TOPIC : **BASIC ELECTRICAL ENGINEERING**

AIM :

1. To predict the behavior of any electrical and magnetic circuits.
2. To Formulate and solve complex AC, DC circuits.
3. Realize the requirement of transformers in transmission and distribution of electric power and other applications.
4. To study the working principles of electrical machines and power converters.
5. To introduce the components of low voltage electrical installations

OBJECTIVES :

1. Impart a basic knowledge of electrical quantities such as current, voltage, power, energy and frequency to understand the impact of technology in a global and societal context.
2. Provide working knowledge for the analysis of basic DC and AC circuits used in electrical and electronic devices.
3. Highlight the importance of transformers in transmission and distribution of electric power
4. Explain the working principle, construction, applications of DC machines, AC machines.
5. Explain the working principle and operation of power converters, switch gears and batteries.

PRE TEST-MCQ TYPE :

1. Current flows in a circuit when

   A. A switch is opened
   B. A switch is closed
   C. The switch is either open or closed
   D. There is no voltage

2. Free electrons make current possible

   A. True
   B. False

3. A voltmeter is connected across the current path.

   A. True
   B. False

4. Free electrons make current possible.

   A. True
   B. False

5. The unit of electrical charge is the

   A. Volt
   B. Ampere
   C. Joule
   D. Coulomb

6. Which of the following is not a type of energy source

   A. Generator
   B. Rheostat
   C. Solar cell
   D. Battery

7. An ammeter is an electrical instrument used to measure

   A. Current
   B. Voltage
   C. Resistance
   D. None of the above

THEORY BEHIND :

SYLLABUS

MODULE I DC CIRCUITS

Electrical circuit elements (R, L and C), voltage and current sources, Kirchoff current and voltage laws, analysis of simple circuits with dc excitation.Superposition, Thevenin and Norton Theorems.Time-domain analysis of first-order RL and RC circuits.

MODULE II AC CIRCUITS

Representation of sinusoidal waveforms, peak and rms values, phasor representation, real power, reactive power, apparent power, power factor. Analysis of single-phase ac circuits consisting of R, L, C, RL, RC, RLC combinations (series and parallel), resonance. Three-phase balanced circuits, voltage and current relations in star and delta connections.

MODULE III TRANSFORMERS

Magnetic materials, BH characteristics, ideal and practical transformer, equivalent circuit, losses in transformers, regulation and efficiency.Auto-transformer and three-phase transformer connections.

MODULE IV ELECTRICAL MACHINES

Generation of rotating magnetic fields, Construction and working of a three-phase induction motor, Significance of torque-slip characteristic. Loss components and efficiency, starting and speed control of induction motor. Single-phase induction motor. Construction, working, torque-speed characteristic and speed control of separately excited dc motor. Construction and working of synchronous generators.

MODULE V POWER CONVERTERS AND ELECTRICAL INSTALLATIONS

DC-DC buck and boost converters, duty ratio control. Single-phase and three-phase voltage source inverters; sinusoidal modulation. Components of LT Switchgear: Switch Fuse Unit (SFU), MCB, ELCB, MCCB, Types of Wires and Cables, Earthing. Types of Batteries, Important Characteristics for Batteries. Elementary calculations for energy consumption, power factor improvement and battery backup.

COURSE MATERIAL

UNIT-I

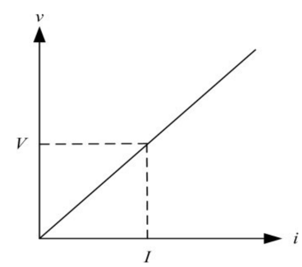
DC CIRCUITS

- **Ohms Law**: At constant temperature potential difference across the conductor is directly proportional to current flowing through the conductor is called ohms law.

$$V \propto I$$

$$V=IR$$

where the constant of proportionality R is called the resistance or electrical resistance, measured in ohms (Ω). Graphically, the $V-I$ relationship for a resistor according to Ohm‟s

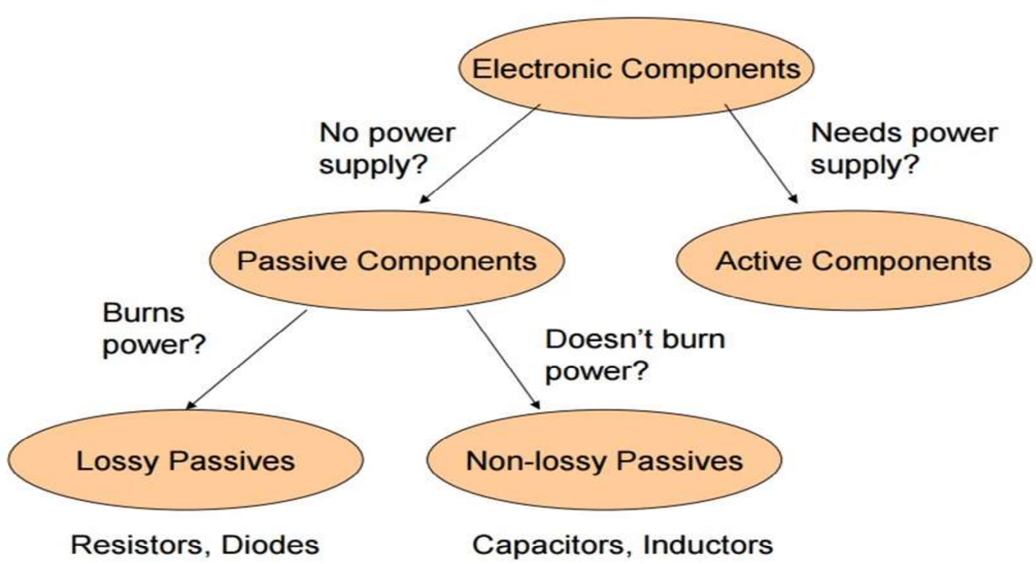


law is depicted in Figure

Figure $V - I$ relationship for a resistor according to Ohm‟s law.

At any given point in the above graph, the ratio of voltage to current is always constant

- **Basic circuit components:**



Circuit Element	Voltage	Current
Resistor	$V = IR$	$I = \frac{V}{R}$
Inductor	$v = L\frac{di}{dt}$	$i = \frac{1}{L}\int_0^t v\,dt$
Capacitor	$v = \frac{1}{C}\int_0^t i\,dt + v(0)$	$i = C\frac{dv}{dt}$, $i = 0$ for DC

$V - I$ relationships for a resistor, inductor and capacitor.

- **Kirchhoff's Voltage Law (KVL)**

Kirchhoff‟s Voltage Law states that the algebraic sum of voltages around each loop at any instant of time is zero

Σ voltage drops = Σ voltage rises

- **Kirchhoff's Current Law (KCL)**

Kirchhoff‟s Current Law states that The algebraic sum of currents a node at any instant

is zero. Σ currents in = Σ currents out

- **<u>Basic Definitions:</u>**

- **Curren**t: the directed flow of electrons (charge) called current. It is denoted by I. units are Amps
- **Electrical potential:** charged body capacity to do work is known as its electrical potential.
- **Potential differenc**e: difference in potentials of two charged bodies is called Potential difference
- **Power:** the rate at which an electrical work done in electrical work is called power. It is denoted by P. units are Watt
- **Electrical work:** Electrical work is said to be done when there is transfer of charge. It is denoted by W. units are joules.
- **Energy:** capacity to do work is called energy.
- **Electrical Network:** A combination of various electric elements (Resistor, Inductor, Capacitor, Voltage source, Current source) connected in any manner what so ever is called an electrical network
- **Classification of element:**

We may classify circuit elements in two categories, passive and active elements.

(R) **Passive Element:** The element which receives energy (or absorbs energy) and then either converts it into heat (R) or stored it in an electric (C) or magnetic (L) field is called passive element.

- **Active Element:** The elements that supply energy to the circuit is called active element. Examples of active elements include voltage and current sources, generators

- **Bilateral Element:** Conduction of current in both directions in an element (example: Resistance; Inductance; Capacitance) with same magnitude is termed as bilateral element

- **Unilateral Element:** Conduction of current in one direction is termed as unilateral (example: Diode, Transistor) element

- **Linear Circuit:** Roughly speaking, a linear circuit is one whose parameters do not change with voltage or current. More specifically, a linear system is one that satisfies (i) homogeneity property (ii) additive property

- **Non-Linear Circuit:** Roughly speaking, a non-linear system is that whose parameters change with voltage or current. More specifically, non-linear circuit does not obey the homogeneity and additive properties.

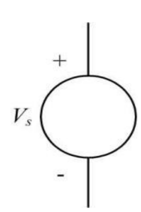
- **DC Sources**
  In general, there are two main types of DC sources
  1. Independent (Voltage and Current) Sources
  2. Dependent (Voltage and Current) Sources

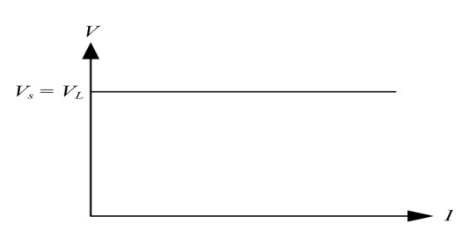
An independent source produces its own voltage and current through some chemical reaction and does not depend on any other voltage or current variable in the circuit. The output of a dependent source, on the other hand, is subject to a certain parameter (voltage or current) change in a circuit element. Herein, the discussion shall be confined to independent sources only.

- **DC Voltage Source**

This can be further subcategorised into ideal and non-ideal sources.

- **The Ideal Voltage Source** An ideal voltage source, shown in Figure has a terminal voltage which is independent of the variations in load. In other words, for an ideal voltage source, the sup- ply current alters with changes in load but the terminal voltage, VL always remains constant. This characteristic is depicted in Figure .



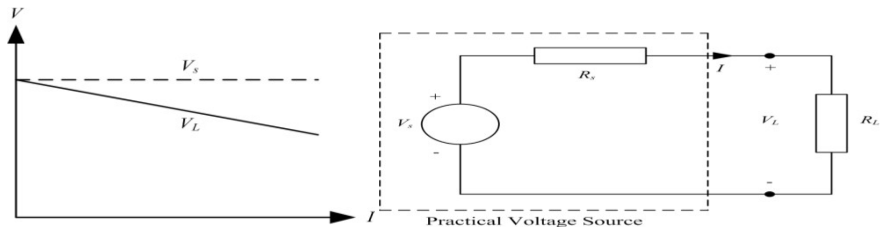


(a) An ideal voltage source

(b) $V - I$ characteristics of an ideal voltage source

Figure: Schematic and characteristics of an ideal voltage source

- **Practical Voltage Source** For a practical source, the terminal voltage falls off with an increase in load current. This can be shown graphically in Figure. This behavior can be modeled by assigning an internal resistance, R_S, in series with the source as shown in Figure



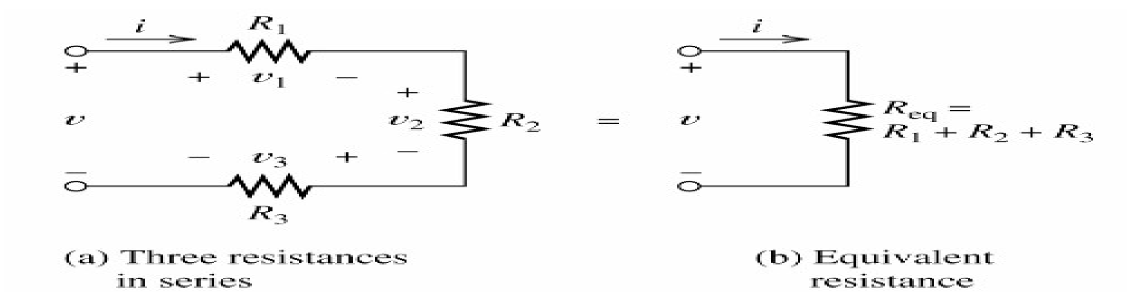
Where RL *represents* the load resistance. The characteristic equation of the practical

voltage source can be written as

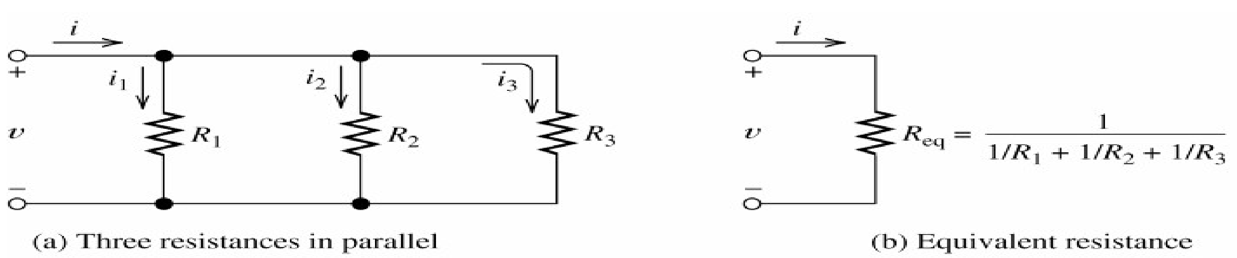
$$V_L = V_S - R_S I$$

For an ideal source, $R_S = 0$ and therefore $V_L = V_S$.

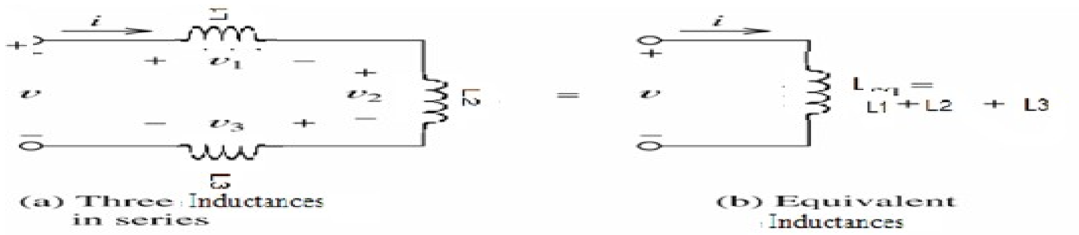
- **<u>Resistive Circuits</u>**
  - **Series Resistors**



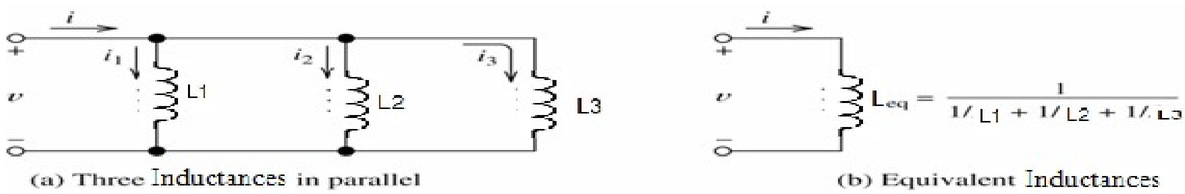
  - **Parallel Resistors**



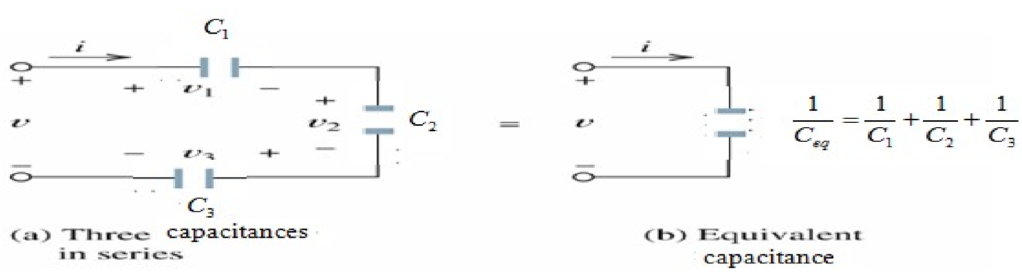
- **Series Inductors**



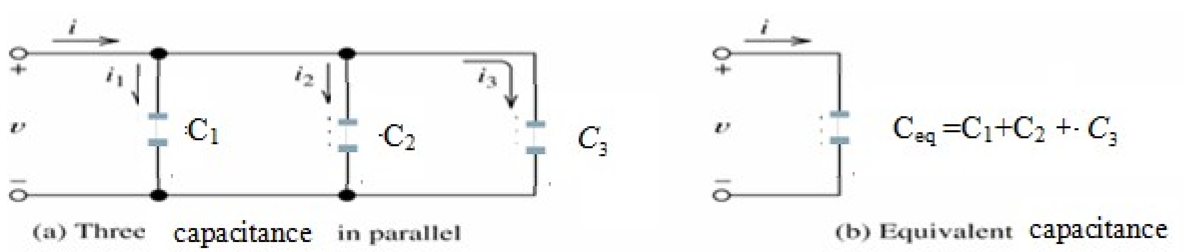
- **Parallel Inductors**



- **Series Capacitors**



- **Parallel Capacitors**



➢ Superposition Theorem

Superposition theorem is extremely useful for analysing electric circuits that contains two or more active sources. In such cases, the theorem considers each source separately to evaluate the current through or voltage across a component. The resultant is given by the algebraic sum of all currents or voltages caused by each source acting independently. Superposition theorem can be formally stated as follows

"*The current through or voltage across any element in a linear circuit containing several sources is the algebraic sum of the currents or voltages due to each source acting alone, all other sources being removed at that time.*"

Linearity is a necessary condition for the theorem to apply. Fortunately, the *v*, *i* relationship for *R*, and *C* are all linear. The sources can be removed using the following methodology

1. Ideal voltage sources are short-circuited
2. Ideal current sources are open-circuited

In general, practical sources are replaced by their internal resistances.

- **Thevenin's Theorem**

The venin's theorem provides a useful tool when solving complex and large electric circuits by reducing them to a single voltage source in series with a resistor. It is particularly advantageous where a single resistor or load in a circuit is subject to change.

Formally, the Th´evenin‟s theorem can be stated as

"*Any two-terminal linear electric circuit consisting of resistors and sources, can be replaced by an equivalent circuit containing a single voltage source in series with a resistor connected across the load.*"

In the circuit diagrams shown in Figure, the current IL through the load resistance RL is the same. Hence the circuits are equivalent as far as the load resistor RL is concerned.

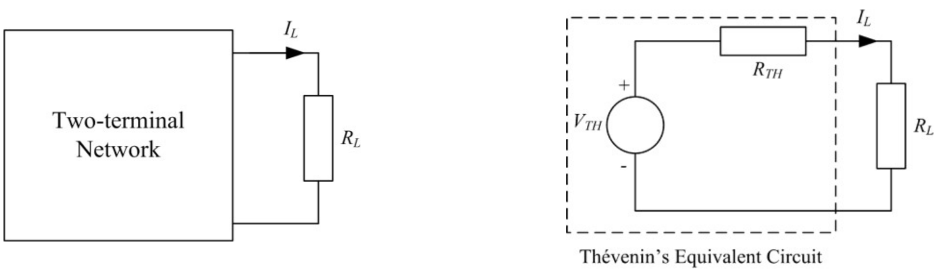


Figure : Illustration of Thévenin‟s theorem.

The following steps outline the procedure to simplify an electric circuit using Th´evenin‟s theorem where VTH and RTH are the Th´evenin‟s voltage and The´evenin‟s resistance respectively.

