1.1. Define following terms

(a) Current

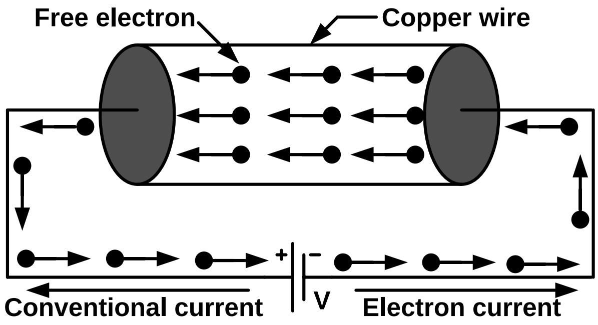


Figure 1.1Concept of electric current

- Flow of electron in closed circuit is called current.
- Amount of charge passing through the conductor in unit time also called current.
- Unit of current is charge/second or Ampere (A).

$$I = \frac{Q}{t}$$

Where, I = Current

Q = Charge

t = Time

(b) Potential or Voltage

- The capacity of a charged body to do work is called potential.
- Unit of potential is joule/coulomb or Volt (V).

$$V = \frac{W}{Q}$$

Where, V= Potential or Voltage

W= Workdone

(c) Potential difference

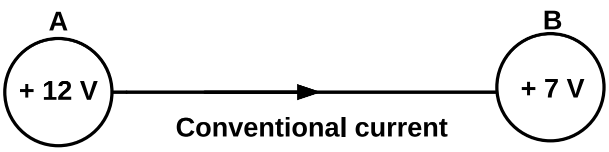


Figure 1. 1Potential differences

- The difference of electrical potential between two charged bodies is called potential difference.
- Unit of Potential Difference is Volt (V).
- If potential of body A is +12V and potential of body B is +7V then potential difference is +5V.
  i.e. (+12V) - (+7V) = +5V

(d) Electro Motive Force (emf)

- The force is required to move electron from negative terminal to positive terminal of electrical source in electrical circuit is called emf.
- Unit of emf is volt (V).
- Emf is denoted as ε.

(e) Energy

- Ability to do work is called energy.
- Unit of energy is Joule or Watt-sec or Kilowatt-hour (KWh).
- 1KWh is equal to 1 Unit.

$$W = P \times t = VIt = I^2Rt = \frac{V^2t}{R}$$

$Where,\ W$=Energy

P =Power

t =Time

(f) Power

- Energy per unit in time is called power.
- Unit of Power is Joule/Second or Watt (W).

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

(g) Resistance

- Property of a material that opposes the flow of electron is called resistance.
- Unit of resistance is Ohm (Ω).

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

$Where,\ R =$ Resistance

(h) Conductance

- Property of a material that allows flow of electron.
- It is reciprocal of resistance.
- Unit of conductance is (Ω^{-1}) or mho or Siemens(S).

$$G = \frac{1}{R}$$

$Where,\ G =$Conductance

(i) Resistivity or Specific Resistance

- Amount of resistance offered by 1m length of wire of 1m^2 cross-sectional area.
- Resistivity is denoted as a ρ.
- Unit of Resistivity is Ohm-meter (Ω-m).

$$R \propto \frac{l}{a}$$

$$R = \rho \frac{l}{a}$$

$$\rho = \frac{Ra}{l}$$

$Where, R =$ Resistance

$\rho =$ Resistivity

$l =$ Length of wire

$a =$ Cross section area of wire

(j) Conductivity

- Ability of a material to allow flow of electron of a given material for 1 m length & 1 m^2cross-sectional area is called conductivity. Unit of conductivity is$\Omega^{-1}m^{-1}$ or Siemens m^{-1}.

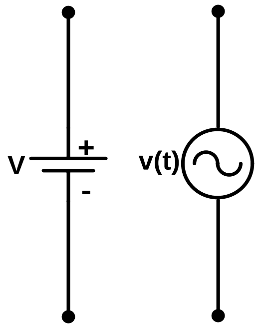
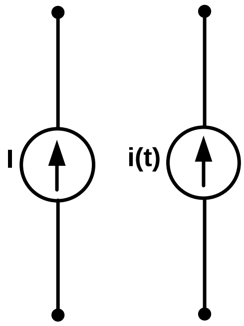
$$\sigma = \frac{1}{\rho}$$

$Where, \sigma =$ Conductivity

1.2. Explain types of electrical energysource

- Electrical source is an element which supplies energy to networks. There are two types of electrical sources.

(a) Independent sources

Independent voltage source	Independent current source
 *Figure 1. 2Independent voltage source* • It is a two terminal element that provide a specific voltage across its terminal. • The value of this voltage at any instant is independent of value or direction of the current that flow through it.	 *Figure 1. 3Independent current source* • It is two-terminal elements that provide a specific current across its terminal. • The value and direction of this current at any instant is independent of value or direction of the voltage that appears across the terminal of source

(b) Dependent sources

Voltage controlled voltage source (VCVS)

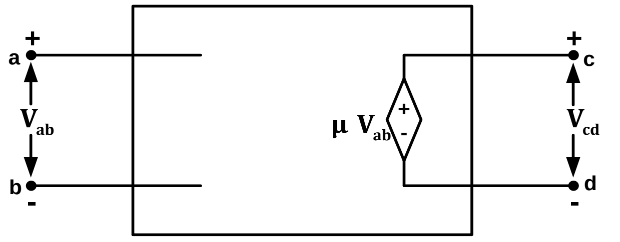


Figure 1.5VCVS

- Voltage controlled voltage source is four terminal network components that established a voltage V_{cd} between two-point c and d.

  $V_{cd} = \mu V_{ab}$

- The voltage V_{cd} depends upon the control voltage V_{ab} and μ is constant so it is dimensionless.
- μ is known as a voltage gain.

Voltage controlled current source (VCCS)

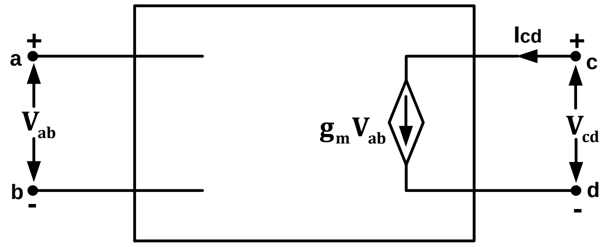


Figure 1.6VCCS

- Voltage controlled current source is four terminal network components that established a current i_{cd} in the branch of circuit.

  $i_{cd} = g_m V_{ab}$

- i_{cd} depends only on the control voltage V_{ab} and constant g_m ,is called trans conductance or mutual conductance.
- Unit of transconductance is Ampere/Volt or Siemens(S).

Current controlled voltage source (CCVS)

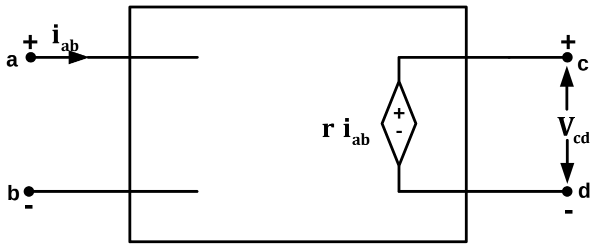


Figure 1.7CCVS

- Current controlled voltage source is four terminal network components that established a voltage V_{cd} between two-point c and d.

  $V_{cd} = r i_{ab}$

- V_{cd} depends on only on the control current i_{ab} and constant r and r is called trans resistance or mutual resistance.
- Unit of transresistance is Volt/Ampere or Ohm (Ω).

Current controlled current source (CCCS)

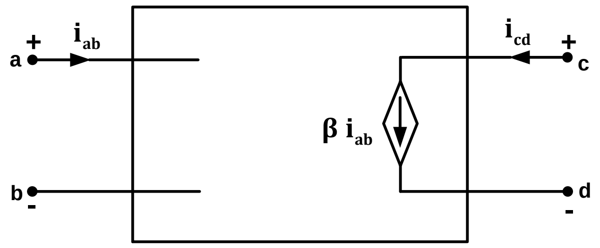


Figure 1.8CCCS

- Current controlled current source is four terminal network components that established a current I_{cd} in the branch of circuit.

  $i_{cd} = \beta i_{ab}$

- i_{cd} depends on only on the control current i_{ab} and constant β and β is called current gain. Current gain is constant.
- Current gain is dimensionless.

1.3. Explain source conversion

- A voltage source with a series resistor can be converted into an equivalent current source with a parallel resistor. Conversely, a current source with a parallel resistor can be converted into a voltage source with a series resistor.
- Open circuit voltages in both the circuits are equal and short circuit currents in both the circuit are equal.Source transformation can be applied to dependent source as well.

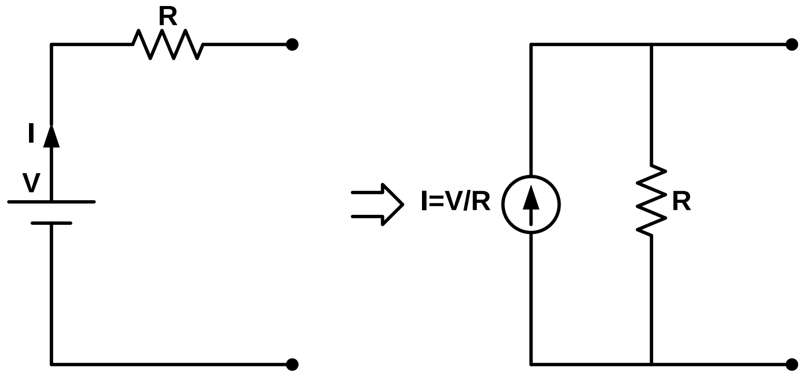
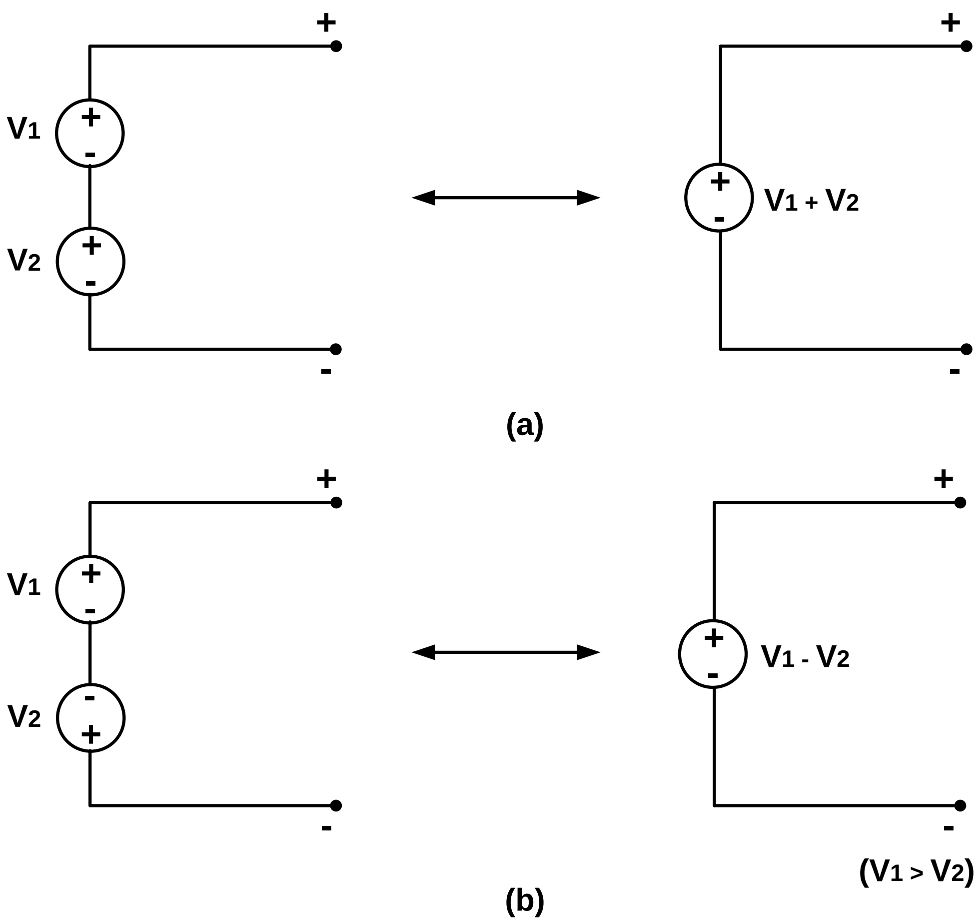
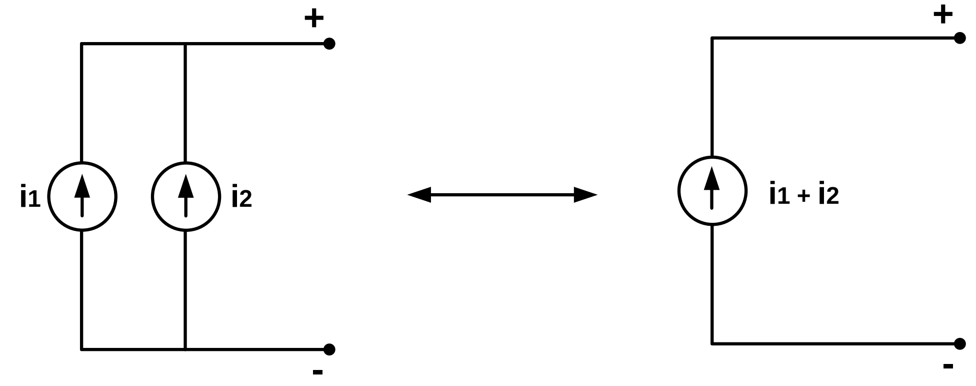


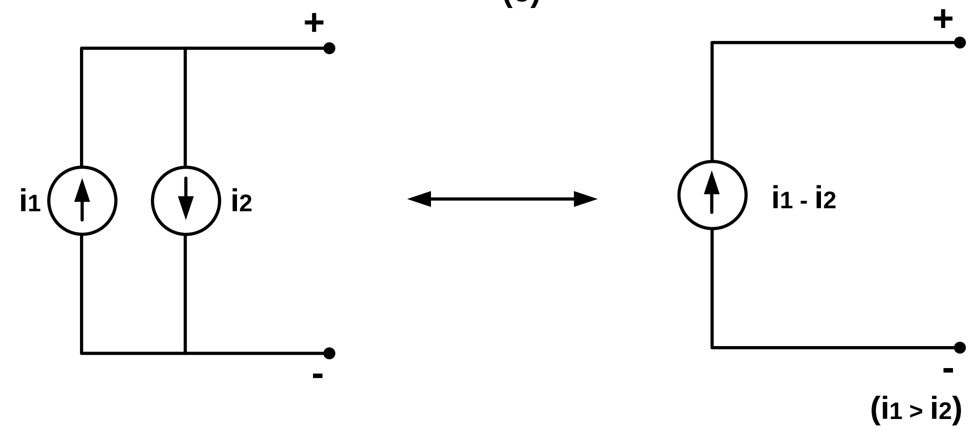
Figure 1. 9Source conversion

Network simplification techniques

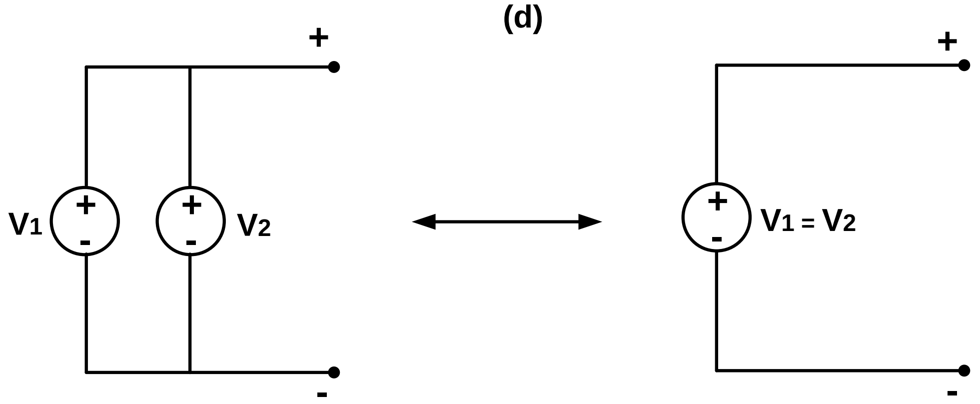




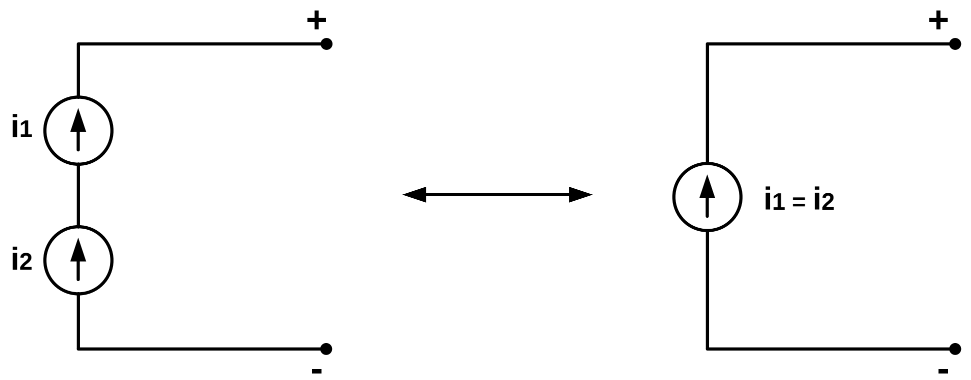
(c)



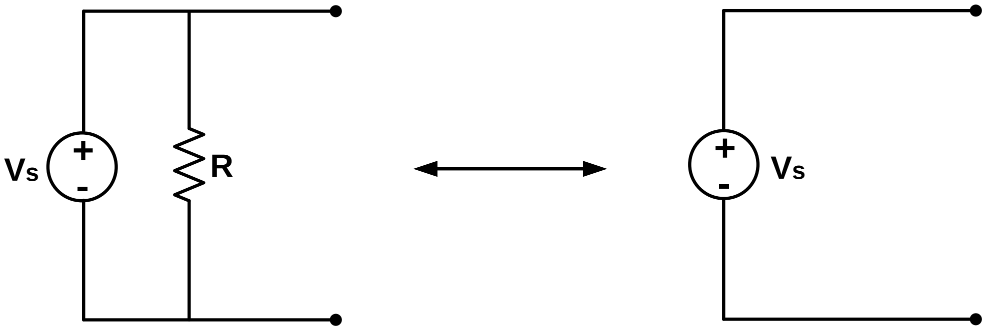
(d)



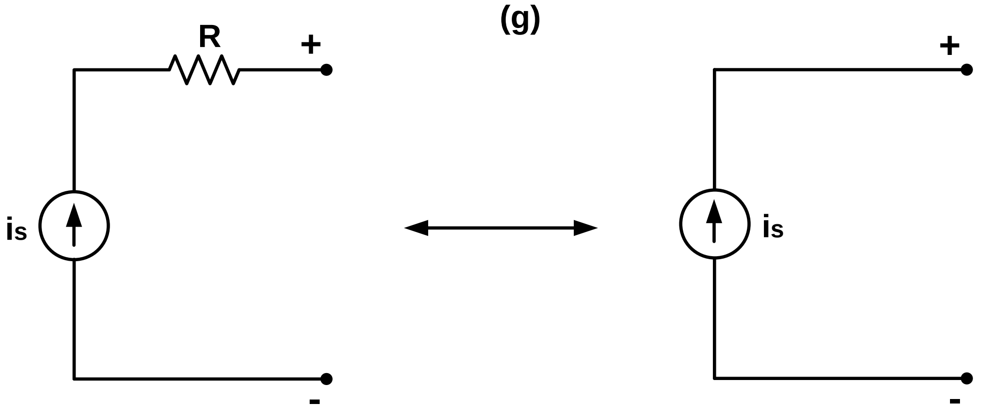
(e)



(f)



(g)



(h)

Figure 1.10Rules under which source may be combined and separated

1.4. Explain ideal electrical circuit element.

- There are major three electrical circuit elements which are discussed below.

(a) Resistor

- Resistor is element which opposes the flow of current.

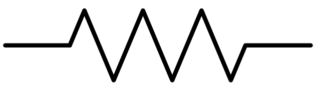


Figure 1.11Resistor

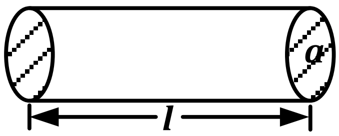


Figure 1.12Conductor

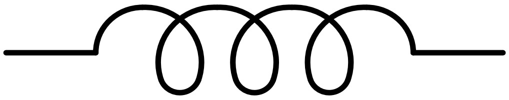
- Resistance is property of material which opposes the flow current. It is measured in Ohms (Ω).
- Value of resistance of conductor is
  - ✓ Proportional to its length.
  - ✓ Inversely proportional to the area of cross section.
  - ✓ Depends on nature of material.
  - ✓ Depends on temperature of conductor.

$$R \propto \frac{l}{a}$$

$$R = \frac{\rho l}{a}$$

(b) Inductor

- An inductor is element which store energy in form of magnetic field.
- The property of the coil of inducing emf due to the changing flux linked with it is known as inductance of the coil.
- Inductance is denoted by L and it is measured in Henry (H).



1.13Inductor

- Value of inductance of coil is
  - ✓ Directly proportional to the square of number of turns.
  - ✓ Directly proportional to the area of cross section.
  - ✓ Inversely proportional to the length.
  - ✓ Depends on absolute permeability of magnetic material.

$$\Phi = \frac{F}{S} = \frac{NI}{S} = \frac{NI}{\dfrac{l}{\mu_0 \mu_r A}} = \frac{NI\mu_0 \mu_r A}{l}$$

$$Now, L = \frac{N\Phi}{I} = \frac{N\left(\dfrac{NI\mu_0 \mu_r A}{l}\right)}{I} = \frac{N^2 \mu_0 \mu_r A}{l}$$

Where, L = Inductance of coil

N = Number of turns of coil

Φ = Flux link in coil

F = Magneto motive force(MMF)

I = Current in the coil

l = Mean length of coil

μ_0 = Permiability of free space

μ_r = Relative permiability of magnetic material

A = Cross sectional area of magnetic material

(c) Capacitor

- Capacitor is an element which stored energy in form of charge.
- Capacitance is the capacity of capacitor to store electric charge.
- It is denoted by C and measured in Farad (F).

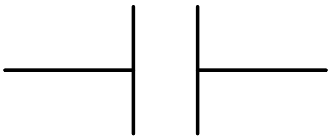


Figure 1.14Capacitor

- Value of capacitance is
  - ✓ Directly proportional to the area of plate.
  - ✓ Inversely proportional to distance between two plates.
  - ✓ Depends on absolute permittivity of medium between the plates.

$$C \propto \frac{A}{d}$$

$$C = \frac{\varepsilon A}{d}$$

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d}$$

Where, C =Capacitance of capacitor

A =Cross sectional area of plates

d =Distance between two plates

ε = Abolute Permittivity

ε_0 = Permittivity of free space

ε_r = Relative permittivity of dielectric material

1.5. Explain Ohm's law and its limitations.

- Current flowing through the conductor is directly proportional to the potential difference applied to the conductor, provided that no change in temperature.

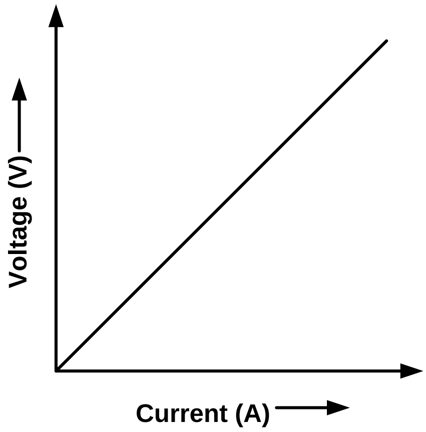


Figure 1.15Change in current w.r.t change in voltage for conducting material

$$V \propto I$$

$$\therefore V = IR$$

- Where R is constant which is called resistance of the conductor.

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

- Limitations of Ohm's Law:
  - ✓ It cannot be applied to non-linear device e.g. Diode, Zener diode etc.
  - ✓ It cannot be applied to non-metallic conductor e.g. Graphite, Conducting polymers
  - ✓ It can only be applied in the constant temperature condition.

1.6. State and explain the Kirchhoff's current and voltage laws

(a) Kirchhoff's current law (KCL)

- **Statement**:
  "Algebraic sum of all current meeting at a junction is zero"
- Let, Suppose

- ✓ Branches are meeting at a junction 'J'
- ✓ Incoming current are denoted with (+ve) sign
- ✓ Outgoing currents are denoted with (-ve) sign

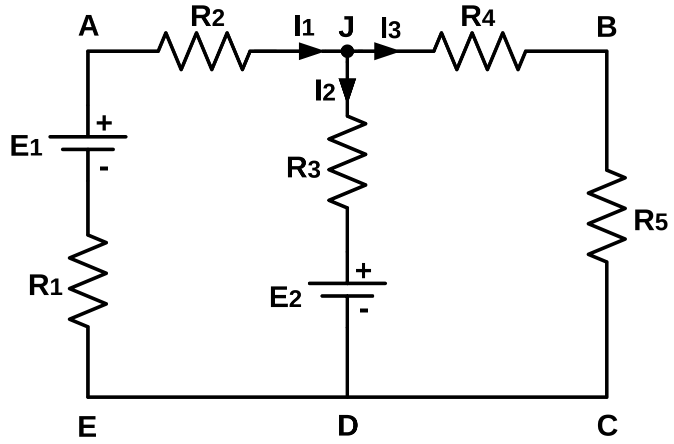


Figure 1.16Kirchhoff's law diagram

- Then,

$$\sum I = 0$$
$$(+I_1)+(-I_2)+(-I_3)=0$$
$$I_1 - I_2 - I_3 = 0$$
$$I_1 = I_2 + I_3$$
$$\therefore \textit{Incoming current} = \textit{Outgoing current}$$

(b) Kirchhoff's voltage law (KVL)

- **Statement**:
  "Algebraic sum of all voltage drops and all emf sources in any closed path is zero"
- Let, Suppose
  - ✓ Loop current in clockwise or anticlockwise direction
  - ✓ Circuit current and loop current are in same direction than voltage drop is denoted by (-ve) sign.
  - ✓ Circuit current and loop current are in opposite direction than voltage drop is denoted by (+ve) sign.
  - ✓ Loop current move through (+ve) to (-ve) terminal of source than direction of emf is (-ve).
  - ✓ If Loop current move through (-ve) to (+ve) terminal of source than direction of emf is (+ve).

