and thus the current flowing through this coil is always proportional to the voltage.

Fixed coil - The fixed coil is divided into two equal parts and these are connected in series with the load, therefore the load current will flow through these coils. Now the reason is very obvious of using two fixed coils instead of one, so that it can be constructed to carry considerable amount of electric current. These coils are called the current coils of electrodynamometer type wattmeter. Earlier these fixed coils are designed to carry the current of about 100 amperes but now the modern wattmeter are designed to carry current of about 20 amperes in order to save power.

Control system - Out of two controlling systems i.e. gravity control and spring control, only spring controlled systems are used in these types of wattmeter. Gravity controlled system cannot be employed because they will contain appreciable amount of errors.

Damping system - Air friction damping is used, as eddy current damping will distort the weak operating magnetic field and thus it may lead to error.

Scale - There is uniform scale is used in these types of instrument as moving coil moves linearly over a range of 40 degrees to 50 degrees on either sides.

Working:

Let

v=supply voltage

i=load current and

R=resistance of the moving coil circuit

Current through fixed coils, $i_f = i$
Current through the moving coil, $i_m = v/R$
Deflecting torque,

$$T_d \propto (i_f * i_m) \propto \frac{iv}{R}$$

For a DC circuit the deflecting torque s thus proportional to the power.

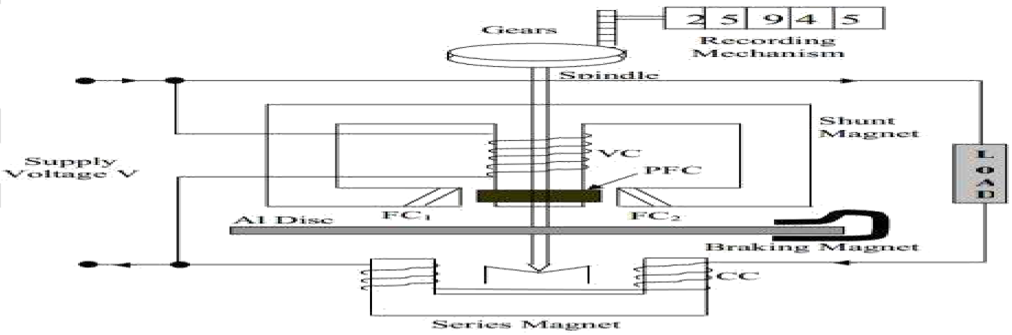
For any circuit with fluctuating torque, the nstantaneous torque is proportional to instantaneous power. In this case due to nert a of moving parts, the deflection will be proportional to the average power. For sinusoidal alternating quantities the average power is V.I.cosϕ, where

V= RMS value of voltage

I = RMS value of current, and
ϕ= phase angle between V and I

Hence an electrodynamometer instrument, when connected as shown in figure, indicates the power, irrespective of the fact it is connected in an AC or DC circuit.

Single Phase Induction Type Energy Meter:



Construction:

It consists of a pressure coil made of thin copper wire of many turns (also called shunt magnet); a current coil made of thick copper wire of one or two turns (also called series magnet), an aluminium disc mounted on spindle

A braking magnet is arranged on a disc to control its movement and to stop the movement under no load.

A phase difference of 90^0 is set between current coil and pressure coil with the help of copper shaded rings.

Working:

This instrument works on the principle of induction that when both the shunt and series coils are energized by ac, there will be tow alternative fluxes re in the shunt coil and one in the series coil these time varying fluxes are cut by a stationary disc.

These currents interacts with the fluxes and results in a to que.

The disc rotates in a particular direction and the num er and speed of rotations depends on the energy consumed by the load.

Unit-1

BALANCED THREE PHASE CIRCUITS

1.1 Introduction:

There are two types of systems available in electrical circuits, single phase and three phase. In single phase circuits, there will be only one phase, i.e the current will flow through only one wire and there will be one return path called neutral line to complete the circuit. So in single phase minimum amount of power can be transported. Here the generating station and load station will also be single phase. This is an old system using from previous time.

In 1882, new invention has been done polyphase system, that more than one phase can be used for generating, transmitting and for load system. Three phase circuit is the polyphase system where three phases are send together from generator to the load. Each phase are having a phase difference of 120^0, i.e 120^0 angle electrically. So from the total of 360^0, three phase are equally divided into 120^0 each. The power in three phase system is continuous as all the three phases are involved in generating the total power. The sinusoidal waves for 3 phase system is shown below .

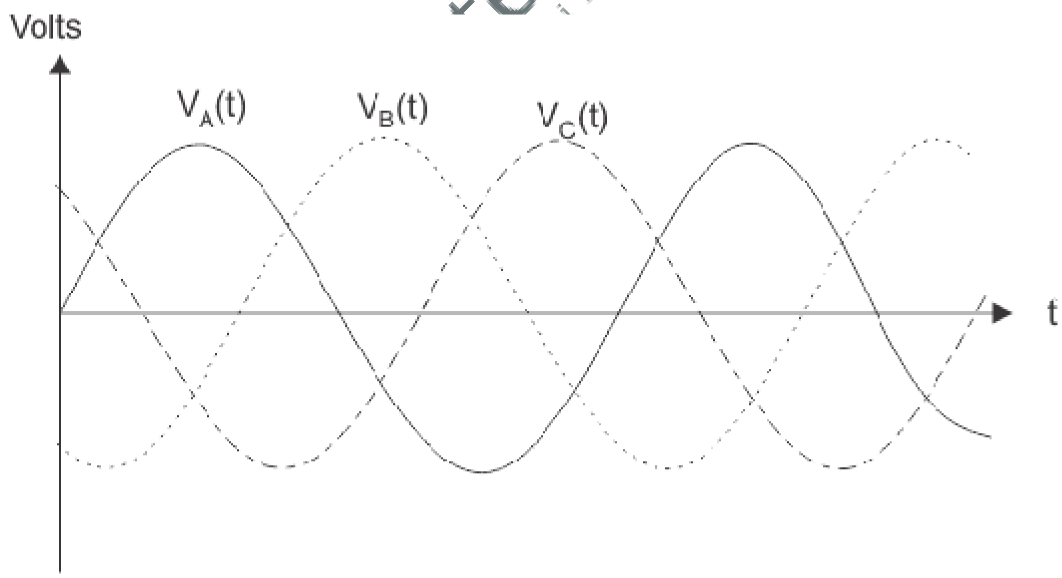


Fig.1.1

The three phase can be used as single phase each. So if the load is single phase, then one phase can be taken from the three phase circuit and the neutral can be used as ground to complete the circuit.

1.1.1 Why three phase is preferred over single phase?

There are various reasons for this question because there are numbers of advantages over single phase circuit. The three phase system can be used as three single phase line so it can act as three single phase system. The three phase generation and single phase generation is same in the generator except the arrangement of coil in the generator to get 120^0 phase difference. The conductor needed in three phase circuit is 75% that of conductor needed in single phase circuit.

And also the instantaneous power in single phase system falls down to zero as in single phase we can see from the sinusoidal curve but in three phase system the net power from all the phases gives a continuous power to the load.

Till now we can say that there are three voltage sources connected together to form a three phase circuit and actually it is inside generator. The generator is having three voltage sources which are acting together in 120^0 phase difference. If we can arrange three single phase circuit with 120^0 phase difference, then it will become a three phase circuit. So 120^0 phase difference is must otherwise the circuit will not work, the three phase load will not be able to get active and it may also cause damage to the system.

The size or metal quantity of three phase devices is not having much difference. Now of we consider the transformer, it will be almost same size fro both single phase and three phase because transformer will make only the linkage of flux. So the three phase system will have higher efficiency compared to single phase for the same or little difference in mass of transformer, three phase line will be out whereas in single phase will be only one. And losses will be minimum in three phase circuit. So overall in conclusion the three phase system will have better and higher efficiency compared to the single phase system.

A balanced polyphase system is one in which there are two or more equal voltages of the same frequency displaced equally in time phase, which supply power to loads connected to the lines. In general, in a *n*-phase balanced polyphase system, there are *n*-equal voltages displaced in time phase by $\frac{360^0}{n}$ or $\frac{2\pi}{n}$ (except in the case of a 2-phase system, in which there are two equal voltages differing in phase by 90^0). Systems of six or more phases are used in polyphase rectifiers to obtain rectified voltage with low ripple. But three phase system is most commonly used polyphase system for generation and transmission of power. Hence we study in detail the 3-phase voltage generation and analysis of 3-phase circuit in this unit.

A 3-phase system has the following advantages over single phase system. For a given frame size of a machine a 3-phase machine will have large capacity than a single phase machine. The torque produced in a 3-phase motor will be more uniform where as in a 1-phase motor it is pulsating. The amount of copper required in a certain amount of power over a particular distance, is less compared to a single phase system.

1.1.2 Phase sequence:

It is the order in which the phase voltages will attain their maximum values. From the fig it is seen that the voltage in A phase will attain maximum value first and followed by B and C phases. Hence three phase sequence is ABC. This is also evident from phasor diagram in which the phasors with its +ve direction of anti-clockwise rotation passes a fixed point is the order ABC, ABC and so on. The phase sequence depends on the direction of rotation of the coils in the magnetic field. If the coils rotate in the opposite direction then the phase voltages attains maximum value in the order ACB. The phase sequence gets reversed with direction of rotation. Then the voltage for this sequence can be represented as

$$e_a = E_m \sin \omega t$$
$$e_c = E_m \sin(\omega t - 120^0)$$
$$e_b = E_m \sin(\omega t - 240^0)$$

The RMS values of voltage can be expressed as

$$E_A = E\angle 0^0$$
$$E_C = E\angle -120^0$$
$$E_B = E\angle -240^0$$

1.1.3 Star and Delta connection

The three phase windings have six terminals i.e., A,B,C are starting end of the windings and A',B' and C' are finishing ends of windings. For 3 phase systems two types of common interconnections are employed.

1.1.3(a) Star connection: the finishing ends or starting ends of the three phase windings are connected to a common point as shown in. A', B', C' are connected to a common point called neutral point. The other ends A, B, C are called line terminals and the common terminal neutral are brought outside. Then it is called a 3 phase 4 wire star connected systems. If neutral point is not available, then it is called 3 phase, 3 wire star connection.

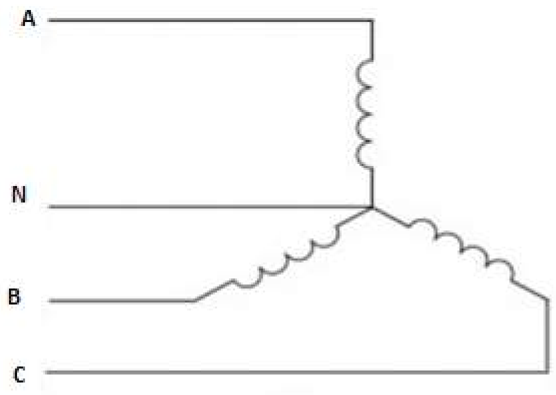


Fig.1.2

1.1.3(b) Delta connection: in this form of interconnection the dissimilar ends of the three coils i.e A and B', B and C', and C and A' are connected to form a closed Δ circuit (starting end of one phase is connected to finishing end of the next phase). The three junction are brought outside as line terminal A, B, C. the three phase windings are connected in series and form a closed path. The sum of the voltages in the closed path for balanced system of voltages at any instant will be zero fig.

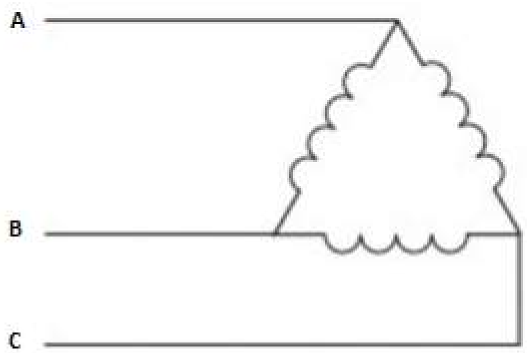


Fig.1.3

The main advantage of star connection is that we can have two different 3-phase voltages. The voltage that was the line terminals between A & B, B&C, and C & A are called line voltages and form a balanced three phase voltage. Another voltage is between the terminals A & N, B& N, and C &N are called phase voltage and form another balanced three phase voltage (line to neutral voltage or wye voltage).

1.2 Relation between line and phase voltage and currents in balanced systems:

In this section we will derive the relation between line and phase values of voltages and currents of 3-phase star connected and delta connected systems.

1.2.1 Star connection:

We will employ double subscript notation to represent voltages and currents. The terminal corresponding to first subscript is assumed to be at a higher potential with respect to the terminal corresponding to second subscript.

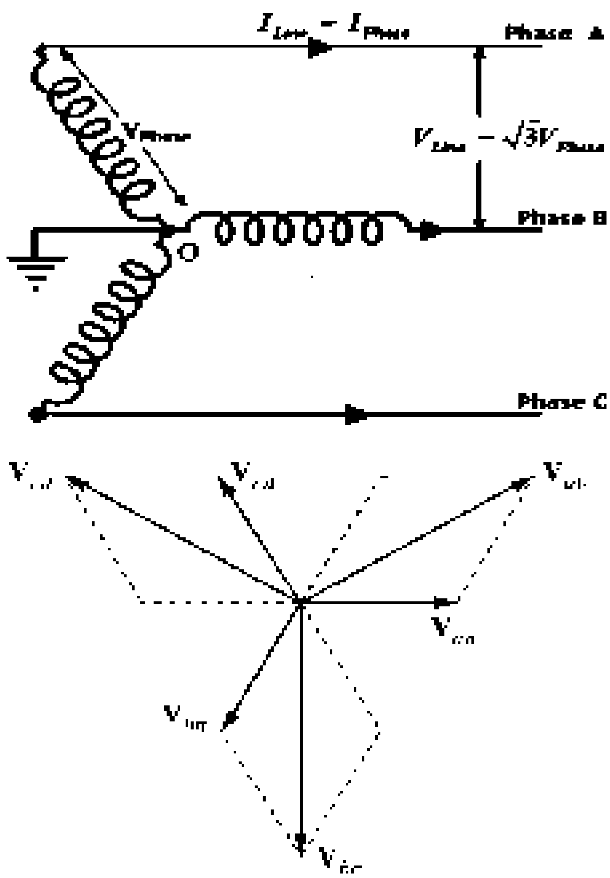


Fig.1.4

The voltage across each coil, i.e., the voltage between A & A',B& B', and C & C' are called phase voltages(acting from finishing end to starting end).

V_{AA}, V_{BB}, V_{CC}, or V_{AN}, V_{BN}, V_{CN} represent phase voltages.

The voltages across line terminals A & B, B & C, C & D are called line voltages. The connection diagram and the corresponding phasor diagram of voltages is shown in fig. From the star connected 3 phase system, it is clearly observed that whatever currents flow through the lines A, B, C also flow through the respective phase windings. Hence in star connected system, the phase currents and line currents are identical.

$$\text{Phase current } (I_{ph}) = \text{Line currents } (I_L)$$

$$I_{ph} = I_{Line}$$

The voltage V_{AB} between lines A and B is obtained by adding V_{AN} and V_{NB} respectively.

$$V_{AB} = V_{AN} + V_{NB} = V_{AN} - V_{BN}$$

Similarly

$$V_{BC} = V_{BN} + V_{NC} = V_{BN} - V_{CN}$$

$$V_{CA} = V_{CN} + V_{NA} = V_{CN} - V_{AN}$$

The line voltage V_{AB} is obtained by adding V_{AN} with reversed vector of V_{BN}.V_{AB} bisects the angle between V_{AN} and $-V_{BN}$

$$V_{AB}^2 = V_L^2 = V_{ph}^2 + V_{ph}^2 + 2\, V_{ph} V_{ph} \cos 60^0$$

$$= 3V_{ph}^2$$

$$V_{AB} = \sqrt{3}\, V_{ph}$$

$$\text{Line voltage} = \sqrt{3} \text{ phase voltage}$$

The line voltages V_{AB}, V_{BC}, V_{CA} are equal in magnitude and differ in phase by 120^0. Hence they form a balanced 3-phase voltage of magnitude $\sqrt{3}\, V_{ph}$. The two voltages differ in phase by 30^0. When the system is balanced, the three phase currents I_A, I_B, I_C are balanced. The magnitude and phase angle of current is determined by circuit parameters.

I_A, I_B, I_C are line or phase currents. The current in the neutral wire is I_N and is by applying kirchoff's current law at star point, we get

$$I_N = -(I_A + I_B + I_C)$$

If the currents are balanced, then the neutral current is zero.

1.2.2 Delta connection or MESH connection:

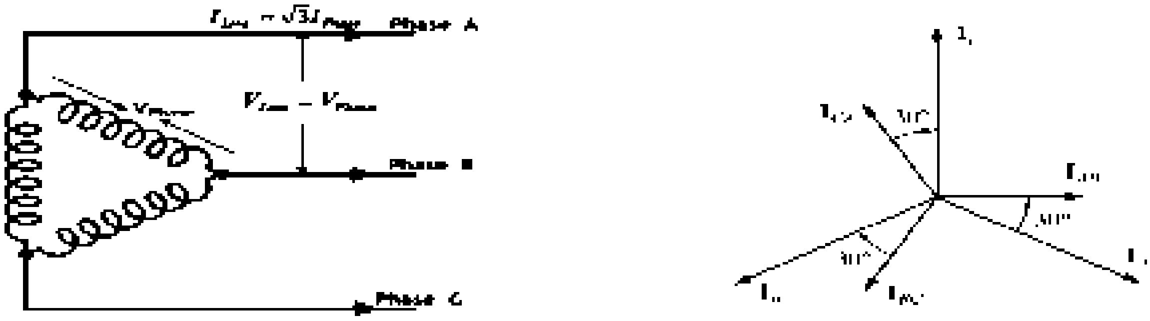


Fig.1.5.

The currents flowing through the phase windings I_{AA}', I_{BB}', and I_{CC}' or I_{AB}, I_{BC}, and I_{CA} are called phase currents and are balanced as shown in phase diagram Fig.1.5.

By applying KCL at node A

$$I_A + I_{CA} = I_{AB} \; , \; I_A = I_{AB} - I_{CA}$$

Similarly by applying KCL at nodes B and C

$$I_B = I_{BC} - I_{AB} I_C = I_{CA} - I_{BC}$$

The line current I_A is obtained by adding I_{AB} and $-I_{CA}$ vectorially. I_A bisects the angle between I_{AB} and $-I_{CA}$

$$I_A^2 = I_{Line}^2 = I_{ph}^2 + I_{ph}^2 + 2\, I_{ph} I_{ph} \cos 60^0$$

$$= 3I_{ph}^2$$

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

Line current(I_L) = √3 phase voltage(I_{ph})

The line current I_A, I_B, I_C and also equal and differ in phase by 120^0. They form a balanced system of currents. The line and phase currents differ in phase by 30^0.

1.3 Analysis of balanced three phase circuits

A set of three impedances interconnected in the form of a star or delta form a 3-phase star or delta connected load. If the three impedances are identical and equal then it is a balanced 3-phase load, otherwise it is an unbalanced 3-phase load.