1. Remove the load resistance R_L.
2. VTH is the open circuit (OC) voltage across the load terminalsand
3. RTH is the resistance across the load terminals with all sources replaced by their internal

resistances. Alternatively, measure the OC voltage across, and the short circuit (SC) current through the load terminals. Then

$V_{TH} = V_{OC}$ and $R_T = V_{OC}/I_{SC}$

- **Maximum Power Transfer Theorem**

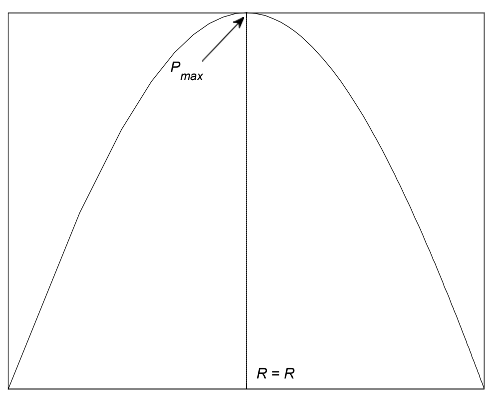
As discussed in the section on Th´evenin‟s theorem, any DC network of sources and resistances can be replaced by a single voltage source in series with a resistance connected across the load (see Figure). The maximum power transfer theorem states that the power delivered to the load is maximum when the load resistance, R_L is equal to the internal (source) resistance, R_S of the DC power supply. In other words, it can be said that the load resistance must match the Thevenin's resistance for maximum power transfer to take place i.e.,

$$(R_S = R_{TH}) = R_L$$

When this occurs, the voltage across the load resistance will be $\frac{V_S}{2}$ and the power delivered to the load is given by

The above equation is plotted in Figure which clearly demonstrates maximum power delivered when $R_S = R_L$. Under this condition, the maximum power will be

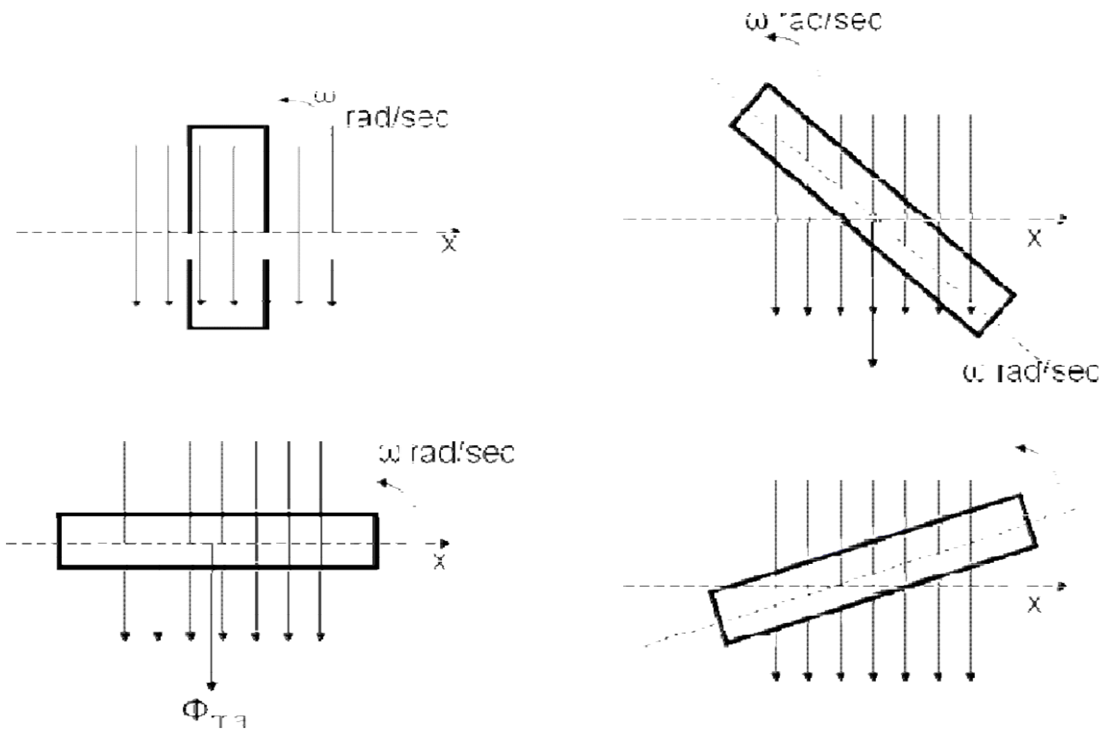
$$\boxed{P_{max} = \frac{V_s^2}{4R_s}}$$



<u>**UNIT-II**</u>

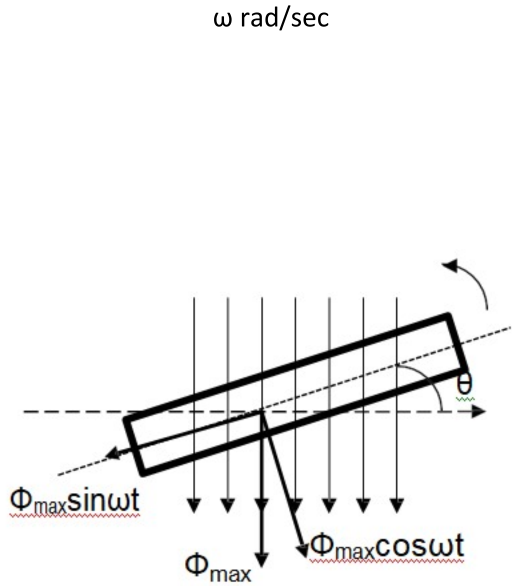
AC CIRCUITS

- **Principle of AC voltage:** Consider a rectangular coil of N turns placed in a uniform magnetic field as shown in the figure. The coil is rotating in the anticlockwise direction at an 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. The generation of sinusoidal AC

Voltage can also be explained using mathematical equations. Consider a rectangular coil of N turns placed in a uniform magnetic field in the position shown in the figure. The maximum flux linking the coil is in the downward direction as shown in the figure. This flux can be divided into two components, one component acting along the plane of the coil $\Phi_{max}\sin\omega t$ and another component acting perpendicular to the plane of the coil $\Phi_{max}\cos\omega t$.



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 ie $\Phi_{max}\cos\omega t$ induces an emf in the coil.

Angular Frequency (ω)

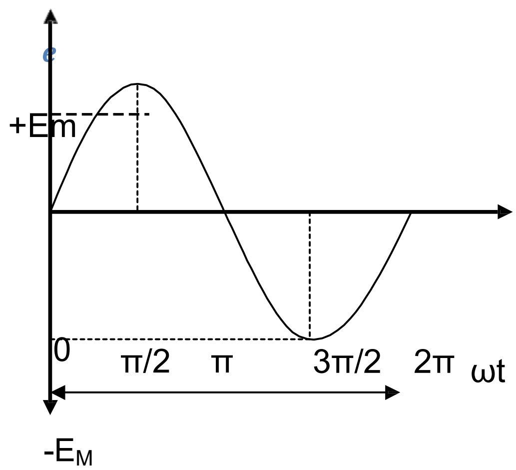
Angular frequency is defined as the number of radians covered in one second(ie the angle covered by the rotating coil). The unit of angular frequency is rad/sec.

$$\omega = \frac{2\pi}{T} = 2\pi f$$

- **Advantages of AC system over DC system**

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

- **Definition of Alternating Quantity**



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.

- **Amplitude**

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

- **Time Period (T)**

It is the Time Taken in seconds to complete one cycle of an alternating quantity Instantaneous Value

It is the value of the quantity at any instant

- **Frequency (f)**

It is the number of cycles that occur in one second. The unit for frequency is Hz or cycles/sec. The relationship between frequency and time period can be derived as follows.

Time taken to complete f cycles = 1 second Time taken to complete 1 cycle = 1/f second

$$T = 1/f$$

- **Average Value**

The arithmetic average of all the values of an alternating quantity over one cycle is called its average value Average value = $\frac{\text{Area under one cycle}}{\text{Base}}$

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

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.

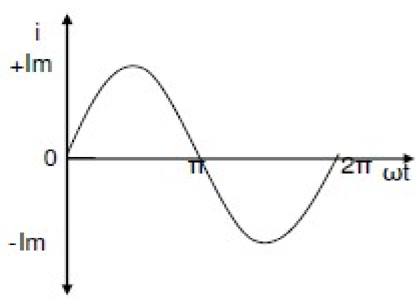
Average value = $\frac{\text{Area under one half cycle}}{\text{Base}}$

- **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.

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

RMS value of a sinusoidal current



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

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

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

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

- **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 alternating quantity is known as

$$PF = \frac{Maximum Value}{RMS Value}$$

the peak factor

- **Phasor Representation**

An alternating quantity can be represented using

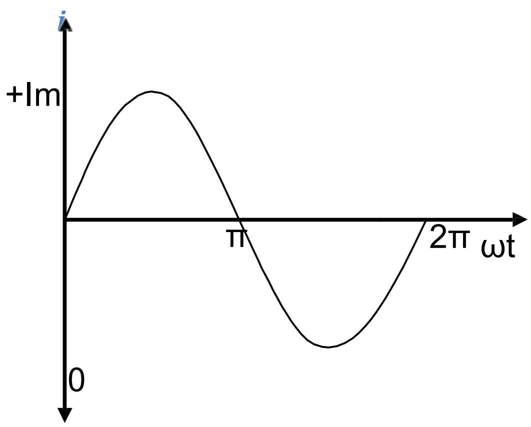
(i) Waveform

(ii) Equations

(iii) Phasor

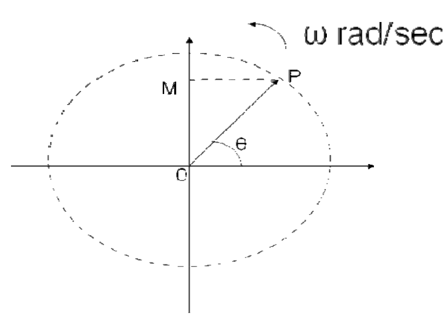
A sinusoidal alternating quantity can be represented by a rotating line called a **Phasor.** A phasor is a line of definite length rotating in anticlockwise direction at a constant angular velocity

The waveform and equation representation of an alternating current is as shown. This sinusoidal quantity can also be represented using phasors.

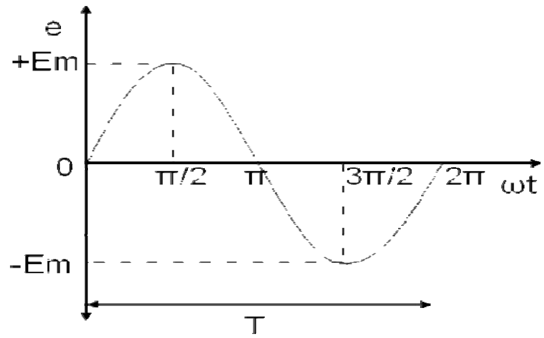


$i = I_m \sin \omega t$

Draw a line OP of length equal to I_m. This line OP rotates in the anticlockwise direction with a uniform angular velocity ω rad/sec and follows the circular trajectory shown in figure. At any instant, the projection of OP on the y-axis is given by $OM = OP\sin\theta = I_m \sin\omega t$. Hence the line OP is the phasor representation of the sinusoidal current

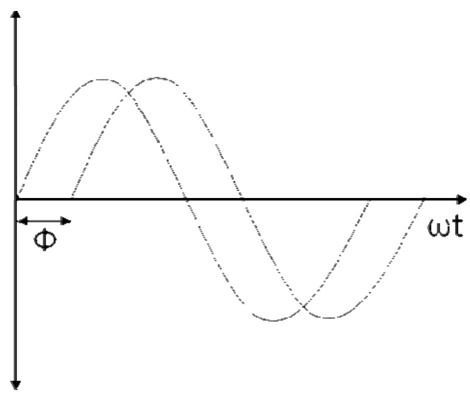


Phase



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 of $+E_m$ is $\pi/2$ rad or
T/4 sec Phase of $-E_m$ is $3\pi/2$
rad or 3T/4 sec

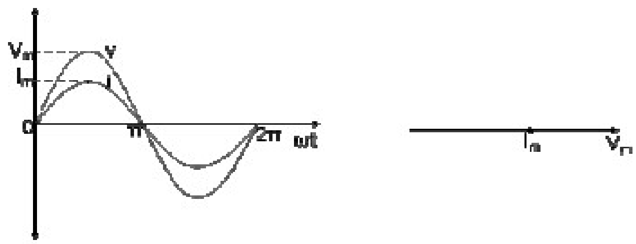
Phase Difference



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

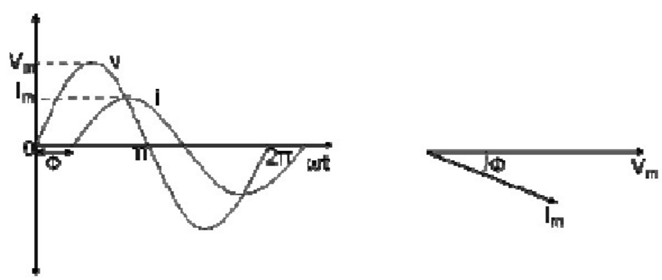
Two waveforms are said to be in phase, when the phase difference between them is zero. That is the zero points of both the waveforms are same. The waveform, phasor and equation representation of two sinusoidal quantities which are in phase is as shown. The figure shows that the voltage and current are in phase.



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

Lagging

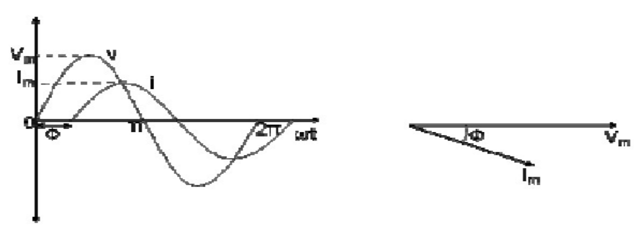
In the figure shown, the zero point of the current waveform is after the zeropoint of the voltage waveform. Hence the current is lagging behind the voltage. The waveform, phasor and equation representation is as shown.



$$v = V_m \sin \omega t$$
$$i = I_m \sin(\omega t - \Phi)$$

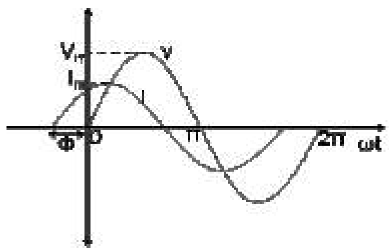
Leading

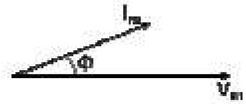
In the figure shown, the zero point of the current waveform is before the zero point of



$$v = V_m \sin \omega t$$
$$i = I_m \sin(\omega t - \Phi)$$

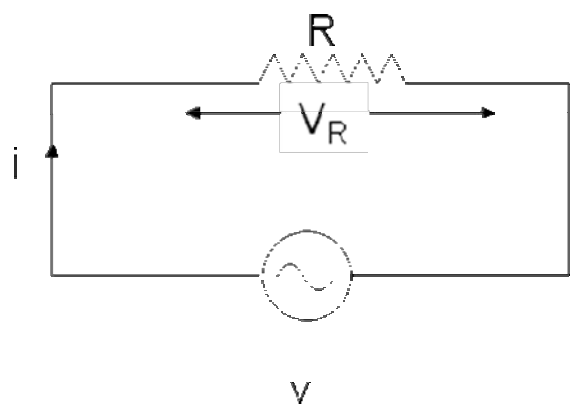
the voltage waveform. Hence the current is leading the voltage. The waveform, phasor and equation representation is as shown.





$$v = V_m \sin \omega t$$
$$i = I_m \sin(\omega t + \Phi)$$

- **AC circuit with a pure resistance**



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

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

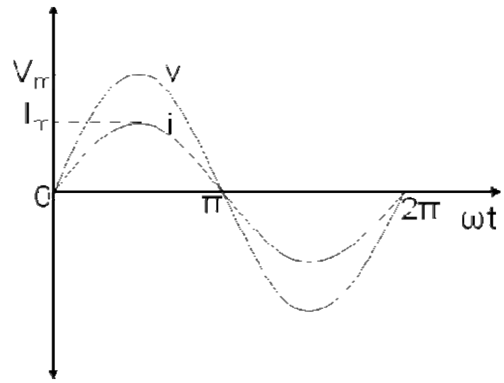
The current flowing in the circuit is i. The voltage across the resistor is given as VR which is the same asv.
Using ohms law, we can write the following relations

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

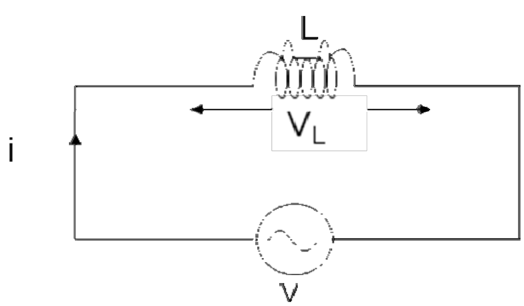
Where

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

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 phasors can be drawn as below.



- **AC circuit with a pure inductance**



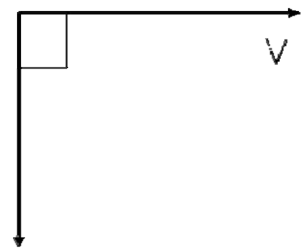
Consider an AC circuit with a pure inductance L as shown in the figure. The alternating voltage v is given by

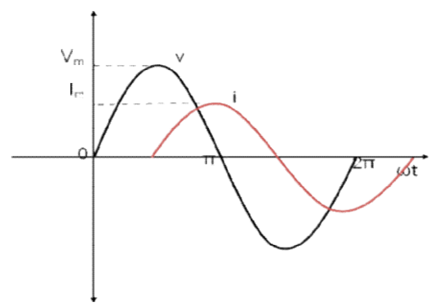
$$v = V_m \sin \omega t \qquad \text{---------- (1)}$$

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

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

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

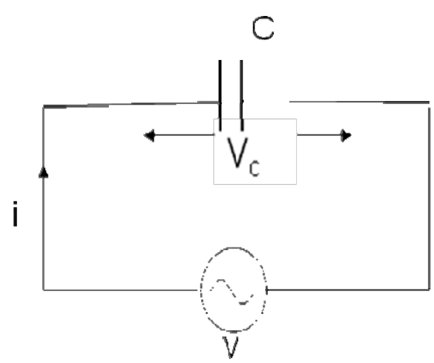




The inductive reactance X_L is given as

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

- **AC circuit with a pure capacitance**



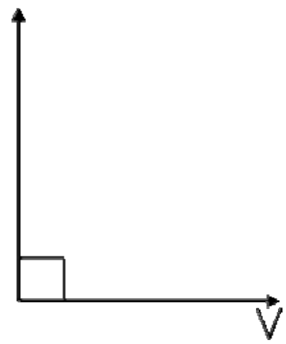
Consider an AC circuit with a pure capacitance C as shown in the figure. The alternating voltage v is
given by

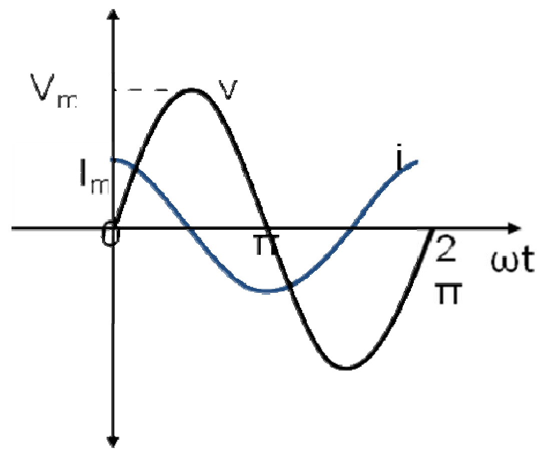
$V = V_m \operatorname{Sin} \omega t$ ----------*(1)*

The current flowing inthe circuit.

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

From equation (1) and (2) we observe that in a pure capacitive circuit, the current leads the voltage by 90º. Hence the voltage and current waveforms and phasors can be drawn as below.





- **Capacitive reactance**

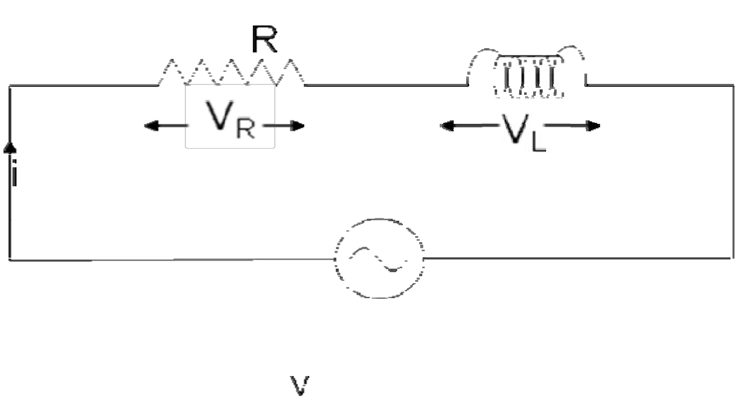
The capacitive reactance XC is given as

$$X_L = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

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

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

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

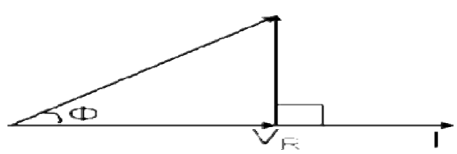
$$v = V_m \sin\omega t$$

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

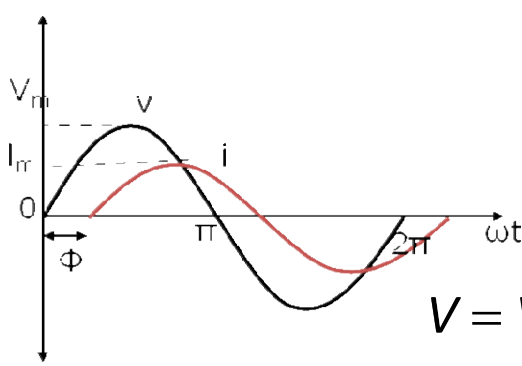
$V_L = IX_L$ leads current by 90 degrees

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 90º. 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.

The waveform and equations for an RL series circuit can be drawn as below.



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

$$I = I_m \sin(\omega t - \Phi)$$

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

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

$$V_R = IR$$

$$V_L = IX_L$$

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

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

$$V = IZ$$

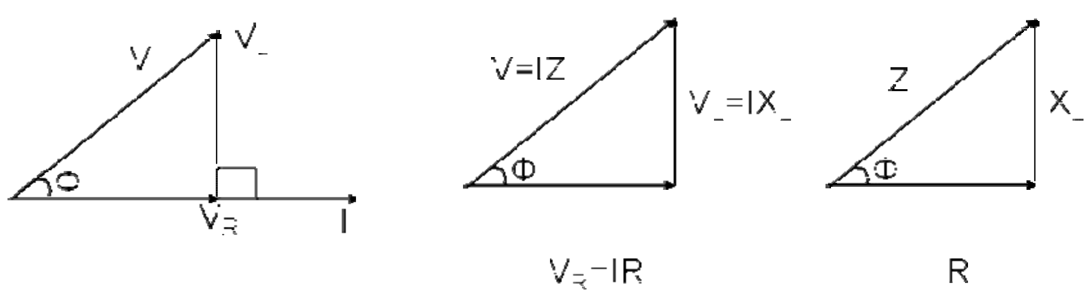
Where impedance

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

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

- **Impedance Triangle**

We can derive a triangle called the impedance triangle from the phasor diagram of an RL series circuit as shown



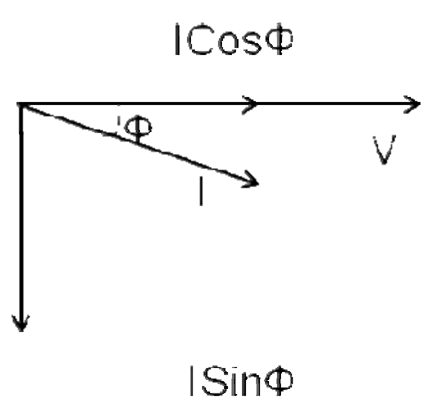
The impedance triangle is right angled triangle with R and X_L as two sides and impedance as thehypotenuse. The angle between the base and hypotenuse is Φ.