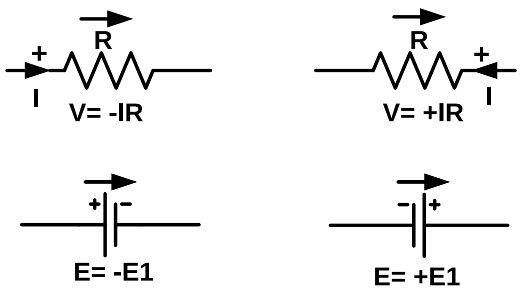


Figure 1.17Sign convention for Kirchhoff's voltage law

$$\therefore \sum IR + \sum E = 0$$

KVL to loop AJDEA

$$-I_1R_2 - I_2R_3 - E_2 - I_1R_1 + E_1 = 0$$

KVL to loop JBCDJ

$$-I_3R_4 - I_3R_5 + E_2 + I_2R_3 = 0$$

1.7. Explain series and parallel combination of resistor

Series combination of resistor

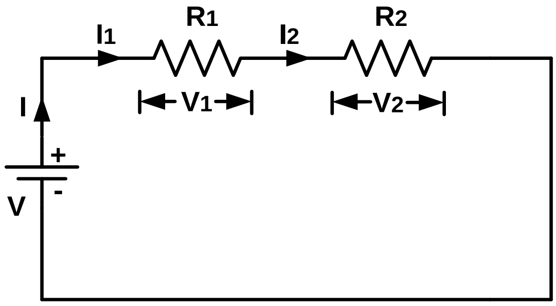


Figure 1.18Series combination of resistors

$$Here, I_1 = I_2 = I$$

As per KVL,

$$V = V_1 + V_2$$

$$V = IR_1 + IR_2$$

$$V = I(R_1 + R_2)$$

$$\frac{V}{I} = (R_1 + R_2)$$

$$R_{eq} = R_1 + R_2$$

For n resistor are connected in series

$$R_{eq} = R_1 + R_2 + R_3 + ... + R_n$$

- Value of equivalent resistance of series circuit is bigger than the biggest value of individual resistance of circuit.

Parallel combination of resistor

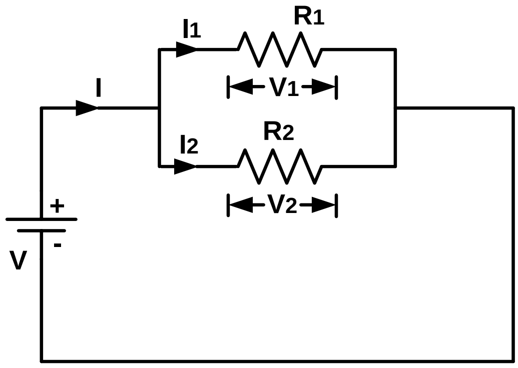


Figure 1.19Parallel combinations of resistors

$$Here, V_1 = V_2 = V$$

As per KCL,

$$I = I_1 + I_2$$

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

$$I = V\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\frac{I}{V} = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\frac{1}{R_{eq}} = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

For n resistor are connected in Parallel

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

- Value of equivalent resistance of parallel circuit is smaller than the smallest value of individual resistance of circuit.

1.8. Explain Voltage divider law and current divider Law.

Voltage Divider Law

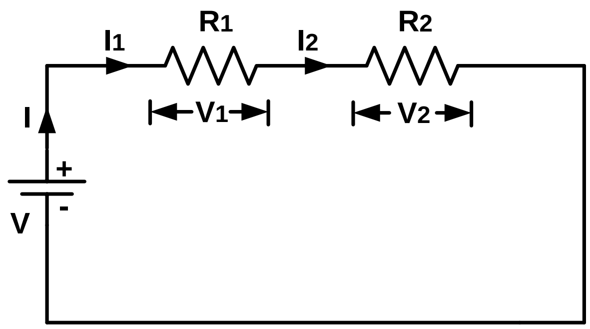


Figure 1.20Voltage divider circuit

$$Here, I_1 = I_2 = I$$

As per KVL,

$$V = V_1 + V_2$$

$$V = I_1R_1 + I_2R_2$$

$$V = IR_1 + IR_2$$

$$V = I(R_1 + R_2)$$

$$I = I_1 = I_2 = \frac{V}{(R_1 + R_2)}$$

$$Now, V_1 = I_1R_1$$

$$V_1 = \frac{V}{R_1 + R_2}R_1$$

$$V_1 = V\left(\frac{R_1}{R_1 + R_2}\right)$$

$$Now, V_2 = I_2R_2$$

$$V_2 = \frac{V}{R_1 + R_2}R_2$$

$$V_2 = V\left(\frac{R_2}{R_1 + R_2}\right)$$

Current Divider Law

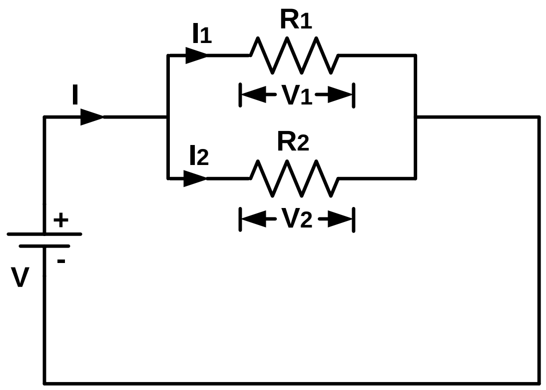


Figure 1.21Current divider circuit

$$Here, V_1 = V_2 = V$$

As per KCL,

$$I = I_1 + I_2$$

$$I = \frac{V_1}{R_1} + \frac{V_2}{R_2}$$

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

$$I = V\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\frac{I}{V} = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$V = V_1 = V_2 = I\left(\frac{R_1R_2}{R_1 + R_2}\right)$$

$$Now, I_1 = \frac{V_1}{R_1}$$

$$I_1 = \frac{I\left(\frac{R_1R_2}{R_1 + R_2}\right)}{R_1}$$

$$I_1 = I\left(\frac{R_2}{R_1 + R_2}\right)$$

$$Now, I_2 = \frac{V_2}{R_2}$$

$$I_2 = \frac{I\left(\frac{R_1R_2}{R_1 + R_2}\right)}{R_2}$$

$$I_2 = I\left(\frac{R_1}{R_1 + R_2}\right)$$

1.9. Derive the equation of delta to star and star to delta transformation

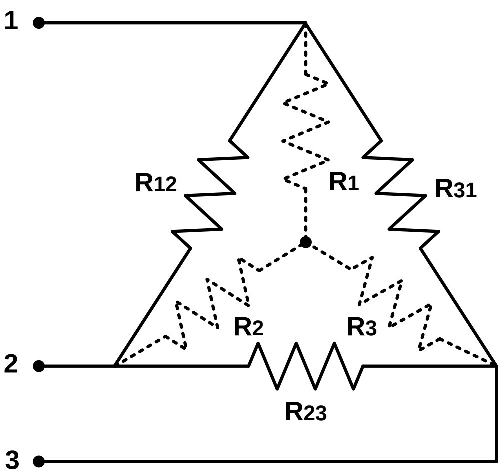


Figure 1.22Delta connected network

Resistance between terminal (1) & (2)

$$= R_{12} \parallel (R_{23} + R_{31})$$

$$= \frac{R_{12}(R_{23} + R_{31})}{R_{12} + R_{23} + R_{31}}$$

Resistance between terminal (2) & (3)

$$= R_{23} \parallel (R_{12} + R_{31})$$

$$= \frac{R_{23}(R_{12} + R_{31})}{R_{12} + R_{23} + R_{31}}$$

Resistance between terminal (3) & (1)

$$= R_{31} \parallel (R_{12} + R_{23})$$

$$= \frac{R_{31}(R_{12} + R_{23})}{R_{12} + R_{23} + R_{31}}$$

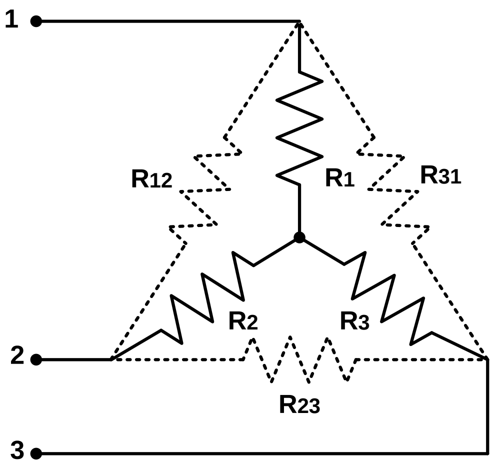


Figure 1.23Star connected network

Resistance between terminal (1) & (2)

$$= R_1 + R_2$$

Resistance between terminal (2) & (3)

$$= R_2 + R_3$$

Resistance between terminal (3) & (1)

$$= R_3 + R_1$$

Resistance between terminals (1) & (2) *in delta equal to resistance between terminals* (1) & (2) *in star*

$$R_1 + R_2 = \frac{R_{12}(R_{23} + R_{31})}{R_{12} + R_{23} + R_{31}} \qquad (i)$$

Similarly,

$$R_2 + R_3 = \frac{R_{23}(R_{12} + R_{31})}{R_{12} + R_{23} + R_{31}} \qquad (ii)$$

$$R_3 + R_1 = \frac{R_{31}(R_{12} + R_{23})}{R_{12} + R_{23} + R_{31}} \qquad (iii)$$

(a) Delta to star conversion

Simplify $(i) + (ii) - (iii)$ *on both the side of equations*

$$R_1 + R_2 + R_2 + R_3 - R_3 - R_1 = \frac{R_{12}(R_{23} + R_{31})}{R_{12} + R_{23} + R_{31}} + \frac{R_{23}(R_{12} + R_{31})}{R_{12} + R_{23} + R_{31}} - \frac{R_{31}(R_{12} + R_{23})}{R_{12} + R_{23} + R_{31}}$$

$$= \frac{(R_{12}R_{23} + R_{12}R_{31})}{R_{12} + R_{23} + R_{31}} + \frac{(R_{23}R_{12} + R_{23}R_{31})}{R_{12} + R_{23} + R_{31}} - \frac{(R_{31}R_{12} + R_{31}R_{23})}{R_{12} + R_{23} + R_{31}}$$

$$= \frac{(R_{12}R_{23} + R_{12}R_{31} + R_{23}R_{12} + R_{23}R_{31} - R_{31}R_{12} - R_{31}R_{23})}{(R_{12} + R_{23} + R_{31})}$$

$$2R_2 = \frac{2R_{12}R_{23}}{R_{12} + R_{23} + R_{31}}$$

$$R_2 = \frac{R_{12}R_{23}}{R_{12} + R_{23} + R_{31}}$$

$$Similarly\ ,\ R_1 = \frac{R_{12}R_{31}}{R_{12} + R_{23} + R_{31}}$$

$$R_3 = \frac{R_{23}R_{31}}{R_{12} + R_{23} + R_{31}}$$

(b) Star to delta conversion

Simplify $(i)(ii) + (ii)(iii) + (iii)(i)$ *on both the side of equation*

$$(R_1 + R_2)(R_2 + R_3) + (R_2 + R_3)(R_3 + R_1) + (R_3 + R_1)(R_1 + R_2)$$

$$= \left(\frac{R_{12}(R_{23} + R_{31})}{R_{12} + R_{23} + R_{31}}\right)\left(\frac{R_{23}(R_{12} + R_{31})}{R_{12} + R_{23} + R_{31}}\right) + \left(\frac{R_{23}(R_{12} + R_{31})}{R_{12} + R_{23} + R_{31}}\right)\left(\frac{R_{31}(R_{12} + R_{23})}{R_{12} + R_{23} + R_{31}}\right) + \left(\frac{R_{31}(R_{12} + R_{23})}{R_{12} + R_{23} + R_{31}}\right)\left(\frac{R_{12}(R_{23} + R_{31})}{R_{12} + R_{23} + R_{31}}\right)$$

$$R_1R_2 + R_1R_3 + R_2^2 + R_2R_3 + R_2R_3 + R_2R_1 + R_3^2 + R_3R_1 + R_3R_1 + R_3R_2 + R_1^2 + R_1R_2$$

$$= \left(\frac{R_{12}R_{23} + R_{12}R_{31}}{R_{12} + R_{23} + R_{31}}\right)\left(\frac{R_{23}R_{12} + R_{23}R_{31}}{R_{12} + R_{23} + R_{31}}\right) + \left(\frac{R_{23}R_{12} + R_{23}R_{31}}{R_{12} + R_{23} + R_{31}}\right)\left(\frac{R_{31}R_{12} + R_{31}R_{23}}{R_{12} + R_{23} + R_{31}}\right) + \left(\frac{R_{31}R_{12} + R_{31}R_{23}}{R_{12} + R_{23} + R_{31}}\right)\left(\frac{R_{12}R_{23} + R_{12}R_{31}}{R_{12} + R_{23} + R_{31}}\right)$$

$$3R_1R_2 + 3R_2R_3 + 3R_3R_1 + R_1^2 + R_2^2 + R_3^2$$

$$= \left(\frac{R_{23}^2R_{12}^2 + R_{12}R_{23}^2R_{31} + R_{12}^2R_{23}R_{31} + R_{12}R_{23}R_{31}^2}{(R_{12} + R_{23} + R_{31})^2}\right) + \left(\frac{R_{12}^2R_{23}R_{31} + R_{12}R_{23}^2R_{31} + R_{12}R_{23}R_{31}^2 + R_{23}^2R_{31}^2}{(R_{12} + R_{23} + R_{31})^2}\right) + \left(\frac{R_{12}^2R_{23}R_{31} + R_{12}^2R_{31}^2 + R_{12}R_{23}^2R_{31} + R_{12}R_{23}R_{31}^2}{(R_{12} + R_{23} + R_{31})^2}\right)$$

$$= \frac{R_{23}^2R_{12}^2 + R_{12}R_{23}^2R_{31} + R_{12}^2R_{23}R_{31} + R_{12}R_{23}R_{31}^2 + R_{12}^2R_{23}R_{31} + R_{12}R_{23}^2R_{31} + R_{12}R_{23}R_{31}^2 + R_{23}^2R_{31}^2 + R_{12}^2R_{23}R_{31} + R_{12}^2R_{31}^2 + R_{12}R_{23}^2R_{31} + R_{12}R_{23}R_{31}^2}{(R_{12} + R_{23} + R_{31})^2}$$

$$= \frac{(R_{12}R_{23}^2R_{31} + R_{12}^2R_{23}R_{31} + R_{12}R_{23}R_{31}^2 + R_{12}^2R_{23}R_{31} + R_{12}R_{23}^2R_{31} + R_{12}R_{23}R_{31}^2 + R_{12}^2R_{23}R_{31} + R_{12}R_{23}^2R_{31} + R_{12}R_{23}R_{31}^2) + (R_{23}^2R_{12}^2 + R_{23}^2R_{31}^2 + R_{12}^2R_{31}^2)}{(R_{12} + R_{23} + R_{31})^2}$$

$$= \frac{R_{12}R_{23}R_{31}(R_{23} + R_{12} + R_{31} + R_{12} + R_{23} + R_{31} + R_{12} + R_{23} + R_{31})}{(R_{12} + R_{23} + R_{31})^2} + \frac{(R_{23}^2R_{12}^2 + R_{23}^2R_{31}^2 + R_{12}^2R_{31}^2)}{(R_{12} + R_{23} + R_{31})^2}$$

$$= \frac{R_{12}R_{23}R_{31}(3R_{12} + 3R_{23} + 3R_{31})}{(R_{12} + R_{23} + R_{31})^2} + \left(\frac{R_{23}^2R_{12}^2}{(R_{12} + R_{23} + R_{31})^2} + \frac{R_{23}^2R_{31}^2}{(R_{12} + R_{23} + R_{31})^2} + \frac{R_{12}^2R_{31}^2}{(R_{12} + R_{23} + R_{31})^2}\right)$$

$$= \frac{3R_{12}R_{23}R_{31}(R_{12} + R_{23} + R_{31})}{(R_{12} + R_{23} + R_{31})^2} + \left(\frac{R_{23}^2R_{12}^2}{(R_{12} + R_{23} + R_{31})^2} + \frac{R_{23}^2R_{31}^2}{(R_{12} + R_{23} + R_{31})^2} + \frac{R_{12}^2R_{31}^2}{(R_{12} + R_{23} + R_{31})^2}\right)$$

$$= 3R_3R_{12} + R_2^2 + R_3^2 + R_1^2$$

Now equation become

$$3R_1R_2 + 3R_2R_3 + 3R_3R_1 + R_1^2 + R_2^2 + R_3^2 = 3R_3R_{12} + R_2^2 + R_3^2 + R_1^2$$

$$3R_1R_2 + 3R_2R_3 + 3R_3R_1 = 3R_3R_{12}$$

$$R_{12} = R_1 + R_2 + \frac{R_1R_2}{R_3}$$

Similarly

$$R_{23} = R_2 + R_3 + \frac{R_2R_3}{R_1}$$

$$R_{31} = R_3 + R_1 + \frac{R_3R_1}{R_2}$$

1.10. Explain Node analysis

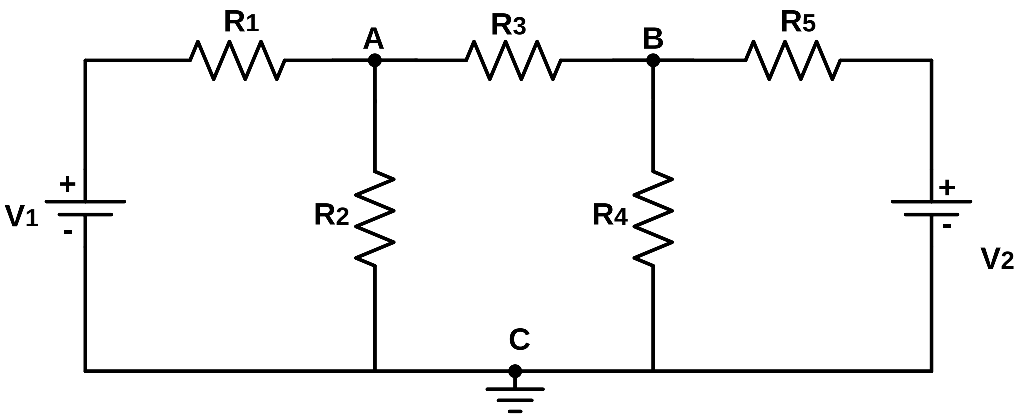


Figure 1.24Node analysis network

- **Node**: Node refers to any point on circuit where two or more circuit elements meet.
- Node analysis based on Kirchhoff's current law states that algebraic summation of currents meeting at junction is zero.
- Node C is taken as reference node in this network. If there are n nodes in any network, the number of equation to be solved will be (n-1).
- Node A,B and C are shown in given network and their voltages areV_A,V_B andV_C . Value of node V_C is zero because V_C is reference node.
- Steps to follow in node analysis:
  - ✓ Consider node in the network, assign current and voltage for each branch and node respectively.
  - ✓ Apply the KCL for each node and apply ohm's law to branch current.
  - ✓ Solve the equation for find the unknown node voltage.
  - ✓ Using these voltages, find the required branch currents.
- **Node A**

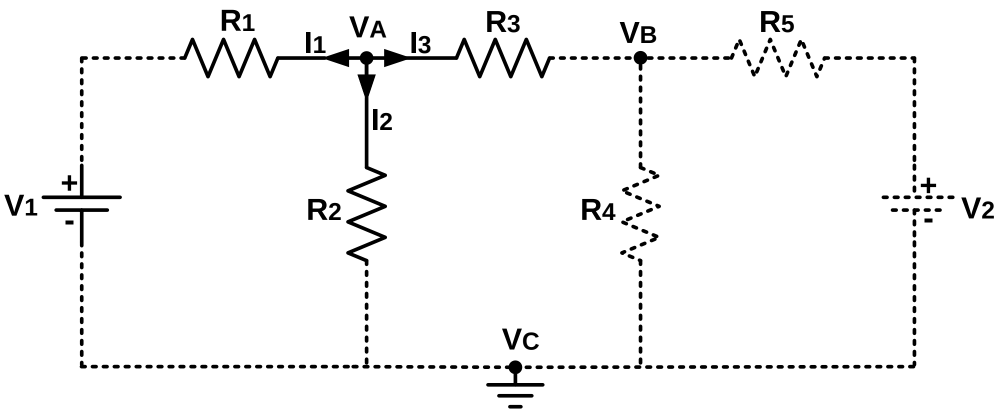


Figure 1.25Node analysis network for node A

Apply KCL at node A,

$$(-I_1)+(-I_2)+(-I_3)=0$$

$$I_1+I_2+I_3=0$$

$$\frac{V_A - V_1}{R_1}+\frac{V_A-V_C}{R_2}+\frac{V_A - V_B}{R_3}=0$$

$$V_A\left[\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}\right]+V_B\left[-\frac{1}{R_3}\right]=\frac{V_1}{R_1} \qquad (i)$$

- **Node B**

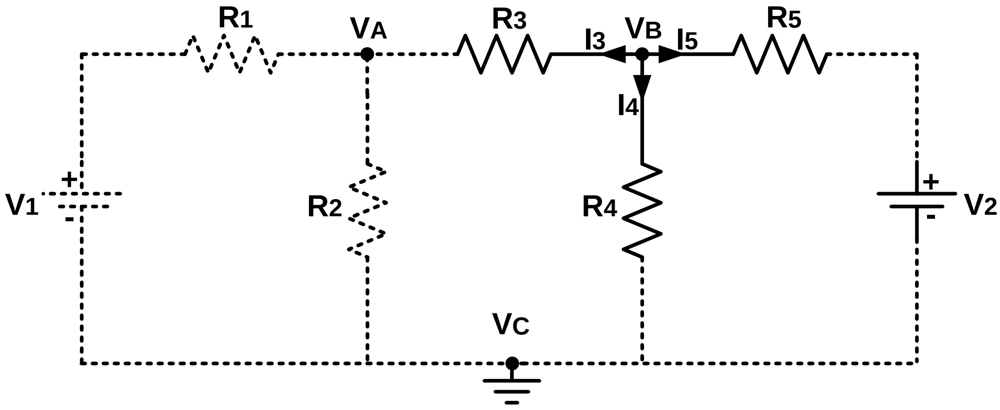


Figure 1.26Node analysis network for node B

Apply the KCL at node B,

$$(-I_3)+(-I_4)+(-I_5)=0$$

$$I_3+I_4+I_5=0$$

$$\frac{V_B - V_A}{R_3}+\frac{V_B-V_C}{R_4}+\frac{V_B - V_2}{R_5}=0$$

$$V_A\left[-\frac{1}{R_3}\right]+V_B\left[\frac{1}{R_3}+\frac{1}{R_4}+\frac{1}{R_5}\right]=\frac{V_2}{R_5} \qquad (ii)$$

From, equation (i) & (ii)

$$\begin{pmatrix} \frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3} & -\frac{1}{R_3} \\ -\frac{1}{R_3} & \frac{1}{R_3}+\frac{1}{R_4}+\frac{1}{R_5} \end{pmatrix}\begin{pmatrix} V_A \\ V_B \end{pmatrix}=\begin{pmatrix} \frac{V_1}{R_1} \\ \frac{V_2}{R_5} \end{pmatrix}$$

- One can easily find branch current of this network by solving equation (i) and (ii),if V_1 , V_2 and all resistance value are given.

1.11. Explain Mesh analysis

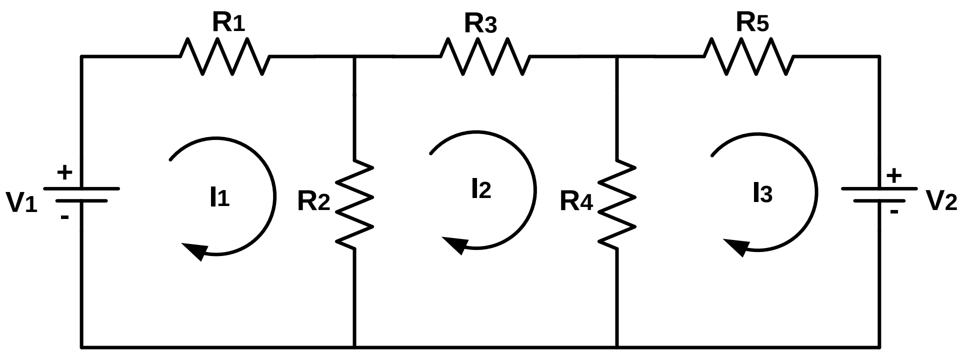


Figure 1.27Mesh analysis network

- **Mesh:** It is defined as a loop which does not contain any other loops within it.

- The current in different meshes are assigned continues path that they do not split at a junction into a branch currents.
- Basically, this analysis consists of writing mesh equation by Kirchhoff's voltage law in terms of unknown mesh current.