The analysis of balanced 3-phase circuits is illustrated as follows

1.3.1 Balanced delta connected load:

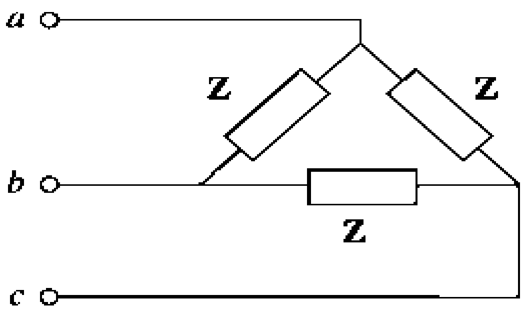


Fig.1.6

Let us consider a balanced 3-phase delta connected load

Determination of phase voltages:

$$V_{AB} = V\angle 0^0,\ V_{BC} = V\angle -120^0,\ V_{CA} = V\angle -240^0 = V\angle 120^0$$

Determination of phase currents:

Phase current = Phase voltage/ Load impedance

$$I_{AB} = \frac{V_{AB}}{Z}\ ;\ I_{BC} = \frac{V_{BC}}{Z}\ ;\ I_{CA} = \frac{V_{CA}}{Z}$$

Determination of line currents:

Line currents are calculated by applying KCL at nodes A,B,C

$$I_A = I_{AB} - I_{CA}\ ;\ I_B = I_{BC} - I_{AB}\ ;\ I_C = I_{CA} - I_{BC}$$

Note: Line currents are also balanced and equal to √3phase current.

1.3.2 Balanced star connected load:

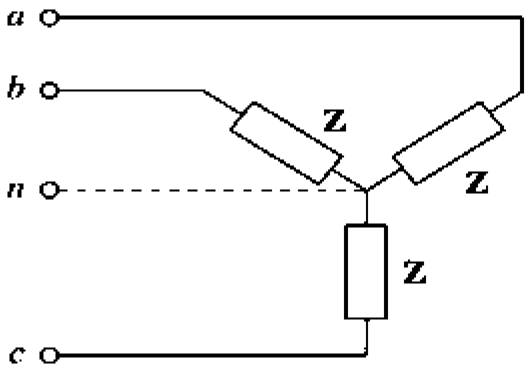


Fig.1.7

Let us consider a balanced 3-phase star connected load.

For star connection, phase voltage= Line voltage/(√3)

For ABC sequence, the phase voltage is polar form are taken as

$$V_{AN} = V_{ph}\angle -90^0 \; ; V_{CN} = V_{ph}\angle 150^0 \; ; V_{BN} = V_{ph}\angle 30^0$$

For star connection line currents and phase currents are equal

$$I_A = \frac{V_{AN}}{Z} ; I_B = \frac{V_{BN}}{Z} ; I_C = \frac{V_{CN}}{Z} ;$$

To determine the current in the neutral wire apply KVL at star point

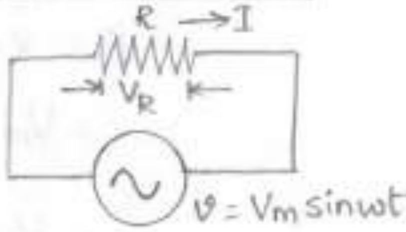
$$I_N + I_A + I_B + I_C = 0$$

$$I_N = -(I_A + I_B + I_C) \quad \text{(since they are balanced)}$$

In a balanced system the neutral current is zero. Hence if the load is balanced, the current and voltage will be same whether neutral wire is connected or not. Hence for a balanced 3-phase star connected load, whether the supply is 3-phase 3 wire or 3-phase 4 wire, it is immaterial. In case of unbalanced load, there will be neutral current.

ANALYSIS OF AC CIRCUITS.

① AC CIRCUITS CONTAINING PURE OHMIC RESISTANCE.



When an alternating voltage is applied across a pure resistance, The current flows in one direction for the first half cycle and in the opposite direction for the next/2nd half cycle. Therefore due to the alternating voltage, The circuit now consists of an alternating current.

Let us consider an ac circuit with a pure resistance 'R' as shown above.

Let the applied voltage be $\boxed{v = V_m \sin wt}$ ——— ⓐ

Then the voltage drop across the resistor is given by

$$v = iR$$

where 'i' is the current flowing in the circuit.

$\therefore \quad V_m \sin wt = i.R$

$$\boxed{i = \frac{V_m}{R} . \sin wt} \quad \text{——— (1)}$$

'i' is the instantaneous current, Also we know that 'i' will be "I_{max}" when "$\sin wt = 1$" in eq^n (1)

$$\therefore \quad \boxed{I_{max} = \frac{V_m}{R}} \quad \text{——— (2)}$$

$\therefore$ From eq^n (1) and (2)

$$\boxed{i = I_m \sin wt} \quad \text{——— (b)}$$

From eq^n ⓐ and ⓑ it can be observed that the eq^n have "$\sin wt$" which shows that there is no phase difference between "v" and "i". Hence in resistive ckts the 'v' and 'i' are inphase with each other.

Now the instantaneous power 'p' is given by.

$$p = v \cdot i$$

$$= V_m \sin\omega t \cdot I_m \sin\omega t$$

$$= V_m I_m \sin^2\omega t$$

But $\sin^2\omega t = \frac{(1-\cos 2\omega t)}{2} = \frac{1}{2} - \frac{\cos 2\omega t}{2}$

$$= V_m I_m \left[\frac{1}{2} - \frac{\cos 2\omega t}{2}\right]$$

$$p = \frac{V_m I_m}{2} - \frac{V_m I_m \cdot \cos 2\omega t}{2}$$

in the power equation obtained above. $\frac{V_m I_m}{2}$ is called as the constant part and $\frac{V_m I_m \cos 2\omega t}{2}$ is called as the fluctuating part.

Because the fluctuating part has a frequency double than that of 'v' and 'i', The average value of the fluctuating power over one complete cycle will be "Zero"

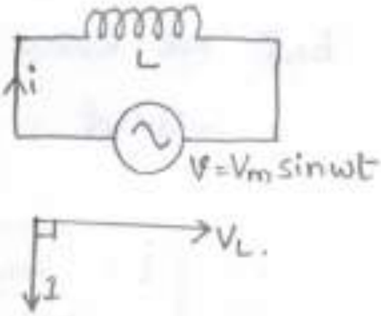
$\therefore$ Power for one complete cycle is

$$P = \frac{V_m I_m}{2} = \frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}} = V_{rms} \cdot I_{rms} = VI \text{ watts}$$

(2) AC CIRCUITS CONTAINING PURE INDUCTANCE.

An inductive coil is a coil of thick copper wire wound on a laminated core, It is impossible to produce a pure inductor because they are made up of conductor and a small amount of resistance will be present.

But for analysis we will assume the coil to be purely inductive, neglecting the small resistance of the coil.



When an alternating voltage is applied across a pure inductance as shown in the figure, Due to the current flowing in the coil there is a magnetic field setup across the coil.

It has to be noted that the direction of current changes for each half cycle. Due to this changing current, the flux linking with the coil also changes which will result in "Self induced" emf in the coil, which is called as the "Back Emf".

This "Back emf" opposes the raise and fall of current and will be exactly equal to the applied voltage but in reverse direction of applied voltage.

$\therefore$ If $v = V_m \sin \omega t$ and ——— (A)

Self induced emf $(e_L) = -L\frac{di}{dt}$

Then $-e_L = v$

$$-\left[-L\frac{di}{dt}\right] = V_m \sin \omega t$$

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

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

$$i = \int \frac{V_m}{L} \sin\omega t \cdot dt$$ (4)

'V_m' and 'L' are constants

$$i = \frac{V_m}{L} \int \sin\omega t \cdot dt = \frac{V_m}{L}\left[-\cos\omega t\right] + A$$

$$i = \frac{V_m}{\omega L}\left[-\cos\omega t\right] \qquad \left[\because \text{constant 'A' is zero from initial conditions}\right]$$

But we know that

$$-\cos\omega t = \sin\left[\omega t - \frac{\pi}{2}\right]$$

$$\therefore \boxed{i = \frac{V_m}{\omega L} \sin\left[\omega t - \frac{\pi}{2}\right]} \qquad \text{——— (B)}$$

$i = I_{max}$ when $\sin\left[\omega t - \frac{\pi}{2}\right] = 1$. $\therefore \boxed{I_m = \frac{V_m}{\omega L}}$

$$\therefore \boxed{i = I_m \sin\left[\omega t - \frac{\pi}{2}\right]} \qquad \text{——— (C)}$$

comparing eqⁿ (A) with eqⁿ (C) we can observe that the Sine component of 'v' is "$\sin\omega t$" and that of current 'i' is $\sin\left[\omega t - \frac{\pi}{2}\right]$ which shows that the current phasor lags behind the voltage phasor by an angle of $\left[\frac{\pi}{2}\right]$ radians or 90°.

POWER

$$p = v \cdot i = V_m \sin\omega t \cdot I_m \sin\left[\omega t - \frac{\pi}{2}\right]$$

$$= V_m I_m \cdot \sin\omega t \cdot \sin\left[\omega t - \frac{\pi}{2}\right]$$

$$= V_m I_m \sin\omega t \cdot (-\cos\omega t)$$

$$\boxed{p = -\frac{V_m I_m}{2} \cdot \sin 2\omega t}$$

The average power over a complete ~~half~~ cycle will be zero for a quantity of double frequency. Therefore

$$p = \int_0^{2\pi} -\frac{V_m I_m}{2} \cdot \sin 2\omega t \cdot dt = 0$$

Therefore the power absorbed in inductive circuit is zero.

Inductive Reactance :-

In the eq^n $I_m = \frac{V_m}{\omega L}$

'ωL' is called as the inductive reactance which is equal to the resistance in resistive circuit.

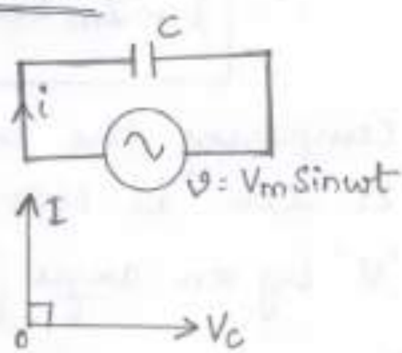
$\omega L = 2\pi f L$

It is denoted by "X_L" and measured in ohms.

$$X_L = 2\pi f L$$

(3) AC CIRCUITS CONTAINING PURE CAPACITANCE.

When an alternating voltage is applied across a capacitor. The capacitor is charged in one direction for first half cycle and in the reverse direction for the next half cycle.



∴ If $v = V_m \sin \omega t$ is the applied voltage.
The instantaneous charge (q) is given by

$q = C \cdot v$

where 'C' is the capacitance of the capacitor in "farads"

∴ $$q = C \cdot V_m \sin \omega t \quad \text{—— (A)}$$

Now the current flowing through the capacitor is given or equal to the rate of change of electric charge w.r.t time.

$$\therefore\ i = \frac{dq}{dt} = \frac{d}{dt}\left(C V_m \sin \omega t\right)$$

$i = \omega . C . V_m \left[\cos \omega t\right]$

But $\cos\omega t = \sin\left[\omega t + \frac{\pi}{2}\right]$

$\therefore i = (\omega C) . V_m \sin\left[\omega t + \frac{\pi}{2}\right]$

The capacitive reactance of the is given by the equation

$$X_C = \frac{1}{\omega C}$$

$$\therefore i = \frac{V_m}{\left[\frac{1}{\omega C}\right]} . \sin\left[\omega t + \frac{\pi}{2}\right]$$

$$i = \frac{V_m}{X_C} \sin\left[\omega t + \frac{\pi}{2}\right]$$

$i = I_{max} = \frac{V_m}{X_c}$ when $\sin\left[\omega t + \frac{\pi}{2}\right] = 1.$

$$\therefore \boxed{i = I_m \sin\left[\omega t + \frac{\pi}{2}\right]}$$

Comparing the instantaneous voltage and current expressions. it can be observed that. The current 'i' leads the voltage 'v' by an angle $\left[\frac{\pi}{2}\right]$ radians or 90°

POWER

$$p = v.i = V_m \sin\omega t . I_m \sin\left[\omega t + \frac{\pi}{2}\right]$$

$$= V_m I_m \sin\omega t . \sin\left[\omega t + \frac{\pi}{2}\right]$$

$$= V_m I_m \left[\sin\omega t . \cos\omega t\right]$$

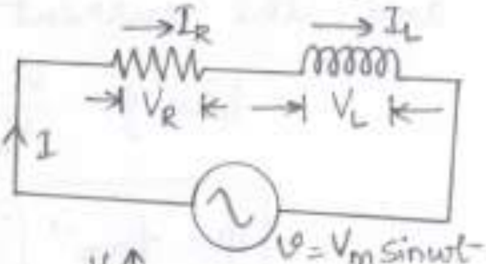
$$= V_m I_m \frac{\sin 2\omega t}{2}.$$

$$\boxed{p = \frac{V_m I_m}{2} . \sin 2\omega t}$$

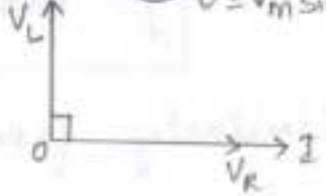
power for one complete cycle $\boxed{p = \int_0^{2\pi} \frac{V_m I_m}{2} . \sin 2\omega t = 0.}$

$\therefore$ power consumed by a pure capacitor is zero.

(4) SERIES R-L circuit.

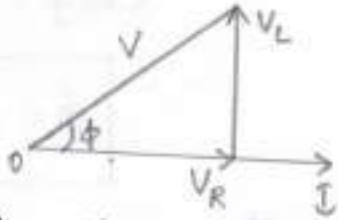


Let us consider an ac circuit containing a pure resistance 'R' ohms. connected in series with a pure inductance 'L' Henry.



Let the applied voltage be "V" and the current flowing through the series ckt be 'I'

$\therefore \; I = I_R = I_L$



Voltage Phasor diagram.

Now the voltage across the 'R' and 'L' is

Voltage drop across 'R' = $V_R = I_R . R = IR$ —— (A)

voltage drop across 'L' = $V_L = I_R . X_L = IX_L$ —— (B)

where V_R is in phase with 'I' and V_L leads I by 90°

Now the applied voltage 'V' will be equal to the vector sum of the two voltages "V_R" and "V_L" i.e $V^2 = V_R^2 + V_L^2$

$$\therefore \; V = \sqrt{V_R^2 + V_L^2}$$

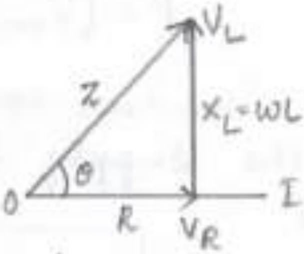
$$= \sqrt{(IR)^2 + (IX_L)^2} = \sqrt{I^2R^2 + I^2X_L^2} = \sqrt{I^2(R^2 + X_L)^2}$$

$$\boxed{V = I\sqrt{R^2 + X_L^2}} \text{ —— (C)}$$

The term $\sqrt{R^2 + X_L^2}$ offers opposition for the current flow and is called as Impedance of the ckt. It is denoted by 'Z' and measured in ohms.

$$\therefore \; \boxed{V = I.Z} \text{ —— (D)}$$

where $Z^2 = R^2 + X_L^2$



Impedance Δle

Now the phase angle "ϕ" between the applied voltage (v) and the current 'I' can be obtained as.

$$\tan\phi = \frac{V_L}{V_R} = \frac{IX_L}{IR} = \frac{X_L}{R}$$

$$\boxed{\phi = \tan^{-1}\left[\frac{X_L}{R}\right]}$$ from Voltage phasor diagram

Similarly from the Impedance triangle

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

$$\boxed{\phi = \cos^{-1}\left[\frac{R}{Z}\right]}$$

∴ For a Series R-L circuit. If the

Applied voltage = $V = V_m \sin\omega t$

current $= i = \frac{V_m}{Z}\sin(\omega t - \phi) = I_m \sin(\omega t - \phi)$

where $\boxed{I_m = \frac{V_m}{Z}}$

∴ Therefore the average power consumed will be

$$P = v.i = V_m \sin\omega t \cdot I_m \sin(\omega t - \phi)$$

$$\boxed{P = V_m I_m \cdot \left[\sin\omega t \cdot \sin(\omega t - \phi)\right]}$$

But $\sin\omega t \cdot \sin(\omega t - \phi) = \frac{\cos\phi - \cos(2\omega t - \phi)}{2}$

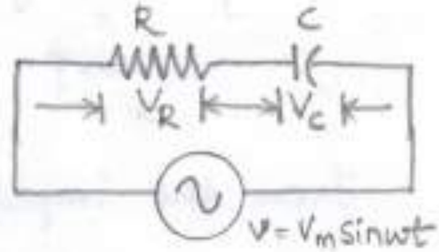
$$P = \frac{V_m I_m}{2}\left[\cos\phi - \cos(2\omega t - \phi)\right]$$

$$P = \left(V_{rms} I_{rms} \cos\phi\right) - \left[V_{rms} I_{rms} \cos(2\omega t - \phi)\right]$$

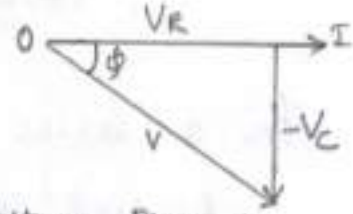
the $V_{rms} I_{rms} \cos(2\omega t - \phi)$ whose frequency is twice that of the supply frequency will be zero over a complete cycle

$$\therefore \boxed{P = V_{rms} \cdot I_{rms} \cdot \cos\phi} \text{ watts.}$$

(5) SERIES R-C CIRCUIT.



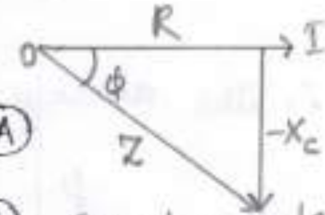
Let us consider an ac circuit containing a pure resistance 'R' ohms connected in series with a pure capacitance 'C' farads.



Voltage Phasor diagram

Let the applied voltage be "V" and the current flowing through the series ckt be 'I'

$\therefore \quad I = I_R = I_C$



Impedance Δle

Now the voltage across 'R' and 'C' is

Voltage drop across $R = V_R = I_R \cdot R = IR$ —— (A)

voltage drop across $C = V_C = I_C \cdot X_C = I X_C$ —— (B)

where 'V_R' is inphase with 'I' and 'V_C' lags 'I' by 90°

Now the applied voltage will be equal to the vector sum of the two voltages V_R and V_C

From the nature of capacitor, The capacitive reactance is always negative $\therefore V_C = (-IX_C)$

$$\therefore \quad V^2 = V_R^2 + (V_C)^2$$

$$= (IR)^2 + (-IX_C)^2$$

$$= I^2R^2 + (-I)^2X_C^2 = I^2R^2 + I^2X_C^2$$

$$= I^2(R^2 + X_C^2)$$

$$V = \sqrt{I^2(R^2+X_C^2)} = I\sqrt{R^2+X_C^2}$$

$$\boxed{V = IZ} \quad \text{—— (C)}$$

From the voltage phasor diagram

$$\tan\phi = -\frac{X_c}{R}$$

From the impedance phasor diagram

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

For a series R-C circuit

Applied voltage = $v = V_m \sin\omega t$

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

∴ The average power consumed

$$P = v.i = V_m I_m \sin\omega t \cdot \sin(\omega t + \phi)$$

$$= V_m I_m \cdot \frac{\cos\phi + \cos(2\omega t + \phi)}{2}$$

$$= \frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}} \left[\cos\phi + \cos(2\omega t + \phi)\right]$$

$$= \left[V_{rms} \cdot I_{rms} \cdot \cos\phi\right] + \left[V_{rms} \cdot I_{rms} \cos(2\omega t + \phi)\right] \quad \text{— (D)}$$

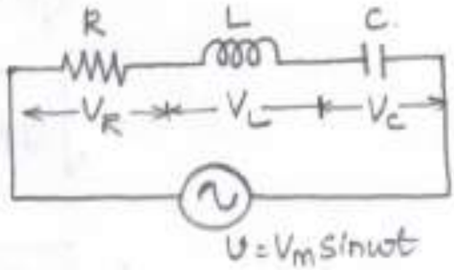
But $\left[V_{rms} \cdot I_{rms} \cos(2\omega t + \phi)\right]$ has a frequency which is twice that of current and voltage. Therefore average value of this term will be zero. for one complete cycle.