- **Power**

In an AC circuit, the various powers can be classified as

1. Real or Active power
2. Reactive power
3. Apparent power

Real or active power in an AC circuit is the power that does useful work in the cicuit. Reactive power flows in an AC circuit but does not do any useful work. Apparent power is the total power in an AC circuit.



From the phasor diagram of an RL series circuit, the current can be divided into two components. One component along the voltage IcosΦ, that is called as the active component of current and another component perpendicular to the voltage IsinΦ that is called as the reactive component of current.

- **Real Power**

The power due to the active component of current is called as the active power or real power. It isdenoted by P.

$P = V \times I\cos\Phi = I^2R$

Real power is the power that does useful power. It is the power that is consumed by the resistance. The unit for real power in Watt(W).

- **Reactive Power**

The power due to the reactive component of current is called as the reactive power. It is denoted by Q.

$Q = V \times I\sin\Phi = I^2X_L$

Reactive power does not do any useful work. It is the circulating power in th L and C components. The unit for reactive power is Volt Amperes Reactive (VAR).

- **Apparent Power**

The apparent power is the total power in the circuit. It is denoted by S.

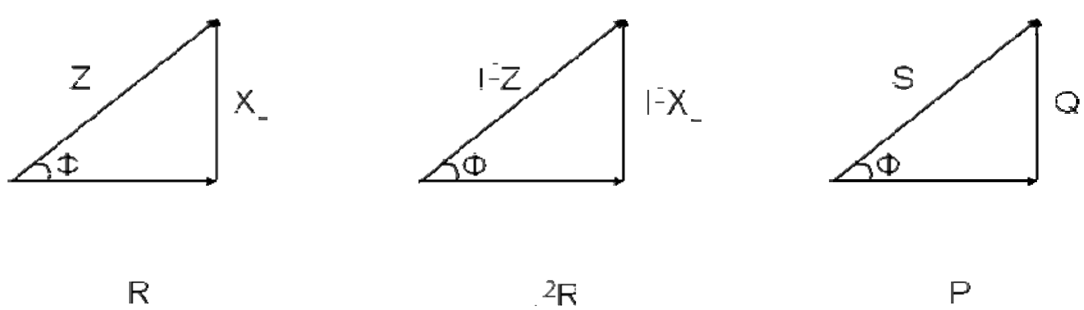
S = V x I = I²Z

$$S = \sqrt{P^2 + Q^2}$$

The unit for apparent power is Volt Amperes (VA).

- **Power Triangle**

From the impedance triangle, another triangle called the power triangle can be derived as shown.



The power triangle is right angled triangle with P and Q as two sides and S as the hypotenuse. The angle between the base and hypotenuse is Φ. The power triangle enables us to calculate the following things.

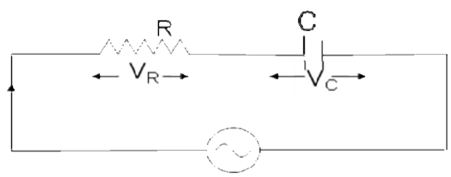
The power triangle is right angled triangle with P and Q as two sides and S as the hypotenuse. The angle between the base and hypotenuse is Φ. The power triangle enables us to calculate the following things.

1. Apparent power $S = \sqrt{P^2 + Q^2}$
2. Power Factor $Cos\Phi = \frac{P}{S} = \frac{Re\,al Power}{Apparent Power}$

The power Factor in an AC circuit can be calculated by any one of the following methods

- Cosine of angle between V and I
- Resistance/Impedance R/Z
- Real Power/Apparent Power P/S

- **R-C Series circuit**



V

can be derived as follows.

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

$$V_R = IR$$

$$V_C = IX_C$$

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

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

$$V = IZ$$

Where impedance $Z = \sqrt{R^2 + X_C^2}$

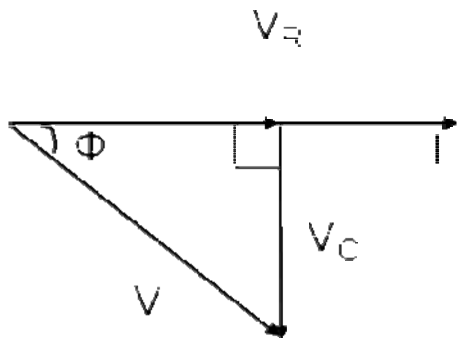
- **Average power**

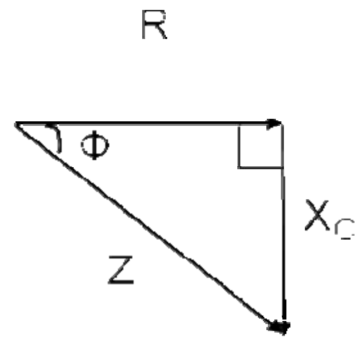
$P = VI\cos\phi$

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

- **Impedance Triangle**

We can derive a triangle called the impedance triangle from the phasor diagram of an RC series circuit as shown





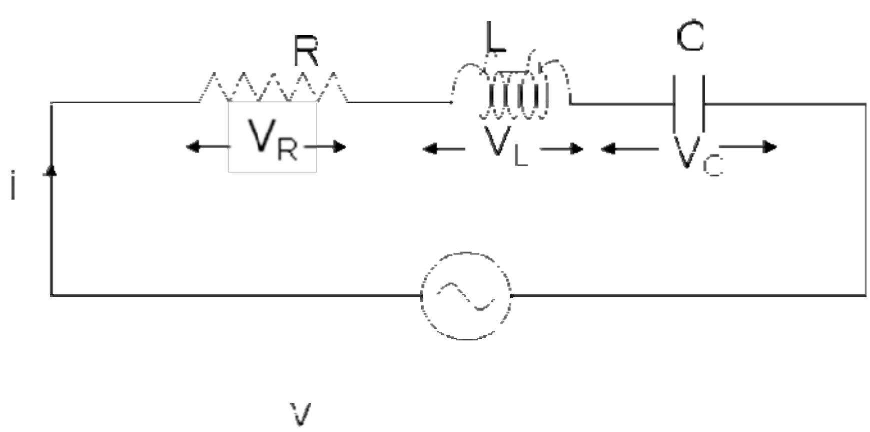
- **Phasor algebra for RC series circuit**

$$V = V + j0 = V\angle 0^{\circ}$$

$$\overline{Z} = R - jX_C = Z\angle -\Phi$$

$$I = \frac{\overline{V}}{\overline{Z}} = \frac{V}{Z}\angle +\Phi$$

➢ **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

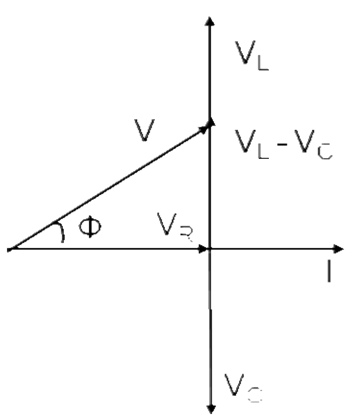
$$v = V_m \sin\omega t$$

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.

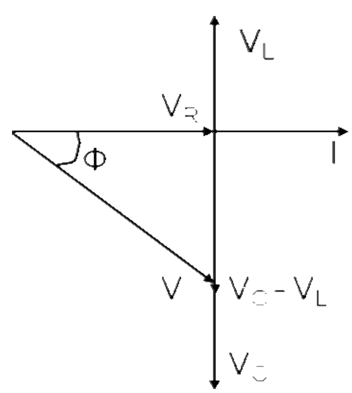
$V_R = IR$ is in phase with I

$V_L = IX_L$ 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 phase with I, the voltage V_L leads the current by 90º and the voltage V_C lags behind the current by 90º. There are two cases that can occur $V_L > V_C$ and $V_L < V_C$ depending on the values of X_L and X_C. And hence there are two possible phasor diagrams. The phasor $V_L - V_C$ or $V_C - V_L$ is drawn and then the resultant voltage V is drawn.



$V_L > V_C$



$V_L < V_C$

From the phasor diagram we observe that when $V_L > V_C$, the voltage leads the current by an angle Φ or in other words the current lags behind the voltage by an angle Φ. When $V_L < V_C$, the voltage lags behind the current by an angle Φ or in other words the current leads 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.

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

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

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

From the expression for phase angle, we can derive the following three cases

Case (i): When $X_L > X_C$

The phase angle Φ is positive and the circuit is inductive. The circuit behaves like a series RL circuit.

Case (ii): When $X_L < X_C$

The phase angle Φ is negative and the circuit is capacitive. The circuit behaves like a series RC circuit.

Case (iii): When $X_L = X_C$

The phase angle Φ = 0 and the circuit is purely resistive. The circuit behaves like a pure resistive circuit.

The voltage and the current can be represented by the following equations. The angle Φ is positive or negative depending on the circuit elements.

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

$$I = I_m \sin(\omega t \pm \Phi)$$

- **Average power**

$$P = VI\cos\phi$$

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

$$P = I^2 R$$

Hence the power in an RLC series circuit is consumed only in the resistance. The inductance and the capacitance do not consume any power.

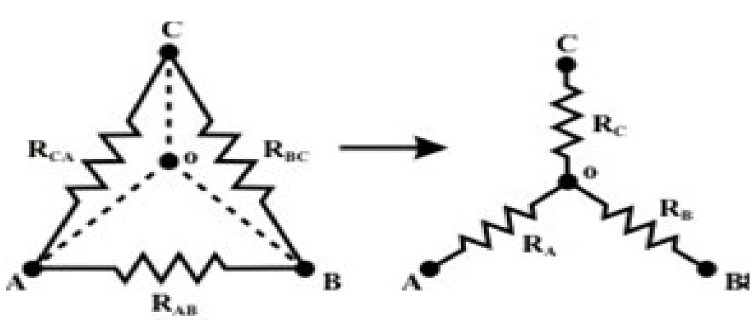
- **Phasor algebra for RLC series circuit**

$$V = V + j0 = V\angle 0^\circ$$

$$\bar{Z} = R + j(X_L - X_C) = Z\angle\Phi$$

$$I = \frac{\bar{V}}{\bar{Z}} = \frac{V}{Z}\angle -\Phi$$

- **Delta – Star Conversion**

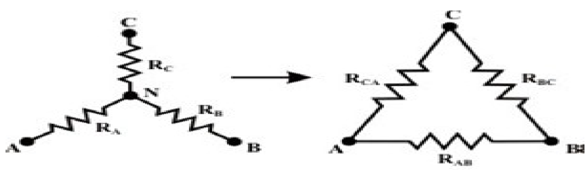


$$R_B = \frac{R_{AB} R_{BC}}{R_{AB} + R_{BC} + R_{CA}}$$

$$R_C = \frac{R_{BC} R_{CA}}{R_{AB} + R_{BC} + R_{CA}}$$

$$R_A = \frac{R_{AB} R_{CA}}{R_{AB} + R_{BC} + R_{CA}}$$

- **Star -Delta Conversion**



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

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

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

UNIT-III

Transformers

INTRODUCTION

Transformer is a static device which transfers electrical energy from one electrical circuit to another electrical circuit without change in frequency through magnetic medium. The winding which receives energy is called primary winding and the winding which delivers energy to the load is called secondary winding.

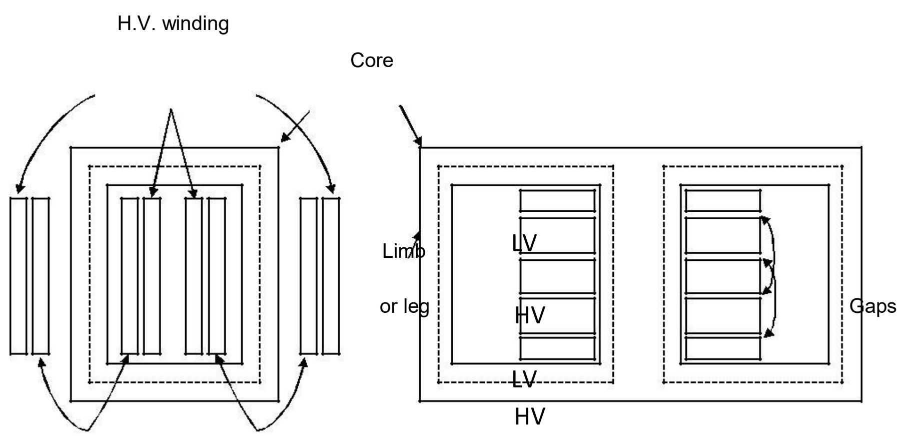
Based on the voltage levels transformers are classified into two types

i. Step down transformer ii. Step up transformer.

CONSTRUCTION

- **CORE-TYPE AND SHELL-TYPE CONSTRUCTION**

Depending upon the manner in which the primary and secondary windings are placed on the core, and the shape of the core, there are two types of transformers, called (a) core type, and (b) shell type. In core type transformers, the windings are placed in the form of concentric cylindrical coils placed around the vertical limbs of the core. The low-voltage (LV) as well as the high-voltage (HV) winding are made in two halves, and placed on the two limbs of core. The LV winding is placed next to the core for economy in insulation cost. Figure a shows the cross-section of the arrangement. In the shell type transformer, the primary and secondary windings are wound over the central limb of a three-limb core as shown in Figure
b. The HV and LV windings are split into a number of sections, and the sections are interleaved or sandwiched i.e. the sections of the HV and LV windings are placed alternately.



L.V. Winding

(a) core type **(b)** Shell Type

- **CORE**

The core is built-up of thin steel laminations insulated from each other. This helps in reducing the eddy current losses in the core, and also helps in construction of the transformer. The steel used for core is of high silicon content, sometimes heat treated to produce a high permeability and low hysteresis loss. The material commonly used for core is CRGO (Cold Rolled Grain Oriented) steel.

Conductor material used for windings is mostly copper. However, for small distribution transformer aluminium is also sometimes used. The conductors, core and whole windings are insulated using various insulating materials depending upon the voltage.

- **INSULATING OIL**

In oil-immersed transformer, the iron core together with windings is immersed in insulating oil. The insulating oil provides better insulation, protects insulation from moisture and transfers the heat produced in core and windings to the atmosphere. The transformer oil should posses the following quantities:

(a) High dielectric strength,

(b) Low viscosity and high purity,

(c) High flash point, and

(d) Free from sludge.

Transformer oil is generally a mineral oil obtained by fractional distillation of crude oil.

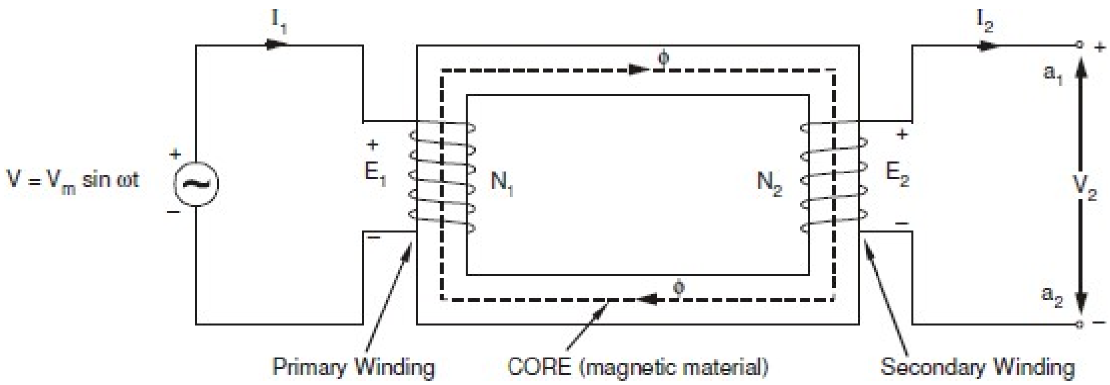
- **TANK AND CONSERVATOR**

The transformer tank contains core wound with windings and the insulating oil. In large transformers small expansion tank is also connected with main tank is known as conservator. Conservator provides space when insulating oil expands due to heating. The transformer tank is provided with tubes on the outside, to permits circulation of oil, which aides in cooling. Some additional devices like breather and Buchholz relay are connected with main tank.

Buchholz relay is placed between main tank and conservator. It protect the transformer under extreme heating of transformer winding. Breather protects the insulating oil from moisture when the cool transformer sucks air inside. The silica gel filled breather absorbs moisture when air enters the tank. Some other necessary parts are connected with main tank like, Bushings, Cable Boxes, Temperature gauge, Oil gauge, Tapings, etc.

➢ WORKING PRINCIPLE

In its simplest form a single-phase transformer consists of two windings, wound on an iron core one of the windings is connected to an ac source of supply f. The source supplies a current to this winding (called primary winding) which in turn produces a flux in the iron core. This flux is alternating in nature If the supplied voltage has a frequency f, the flux in the core also alternates at a frequency f. the alternating flux linking with the second winding, induces a voltage E_2 in the second winding (according to faraday‟s law). [Note that this alternating flux linking with primary winding will also induce a voltage in the primary winding, denoted as E_1. Applied voltage V_1 is very nearly equal to E_1]. If the number of turns in the primary and secondary windings is N_1 and N_2 respectively, we shall see later in this unit that E1/N1 = E2/N2. The load is connected across the secondary winding, between the terminals a_1, a_2. Thus, the load can be supplied at a voltage higher or lower than the supply voltage depending upon the ratio N1/N2.



➢ IDEAL TRANSFORMER

Under certain conditions, the transformer can be treated as an ideal transformer. The assumptions necessary to treat it as an ideal transformer are :

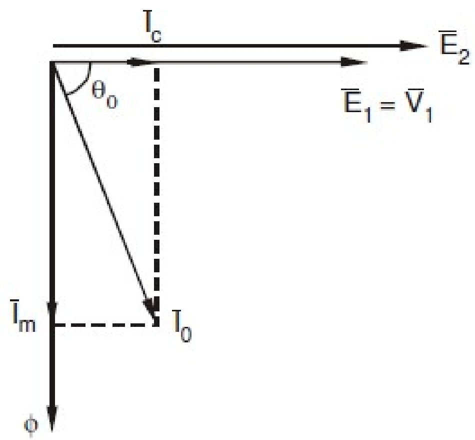
(a) Primary and secondary windings have zero resistance. This means that ohmic loss ($I^2 R$ loss), and resistive voltage drops in windings are zero.

(b) There is no leakage flux, i.e. the entire flux is mutual flux that links both the primary and secondary windings.

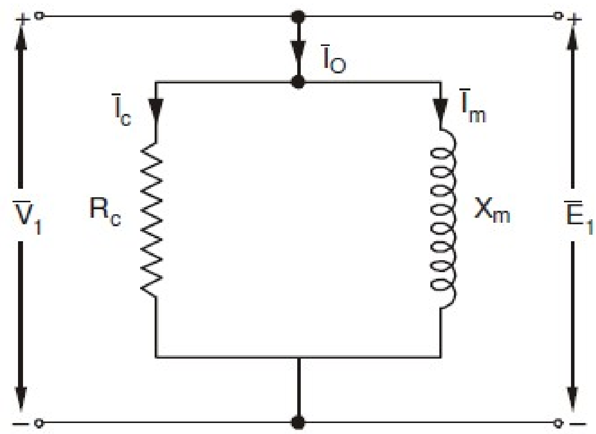
(c) Permeability of the core is infinite this means that the magnetizing current needed for establishing the flux is zero.

(d) Core loss (hysteresis as well as eddy current losses) are zero.

➢ IDEAL TRANSFORMER ON NO LOAD

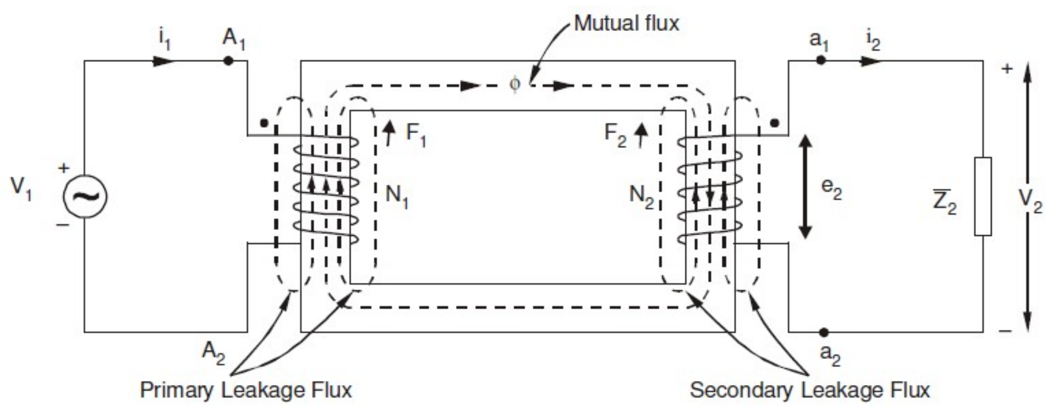


(a) Phasor Diagram at No Load



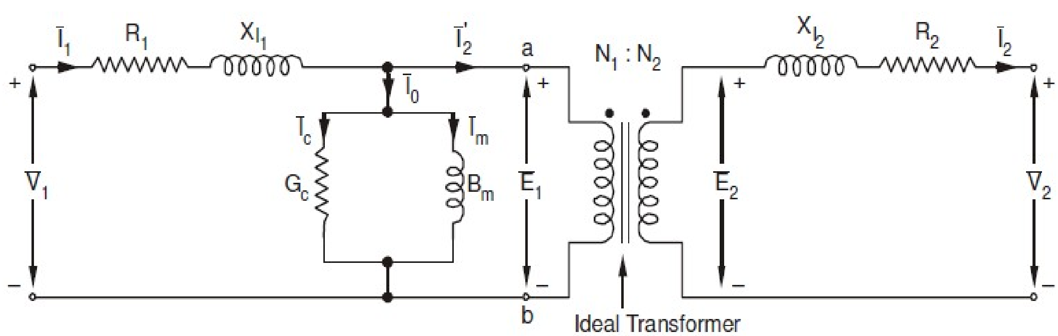
(b) Equivalent Circuit at No Load

➢ IDEAL TRANSFORMER ON LOAD



$$V_1/V_2=N_1/N_2=I_1/I_2$$

EQUIVALENT CIRCUIT OF REAL TRANSFORMER



REGULATION OF TRANSFORMER

Voltage regulation of a transformer is defined as the drop in the magnitude of load voltage (or secondary terminal voltage) when load current changes from zero to full load value. This is expressed as a fraction of secondary rated voltage

(%) Regulation = (Secondary terminal voltage at no load − Secondary terminal voltage at any load)/ secondary rated voltage.