- Steps to be followed in mesh analysis:
  - ✓ Identify the mesh, assign a direction to it and assign an unknown current in it.
  - ✓ Assigned polarity for voltage across the branches.
  - ✓ Apply the KVL around the mesh and use ohm's law to express the branch voltage in term of unknown mesh current and resistance.
  - ✓ Solve the equations for unknown mesh current.
- **Loop 1**

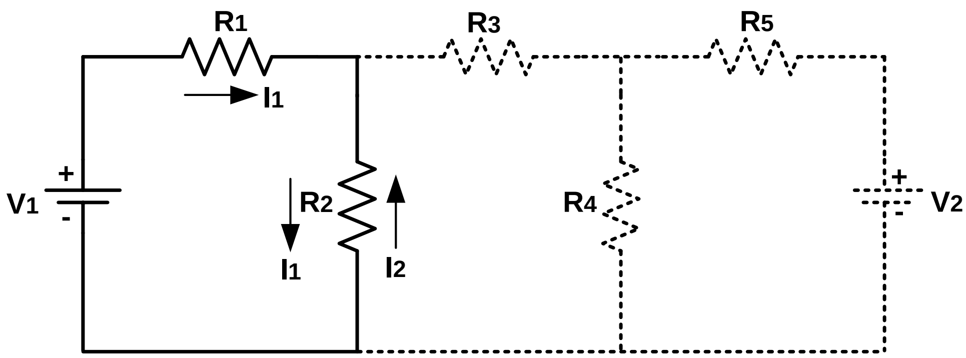


Figure 1.28Mesh analysis network for loop-1

$$Now\ apply\ the\ KVL\ in\ loop-1,$$
$$-I_1R_1-(I_1-I_2)R_2+V_1=0$$
$$-I_1R_1-I_1R_2+I_2R_2+V_1=0$$
$$-(R_1+R_2)I_1+R_2I_2=-V_1 \qquad \text{(i)}$$

- **Loop 2**

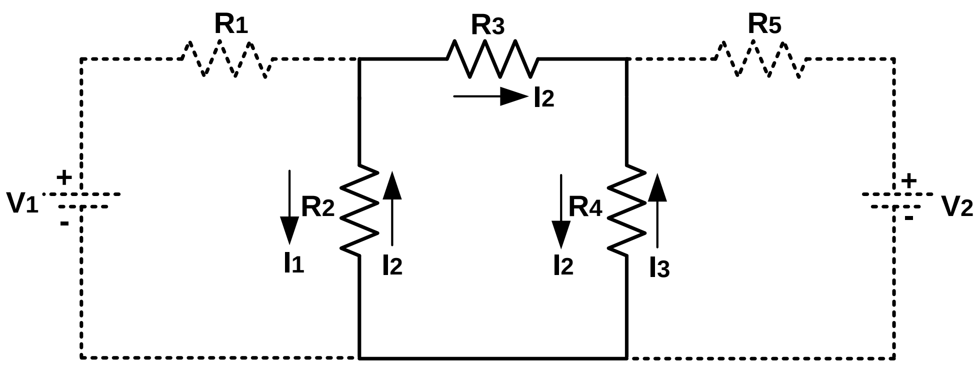


Figure 1.29Mesh analysis network for loop-2

$$Now\ Apply\ the\ KVL\ loop-2,$$
$$-I_2R_3-(I_2-I_3)R_4-(I_2-I_1)R_2=0$$
$$-I_2R_3-I_2R_4+I_3R_4-I_2R_2+I_1R_2=0$$
$$I_1R_2-I_2(R_3+R_4+R_2)+I_3R_4=0$$
$$R_2I_1-(R_3+R_4+R_2)I_2+R_4I_3=0 \qquad \text{(ii)}$$

- **Loop 3**

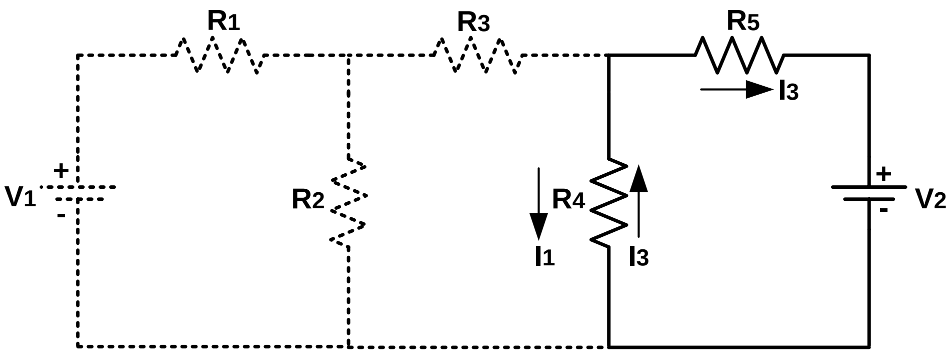


Figure 1.30Mesh analysis network for loop-3

Now Apply the KVL loop -3,

$$-I_3R_5 - V_2 - (I_3 - I_2)R_4 = 0$$

$$-I_3R_5 - V_2 - I_3R_4 + I_2R_4 = 0$$

$$I_2R_4 - I_3(R_5 + R_4) = V_2$$

$$R_4I_2 - (R_5 + R_4)I_3 = V_2 \qquad \text{(iii)}$$

From equation $(i),(ii)$ & (iii)

$$\begin{pmatrix} -(R_1+R_2) & R_2 & 0 \\ R_2 & (R_3+R_4+R_2) & R_4 \\ 0 & R_4 & -(R_5+R_4) \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} = \begin{pmatrix} -V_1 \\ 0 \\ V_2 \end{pmatrix}$$

$$\Delta = \begin{pmatrix} -(R_1+R_2) & R_2 & 0 \\ R_2 & (R_3+R_4+R_2) & R_4 \\ 0 & R_4 & -(R_5+R_4) \end{pmatrix}$$

$$\Delta_1 = \begin{pmatrix} -V_1 & R_2 & 0 \\ 0 & (R_3+R_4+R_2) & R_4 \\ V_2 & R_4 & -(R_5+R_4) \end{pmatrix}$$

$$\Delta_2 = \begin{pmatrix} -(R_1+R_2) & -V_1 & 0 \\ R_2 & 0 & R_4 \\ 0 & V_2 & -(R_5+R_4) \end{pmatrix}$$

$$\Delta_3 = \begin{pmatrix} -(R_1+R_2) & R_2 & -V_1 \\ R_2 & (R_3+R_4+R_2) & 0 \\ 0 & R_4 & V_2 \end{pmatrix}$$

Now,

$$I_1 = \frac{\Delta_1}{\Delta},\ I_2 = \frac{\Delta_2}{\Delta},\ I_3 = \frac{\Delta_3}{\Delta}$$

1.12. Explain Superposition theorem

- The superposition theorem states that in any linear network containing two or more sources, the current in any element is equal to the algebraic sum of the current caused by individual sources acting alone, while the other sources are inoperative.

- According to the application of the superposition theorem. It may be noted that each independent source is considered at a time while all other sources are turned off or killed. To kill a voltage source means the voltage source is replaced by its internal resistance whereas to kill a current source means to replace the current source by its internal resistance.
- To consider the effects of each source independently requires that sources be removed and replaced without affecting the final result. To remove a voltage source when applying this theorem, the difference in potential between the terminals of the voltage source must be set to zero (short circuit) removing a current source requires that its terminals be opened (open circuit).
- Any internal resistance or conductance associated with the displaced sources is not eliminated but must still be considered.
- The total current through any portion of the network is equal to the algebraic sum of the currents produced independently by each source.
- That is, for a two-source network, if the current produced by one source is in one direction, while that produced by the other is in the opposite direction through the same resistor, the resulting current is the difference of the two and has the direction of the larger.
- If the individual currents are in the same direction, the resulting current is the sum of two in the direction of either current. This rule holds true for the voltage across a portion of a network as determined by polarities, and it can be extended to networks with any number of sources.
- The superposition principle is not applicable to power effects since the power loss in a resistor varies as the square (nonlinear) of the current or voltage.
- Steps to be followed to apply the superposition theorem:
  - ✓ Select any one energy source.
  - ✓ Replace all the other energy sources by their internal series resistances for voltage sources. Their internal shunt resistances for current sources.
  - ✓ With only one energy source calculate the voltage drops or branch currents paying attention to the voltage polarities and current directions.
  - ✓ Repeat steps 1, 2 and 3 for each source individually.
  - ✓ Add algebraically the voltage drops or branch currents obtained due to the individual source to obtain the combined effect of all the sources.
- **Example network:**

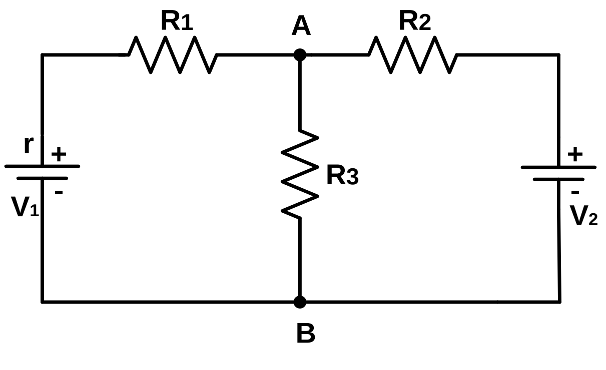


Figure 1.31Superposition theorem network

Step-1

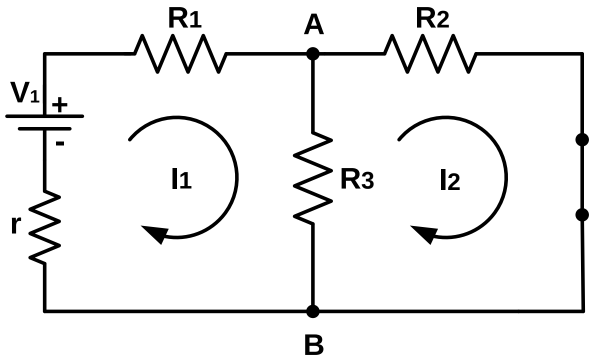


Figure 1.32Superposition theorem network for step-1

$Now\ apply\ Mesh\ analysis\ in\ loop-1,$

$-I_1R_1 - I_1R_3 + I_2R_3 - I_1r + V_1 = 0$

$Now\ apply\ Mesh\ analysis\ in\ loop-2,$

$-I_2R_2 - I_2R_3 + I_1R_3 = 0$

$Now, current\ flow\ from\ R_3\ branch\ is\ algebric\ sum\ of\ I_1\ and\ I_2$

Step-2

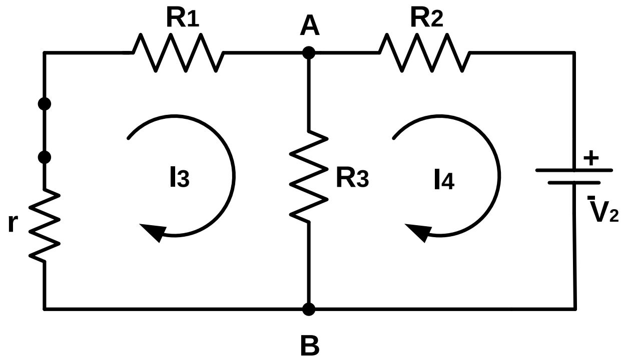


Figure 1.33Superposition theorem network for step-2

$Now\ apply\ Mesh\ analysis\ in\ loop-1,$

$-I_3R_1 - I_3R_3 + I_4R_3 - I_3r = 0$

$Now\ apply\ Mesh\ analysis\ in\ loop-2,$

$-I_4R_2 - V_2 - I_4R_3 + I_3R_3 = 0$

$Now, current\ flow\ from\ R_3\ branch\ is\ algebric\ sum\ of\ I_3\ and\ I_4$

$Finally,\ current\ flow\ from\ R_3\ is\ algebric\ sum\ of\ step-1\ and\ step-2$

1.13. Explain Thevenin's theorem

- Thevenin theorem is an analytical method used to change a complex circuit into a simple equivalent circuit consisting of a single resistance in series with a source voltage.
- Thevenin's can calculate the currents and voltages at any point in a circuit.
- Thevenin's Theorem states that "Any linear circuit containing several voltages and resistances can be replaced by just one single voltage in series with a single resistance

Connected across the load".

- In other words, it is possible to simplify any electrical circuit, no matter how complex, to an equivalent two-terminal circuit with just a single constant voltage source in series with a resistance (or impedance) connected to a load as shown below.
- Thevenin's Theorem is especially useful in the circuit analysis of power or battery systems and other interconnected resistive circuits where it will have an effect on the adjoining part of the circuit.
- **Thevenin's equivalent circuit**

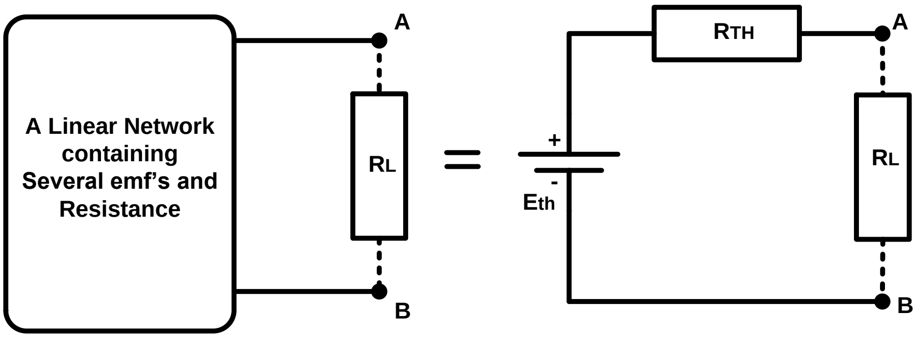


Figure 1.34Thevenin's equivalent circuit

- As far as the load resistor R_L is concerned, any complex "one-port" network consisting of multiple resistive circuit elements and energy sources can be replaced by one single equivalent resistance R_{th} and one single equivalent voltage E_{th}.
- R_{th} is the thevenin resistance value looking back into the circuit and E_{th} is the Thevenin's voltage (open circuit voltage) at the terminals.
- Steps to be followed to apply the Thevenin's theorem:
  - ✓ Remove the load resistor R_{th} or component concerned.
  - ✓ Find R_{th} by shorting all voltage sources or by open circuiting all the current sources.
  - ✓ Find E_{th} by the usual circuit analysis methods.
  - ✓ Find the current flowing through the load resistor R_{th}.
- **Example network:**

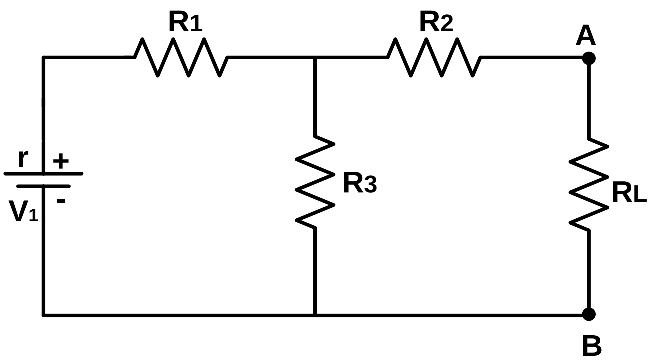


Figure 1.35Thevenin's theorem network

Step-1

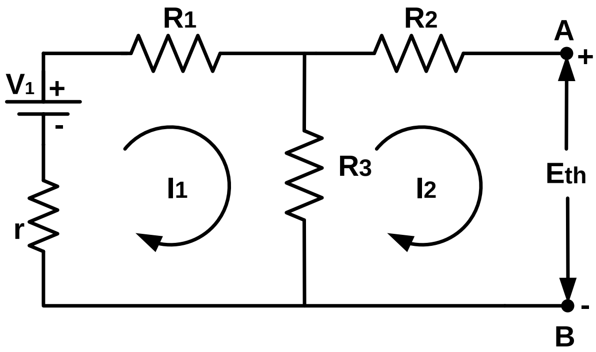


Figure 1.36Thevenin's theorem network (step-1)

Now apply Mesh analysis in loop – 1,

$$-I_1R_1 - I_1R_3 + I_2R_3 - I_1r + V_1 = 0$$

Now apply Mesh analysis in loop – 2,

$$-I_2R_2 - E_{th} - I_2R_3 + I_1R_3 = 0$$

Loop - 2 is open that's way $I_2 = 0$,

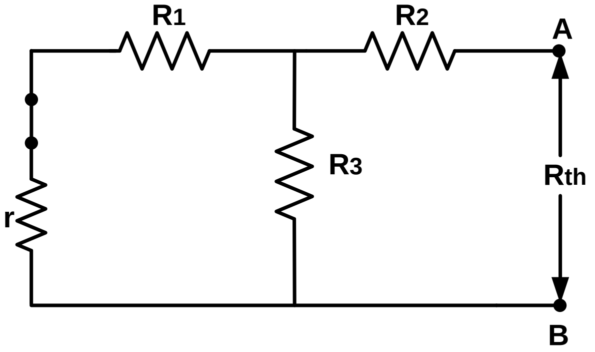
So, $E_{th} = I_1R_3$

E_{th} = Thevenin equivalent voltage

R_{th} = Thevenin equivalent Resistance

R_L = Load Resistance

Step-2

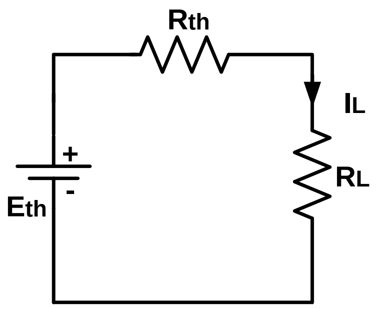


$$R_{th} = \left(\left((r + R_1) \parallel R_3\right) + R_2\right)$$

$$R_{th} = \left(\left(\frac{(r + R_1) \times R_3}{(r + R_1) + R_3}\right) + R_2\right)$$

Figure 1.37Thevenin's theorem network (step-2)

Step-3



$$I_L = \frac{E_{th}}{R_{th} + R_L}$$

Figure 1.38Thevenin's theorem network (step-3)

1.14. Explain Norton's theorem

- Norton's theorem is an analytical method used to change a complex circuit into a simple equivalent circuit consisting of a single resistance in parallel with a current source.
- Norton's Theorem states that "Any linear circuit containing several energy sources and resistances can be replaced by a single Constant Current generator in parallel with a Single Resistor".
- As far as the load resistance, R_L is concerned this single resistance, R_N is the value of the resistance looking back into the network with all the current sources open circuited and I_N is the short circuit current at the output terminals as shown below.
- **Norton's equivalent circuit**

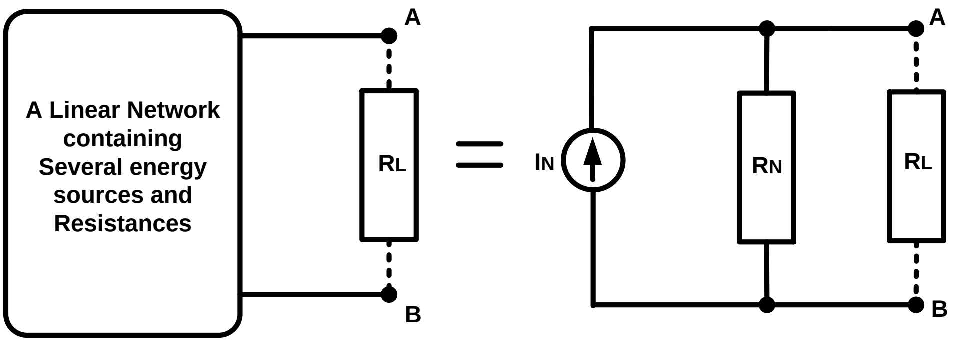


Figure 1.39Norton's theorem equivalent circuit

- The value of this "constant current" is one which would flow if the two output terminals where shorted together while the Norton's resistance would be measured looking back into the terminals.
- The basic procedure for solving a circuit using Norton's Theorem is as follows:
  - ✓ Remove the load resistor R_L or component concerned.
  - ✓ Find R_N by shorting all voltage sources or by open circuiting all the current sources.
  - ✓ Find I_N by placing a shorting link on the output terminals A and B.
  - ✓ Find the current flowing through the load resistor R_L.
- **Example network:**

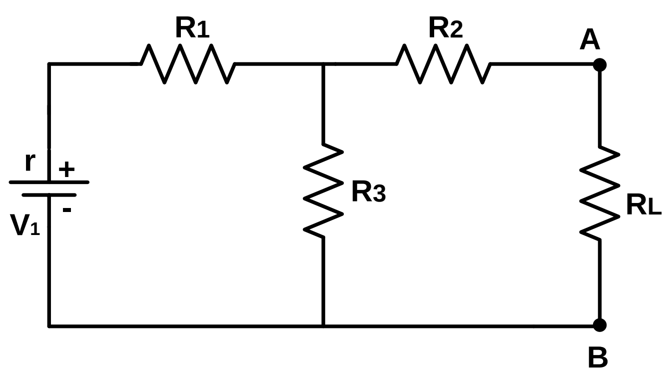


Figure 1.40Norton's theorem network

Step-1

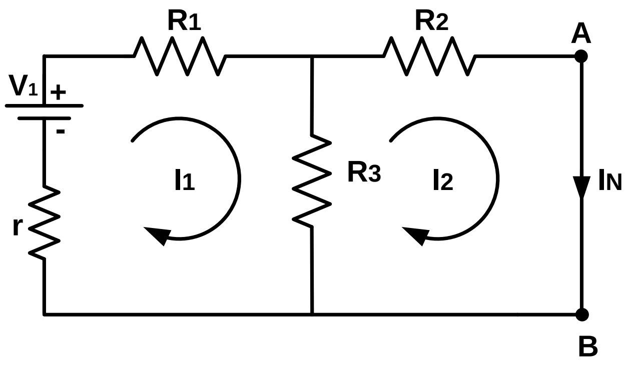


Figure 1.41 Norton's theorem network (step-1)

Now apply Mesh analysis in loop -1,

$$-I_1R_1 - I_1R_3 + I_2R_3 - I_1r + V_1 = 0$$

Now apply Mesh analysis in loop -2,

$$-I_2R_2 - I_2R_3 + I_1R_3 = 0$$

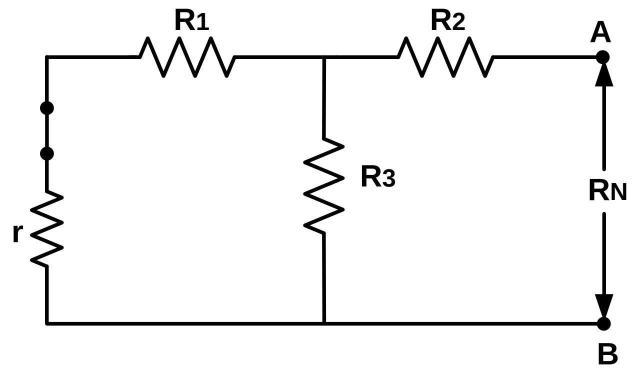
Here $I_2 = I_N$

$I_N =$ *Norton's equivalent current*

$R_N =$ *Norton's equivalent* Resistance

$R_L =$ *Load* Resistance

Step-2

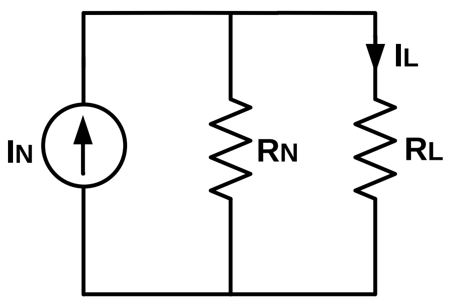


$$R_N = \left(\left(\left(r + R_1\right) \parallel R_3\right) + R_2\right)$$

$$R_N = \left(\left(\frac{\left(r + R_1\right) \times R_3}{\left(r + R_1\right) + R_3}\right) + R_2\right)$$

Figure 1.42 Norton's theorem network (step-2)

Step-3



$$I_L = I_N \frac{R_N}{R_N + R_L}$$

Figure 1.43 Norton's theorem network (step-3)

1.15. Time domain analysis of first order RC circuit

Charging of Capacitor

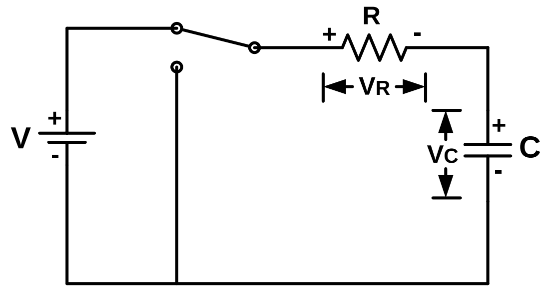


Figure 1.44Charging of capacitor

Apply KVL in circuit ,

$$V - V_R - V_c = 0$$

$$V = V_R + V_c$$

$$V = iR + V_c$$

$$V = \frac{dq}{dt}R + V_c$$

$$V = \frac{d(CV_c)}{dt}R + V_c$$

$$V = RC\frac{dV_c}{dt} + V_c$$

$$V - V_c = RC\frac{dV_c}{dt}$$

$$\int \frac{1}{V - V_c}\, dV_c = \int \frac{1}{RC}\, dt$$

Multiply minus sign both the side

$$\int \frac{-1}{V - V_c}\, dV_c = \int \frac{-1}{RC}\, dt$$

$$\log(V - V_c) = \frac{-t}{RC} + K \qquad (i)$$

When, $t = 0,\ V_c = 0$

$$\log(V) = K \qquad (ii)$$

Solve equation (i) *and* (ii)

$$\log(V - V_c) = \frac{-t}{RC} + \log(V)$$

$$\log(V - V_c) - \log(V) = \frac{-t}{RC}$$

$$\log\left(\frac{V - V_c}{V}\right) = \frac{-t}{RC}$$

$$\left(\frac{V - V_c}{V}\right) = e^{\frac{-t}{RC}}$$

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

Discharging of Capacitor

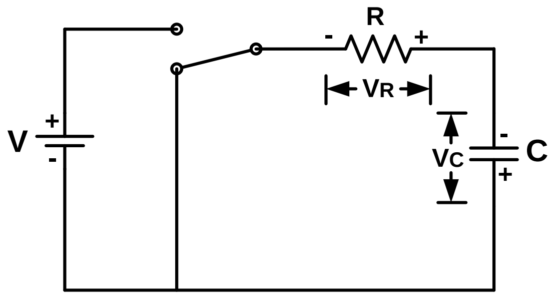


Figure 1.45Discharging of capacitor

Apply KVL in circuit ,

$$0 = V_R + V_c$$

$$0 = iR + V_c$$

$$0 = R\frac{dq}{dt} + V_c$$

$$0 = R\frac{d(CV_c)}{dt} + V_c$$

$$0 = RC\frac{dV_c}{dt} + V_c$$

$$V_c = -RC\frac{dV_c}{dt}$$

$$\int \frac{1}{V_c}\, dV_c = \int \frac{-1}{RC}\, dt$$

$$\log(V_c) = \frac{-t}{RC} + K \qquad (i)$$

When, $t = 0,\ V_c = V$

$$\log(V) = K \qquad (ii)$$

Solve equation (i) *and* (ii)

$$\log(V_c) = \frac{-t}{RC} + \log(V)$$

$$\log(V_c) - \log(V) = \frac{-t}{RC}$$

$$\log\left(\frac{V_c}{V}\right) = \frac{-t}{RC}$$

$$\left(\frac{V_c}{V}\right) = e^{\frac{-t}{RC}}$$

$$V_c = Ve^{\frac{-t}{RC}}$$

$$V_c = V(1 - e^{\frac{-t}{RC}})$$

$$Also, \quad i = \frac{dq}{dt}$$

$$i = \frac{d(CV_c)}{dt}$$

$$i = C\frac{d}{dt}(V(1 - e^{\frac{-t}{RC}}))$$

$$i = VC\frac{d}{dt}(1 - e^{\frac{-t}{RC}})$$

$$i = VC\left(0 - \left(-\frac{1}{RC}\right)e^{\frac{-t}{RC}}\right)$$

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

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

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

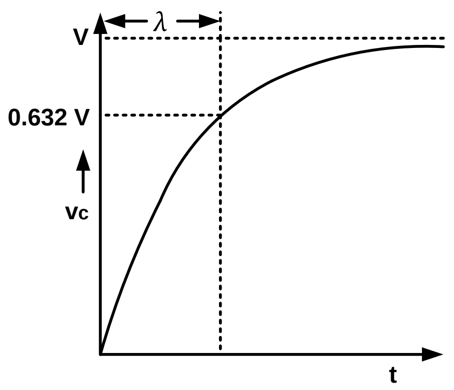


Figure 1.46Charging voltage of capacitor

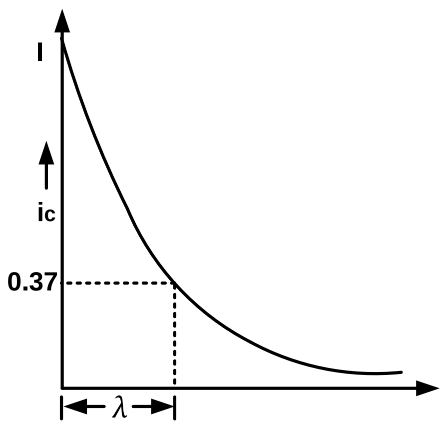


Figure 1.47Charging current of capacitor

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

$$i = \frac{d(CV_c)}{dt}$$

$$i = C\frac{dV_c}{dt}$$

$$i = C\frac{d}{dt}(Ve^{\frac{-t}{RC}})$$

$$i = CV\frac{-1}{RC}e^{\frac{-t}{RC}}$$

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

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

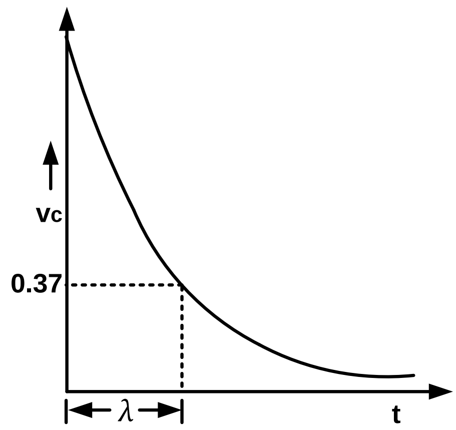


Figure 1.48Dicharging voltage of capacitor

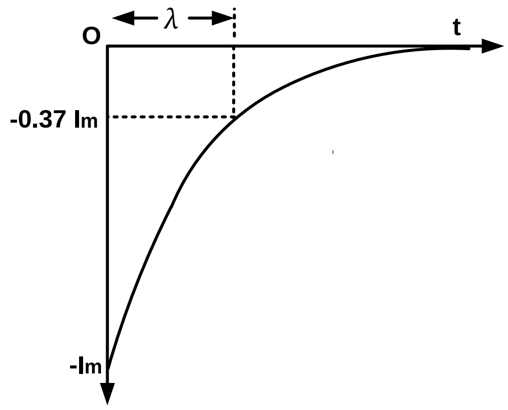


Figure 1.49Dicharging current of capacitor

1.16. Time domain analysis of first order RL circuit

Charging of Inductor

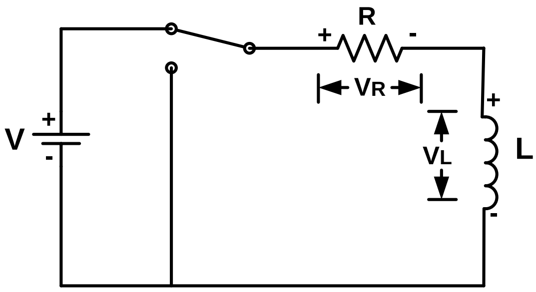


Figure 1.50Charging of inductor

From KVL,

$$V - iR - L\frac{di}{dt} = 0$$

$$\therefore V - iR \ = L\frac{di}{dt}$$

$$\therefore \frac{di}{V - iR} = \frac{dt}{L}$$

$$\therefore \int \frac{1}{V - iR} di = \frac{1}{L}\int dt$$

$$\therefore \int \frac{-R}{V - iR} di = \frac{-R}{L}\int dt$$

$$\therefore \log(V - iR) = \left(\frac{-R}{L}\right)t + K \qquad (i)$$

When, $t = 0,\ i = 0$

$$\log(V) = K \qquad (ii)$$

Solve equation (i) *and* (ii)