Therefore

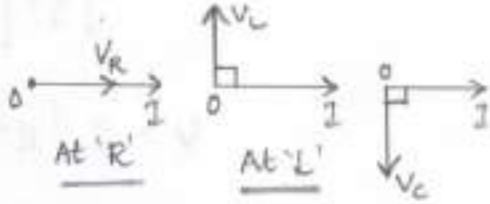
$$\boxed{P = V_{rms} \cdot I_{rms} \cdot \cos\phi} \quad \text{— (E)}$$

in watts

(6) SERIES RLC CIRCUIT.



Let us consider an ac series circuit containing Resistance 'R' ohms, Inductance 'L' henries and Capacitance 'C' farads as shown.



If V = applied voltage

I = Current

Then

Voltage drop across $R = V_R = IR$.

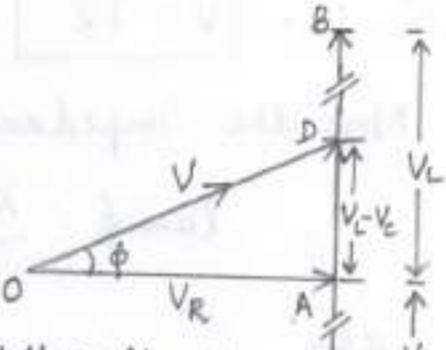
Voltage drop across $L = V_L = IX_L$

Voltage drop across $C = V_C = IX_C$

where V_R is in phase with I

V_L leads I by an angle $90°$

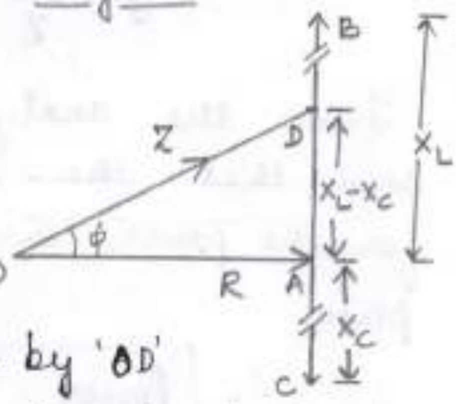
V_C lags behind 'I' by an angle $90°$



• Voltage Phasor diagram

Now from the voltage phasor

$$AC = -BD.$$



Impedance triangle.

Now the resultant voltage 'V' is given by 'OD'

where $AD = AB - AC$ (The net reactive voltage drop).

$$= AB - BD$$

$$AD = V_L - V_C$$

$$\boxed{AD = V_L - V_C}$$

From the voltage phasor diagram Resultant voltage 'V' is the phasor sum of V_R and $(V_L - V_C)$

$$\therefore \quad V = \sqrt{V_R^2 + (V_L - V_C)^2}$$

$$= \sqrt{(IR)^2 + (IX_L - IX_C)^2}$$

$$= \sqrt{(IR)^2 + [I(X_L - X_C)]^2}$$

$$= \sqrt{I^2 [R^2 + (X_L - X_C)^2]}$$

$$V = I\sqrt{R^2 + X^2} \quad \text{where } X = [X_L - X_C].$$

$$\therefore \boxed{V = IZ}$$

Now the Impedance phasor diagram

$$\tan\phi = \frac{X_L - X_C}{R} = \frac{X}{R}.$$

also

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

From the analysis for R-L and R-C circuit we have seen that the reactance in the circuit doesnt Contribute for the power consumption. But the Resistance consumes power

$$\therefore \boxed{\text{Power} = VI\cos\phi}$$

In R-L-C in series

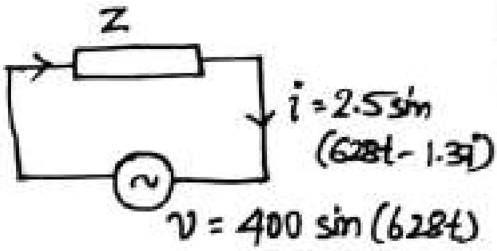
If $X_C > X_L$ then the current leads the applied voltage

If $X_L > X_C$ then the current lags behind the applied voltage

If $X_L = X_C$ Then $Z = R$ which is the resonance condition.

① An EMF of 400 sin(628t) is applied to a series circuit and the resulting current is 2.5 sin(628t − 1.37°). Find (i) Frequency
(ii) Phase Angle between voltage and current.
(iii) Parameters of the circuit.

(i) To find Frequency



$v = 400 \sin(628t)$

$i = 2.5 \sin(628t - 1.37^\circ)$ → circuit elements are 'R' & 'L'

$\omega = 628$ rad/sec

$\omega = 2\pi f$

$f = \dfrac{\omega}{2\pi} = 100\text{Hz}$

(ii) Phase Angle between Voltage & current

$i = 2.5 \sin(628t - 1.37^\circ)$

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

$\boxed{\phi = 1.37^\circ \text{ degrees}}$

$I_m = 2.5A$

$V_m = 400V$

$Z = \dfrac{V_m}{I_m} = \dfrac{400}{2.5} = 600\Omega$ $\boxed{Z = 600\Omega}$

$R = Z\cos\phi$

$R = 600\cos(1.37^\circ)$

$\boxed{R = 599.828\Omega}$

$X_L = Z\sin\phi$

$X_L = 600\sin(1.37^\circ)$

$\boxed{X_L = 14.345\Omega}$

$\omega L = 14.345$

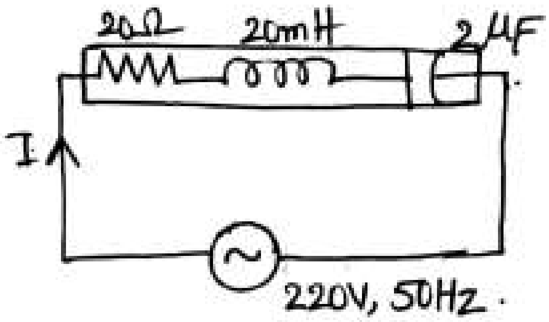
$\boxed{L = 22mH}$

values of circuit parameters.

Scanned with CamScanner

② A circuit with $R = 20\Omega$, and $L = 20mH$ is connected in series with a $2\mu F$. The AC voltage is 220V, 50Hz system

Find the Main Current, Inductive Reactance (X_L) and Capacitive Reactance (X_c). Frequency of ~~Response~~ Resonance (f_r).



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

V & I are the RMS values

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

$$Z = \frac{V}{I} = \frac{220}{I}$$

$$X_L = \omega L$$

$$= 2\pi \times 50 \times 20 \times 10^{-3}$$

Inductive Reactance → $X_L = 6.283\Omega$

Capacitive Reactance → $X_C = \frac{1}{\omega C}$

$$X_c = \frac{1}{2\pi \times 50 \times 2 \times 10^{-6}}$$

$$= \frac{10^6}{100\pi \times 2}$$

$X_c = 1591.54\,\Omega$

$$Z = \sqrt{(20)^2 + (2513039.75)}$$

$Z = 1585.38\,\Omega$

~~$X_L - X_c$~~ =

$Z = \frac{V}{I} \quad > \quad I = \frac{V}{Z} = \frac{220}{1585.38} = 138mA$

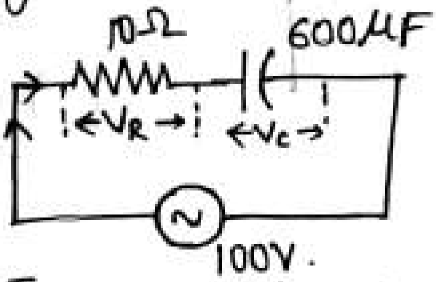
Main Current $I = 138mA$

f_r = Frequency at Resonance $= \frac{1}{2\pi\sqrt{LC}}$

$= \frac{1}{2\times3.14\times\sqrt{20\times10^{-3}\times2\times10^{-6}}}$

$f_r = 795.77$ Hz

③. A resistance of 10Ω is in series with 600μF. This is connected across 100V supply. The main current is 5A. Find the supply frequency, the impedance of the circuit, power taken & p.f.



① Find Supply Frequency 'f' in Hz

Main current (I) = 5A

power taken (Due to Resistive element only) $= I^2R = (5)^2\times10$

$= 250W.$

② To find Impedance (z)

$Z = \frac{V}{I} = \frac{100}{5} = 20\Omega$

③. In the above circuit, for series R-C Circuit

$P = I^2R = VI\cos\phi$

$= 250 = 100\times5\times\cos\phi$

$\cos\phi = 0.5$

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

$$20 = \sqrt{(10)^2 + X_c^2}$$

$$400 = (10)^2 + X_c^2$$

$$\boxed{X_c = 17.320\,\Omega}$$

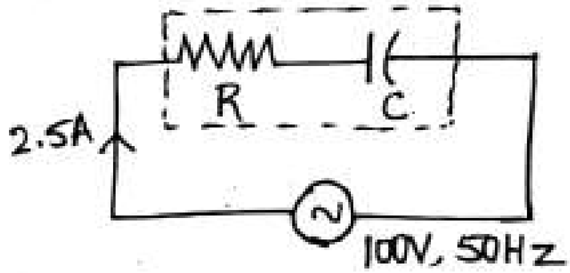
$$X_c = \frac{1}{2\pi \times f \times 600\times10^{-6}}$$

$$17.320 = \frac{1}{2\pi \times f \times 600\times10^{-6}}$$

$$(17.320)\times(2\times3.14\times600\times10^{-6}) = \frac{1}{f}$$

$$\boxed{f = 15.314\ \text{Hz}}$$

④ A voltage of 100V, at 50Hz is applied to a circuit with R and C in series. The current is 2.5A. Power dissipated is 100W. Calculate 'R' and 'C'.



power dissipated = 100W.

$$I^2R = 100$$

$$R = \frac{100}{I^2} = \frac{100}{(2.5)^2}$$

$$\boxed{R = 16\,\Omega}$$

$$Z = \frac{V}{I} = \frac{100}{2.5}$$

$$\boxed{Z = 40\,\Omega}$$

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

$$40 = \sqrt{(16)^2 + X_c^2}$$

$$\boxed{X_c = 36.60\,\Omega}$$

$$X_c = \frac{1}{\omega C}$$

$$C = \frac{1}{2\pi \times 50 \times 36.60}$$

$$\boxed{C = 86.96\,\mu F}$$

5. A resistance of 20Ω, an inductance of 0.2H and a capacitor of 100μF are connected in series across a supply of 200V, 50Hz.

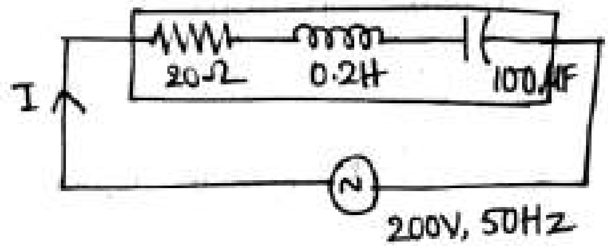
Determine

(i) Impedance (Z)

(ii) Main Current (I)

(iii) Power and Power Factor

(iv) Voltage across Capacitor (V_c).



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

$= \sqrt{(20)^2 + (62.83 - 31.83)^2}$

$= \sqrt{400 + 961.124} = 36.89\Omega$

X_L = Inductive Reactance

$= \omega L$

$= (2\pi \times 50 \times 0.2)$

$X_L = 62.832\Omega$

$X_c = \frac{1}{\omega C} = \frac{1}{2 \times \pi \times 50 \times 100 \times 10^{-6}}$

$= \frac{1}{100 \times 3.1416 \times 100 \times 10^{-6}}$

$X_c = 31.83\Omega$

$Z = 36.89\Omega$

Main-Current

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

$= \frac{200}{36.89}$

$I = 5.421A$

Power = $VI\cos\phi$

$= 200 \times 5.421 \times 0.542$

Power = 587.63 W

$\cos\phi = \frac{R}{Z} = \frac{(20)}{36.89}$

$\cos\phi = 0.542$

Voltage across the Capacitor 'X_c'

$V_c = I X_c$

$= (5.421)(31.83)$

$\boxed{V_c = 172.55 \text{ Volts}}$

---

⑥. A circuit having a resistance of 12Ω and an inductance of

H.W. 0.15H and a capacitance of $100\mu F$ in series is connected across a 100V, 50 Hz Supply. Calculate

(i) Impedance

(ii) Main Current (I)

(iii) Power, & power factor

(iv) Voltage across Capacitor.

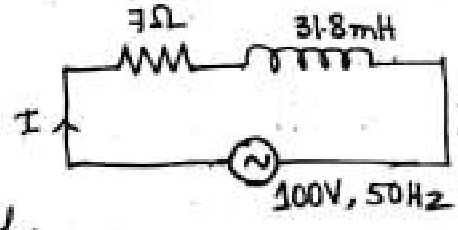
① A resistance of 7Ω is connected in series with a pure inductance of 31.8mH and a circuit is connected to a 100V, 50Hz. Sinusoidal AC supply. Calculate

(a) Circuit Current(t) (RMS and Maximum value)

(b) Phase Angle

(c) Power Factor

(d) Power (Average), Sketch the waveforms of voltage & current



(a) To calculate Circuit Current

$I = \frac{V}{Z}$ (V, & I are RMS values)

Z = Impedance $= \sqrt{R^2 + X_L^2}$

$X_L = \omega L$

$= 2\pi \times 50 \times 31.8 \times 10^{-3}$

$X_L = 9.99\Omega$

$Z = \sqrt{(7)^2 + (9.99)^2}$

$= \sqrt{144.92}$

$Z = 12.19\Omega$

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

$= \tan^{-1}(1.428)$

$\phi = 55°$

$I = \frac{(100)}{12.19\angle 55°}$

$I = 8.203\angle -55°$ A

$i = I_m \sin(\omega t - 55°)$

$i = 11.60 \sin(100\pi t - 55°)$

$v = V_m \sin(100\pi t)$

$v = 141.42 \sin(100\pi t)$

ⓑ Phase angle

$\phi = 55°$ (Lagging)

ⓒ Power Factor $\cos\phi = \cos(55°) = 0.5735$ (Lagging)

Power = $VI\cos\phi$

$= 100 \times 8.203 \times 0.5735$

$\boxed{P = 470.44\,W}$

$V = 100V$
$I = 8.203$ } RMS values

$\cos\phi = 0.5735$

②. A 318μF capacitor is connected across a 230V, 50Hz. system. Determine

(i) Capacitive Reactance(X_c) (ii) RMS value of current

(iii) Equations of voltage and current

$X_c = \frac{1}{\omega C}$

$= \frac{1}{100\pi \times 318 \times 10^{-6}}$

$\boxed{X_c = 10\,\Omega}$

$C = 318\mu F$

$= 318 \times 10^{-6}$

$= 3.18 \times 10^{-4} F$

$\omega = 2\pi f$

$\boxed{\omega = 100\pi}$

$\boxed{V = IZ}$ → For an AC Circuit

$I = \frac{V}{+X_c} = \frac{230V}{10}$

$\boxed{I = 23A}$

$I_{rms} = 23A$

$V_{rms} = 230V$

$\boxed{V_m = 325.26\,V}$

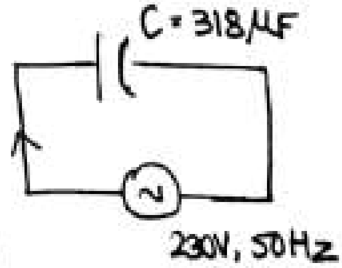
$\boxed{I_m = 32.52\,A}$

$v = V_m \sin\omega t$ ✓ $= 325.26 \sin(100\pi t)$ → ①

$i = I_m \sin(\omega t + \phi)$ | $\phi = \pi/2$

$= I_m \sin(\omega t + \pi/2)$ ✓

$32.52 \sin(100\pi t + \pi/2)$ → ②

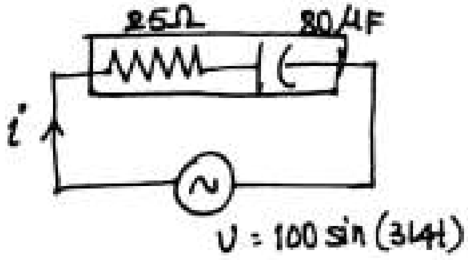


③. A voltage $v = 100\sin(314t)$ is applied to a circuit consisting of a 25Ω resistor and an $80\mu F$ capacitor in series. Determine

(i) An expression for the value of current

(ii) Power consumed by the circuit.

series RC circuit



$v = 100\sin(314t)$

$v = V_m \sin(\omega t)$

$\boxed{V_m = 100V}$

$\boxed{V_{rms} = 70.71V}$

~~$i = I_m \sin(\omega t + \pi/2)$~~

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

$X_c = \frac{1}{\omega C} = \frac{1}{314 \times 80 \times 10^{-6}}$

$\boxed{X_c = 39.80\Omega}$

$I_m = \frac{V_m}{Z}$

$= \frac{100}{47}$

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

$= \sqrt{625 + 1584.04}$

$\boxed{Z = 47\Omega}$

$\boxed{\phi = 57.86^\circ}$

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

$\boxed{i = 2.127 \sin(314t + 57.86^\circ)}$

$v = V_m \sin(\omega t)$

$\boxed{v = 100\sin(314t)}$

$P = VI\cos\phi$

$\boxed{P = 100 \times 1.504 \times 0.5319}$

$\boxed{P = 80.01W}$

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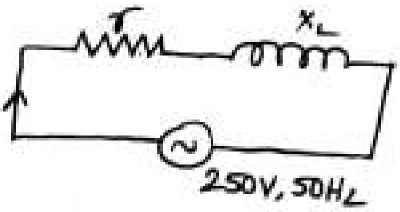
* An inductive coil takes 10A and dissipates 1kW, when connected to a supply of 250V, 50Hz. Calculate the inductance of choke coil. (Repeat)!



$X_L = \omega L$

$L = \frac{X_L}{\omega}$

$P = I^2 R$

$1000 = (10)^2 R$

$1000 = 100 R$

$\boxed{R = 10\Omega}$

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

$\frac{250}{10} = Z$

$\boxed{Z = 25\Omega}$

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

$\frac{230}{10} = Z$

$\boxed{Z = 23\Omega}$

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

$Z^2 = R^2 + X_L^2$

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

$= \sqrt{625 - 100}$

$\boxed{X_L = 22.91 H}$

$X_L = \omega L$

$L = \frac{22.91}{314.15}$

$\boxed{L = 0.0729 H}$

$\boxed{L = 0.0659 H}$

You Try !!

* $R = 10\Omega$, $L = 0.1 H$, $C = 50\mu F$ } series RLC circuit. 230V, 50Hz.

Z = ?

Current

Power & p.F.

$R = 8\Omega$

$L = 15 mH$

$C = 150\mu F$

200V, 50Hz.

Z = ?

I = ?

Power = ? & p.F.