Percentage voltage regulation =(V-E_0)*100/V

- **LOSSES AND EFFICIENCY OF TRANSFORMER**

A transformer does‟t contains any rotating part so it is free from friction and windage losses.

In transformer the losses occur in iron parts as well as in copper coils. In iron core the losses are sum of hysteresis and eddy current losses. The hysteresis losses are

$P_h \alpha f B^x_{\max}$ and eddy current loss is equal to $P_e \alpha f^2 B_{\max}$. Where "f" is frequency "$B_{\max}$" is maximum flux density.

- **IRON LOSSES OR CORE LOSSES**

To minimize hysteresis loss in transformer, we use Cold Rolled Grain Oriented (CRGO) silicon steel to build up the iron core.

- **EDDY CURRENT LOSS**

When the primary winding variable flux links with iron core then it induces some EMF on the surface of core. The magnitude of EMF is different at various points in core. So, there is current between different points in Iron Core having unequal potential.

These currents are known at eddy currents. $I^2 R$ loss in iron core is known as eddy current loss. These losses depend on thickness of core. To minimize the eddy current losses we use the Iron Core which is made of laminated sheet stampings. The thickness of stamping is around 0.5 mm.

- **COPPER LOSSES**

In a transformer the primary and secondary winding currents increase with increases in load. Due to these currents there is some $I^2 R$ losses. These are known as copper losses or ohmic losses. The total $I^2 R$ loss in both windings at rated or full load current is equal to $I_1^2 R_1 = I_2^2$.

EFFICIENCY OF SINGLE PHASE TRANSFORMER

Efficiency (η)= output power/input power

=(input power –total losses)/input power

Alternatively

η= output power/(output power + total losses)

In a transformer, if P_i is the iron loss, and P_c is the copper loss at full load (when the load current is equal to the rated current of the transformer, the total losses in the transformer are $P_i + P_c$. In any transformer, copper losses are variable and iron losses are fixed.

When the load on transformer is x times full load then

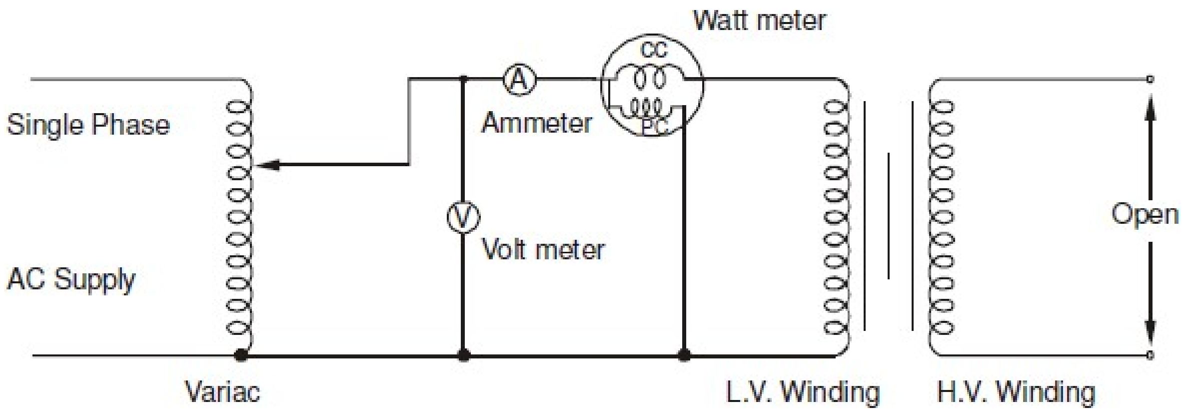
$$\eta = x V_2 I_2 \cos\phi / (x V_2 I_2 \cos\phi + P_i + x^{2*} P_c)$$

or

$$\eta = x \, KVA \cos\phi / (x \, KVA \cos\phi + P_i + x^{2*} P_c)$$

- **OPEN CIRCUIT TEST**

Practically we can determine the iron losses by performing the open circuit test and also the core loss components of equivalent circuit.We perform open circuit test in low voltage winding in transformer keeping the high voltage winding open. The circuit is connected as shown in Figure. The instruments are connected on the LV side. The advantage of performing the test from LV side is that the test can be performed at rated voltage.When we apply rated voltage then watt meter shows iron losses [There is some copper loss but this is negligible when compared to iron loss]. The ammeter shows no load current I_0 which is very small [2-5 % of rated current]. Thus, the drops in R_1 and X_{l1} can be neglected.



We have W_0= iron loss

I_0= no load current

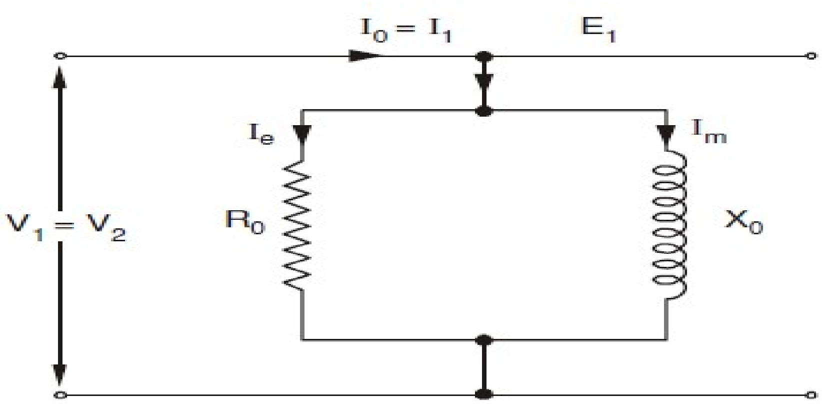
Then $\cos\varphi = \dfrac{W_0}{V_i I_0}$

So $I_e = I_0 \cos\varphi$

And $I_m = I_0 \sin\varphi$.

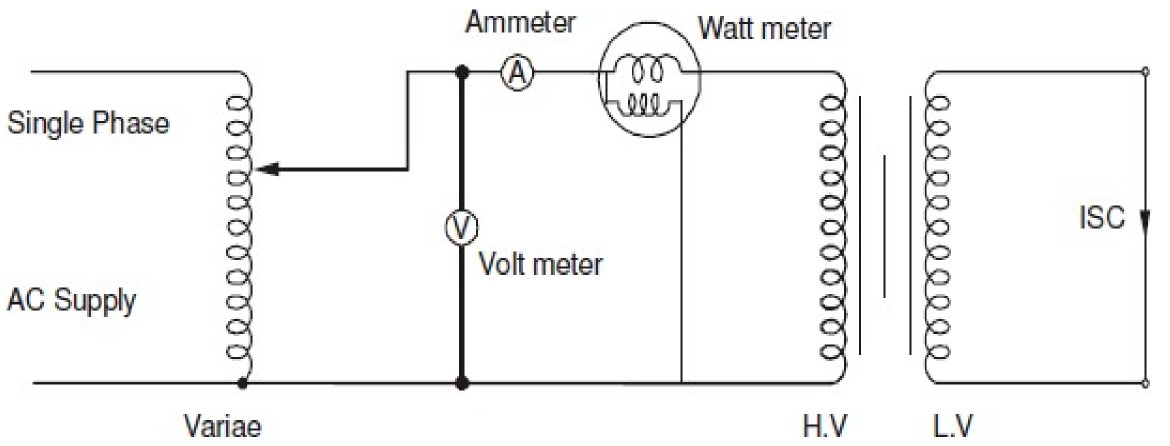
$R_0 = V_i / I_e$

$X_0 = V_i / I_m$

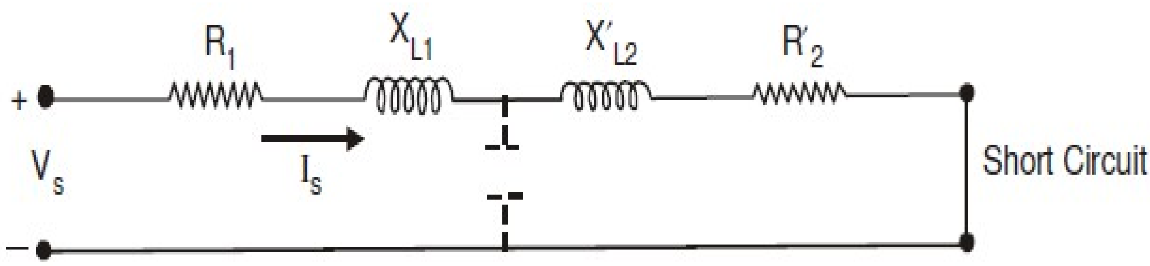


➢ SHORT CIRCUIT TEST

From short circuit test we can determine copper losses and also the winding components of equivalent circuit. It‟s an indirect method to find out the copper losses. To perform this test, we apply a reduced voltage to the primary winding through instruments keeping LV winding short circuited. The connections are shown in Figure. We need to apply only 5-10% of rated voltage to primary to circulated rated current in the primary and secondary winding. The applied voltage is adjusted so that the ammeter shows rated current of the winding. Under this condition, the watt-meter reading shows the copper losses of the transformer. Because of low value of applied voltage, iron losses, are very small and can be neglected



Connection diagram for short circuit test



Equivalent circuit under shot circuit

At a rated current watt meter shows full load copper loss. We have

W_{sc}= copper loss
I_{sc} = full load current
V_{sc} =supply voltage
$R_{eq} = W_{sc}/I_{sc}^2$
$Z_{eq} = V_{sc}/I_{sc}$
$X_{eq} = \sqrt{(Z_{eq}^2 - R_{eq}^2)}$

and equivalent impedance

So we calculate equivalent reactance. These R_{eq} and X_{eq} are equivalent resistance and reactance of both windings referred in HV side. These are known as equivalent circuit resistance and reactance.

UNIT-IV

ELECTRICAL MACHINES

➢ Three Phase Induction Motor

The most common type of AC motor being used throughout the work today is the "Induction Motor". Applications of three-phase induction motors of size varying from half a kilowatt to thousands of kilowatts are numerous. They are found everywhere from a small workshop to a large manufacturing industry.

The advantages of three-phase AC induction motor are listed below:

- Simple design
- Rugged construction
- Reliable operation
- Low initial cost
- Easy operation and simple maintenance
- Simple control gear for starting and speed control
- High efficiency.

Induction motor is originated in the year 1891 with crude construction (The induction machine principle was invented by *NIKOLA TESLA* in 1888.). Then an improved construction with distributed stator windings and a cage rotor was built.

The slip ring rotor was developed after a decade or so. Since then a lot of improvement has taken place on the design of these two types of induction motors. Lot of research work has been carried out to improve its power factor and to achieve suitable methods of speed control.

➢ Types and Construction of Three Phase Induction Motor

Three phase induction motors are constructed into two major types:

1. Squirrel cage Induction Motors

2. Slip ring Induction Motors

- ***Squirrel cage Induction Motors***

(a) **Stator Construction**

The induction motor stator resembles the stator of a revolving field, three phase alternator. The stator or the stationary part consists of three phase winding held in place in the slots of a laminated steel core which is enclosed and supported by a cast iron or a steel frame as shown in Fig: 3.1(a).

The phase windings are placed 120 electrical degrees apart and may be connected in either star or delta externally, for which six leads are brought out to a terminal box mounted on the frame of the motor. When the stator is energized from a three phase voltage it will produce a rotating magnetic field in the stator core.

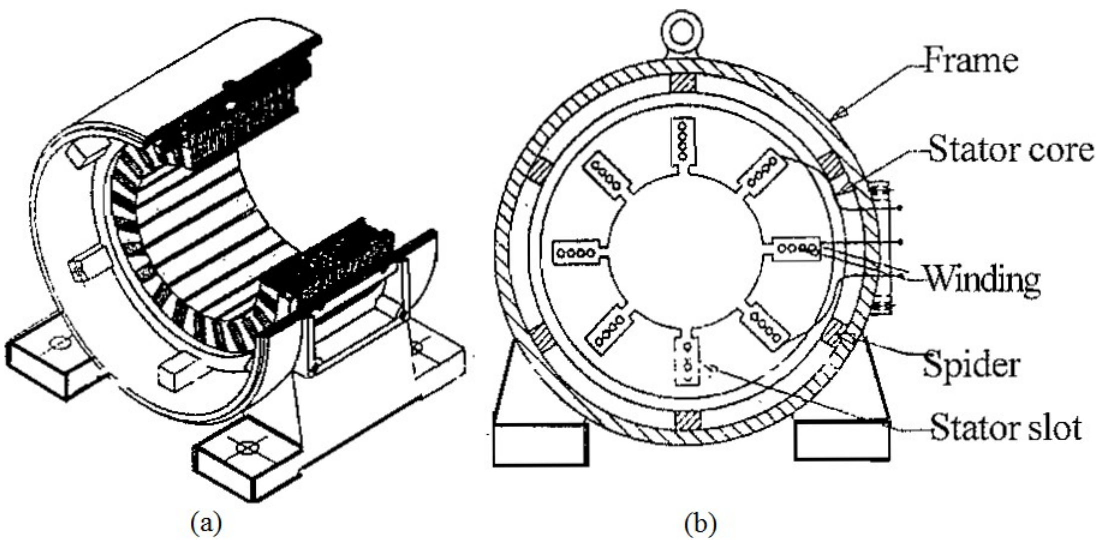


Fig: 3.1

(b) Rotor Construction

The rotor of the squirrel cage motor shown in Fig: 3.1(b) contains no windings. Instead it is a cylindrical core constructed of steel laminations with conductor bars mounted parallel to the shaft and embedded near the surface of the rotor core.

These conductor bars are short circuited by an end rings at both end of the rotor core. In large machines, these conductor bars and the end rings are made up of copper with the bars brazed or welded to the end rings shown in Fig: 3.1(b).In small machines the conductor bars and end rings are sometimes made of aluminium with the bars and rings cast in as part of the rotor core. Actually the entire construction (bars and end-rings) resembles a squirrel cage, from which the name is derived.

The rotor or rotating part is not connected electrically to the power supply but has voltage induced in it by transformer action from the stator. For this reason, the stator is sometimes called the primary and the rotor is referred to as the secondary of the motor since the motor operates on the principle of induction and as the construction of the rotor with the bars and end rings resembles a squirrel cage, the squirrel cage induction motor is used.

The rotor bars are not insulated from the rotor core because they are made of metals having less resistance than the core. The induced current will flow mainly in them. Also the rotor bars are usually not quite parallel to the rotor shaft but are mounted in a slightly skewed position. This feature tends to produce a more uniform rotor field and torque. Also it helps to reduce some of the internal magnetic noise when the motor is running.

(c) End Shields

The function of the two end shields is to support the rotor shaft. They are fitted with bearings and attached to the stator frame with the help of studs or bolts attention.

- *Slip ring Induction Motors*

***(a)* Stator Construction**

The construction of the slip ring induction motor is exactly similar to the construction of squirrel cage induction motor. There is no difference between squirrel cage and slip ring motors.

***(b)* Rotor Construction**

The rotor of the slip ring induction motor is also cylindrical or constructed of lamination.

Squirrel cage motors have a rotor with short circuited bars whereas slip ring motors have wound rotors having "three windings" each connected in star.The winding is made of copper wire. The terminals of the rotor windings of the slip ring motors are brought out through slip rings which are in contact with stationary brushes as shown in Fig: 3.2.

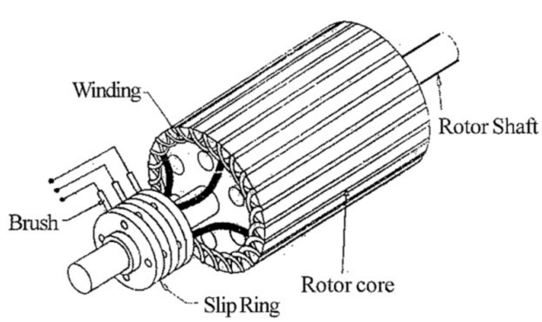


Fig: 3.2

THE ADVANTAGES OF THE SLIPRING MOTOR ARE

- It has susceptibility to speed control by regulating rotor resistance.
- High starting torque of 200 to 250% of full load value.
- Low starting current of the order of 250 to 350% of the full load current.

Hence slip ring motors are used where one or more of the above requirements are to be met.

➢ **Comparison of Squirrel Cage and Slip Ring Motor**

Sl.No.	Property	*Squirrel cage motor*	*Slip ring motor*
1.	**Rotor Construction**	*Bars are used in rotor. Squirrel cage motor is very simple, rugged and long lasting. No slip rings and brushes*	*Winding wire is to be used.* *Wound rotor required attention.* *Slip ring and brushes are needed also need frequent maintenance.*
2.	**Starting**	*Can be started by D.O.L., star-delta, auto transformer starters*	*Rotor resistance starter is required.*
3.	**Starting torque**	*Low*	*Very high*
4.	**Starting Current**	*High*	*Low*
5.	**Speed variation**	*Not easy, but could be varied in large steps by pole changing or through smaller incremental steps through thyristors or by frequency variation.*	*Easy to vary speed.* *Speed change is possible by inserting rotor resistance using thyristors or by using frequency variation injecting emf in the rotor circuit cascading.*
6.	**Maintenance**	*Almost ZERO maintenance*	*Requires frequent maintenance*
7.	**Cost**	*Low*	*High*

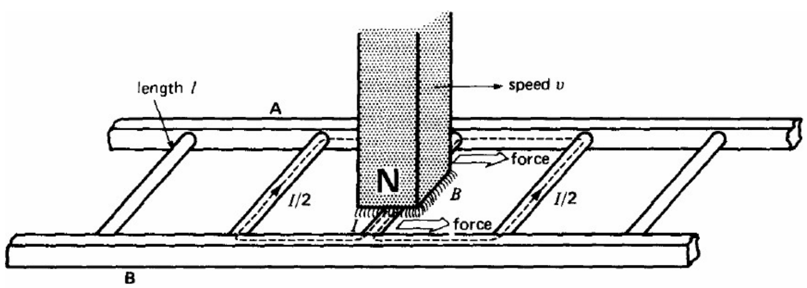
- **Principle of Operation**

The operation of a 3-phase induction motor is based upon the application of Faraday Law and the Lorentz force on a conductor. The behaviour can readily be understood by means of the following example.

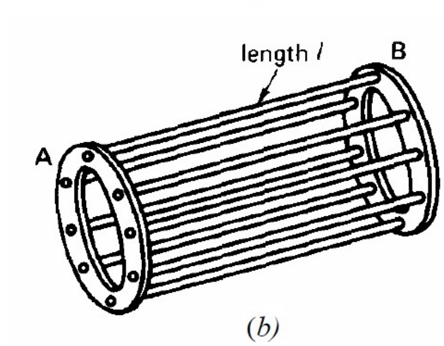
Consider a series of conductors of length l, whose extremities are short-circuited by two bars A and B (Fig.3.3 a). A permanent magnet placed above this conducting ladder, moves rapidly to the right at a speed v, so that its magnetic field B sweeps across the conductors. The following sequence of events then takes place:

1. A voltage E = Blv is induced in each conductor while it is being cut by the flux (Faraday law).
2. The induced voltage immediately produces a current I, which flows down the conductor underneath the pole face, through the end-bars, and back through the other conductors.
3. Because the current carrying conductor lies in the magnetic field of the permanent magnet, it experiences a mechanical force (Lorentz force).

The force always acts in a direction to drag the conductor along with the magnetic field. If the conducting ladder is free to move, it will accelerate toward the right. However, as it picks up speed, the conductors will be cut less rapidly by the moving magnet, with the result that the induced voltage E and the current I will diminish. Consequently, the force acting on the conductors wilt also decreases. If the ladder were to move at the same speed as the magnetic field, the induced voltage E, the current I, and the force dragging the ladder along would all become zero



(a)



(b)

Fig: 3.3

In an induction motor the ladder is closed upon itself to form a squirrel-cage (Fig.3.3b) and the moving magnet is replaced by a rotating field. The field is produced by the 3-phase currents that flow in the stator windings.