$$\therefore \log(V - iR) = \left(\frac{-R}{L}\right)t + \log(V)$$

$$\therefore \log(V - iR) - \log(V) = \left(\frac{-R}{L}\right)t$$

$$\therefore \log\left(\frac{V - iR}{V}\right) = \left(\frac{-R}{L}\right)t$$

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

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

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

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

$$\therefore i = I_m\left(1 - e^{-\lambda t}\right)$$

Discharging of Inductor

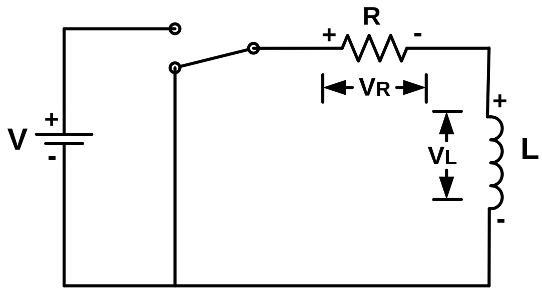


Figure 1.51Discharging of inductor

From KVL,

$$-iR - L\frac{di}{dt} = 0$$

$$\therefore -iR \ = L\frac{di}{dt}$$

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

$$\therefore \int \frac{1}{i}di \ = \frac{-R}{L}\int dt$$

$$\therefore \log(i) = \left(\frac{-R}{L}\right)t + K \qquad (i)$$

When, $t = 0,\ i = \dfrac{V}{R}$

$$\log\left(\frac{V}{R}\right) = K \qquad (ii)$$

Solve (i) *and* (ii)

$$\therefore \log(i) = \left(\frac{-R}{L}\right)t + \log\left(\frac{V}{R}\right)$$

$$\therefore \log(i) - \log\left(\frac{V}{R}\right) = \left(\frac{-R}{L}\right)t$$

$$\therefore \log\left(\frac{i}{V/R}\right) = \left(\frac{-R}{L}\right)t$$

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

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

$$\therefore i = \frac{V}{R}e^{-\lambda t}$$

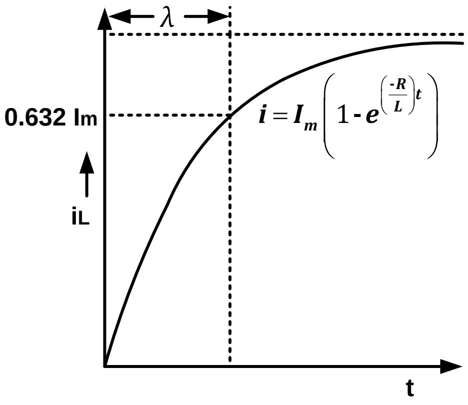


Figure 1.52Charging current of inductor

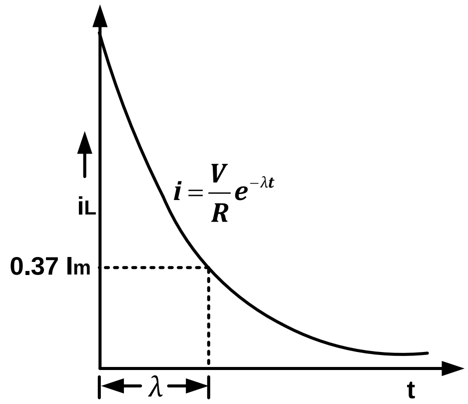
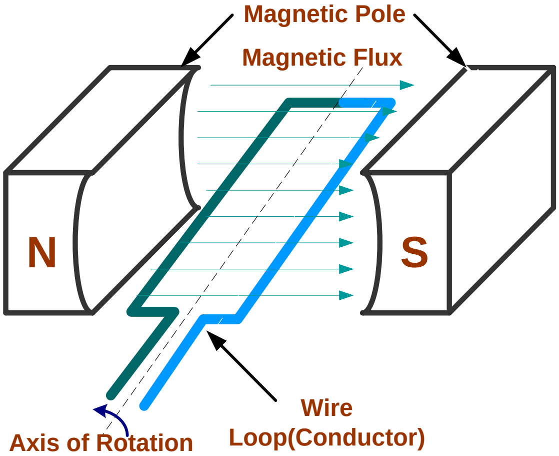


Figure 1.53Dicharging current of inductor

Single - Phase AC Circuits

2.1 Equation for generation of alternating induce EMF

- An AC generator uses the principle of Faraday's electromagnetic induction law. It states that when current carrying conductor cut the magnetic field then emf induced in the conductor.
- Inside this magnetic field a single rectangular loop of wire rotes around a fixed axis allowing it to cut the magnetic flux at various angles as shown below figure 2.1.



Where,
N =No. of turns of coil
A = Area of coil (m^2)
ω=Angular velocity (radians/second)
ϕ_m= Maximum flux (wb)

Figure 2.2.1 Generation of EMF

- When coil is along XX' (perpendicular to the lines of flux), flux linking with coil= ϕ_m. When coil is along YY' (parallel to the lines of flux), flux linking with the coil is zero. When coil is making an angle θ with respect to XX' flux linking with coil, $\phi = \phi_m \cos\omega t$ [$\theta = \omega t$].

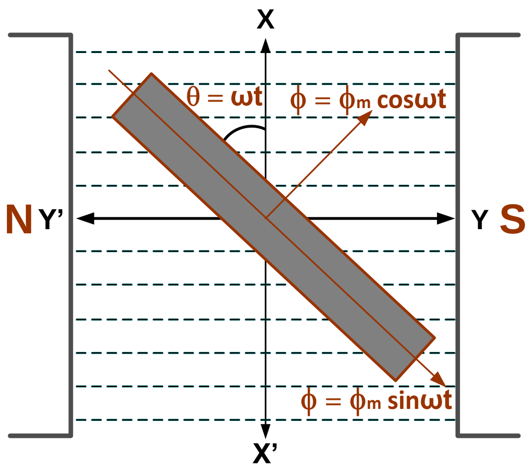


Figure 2.2 Alternating Induced EMF

- According to Faraday's law of electromagnetic induction,

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

$$e = -Nd\frac{(\phi_m \cos\omega t)}{dt}$$

$$e = -N\phi_m(-\sin\omega t)\times\omega$$

$$e = N\phi_m\omega\sin\omega t$$

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

Where,

$E_m = N\phi_m\omega$

$N =$ no. of turns of the coil

$\phi_m = B_m A$

$B_m =$ Maximum flux density (wb/m^2)

$A =$ Area of the coil (m^2)

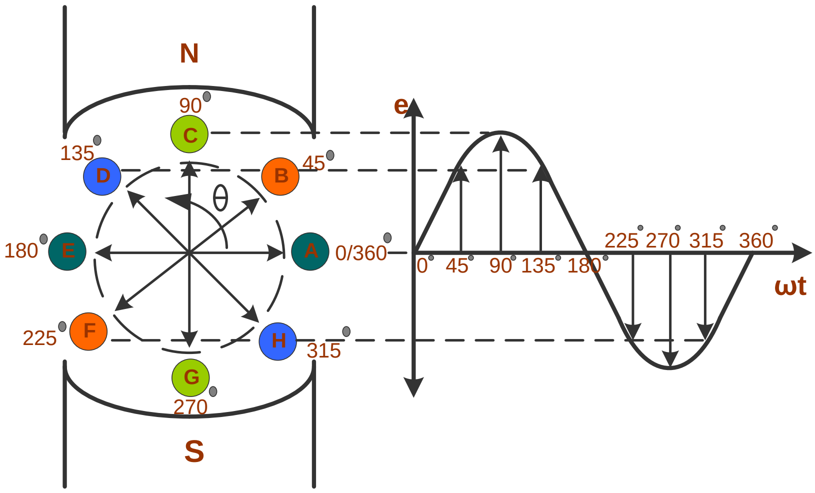
$\omega = 2\pi f$

$$\therefore e = N B_m A 2\pi f \sin \omega t$$

- Similarly, an alternating current can be express as

  $i = I_m \sin \omega t$ Where, I_m = Maximum values of current

- Thus, both the induced emf and the induced current vary as the sine function of the phase angle $\omega t = \theta$. Shown in figure 2.3.



Phase angle	Induced emf $e = E_m \sin \omega t$
$\omega t = 0^0$	$e = 0$
$\omega t = 90^0$	$e = E_m$
$\omega t = 180^0$	$e = 0$
$\omega t = 270^0$	$e = -E_m$
$\omega t = 360^0$	$e = 0$

Figure 2.3 Waveform of Alternating Induced EMF

2.2 Definitions

➢ **Waveform**

It is defined as the graph between magnitude of alternating quantity (on Y axis) against time (on X axis).

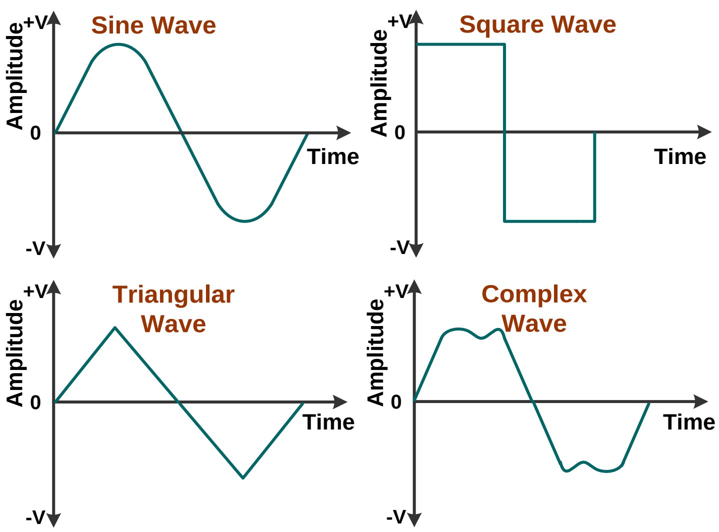


Figure 2.4 A.C. Waveforms

➢ **Cycle**

It is defined as one complete set of positive, negative and zero values of an alternating quantity.

- **Instantaneous value**

  It is defined as the value of an alternating quantity at a particular instant of given time. Generally denoted by small letters.

  e.g. i= Instantaneous value of current

  v= Instantaneous value of voltage

  p= Instantaneous values of power

- **Amplitude/ Peak value/ Crest value/ Maximum value**

  It is defined as the maximum value (either positive or negative) attained by an alternating quantity in one cycle. Generally denoted by capital letters.

  e.g. I_m= Maximum Value of current

  V_m= Maximum value of voltage

  P_m= Maximum values of power

- **Average value**

  It is defined as the average of all instantaneous value of alternating quantities over a half cycle.

  e.g. V_{ave} = Average value of voltage

  I_{ave} = Average value of current

- **RMS value**

  It is the equivalent dc current which when flowing through a given circuit for a given time produces same amount of heat as produced by an alternating current when flowing through the same circuit for the same time.

  e.g. V_{rms} =Root Mean Square value of voltage

  I_{rms} = Root Mean Square value of current

- **Frequency**

  It is defined as number of cycles completed by an alternating quantity per second. Symbol is f. Unit is Hertz (Hz).

- **Time period**

  It is defined as time taken to complete one cycle. Symbol is T. Unit is seconds.

- **Power factor**

  It is defined as the cosine of angle between voltage and current. Power Factor = pf = cosϕ, where ϕ is the angle between voltage and current.

- **Active power**

  It is the actual power consumed in any circuit. It is given by product of rms voltage and rms current and cosine angle between voltage and current. (VI cosϕ).

  Active Power= P= I^2R = VI cosϕ.

  Unit is Watt (W) or kW.

- **Reactive power**

  The power drawn by the circuit due to reactive component of current is called as reactive power. It is given by product of rms voltage and rms current and sine angle between voltage and current (VI sinϕ).

  Reactive Power = Q= I^2X = VIsinϕ.

  Unit is VAR or kVAR.

- **Apparent power**

  It is the product of rms value of voltage and rms value of current. It is total power supplied to the circuit.

  Apparent Power = S = VI.

  Unit is VA or kVA.

- **Peak factor/ Crest factor**

  It is defined as the ratio of peak value (crest value or maximum value) to rms value of an alternating quantity.

  Peak factor = Kp = 1.414 for sine wave.

- **Form factor**

  It is defined as the ratio of rms value to average value of an alternating quantity. Denoted by K_f. Form factor K_f = 1.11 for sine wave.

- **Phase difference**

  It is defined as angular displacement between two zero values or two maximum values of the two-alternating quantity having same frequency.

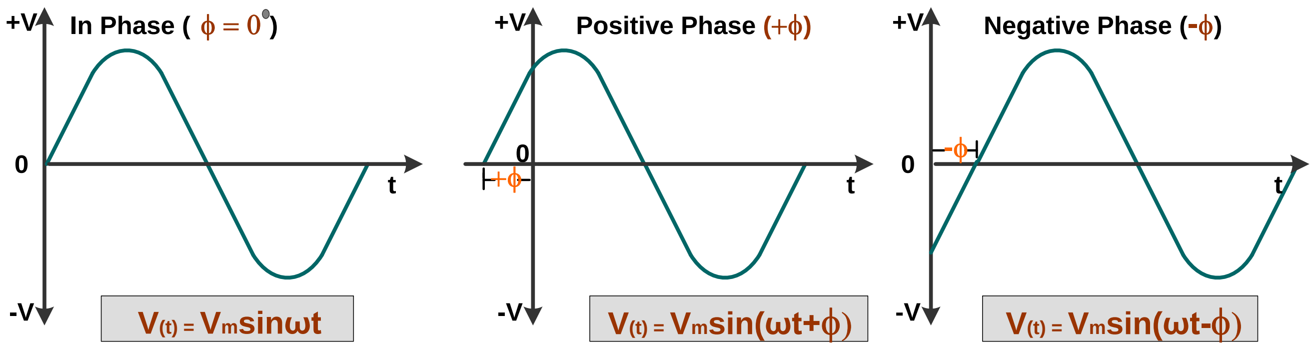


Figure 2.5 A.C. Phase Difference

- **Leading phase difference**

  A quantity which attains its zero or positive maximum value before the compared to the other quantity.

- **Lagging phase difference**

  A quantity which attains its zero or positive maximum value after the other quantity.

2.3 Derivation of average value and RMS value of sinusoidal AC signal

➢ **Average Value**

<table>
<tr><th><u>Graphical Method</u></th><th><u>Analytical Method</u></th></tr>
<tr><td>

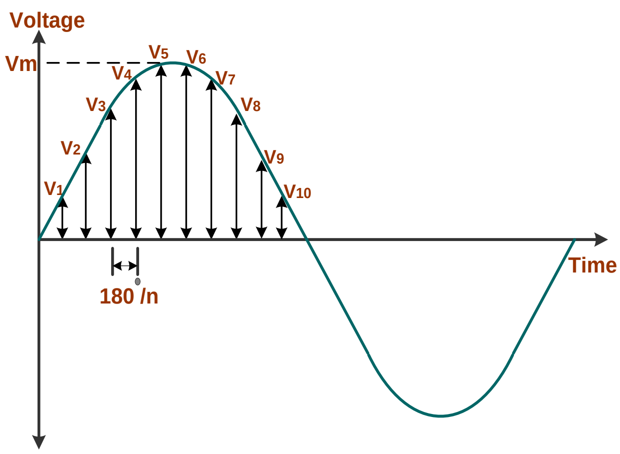


Figure 2.6 Graphical Method for Average Value

$$V_{ave} = \frac{Sum\ of\ All\ Instantaneous\ Values}{Total\ No.\ of\ Values}$$

$$V_{ave} = \frac{v_1 + v_2 + v_3 + v_4 + v_5 + ... + v_{10}}{10}$$

</td><td>

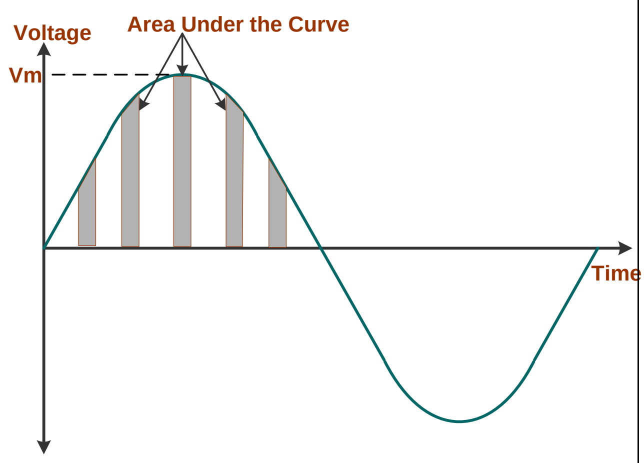


Figure 2.7 Analytical Method for Average Value

$$V_{ave} = \frac{Area\ Under\ the\ Curve}{Base\ of\ the\ Curve}$$

$$V_{ave} = \frac{\int_0^{\pi} V_m \sin\ \omega t\ d\omega t}{\pi}$$

$$V_{ave} = \frac{V_m}{\pi}\left(-\cos \omega t\right)_0^{\pi}$$

$$V_{ave} = -\frac{V_m}{\pi}\left(\cos \pi - \cos 0\right)$$

$$V_{ave} = \frac{2V_m}{\pi}$$

$$V_{ave} = 0.637\ V_m$$

</td></tr>
</table>

➢ RMS Value

Graphical Method

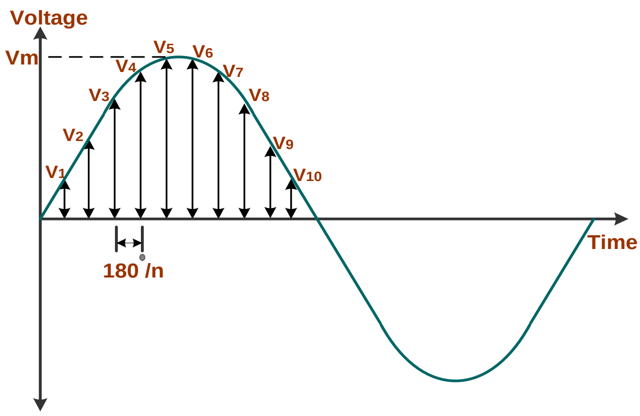


Figure 2.8 Graphical Method for RMS Value

$$V_{rms} = \sqrt{\frac{Sum\ \ of\ \ all\ \ sq.\ of\ instantaneous\ values}{Total\ \ No.\ \ of\ \ Values}}$$

$$V_{rms} = \sqrt{\frac{v_1^2 + v_2^2 + v_3^2 + v_4^2 + v_5^2 + \ldots\ldots + v_{10}^2}{10}}$$

Analytical Method

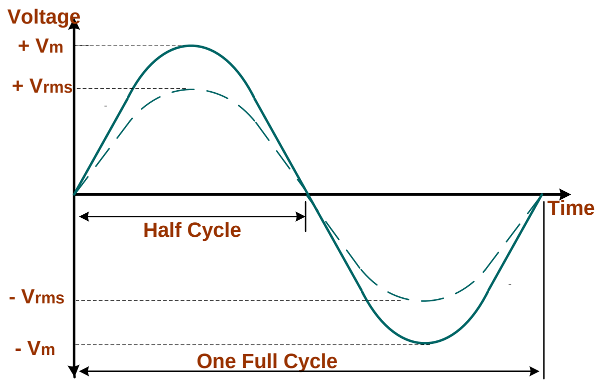


Figure 2.9 Analytical Method for RMS Value

$$V_{rms} = \sqrt{\frac{Area\ \ under\ \ the\ sq.\ curve}{Base\ of\ the\ curve}}$$

$$V_{rms} = \sqrt{\frac{\int_0^{2\pi} V_m^2\ Sin^2\ \omega t\ \ d\omega t}{2\pi}}$$

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

$$V_{rms} = \sqrt{\frac{V^2{}_m}{4\pi}\left[\left[\omega t\right]_0^{2\pi} - \left[\frac{(\sin 2\omega t)}{2}\right]_0^{2\pi}\right]}$$

$$V_{rms} = \sqrt{\frac{V_m}{4\pi}(2\pi - 0)}$$

$$V_{rms} = \frac{V_m}{\sqrt{2}}$$

$$V_{rms} = 0.707\ \ V_m$$

2.4 Phasor Representation of Alternating Quantities

- Sinusoidal expression given as: $v_{(t)} = V_m \sin(\omega t \pm \Phi)$ representing the sinusoid in the time-domain form.
- Phasor is a quantity that has both "Magnitude" and "Direction".

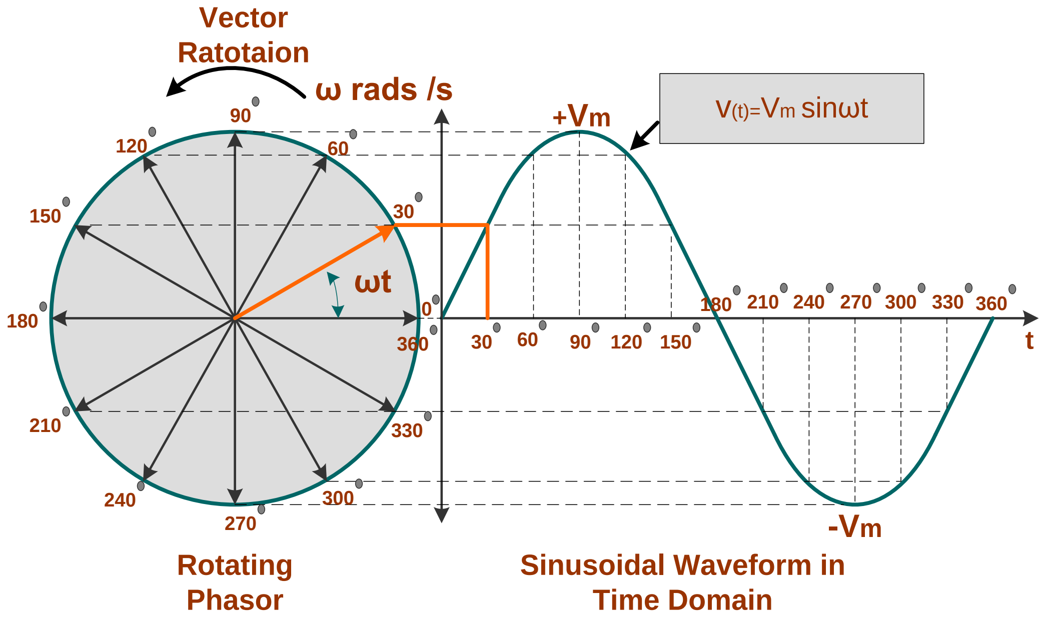


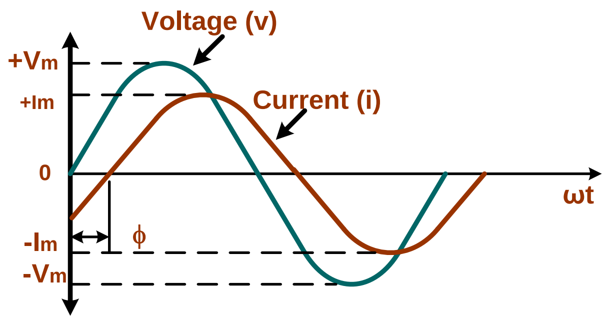
Figure 2.10 Phasor Representation of Alternating Quantities

Phase Difference of a Sinusoidal Waveform

- The generalized mathematical expression to define these two sinusoidal quantities will be written as:

$$v = V_m \, Sin \; \omega t$$

$$i = I_m \, sin \; (\omega t - \varphi)$$



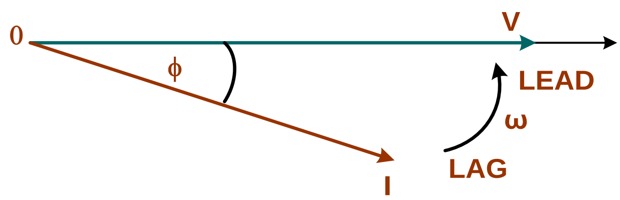


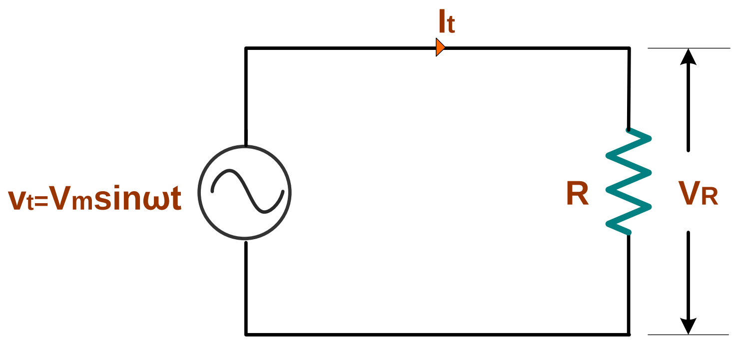
Figure 2.11 Wave Forms of Voltage & Current *Figure 2.12 Phasor Diagram of Voltage & Current*

- As show in the above voltage and current equations, the current, i is lagging the voltage, v by angle ϕ.
- So, the difference between the two sinusoidal quantities representing in waveform shown in Fig. 2.11 & phasors representing the two sinusoidal quantities is angle ϕ and the resulting phasor diagram shown in Fig. 2.12.