NUMERICAL PROBLEMS ON STAR & DELTA CONNECTION

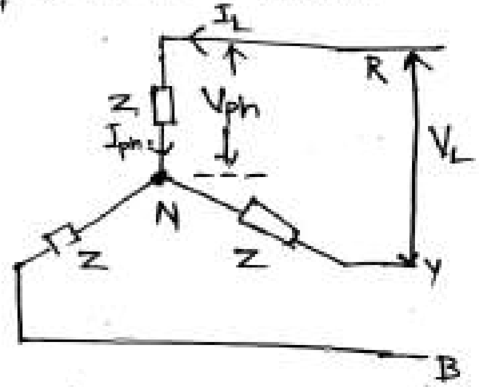
23/03/2020

LIST OF FORMULAE :-

APPLICABLE ONLY FOR A BALANCED SUPPLY

① STAR-CONNECTION .

- $V_L \rightarrow$ LINE VOLTAGE
- $V_{ph} \rightarrow$ PHASE VOLTAGE
- $I_L \rightarrow$ LINE CURRENT
- $I_{PH} \rightarrow$ PHASE CURRENT.



$$V_L = \sqrt{3}\, V_{ph}$$

$$I_L = I_{ph}$$

power in a Three-phase AC circuit

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

(or)

$$P = 3\, V_{ph} I_{ph} \cos\phi$$

FOR A BALANCED SUPPLY THE LOADS MIGHT BE (IN ALL 3-PHASES)

- PURELY RESISTANCE 'R'
- " INDUCTIVE (X_L)
- " CAPACITIVE (X_C).

- SERIES R-L CIRCUIT
- SERIES R-C CIRCUIT
- SERIES R-L-C CIRCUIT.

EACH PHASE IN 3-ϕ SYSTEM CAN CONTAIN ANY COMBINATION OF THE ABOVE SAID CIRCUIT ELEMENTS

$I_{ph} = \dfrac{V_{ph}}{R}$; $I_{ph} = \dfrac{V_{ph}}{Z}$ Z = Impedance in Ω

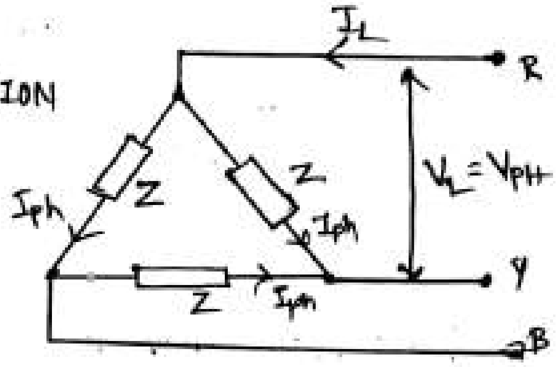
R. Resistance in Ω

DELTA CONNECTION

IN BALANCED DELTA CONNECTION

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

$V_L = V_{ph}$



power in Delta circuit is

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

NUMERICAL PROBLEMS ON STAR AND DELTA CONNECTED SYSTEMS

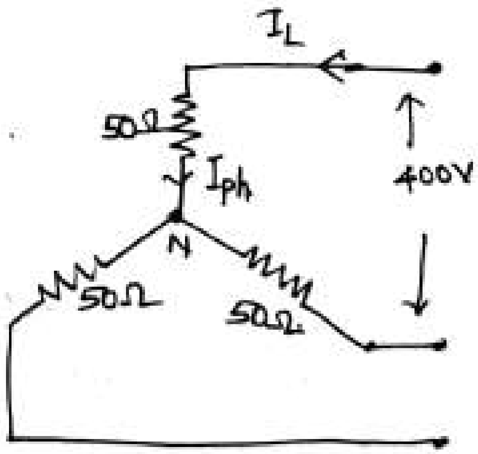
① Three resistors, each of 50Ω, are connected in Y-(STAR) connection across 400V supply. Find the

1. Line-current and Phase-current (I_L & I_{ph})
2. Phase-voltage (V_{ph})
3. Power consumed in Watts. (P in W)

Solution:-

TYPE OF CONNECTION = STAR

Resistance in each phase R (Ω)/phase = 50Ω



Given value of voltage V_L = Line-voltage = 400V

(Either the connection is star or Delta.) given value is always Line-voltage.

To find Phase-current (I_{ph})

$$I_{ph} = \frac{V_{ph}}{R}$$

$$= \frac{230.94}{50}$$

$$\boxed{I_{ph} = 4.618\text{ A}}$$

For star-connection

$$V_L = \sqrt{3}\, V_{ph}.$$

$$V_{ph} = \frac{V_L}{\sqrt{3}}$$

$$= \frac{400}{\sqrt{3}}$$

$$\boxed{V_{ph} = 230.94\text{ V}}$$

For star-connection

I_L = Line Current =

(I_{ph}) Phase Current = 4.168A

$$\boxed{I_L = I_{ph} = 4.168\text{A}}$$

power consumed in Watts

$$P = \sqrt{3}\, V_L I_L [\cos\phi]$$

$\cos\phi \rightarrow 1$ (For Resistive Load Only.)

$$= \sqrt{3} \times 400 \times 4.168 \times 1$$

$$= \sqrt{3} \times 400 \times 4.168$$

$$\boxed{P = 3.2\text{ kW}}$$

• "(Repeat Problem ① for Delta-connection.)"

(2). A three-phase load consists of impedance $(12+j16)\,\Omega$/phase. If the supply is at 400V. Find the

(a) Line-current and Phase-Current.

(b) Power consumed.

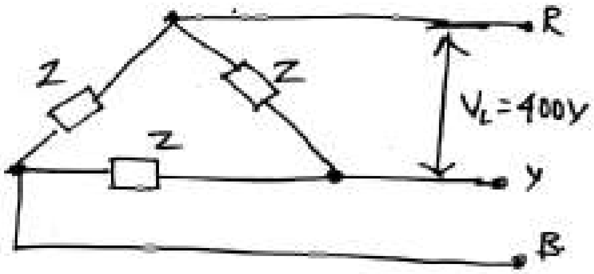
(c) Power Factor.

If the load is connected in (Δ) Delta connection.

Solution :-

$Z = (12+j16)\,\Omega/\text{phase}$

$V_L = 400V$



For Delta-connection

$V_L = 400V = V_{ph}$

phase-voltage = $400V = V_{ph}$

$$\boxed{V_{ph} = 400V}$$

Phase-current (I_{ph}) = ?

$$I_{ph} = \frac{V_{ph}}{Z}$$

$Z = (12+j16)\,\Omega/\text{phase}$

$= 20 \angle 53.10^\circ \,\Omega/\text{phase}$

$$= \frac{400 \angle 0^\circ}{20 \angle 53.10^\circ}$$

Divide

$$\boxed{I_{ph} = 20 \angle -53.10^\circ \text{ A}}$$

Phase-Angle in Degrees. (ϕ)

Magnitude of Phase-current

For Delta Connection.

Line-current (I_L) = $\sqrt{3} \times$ Phase-Current (I_{ph})

$$I_L = \sqrt{3} \times 20$$

$$\boxed{I_L = 34.64\ A}$$

① **Power consumed**

$= \sqrt{3}\, V_L I_L \cos\phi \rightarrow$ P.F.

$= \sqrt{3} \times 400 \times 34.64 \times \cos(-53.10^\circ)$

$= (\sqrt{3} \times 400 \times 34.64) \times 0.60$

$= 14409.66\ W$

$= 14.409\ kW$

Power Factor

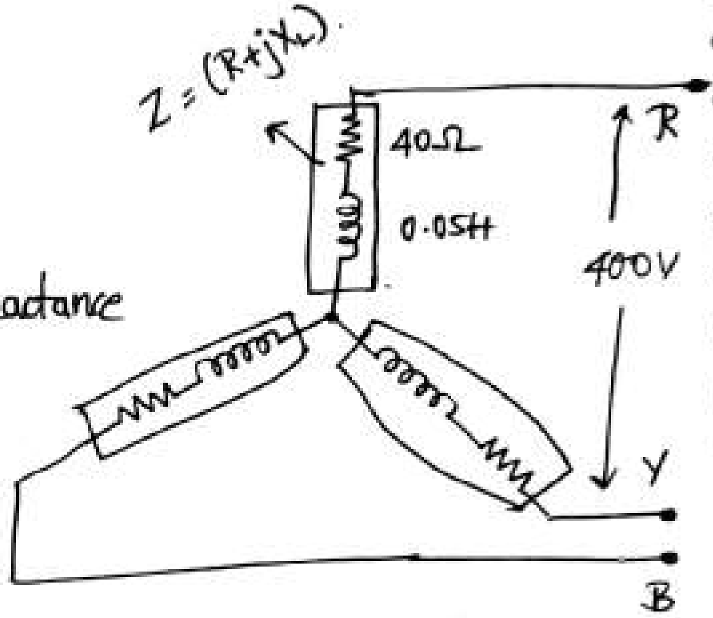
$= \cos\phi$

$= \cos(-53.10^\circ)$

$= 0.60$ (Lagging)

("Repeat problem ② for star (Y-) connection.").

(3). Three Identical coils, each of resistance $R = 40\Omega$ and inductance $L = 0.05H$ are connected in star (Y) and a voltage of 400V, 50Hz supply is applied. Determine the line-current and the total power consumed.



$R = 40\Omega$

$L = 0.05H$

$X_L = 2\pi f L$ = Inductive Reactance

$V_L = 400V$

$f = 50Hz$

$X_L = (2 \times 3.1416 \times 50 \times 0.05)$

$\boxed{X_L = 15.708\Omega}$

$(R + jX_L)$

Impedance / phase $= (40 + j15.708)\ \Omega$/phase

Z / phase $= 42.973 \angle 21.43° \ \Omega$/phase.

__For__ __Star-connection__

$V_L = \sqrt{3} V_{ph}$

Phase-voltage $(V_{ph}) = \dfrac{V_L \text{ (Line-voltage)}}{\sqrt{3}}$

$V_{ph} = \dfrac{400}{\sqrt{3}} = 230.94$ Volts.

$\boxed{V_{ph} = 230.94 \text{ Volts}}$

Phase- current (I_{ph}) = $\frac{V_{ph}}{Z}$

$= \frac{230.94 \angle 0^\circ}{42.973 \angle 21.43^\circ}$

$I_{ph} = 5.37 \angle -21.43^\circ$ A

5.37 → Magnitude

−21.43° → phase Angle (ϕ) in degrees

$I_{ph} = 5.37$ A

Line- current (I_L) = Phase current (I_{ph}) = 5.37 A

→ $I_L = I_{ph} = 5.37$ A

power consumed

$= \sqrt{3}\, V_L I_L \cos\phi$

$= \sqrt{3} \times 400 \times 5.37 \times 0.930$

$P = 3.463$ kW.

power factor

$= \cos(\phi)$

$= \cos(-21.43^\circ)$

$= 0.930$ (Lagging)

("Repeat the problem for Delta Connection")

TRY IT!

1. A 3-phase, 230V supply is given to a balanced load which is Δ (Delta) connected. Impedance in each phase of the load is $(8+j6)\,\Omega$/phase. Determine the phase current and Total power consumed.

(4). A three phase 400V, 50Hz supply is applied to a three-phase circuit, each phase has a resistance of 5Ω and a capacitance of 500μF. Find the current in each line and phase, power-factor, power consumed when it is connected in (i) STAR (ii) DELTA

(5) A three-phase Load, where each arm comprise of Resistance is 25Ω and of inductance 0.15H and capacitor of 120μF in series. The supply voltage is 415V, 50Hz. Calculate (i) Line-current (ii) Total power in watts when they are connected in Δ (Delta).

MODULE: 3
PART A : SINGLE PHASE TRANSFORMERS

TRANSFORMER

Transformer is a static electrical machine which **transfers AC electrical power from one circuit (Primary side / Input side) to the other circuit (Secondary side / Output side) at a constant frequency**, but the voltage level can be altered that means voltage can be increased or decreased according to the requirement.

NECISSITY OF A TRANSFORMER

1. Usually, electrical power is generated at 11Kv. For economic reasons (to reduce transmission losses) AC power is transmitted at very high voltages say 220 kV or 440 kV over long distances. Therefore, a step-up transformer is applied at the generating stations.

2. Also, for safety reasons the voltage is stepped down to different levels by step down transformer at various substations to feed the power to the different locations and thus the utilisation of power is done at 400/230 V.

    a. If ($V_2 > V_1$) i.e. the voltage is **raised on the output side,** then the transformer is known as **Step up transformer**.

    b. If ($V_2 < V_1$) i.e. the voltage level is **lowered on the output side,** then the transformer is known as **Step down transformer**.

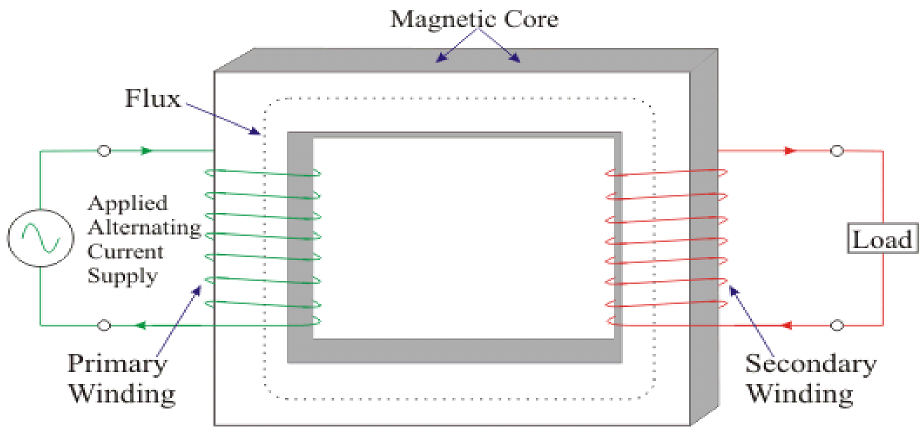
    c. If ($V_2 = V_1$) i.e. the voltage level at the **output side is same as that of the input side,** then the transformer is known as **Isolation transformer**.

BASIC CONSTRUCTION OF TRANSFORMER

The main parts of a transformer are

1. **Primary Winding**

    The winding that takes electrical power, and produces magnetic flux when it is connected to an electrical source.



Single Phase Transformer

2. **Magnetic Core**

    The core is the low reluctance path through which the flux passes and links with secondary winding creating a closed magnetic circuit.

3. Secondary Winding

The winding that provides the desired output voltage due to mutual induction in the transformer.

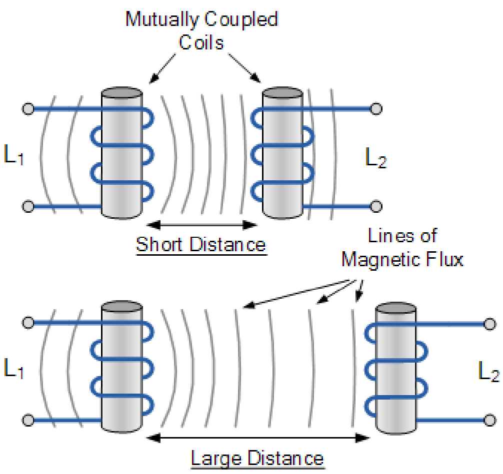
TRANSFORMER OPERATION

Mutual Inductance

Mutual Inductance is the interaction of one coil's magnetic field with another coil and inducing a voltage (emf) in the second coil.

The primary winding (first coil) is supplied with an alternating electrical supply. The alternating current through the primary winding produces an alternating flux that surrounds the winding.

Another winding (Second coil) , also known as the secondary winding, is brought close to the primary winding. Now some portion of the flux in the primary will link with the secondary.



Mutual Inductance

As this flux produced by primary winding is continually changing in amplitude and direction, there is a change in flux linking with the second winding. Therefore, according to Faraday's law of electromagnetic induction, an electromotive force (emf) is induced in the secondary winding which is called as induced emf.

If the circuit of the secondary winding is closed an induced current will flow through it. This is the simplest form of electrical power transformation; this is the most basic working principle of a transformer.

The principle of operation of a transformer has been explained in the following simple steps:

- The primary winding is connected to a single - phase supply and an AC current starts flowing through it.
- Due to the flow of alternating current an alternating flux is produced which then flows through the core.
- The alternating flux gets linked with the secondary winding on the other end of the core.
- Due to the varying flux linking with the secondary winding an emf is induced in the secondary winding.

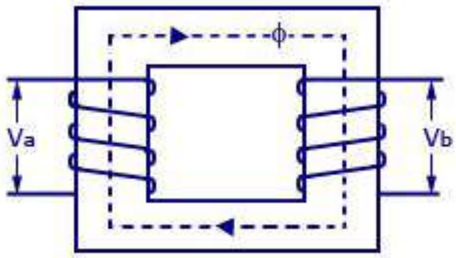
TYPES OF TRANSFORMERS BASED ON CONSTRUCTION

There are two main types of transformers which can be categorized by the shape of the magnetic core. These are

1. Core type transformers
2. Shell-type transformers

CORE TYPE TRANSFORMERS

The core of single-phase core type transformer is a single window core. This means there are two limbs as shown in the figure. Both LV and HV windings are wrapped on both limbs.

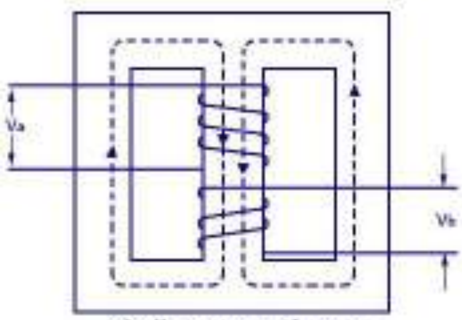


Core type Transformer

Practically speaking both the windings **(Primary and Secondary winding)** are divided into two equal halves and one half of both the windings is wrapped on one limb and other half of both the windings is wrapped on the other limb of the core.

SHELL TYPE TRANSFORMERS

The core of a single-phase shell type transformer is constructed with of three limbs (legs) to increases the mechanical strength of the core.


Shell type transformer

The HV and LV windings are wound around the central limb. The central limb carries the entire flux (ϕ), whereas the side limbs carry half of the flux (ϕ/2).

Hence, to accommodate the flux the cross-section of the central limb is twice than that of the side limbs.

Difference between CORE TYPE TRANSFORMERS and SHELL TYPE TRANSFORMERS

BASIS FOR COMPARISON	CORE TYPE TRANSFORMER	SHELL TYPE TRANSFORMER
Definition	The winding surrounds the core.	The core surrounds the winding.
Lamination Shape	The lamination is cut in the form of the L strips.	Lamination are cut in the form of the long strips of E and L.
Cross Section	Cross-section may be square, cruciform and three stepped	The cross section is rectangular in shape.
Copper Required	More	Less
Limb	Two	Three
Insulation required	More	Less
Flux	The flux is equally distributed on the side limbs of the core.	Central limb carries the whole flux and side limbs carries the half of the flux.

BASIS FOR COMPARISON	CORE TYPE TRANSFORMER	SHELL TYPE TRANSFORMER
Winding placement	The primary and secondary winding are placed on the side limbs.	Primary and secondary windings are placed on the central limb
Losses	More	Less
Maintenance	Easy	Difficult
Mechanical Strength	Low	High
Output range	Low	High
Natural Cooling	Does not Exist	Exist

TYPES OF LOSSES IN A TRANSFORMERS BASED

There are various types of losses in the transformer such as iron losses, copper losses, eddy current losses, stray loss, and dielectric losses. Among these losses Iron loss and copper loss contribute more for the losses.