- **Rotating Magnetic Field and Induced Voltages**

Consider a simple stator having 6 salient poles, each of which carries a coil having 5 turns (Fig.3.4). Coils that are diametrically opposite are connected in series by means of three jumpers

that respectively connect terminals a-a, b-b, and c-c. This creates three identical sets of windings AN, BN, CN, which are mechanically spaced at 120 degrees to each other. The two coils in each winding produce magneto motive forces that act in the same direction.

The three sets of windings are connected in wye, thus forming a common neutral N. Owing to the perfectly symmetrical arrangement, the line to neutral impedances are identical. In other words, as regards terminals A, B, C, the windings constitute a balanced 3-phase system.

For a two-pole machine, rotating in the air gap, the magnetic field (i.e., flux density) being sinusoidally distributed with the peak along the centre of the magnetic poles. The result is illustrated in Fig.3.5. The rotating field will induce voltages in the phase coils aa', bb', and cc'. Expressions for the induced voltages can be obtained by using Faraday laws of induction.

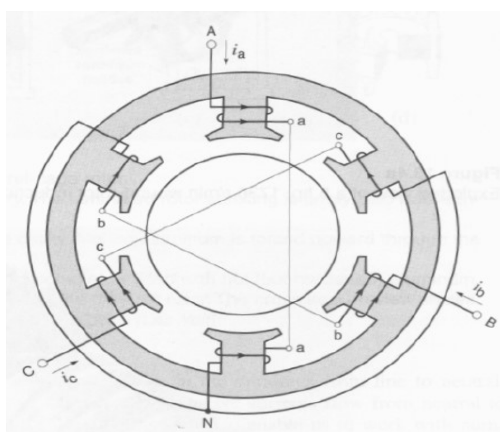


Fig: 3.4 Elementary stator having terminals A, B, C connected to a 3-phase source (not shown).
Currents flowing from line to neutral are considered to be positive.

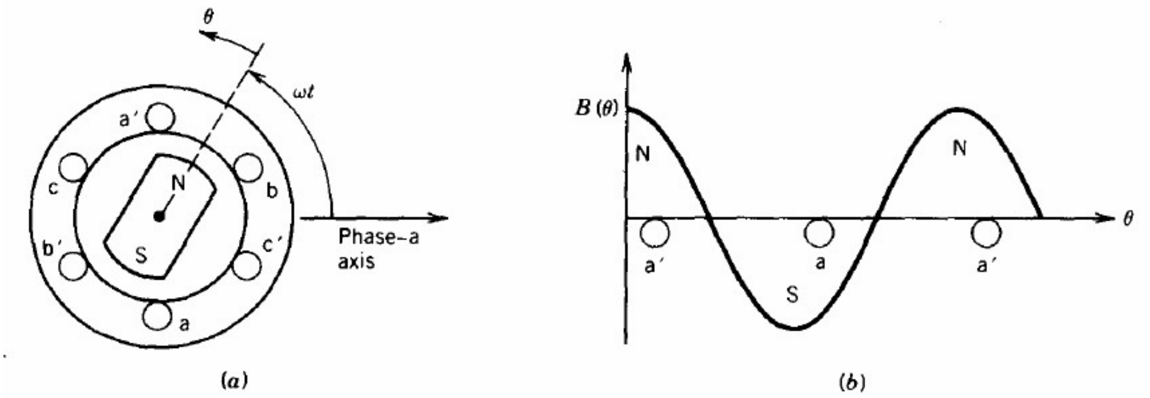


Fig: 3.5 Air gap flux density distribution

The flux density distribution in the air gap can be expressed as:

$$B(\theta) = B_{\max} \cos \theta$$

The air gap flux per pole, ϕ_P, is:

$$\phi_p = \int_{-\pi/2}^{\pi/2} B(\theta) lr d\theta = 2B_{\max} lr$$

Where,

l is the axial length of the stator.

r is the radius of the stator at the air gap.

Let us consider that the phase coils are full-pitch coils of N turns (the coil sides of each phase are 180 electrical degrees apart as shown in Fig.3.5). It is obvious that as the rotating field moves (or the magnetic poles rotate) the flux linkage of a coil will vary. The flux linkage for coil aa' will be maximum.

($= N\phi_P \ at \ \omega t = 0^o$) (Fig.3.5a) and zero at $\omega t = 90^o$. The flux linkage $\lambda_a(\omega t)$ will vary as the cosine of the angle ωt.

Hence,

$$\lambda_a(\omega t) = N\phi_p \cos\omega t$$

Therefore, the voltage induced in phase coil **aa'** is obtained from *Faraday law* as:

$$e_a = -\frac{d\lambda_a(\omega t)}{dt} = \omega N\phi_p \sin\omega t = E_{\max}\sin\omega t$$

The voltages induced in the other phase coils are also sinusoidal, but phase-shifted from each other by 120 electrical degrees. Thus,

$$e_b = E_{\max}\sin(\omega t - 120)$$

$$e_c = E_{\max}\sin(\omega t + 120).$$

the *rms* value of the induced voltage is:

$$E_{rms} = \frac{\omega N\phi_p}{\sqrt{2}} = \frac{2\pi f}{\sqrt{2}} N\phi_p = 4.44 fN\phi_p$$

Where f is the frequency in hertz. Above equation has the same form as that for the induced voltage in transformers. However, $Ø_P$ represents the flux per pole of the machine.

The above equation also shows the rms voltage per phase. The N is the total number of series turns per phase with the turns forming a concentrated full-pitch winding. In an actual AC machine each phase winding is distributed in a number of slots for better use of the iron and copper and to improve the waveform. For such a distributed winding, the EMF induced in various coils placed in different slots are not in time phase, and therefore the phasor sum of the EMF is less than their numerical sum when they are connected in series for the phase winding. A reduction factor K_W, called the winding factor, must therefore be applied. For most three-phase machine windings K_W is about 0.85 to 0.95.

Therefore, for a distributed phase winding, the rms voltage per phase is

$$Erms = 4.44fN_{ph}\varphi_p K_W$$

Where N_{ph} is the number of turns in series per phase.

Alternate Analysis for Rotating Magnetic Field

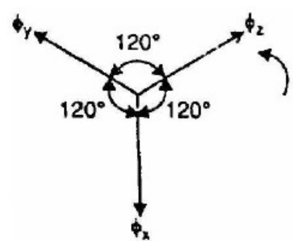
When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced. This field is such that its poles do no remain in a fixed position on the stator but go on shifting their positions around the stator. For this reason, it is called a rotating Held. It can be shown that magnitude of this rotating field is constant and is equal to 1.5 m where m is the maximum flux due to any phase.

To see how rotating field is produced, consider a 2-pole, 3-phase winding as shown in Fig. 3.6 (i). The three phases X, Y and Z are energized from a 3-phase source and currents in these phases are indicated as Ix, Iy and Iz [See Fig. 3.6 (ii)]. Referring to Fig. 3.6 (ii), the fluxes produced by these currents are given by:

Here ϕ_m is the maximum flux due to any phase. Above figure shows the phasor diagram of the three fluxes. We shall now prove that this 3-phase supply produces a rotating field of constant magnitude equal to 1.5 ϕ_m.

At instant 1 [See Fig. 3.6 (ii) and Fig. 3.6 (iii)], the current in phase X is zero and currents in phases Y and Z are equal and opposite. The currents are flowing outward in the top conductors and inward

$$\phi_x = \phi_m \sin \omega t$$
$$\phi_y = \phi_m \sin (\omega t - 120°)$$
$$\phi_z = \phi_m \sin (\omega t - 240°)$$



in the bottom conductors. This establishes a resultant flux towards right. The magnitude of the resultant flux is constant and is equal to 1.5 ϕ_m as proved under:

At instant 1, $\omega t = 0°$. Therefore, the three fluxes are given by;

$$\phi_x = 0; \qquad \phi_y = \phi_m \sin(-120°) = -\frac{\sqrt{3}}{2}\phi_m;$$
$$\phi_z = \phi_m \sin(-240°) = \frac{\sqrt{3}}{2}\phi_m$$

The phasor sum of $-\phi_y$ and ϕ_z is the resultant flux ϕ_r

So,

$$\text{Resultant flux,} \quad \phi_r = 2 \times \frac{\sqrt{3}}{2} \phi_m \cos \frac{60°}{2} = 2 \times \frac{\sqrt{3}}{2} \phi_m \times \frac{\sqrt{3}}{2} = 1.5\ \phi_m$$

At instant 2 [Fig: 3.7 (ii)], the current is maximum (negative) in ϕ_y phase Y and 0.5 maximum (positive) in phases X and Y. The magnitude of resultant flux is 1.5 ϕ_m as proved under:

At instant 2, $\omega t = 30°$. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 30° = \frac{\phi_m}{2}$$
$$\phi_y = \phi_m \sin(-90°) = -\phi_m$$
$$\phi_z = \phi_m \sin(-210°) = \frac{\phi_m}{2}$$

The phasor sum of ϕ_x, $-\phi_y$ and ϕ_z is the resultant flux ϕ_r

Phasor sum of ϕ_x and ϕ_z, $\phi'_r = 2 \times \frac{\phi_m}{2} \cos \frac{120°}{2} = \frac{\phi_m}{2}$

Phasor sum of ϕ'_r and $-\phi_y$, $\phi_r = \frac{\phi_m}{2} + \phi_m = 1.5\ \phi_m$

Note that resultant flux is displaced 30° clockwise from position 1.

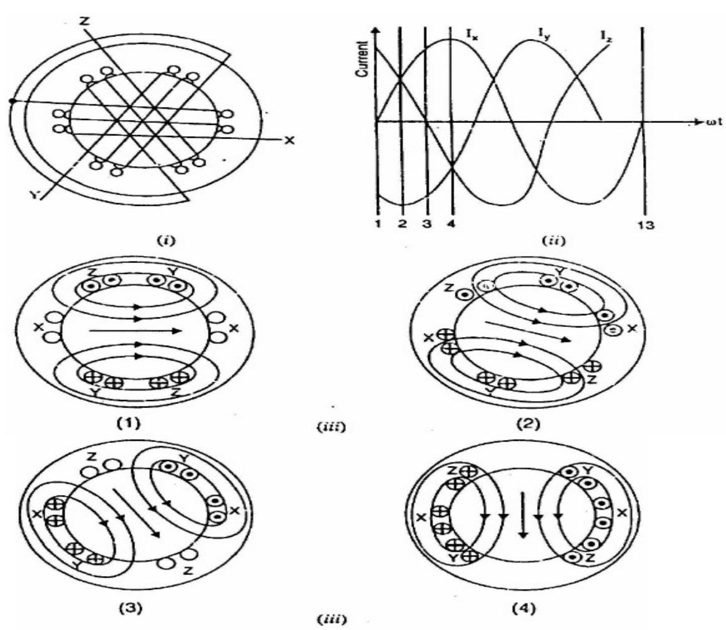


Fig: 3.6

At instant 3[Fig: 3.7 (iii)], current in phase Z is zero and the currents in phases X and Y are equal and opposite (currents in phases X and Y arc 0.866 × max. value). The magnitude of resultant flux is 1.5 ϕ_m as proved under:

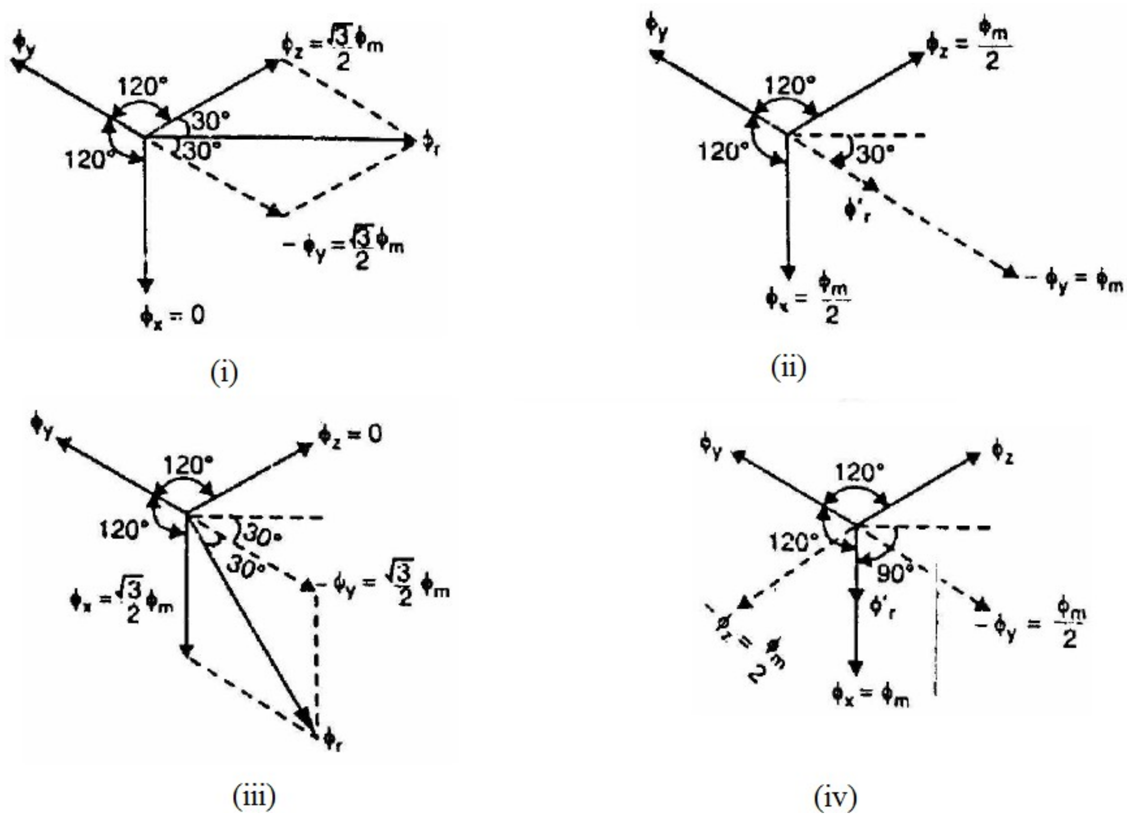


Fig: 3.7

At instant 3, $\omega t = 60°$. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 60° = \frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_y = \phi_m \sin(-60°) = -\frac{\sqrt{3}}{2}\phi_m;$$

$$\phi_z = \phi_m \sin(-180°) = 0$$

The resultant flux ϕ_r is the phasor sum of ϕ_x and $-\phi_y$ $(\because \ \phi_z = 0)$.

$$\phi_r = 2 \times \frac{\sqrt{3}}{2}\phi_m \cos\frac{60°}{2} = 1.5\ \phi_m$$

Note that resultant flux is displaced 60° clockwise from position 1.

At instant 4 [Fig: 3.7 (iv)], the current in phase X is maximum (positive) and the currents in phases V and Z are equal and negative (currents in phases V and Z are 0.5 × max. value). This establishes a resultant flux downward as shown under:

At instant 4, $\omega t = 90°$. Therefore, the three fluxes are given by;

$$\phi_x = \phi_m \sin 90° = \phi_m$$

$$\phi_y = \phi_m \sin(-30°) = -\frac{\phi_m}{2}$$

$$\phi_z = \phi_m \sin(-150°) = -\frac{\phi_m}{2}$$

The phasor sum of ϕ_x, $-\phi_y$ and $-\phi_z$ is the resultant flux ϕ_r

Phasor sum of $-\phi_z$ and $-\phi_y$, $\phi'_r = 2 \times \frac{\phi_m}{2} \cos\frac{120°}{2} = \frac{\phi_m}{2}$

Phasor sum of ϕ'_r and ϕ_x, $\phi_r = \frac{\phi_m}{2} + \phi_m = 1.5\,\phi_m$

Note that the resultant flux is downward i.e., it is displaced 90° clockwise from position 1.

It follows from the above discussion that a 3-phase supply produces a rotating field of constant value (= 1.5 ϕ_m, where ϕ_m is the maximum flux due to any phase).

- **Speed of rotating magnetic field**

The speed at which the rotating magnetic field revolves is called the synchronous speed (Ns). Referring to Fig. 3.6 (ii), the time instant 4 represents the completion of one-quarter cycle of alternating current Ix from the time instant 1. During this one quarter cycle, the field has rotated through 90°. At a time instant represented by 13 [Fig. 3.6 (ii)] or one complete cycle of current Ix from the origin, the field has completed one revolution. Therefore, for a 2-pole stator winding, the field makes one revolution in one cycle of current. In a 4-pole stator winding, it can be shown that the rotating field makes one revolution in two cycles of current. In general, fur P poles, the rotating field makes one revolution in P/2 cycles of current.

$$\therefore \quad \text{Cycles of current} = \frac{P}{2} \times \text{revolutions of field}$$

or $$\text{Cycles of current per second} = \frac{P}{2} \times \text{revolutions of field per second}$$

Since revolutions per second is equal to the revolutions per minute (N_s) divided by 60 and the number of cycles per second is the frequency f,

$$\therefore \quad f = \frac{P}{2} \times \frac{N_s}{60} = \frac{N_s P}{120}$$

or $$N_s = \frac{120\,f}{P}$$

The speed of the rotating magnetic field is the same as the speed of the alternator that is supplying power to the motor if the two have the same number of poles. Hence the magnetic flux is said to rotate at synchronous speed.

- **Slip**

We have seen above that rotor rapidly accelerates in the direction of rotating field. In practice, the rotor can never reach the speed of stator flux. If it did, there would be no relative speed between the stator field and rotor conductors, no induced rotor currents and, therefore, no torque to drive the rotor. The friction and windage would immediately cause the rotor to slow down. Hence, the rotor speed (N) is always less than the suitor field speed (Ns). This difference in speed depends upon load on the motor. The difference between the synchronous speed Ns of the rotating stator field and the actual rotor speed N is called slip. It is usually expressed as a percentage of synchronous speed i.e.

$$\% \text{ age slip, } s = \frac{N_s - N}{N_s} \times 100$$

(i) The quantity $N_s - N$ is sometimes called slip speed.
(ii) When the rotor is stationary (i.e., N = 0), slip, s = 1 or 100 %.
(iii) In an induction motor, the change in slip from no-load to full-load is hardly 0.1% to 3% so that it is essentially a constant-speed motor.

- **Induction Motor Torque**

The mechanical power P available from any electric motor can be expressed as:

$$P = \frac{2\pi NT}{60} \quad \text{watts}$$

where N = speed of the motor in r.p.m.
T = torque developed in N-m

$$\therefore \quad T = \frac{60}{2\pi}\frac{P}{N} = 9.55\,\frac{P}{N} \text{ N - m}$$

If the gross output of the rotor of an induction motor is P_m and its speed is N r.p.m., then gross torque T developed is given by:

$$T_g = 9.55\frac{P_m}{N} \text{ N - m}$$

Similarly, $$T_{sh} = 9.55\frac{P_{out}}{N} \text{ N - m}$$

Note. Since windage and friction loss is small, $T_g = T_{sh}$,. This assumption hardly leads to any significant error.

➢ Torque Equations

The gross torque Tg developed by an induction motor is given by;

$$T_g = \frac{\text{Rotor input}}{2\pi N_s} \qquad \text{... } N_s \text{ is r.p.s.}$$

$$= \frac{60 \times \text{Rotor input}}{2\pi N_s} \qquad \text{... } N_s \text{ is r.p.s.}$$

Now Rotor input $= \frac{\text{Rotor Cu loss}}{s} = \frac{3(I'_2)^2 R_2}{s}$ (i)

As shown in Sec. 8.16, under running conditions,

$$I'_2 = \frac{s E_2}{\sqrt{R_2^2 + (s X_2)^2}} = \frac{s K E_1}{\sqrt{R_2^2 + (s X_2)^2}}$$

where K = Transformation ratio $= \frac{\text{Rotor turns/phase}}{\text{Stator turns/phase}}$

$$\therefore \quad \text{Rotor input} = 3 \times \frac{s^2 E_2^2 R_2}{R_2^2 + (s X_2)^2} \times \frac{1}{s} = \frac{3 s E_2^2 R_2}{R_2^2 + (s X_2)^2}$$

(Putting me value of I'_2 in eq.(i))

Also $$\text{Rotor input} = 3 \times \frac{s^2 K^2 E_1^2 R_2}{R_2^2 + (s X_2)^2} \times \frac{1}{s} = \frac{3 s K^2 E_1^2 R_2}{R_2^2 + (s X_2)^2}$$

(Putting me value of I'_2 in eq.(i))

$$\therefore \quad T_g = \frac{\text{Rotor input}}{2\pi N_s} = \frac{3}{2\pi N_s} \times \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2} \qquad \text{...in terms of } E_2$$

$$= \frac{3}{2\pi N_s} \times \frac{s K^2 E_1^2 R_2}{R_2^2 + (s X_2)^2} \qquad \text{...in terms of } E_1$$

Note that in the above expressions of T_g, the values E_1, E_2, R_2 and X_2 represent the phase values.

➢ Condition for Maximum Starting Torque

It can be proved that starting torque will be maximum when rotor resistance/phase is equal to standstill rotor reactance/phase

Now $$T_s = \frac{K_1 R_2}{R_2^2 + X_2^2} \qquad \text{(i)}$$

Differentiating eq. (i) w.r.t. R_2 and equating the result to zero, we get,

$$\frac{dT_s}{dR_2} = K_1 \left[\frac{1}{R_2^2 + X_2^2} - \frac{R_2(2R_2)}{\left(R_2^2 + X_2^2\right)^2} \right] = 0$$

or $$R_2^2 + X_2^2 = 2R_2^2$$

or $$R_2 = X_2$$

Hence starting torque will be maximum when:

Rotor resistance/phase = Standstill rotor reactance/phase

Under the condition of maximum starting torque, $\phi_2 = 45°$ and rotor power factor is 0.707 lagging.