2.5 Purely Resistive Circuit

- The Fig. 2.13 an AC circuit consisting of a pure resistor to which an alternating voltage $v_t = V_m \sin\omega t$ is applied.

Circuit Diagram



Where,
v_t = Instantaneous Voltage
V_m = Maximum Voltage
V_R = Voltage across Resistance

Figure 2.13 Pure Resistor Connected to AC Supply

Equations for Voltage and Current

- As show in the Fig. 2.13 voltage source

$$v_t = V_m \, Sin \;\; \omega t$$

- According to ohm's law

$$i_t = \frac{v_t}{R}$$

$$i_t = \frac{V_m \sin\omega t}{R}$$

$$i_t = I_m \sin\omega t$$

- From above equations it is clear that current is in phase with voltage for purely resistive circuit.

Waveforms and Phasor Diagram

- The sinewave and vector representation of $v_t = V_m \, Sin\,\omega t$ & $i_t = I_m \sin\omega t$ are given in Fig. 2.14 & 2.15.

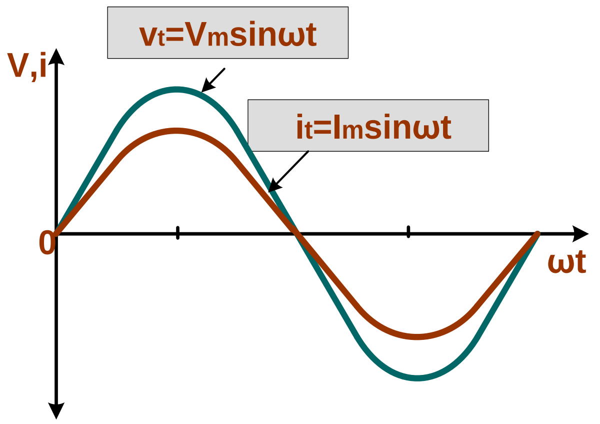


Figure 2.14 Waveform of Voltage & Current for Pure Resistor

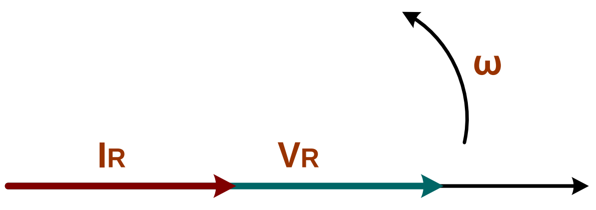


Figure 2.15 Phasor Diagram of Voltage & Current for Pure Resistor

Power

- The instantaneous value of power drawn by this circuit is given by the product of the instantaneous values of voltage and current.

Instantaneous power

$$p_{(t)} = v \times i$$

$$p_{(t)} = V_m \sin \omega t \times I_m \sin \omega t$$

$$p_{(t)} = V_m I_m \sin^2 \omega t$$

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

Average Power

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

$$P_{ave} = \frac{V_m I_m}{4\pi} \left[\left[\omega t \right]_0^{2\pi} - \left[\frac{(\sin 2\omega t)}{2} \right]_0^{2\pi} \right]$$

$$P_{ave} = \frac{V_m I_m}{4\pi} \left[[2\pi - 0] - [0 - 0] \right]$$

$$P_{ave} = \frac{V_m I_m}{2}$$

$$P_{ave} = \frac{V_m}{\sqrt{2}} \frac{I_m}{\sqrt{2}}$$

$$P_{ave} = V_{rms} \quad I_{rms}$$

$$P_{ave} = VI$$

- The average power consumed by purely resistive circuit is multiplication of Vrms & I_{rms} .

2.6 Purely Inductive Circuit

- The Fig. 2.16 an AC circuit consisting of a pure Inductor to which an alternating voltage $v_t = V_m \sin \omega t$ is applied.

Circuit Diagram

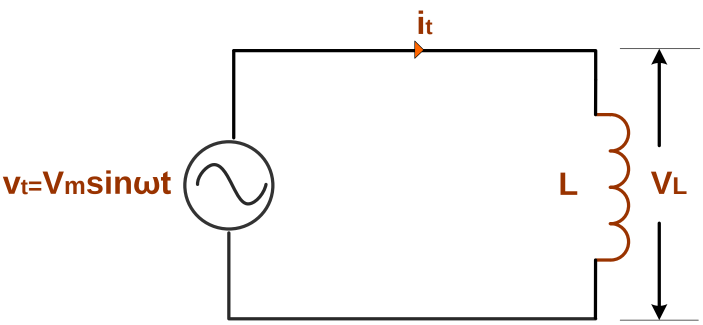


Figure 2.16 Pure Inductor Connected to AC Supply

Equations for Voltage and Current

- As show in the Fig. 2.16 voltage source

$$v_t = V_m \, Sin \;\; \omega t$$

- Due to self-inductance of the coil, there will be emf indued in it. This back emf will oppose the instantaneous rise or fall of current through the coil, it is given by

$$e_b = -L\frac{di}{dt}$$

- As, circuit does not contain any resistance, there is no ohmic drop and hence applied voltage is equal and opposite to back emf.

$$v_t = -e_b$$

$$v_t = -\left(-L\frac{di}{dt}\right)$$

$$v_t = L\;\frac{di}{dt}$$

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

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

- Integrate on both the sides,

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

$$i_t = \frac{V_m}{L}\left(\frac{-\cos\omega t}{\omega}\right)$$

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

$$i_t = I_m \sin\left(\omega t - 90^\circ\right) \qquad \left(\because \frac{V_m}{\omega L} = I_m\right)$$

- From the above equations it is clear that the current lags the voltage by 90^0 in a purely inductive circuit.

Waveform and Phasor Diagram

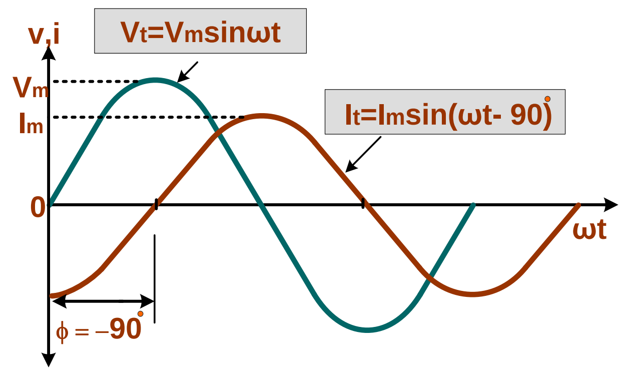


Figure 2.17 Waveform of Voltage & Current for Pure Inductor

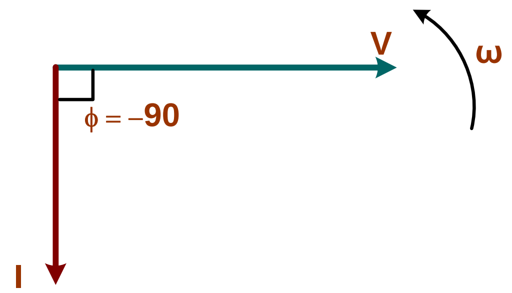


Figure 2.18 Phasor Diagram of Voltage & Current for Pure Inductor

Power

- The instantaneous value of power drawn by this circuit is given by the product of the instantaneous values of voltage and current.

Instantaneous Power

$$p_t = v \times i$$

$$p_t = V_m \sin\omega t \times I_m \sin\;\left(\omega t - 90^\circ\right)$$

$$p_t = V_m \sin\omega t \times (-\,I_m \cos\omega t\,)$$

$$p_t = \frac{-\,2V_m\;I_m \sin\omega t\;\;\cos\omega t}{2}$$

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

Average Power

$$P_{ave} = \frac{\int_0^{2\pi} -\frac{V_m I_m}{2} \sin 2\omega t}{2\pi} \, d\omega t$$

$$P_{ave} = -\frac{V_m I_m}{4\pi} \left[\frac{-\cos 2\omega t}{2} \right]_0^{2\pi}$$

$$P_{ave} = \frac{V_m I_m}{8\pi} [\cos 4\pi - \cos 0]$$

$$P_{ave} = 0$$

- The average power consumed by purely inductive circuit is zero.

2.7 Purely Capacitive Circuit

- The Fig. 2.19 shows a capacitor of capacitance C farads connected to an a.c. voltage supply $v_t = V_m \sin\omega t$.

Circuit Diagram

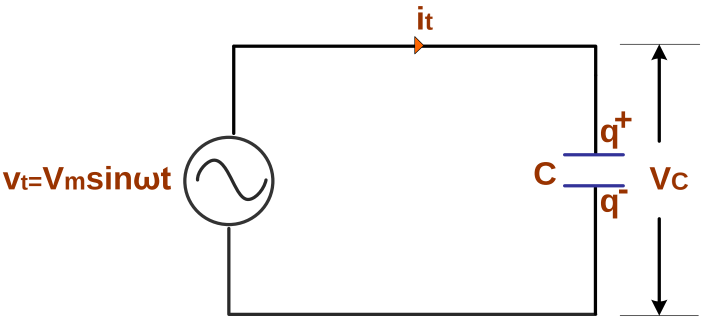


Figure 2.19 Pure Capacitor Connected AC Supply

Equations for Voltage & Current

- As show in the Fig. 2.19 voltage source

$$v_t = V_m \, Sin \;\, \omega t$$

- A pure capacitor having zero resistance. Thus, the alternating supply applied to the plates of the capacitor, the capacitor is charged.
- If the charge on the capacitor plates at any instant is 'q' and the potential difference between the plates at any instant is 'v_t' then we know that,

$$q = Cv_t$$

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

- The current is given by rate of change of charge.

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

$$i_t = \frac{dCV_m \sin\omega t}{dt}$$

$$i_t = \omega C V_m \sin\omega t$$

$$i_t = \frac{V_m}{1/\omega C}\cos\omega t$$

$$i_t = \frac{V_m}{X_c}\cos\omega t$$

$$i_t = I_m \sin(\omega t + 90^o) \qquad (\because \frac{V_m}{X_c} = I_m)$$

- From the above equations it is clear that the current leads the voltage by 90^0 in a purely capacitive circuit.

Waveform and Phasor Diagram

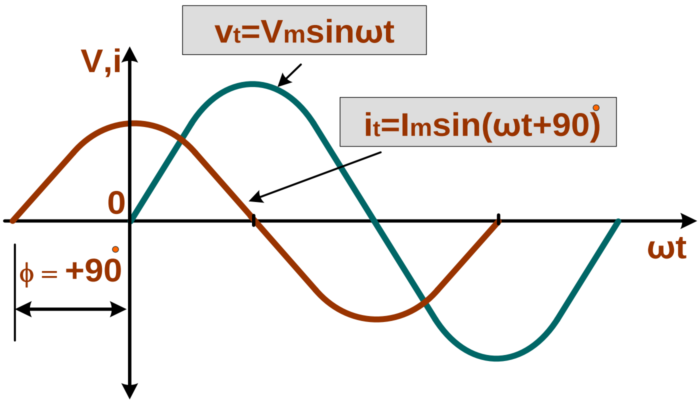


Figure 2.20 Waveform of Voltage & Current for Pure Capacitor

Figure 2.21 Phasor Diagram of Voltage & Current for Pure Capacitor

Power

- The instantaneous value of power drawn by this circuit is given by the product of the instantaneous values of voltage and current.

Instantaneous Power

$$p_{(t)} = v \times i$$

$$p_{(t)} = V_m \sin\omega t \times I_m \sin\left(\omega t + 90^\circ\right)$$

$$p_{(t)} = V_m \sin\omega t \times I_m \cos\omega t$$

$$p_{(t)} = V_m\ I_m \sin\omega t\ \cos\omega t$$

$$p_{(t)} = \frac{2V_m\ I_m \sin\omega t\ \cos\omega t}{2}$$

$$p_{(t)} = \frac{V_m I_m}{2}\sin 2\omega t$$

Average Power

$$P_{ave} = \frac{\int_0^{2\pi} \frac{V_m I_m}{2}\sin\ 2\ \omega t}{2\pi}\ d\omega t$$

$$P_{ave} = \frac{V_m I_m}{4\pi}\left[\frac{-\cos\omega t}{2}\right]_0^{2\pi}$$

$$P_{ave} = \frac{V_m I_m}{8\pi}\left[-\cos 4\pi + \cos 0\right]$$

$$P_{ave} = 0$$

- The average power consumed by purely capacitive circuit is zero.

2.8 Series Resistance-Inductance (R-L) Circuit

- Consider a circuit consisting of a resistor of resistance R ohms and a purely inductive coil of inductance L henry in series as shown in the Figure 2.22.

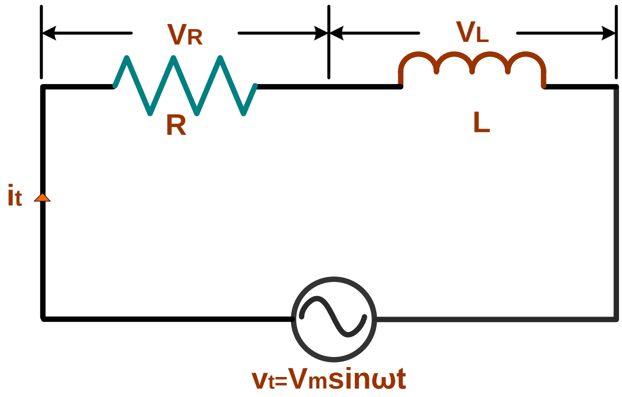


Figure 2.22 Circuit Diagram of Series R-L Circuit

- In the series circuit, the current i_t flowing through R and L will be the same.
- But the voltage across them will be different. The vector sum of voltage across resistor V_R and voltage across inductor V_L will be equal to supply voltage v_t.

Waveforms and Phasor Diagram

- The voltage and current waves in R-L series circuit is shown in Fig. 2.23.

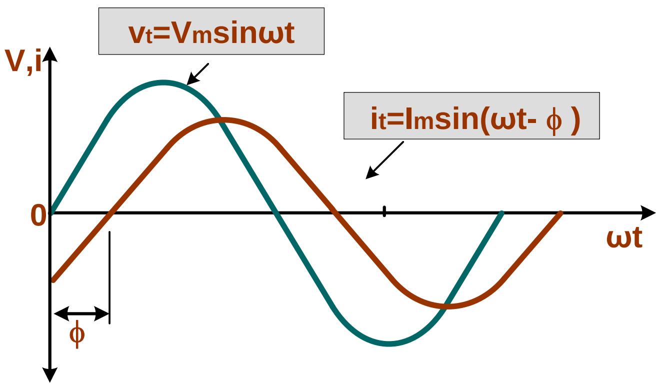


Figure 2.23 Waveform of Voltage and Current of Series R-L Circuit

- We know that in purely resistive the voltage and current both are in phase and therefore vector V_R is drawn superimposed to scale onto the current vector and in purely inductive circuit the current I lag the voltage V_L by 90^o.
- So, to draw the vector diagram, first I taken as the reference. This is shown in the Fig. 2.24. Next V_R drawn in phase with I. Next V_L is drawn 90^o leading the I.
- The supply voltage V is then phasor Addition of V_R and V_L.

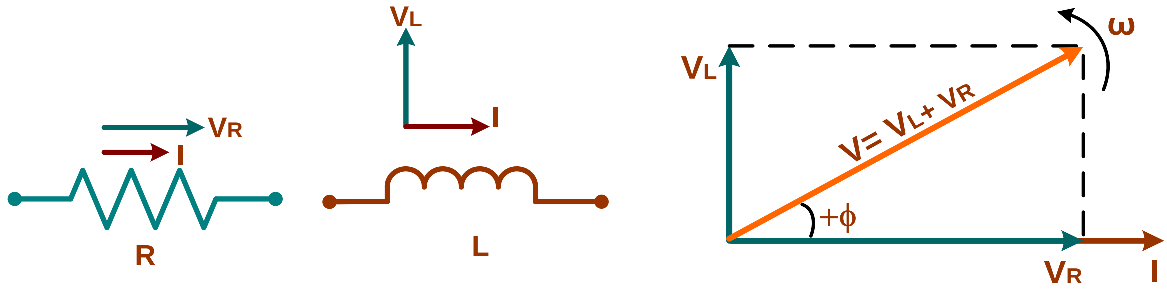
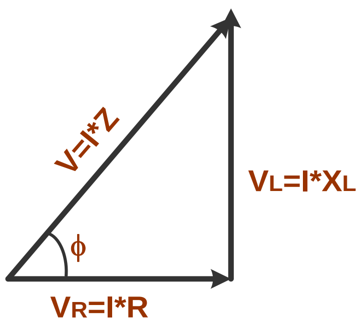
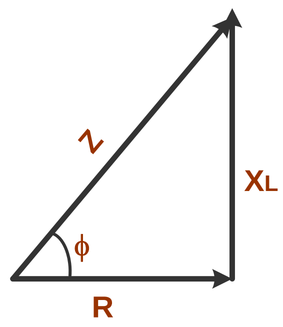
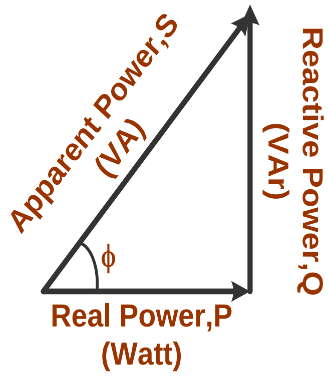


Figure 2.24 Phasor Diagram of Series R-L Circuit

- Thus, from the above, it can be said that the current in series R-L circuit lags the applied voltage V by an angle ϕ. If supply voltage

$$v = V_m \, Sin \; \omega t$$

$$i = I_m \, sin \quad (\omega t - \phi) \qquad \text{Where } I_m = \frac{V_m}{Z}$$

Voltage Triangle	Impedance Triangle	Power Triangle
 *Figure 2.25 Voltage Triangle Series R-L Circuit* $V = \sqrt{V_R^2 + V_L^2}$ $= \sqrt{(IR)^2 + (IX_L)^2}$ $= I \sqrt{R^2 + X_L^2}$ $= IZ$ $where, \; Z = \sqrt{R^2 + X_L^2}$	 *Figure 2.26 Impedance Triangle Series R-L Circuit* $Z = \sqrt{R^2 + X_L^2}$ $\phi = tan^{-1} \frac{X_L}{R}$	 *Figure 2.27 Power Triangle Series R-L Circuit* $Real \; Power \;\; P = V \, I \;\; \cos\phi$ $= I^2 R$ $Reactive \;\; Power \; Q = V \, I \;\; \sin\phi$ $= I^2 X_L$ $Apparent \;\; Power \; S = V \, I$ $= I^2 Z$

Power Factor

$$Power \quad factor = cos\,\varphi = \frac{R}{Z}$$

$$= \frac{P}{S}$$

Power

- The instantaneous value of power drawn by this circuit is given by the product of the instantaneous values of voltage and current.

Instantaneous power

$$p_t = v \times i$$

$$p_t = V_m \sin\omega t \times I_m \sin(\omega t - \phi)$$

$$p_t = V_m \ I_m \sin\omega t \times \sin(\omega t - \phi)$$

$$p_t = \frac{2\, V_m \ I_m \sin\omega t \times \sin(\omega t - \phi)}{2}$$

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

- Thus, the instantaneous values of the power consist of two components.
- First component is constant w.r.t. time and second component vary with time.

Average Power

$$P_{ave} = \int_0^{2\pi} \frac{V_m I_m}{2}\left[\cos\ \phi\text{-} \cos(2\omega t\text{-}\phi)\right] d\omega t$$

$$P_{ave} = \frac{V_m I_m}{2\pi}\int_0^{2\pi} \frac{1}{2}\left[\cos\ \phi\text{-} \cos(2\omega t\text{-}\phi)\right] d\omega t$$

$$P_{ave} = \frac{V_m I_m}{4\pi}\left[\int_0^{2\pi} \cos\phi d\omega t\text{-} \int_0^{2\pi} \cos(2\omega t\text{-}\phi)\, d\omega t\right]$$

$$P_{ave} = \frac{V_m I_m}{4\pi}\left[\cos\phi(\omega t)_0^{2\pi} \text{-} \left\{\frac{\sin(2\omega t\text{-}\phi)}{2}\right\}_0^{2\pi}\right]$$

$$P_{ave} = \frac{V_m I_m}{4\pi}\left[2\pi\cos\phi\right]\text{-}\frac{V_m I_m}{8\pi}\left[\sin(4\pi-\phi) - \sin(-\phi)\right]$$

$$P_{ave} = \frac{V_m I_m}{2}\left[\cos\phi\right]\text{-}\frac{V_m I_m}{8\pi}\left[-\sin\phi + \sin\phi\right]$$

$$P_{ave} = \frac{V_m I_m}{2}\cos\phi\text{-}0$$

$$P_{ave} = \frac{V_m I_m}{2}\cos\ \phi$$

$$P_{ave} = \frac{V_m}{\sqrt{2}}\frac{I_m}{\sqrt{2}}\cos\ \phi$$

$$P_{ave} = VI\cos\phi$$

2.9 Series Resistance-Capacitance Circuit

- Consider a circuit consisting of a resistor of resistance R ohms and a purely capacitive of capacitance farad in series as in the Fig. 2.28.

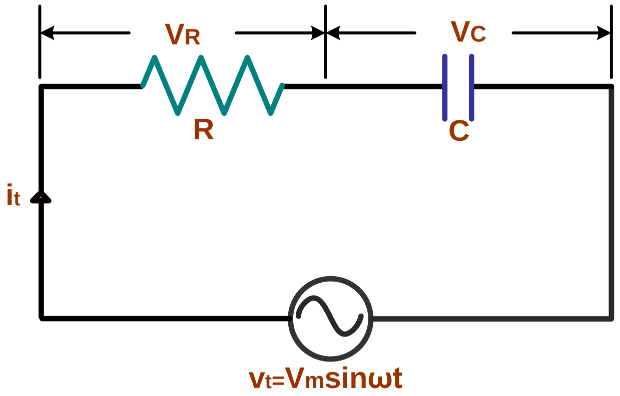


Figure 2.28 Circuit Diagram of Series R-C Circuit

- In the series circuit, the current i_t flowing through R and C will be the same. But the voltage across them will be different.
- The vector sum of voltage across resistor V_R and voltage across capacitor V_C will be equal to supply voltage v_t.

Waveforms and Phasor Diagram

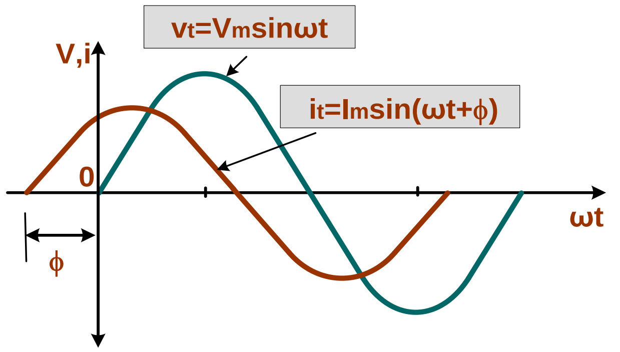


Figure 2.29 Waveform of Voltage and Current of Series R-C Circuit

- We know that in purely resistive the voltage and current in a resistive circuit both are in phase and therefore vector V_R is drawn superimposed to scale onto the current vector and in purely capacitive circuit the current I lead the voltage V_C by 90^o.
- So, to draw the vector diagram, first I taken as the reference. This is shown in the Fig. 2.30. Next V_R drawn in phase with I. Next V_C is drawn 90^o lagging the I. The supply voltage V is then phasor Addition of V_R and V_C.

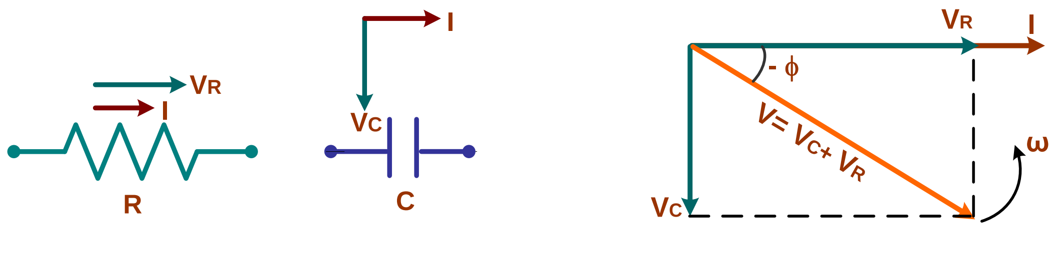


Figure 2.30 Phasor Diagram of Series R-C Circuit

- Thus, from the above equation it is clear that the current in series R-C circuit leads the applied voltage V by an angle ϕ. If supply voltage

$$v = V_m \, Sin \;\; \omega t$$

$$i = I_m \, sin(\omega t + \phi) \qquad \text{Where, } I_m = \frac{V_m}{Z}$$

Voltage Triangle	Impedance Triangle	Power Triangle

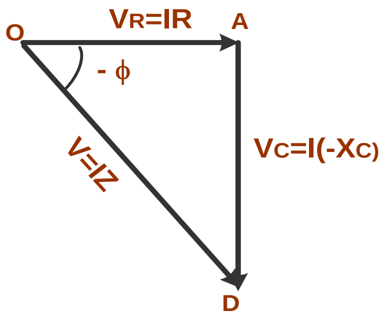
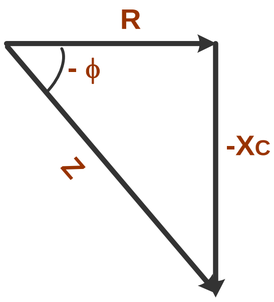
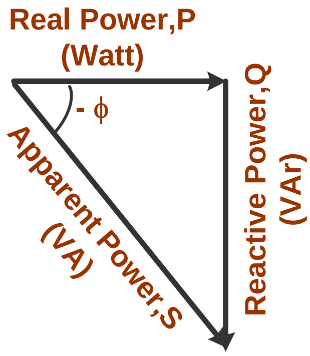

		

Figure 2.31 Voltage Triangle of Series R-C Circuit	*Figure 2.32 Impedance Triangle Series R-L Circuit*	*Figure 2.33 Power Triangle Series R-L Circuit*
$V = \sqrt{V_R^2 + V_C^2}$ $= \sqrt{(IR)^2 + (IX_C)^2}$ $= I \sqrt{R^2 + X_C^2}$ $= IZ \quad where, \; Z = \sqrt{R^2 + X_C^2}$	$Z = \sqrt{R^2 + X_C^2}$ $\phi = tan^{-1} \frac{-X_C}{R}$	$Real \;\; Power, \; P = V I \; cos\phi$ $= I^2 R$ $Reactive \;\; Power, Q = V I \; sin\phi$ $= I^2 X_L$ $Apparent \;\; Power, S = V \; I$ $= I^2 Z$

Power Factor

$$p.f. = cos\,\phi = \frac{R}{Z} or \frac{P}{S}$$

Power

- The instantaneous value of power drawn by this circuit is given by the product of the instantaneous values of voltage and current.