IRON LOSSES

Iron losses are caused by the alternating flux in the core of the transformer as this loss occurs in the core it is also known as Core loss. Iron loss is further divided into **Hysteresis** and **Eddy current** loss. Iron losses are also called as Constant losses as they don't vary with respect to change in load.

- **HYSTERESIS LOSS**

  When the core of the transformer is subjected to an alternating magnetising force, for each cycle of emf, a hysteresis loop is traced out because of which Power is dissipated in the form of heat known as hysteresis loss.

- **EDDY CURRENT LOSS**

  When the flux links with a closed circuit, an emf is induced in the circuit and the current flows, the value of the current depends upon the amount of emf around the circuit and the resistance of the circuit. Since the core is made of conducting material, these EMFs circulates currents within the body of the material. These circulating currents are called Eddy Currents. They will occur when the conductor experiences a changing magnetic field. As these currents are not responsible for doing any useful work, and it produces a loss (**I^2R loss**) in the magnetic material known as an Eddy Current Loss. The eddy current loss is minimised by making the core with thin laminations.

COPPER LOSSES or OHMIC LOSSES

These losses occur due to ohmic resistance of the transformer windings. If I_1 and I_2 are the primary and the secondary current. R_1 and R_2 are the resistance of primary and secondary winding then the copper losses occurring in the primary and secondary winding will be $I_1^2R_1$ and $I_2^2R_2$ respectively. Therefore $P_c = I_1^2R_1 + I_2^2R_2$

Copper losses varies according to the load and known hence it is also known as variable losses. **Copper losses vary as the square of the load current**.

MODULE: 3

PART B : DOMESTIC WIRING

ELECTRICAL WIRING

Electrical Wiring is a process of connecting cables and wires to the related devices such as fuse, switches, sockets, lights, fans etc. to the main distribution board is a specific structure to the utility pole for continues power supply.

Different Types of Electrical Wiring Systems

The types of internal wiring usually used are

1. Cleat wiring
2. Wooden casing and capping wiring
3. CTS or TRS or PVC sheath wiring
4. Lead sheathed or metal sheathed wiring
5. Conduit wiring

CONDUIT WIRING

There are two additional types of conduit wiring according to pipe installation

1. Surface Conduit Wiring
2. Concealed Conduit Wiring

CONCEALED CONDUIT WIRING

In this type of wiring the conduits (metal or PVC) are placed inside the ceiling / walls and plastered at the time of building construction. The conduits are fixed by means of saddles or staples. Fixing of bends or elbows should be avoided as far as possible. All curves should be made by bending the conduit pipe itself to permit easy drawing in of cables. The VIR or PVC cables are drawn into the concealed by means of springs or GI wire of size 18 SWG. Suitable inspection boxes will be provided to permit periodical inspection, drawing of cables and to facilitate removal of cables if necessary.

Now a days PVC conduit are used in place of steel conduits. PVC conduits are less expensive and the Labour time saved may be as much as 25% to 50% compared to the time taken when installing steel conduits. PVC conduits are resistant to acids alkalies, oil and moisture. They can be buried in lime or cement plaster without ill – effects. Concealed conduit wiring is used in residential, commercial and public buildings.

ADVANTAGES

1. It provides protection against mechanical damage.
2. Metal conduits provides protection against fire due to short circuit etc.
3. The whole system is water proof & requires less time.
4. It has a long life & appearance is very good.
5. Replacement of defective wiring is easy.

6. It is shock proof if earthing is done properly.
7. PVC conduit wiring (particularly concealed) is cheap.

DISADVANTAGES

1. PVC conduit does not provide protection against fire.
2. Metal conduit wiring is very costly.
3. Metal conduit wiring requires more time.
4. Metal conduit wiring needs skilled Labour.

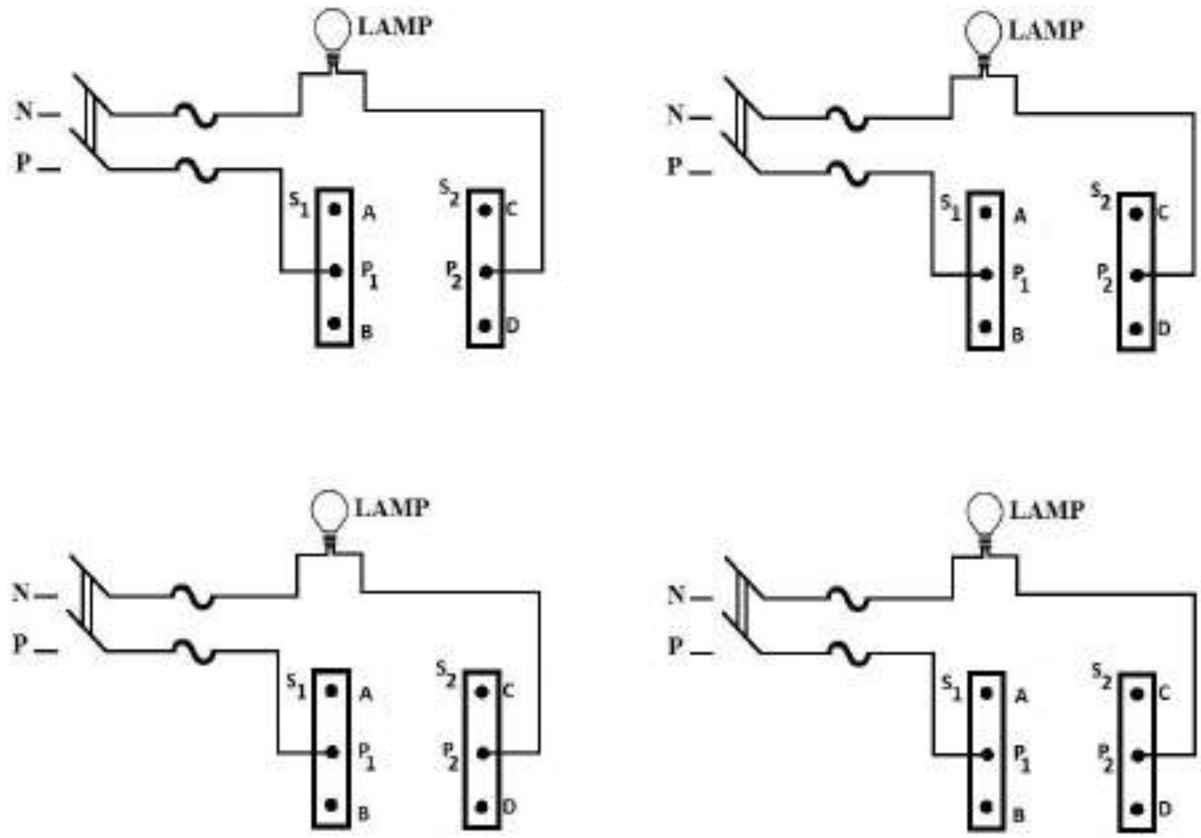
TWO WAY CONTROL / STAIRCASE WIRING

In this wiring system we can control a load from two different places by using two, 2-way switches.

OPERATION: (DIRECT CONNECTION)

Let the two-way switch SW1 be at the bottom of the stair case and two-way switch SW2 be at the top of the staircase. Now the circuit will be complete when the position of both the switches is same (both Up / both Down) and the lamp glows. If the position of the switches is different then the circuit is incomplete and the lamp doesn't glow.

Now assume the position of both the switches are different (as shown in fig. b & d). If a person intends to go up the staircase, then he has to operate the switch SW1 at the bottom and the circuit will be complete (as shown in fig. a & c) and the lamp will be turned on. After reaching the top the person will operate SW2 at the top and the circuit will be incomplete so the lamp doesn't glow. The switching table is as shown. The two way switching is used in big halls, bed rooms, corridors etc..



TRUTH TABLE

Case No.	Switch Position		Condition of lamp
	S_1	S_2	
1	**A**	**C**	**ON**
2	**A**	**D**	**OFF**
3	**B**	**D**	**ON**
4	**B**	**C**	**OFF**

THREE WAY CONTROL / LONG CORRIDOR WIRING:

Here an Intermediate switch is added in between the Two switches intermediate switch, throw 1 of the switches makes straight connection (EF & GH) and throw 2 makes cross connection (EH & GF).

Sometimes in very long corridors, godowns and workshops, it may be necessary to control a lamp from three points. In such cases, the circuit connection requires, 2 two way switches and an intermediate switch as shown in the circuit.

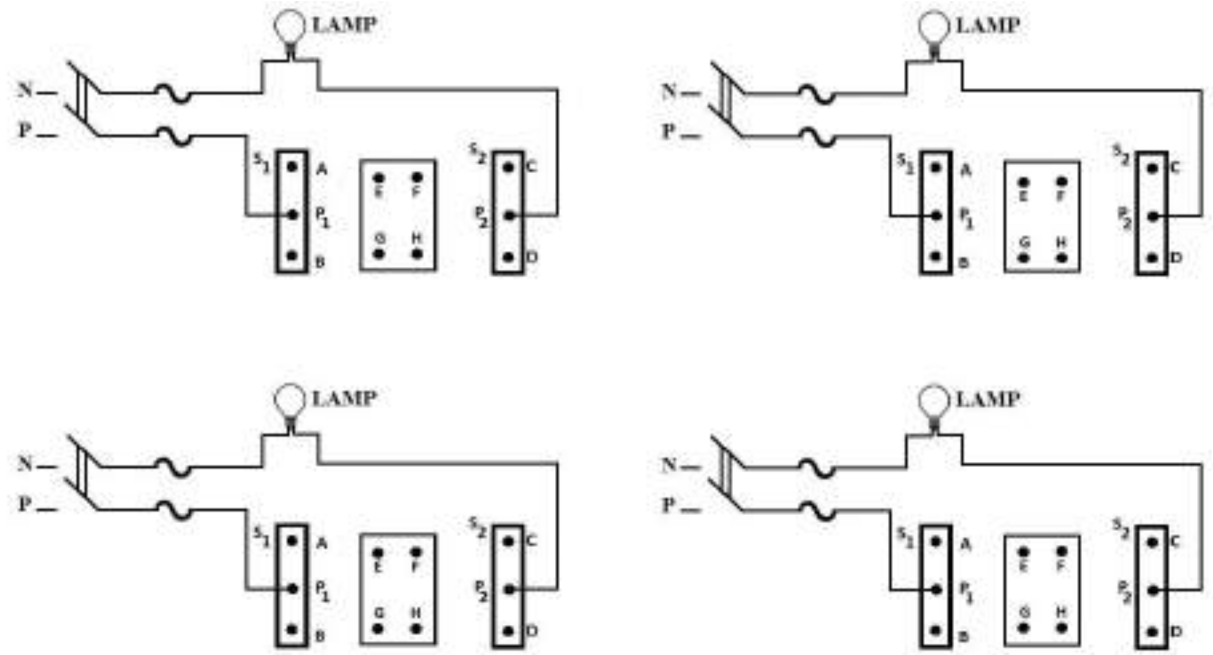
An Intermediate switch couples the 2 two way switches SW1 and SW2 together. It has four terminals E, F, G &H. And it has two ways of connection (Straight and Cross connection)

- **If EF & GH point combination are connected, then it is Straight connection.**

- **If EH & GF point connections are connected, then it is cross connection.**

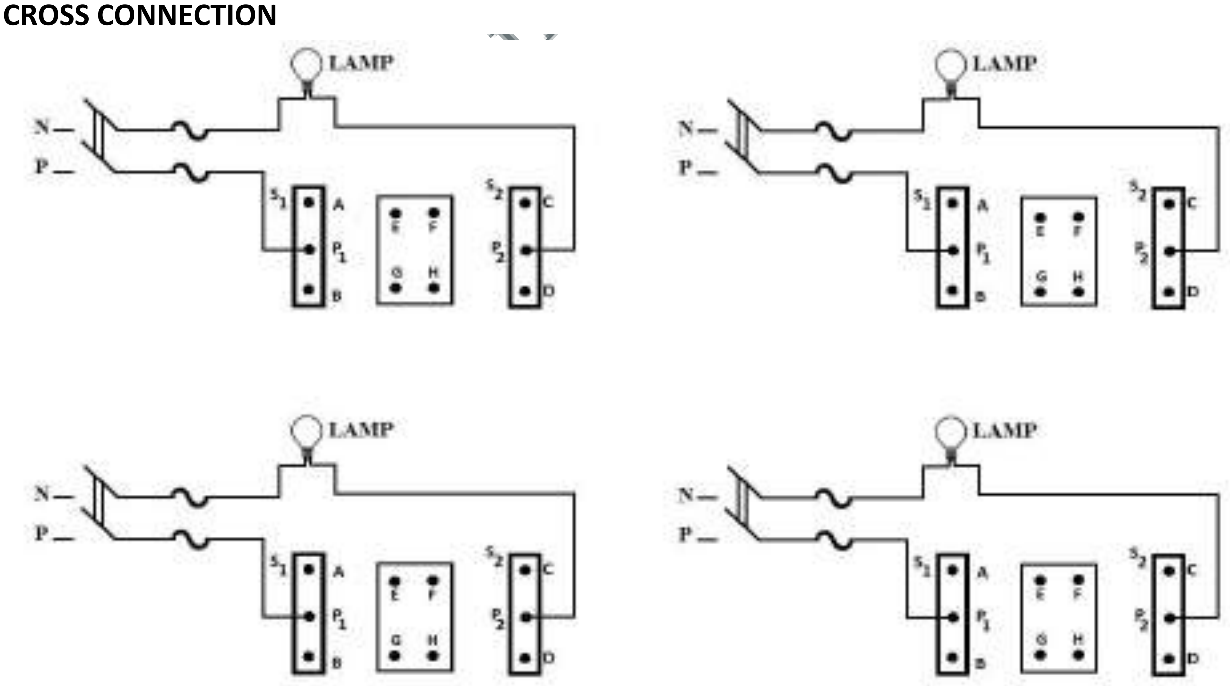
When the intermediate switch is connected straight i.e EF and GH are connected, then the lamp glows if both the Two way switches are in same position (both up / both down)

STRAIGHT CONNECTION



When the intermediate switch is cross connected i.e EH and GF are connected, then the lamp glows only if both the Two-way switches are in different position (one up and one down)

CROSS CONNECTION



Truth Table

Sl. No.	S1	S2	S3	Condition of lamp
STRAIGHT CONNECTION				
1	**A**	**C**	**EF, GH**	**ON**
2	**A**	**D**	**EF, GH**	**OFF**
3	**B**	**D**	**EF, GH**	**ON**
4	**B**	**C**	**EF, GH**	**OFF**
CROSS CONNECTION				
5	**B**	**C**	**EH, GF**	**ON**
6	**B**	**D**	**EH, GF**	**OFF**
7	**A**	**D**	**EH, GF**	**ON**
8	**A**	**C**	**EH, GF**	**OFF**

For both the cases shown above, to turn off the lamp at the intermediate switch point, the position of the IMS has to be changed to

For STRAIGHT CONNECTION : Changed to Cross connection from straight connection
For CROSS CONNECTION : Changed to straight connection from cross connection

FUSE

It is the simplest and cheapest device used for interrupting an electrical circuit under short circuit, or excessive overload current magnitudes. The working principle of a Fuse is based upon the Heating effect of the electric current.

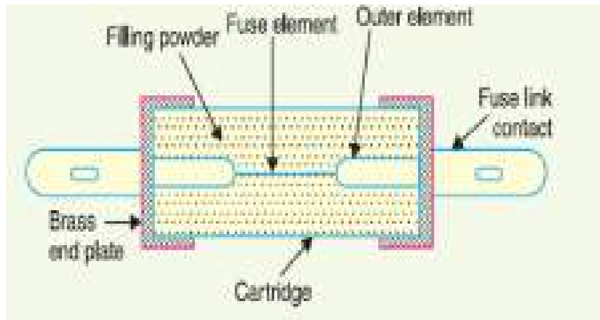
REWIREABLE FUSES OR KIT – KAT TYPE FUSES

Rewireable or Kit – Kat Type Fuses are a type of Low Voltage (LV) Fuses. They are most commonly used in house wiring, small industries and other small current applications.

Rewireable Fuses consists of two main parts: a Fuse Base, which contains the in and out terminal, and a Fuse Carrier, which holds the Fuse Element. The Fuse Base is generally made up of Porcelain and the Fuse Element is made up of Tinned Copper, Aluminum, Lead, etc.

The Fuse Carrier can be easily plugged in or removed from the Fuse Base without the risk of any electric shock. When the fuse is blown due to over current, we can easily remove the Fuse Carrier and replace the fuse wire. This is the main advantage of Rewireable Fuses.

HIGH RUPTURING CAPACITY FUSE



In such type of fuses, the fuse element carries the fault current for a long duration. If the fault is not clear, then the fuse element will melt and open the circuit. The major advantage of HRC fuse is that it clears the low as well as a high fault current.

HRC fuse has the high-speed operation and also does not require maintenance. But the fuse element of the HRC fuses needs to be replaced after each operation, and it also produced the heat during the faults which will affect the operations of the nearby switches.

The enclosure of the HRC fuse is filled with powdered pure quartz, which acts as an arc extinction medium. The silver and copper wires are used for making the fuse wire. The fuse wire has two or more sections which are joint by using tin-joint. The tin-joint reduces the temperature under overloaded condition.

For increasing the breaking capacity of the fuses two or more silver wire is joined in parallel with each other. These wires are adjusted in such a way so that only one wire will melt at a time. The HRC fuse is of two types

MINIATURE CIRCUIT BREAKER (MCB)

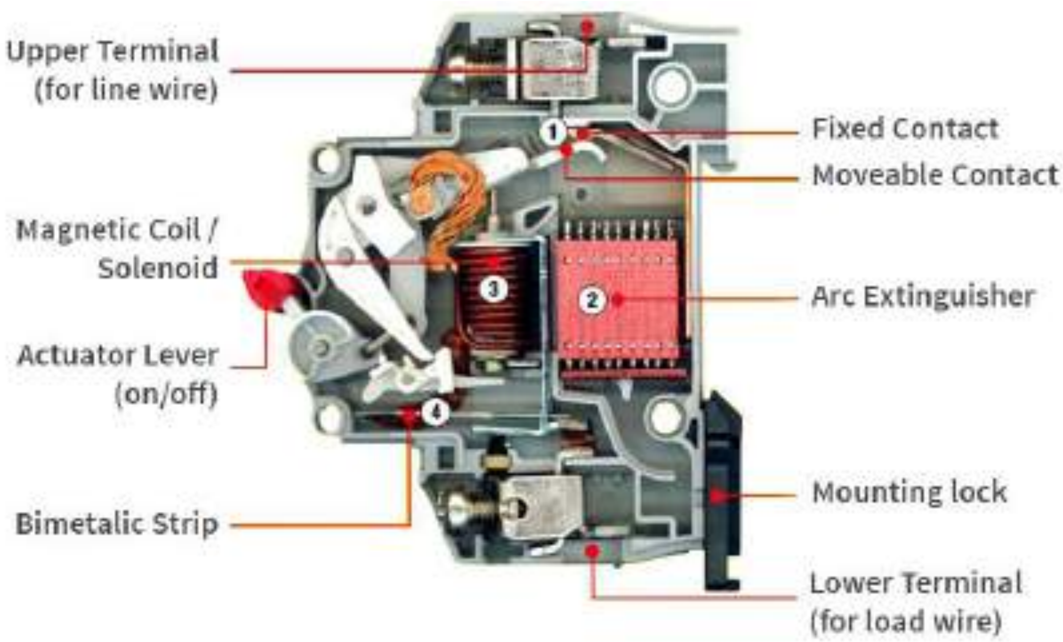
A miniature circuit breaker (MCB) automatically switches off electrical circuit during an abnormal condition of the network means in overload condition as well as faulty condition.