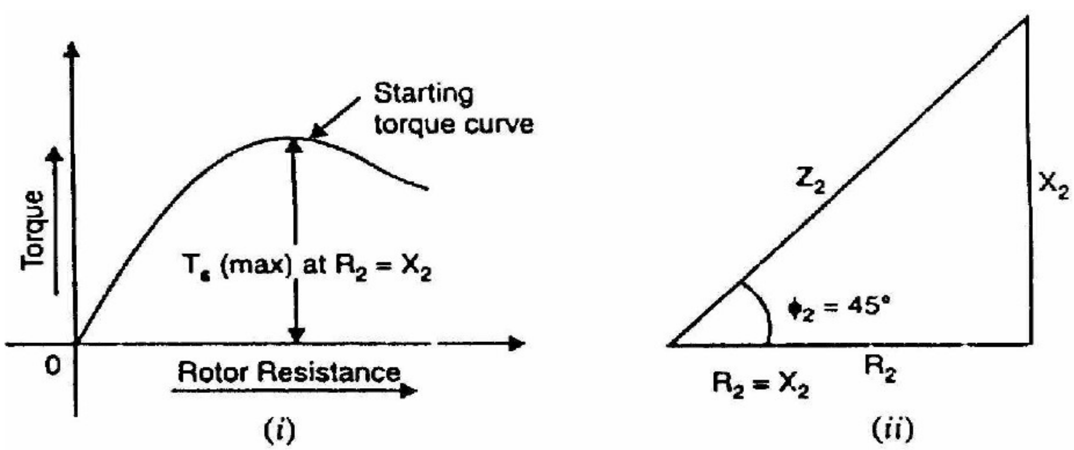


Fig. 3.14 shows the variation of starting torque with rotor resistance. As the rotor resistance is increased from a relatively low value, the starting torque increases until it becomes maximum when $R_2 = X_2$. If the rotor resistance is increased beyond this optimum value, the starting torque will decrease.

Starting of Three Phase Induction Motor

The induction motor is fundamentally a transformer in which the stator is the primary and the rotor is short-circuited secondary. At starting, the voltage induced in the induction motor rotor is maximum (s = 1). Since the rotor impedance is low, the rotor current is excessively large. This large rotor current is reflected in the stator because of transformer action. This results in high starting current (4 to 10 times the full-load current) in the stator at low power factor and consequently the value of starting torque is low. Because of the short duration, this value of large current does not harm the motor if the motor accelerates normally.

However, this large starting current will produce large line-voltage drop. This will adversely affect the operation of other electrical equipment connected to the same lines. Therefore, it is desirable and necessary to reduce the magnitude of stator current at starting and several methods are available for this purpose.

Methods of Starting Three Phase Induction Motors

The method to be employed in starting a given induction motor depends upon the size of the motor and the type of the motor. The common methods used to start induction motors are:

(i) Direct-on-line starting
(ii) Stator resistance starting
(iii) Autotransformer starting
(iv) Star-delta starting
(v) Rotor resistance starting

Methods (i) to (iv) are applicable to both squirrel-cage and slip ring motors. However, method (v) is applicable only to slip ring motors. In practice, any one of the first four methods is used for starting squirrel cage motors, depending upon, the size of the motor. But slip ring motors are invariably started by rotor resistance starting.
Except direct-on-line starting, all other methods of starting squirrel-cage motors employ reduced voltage across motor terminals at starting.

Direct-on-line starting

This method of starting in just what the name implies—the motor is started by connecting it directly to 3-phase supply. The impedance of the motor at standstill is relatively low and when it is directly connected to the supply system, the starting current will be high (4 to 10 times the full-load current) and at a low power factor. Consequently, this method of starting is suitable for relatively small (up to 7.5 kW) machines.

Relation between starling and F.L. torques. We know that:

$$\text{Rotor input} = 2\pi\, N_s\, T = kT$$

But $\quad$ Rotor Cu loss = s × Rotor input

$$\therefore \quad 3(I'_2)^2 R_2 = s \times kT$$

or $$T \propto (I'_2)^2 / s$$

or $$T \propto I_1^2 / s \qquad (\because I'_2 \propto I_1)$$

If I_{st} is the starting current, then starting torque (T_{st}) is

$$T \propto I_{st}^2 \qquad (\because \text{ at starting } s = 1)$$

If I_f is the full-load current and s_f is the full-load slip, then,

$$T_f \propto I_f^2 / s_f$$

$$\therefore \quad \frac{T_{st}}{T_f} = \left(\frac{I_{st}}{I_f}\right)^2 \times s_f$$

When the motor is started direct-on-line, the starting current is the short-circuit (blocked-rotor) current I_{sc}.

$$\therefore \quad \frac{T_{st}}{T_f} = \left(\frac{I_{sc}}{I_f}\right)^2 \times s_f$$

Let us illustrate the above relation with a numerical example. Suppose $I_{sc} = 5\ I_f$ and full-load slip $s_f = 0.04$. Then,

$$\frac{T_{st}}{T_f} = \left(\frac{I_{sc}}{I_f}\right)^2 \times s_f = \left(\frac{5\ I_f}{I_f}\right)^2 \times 0.04 = (5)^2 \times 0.04 = 1$$

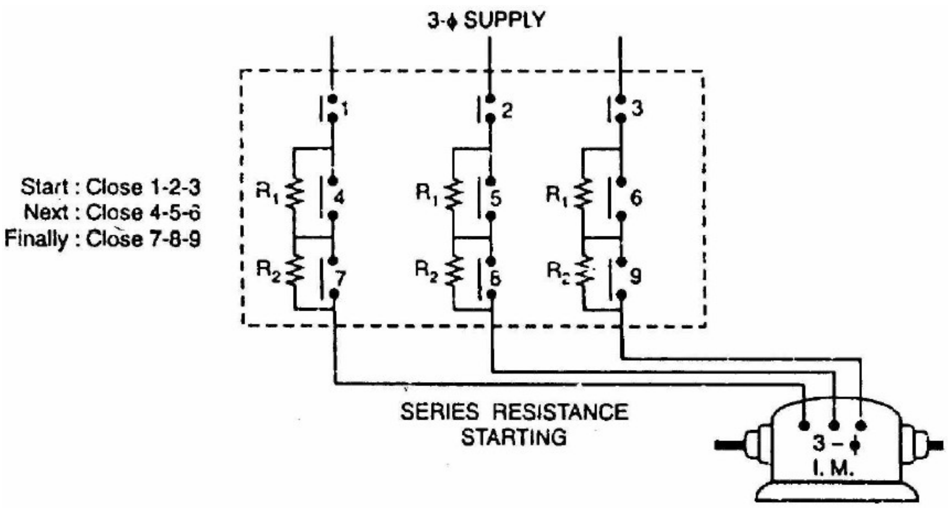
$$\therefore \quad T_{st} = T_f$$

Note that starting current is as large as five times the full-load current but starting torque is just equal to the full-load torque. Therefore, starting current is very high and the starting torque is comparatively low. If this large starting current flows for a long time, it may overheat the motor and damage the insulation.

- **Stator resistance starting**

In this method, external resistances are connected in series with each phase of stator winding during starting. This causes voltage drop across the resistances so that voltage available across motor terminals is reduced and hence the starting current. The starting resistances are gradually cut out in steps (two or more steps) from the stator circuit as the motor picks up speed. When the motor attains rated speed, the resistances are completely cut out and full line voltage is applied to the rotor see Fig: 3.23.

This method suffers from two drawbacks. First, the reduced voltage applied to the motor during the starting period lowers the starting torque and hence increases the accelerating time. Secondly, a lot of power is wasted in the starting resistances.



3.12 Speed control of Three Phase Induction Motors

The induction machine, when operating from mains is essentially a constant speed machine. Many industrial drives, typically for fan or pump applications, have typically constant speed requirements and hence the induction machine is ideally suited for these. However, the induction machine, especially the squirrel cage type, is quite rugged and has a simple construction. Therefore it is good candidate for variable speed applications if it can be achieved.

- **Speed control by changing applied voltage**

From the torque equation of the induction machine we can see that the torque depends on the square of the applied voltage. The variation of speed torque curves with respect to the applied voltage is shown in Fig: 3.28. These curves show that the slip at maximum torque ss remains same, while the value of stall torque comes down with decrease in applied voltage. The speed range for stable operation remains the same.

Further, we also note that the starting torque is also lower at lower voltages. Thus, even if a given voltage level is sufficient for achieving the running torque, the machine may not start. This method of trying to control the speed is best suited for loads that require very little starting torque, but their torque requirement may increase with speed.

Fig: 3.28 also shows a load torque characteristic — one that is typical of a fan type of load. In a fan (blower) type of load, the variation of torque with speed is such that $TT \propto \omega\omega^2$.

Here one can see that it may be possible to run the motor to lower speeds within the range n_s to $(1 - \hat{}s)$ $n_{s.}$ Further, since the load torque at zero speed is zero, the machine can start even at reduced voltages. This will not be possible with constant torque type of loads.

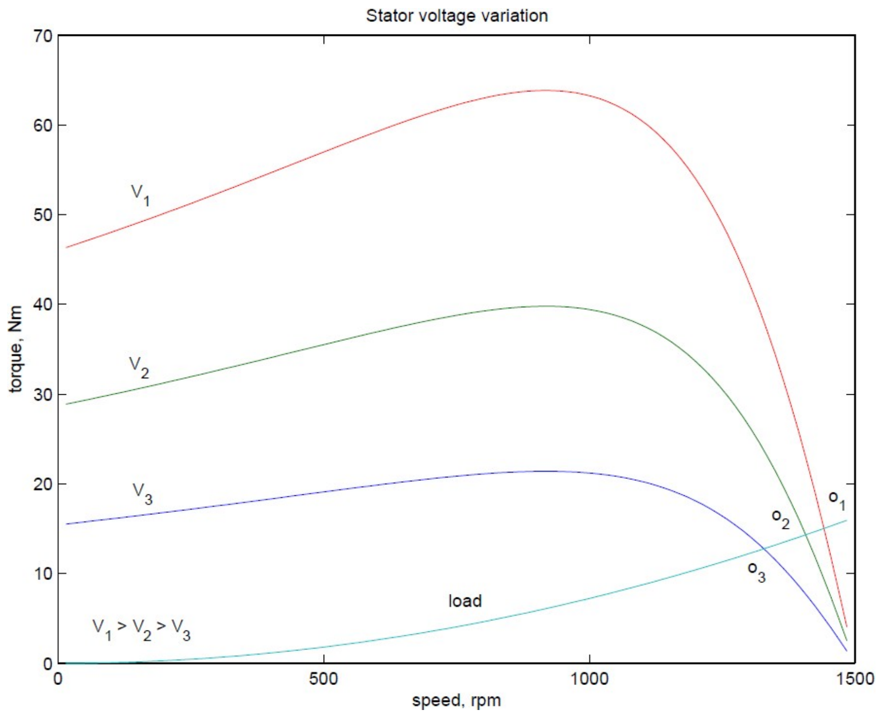


Fig: 3.28

One may note that if the applied voltage is reduced, the voltage across the magnetising branch also comes down. This in turn means that the magnetizing current and hence flux level are reduced. Reduction in the flux level in the machine impairs torque production which is primarily the explanation for Fig: 3.28. If, however, the machine is running under lightly loaded conditions, then operating under rated flux levels is not required. Under such conditions,

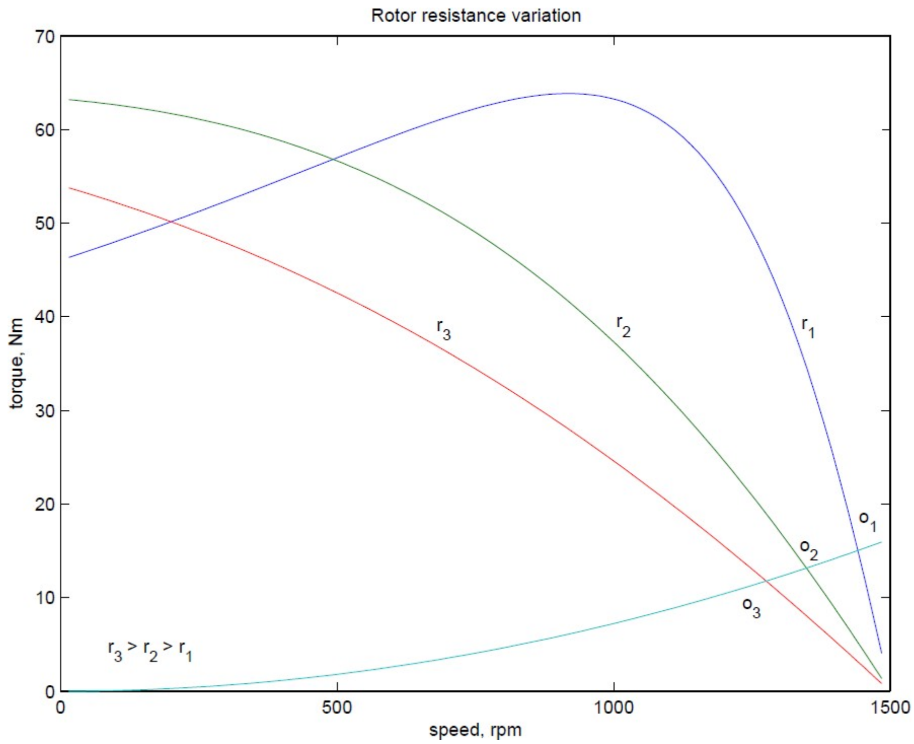
reduction in magnetizing current improves the power factor of operation. Some amount of energy saving may also be achieved.

Voltage control may be achieved by adding series resistors (a lossy, inefficient proposition), or a series inductor / autotransformer (a bulky solution) or a more modern solution using semiconductor devices. A typical solid state circuit used for this purpose is the AC voltage controller or AC chopper.

- **Rotor resistance control**

The expression for the torque of the induction machine is dependent on the rotor resistance. Further the maximum value is independent of the rotor resistance. The slip at maximum torque is dependent on the rotor resistance. Therefore, we may expect that if the rotor resistance is changed, the maximum torque point shifts to higher slip values, while retaining a constant torque. Fig: 3.29 shows a family of torque-speed characteristic obtained by changing the rotor resistance.

Note that while the maximum torque and synchronous speed remain constant, the slip at which maximum torque occurs increases with increase in rotor resistance, and so does the starting torque. Whether the load is of constant torque type or fan-type, it is evident that the speed control range is more with this method. Further, rotor resistance control could also be used as a means of generating high starting torque.

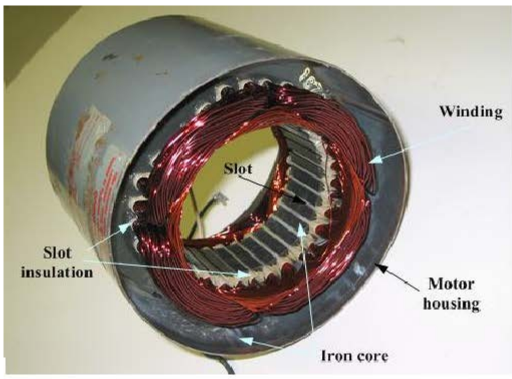


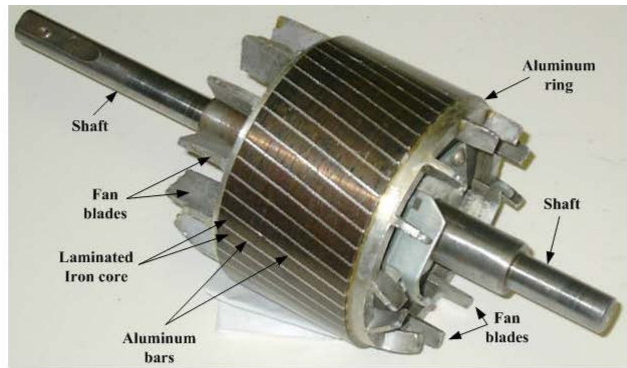
For all its advantages, the scheme has two serious drawbacks. Firstly, in order to vary the rotor resistance, it is necessary to connect external variable resistors (winding resistance itself cannot be changed). This, therefore necessitates a slip-ring machine, since only in that case rotor terminals are available outside. For cage rotor machines, there are no rotor terminals. Secondly, the method is not very efficient since the additional resistance and operation at high slips entails dissipation.

The resistors connected to the slip-ring brushes should have good power dissipation capability. Water based rheostats may be used for this. A ‘solid-state’ alternative to a rheostat is a chopper controlled resistance where the duty ratio control of the chopper presents a variable resistance load to the rotor of the induction machine.

➢ Single Phase Induction Motors

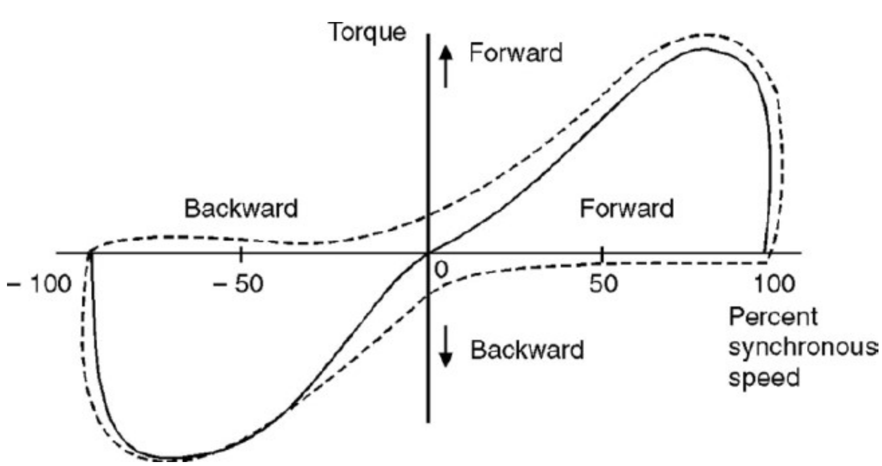
Single phase Induction motors perform a great variety of useful services at home, office, farm, factory and in business establishments. Single phase motors are generally manufactured in fractional HP ratings below 1 HP for economic reasons. Hence, those motors are generally referred to as fractional horsepower motors with a rating of less than 1 HP. Most single phase motors fall into this category. Single phase Induction motors are also manufactured in the range of 1.5, 2, 3 and up to 10 HP as a special requirement





4.1 Theory of Operation

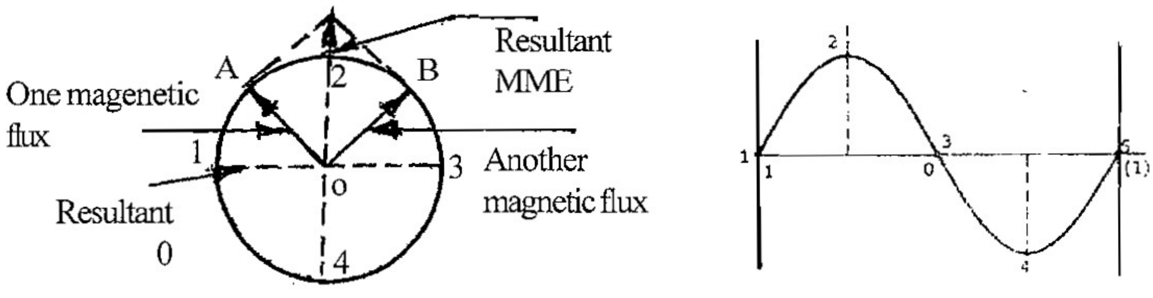
A single phase induction motor is similar in construction to that of a polyphase induction motor with difference that its stator has only one winding. If such a stator is supplied with single phase alternating current, the field produced by it changes in magnitude and direction sinusoidally. Thus the magnetic field produced in the air gap is alternating one but not rotating as a result these kind of motors are not self starting. Fig: 4.2 (a) shows the torque-speed characteristic of single-phase induction motor.



Such an alternating filed is equivalent to two fields of equal magnitude rotating in opposite directions at equal speed as explained below:

- **Double Revolving Field Theory of Single Phase Induction Motor**

  Consider two magnetic fields represented by quantities OA and OB of equal magnitude revolving in opposite directions as shown in fig: 4.1.



The resultant of the two fields of equal magnitude rotating in opposite directions is alternating. Therefore an alternating current can be considered as having two components which are of equal in magnitude and rotating in opposite directions.

From the above, it is clear that when a single phase alternating current is supplied to the stator of a single phase motor, the field produced will be of alternating in nature which can be divided into two components of equal magnitude one revolving in clockwise and other in counter clockwise direction.

If a stationary squirrel cage rotor is kept in such a field equal forces in opposite direction will act and the rotor will simply vibrate and there will be no rotation.

But if the rotor is given a small jerk in any direction in this condition, it will go on revolving and will develop torque in that particular direction. It is clear from the above that a single phase induction motor when having only one winding is not a self-starting. To make it a self-starting anyone of the following can be adopted.

(i) Split phase starting.
(ii) Repulsion starting.
(iii) Shaded pole starting.

- **Methods of Starting**

It is clear from previous discussion that a single phase induction motor when having only one winding and it is not self-starting. To make it a self-starting anyone of the following can be adopted.

(1) Split phase starting.

(2) Repulsion starting.

(3) Shaded pole starting.