Instantaneous power

$$p_t = v \times i$$

$$p_t = V_m \, sin\,\omega t \times I_m \, sin(\omega t + \phi)$$

$$p_t = V_m \; I_m \, sin\,\omega t \times sin(\omega t + \phi)$$

$$p_t = \frac{2 \, V_m \; I_m \, sin\,\omega t \;\; \times \;\; sin \;\; (\omega t + \phi)}{2}$$

$$p_t = \frac{V_m I_m}{2}[cos \;\; \phi \text{- } cos(2\omega t + \phi)]$$

- Thus, the instantaneous values of the power consist of two components. First component remains constant w.r.t. time and second component vary with time.

Average Power

$$P_{ave} = \int_0^{2\pi} \frac{V_m I_m}{2}[\cos\ \phi - \cos(2\omega t+\phi)]\ d\omega t$$

$$P_{ave} = \frac{V_m I_m}{2\pi}\int_0^{2\pi} \frac{1}{2}[\cos\ \phi - \cos(2\omega t+\phi)]\ d\omega t$$

$$P_{ave} = \frac{V_m I_m}{4\pi}\left[\int_0^{2\pi} \cos\phi d\omega t - \int_0^{2\pi} \cos(2\omega t+\phi)\ d\omega t\right]$$

$$P_{ave} = \frac{V_m I_m}{4\pi}\left[\cos\phi(\omega t)_0^{2\pi} - \left\{\frac{\sin(2\omega t+\phi)}{2}\right\}_0^{2\pi}\right]$$

$$P_{ave} = \frac{V_m I_m}{4\pi}[\cos\phi(2\pi-0)] - \frac{V_m I_m}{8\pi}[\sin(4\pi+\phi)-\sin(\phi)]$$

$$P_{ave} = \frac{V_m I_m}{2}[\cos\phi] - \frac{V_m I_m}{8\pi}[\sin\phi - \sin\phi]$$

$$P_{ave} = \frac{V_m I_m}{2}\cos\phi - 0$$

$$P_{ave} = \frac{V_m}{\sqrt{2}}\frac{I_m}{\sqrt{2}}\cos\ \phi$$

$$P_{ave} = VI\cos\ \phi$$

2.10 Series RLC circuit

- Consider a circuit consisting of a resistor of R ohm, pure inductor of inductance L henry and a pure capacitor of capacitance C farads connected in series.

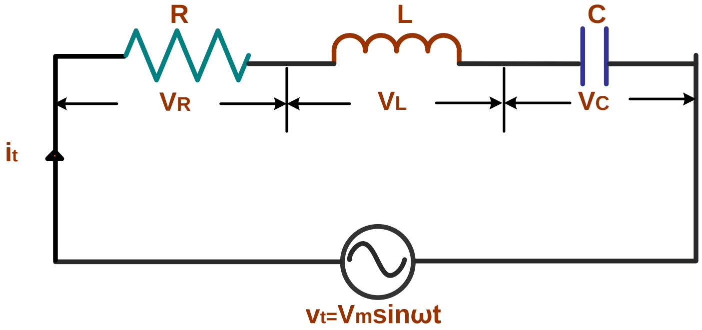
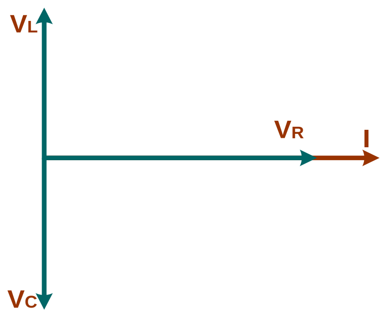


Figure 2.34 Circuit Diagram of Series RLC Circuit

Phasor Diagram



Current I is taken as reference.
V_R is drawn in phase with current,
V_L is drawn leading I by 90^0,
V_C is drawn lagging I by 90^0

Figure 2.35 Phasor Diagram of Series RLC Circuit

- Since V_L and V_C are in opposition to each other, there can be two cases:
  (1) $V_L > V_C$
  (2) $V_L < V_C$

Case-1

When, $V_L > V_C$, the phasor diagram would be as in the figure 2.36

Phasor Diagram

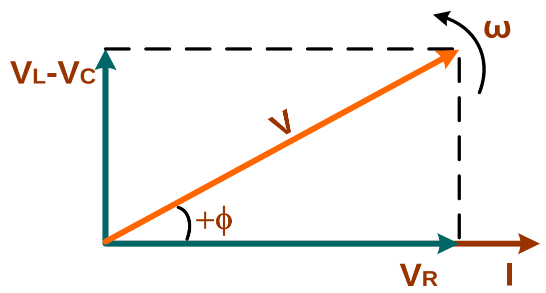


Figure 2.36 Phasor Diagram of Series R-L-C Circuit for Case VL > VC

$$V=\sqrt{V_R^2+\left(V_L-V_C\right)^2}$$
$$=\sqrt{(IR)^2+I\left(X_L-X_C\right)^2}$$
$$=I\sqrt{R^2+\left(X_L-X_C\right)^2}$$
$$=IZ \quad where,\ Z=\sqrt{R^2+\left(X_L-X_C\right)^2}$$

- The angle ϕ by which V leads I is given by

$$tan\phi=\frac{\left(V_L-V_C\right)}{R}$$
$$\therefore\phi=tan^{-1}\frac{I\left(X_L-X_C\right)}{IR}$$
$$\therefore\phi=tan^{-1}\frac{\left(X_L-X_C\right)}{R}$$

- Thus, when $V_L > V_C$ the series current I lags V by angle ϕ.

  If $v_t=V_m\ Sin\ \omega t$

  $i_t=I_m\ Sin\ \left(\omega t-\phi\right)$

- Power consumed in this case is equal to series RL circuit $P_{ave}=VI\cos\ \phi$.

Case-2

When, $V_L < V_C$, the phasor diagram would be as in the figure 2.37

Phasor Diagram

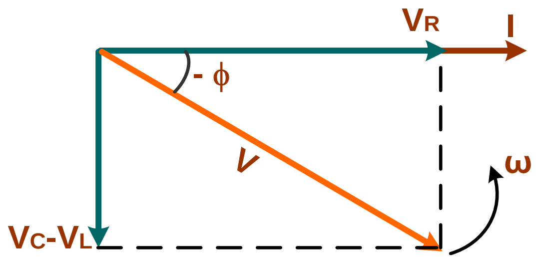


Figure 2.37 Phasor Diagram of Series R-L-C Circuit for Case VL < VC

$$V=\sqrt{V_R^2+\left(V_C-V_L\right)^2}$$
$$=\sqrt{(IR)^2+I\left(X_C-XL\right)^2}$$
$$=I\sqrt{R^2+\left(X_C-X_L\right)^2}$$
$$=IZ \quad where,\ Z=\sqrt{R^2+\left(X_C-X_L\right)^2}$$

- The angle ϕ by which V lags I is given by

$$tan\phi=\frac{\left(V_C-V_L\right)}{R}$$
$$\therefore\phi=tan^{-1}\frac{I\left(X_C-X_L\right)}{IR}$$
$$\therefore\phi=tan^{-1}\frac{\left(X_C-X_L\right)}{R}$$

- Thus, when $V_L < V_C$ the series current I leads V by angle ϕ.

  If $v_t=V_m\ Sin\ \omega t$

  $i_t=I_m\ Sin\ \left(\omega t+\phi\right)$

- Power consumed in this case is equal to series RC circuit $P_{ave}=VI\cos\ \phi$.

2.11 Series resonance RLC circuit

- Such a circuit shown in the Fig. 2.38 is connected to an A.C. source of constant supply voltage V but having variable frequency.

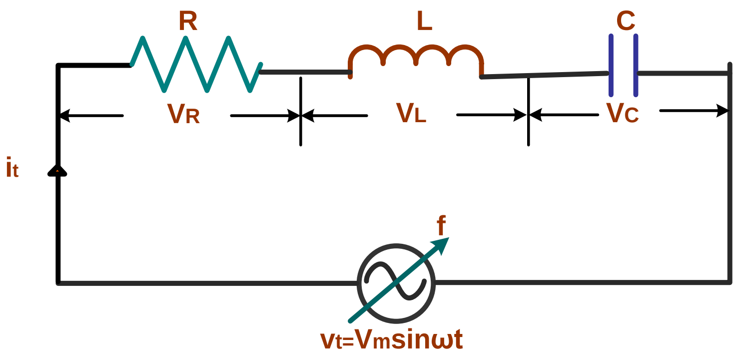


Figure 2.38 Circuit Diagram of Series Resonance RLC Circuit

- The frequency can be varied from zero, increasing and approaching infinity. Since X_L and X_C are function of frequency, at a particular frequency of applied voltage, X_L and X_C will become equal in magnitude and power factor become unity.

  Since $X_L = X_C$,

  $\therefore X_L - X_C = 0$

  $$\therefore \quad Z = \sqrt{R^2 + 0} = R$$

- The circuit, when $X_L = X_C$ and hence Z = R, is said to be in resonance. In a series circuit since current I remain the same throughout we can write,

  $IX_L = IX_C$ i.e. $V_L = V_C$

Phasor Diagram

- Shown in the Fig. 2.39 is the phasor diagram of series resonance RLC circuit.

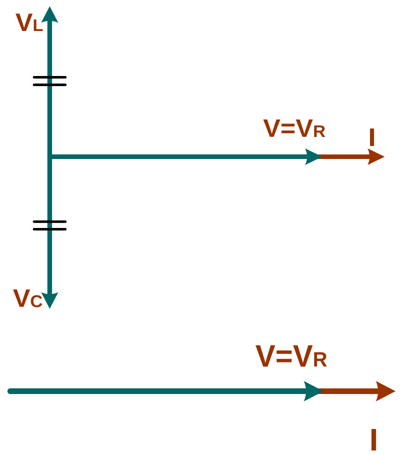


Figure 2.39 Phasor Diagram of Series Resonance RLC Circuit

- So, at resonance V_L and V_C will cancel out of each other.

$\therefore$ *The supply voltage*

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

$$\therefore \quad V = V_R$$

- i.e. the supply voltage will drop across the resistor R.

Resonance Frequency

- At resonance frequency $X_L = X_C$

$$\therefore \quad 2\pi f_r L = \frac{1}{2\pi f_r C} \qquad (f_r \text{ is the resonance frequency})$$

$$\therefore \quad f_r^2 = \frac{1}{(2\pi)^2 LC}$$

$$\therefore \quad f_r = \frac{1}{2\pi\sqrt{LC}}$$

Q- Factor

- The Q- factor is nothing but the voltage magnification during resonance.
- It indicates as to how many times the potential difference across L or C is greater than the applied voltage during resonance.
- Q- factor = Voltage magnification

$$Q - Factor = \frac{V_L}{V_S}$$

$$= \frac{IX_L}{IR} = \frac{X_L}{R}$$

$$= \frac{\omega_r L}{R}$$

$$= \frac{2\pi f_r L}{R} \qquad But \quad f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \quad Q - Factor = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Graphical Representation of Resonance

- **Resistance (R)** is independent of frequency. Thus, it is represented by straight line.
- **Inductive reactance (X_L)** is directly proportional to frequency. Thus, it is increases linearly with the frequency.

$$\because X_L = 2\pi fL$$

$$\therefore X_L \propto f$$

- **Capacitive reactance(X_C)** is inversely proportional to frequency. Thus, it is show as hyperbolic curve in fourth quadrant.

$$\because X_C = \frac{1}{2\pi fC}$$

$$\therefore X_C \propto \frac{1}{f}$$

- **Impedance (Z)** is minimum at resonance frequency.

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

For, $f = f_r, Z = R$

- **Current (I) is** maximum at resonance frequency.

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

For $f = f_r, I = \frac{V}{R}$ is maximum, I_{MAX}

- **Power factor** is unity at resonance frequency.

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

  For $f = f_r, p.f. = 1$ (unity)

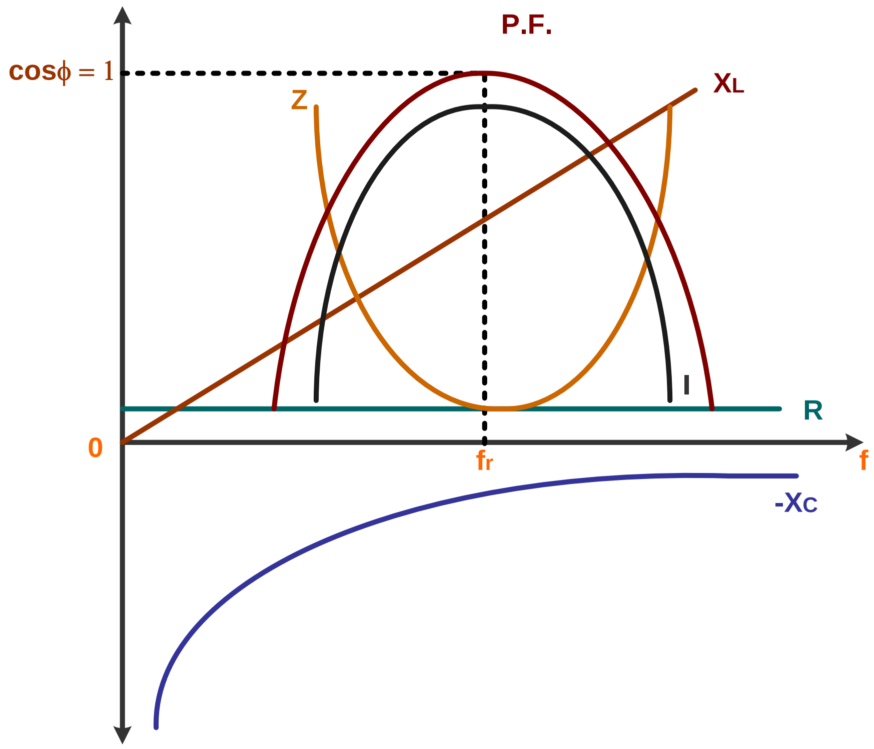


Figure 2.40 Graphical Representation of Series Resonance RLC Circuit

2.11 Parallel Resonance RLC Circuit

- Fig. 2.41 Shows a parallel circuit consisting of an inductive coil with internal resistance R ohm and inductance L henry in parallel with capacitor C farads.

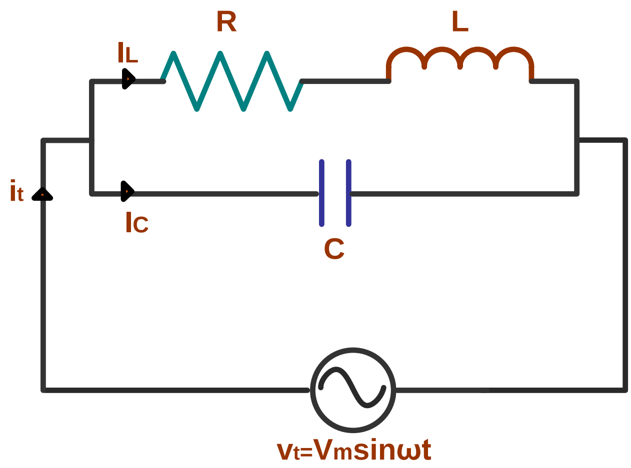


Figure 2.41 Circuit Diagram of Parallel Resonance RLC Circuit

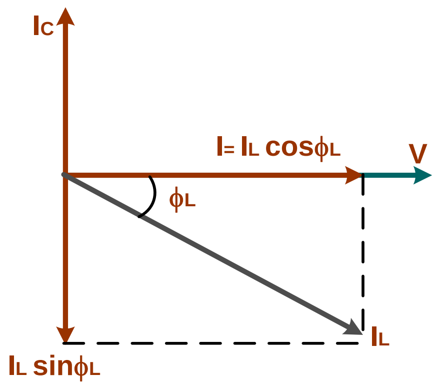


Figure 2.42 Circuit Diagram of Parallel Resonance RLC Circuit

- The current I_C can be resolved into its active and reactive components. Its active component $I_L \cos\phi$ and reactive component $I_L \sin\phi$.

- A parallel circuit is said to be in resonance when the power factor of the circuit becomes unity. This will happen when the resultant current I is in phase with the resultant voltage V and hence the phase angle between them is zero.
- In the phasor diagram shown, this will happen when $I_C = I_L \sin\phi$ and $I = I_L \cos\phi$.

Resonance Frequency

- To find the resonance frequency, we make use of the equation $I_C = I_L \sin\phi$.

$$I_C = I_L \sin\phi$$

$$\frac{V}{X_C} = \frac{V}{Z_L}\frac{X_L}{Z_L}$$

$$Z_L^2 = X_L X_C$$

$$Z_L^2 = 2\pi f_r L \quad \frac{1}{2\pi f_r C} = \frac{L}{C}$$

$$\left(R^2 + \omega_r^2 L^2\right) = \frac{L}{C}$$

$$\omega_r^2 = \frac{L}{C}\left(\frac{1}{L^2}\right) - \frac{R^2}{L^2}$$

$$\left(2\pi f_r\right)^2 = \frac{L}{C}\left(\frac{1}{L^2}\right) - \frac{R^2}{L^2}$$

$$f_r = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}$$

- If the resistance of the coil is negligible,

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

Impedance

- To find the resonance frequency, we make use of the equation $I = I_L \cos\phi$ because, at resonance, the supply current I will be in phase with the supply voltage V.

$$I = I_L \cos\phi$$

$$\frac{V}{Z} = \frac{V}{Z_L}\frac{R}{Z_L}$$

$$Z = \frac{Z_L^2}{R} \qquad But\ Z_L^2 = \frac{L}{C}$$

$$Z = \frac{L}{RC}$$

- The impedance during parallel resonance is very large because of L and C has a very large value at that time. Thus, impedance at the resonance is maximum.

$$I = \frac{V}{Z}\ will\ \ be\ minimum.$$

Q-Factor

- Q- factor = Current magnification

$$Q - Factor = \frac{I_L}{I}$$

$$= \frac{I_L \sin\phi}{I_L \cos\phi} = \frac{\sin\phi}{\cos\phi}$$

$$= \tan\phi = \frac{\omega_r L}{R}$$

$$= \frac{2\pi f_r L}{R} \qquad But \quad f_r = \frac{1}{2\pi\sqrt{LC}}$$

$$\therefore \quad Q - Factor = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Graphical representation of Parallel Resonance

- **Conductance (G)** is independent of frequency. Hence it is represented by straight line parallel to frequency.
- **Inductive Susceptance (B_L)** is inversely proportional to the frequency. Also, it is negative.

$$B_L = \frac{1}{jX_L} = \frac{1}{j2\pi fL}, \qquad \therefore B_L \propto \frac{1}{f}$$

- **Capacitive Susceptance (B_C)** is directly proportional to the frequency.

$$B_C = \frac{1}{-jX_C} = \frac{j}{X_C} = j2\pi fC, \quad \therefore B_C \propto f$$

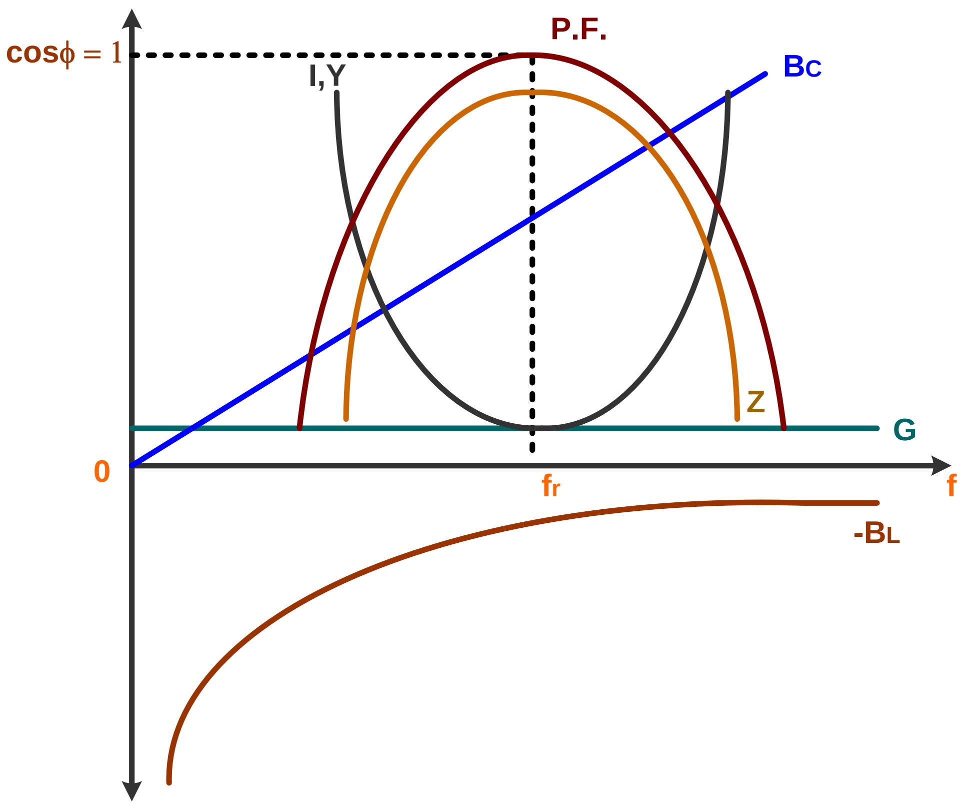


Figure 2.43 Graphical Representation of Parallel Resonance RLC Circuit

- **Admittance (Y)** is minimum at resonance frequency.

  $Y = \sqrt{G^2 + \left(B_L - B_C\right)^2}$

  For, $f = f_r, Y = G$

- **Current (I)** is minimum at resonance frequency.

  $\because I = VY$

- **Power factor** is unity at resonance frequency.

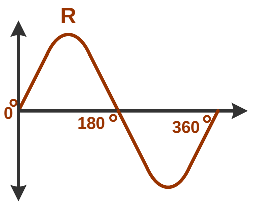
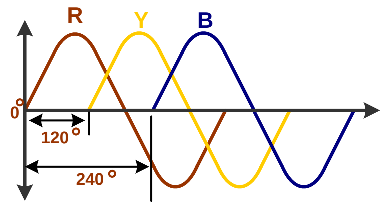
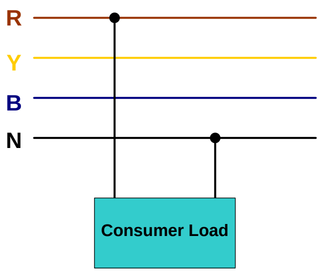
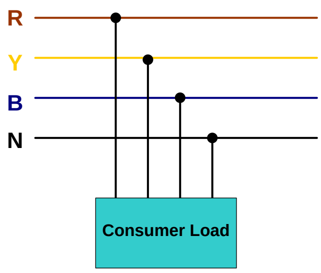
  Power factor$=\cos\phi=\dfrac{G}{Y}$

2.12 Comparison of Series and Parallel Resonance

Sr.No.	Description	Series Circuit	Parallel Circuit
1	Impedance at resonance	Minimum Z = R	Maximum $Z = \dfrac{L}{RC}$
2	Current	Maximum $I = \dfrac{V}{R}$	Minimum $I = \dfrac{V}{L/RC}$
3	Resonance Frequency	$f_r = \dfrac{1}{2\pi\sqrt{LC}}$	$f_r = \dfrac{1}{2\pi\sqrt{LC}}$
4	Power Factor	Unity	Unity
5	Q- Factor	$f_r = \dfrac{1}{R}\sqrt{\dfrac{L}{C}}$	$f_r = \dfrac{1}{R}\sqrt{\dfrac{L}{C}}$
6	It magnifies at resonance	Voltage	Current

Three - Phase AC Circuits

2.13 Comparison between single phase and three phase

Basis for Comparison	**Single Phase**	**Three Phase**
Definition	The power supply through one conductor.	The power supply through three conductors.
Wave Shape		
Number of wire	Require two wires for completing the circuit	Requires four wires for completing the circuit
Voltage	Carry 230V	Carry 415V
Phase Name	Split phase	No other name
Network	Simple	Complicated
Loss	Maximum	Minimum
Power Supply Connection		
Efficiency	Less	High
Economical	Less	More
Uses	For home appliances.	In large industries and for running heavy loads.

2.14 Generation of three phase EMF

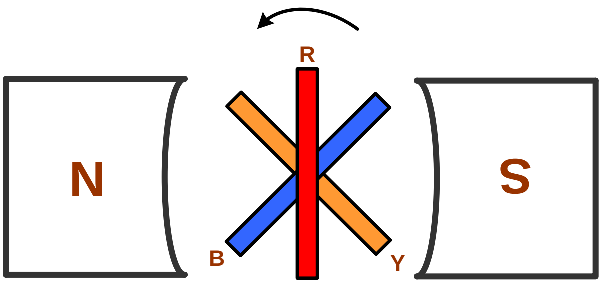


Figure 2.44 Generation of three phase emf

- According to Faraday's law of electromagnetic induction, we know that whenever a coil is rotated in a magnetic field, there is a sinusoidal emf induced in that coil.

- Now, we consider 3 coil C_1(R-phase), C_2(Y-phase) and C_3(B-phase), which are displaced 120^0 from each other on the same axis. This is shown in fig. 2.44.
- The coils are rotating in a uniform magnetic field produced by the N and S pols in the counter clockwise direction with constant angular velocity.
- According to Faraday's law, emf induced in three coils. The emf induced in these three coils will have phase difference of 120^0. i.e. if the induced emf of the coil C_1 has phase of 0^0, then induced emf in the coil C_2 lags that of C_1 by 120^0 and C_3 lags that of C_2 120^0.

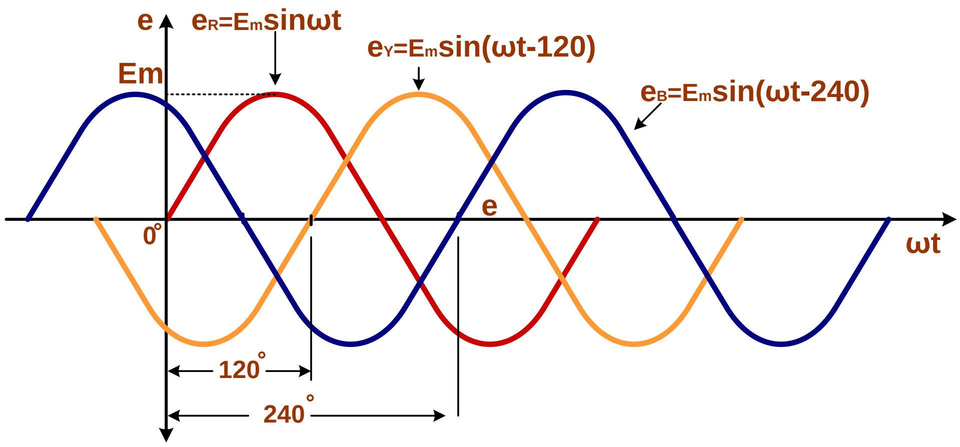


Figure 2.45 Waveform of Three Phase EMF

- Thus, we can write,

$$e_R = E_m \sin\omega t$$

$$e_Y = E_m \sin\left(\omega t - 120^0\right)$$

$$e_B = E_m \sin\left(\omega t - 240^0\right)$$

- The above equation can be represented by their phasor diagram as in the Fig. 2.46.