Nowadays we use an MCB in low voltage electrical network instead of a fuse. The fuse may not sense it but the miniature circuit breaker does it in a more reliable way. MCB is much more sensitive to overcurrent than fuse.

Handling an MCB is electrically safer than a fuse. Quick restoration of supply is possible in case of a fuse as because fuses must be re-wearable or replaced for restoring the supply. Restoration is easily possible by just switching it ON. Let’s look at the working of the miniature circuit breaker.

The working principle of MCB Whenever continuous overcurrent flows through MCB, the bimetallic strip is heated and deflects by bending. This deflection of bimetallic strip releases a mechanical latch. As this mechanical latch is attached with the operating mechanism, it causes to open the miniature circuit breaker contacts, and the MCB turns off thereby stopping the current to flow in the circuit. To restart the flow of current the MCB must be manually turned ON. This mechanism protects from the faults arising due to overcurrent or overload. But during short circuit condition, the current rises suddenly, causing electromechanical displacement of plunger associated with a tripping coil or solenoid. The plunger strikes the trip lever causing immediate release of latch mechanism consequently open the circuit breaker contacts. This was a simple explanation of a miniature circuit breaker working principle.

An MCB is very simple, easy to use and is not generally repaired. It is just easier to replace. The trip unit is the main part, responsible for its proper working. There are two main types of trip mechanism. A bi-metal provides protection against overload current and an electromagnet provides protection against short-circuit current.



MCB operation

If the circuit is overloaded for a long time, the bi-metallic strip becomes overheated and deformed. This deformation of Bi-metallic strip causes, displacement of latch point. The moving contact of the MCB is arranged by means of spring pressure, with this latch point, that a little displacement of latch causes, release of spring and makes the moving contact to move for opening the MCB.

The current coil or trip coil is placed so that during short circuit fault the magneto-motive force (mmf) of the coil causes its plunger to hit the same latch point and make the latch to be displaced. Again, when operating lever of the miniature circuit breaker is operated by hand, that means when MCB goes off position manually, the same latch point is displaced as a result moving contact separated from fixed contact in the same manner.

It may be due to deformation of a bi-metallic strip, or increased mmf of a trip coil or maybe a manual operation, the same latch point is displaced and same deformed spring is released, which ultimately responsible for movement of the moving contact. When the moving contact separated from fixed contact, there may be a high chance of arc. This arc then goes up through the arc runner and enters arc splitters and is finally quenched. When we switch it on, we reset the displaced operating latch to its previous on position and the MCB is ready for another switch off or trip operation.

MODULE: 4

DC MACHINES

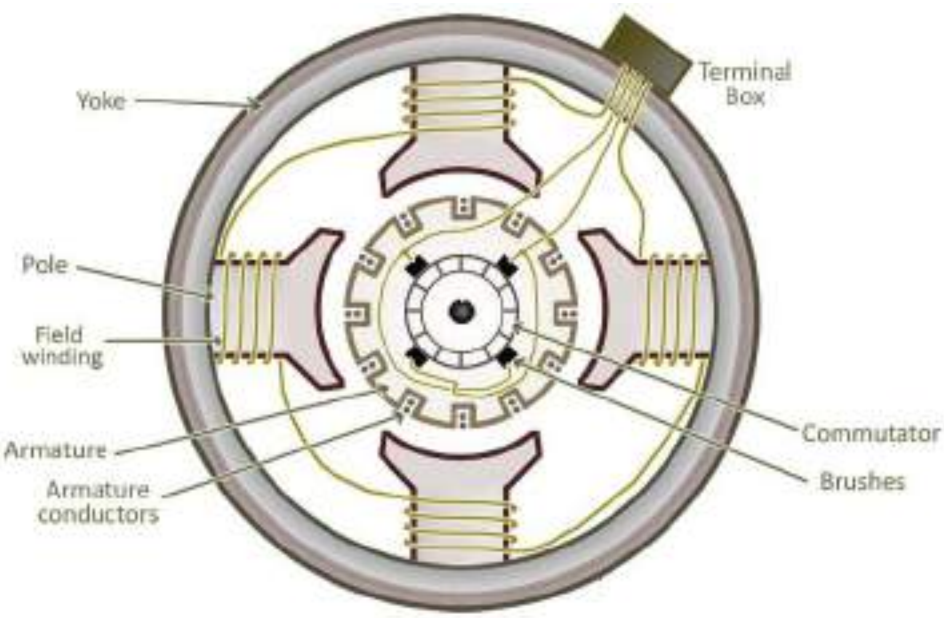
An electrical machine is the generic name for a device that converts mechanical energy to electrical energy, converts electrical energy to mechanical energy, or changes alternating current from one voltage level to a different voltage level.

Electrical machines are divided into two types

1. **Generators** : Converts **Mechanical energy** into **Electrical energy**.
2. **Motors** : Converts **Electrical energy** into **Mechanical energy**.

Construction of DC Machines

A **DC generator can be used as a DC motor without any constructional changes** and vice versa is also possible. Thus, a **DC generator or a DC motor can be broadly termed as a DC machine**. These basic constructional details are also valid for the construction of a DC motor.There are two main parts of a generator



A four-pole DC generator

1. Stator :
   The part that is stationary, In Dc machines **Field system** is the **Stator**. Field system consists of the following parts
   - Field core / Field pole
     - ✓ Pole core
     - ✓ Pole shoe
   - Field winding

2. Rotor :
   The part that is rotating, In Dc machines armature is the rotor. Armature consists of the following parts
   - Armature core
     - ✓ Armature slots
     - ✓ Armature conductors
   - Armature Windings (Lap / Wave Windings)

1) YOKE

The outer frame of a dc machine is called as yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.

2) FIELD SYSTEM

Poles and pole shoes

Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes

- ✓ They support field coils
- ✓ Spread out the flux in air gap uniformly.

Field winding

They are usually made of copper. Field coils are former wound and placed on each pole and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles.

3) ARMATURE

Armature core

Armature core is the rotor of a dc machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial air flow for cooling purposes. Armature is keyed to the shaft.

Armature winding

It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding. Double layer lap or wave windings are generally used. A double layer winding means that each armature slot will carry two different coils.

4) COMMUTATOR

The function of a commutator, in a dc generator, is to collect the current generated in armature conductors.

In case of a dc motor, commutator helps in providing current to the armature conductors.

A commutator consists of a set of copper segments which are insulated from each other. The number of segments is equal to the number of armature coils. It works as a DC-AC converter while acting as a motor and AC-DC converter while working as a DC generator

5) BRUSHES

They are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

WORKING OF DC MACHINES

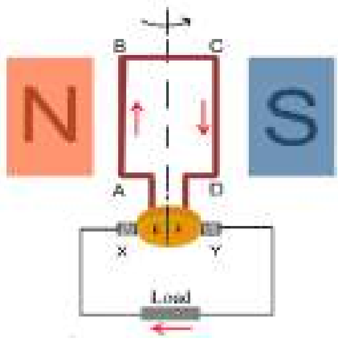
As DC Generator

When a DC machine has to operate as a generator, the working principle follows Faraday's **laws of electromagnetic induction** which states that "**Whenever a conductor is placed in a varying magnetic field (OR a conductor is moved in a magnetic field), an emf (electromotive force) gets induced in the conductor**".

Faraday's Law of EMI

WORKING

In a DC generator, field system produces an electromagnetic field and the armature conductors are rotated inside the electromagnetic field using a prime mover (Motor or turbines). Because the armature conductors are rotated, the flux linking with the armature conductors also changes / varies. Thus, an emf is induced in the armature conductors.



The direction of induced current is given by Fleming's right hand rule which states that "**if the thumb, fore finger and middle finger of the right hand are stretched to be perpendicular to each other as shown in the illustration at right, and if the thumb represents the direction of the movement of conductor, fore-finger represents direction of the magnetic field, then the middle finger represents direction of the induced current**".

The magnitude of induced emf can be calculated from the emf equation of dc generator. The armature conductors are wound in such a way that they provide a closed path, hence an induced current will circulate within the path of the armature winding (Armature coil).

As DC Motor

An electric motor is an electrical machine which converts electrical energy into mechanical energy. The basic working principle of a DC motor is "**whenever a current carrying conductor is placed in a magnetic field, it experiences a mechanical force twisting force called as Torque**".

The direction of this force is given by Fleming's left-hand rule which states that "**If we stretch the first finger, second finger and thumb of our left hand to be perpendicular to each other, and the direction of magnetic field is represented by the first finger, direction of the current is represented by the second finger, then the thumb represents direction of the force experienced by the current carrying conductor**".

BACK EMF

When the armature of a DC motor rotates under the influence of the driving torque , the armature conductors move through the magnetic field and hence emf is induced in them as in a generator. This induced emf acts in the opposite direction to the applied voltage V (Lenz's law) and is known as Back EMF or Counter EMF (E_b).

SIGNIFICANCE OF BACK EMF

1. The presence of back emf **makes the D.C. motor a self-regulating machine** i.e., it makes the motor to draw armature current which is sufficient to develop the torque required by the load.

2. Back emf in a DC motor **regulates the flow of armature current** i.e., it automatically **changes the armature current to meet the load requirement**.

   a. **When the motor is running on no load**, small torque is required to overcome the friction and windage losses. Therefore, the armature current Ia is small and the back emf is nearly equal to the applied voltage.

   b. **If the load on the motor is increased**, the armature speed will be decreased and hence the back emf E_b falls. The decreased back emf allows a larger current to flow through the armature and larger current means increased driving torque. Thus, the driving torque increases as the motor slows down. The motor will stop slowing down when the armature current is just sufficient to produce the increased torque required by the load.

   c. **If the load on the motor is decreased**, the driving torque is momentarily in excess of the requirement so that armature speed increases. As the armature speed increases, the back emf E_b also increases and causes the 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.

CLASSIFICATION OF DC MACHINES (same classification for both motors and generators)

DC machines are generally classified according to these methods of field excitation. On this basis, different types of dc machines are

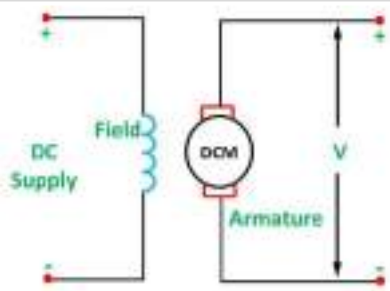
1. **Permanent magnet dc machines**
2. **Separately excited dc machines**
3. **Self-excited dc machines**
   a) Series Wound dc machine
   b) Shunt Wound dc machine
   c) Compound Wound dc machine

PERMANENT MAGNET DC MACHINES

In permanent magnet dc machines, a permanent magnet is used to establish flux in the magnetic circuit. These machines are not found in industrial applications because of the low power generated from it. Such machines are employed only in small sizes like dynamos in motorcycles. The behaviour of a dc machine on load depends upon the method of field excitation adopted.

SEPARATELY EXCITED D.C. MACHINES

A dc machine whose field magnet winding is supplied from an independent external d.c. source (e.g., a battery etc.) is called a separately excited machine. The figure below shows the connections of a separately excited machine.



Applications of separately excited DC Generators

a) Because of their ability to give wide range of voltage output, they are generally used for testing purpose in the laboratories.

b) Separately excited generators operate in a stable condition under varying field excitation. Therefore they are used as supply source of DC motors, whose speeds are to be controlled for various applications. Example- Ward Leonard Systems of speed control.

SELF EXCITED D.C. MACHINES

D.C. machines whose field magnet winding is supplied current

a) from the output of the generator (when working as generator)
b) From the same input given to the motor (when working as a motor)

Self-excited D.C. Generator

A D.C. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator.

A generator that supplies its own field excitation is called a self-excited generator. Self-excitation is possible only if the field pole pieces have retained a slight amount of permanent magnetism, called residual magnetism.

When the generator's armature is rotated, the weak residual magnetism in the field coils induces a small voltage in the armature. This small voltage applied to the field coils causes a small field current.

Although small, this field current strengthens the magnetic field and allows the armature to generate a higher voltage. The higher voltage increases the field strength, and so on. This process continues until the output voltage reaches the rated output of the generator.

Self-excited D.C. motor

A D.C. motor whose field magnet winding is supplied current from the same input which is given to the motor is called as Self excited DC motor.

There are three types of self-excited dc machines depending upon the manner in which the field winding is connected to the armature, namely;

a) Series generator / Series motor
b) Shunt generator / Shunt motor
c) Compound generator / Compound motor

D.C. Series machine

In a series-wound machine, the field winding is connected in series with armature winding. **The series Field winding has few turns of thick wire having low resistance**.

Applications of Series Wound DC Generators

a) They are used to provide field excitation current in DC locomotives for regenerative breaking.
b) These types of generators are used as boosters to compensate the voltage drop in the feeder in various types of distribution systems such as railway service.
c) They are used in series arc lightening.

Applications of Series Wound DC motor

It is a variable speed motor. The speed is low at high torque at light or no load, the motor speed attains dangerously high speed. The motor has a high starting torque. They are used in

a) Electric traction
b) Cranes
c) Elevators
d) Air compressor
e) Vacuum cleaner
f) Hair drier
g) Sewing machine

D.C. Shunt machine

In a Shunt-wound machine, the field winding is connected in parallel with armature winding. **The shunt field winding has many turns of fine wire having high resistance.**

Applications of Shunt Wound DC Generators

a) They are used for general lighting.
b) They are used to charge battery because they can be made to give constant output voltage.
c) They are used for giving the excitation to the alternators.
d) They are also used for small power supply (such as a portable generator).

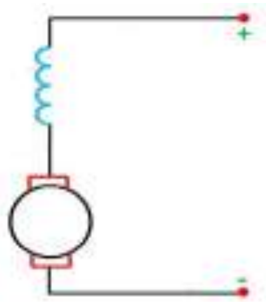
Applications of Shunt Wound DC motor

They are constant speed motors irrespective of the nature of the load. They are used in

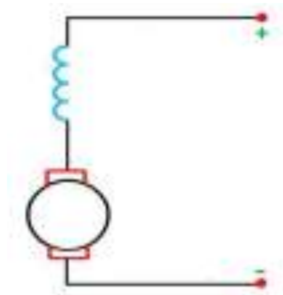
a) Lathes
b) Drills
c) Boring mills
d) Shapers
e) Spinning and weaving machines.

D.C. Series machine

As a Generator

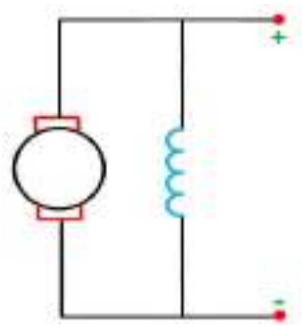


As a Motor

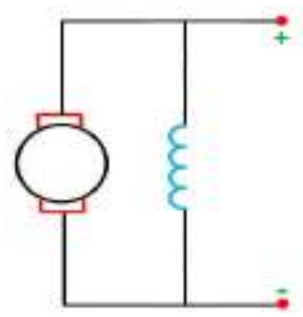


D.C. Shunt machine

As a Generator



As a Motor



Module 5

5A: Three Phase Synchronous Generators: Principle of operation, Constructional details, Synchronous speed, Frequency of generated voltage, emf equation, Concept of winding factor (excluding the derivation and calculation of distribution and pitch factors).

5B: Three Phase Induction Motors: Principle of operation, Generation of rotating magnetic field, Construction and working of three-phase induction motor, Slip and its significance. Necessity of starter, star-delta starter.

MODULE 5

5A – Three Phase Synchronous Generator

Introduction

AC generators or alternators operate on the fundamental principle of electromagnetic induction [EMI], similar to that of Dc generators. Both AC and DC generators consist of an armature winding and a magnetic field. But one major difference between that two is that, in Dc generators, the armature rotates field system is stationary. The arrangement in alternators is just the reverse of it. In the case of alternators, standard construction consists of armature winding mounted on a stationary element called stator and field windings on a rotating element call rotor.

Whenever making flux linking the conductor changes an EMF will be induced in the conductor this type of EMF induction is called statically induced EMF where conductor is stationary and magnetic field is rotating.

Constructional features

Basically an alternator consists of two parts stator and Rotor

1. Stator

Stator consists of cast iron or steel frame which supports armature core having slots on its periphery for housing armature conductors. The stator core used a laminated construction in order to reduce eddy current loss. The material used special magnetic iron steel alloy so as to keep the hysteresis losses minimum. The frame does not carry any flux and serves as the support to the core. Ventilation is provided with the help of holes (ducts) casted in the frame.

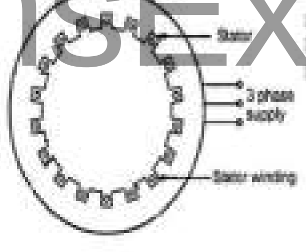


Fig.5.1

2. Rotor

There are two types of Rotor

Salient pole type Rotor.

This is also called projected pole type as all the poles are projected out the surface of the rotor. The Poles are made up of thick steel laminations and are bolted to the rotor as shown in the fig.5.2.

The field winding is placed on the pole core and is supported by the pole shoe. These rotors have large diameters small axial length.

The mechanical strength of salient pole type less, hence this is preferred for low speed alternators. Salient pole type rotors are engine driven.

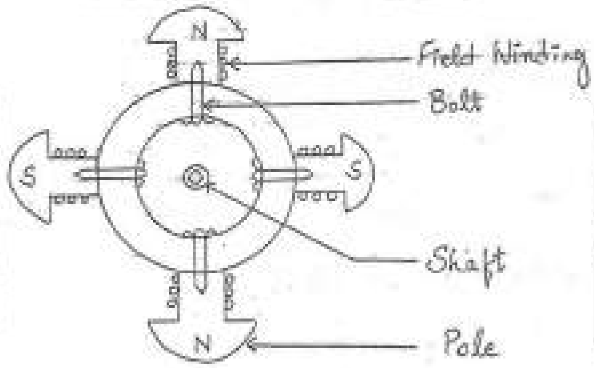


Fig.5.2: Salient Pole Type Rotor

Smooth cylindrical / Non salient type Rotor

- This is also called as non projected pole type of rotor.
- The rotor consists of smooth solid Steel cylinder having number of slots to accommodate the field coil.

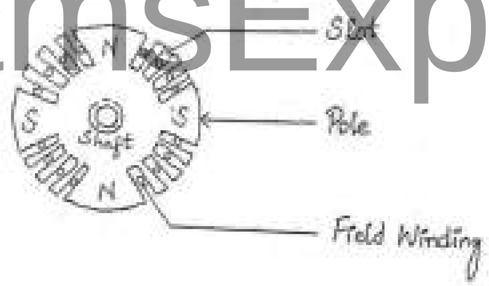


Fig.5.3: Non- Salient Pole Type Rotor

- The unslotted portions of the cylinder itself act as the poles.

- The poles are not projected out and the surface of the rotor is smooth which maintains uniform air gap between stator and rotor.
- These rotors have small diameter and large axial length.
- These types of rotors are mechanically very strong and are preferred for high speed alternators up 3000 rpm.
- These are turbine driven hence they are called as Turbo alternators.

Types of Alternators

Depending on the type of rotor, we have two types of alternator they are:

i) Salient pole alternator

ii) Non salient pole alternator

Principle of operation

The alternators work on the principle of electromagnetic induction. For the purpose of better understanding, let us consider the armature conductors are rotating with respect to the field which is stationary as shown in the fig.5.4.