4.1.2 PRINCIPLE OF SPLIT PHASE INDUCTION MOTOR

The basic principle of operation of a split phase induction motor is similar to that of a polyphase induction motor. The main difference is that the single phase motor does not produce a rotating magnetic field but produces only a pulsating filed.

Hence, to produce the rotating magnetic field for self-starting, phase splitting is to be done to make the motor to work as a two phase motor for starting.

4.3.1 Working of Split Phase Motor

In split phase motor two windings named as main winding and starting winding are provided. At the time of starting, both the main and starting windings should be connected across the supply to produce the rotating magnetic field.

The rotor is of a squirrel cage type and the revolving magnetic field sweeps part the stationary rotor, inducing emf in the rotor. As the rotor bars are short-circuited, a current flows through them producing a magnetic field.

This magnetic field opposes the revolving magnetic field and will combine with the main filed to produce a revolving filed. By this action, the rotor starts revolving in the same direction of the rotating magnetic field as in the case of a squirrel cage induction motor.

Hence, once the rotor starts rotating, the starting winding can be disconnected from the supply by some mechanical means as the rotor and stator fields from a revolving magnetic field. There are several types of split phase motors.

➢ TYPES OF SPLIT-PHASE INDUCTION MOTORS

1. Resistance-start, induction-run motors
2. Capacitor-start, induction-run motors
3. Capacitor-start, capacitor-run motors
4. Shaded pole motors.

1. RESISTANCE-START, INDUCTION-RUN MOTORS

As the starting torque of this type of motor is relatively small and its starting current is high, these motors are most commonly used for rating up to 0.5 HP where the load could be started easily. The essential parts are shown in Fig: 4.7.

→ Main winding or running winding.

→ Auxiliary winding or starting winding

→ Squirrel cage type rotor.

→ Centrifugal switch.

- CONSTRUCTION AND WORKING

The starting winding is designed to have a higher resistance and lower reactance than the main winding. This is achieved by using small conductors in the auxiliary winding than in the main winding. The main winding will have higher inductance when surrounded by more iron, which could be made possible by placing it deeper into the stator slots, it is obvious that the current would split as shown in Fig: 4.7(b).

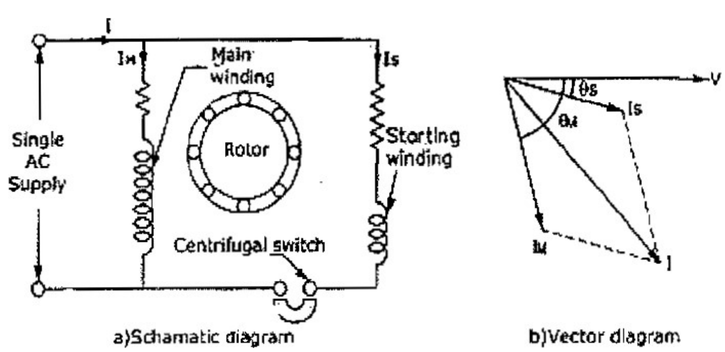


Fig: 4.7

The starting current "I" start will lag the main supply voltage "V" line by 15 degree and the main winding current. "I" main lags the main voltage by about 80 degree. Therefore, these currents will differ in time phase and their magnetic fields will combine to produce a rotating magnetic field.

When the motor has come upto about 75 to 80% of synchronous speed, the starting winding is opened by a centrifugal switch and the motor will continue to operate as a single phase motor.

- APPLICATIONS

These motors are used for driving fans, grinders, washing machines.

2. CAPACITOR-START, INDUCTION-RUN MOTOR

A drive which requires a large starting torque may be fitted with a capacitor-start, induction- run motor as it has excellence starting torque as compared to the resistance-start, induction-run motor.

- CONSTRUCTION AND WORKING

Fig: 4.9(a) shows the schematic diagram of a capacitor-start, induction-run motor. As shown, the main winding is directly connected across the main supply whereas the starting winding is connected across the main supply through a capacitor and centrifugal switch.

Both these windings are placed in a stator slot at 90 degree electrical apart, and a squirrel cage type rotor is used.

As shown in Fig: 4.9(b), at the time of starting the current in the main winding lags the supply voltages by 90 degrees, depending upon its inductance and resistance. On the other hand, the current in the starting winding due to its capacitor will lead the applied voltage, by say 20 degrees.

Hence, the phase difference between the main and starting winding becomes near to 90 degrees. This in turn makes the line current to be more or less in phase with its applied voltage, making the power factor to be high, thereby creating an excellent starting torque.

However, after attaining 75% of the rated speed, the centrifugal switch operates opening the starting winding and the motor then operates as an induction motor, with only the main winding connected to the supply.

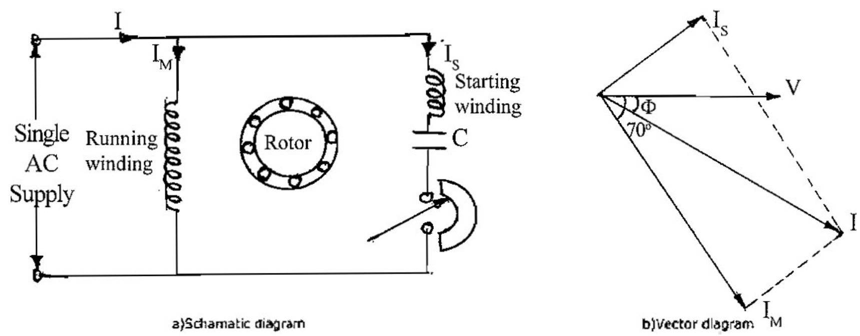


Fig: 4.9

As shown in Fig: 4.9(b), the displacement of current in the main and starting winding is about 80/90 degrees, and the power factor angle between the applied voltage and line current is very small. This results in producing a high power factor and an excellent starting torque, several times higher than the normal running torque as shown in Fig: 4.10.

- APPLICATIONS

Due to the excellent starting torque and easy direction-reversal characteristics,

- Used in belted fans,
- Used in blowers dryers,
- Used in washing machines,
- Used in pumps and compressors.

3. CAPACITOR-START, CAPACITOR-RUN MOTORS

As discussed earlier, one capacitor-start, induction-run motors have excellent starting torque, say about 300% of the full load torque and their power factor during starting in high.

However, their running torque is not good, and their power factor, while running is low. They also have lesser efficiency and cannot take overloads.

- CONSTRUCTION AND WORKING

The aforementioned problems are eliminated by the use of a two valve capacitor motor in which one large capacitor of electrolytic (short duty) type is used for starting whereas a smaller

capacitor of oil filled (continuous duty) type is used for running, by connecting them with the starting winding as shown in Fig:4.11. A general view of such a two valve capacitor motor is shown in Fig: 4.11.

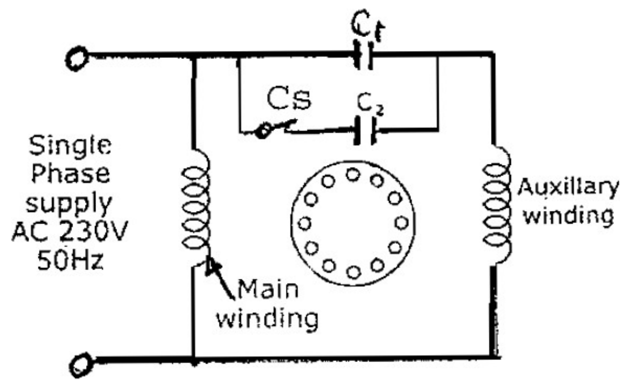


Fig: 4.11

This motor also works in the same way as a capacitor-start, induction-run motor, with exception, that the capacitor C1 is always in the circuit, altering the running performance to a great extent.

The starting capacitor which is of short duty rating will be disconnected from the starting winding with the help of a centrifugal switch, when the starting speed attains about 75% of the rated speed.

This motor has the following advantages:

- The starting torque is 300% of the full load torque
- The starting current is low, say 2 to 3 times of the running current.
- Starting and running power factor are good.
- Highly efficient running.
- Extremely noiseless operation.
- Can be loaded upto 125% of the full load capacity.

- APPLICATIONS

- Used for compressors, refrigerators, air-conditioners, etc.
- Higher starting torque.
- High efficiency, higher power factor and overloading.

- Costlier than the capacitor-start — Induction run motors of the same capacity.

➢ REPULSION STARTING

This type of starting need a wound rotor with brush and commutator arrangement like a dc armature Fig 4.13(a). The starting operation is based on the principle of repulsion and hence the name.

- CONSTRUCTION AND WORKING

Repulsion starting, though complicated in construction and higher in cost, are still used in certain industries due to their excellent starting torque, low starting current, ability to withstand long spell of starting currents to drive heavy loads and their easy method of reversal of direction.Now there is a condition that the rotor north pole will be repelled by the main north pole and the rotor south pole is repelled by the main south pole, so that a torque could be developed in the rotor. Now due to the repulsion action between the stator and the rotor poles, the rotor will start rotating in a clockwise direction. As the motor torque is due to repulsion action, this starting method is named as repulsion starting.

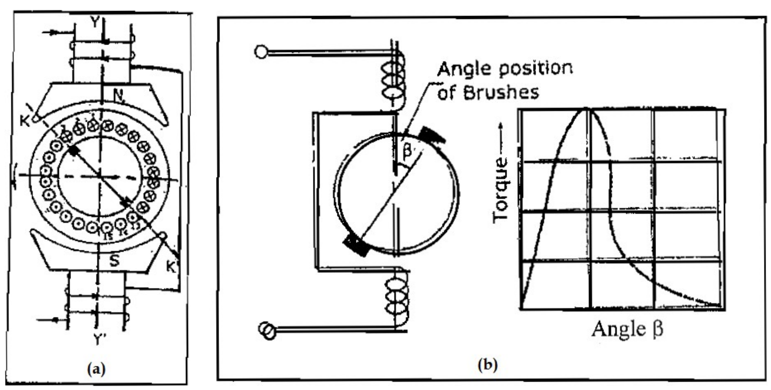


Fig: 4.13

To change the direction of rotation of this motor, the brush axis needs to be shifted from the right side as shown in Fig:4.13(b) to the left side of the main axis in a counter clockwise direction as shown in Fig:4.13(b).

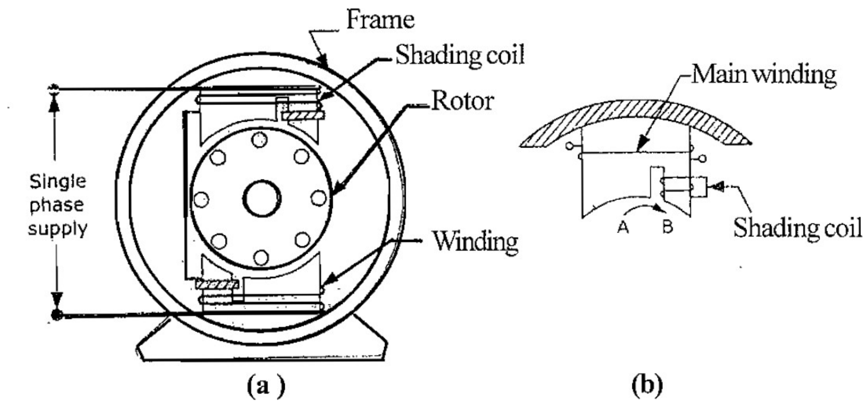


Fig: 4.14

A shaded pole made of laminated sheets has a slot cut across the lamination at about one third the distance from the edge of the pole.Around the smaller portion of the pole, a short-circuited copper ring is placed which is called the shading coil, and this part of the pole is known as the shaded part of the pole. The remaining part of the pole is called the unshaded part which is clearly shown in Fig: 4.14(b).

Around the poles, exciting coils are placed to which an AC supply is connected. When AC supply is effected to the exciting coil, the magnetic axis shifts from the unshaded part of the pole to the shaded part as will be explained in details in the next paragraph. This shifting of axis is equivalent to the physical movement of the pole.This magnetic axis, which is moving, cuts the rotor conductors and hence, a rotational torque is developed in the rotor.

By this torque the rotor starts rotating in the direction of the shifting of the magnetic axis that is from the unshaded part to the shaded part.

UNIT-IV

POWER CONVERTERS AND ELECTRICAL INSTALLATIONS

DC-DC CONVERTER:

A dc-to-dc converter, also known as dc chopper, is a static device which is used to obtain a variable dc voltage from a constant dc voltage source. Choppers are widely used in trolley cars, battery operated vehicles, traction motor control, control of large number of dc motors, etc….. They are also used as dc voltage regulators. Choppers are of two types: (1) Step-down choppers, and (2) Step-up choppers. In step-down choppers, the output voltage will be less than the input voltage, whereas in step-up choppers output voltage will be more than the input voltage.

PRINCIPLE OF STEP-DOWN CHOPPER:

Figure 9.1 shows a step-down chopper with resistive load. The thyristor in the circuit acts as a switch. When thyristor is ON, supply voltage appears across the load and when thyristor is OFF, the voltage across the load will be zero. The output voltage waveform is as shown in Fig. 9.2

9.2.

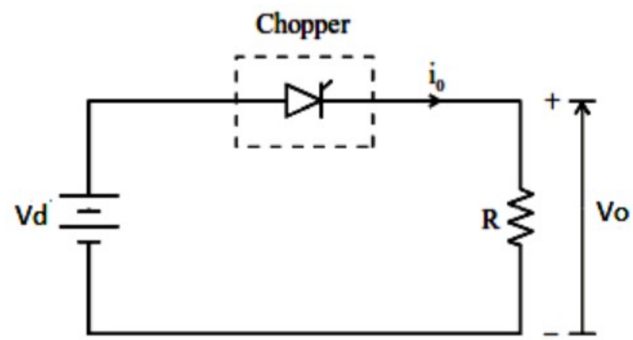


Fig.9.1 Chopper circuit.

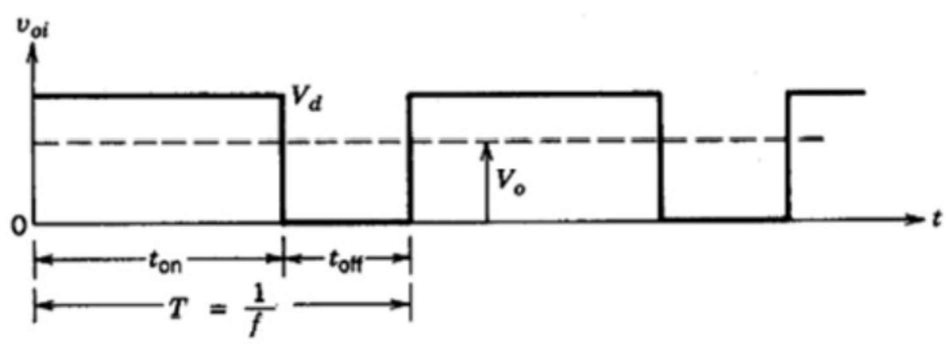


Fig.9.2 Chopper output voltage waveform, R- load.

METHODS OF CONTROL:

The output dc voltage can be varied by the following methods.

- Pulse width modulation control or constant frequency operation.
- Variable frequency control.

PULSE WIDTH MODULATION

- tON is varied keeping chopping frequency ‘f’ & chopping period ‘T’ constant.
- Output voltage is varied by varying the ON time tON

ANALYSIS OF A STEP-DOWN CHOPPER WITH RLOAD

Referring to Fig.9.2, the average output voltage can be found as

Let T= control period = $t_{on} + t_{off}$

$$v_o = V_{av} = \frac{1}{T}\int_0^{t_{on}} V_d \ dt$$

$$V_o = V_d \frac{t_{on}}{T} = V_d(\gamma)$$

$$where\ , \gamma = \frac{t_{on}}{T} = Duty\ cycle$$

- Maximum value of γ =1 when t_{on} =T (t_{off}= 0)
- Minimum value of γ = 0 when t_{on} = 0 (t_{off} = 0)

The output voltage is stepped down by the factor γ ($0 \leq V_o \leq V_d$) .Therefore this form of chopper is a step down chopper.

The R.M.S. value of the output voltage $v_{o,rms} = \sqrt{\frac{1}{T}\int_0^{ton} {v_0}^2 dt} = \sqrt{\gamma}\ v_d$

$$\text{The Output power} = \frac{{v_{o,rms}}^2}{R} = \gamma\,\frac{{v_d}^2}{R}$$

Input current (Assume 100% efficiency) $I_a = \frac{P}{V} = \frac{\gamma\, {v_d}^2}{R}\,\frac{1}{v_d} = \frac{\gamma\, v_d}{R}$

f= chopping frequency = $(\frac{1}{chopping \quad period\,(T)})$ = 1/ T

<u>The ripple factor</u>, *RF*

It is a measure of the ripple content.

$$RF = \sqrt{(\frac{Vo_{rms}}{Vo})^2 - 1} = \sqrt{(\frac{\gamma {V_d}^2}{\gamma^2 V_d^2}) - 1} = \sqrt{\frac{1}{\gamma} - 1} = \sqrt{\frac{1-\gamma}{\gamma}}$$

Note1: In this type of chopper both the voltage and current are always positive, hence this chopper is called a single-quadrant Buck converter or class – A chopper.

- **STEP-DOWN CHOPPER WITH R-L LOAD**

Consider a class-A chopper circuit with R-L load as shown in Fig.9.4.This is a step down chopper with one quadrant operation. If we use the simplified linear analysis by considering that T<< τ, where (T = ton + toff) . In this case the current is continuous as shown in Fig.9.5

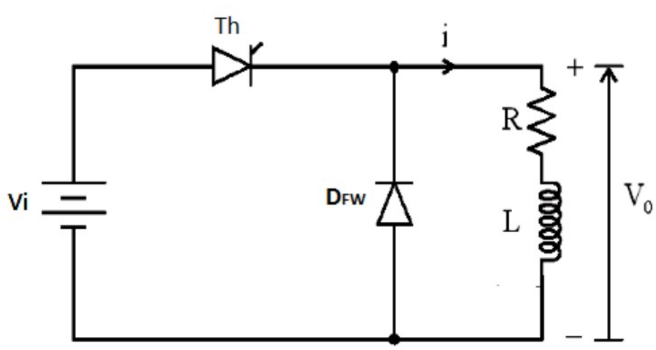


Fig.9.4

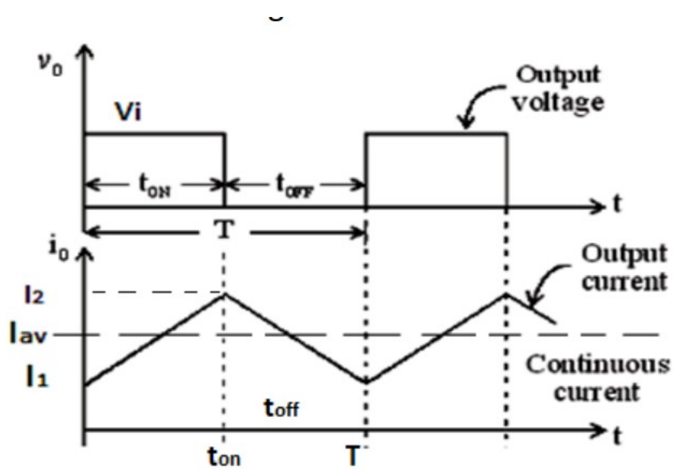


Fig.9.5

Referring to Fig.9.5:

- The current variation is almost linear and the current waveform becomes triangular.
- During the ON period , the equation govern the circuit is

$$V_d = Ri + L\frac{di}{dt}$$

Since $\frac{di}{dt}$ = constant, hence during ON period:

$$\frac{di}{dt} = \frac{I_2 - I_1}{t_{on}} = \frac{\Delta I}{t_{on}}$$

Where ΔI is the peak – to –peak of the load current .Thus the equation of the current is given by:

$$i_1 = I_1 + \frac{\Delta \mathrm{I}}{\gamma T}t \qquad\qquad 0 \leq t \ \leq t_{on}$$

Where $\gamma = \frac{t_{on}}{T}$

During the off period:

$$\frac{di}{dt} = \frac{I_1 - I_2}{t_{off}} = -\frac{\Delta I}{t_{off}} = -\frac{\Delta \mathrm{I}}{T - t_{on}} = -\frac{\Delta \mathrm{I}}{T - \gamma T} = -\frac{\Delta \mathrm{I}}{(1-\gamma)T}$$

Hence, during the off the equation of the current is

$$i_2 = I_2 - \frac{\Delta \mathrm{I}}{(1-\gamma)T}(t - t_{on}) \qquad t_{on} \le t \le T$$

The average value of the output current is

$$I_{av} = \frac{1}{T}\left[\frac{1}{2}t_{on}(I_2 - I_1) + \frac{1}{2}t_{off}(I_2 - I_1) + I_1 T\right]$$

$$I_{av} = \frac{1}{2}(I_2 + I_1)$$

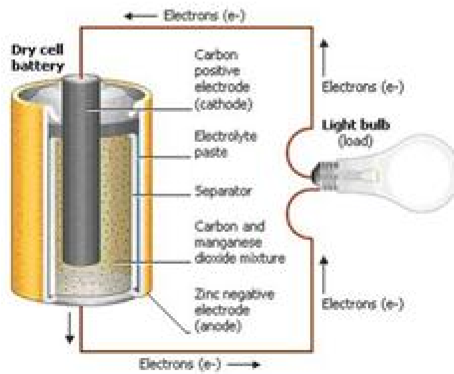
- **Batteries – Types & working**

Batteries are the most common power source for basic handheld devices to large scale industrial applications. A battery can be defined as; it is a combination of one or more electrochemical cells that are capable of converting stored chemical energy into electrical energy.