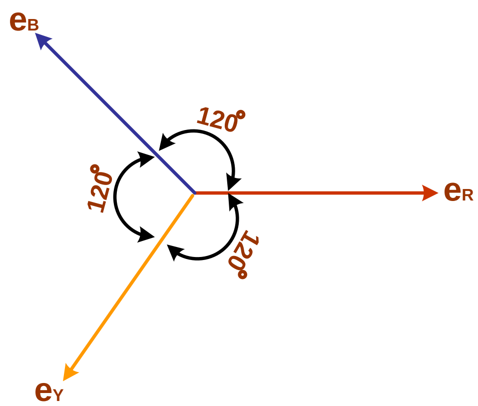


Figure 2.46 Phasor Diagram of Three Phase EMF

2.15 Important definitions

➢ **Phase Voltage**

It is defined as the voltage across either phase winding or load terminal. It is denoted by V_{ph}.

Phase voltage V_{RN}, V_{YN} and V_{BN} are measured between R-N, Y-N, B-N for star connection and between R-Y, Y-B, B-R in delta connection.

- **Line voltage**

  It is defined as the voltage across any two-line terminal. It is denoted by V_L.

  Line voltage V_{RY}, V_{YB}, V_{BR} measure between R-Y, Y-B, B-R terminal for star and delta connection both.

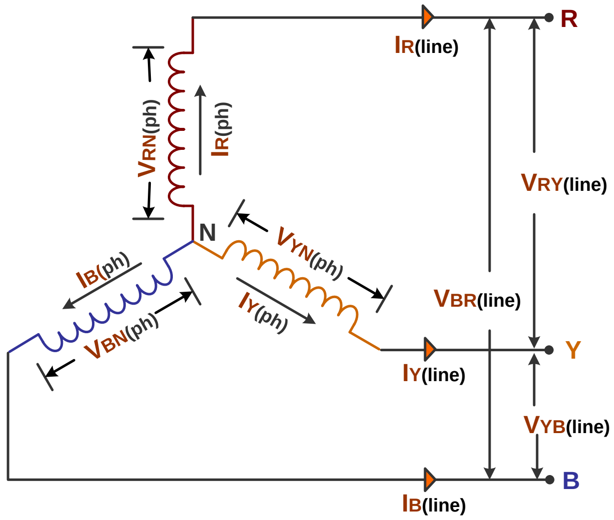


Figure 2.47 Three Phase Star Connection System

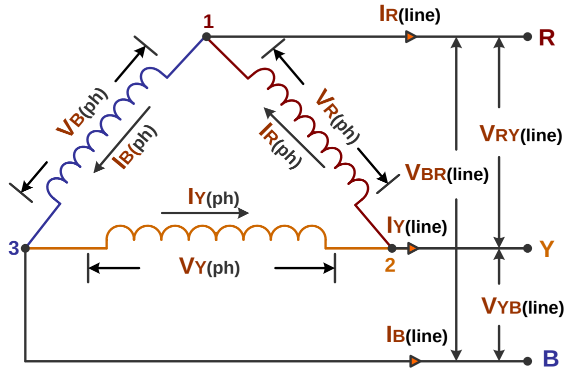


Figure 2.48 Three Phase Delta Connection System

- **Phase current**

  It is defined as the current flowing through each phase winding or load. It is denoted by I_{ph}.

  Phase current $I_{R(ph)}$, $I_{Y(ph)}$ and $I_{B(Ph)}$ measured in each phase of star and delta connection. respectively.

- **Line current**

  It is defined as the current flowing through each line conductor. It denoted by I_L.

  Line current $I_{R(line)}$, $I_{Y(line)}$, and $I_{B((line)}$ are measured in each line of star and delta connection.

- **Phase sequence**

  The order in which three coil emf or currents attain their peak values is called the phase sequence. It is customary to denoted the 3 phases by the three colours. i.e. red (R), yellow (Y), blue (B).

- **Balance System**

  A system is said to be balance if the voltages and currents in all phase are equal in magnitude and displaced from each other by equal angles.

- **Unbalance System**

  A system is said to be unbalance if the voltages and currents in all phase are unequal in magnitude and displaced from each other by unequal angles.

- **Balance load**

  In this type the load in all phase are equal in magnitude. It means that the load will have the same power factor equal currents in them.

- **Unbalance load**

  In this type the load in all phase have unequal power factor and currents.

2.16 Relation between line and phase values for voltage and current in case of balanced delta connection.

- **Delta (Δ) or Mesh connection**, starting end of one coil is connected to the finishing end of other phase coil and so on which giving a closed circuit.

Circuit Diagram

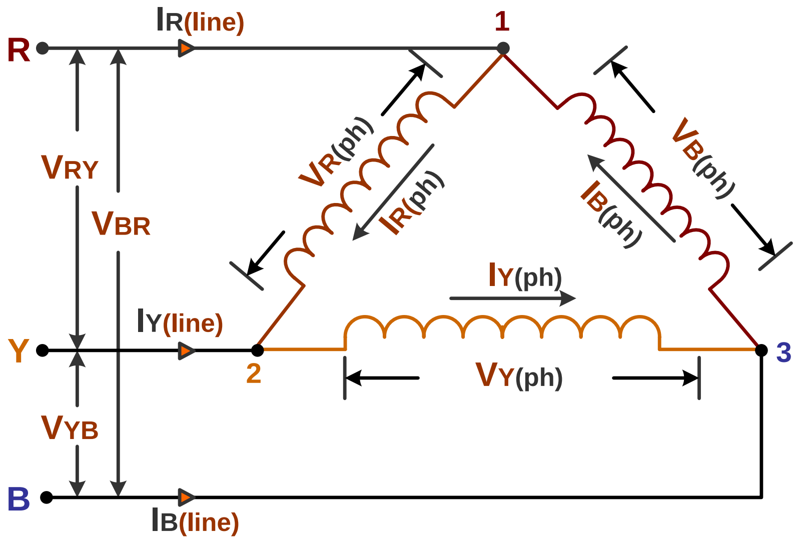


Figure 2.49 Three Phase Delta Connection

- Let,

$$\text{Line voltage, } V_{RY} = V_{YB} = V_{BR} = V_L$$

$$\text{Phase voltage, } V_{R(ph)} = V_{Y(ph)} = V_{B(ph)} = V_{ph}$$

$$\text{Line current,} I_{R(line)} = I_{Y(line)} = I_{B(line)} = I_{line}$$

$$\text{Phase current,} I_{R(ph)} = I_{Y(ph)} = I_{B(ph)} = I_{ph}$$

Relation between line and phase voltage

- For delta connection line voltage V_L and phase voltage V_{ph} both are same.

$$V_{RY} = V_{R(ph)}$$

$$V_{YB} = V_{Y(ph)}$$

$$V_{BR} = V_{B(ph)}$$

$$\therefore V_L = V_{ph}$$

Line voltage = Phase Voltage

Relation between line and phase current

- For delta connection,

$$I_{R(line)} = I_{R(ph)} - I_{B(ph)}$$

$$I_{Y(line)} = I_{Y(ph)} - I_{R(ph)}$$

$$I_{B(line)} = I_{B(ph)} - I_{Y(ph)}$$

- i.e. current in each line is vector difference of two of the phase currents.

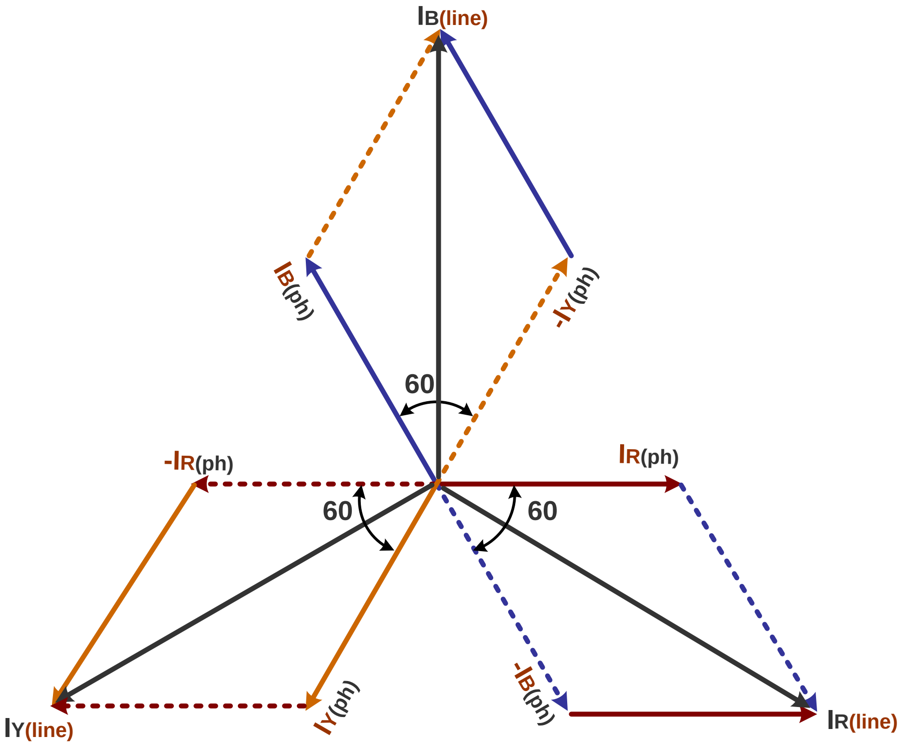


Figure 2.50 Phasor Diagram of Three Phase Delta Connection

- So, considering the parallelogram formed by I_R and I_B.

$$I_{R(line)}=\sqrt{I_{R(ph)}^{\ 2}+I_{B(ph)}^{\ 2}+2I_{R(ph)}I_{B(ph)}\cos\theta}$$

$$\therefore I_L=\sqrt{I_{ph}^{\ 2}+I_{ph}^{\ 2}+2I_{ph}I_{ph}\cos 60^\circ}$$

$$\therefore I_L=\sqrt{I_{ph}^{\ 2}+I_{ph}^{\ 2}+2I_{ph}^{\ 2}\times\left(\frac{1}{2}\right)}$$

$$\therefore I_L=\sqrt{3I_{ph}^{\ 2}}$$

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

- Similarly, $I_{Y(line)}=I_{B(line)}=\sqrt{3}\ I_{ph}$
- Thus, in delta connection Line current = $\sqrt{3}$ Phase current

Power

$$P=V_{ph}I_{ph}\cos\phi+V_{ph}I_{ph}\cos\phi+V_{ph}I_{ph}\cos\phi$$

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

$$P=3V_L\left(\frac{I_L}{\sqrt{3}}\right)\cos\phi$$

$$\therefore P=\sqrt{3}V_LI_L\cos\phi$$

2.17 Relation between line and phase values for voltage and current in case of balanced star connection.

- In the **Star Connection**, the similar ends (either start or finish) of the three windings are connected to a common point called star or neutral point.

Circuit Diagram

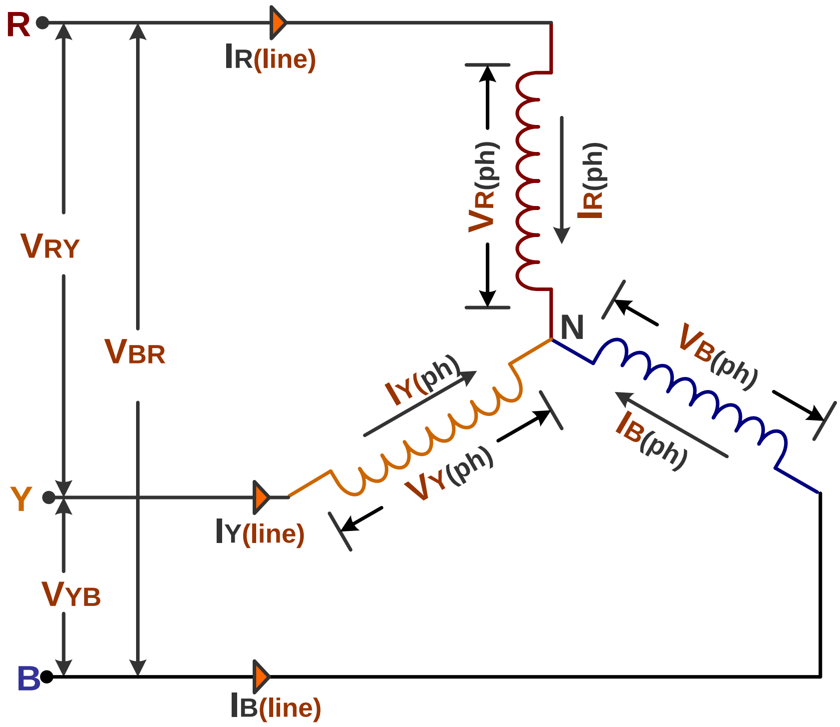


Figure 2.51 Circuit Diagram of Three Phase Star Connection

- Let,

line voltage, $V_{RY} = V_{BY} = V_{BR} = V_L$

phase voltage, $V_{R(ph)} = V_{Y(ph)} = V_{B(ph)} = V_{ph}$

line current, $I_{R(line)} = I_{Y(line)} = I_{B(line)} = I_{line}$

phase current, $I_{R(ph)} = I_{Y(ph)} = I_{B(ph)} = I_{ph}$

Relation between line and phase voltage

- For star connection, line current I_L and phase current I_{ph} both are same.

$$I_{R(line)} = I_{R(ph)}$$

$$I_{Y(line)} = I_{Y(ph)}$$

$$I_{B(line)} = I_{B(ph)}$$

$$\therefore \quad I_L = I_{ph}$$

Line Current = Phase Current

Relation between line and phase voltage

- For delta connection,

$$V_{RY} = V_{R(ph)} - V_{Y(ph)}$$
$$V_{YB} = V_{Y(ph)} - V_{B(ph)}$$
$$V_{BR} = V_{B(ph)} - V_{R(ph)}$$

- i.e. line voltage is vector difference of two of the phase voltages. Hence,

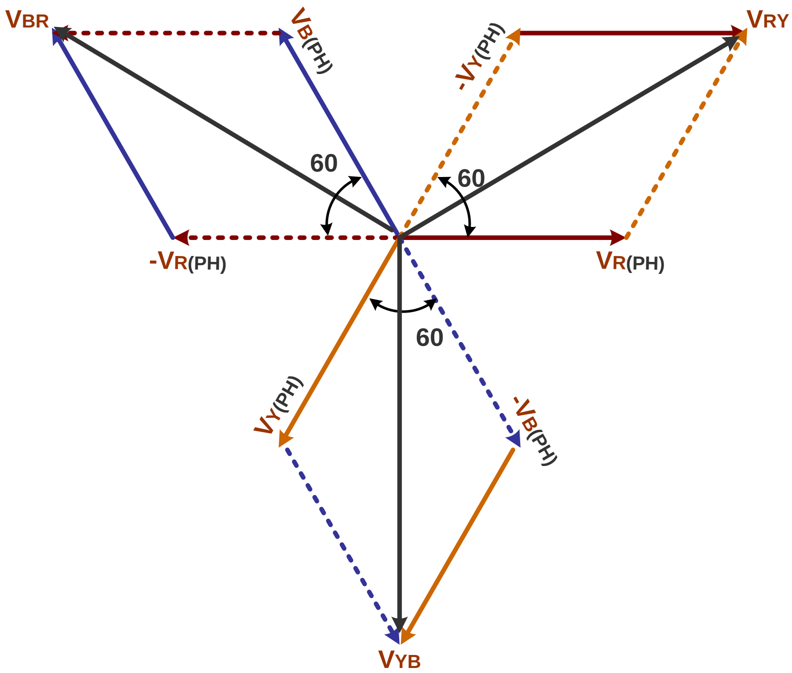


Figure 2.52 Phasor Diagram of Three Phase Star Connection

From parallelogram,

$$V_{RY} = \sqrt{V_{R(ph)}^2 + V_{Y(ph)}^2 + 2V_{R(ph)}V_{Y(ph)}\cos\theta}$$
$$\therefore V_L = \sqrt{V_{ph}^2 + V_{ph}^2 + 2V_{ph}V_{ph}\cos 60^\circ}$$
$$\therefore V_L = \sqrt{V_{ph}^2 + V_{ph}^2 + 2V_{ph}^2 \times \left(1/2\right)}$$
$$\therefore V_L = \sqrt{3V_{ph}^2}$$
$$\therefore V_L = \sqrt{3}V_{ph}$$

- Similarly, $V_{YB} = V_{BR} = \sqrt{3}\ V_{ph}$
- Thus, in star connection Line voltage = $\sqrt{3}$ Phase voltage

Power

$$P = V_{ph}I_{ph}\cos\phi + V_{ph}I_{ph}\cos\phi + V_{ph}I_{ph}\cos\phi$$
$$P = 3V_{ph}I_{ph}\cos\phi$$
$$P = 3\left(\frac{V_L}{\sqrt{3}}\right)I_L\cos\phi$$
$$\therefore P = \sqrt{3}V_LI_L\cos\phi$$

2.18 Measurement of power in balanced 3-phase circuit by two-watt meter method

- This is the method for 3-phase power measurement in which sum of reading of two wattmeter gives total power of system.

Circuit Diagram

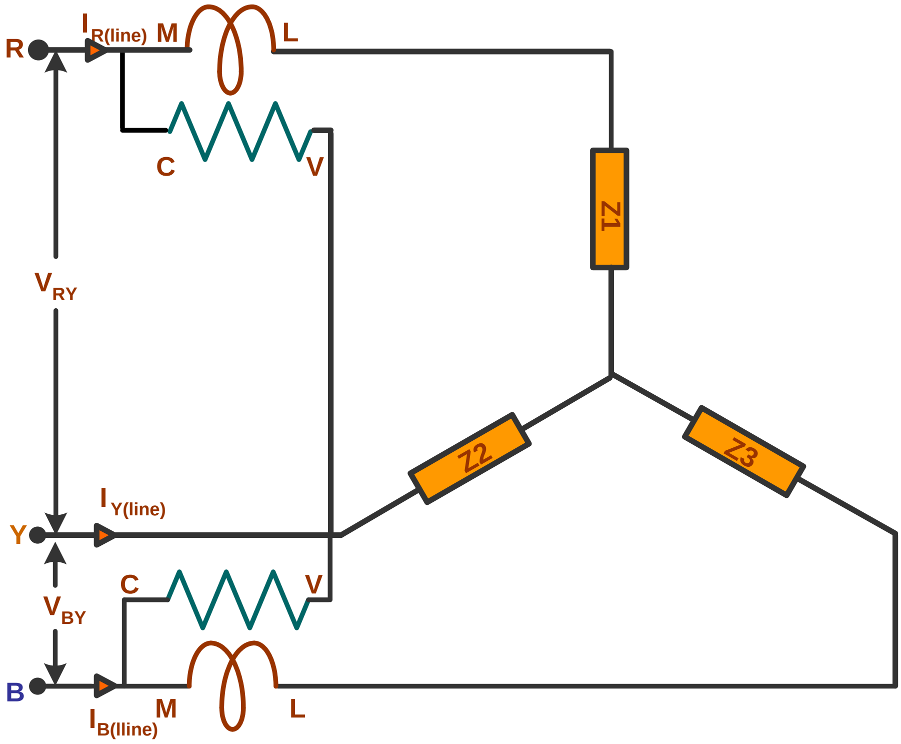


Figure 2.53 Circuit Diagram of Power Measurement by Two-Watt Meter in Three Phase Star Connection

- The load is considered as an inductive load and thus, the phasor diagram of the inductive load is drawn below in Fig. 2.54.

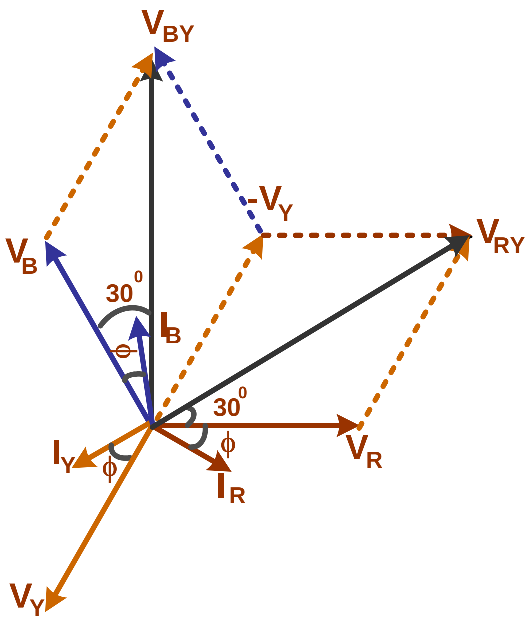


Figure 2.54 Phasor Diagram of Power Measurement by Two-Watt Meter in Three Phase Star Connection

- The three voltages V_{RN}, V_{YN} and V_{BN}, are displaced by an angle of 120^0 degree electrical as shown in the phasor diagram. The phase current lag behind their respective phase voltages by an angle ϕ. The power measured by the Wattmeter, W_1 and W_2.

  Reading of wattmeter, $W_1 = V_{RY} I_R \cos\phi_1 = V_L I_L \cos(30+\phi)$

  Reading of wattmeter, $W_2 = V_{BY} I_B \cos\phi_2 = V_L I_L \cos(30-\phi)$

  Total power, P = W_1+W_2

$$\therefore P = V_L I_L \cos(30+\phi) + V_L I_L \cos(30-\phi)$$
$$= V_L I_L \left[\cos(30+\phi) + \cos(30-\phi)\right]$$
$$= V_L I_L \left[\cos 30 \cos\phi + \sin 30 \sin\phi + \cos 30 \cos\phi - \sin 30 \sin\phi\right]$$
$$= V_L I_L \left[2\cos 30 \cos\phi\right]$$
$$= V_L I_L \left[2\left(\frac{\sqrt{3}}{2}\right)\cos\phi\right]$$
$$= \sqrt{3} V_L I_L \cos\phi$$

- Thus, the sum of the readings of the two wattmeter is equal to the power absorbed in a 3-phase balanced system.

Determination of Power Factor from Wattmeter Readings

- As we know that

$$W_1 + W_2 = \sqrt{3} V_L I_L \cos\phi$$

Now,

$$W_1 - W_2 = V_L I_L \cos(30+\phi) - V_L I_L \cos(30-\phi)$$
$$= V_L I_L \left[\cos 30 \cos\phi + \sin 30 \sin\phi - \cos 30 \cos\phi + \sin 30 \sin\phi\right]$$
$$= V_L I_L \left[2\sin 30 \sin\phi\right]$$
$$= V_L I_L \left[2\left(\frac{1}{2}\right)\sin\phi\right] = V_L I_L \sin\phi$$

$$\therefore \frac{\sqrt{3}(W_1 - W_2)}{(W_1 + W_2)} = \frac{\sqrt{3} V_L I_L \sin\phi}{\sqrt{3} V_L I_L \cos\phi} = \tan\phi$$

$$\therefore \tan\phi = \frac{\sqrt{3}(W_1 - W_2)}{(W_1 + W_2)}$$

- Power factor of load given as,

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

Effect of power factor on wattmeter reading:

- From the Fig. 2.54, it is clear that for lagging power factor $\cos\phi$, the wattmeter readings are

$$W_1 = V_L I_L \cos(30+\phi)$$

$$W_2 = V_L I_L \cos(30-\phi)$$

- Thus, readings W1 and W2 will very depending upon the power factor angle ϕ.

p.f	ϕ	$W_1 = V_L I_L \cos(30+\phi)$	$W_2 = V_L I_L \cos(30-\phi)$	**Remark**
$\cos\phi = 1$	0^0	$\frac{\sqrt{3}}{2} V_L I_L$	$\frac{\sqrt{3}}{2} V_L I_L$	Both equal and +ve
$\cos\phi = 0.5$	60^0	0	$\frac{\sqrt{3}}{2} V_L I_L$	One zero and second total power
$\cos\phi = 0$	90^0	$-\frac{1}{2} V_L I_L$	$\frac{1}{2} V_L I_L$	Both equal but opposite

****

3.1 What is magnetic material and give difference between magnetic and non magnetic material.

- The magnetic material are define as material in which a state of magnetism can be induced. Magnetic materials, when magnetized create a magnetic field.

Magnetic material	Nonmagnetic material
• Magnetic materials are materials having a magnetic domain and are attracted to an external magnetic field.	• Non-magnetic materials are materials that are not attracted to an external magnetic field.
• The magnetic domains of magnetic materials are aligned either parallel or anti parallel arrangements thus they can respond to a magnetic field when they are under the influence of an external magnetic field.	• The magnetic domains of non-magnetic materials are arranged in a random manner in such a way that the magnetic moments of these domains are cancelled out. Thus, they do not respond to a magnetic field.
• Magnetic materials are used to make permanent magnets are the parts of operating systems where magnetic properties are required.	• Magnetic materials are used to make permanent magnets are the parts of operating systems where magnetic properties are required.