Consider a relative motion of a single conductor under the magnetic field produced by two stationary poles.

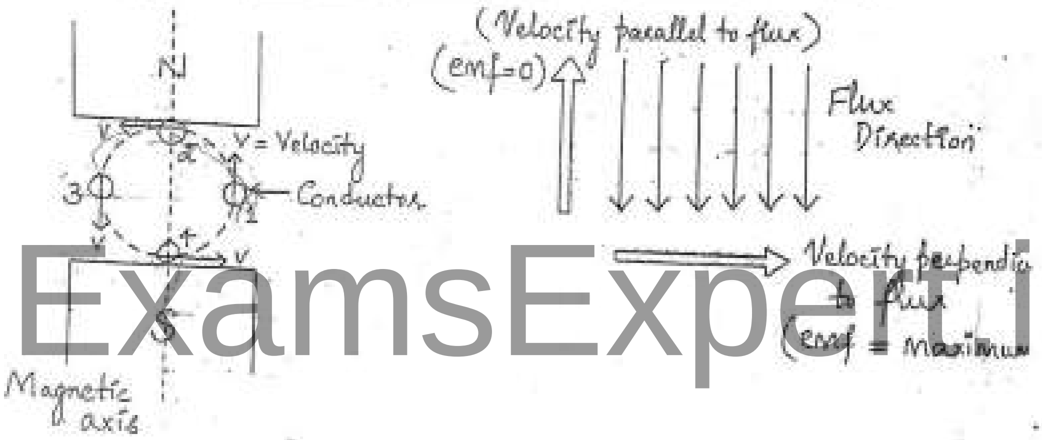
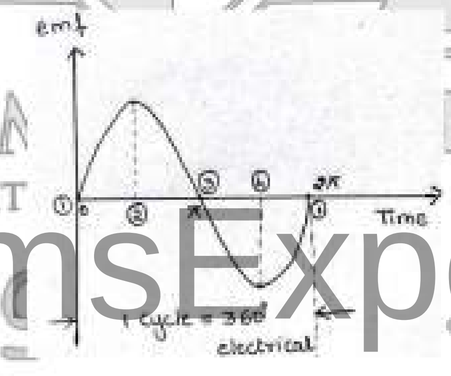


Fig.5.4: Two Pole Alternator

- Let the conductor start rotating position 1 at this instant the entire velocity component is parallel to the flux lines the conductor is not cutting any flux lines and the emf induced in the conductor is zero.

- As the conductor moves from position 1 to position 2, the flux lines cut by the conductor increases, accordingly the magnitude of emf induced also increases. At position 2 enter velocity component is perpendicular to the flux lines and at this instant, the induced emf is maximum.
- As the conductor changes its position from 2 to 3, the velocity component perpendicular to the flux starts decreasing and hence the magnitude of emf also decreases. At position 3 the emf induced in the conductor is zero.
- Now when the conductor moves from position 3 to position 4 the velocity component perpendicular to the flux lines again starts increasing. But the direction of velocity component is opposite in direction of velocity component existing during the movement of conductor from position 1 to 2 . Hence the induced emf in the conductor increases but in the opposite direction.
- At position 4, the velocity component becomes perpendicular to the flux lines, hence the induced emf is maximum. But the direction of the velocity component is opposite hence the induced emf is opposite to that of in position 2.
- As the conductor moves from position 4 to 1, the induced emf decreases and finally becomes zero at position 1.



1 rotation = 360^0 = Mechanical angle

1 cycle= { one positive cycle of induced emf} + { one negative cycle of induced emf}

= 360^0 = electrical angle

For 2 pole alternator, one mechanical angle corresponds to one electrical angle.

But in general,

1^0 mechanical angle = $\frac{p}{2}$ electrical angle.

Frequency of generated voltage:

Let P = Number of poles

f = Frequency of induced emf

N = speed of the rotor in rpm.

One mechanical revolution = $\frac{P}{2}$ Electrical cycles

Electrical cycles / revolution = $\frac{P}{2}$

As speed is N rpm, in one second, rotor will complete $\frac{N}{60}$

Frequency = No. of electrical cycles per second.

= (No. of electrical cycles per revolution) x (Revolutions per second)

$$= \left(\frac{P}{2}\right) \times \left(\frac{N}{60}\right) = \frac{PN}{120}$$

$$\therefore \quad f = \frac{PN}{120} \text{ Hz.}$$

Synchronous speed (Ns)

For fixed number of poles, alternator has to be rotated at a particular speed to keep the frequency of the generated emf constant at the required value. Such a speed is called synchronous speed. Synchronous speed is denoted by Ns.

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

f = required rated frequency.

In India, the frequency of an alternating emf is standard value which is 50Hz.

EMF equation of an alternator

Let, Z= Total number of conductors.

Z_{ph} = Conductor per phase

T_{ph} = Turns per phase, $T_{ph} = \frac{Zph}{2}$ ($\because$ 1 turn = 2 conductors)

N_s = Synchronous speed in rpm

$N_s = \frac{120f}{P}$ rpm

f = frequency of induced emf in Hz.

P = Number of poles

E_{ph}= Phase voltage

ϕ = Flux / pole in wb.

E_L = Line voltage.

The average value of emf induced (e) / conductor, $= \frac{d\phi}{dt}$

Flux cut / Conductors / revolution ($d\phi$) = ϕ x P

Time taken / revolution (dt) = $\frac{60}{Ns}$ seconds

The average value of emf induced (e) / conductor = $\frac{d\phi}{dt} = \frac{\phi P}{\frac{60}{N_s}} = \frac{P\phi N_s}{60} = \frac{P\phi 120 f}{60P} = 2\phi f$

If there are Z_{ph} conductors / phase,

Average emf / phase = $E_{ph} = 2\phi f\ Zph$ volts.

But in ac circuits RMS value of an alternating is used for analysis.

The form factor (k_f) for sine wave = $\frac{RMSvalue}{Avg.value} = 1.11$

$\therefore$ RMS value of EMF / phase = k_f x (Avg.value)

$E_{Ph} = 1.11 \times (2 \times \phi \times f \times Zph)$

But $Zph = 2\,T_{ph}$

$\therefore E_{ph} = 1.11 \times (2 \times \phi \times f \times 2 \times T_{ph})$

$E_{ph} = 4.44 \times \phi \times f \times T_{ph}$ volts

This would have been actual value of emf induced, if all the coils in phase were full pitched & concentrated. But practically due to short pitching & distributed coils, the actual available voltage is reduced by the ratio of winding factors i.e k_p and k_d .

$\therefore E_{ph} = 4.44 \times k_p \times k_d \times \phi \times f \times T_{ph}$ volts

i.e $E_{ph} = 4.44\, k_p\, k_d\, \phi\, f\, T_{ph}$ volts

This is the emf equation of an alternator. For a 3 - ϕ alternator which is star connected, line emf is given by,

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

Problems:

5.1 A 2 pole, 3-ϕ alternator running at 3000rpm has 42 armature slots with 2 conductors in each slot. Calculate flux/ pole required to generate a line voltage of 2300 volts. $K_d = 0.952$ and $K_p = 0.956$.

Given:

P=2, N_s = 3000 rpm, Slots = 42, Conductor/slot = 2, E_L = 2300V, K_d = 0.952, Kp = 0.956.

To find ϕ, we have

$E_{ph} = 2.22 \times \phi \times f \times Z_{ph}\ K_p\, K_d$ volts ....(1)

Z_{ph} = Conductors / Phase = $\frac{Slots * Conductors/\,Slot}{Phase}$

$Z_{ph} = \frac{42 * 2}{3}$

$Z_{ph} = 28$

Given, $N_s = 3000$

$$N_S = \frac{120f}{P} = 3000$$

$$f = \frac{P*3000}{120} = 50Hz$$

$$E_{Ph} = \frac{E_L}{\sqrt{3}} = 1327.9 \text{ volts}$$

∴ Substituting the values in eq.(1)

$1327.9 = 2.22*\phi*50*28*0.952*0.956$

$$\phi = \frac{1327.9}{2828.62} = 0.469 \text{ wb}$$

$\phi = 0.469$ wb

5.2 A 3 phase, 6 pole star connected alternator revolves at 1000rpm. The stator has 90 plots and 8 conductors per slot. The flux per pole is 0.05wb (sinusoidally distributed). Calculate the voltage generated by the machine if the winding factor is 0.96.

Given:

P= 6

$N_s = 1000$**rpm**

No. of slots = 90

Conductors/ slot = 8

$\phi = 0.05$wb

$K_w = 0.96$

The emf of an alternator is given by,

$E_{ph} = 2.22 \, f * \phi * Z_{ph} * K_w$ ……………… (1)

$N_S = \frac{120f}{P} = 1000$

$f = \frac{P*1000}{120} = \frac{6*1000}{120} = 50Hz$

$Z_{ph} = \frac{Slots*Conductors/Slot}{Phase} = \frac{90*8}{3} = 240$

Substituting f and Z_{ph} in eq(1)

$E_{ph} = 2.22 * 50 * 0.05 * 240 * 0.96$

$E_{ph} = 1278.72V$

For Star connected system

$E_L = \sqrt{3}\, E_{ph} = \sqrt{3} * 1278.72 = 2214.80$ volts.

Winding Factor:

Pitch factor (K_p) or Coil span factor or Chording factor (K_c) :

The factor by which the emf per coil is reduced because of short pitching is called as pitch factor or coil span factor.

$K_P = \cos\left(\frac{\alpha}{2}\right)$ α - angle of short pitch

Distribution Factor (K_d)

The factor by which there is a reduction in the emf due to distribution of coils is called distribution factor and is denoted by K_d.

$K_d = \left[\frac{\sin\left(\frac{m\beta}{2}\right)}{m\sin\left(\frac{\beta}{2}\right)}\right]$ β = slot angle,

$\beta = \frac{180}{n}$, n = no. of slots/pole , m = No. of slots / pole / phase.

Winding Factor is given by $K_W = K_P * K_d$.

5B-Three Phase Induction Motors

Introduction:

An electric motor which works on a.c. supply is called a.c. motor. The a.c. motors are classified as

i) Asynchronous Motors (Single Phase Induction Motors and Three Phase Induction Motors)

ii) Synchronous Motors

iii) Special Purpose Motors.

The most common and frequently used electrical machines in industry is the Three Phase Induction Motor for the following reasons

i) Simple Design and Rugged Construction

ii) Low-Price and Easy Maintenance

iii) Operations are highly reliable

iv) Wide range of power ratings

v) Run essentially as constant speed from no-load to full load

vi) Self starting

vii) High efficiency and good speed regulation

The various advantages of induction motor are accompanied with following disadvantages

i) The starting torque of induction motors are inferior to that of DC motor

ii) Induction motor is a constant speed machine; therefore the speed variation of induction motors is done at the expense of money and motor efficiency.

Construction:

Induction motors have two main parts – stator and rotor.

1) Stator: Stator is the stationary part of induction motor. A three phase winding is placed in the stator of induction motor and the three phase supply is given to it.

2) Rotor: Rotor is the rotating part of induction motor. The rotor is connected to the mechanical load through the shaft.

Stator:

The construction of stator for both the kinds of three phase induction motor remains the same.

The stator of the three-phase induction motor consists of three main parts:

a) Stator frame - It is the outer part of the three phase induction motor. Its main function is to support the stator core and the field winding. It acts as a covering, and it provides protection and mechanical strength to all the inner parts of the induction motor. The frame is either made up of die-cast or fabricated steel. The frame of three phase induction motor should be strong and rigid as the air gap length of three phase induction motor is very small.

b) Stator core

c) Stator winding or field winding.

- The stator core has a laminated type of construction made up of stampings which are 0.4mm to 0.5mm thick. The stampings are insulated from each other. Such a construction keeps the iron losses / core losses to a minimum value.
- The stampings are slotted to receive the balanced three phase windings (star or delta) and it is fed from a balanced three phase supply.
- Stator winding is wound for a definite number of poles, depending on the requirement of speed. The exact number of poles being determined by speed equation, $N_S = \frac{120f}{P}$.
- The ducts are provided for cooling purposes. The stator core is fitted in a casted or fabricated steel frame.
- When the stator windings are supplied by three phase supply, a rotating magnetic field is produced below the stator in the air gap and this rotating magnetic field induces an e.m.f. in rotor conductors by mutual induction principle.
- The stator construction is as shown in figure 5.5

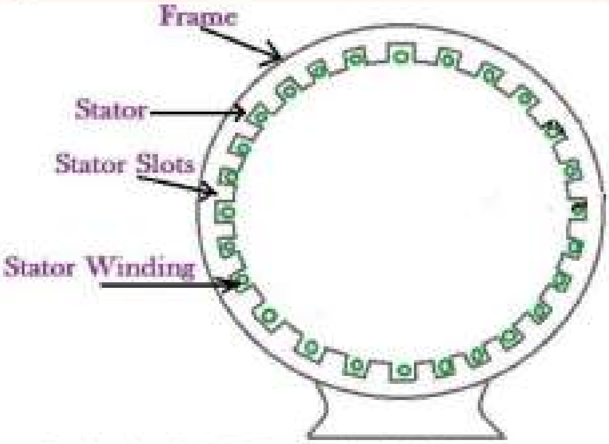


Fig 5.5

Rotor:

The rotor of the three phase induction motor are further classified as

i) Squirrel Cage Rotor
ii) Slip Ring Rotor or Wound Rotor or Phase Wound Rotor

Depending upon the type of rotor construction used the three phase induction motor areclassified as:

i) Squirrel Cage Induction Motor
ii) Slip Ring Induction Motor or Wound Induction Motor or Phase Wound Induction Motor.

1. Squirrel cage:

- This type of rotor has the simplest, cheap and most rugged type of construction as shown in figure 5.6.
- This type of rotor consists of a cylindrical laminated core with skewed slots.
- The rotor consists of uninsulated copper or aluminium bars called rotor conductors. The bars are placed in the slots.
- These bars are permanently shorted at each end with the help of conducting copper ring called end ring, because of which rotor resistance is very less. Hence this rotor is also called short circuited rotor.
- The bars are usually brazed to the end rings to provide good mechanical strength.

- As the rotor is short circuited, no external resistance can be introduced so slip ring and brush assembly is not required for this type of rotor.

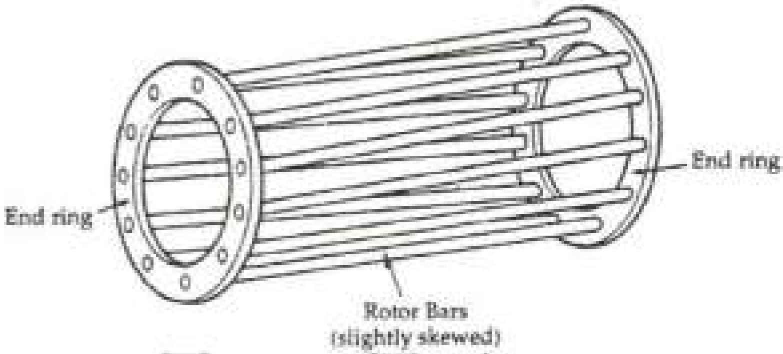


Fig 5.6

Skewing: It is a method where the slots on the periphery of the rotor are not arranged parallel to the shaft axis. Skewing has various advantages:

i) The magnetic hum gets reduced due to skewing thereby making the motor operation quite.

ii) The tendency of stator and rotor teeth getting magnetically locked gets reduced due to skewing.

iii) Skewing increases the effective transformation ratio between stator and rotor.

2. Slip Ring Rotor / Phase Wound Rotor:

- In this type of construction, rotor winding is similar to the stator. The rotor carries a three phase (star / delta) connected, distributed winding, wound for same number of poles as that of stator as shown in figure 5.7.
- The rotor core is laminated and slotted. The slots carry the rotor winding.
- The three phase rotor windings are star connected internally. The other end of the winding terminals are brought out and connected to three insulated slip rings mounted on the shaft with brushes resting on them.
- These brushes are connected externally to a star connected rheostat for increasing the starting torque of motor.

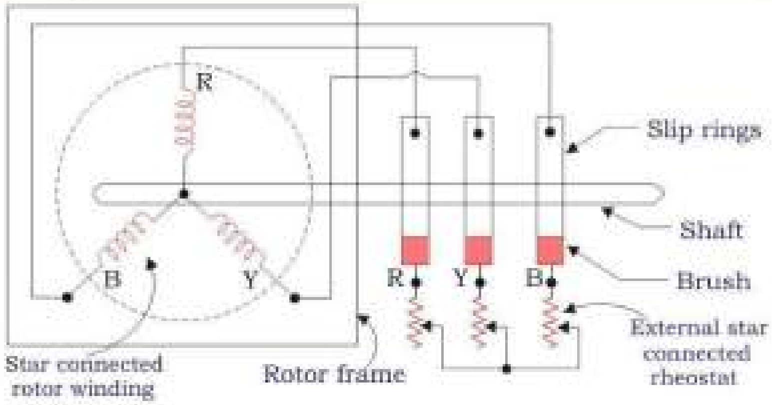


Fig 5.7

Comparison between Squirrel Cage and Slip Ring Induction Motor:

Slip Ring Induction Motor	Squirrel Cage Induction Motor
Construction is complicated due to presence of slip ring and brushes	Construction is very simple
The rotor winding is similar to the stator winding	The rotor consists of rotor bars which are permanently shorted with the help of end rings
We can easily add rotor resistance by using slip ring and brushes	Since the rotor bars are permanently shorted, it's not possible to add external resistance
Due to presence of external resistance high starting torque can be obtained	Staring torque is low and cannot be improved
Slip ring and brushes are present	Slip ring and brushes are absent
Frequent maintenance is required due to presence of brushes	Less maintenance is required
The construction is complicated and the presence of brushes and slip ring makes the motor more costly	The construction is simple and robust and it is cheap as compared to slip ring induction motor
This motor is rarely used only 10% industry uses slip ring induction motor	Due to its simple construction and low cost. The squirrel cage induction motor is widely used

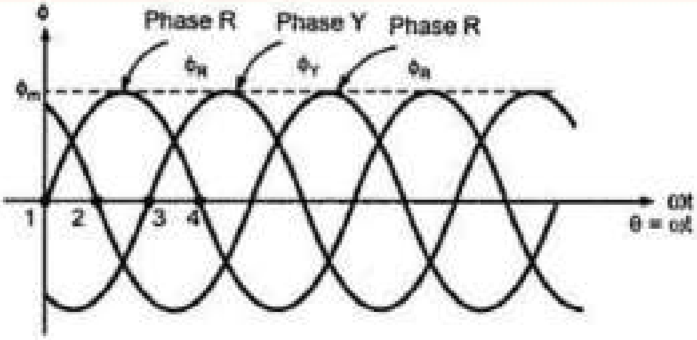
Rotor copper losses are high and hence less efficiency	Less rotor copper losses and hence high efficiency
Speed control by rotor resistance method is possible	Speed control by rotor resistance method is not possible
Slip ring induction motor are used where high starting torque is required i.e. in hoists, cranes, elevator etc.	Squirrel cage induction motor is used in lathes, drilling machine, fan, blower printing machines etc.

Applications:

1. **Squirrel Cage Induction Motor:**
   As these motors have constant speed and moderate torque, they are used in fans, blowers, water pumps, grinders, lathe machines, printing machines, drilling machines, etc.
2. **Slip Ring Induction Motor:**
   These motors have high starting torques hence are used in lifts, hoists, elevators, cranes, compressors, etc.