- **Working of Battery:**

A battery is a device, which consists of a various voltaic cells. Each voltaic cell consists of two half cells connected in series by a conductive electrolyte holding anions and cat ions. One half-cell includes electrolyte and the electrode to which anions move, i.e. the anode or negative electrode; the other half-cell includes electrolyte and the electrode to which cat ions move, i.e. the cathode or positive electrode.

In the redox reaction that powers the battery, reduction occurs to cations at the cathode, while oxidation occurs to anions at the anode. The electrodes do not touch one another but are electrically connected by the electrolyte. Mostly the half cells have different electrolytes. All things considered every half-cell is enclosed in a container and a separator that is porous to ions but not the bulk of the electrolytes prevent mixing.



Each half cell has an electromotive force (Emf), determined by its capacity to drive electric current from the interior to the exterior of the cell. The net emf of the cell is the difference between the emf of its half-cells. In this way, if the electrodes have emf and in other words, the net emf is the difference between the reduction potentials of the half-reactions.

- **How to maintain the Battery?**

To maintain the battery in good condition, battery equalization is necessary. Due to aging, all the cells do not charge similarly and some cells accept charge extremely fast while others charge gradually. Equalization can be done by marginally over charging the battery to allow the weaker cells also to charge completely. The terminal voltage of a completely charged battery is12V, automobile battery shows 13.8V in its terminals while a 12 volt tubular battery will show 14.8V. Automobile battery should be firmly fixed in the vehicle to avoid shake. Inverter battery should be placed on a wooden plank if possible.

- **Types of Batteries**

1) Primary Batteries:

As the name indicates these batteries are meant for single usage. Once these batteries are used they cannot be recharged as the devices are not easily reversible and active materials may not return to their original forms. Battery manufacturers recommend against recharge of primary cells.

Some of the examples for the disposable batteries are the normal AA, AAA batteries which we use in wall clocks, television remote etc. Other name for these batteries is disposable batteries.

2) Secondary Batteries:

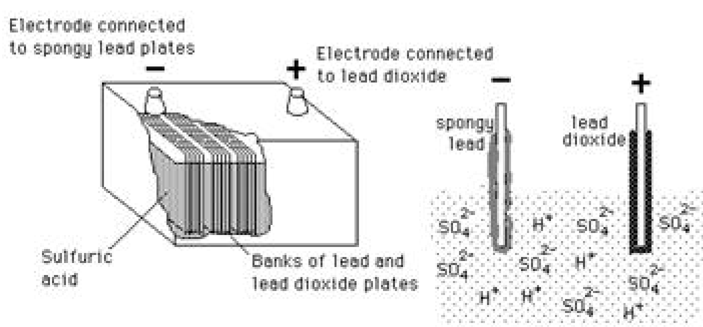
Secondary batteries are also called as rechargeable batteries. These batteries can be used and recharges simultaneously. They are usually assembled with active materials with active in the discharged state. Rechargeable batteries are recharged by applying electric current, which reverses the chemical reactions that occur during discharge. Chargers are devices which supply the required current.

Some examples for these rechargeable batteries are the batteries used in mobile phones, MP3 players etc. Devices such as hearing aids and wristwatches use miniature cells and in places such as telephone exchanges or computer data centre's, larger batteries are used.

Lead Acid Battery:

Lead Acid batteries are widely used in automobiles, inverters, backup power systems etc. Unlike tubular and maintenance free batteries, Lead Acid batteries require proper care and maintenance to prolong its life. The Lead Acid battery consists of a series of plates kept immersed in sulphuric acid solution. The plates have grids on which the active material is attached. The plates are

divided into positive and negative plates. The positive plates hold pure lead as the active material while lead oxide is attached on the negative plates.



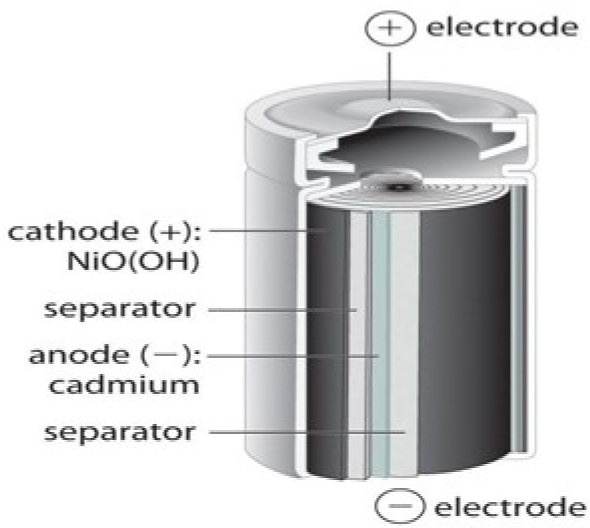
A completely charged battery can discharge its current when connected to a load. During the process of discharge, the sulphuric acid combines with the active materials on the positive and negative plates resulting in the formation of Lead sulphate. Water is the single most important step in maintaining a Lead Acid battery. The frequency of water depends on usage, charge method and operating temperature. During process, the hydrogen atoms from the sulphuric acid react with oxygen to form water.

This results in the release of electrons from the positive plates which will be accepted by the negative plates. This leads to the formation of an electric potential across the battery. The electrolyte in the Lead Acid battery is a mixture of Sulphuric acid and water which has a specific gravity. Specific gravity is the weight of the acid-water mixture compared to equal volume of water. The specific gravity of pure ions free water is 1.

The lead-acid batteries provide the best value for power and energy per kilowatt-hour; have the longest life cycle and a large environmental advantage in that they are recycled at an extraordinarily high rate. No other chemistry can touch the infrastructure that exists for collecting, transporting and recycling lead-acid batteries.

Nickel Cadmium (Nicd) Battery:

The Nickel Cadmium batteries have the advantage of being recharged many times and possess a relatively constant potential during discharge and have more electrical and physical withstanding capacity. This battery uses nickel oxide for cathode, a cadmium compound for anode and potassium hydroxide solution as its electrolyte.



When the battery is charged, the chemical composition of the cathode is transformed and the nickel hydroxide changes to NIOOH. In the anode, formation of Cadmium ions take place from Cadmium Hydroxide. When battery is discharged, the cadmium reacts with NiOOH to form back nickel hydroxide and Cadmium Hydroxide.

Cd + 2H2O + 2NiOOH —> 2Ni(OH)2 + Cd(OH)2

➢ Low Tension Switches – SFU, MCB, MCCB, ELCB & RCCB

Switch Fuse units Switch Fuse units, or main switches as they are generally called are suitable for diverse applications, in motor control centers, in switchboards and as main switches in various equipments and machines.

L&T provides state of the art FN range of main switches that are safe to use, rate high on asthetics, and provide energy saving fuses.

The main functions of switchgear are:

1. Electrical protection;
2. Electrical isolation of sections of an installation;
3. Local or remote switching.

Electrical protection against	Isolation	Control
1. Overload currents short-circuit currents insulation failure	1. Isolation clearly indicated by an authorized fail-proof mechanical indicator 2. A gap or interposed insulating barrier between the open contacts, clearly visible.	1. Functional switching 2. Emergency switching 3. Emergency stopping 4. Switching off for mechanical maintenance

These functions are summarized below in table H2-1.

Electrical protection at low voltage is (apart from fuses) normally incorporated in circuit breakers, in the form of thermal-magnetic devices and/or residual-current-operated tripping devices (less-commonly, residual-voltage-operated devices – acceptable to, but not recommended by IEC).

In addition to those functions shown in table H2-1, other functions, namely:

- Over-voltage protection;
- Under-voltage protection is provided by specific devices (lightning and various other types of voltage-surge arrester; relays associated with: contactors, remotely- controlled circuit breakers, and with combined circuit breaker/isolators… and so on).

Difference between MCB, MCCB, ELCB, RCCB and Its Characteristics

Electrical circuit breaker is a one kind of switching device which can be activated automatically as well as manually to control and protect an electrical power system respectively. As the current power system deals with vast currents, the special notice should be given throughout designing of circuit breaker to secure break of arc produced during the process of the circuit breaker. This was the fundamental definition of circuit breakers. These have been divided into a various types based on special categories they have been subdivided into.

1. **MCB - Miniature Circuit Breaker**

MCB is an electromechanical device which guards an electrical circuit from an over current, that may effect from short circuit, overload or imperfect design. This is a better option to a Fuse since it doesn't require alternate once an overload is identified. An MCB can be simply rearranged and thus gives a better operational protection and greater handiness without incurring huge operating cost. The operating principle of MCB is simple.

An MCB function by interrupting the stability of electrical flow through the circuit once an error is detected. In simple conditions this circuit breaker is a switch which routinely turns off when the current flows through it and passes the maximum acceptable limit. Generally, these are designed to guard against over current and overheating.

MCB is substituting the rewirable switch-fuse units for low power domestic and industrial applications in a very quick manner. In wiring system, the MCB is a blend of all three functions such as protection of short circuit, overload and switching. Protection of overload by using a bimetallic strip & short circuit protection by used solenoid.

These are obtainable in different pole versions like single, double, triple pole & four poles with neutral poles if necessary. The normal current rating is ranges from 0.5-63 A with a symmetrical short circuit breaking capacity of 3-10 KA, at a voltage level of 230 or 440V.

Characteristics of MCB

The characteristics of an MCB mainly include the following

- Rated current is not more than 100 amperes
- Normally, trip characteristics are not adjustable
- Thermal/thermal magnetic operation

2. MCCB-Molded Case Circuit Breaker

The MCCB is used to control electric energy in distribution n/k and is having short circuit and overload protection. This circuit Breaker is an electromechanical device which guards a circuit from short circuit and over current. They offer short circuit and over current protection for circuits ranges from 63 Amps-3000 Amps. The primary functions of MCCB is to give a means to manually open a circuit, automatically open a circuit under short circuit or overload conditions. In an electrical circuit, the over current may result faulty design

The MCCB is an option to a fuse since it doesn’t need an alternate once an overload is noticed. Unlike a fuse, this circuit breaker can be simply reset after a mistake and offers enhanced operator safety and ease without acquiring operating cost. Generally, these circuits have thermal current for over current and the magnetic element for short circuit release to work faster.

Characteristics of MCCB

The characteristics of an MCCB mainly include the following

- The range of rated current us up to 1000 amperes
- Trip current may be adjusted
- Thermal/thermal magnetic operation

3. ELCB - Earth Leakage Circuit Breaker

The ELCB is used to protect the circuit from the electrical leakage. When someone gets an electric shock, then this circuit breaker cuts off the power at the time of 0.1 secs for protecting the personal safety and avoiding the gear from the circuit against short circuit and overload.

ELCB is a security device used in electrical system with high Earth impedance to avoid shock. It notices small stray voltages on the metal fields of electrical gear, and interrupt the circuit if an unsafe voltage is detected. The main principle of Earth leakage protectors is to stop injury to humans and nature due to electric shock.

This circuit breaker is a specialized kind of latching relay that has structures incoming mains power connected through its switching contacts so that this circuit breaker disconnects the power supply in an unsafe condition.

The ELCB notices fault currents from live to the ground wire inside the installation it guards. If enough voltage emerges across the sense coil in the circuit breaker, it will turn off the supply, and stay off until reset by hand. A voltage-sensing earth leakage circuit breaker doesn’t detect fault currents from exist to any other ground body.

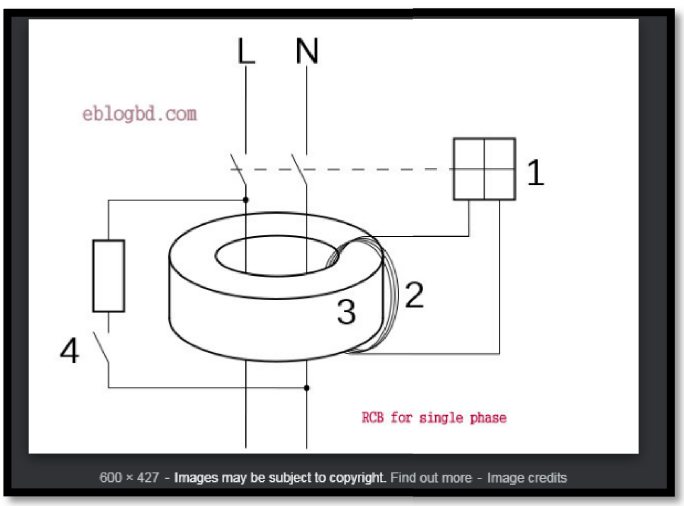
Characteristics of ELCB

The characteristics of an ELCB mainly include the following

- This circuit breaker connects the phase, earth wire and neutral
- The working of this circuit breaker depends on current leakage

4. RCCB (Residual Current Circuit Breaker)

A RCCB is essential current sensing equipment used to guard a low voltage circuit from the fault. It comprises of a switch device used to turn off the circuit when a fault occurs in the circuit. RCCB is aimed at guarding a person from the electrical shocks. Fires and electrocution are caused due to the wrong wiring or any earth faults. This **type of circuit breaker** is used in situations where there is a sudden shock or fault happening in the circuit.



For instance, a person suddenly enters in contact with an open live wire in an electrical circuit. In that situation, in the absence of this circuit breaker, a ground fault may occur and an individual is at the hazardous situation of receiving a shock. But, if the similar circuit is defended with the circuit breaker, it will tour the circuit in a second therefore, avoiding a person from the electric shock. Therefore, this circuit breaker is good to **install in an electrical circuit.**

Characteristics of RCCB

The characteristics of an RCCB mainly include the following

- Both wires phase and neutral are connected through RCCB
- Whenever there is any ground fault occurs, then it trips the circuit
- The amount of current supplies through the line should go back through neutral
- These are a very effective type of shock protection

APPLICATIONS :

→ **Applications of Kirchhoff's Laws**

- They can be used to analyze any electrical circuit.
- Computation of current and voltage of complex circuits.

→ **Applications of Thevenin's theorem**

- In our day-to-day life, whenever we overload a voltage source e.g. domestic supply or a battery, we observe a dip in voltage. This is basically an application of thevenins theorem, in the most observable form.
- Any practical voltage source can be represented by an ideal voltage source in series with a resistance (or impedance). When a current is drawn from the source, some voltage drop takes place across the series impedance, and therefore, terminal voltage falls.

→ **Applications of Norton's theorem**

One very useful application of Norton's theorem is in solving the problem of parallel generators having unequal emf's and unequal internal impedances. All generators (voltage generators) are converted into current generators by applying Norton's theorem. Then, these current generators can be combined easily to form one single current generator with only one impedance connected across it. Now, the current generator is converted back into voltage generator, using thevenins theorem. Thus, finally we get one single voltage generator with a single series impedance.

→ **Applications of Superposition theorem**

Superposition theorem provides easy solution when a circuit is energized by a variety of sources. Consider a circuit energized by two AC sources having different frequencies or two sources having different voltage or current waveforms. Or a circuit energized by a voltage source and a current source. Such problems can be solved using superposition theorem i.e. considering one source at a time and then adding the responses to find out currents and voltages in various parts of the circuit.

MCQ POST TEST :

1. A voltage across a series resistor circuit is proportional to?

a) The amount of time the circuit was on for
b) The value of the resistance itself
c) The value of the other resistances in the circuit
d) The power in the circuit

2. Many resistors connected in series will?

a) **Divide the voltage proportionally among all the resistors**
b) Divide the current proportionally
c) Increase the source voltage in proportion to the values of the resistors
d) Reduce the power to zero

3. What is the voltage measured across a series short?

a) Infinite
b) Zero
c) The value of the source voltage
d) Null

4. What happens to the current in the series circuit if the resistance is doubled?

a) It becomes half its original value
b) It becomes double its original value
c) It becomes zero
d) It becomes infinity

5. Batteries are generally connected in______

a) Series
b) Parallel
c) Either series or parallel
d) Neither series nor parallel

6. The value of a given waveform at any instant time is termed as

a) Waveform
b) **Instantaneous value**
c) Cycle
d) Period

7. The maximum instantaneous value measured from zero value is known as?

a) **Peak value**
b) Peak to peak value
c) Cycle
d) Period

8.The maximum variation between the maximum positive and the maximum negative value is known as?

a) Peak value
b) **Peak to peak value**
c) Cycle
d) Period

9. RMS stands for

a) **Root Mean Square**
b) Root Mean Sum
c) Root Maximum sum
d) Root Minimum Sum

10. What is the effective value of current?

a) **RMS current**
b) Average current
c) Instantaneous current
d) Total current

11. The function of transformer is to

a) Convert AC to DC
b) Convert DC to AC
c) Step down or up the DC voltages and currents
d) **Step down or up the AC voltages and currents**

12. Transformers windings are generally made of

a) Steel
b) Iron
c) **Copper**
d) Steel iron alloy

13. An induction motor can be said analogous to

a) transformer
b) Synchronous motor
c) Universal motor
d) Stepper motor

14.The external resistance can be inserted in rotor circuit of

a) Wound rotor induction motor
b) Slip ring induction motor
c) Wound rotor as slip ring induction motor
d) Neither of motors

15. A step - down choppers can be used in

a) Electric traction

b) Electric vehicles
c) Machine tools
d) **All of these**

16. Choppers is a
a) AC - DC converters
b) AC - AC converters
c) DC - AC converters
d) **DC - DC converters**

17. A chopper may be thought as a
a) Inverter with DC input
b) DC equivalent of an AC transformer
c) Diode rectifier
d) DC equivalent of an induction motor

18. The fault clearing time of a circuit breaker is usually
a) few minutes
b) few seconds
c) one second
d) **few cycles of supply voltage**

19. A circuit breaker is
a) power factor correcting device
b) a device to neutralize the effect of transients
c) a waveform correcting device
d) a current interrupting device

20. If energy is taken from the AC side of the inverter and sends it back into the DC side, then it is known as

a) Motoring mode operation
b) Braking mode operation
c) Regenerative mode operation
d) None of these

CONCLUSION :

After the successful completion of the course, students will be able to

- Understand and analyze basic electric and magnetic circuits
- Explain the basic electrical quantities and laws.
- Understand the working principles of electrical machines and power converters.
- Explain the construction, types and applications of electrical machines.
- Study the working principles of power converters
- Introduce the components of low voltage electrical installations and its applications.

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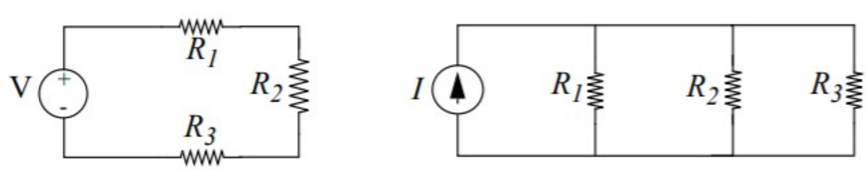
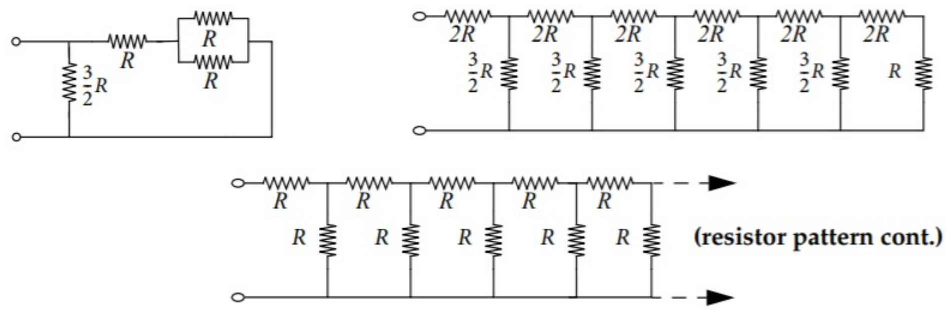
ASSIGNMENTS :

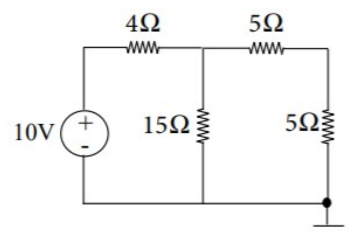
1. For both networks shown below, find the voltage across and the current through each element in the network. Be sure to make the polarity of the voltages and currents clear. Also, find the power generated or dissipated by each network element, and show that energy is conserved in total over the network.



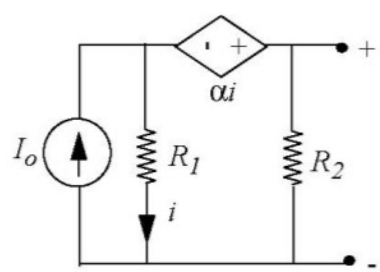
2. Find the equivalent resistance of the following networks as viewed from their ports.



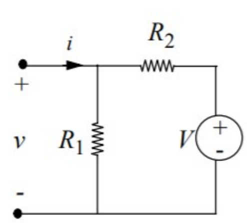
3. Determine the power consumed by the 5Ω resistor in the network shown below.



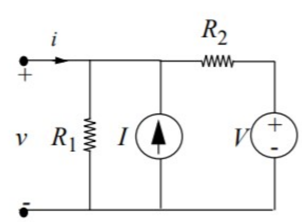
4. Determine the Thevenin equivalent of the following circuit. Note that it contains a dependent voltage source, and that the parameter α has units of Ohms.



5. Find the Thevenin and Norton equivalents of the following networks, and graph their i−v relations as viewed from their ports. (Hint: use superposition for Network B.)



Network (A)



Network (B)