Concept of Rotating Magnetic Field:

Three phase induction motor consists of stator and rotor. The area of separation between stator and rotor is called as air gap. Stator consists of a three similar coils connected in star or delta displacedfrom each other by 120°. When these coils are supplied by three phase balanced voltages, a rotating magnetic field (R.M.F.) is set up in the air gap.The fluxesthus produced due to three phase supply given to three phase symmetrical winding are sinusoidal and are displaced by 120° from each other as shown in figure 5.8.



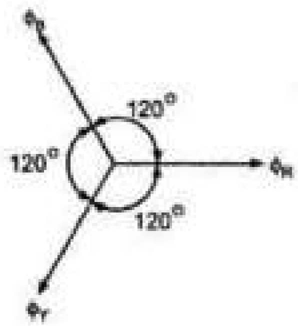


Fig 5.8

$$\phi_R = \phi_m \sin \omega t$$

$$\phi_Y = \phi_m \sin\left(\omega t - 120^\circ\right) \quad \text{.......................................(1)}$$

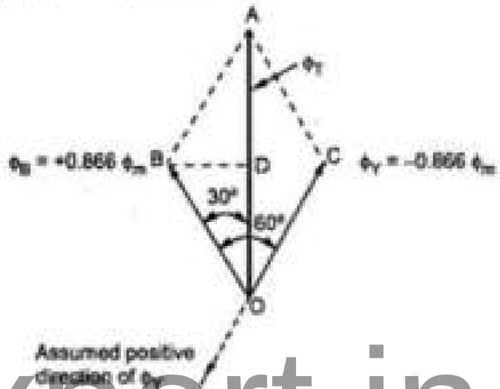
$$\phi_B = \phi_m \sin\left(\omega t + 120^\circ\right)$$

The resultant flux is given by the vector of three fluxes

$$\phi_T = \phi_R + \phi_Y + \phi_B \quad \text{.......................................(2)}$$

Case 1: $\omega t = 0^\circ$

Substituting for $\omega t = 0$ in equation (1)



$$\phi_R = 0$$

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

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

$$\phi_T = \phi_Y + \phi_B$$

The positive values are shown in assumed positive directions while negative values are shown in opposite direction to the assumed positive directions of the respective fluxes.

BD is drawn perpendicular from B on ϕ_T. It bisects ϕ_T.

$\therefore OD = DA = \frac{\phi_T}{2}$

In triangle OBD = 30°

$\therefore \cos 30^\circ = \frac{OD}{OB} = \frac{\phi_T / 2}{0.866\phi_m}$

$\therefore \phi_T = 2 \times 0.866\phi_m \times \cos 30^\circ = 1.5\phi_m$

So magnitude of ϕ_T is $1.5\phi_m$ and its position is vertically upwards at $\phi = 0^\circ$

Case 2: ωt = 60°

Substituting for *ωt = 60* in equation (1)

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

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

$\phi_B = 0$

$\phi_T = \phi_R + \phi_Y$

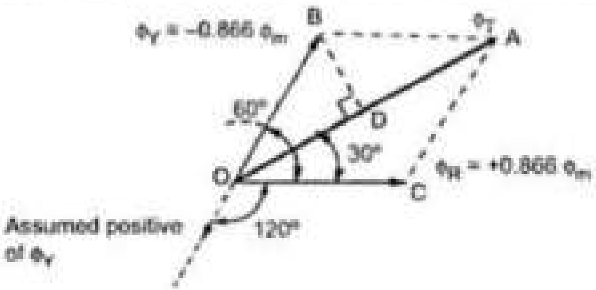


Fig 5.10

Repeating the same construction, drawing perpendicular from B on at D we get the same result as, $\phi_T = 1.5\phi_m$. It can be observed that though its magnitude is $1.5\phi_m$ it has rotated through 60° in space, in clockwise direction, from its previous position.

Case 3: ωt = 120°

Substituting for *ωt = 120* in equation (1)

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

$\phi_Y = 0$

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

$\phi_T = \phi_R + \phi_B$

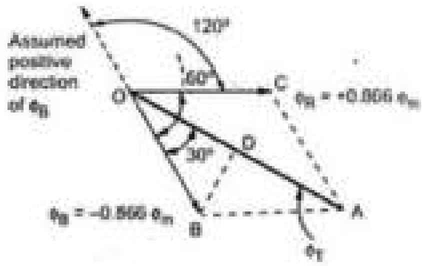


Fig 5.11

Repeating the same construction, drawing perpendicular from B on at D we get the same result as, $\phi_T = 1.5\phi_m$.

It can be observed that though its magnitude is $1.5\phi_m$ it has rotated through 60° in space, in clockwise direction, from its previous position. And from its position at $\phi = 0°$ it has rotated through 120° in space, in clockwise direction.

Case 4: ωt = 180°

Substituting for *ωt = 180* in equation (1)

$\phi_R = 0$

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

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

$\phi_T = \phi_Y + \phi_B$

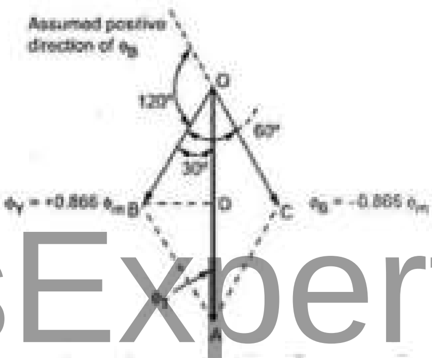


Fig 5.12

Repeating the same construction, drawing perpendicular from B on at D we get the same result as, $\phi_T = 1.5\phi_m$. It can be observed that though its magnitude is $1.5\phi_m$ it has rotated through 60° in space, in clockwise direction, from its previous position. And from its position at $\phi = 0°$, it has rotated through 180° in space, in clockwise direction.

From the above discussions following conclusions can be made:

a) The resultant of the three alternating fluxes, separated from each other has constant amplitude of 1.5 Φ_m where Φ_m is maximum amplitude of an individual flux due to any phase.

b) The resultant flux always keeps rotating in space at the same frequency as that of supply frequency.

Principle of Operation:

- Induction motor works on the principle of electromagnetic induction.
- When a three phase supply is given to the three phase stator winding, a rotating magnetic field is produced. The speed of the rotating magnetic field is called synchronous speed, N_S in r.p.m. $N_S = \frac{120f}{P}$
- The rotating field produces an effect of rotating poles around the rotor.
- Let the direction of rotation of the rotating magnetic field is clockwise as shown in the figure 5.12(a).

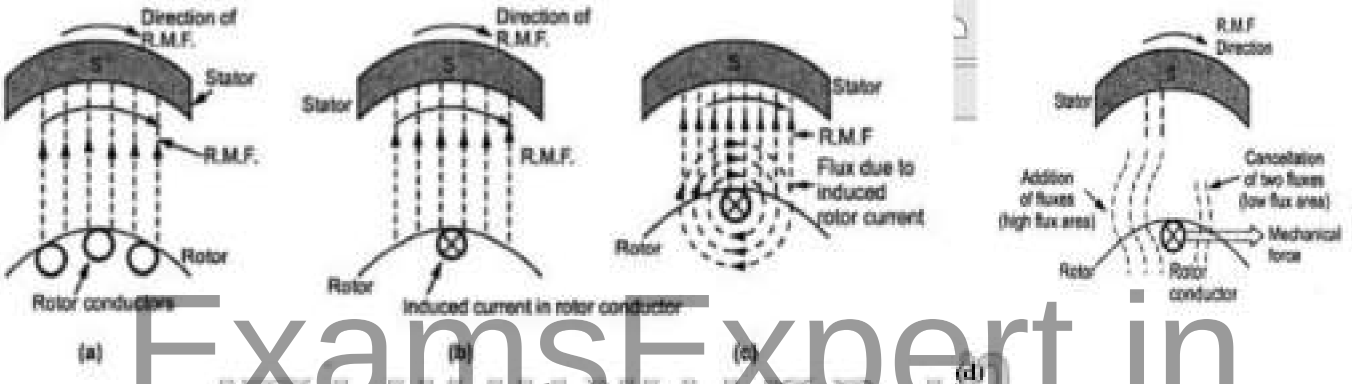


Fig 5.12

- At this instant rotor is stationary and stator flux R.M.F. is rotating. Because of this there exists a relative motion between the R.M.F. and rotor conductors.

- The R.M.F. gets cut by rotor conductors as R.M.F. sweeps over rotor conductors. Whenever conductors cut the flux, e.m.f. gets induced in it. So e.m.f. gets induced in the rotor conductors called rotor induced e.m.f.
- As rotor forms closed circuit, induced e.m.f. circulates current through rotor called rotor current as shown in figure 5.12 (b).
- Current carrying conductor produces its own flux. So rotor produces its flux called rotor flux. For assumed direction of rotor current, the direction of rotor flux is clockwise as shown in the figure 5.12 (c).
- There are two fluxes, one R.M.F. and other rotor flux. Both the fluxes interact with each other and rotor conductor experience a force from left to right as shown in figure 5.12 (d).
- The overall rotor experiences a torque and starts rotating. Hence rotor starts rotating in the same direction as that of rotating magnetic field.
- Let

  N_S is the speed of rotating magnetic field (synchronous speed) in r.p.m.

  N is the speed of rotor / motor in r.p.m.

  Then (N_S – N) is the relative speed between the R.M.F and the rotor and is called slip speed.

Slip:

- The slip speed is generally expressed as the percentage of synchronous speed. The difference between the synchronous speed (N_S) and the speed of the rotor (N) expressed as a fraction of the synchronous speed (N_S) is called 'SLIP'. It is denoted by's'.

$$\%s = \frac{N_S - N}{N_S} \times 100$$

- Actual speed of rotor in terms of slip can be expressed as N = N_S (1- s).
- At start, motor is at rest, i.e., N = 0, therefore s = 1 at start or standstill.
- Practically motor operates in the slip range of 1% to 5%. The slip corresponding to full load speed of the motor is called "full load slip."

Can N = Ns?

- When rotor starts rotating, it tries to catch the speed of rotating magnetic field.
- If rotor catches the speed of the rotating magnetic field, the relative motion between rotor and the rotating magnetic field will vanish ($N_s - N = 0$).
- The relative motion is the main cause for the induced e.m.f. in the rotor. So induced e.m.f. will vanish and hence there cannot be rotor current and the rotor flux which is essential to produce the torque on the rotor. Eventually motor will stop.
- But due to inertia of rotor, this does not happen in practice and motor continues to rotate with a speed slightly less than the synchronous speed of the rotating magnetic field in the steady state.
- The induction motor never rotates at synchronous speed. The speed at which it rotates is hence called sub-synchronous speed. $\therefore N < NS$. So it can be said that rotor slips behind the rotating magnetic field produced by stator. The difference between the two is called slip speed of the motor. $N_s - N$ = Slip speed of the motor in r.p.m.
- This speed decides the magnitude of the induction e.m.f. and the rotor current, which in turn decides the torque produced.

Effect of Slip on Rotor Frequency:

- The speed of rotating magnetic field is,

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

  Also, $N = N_s(1 - s)$. At start $N = 0$, $\therefore s = 1$.
- If f_r be the frequency of rotor induced e.m.f. and rotor current, in rotor running condition at slip speed ($N_s - N$), then there exists a fixed relation between, $NS - N$, f_r and P.

$$N_s - N = \frac{120 f_r}{P}$$

$$\frac{N_s - N}{N_s} = \frac{120 f_r}{P N_s}$$

$$\frac{N_s - N}{N_s} = \frac{120 f_r / P}{120 f / P}$$

$$s = \frac{f_r}{f}$$

$$\therefore f_r = sf$$

Thus the frequency of rotor induced e.m.f. in running condition is slip times the supply frequency.

Starter:

Necessity of Starter: 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 current. As rotor conductors are short circuited, the e.m.f. circulates very high current through rotor conductors at start. Due to such high current at starting there is a possibility of damage to the motor winding. This will also cause a drop in the voltage affecting the performance of other loads connected to the mains. To avoid such kind of adverse effects it is necessary to limit the starting current. Hence starters are used to limit the initial current drawn by the 3 phase induction motors.

Starter not only limits the starting current but also provides protection to the induction motor against overloading and low voltage conditions. The starter also provides single phasing protection. Some of the starters used with three phase induction motor are:

i) Direct On Line Starter (DOL starter)

ii) Series Reactance Starter

iii) Auto Transformer Starter

iv) Star Delta Starter:

Star – Delta Starter:

- This is the cheapest and simplest starter of all and hence used very commonly for the induction motors.
- It uses triple pole double throw (TPDT) switch.
- The switch connects the stator winding in star at start. Hence per phase voltage get reduced by the factor $1/\sqrt{3}$, $V_{ph} = \frac{V_L}{\sqrt{3}}$. Due to this reduced voltage, the starting current also gets reduced by factor $1/\sqrt{3}$.
- When the motor attains 50 – 60% of rated speed , the switch is thrown on other side (RUN), the winding gets connected in delta, across the supply $V_{ph} = V_L$. So it gets normal rated voltage.
- Each phase of the winding gets rated voltage, which is sufficient to produce running torque.
- The arrangement of star – delta starter is shown in the figure

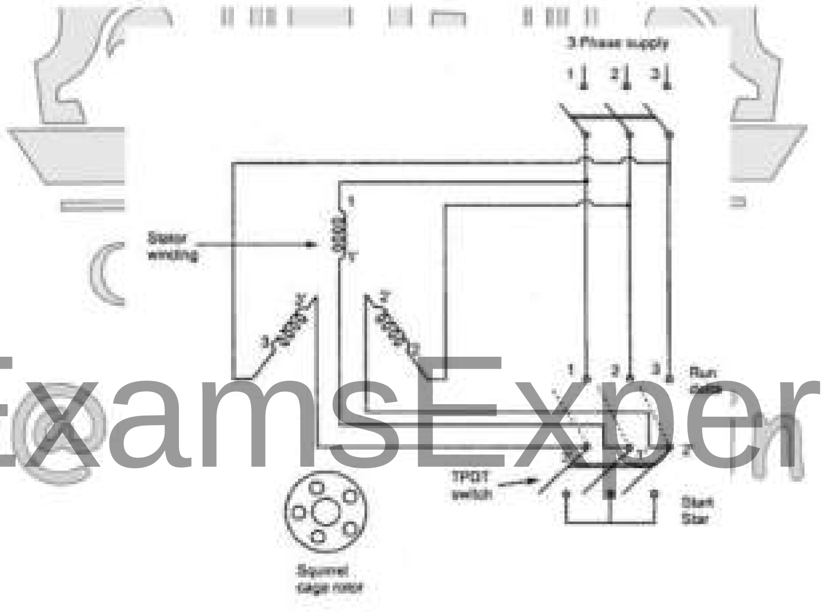


Fig 5.13

- This of starter is suitable only for those motors designed to run with delta connected stator winding.
- The factor by which the voltage change is $1/\sqrt{3}$ and cannot be changed.

Problems:

5.3 A six pole induction motor is supplied by a 10 pole alternator which is driven at 600 r.p.m. If the motor is running at 970 r.p.m. Determine the percentage slip.

Data:

Alternator:	Induction Motor:
N_S = 600 r.p.m.	N = 970 rpm
P = 10	P = 6

For an alternator,

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

$$\therefore f = \frac{PN_S}{120} = \frac{10 \times 600}{120} = 50Hz$$

For an induction motor,

$$N_S = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000 r.p.m.$$

$$s = \frac{N_S - N}{N_S} = \frac{1000 - 970}{1000} = 0.03$$

∴ slip = 3%

5.4 A 4 pole induction motor is supplied from a 50 Hz source. The rotor e.m.f. makes 2 alterations / second. Find slip and speed of motor.

Data:

P = 4

f = 50 Hz

f_r = 2 Hz

$$s = \frac{f_r}{f} = \frac{2}{50} = 0.04$$

$$N_S = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 r.p.m.$$

$$N = N_S(1-s) = 1500(1-0.04) = 1440 r.p.m.$$

∴ slip = 4% and N = 1440 r.p.m.

5.5 A 4 pole, 50 Hz induction motor has a slip of 1% at no-load. When operated at full load, the slip is 2.5%. Find the change in speed from no load to full load.

Data:

P = 4

f = 50 Hz

s_{NL} = 0.01

s_{FL} = 0.025

$$N_S = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500 r.p.m.$$

$$N_{NL} = N_S(1-s_{NL}) = 1500(1-0.01) = 1485 r.p.m.$$

$$N_{FL} = N_S(1-s_{FL}) = 1500(1-0.025) = 1462.5 r.p.m.$$

$$N_{NL} - N_{FL} = 22.5 r.p.m.$$

∴ Change in speed from no load to full load is 22.5 r.p.m.

5.6 A 4 pole, 3 phase, 50 Hz induction motor runs at a speed of 1470 r.p.m. Find the synchronous speed, the slip and frequency of the induced e.m.f. in the rotor under this condition.

Data: P = 4

f = 50 Hz

N = 1470 r.p.m.

$$N_S = \frac{120f}{P} = \frac{120\times 50}{4} = 1500 r.p.m.$$

$$s = \frac{N_S - N}{N_S} = \frac{1500-1470}{1500} = 0.02$$

$$f_r = sf = 0.02\times 50 = 1Hz$$

∴ Synchronous speed is 1500 r.p.m., slip = 0.02%, rotor frequency = 1 Hz

5.7 A 6 pole alternator runs at 1000 r.p.m. supplies power to a 4 pole induction motor. The frequency of rotor of induction motor is 2Hz. Determine the slip and speed of the motor.

Data:

Alternator:	Induction Motor:
P = 6	P = 4
N_S = 1000 r.p.m.	f_r = 2 Hz

For the alternator

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

$$\therefore f = \frac{PN_S}{120} = \frac{6\times 1000}{120} = 50Hz$$

For the induction motor

$$N_S = \frac{120f}{P} = \frac{120\times 50}{4} = 1500 r.p.m.$$

$$s = \frac{f_r}{f} = \frac{2}{50} = 0.04$$

$$N = N_S(1-s) = 1500(1-0.04) = 1440 r.p.m.$$

∴ slip = 4%, speed of motor = 1440 r.p.m.

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Additional Problems:

1. A three phase 6 pole 50Hz induction motor has a slip of 1% at no load and 3% at full load. Determine: i) Synchronous speed, (ii) No load speed, (iii) Full-load speed, (iv) Frequency of rotor current at standstill, (v) Frequency of rotor current at full-load.
2. A 3 phase induction motor is wound for 4 poles and is supplied from 50Hz system. Calculate (i) Synchronous speed (ii) The speed of the motor when slip is 4% (iii) The rotor current frequency when motor runs at 1440 r.p.m.
3. A 3 phase, 4 poles, 400V, 50Hz induction motor run with a slip of 4% find rotor speed and frequency.
4. A 3 phase induction motor with 4 pole is supplied from an alternator having 6 poles and running at 1000 r.p.m. Calculate (i) The synchronous speed of induction motor (ii) Its speed when slip is 0.04 (iii) Frequency of the rotor e.m.f. when the speed is 600 r.p.m.
5. A 3 phase, 4 pole induction motor is supplied from 50 Hz supply. Find its synchronous speed. On full load its speed is observed to be 1410 r.p.m. Calculate its full load slip.
6. The frequency of the e.m.f. in the stator of 4 pole induction motor is 50 Hz and in the motor is 1.5 Hz. What is the slip and at what speed is the motor running.