3.2 Explain the different types of magnetic material

- Classification of magnetic material as below:
  - ✓ Paramagnetic material
  - ✓ Diamagnetic material
  - ✓ Ferromagnetic material

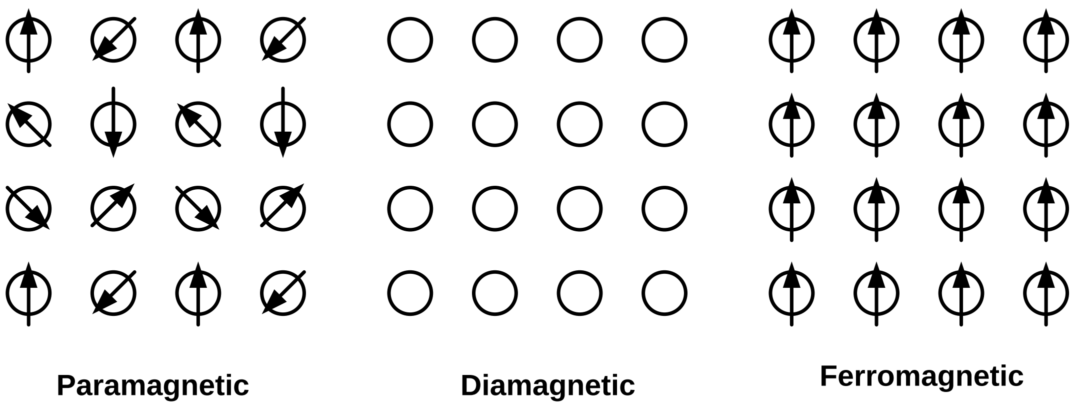


Figure 2.1 Types of magnetic materials

(1) Paramagnetic material

- If a bar of paramagnetic material is suspended in between the pole pieces of an electromagnet, it sets itself parallel to the lines of force.
- When a bar of paramagnetic material is placed in a magnetic filed the lines of force tend to accumulate in it.
- If a paramagnetic liquid is placed in a watch glass resting on the pole pieces of an electromagnet then it accumulates in the middle.
- It is because in the central region the field is the strongest. If the pole pieces are not close together the field is strongest near the poles and the liquid moves away from the

- center giving an almost opposite effect.
- If one end of a narrow u-tube containing a paramagnetic liquid is placed within the pole pieces of an electromagnet in such a manner that the level of the liquid is in the lie with the field, then on applying the field the level of the liquid rises.
- The rises in proportional to the susceptibility of the liquid.
- When a paramagnetic gas is allowed to ascend between the poles pieces of an electromagnet it spreads along the direction of the field.
- Example of paramagnetic material aluminum, manganese platinum, crown glass solution of salts of iron and oxygen

(2) Diamagnetic material

- When a diamagnetic substance is placed in a magnetic field it sets itself at right angles to the direction of the lines of force.
- When a diamagnetic material is placed within a magnetic field the lines of force tend to go away from the material.
- When a diamagnetic substance is placed in a watch glass on the pole pieces of a magnet the liquid accumulates on the sides causing a depression at the center which is the strongest part of the field.
- When the distance between the pole pieces is larger, the effect is reversed.
- A diamagnetic liquid in a u-tube placed in a magnetic field shows as depression. When a diamagnetic gas is allowed to ascend between, the poles piece of an electromagnet it spreads across the field.
- Example of diamagnetic material bismuth, phosphorus ,antimony, copper, water, alcohol, ,hydrogen

(3) Ferromagnetic material

- Ferromagnetic substance shows the properties of the paramagnetic substance to a much greater degree.
- The susceptibility has a positive value and the permeability is also very large.
- The intensity of magnetization I is proportional to the magnetizing field H for small value.
- Example of Ferromagnetic material Iron nickel, cobalt and their alloys
- Comparison of difference types of magnetic material

Properties	Paramagnetic Materials	Diamagnetic Material	Ferromagnetic Materials
State	They can be solid, liquid or gas.	They can be solid, liquid or gas.	They are solid.
Effect of Magnet	Weakly attracted by a magnet.	Weakly repelled by a magnet.	Strongly attracted by a magnet.
Behavior under non-uniform field	Tend to move from low to high field region.	Tend to move from high to low region.	Tend to move from low to high field region.
Behavior under external field	They do not preserve the magnetic properties once the external field	They do not preserve the magnetic properties once the external field	They preserve the magnetic properties after the external field is removed.

	is removed.	is removed.	
Effect of Temperature	With the rise of temperature, it becomes a diamagnetic.	No effect.	Above curie point, it becomes a paramagnetic.
Permeability	Little greater than unity	Little less than unity	Very high
Susceptibility	Little greater than unity and positive	Little less than unity and negative	Very high and positive
Examples	Lithium, Tantalum, Magnesium	Copper, Silver, Gold	Iron, Nickel, Cobalt

3.3 B-H curve and magnetic hysteresis of magnetic material

- **B-H Curve**
- The curve plotted between flux density B and magnetizing force H of a material is called magnetizing or B-H curve.
- The shape of curve is non-linear. This indicates that relative permeability ($\mu_r = B / \mu_0 H$) of a material is not constant but it varies.
- B-H curves are very useful to analyze the magnetic circuit. If value of flux density and dimension of magnetic circuit is known than from B-H curve total ampere turn can be easily known.

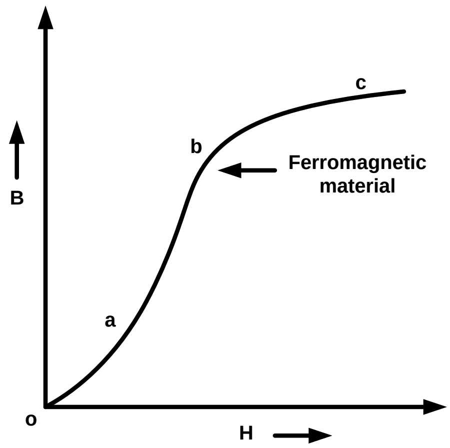


Figure 2.2 B-H Curve

- **Magnetic hysteresis**
- The phenomenon of lagging behind of induction flux density (B) behind the magnetizing force (H) in magnetic material is called magnetic hysteresis.
- Hysteresis loop is a four quadrant B – H graph from where the hysteresis loss, coercive force and retentively of magnetic material are obtained.
- To understand hysteresis loop, we suppose to take a magnetic material to use as a core around which insulated wire is wound.
- The coils is connected to the supply (DC) through variable resistor to vary the current I. We know that current I is directly proportional to the value of magnetizing force (H).
- When supply current I = 0, so no existence of flux density (B) and magnetizing force (H). The corresponding point is o in the graph above.

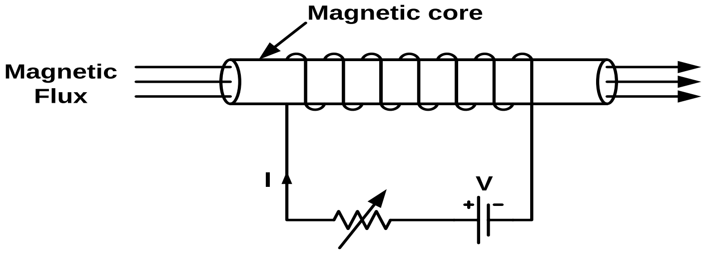


Figure 2.3 Circuit diagram form Magnetic hysteresis

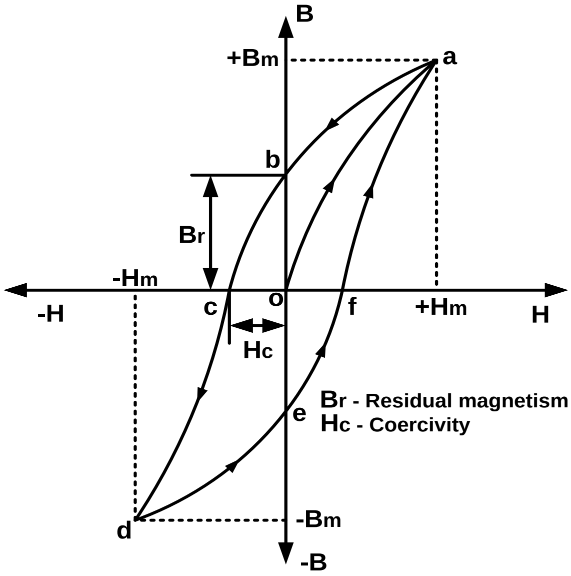


Figure 2.4 magnetic hysteresis loop

- When current is increased from zero value to a certain value, magnetizing force and flux density both are set up and increased following the path o to a.
- For a certain value of current, flux density becomes maximum (B_m). The point indicates the magnetic saturation or maximum flux density of this core material. All element of core material get aligned perfectly.
- When the value of current is decreased from its value of magnetic flux saturation, H is decreased along with decrement of B not following the previous path rather following the curve a to b.
- The point b indicates H = 0 for I = 0 with a certain value of B. This lagging of B behind H is called hysteresis.
- The point b explains that after removing of magnetizing force (H), magnetism property with little value remains in this magnetic material and it is known as residual magnetism (B_r) or residual flux density.
- If the direction of the current I is reversed, the direction of H also gets reversed. The increment of H in reverses direction following path b – c decreases the value of residual magnetism that gets zero at point c with certain negative value of H. This negative value of H is called coercive force (H_c)

- Now B gets reverses following path c to d. At point'd', again magnetic saturation takes place but in opposite direction with respect to previous case. At point'd', B and H get maximum values in reverse direction.
- If decrease the value of H in this direction, again B decreases following the path d. At point e, H gets zero valued but B is with finite value.
- The point e stands for residual magnetism ($-B_r$) of the magnetic core material in opposite direction with respect to previous case.
- If the direction of H again reversed by reversing the current I, then residual magnetism or residual flux density ($-B_r$) again decreases and gets zero at point 'f' following the path e to f.
- Again further increment of H, the value of B increases from zero to its maximum value or saturation level at point a following path f to a.
- Hard and soft material hysteresis loop are given below.

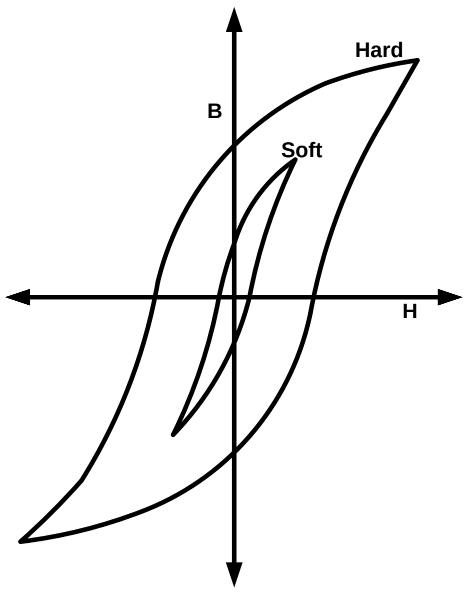


Figure 2.5 Types of hysteresis loop

3.4 What is requirement of transformer?

- A transformer is defined as a static device converts the electric power from one electrical circuit to another electrical circuit without change of frequency. It can also up and down the voltage level.
- In our country usually electrical power is generated at 11kV. For economical reason a.c. power is transmitted at very high voltage (220kV or 400 kV) over long distance, therefore, a step up transformer is applied at the generating station.
- To feed different area, voltage is step down to different levels by transformer at various substations.
- Ultimately for utilization of electrical power, the voltage is step down to 400/230 V for safety reasons.

3.5 Explain construction and working of single phase transformer

- A transformer is defined as a static device converts the electric power from one electrical circuit to another electrical circuit without change of frequency. It can also up and down the voltage level.
- **Construction**

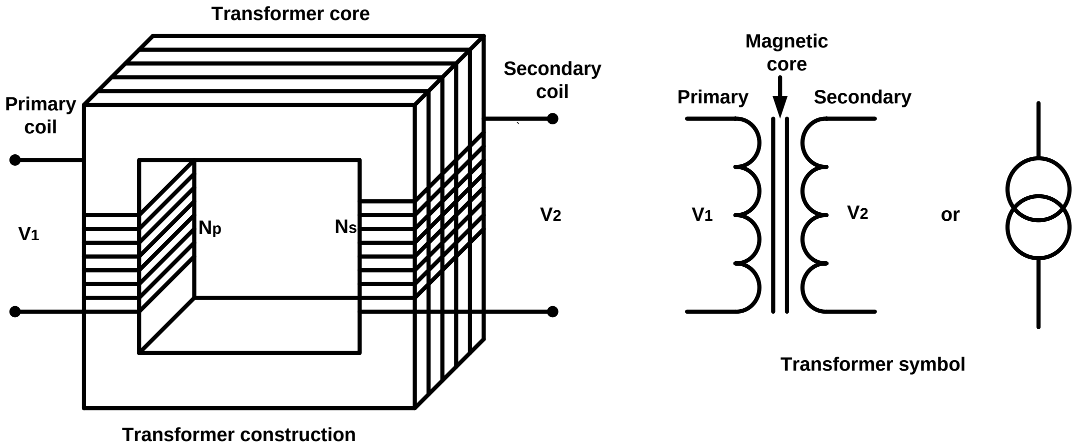


Figure 2.6 Transformer

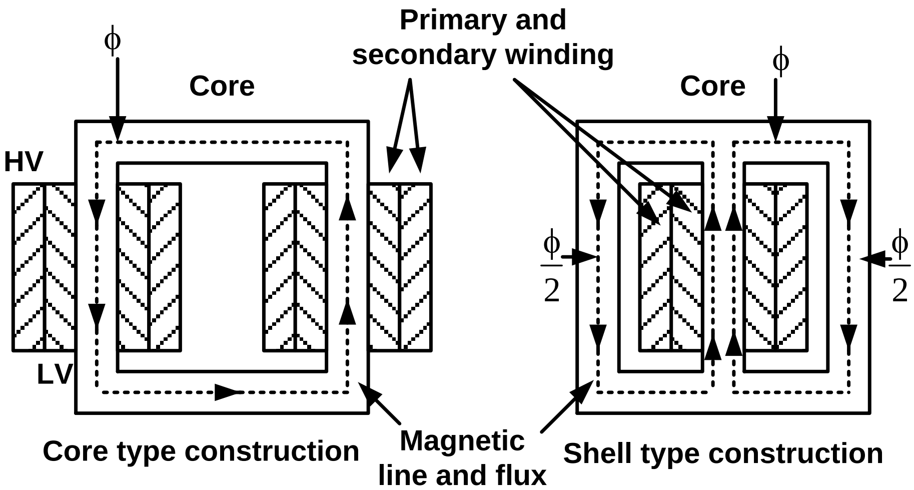


Figure 2.7 Types of construction of 1-phase transformer

- For the simple construction of a transformer, you must need two coils having mutual inductance and a laminated steel core.
- The device will need some suitable container for the assembled core and windings, a medium with which the core and its windings from its container can be insulated.
- In order to insulate and to bring out the terminals of the winding from the tank, the bushings that are made from either porcelain or capacitor type must be used.
- In all transformers that are used commercially, the core is made out of transformer sheet steel laminations assembled to provide a continuous magnetic path with minimum of air-gap included.
- The steel should have high permeability and low hysteresis loss. For this to happen, the steel should be made of high silicon content and must also be heat treated.

- By effectively laminating the core, the eddy-current losses can be reduced. The lamination can be done with the help of a light coat of core plate varnish or lay an oxide layer on the surface. The thickness of the lamination varies from 0.35mm to 0.5mm.
- The types of transformers differ in the manner in which the primary and secondary coils are provided around the laminated steel core. According to the design, transformers can be classified into two:
  (1) Core type of transformer
  (2) Shell type of transformer

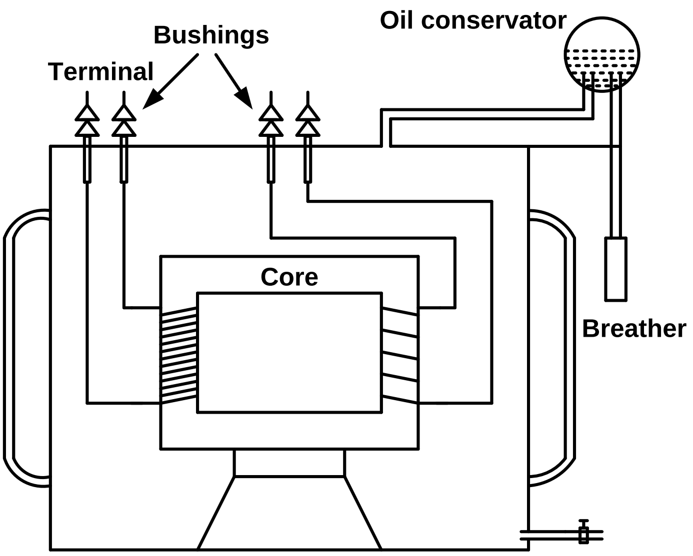


Figure 2.8 Transformer inside view

(1) Core type of transformer

- In core-type transformer, the windings are given to a considerable part of the core. The coils used for this transformer are form-wound and are of cylindrical type.
- Such type of transformer can be applicable for small sized and large sized transformers.
- In the small sized type, the core will be rectangular in shape and the coils used are cylindrical.
- Round or cylindrical coils are wound in such a way as to fit over a cruciform core section is shown in figure.
- In case of circular cylindrical coils, they have a fair advantage of having good mechanical strength. The cylindrical coils will have different layers and each layer will be insulated from the other with the help of materials like paper, cloth, mica board and so on.
- The general arrangement of the core-type transformer with respect to the core is shown in figure. Both low-voltage (LV) and high voltage (HV) windings are shown. The low voltage windings are placed nearer to the core as it is the easiest to insulate.
- The effective core area of the transformer can be reduced with the use of laminations and insulation.

(2) Shell type of transformer:

- In shell-type transformers, the core surrounds a considerable portion of the windings. The comparison is shown in the figure below.

- The coils are form-wound but are multi-layer disc type usually wound in the form of pancakes. Paper is used to insulate the different layers of the multi-layer discs.
- The whole winding consists of discs stacked with insulation spaces between the coils. These insulation spaces form the horizontal cooling and insulating ducts. Such a transformer may have the shape of a simple rectangle or may also have a distributed form.
- A strong rigid mechanical bracing must be given to the cores and coils of the transformers. This will help in minimizing the movement of the device and also prevents the device from getting any insulation damage.
- A transformer with good bracing will not produce any humming noise during its working and will also reduce vibration.
- **Working**

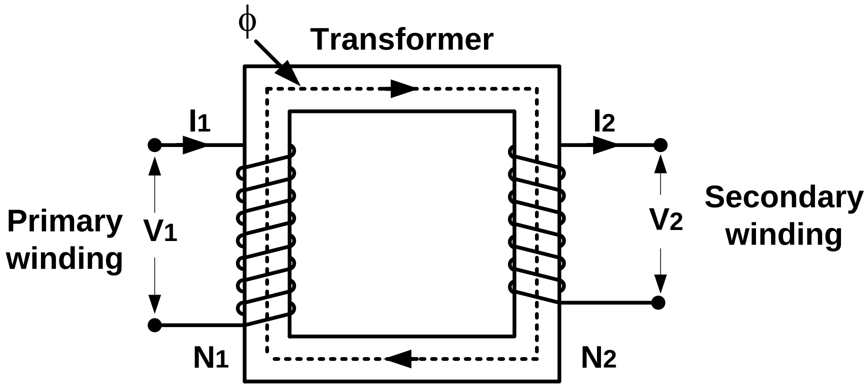


Figure 2.9 Working of Transformer

- The main principle of operation of a transformer is mutual inductance between two circuits which is linked by a common magnetic flux.
- A basic transformer consists of two coils that are electrically separate and inductive, but are magnetically linked through a path of reluctance.
- The transformer has two windings, (1) Primary and (2) Secondary winding. Primary winding is connected with input supply side and the secondary winding is connected with output load side.
- The core laminations are joined in the form of strips in between the strips you can see that there are some narrow gaps right through the cross-section of the core. These joints are said to be 'laminated'.
- Both the coils have high mutual inductance. A mutual electro-motive force is induced in the transformer from the alternating flux that is set up in the laminated core, due to the coil that is connected to a source of alternating voltage.
- Most of the alternating flux developed by this coil is linked with the other coil and thus produces the mutual induced electro-motive force. So the produced electro-motive force can be explained with the help of Faraday's laws of Electromagnetic Induction as,

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

- If the secondary coil circuit is closed, a current flows in it and thus electrical energy is transferred magnetically from the first to the second coil. In short the transformer carries the operations as shown below:
  - ✓ Transfer of electric power from one circuit to another.
  - ✓ Transfer of electric power without any change in frequency.
  - ✓ Transfer with the principle of electromagnetic induction.
  - ✓ The two electrical circuits are linked by mutual induction.

3.6 Emf equation of single phase transformer

- When a AC voltage is applied to the primary winding of a transformer, alternating flux sets up in the iron core of the transformer. This alternating flux links with both primary and secondary winding.
- The function of flux is a sine function. The rate of change of flux with respect to time is derived mathematically.
- Let,
  - ✓ Φ_m be the maximum value of flux in Wb
  - ✓ f be the supply frequency in Hz
  - ✓ N_1 is the number of turns in the primary winding
  - ✓ N_2 is the number of turns in the secondary winding
  - ✓ Φ is the flux per turn (in Weber)

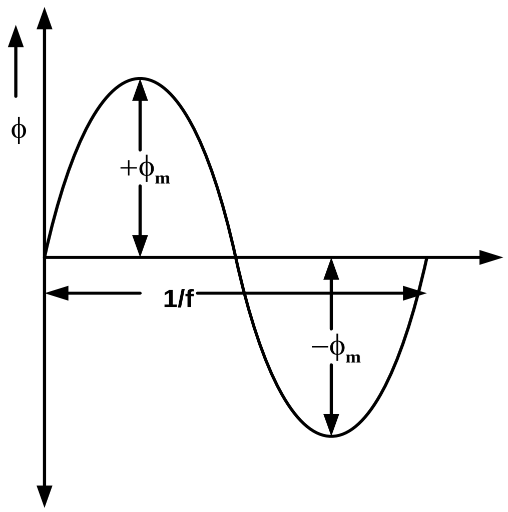


Figure 2.10 Waveform of flux

- As shown in the above figure that the flux changes from + to – in half a cycle of 1/2f second.
- By Faraday's Law of electromagnetic induction, Let E_1 is the emf induced in the primary winding

$$E_1 = -N\frac{d\phi}{dt}$$

- Maximum valve of induced emf

$$E_{1(\max)} = N_1 \omega \phi_m$$
$$But\ \ \omega = 2\pi f$$
$$E_{1(\max)} = 2\pi f N_1 \phi_m$$
RMS value is given by,
$$E_1 = \frac{E_{1(\max)}}{\sqrt{2}}$$
Putting the value of $E_{1(\max)}$ *in above equation we get,*
$$E_1 = \sqrt{2}\pi f N_1 \phi_m$$
$$E_1 = 4.44\, f N_1 \phi_m$$
Similarly, we get,
$$E_2 = 4.44\, f N_2 \phi_m$$

3.7 Explain construction and working of three phase transformer

Construction

- Three-phase transformer is effectively three interconnected single phase transformers on a single laminated core and considerable savings in cost, size and weight can be achieved by combining the three windings onto a single magnetic circuit as shown.

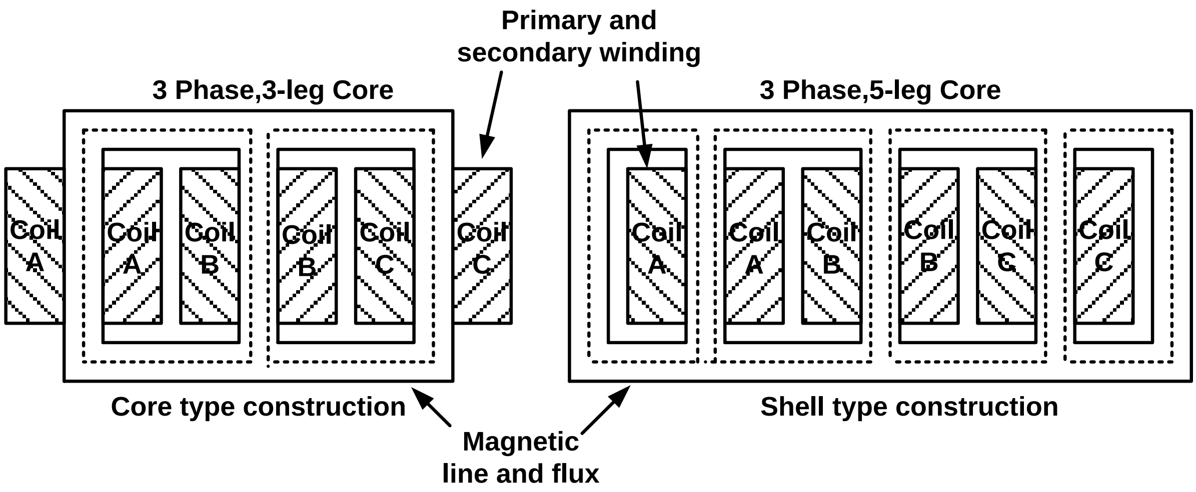


Figure 2.11 Type of construction of 3-phase transformer

- A three-phase transformer generally has the three magnetic circuits that are interlaced to give a uniform distribution of the dielectric flux between the high and low voltage windings.
- The exception to this rule is a three-phase shell type transformer. In the shell type of construction, even though the three cores are together, they are non-interlaced.
- The three-limb core-type three-phase transformer is the most common method of three-phase transformer construction allowing the phases to be magnetically linked.
- Flux of each limb uses the other two limbs for its return path with the three magnetic flux's in the core generated by the line voltages differing in time-phase by 120 degrees.
- Thus the flux in the core remains nearly sinusoidal, producing a sinusoidal secondary supply voltage.

- The shell-type five-limb type three-phase transformer construction is heavier and more expensive to build than the core-type. Five-limb cores are generally used for very large power transformers as they can be made with reduced height.
- Shell-type transformers core materials, electrical windings, steel enclosure and cooling are much the same as for the larger single-phase types.

Working

- Consider the below figure in which the primary of the transformer is connected in star fashion on the cores. For simplicity, only primary winding is shown in the figure which is connected across the three phase AC supply.
- The three cores are arranged at an angle of 120 degrees to each other. The empty leg of each core is combined in such that they form center leg as shown in figure.
- When the primary is excited with the three phase supply source, the currents I_R, I_Y and I_B are starts flowing through individual phase windings. These currents produce the magnetic fluxes Φ_R, Φ_Y and Φ_B in the respective cores.
- Since the center leg is common for all the cores, the sum of all three fluxes are carried by it. In three phase system, at any instant the vector sum of all the currents is zero.
- In turn, at the instant the sum of all the fluxes is same. Hence, the center leg doesn't carry any flux at any instant.

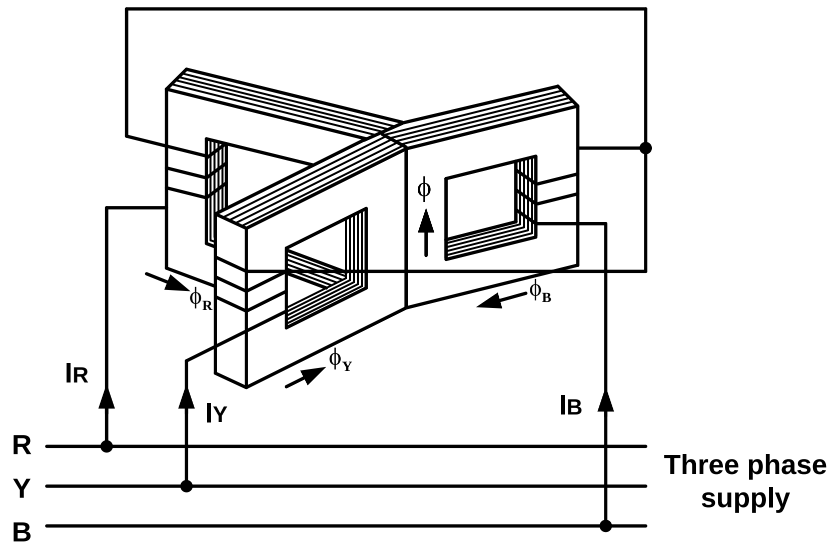


Figure 2.12 3-phase transformer

- So even if the center leg is removed it makes no difference in other conditions of the transformer.
- Likewise, in three phase system where any two conductors acts as return for the current in third conductor.
- Two legs act as a return path of the flux for the third leg if the center leg is removed in case of three phase transformer.
- Therefore, while designing the three phase transformer, this principle is used.
- These fluxes induce the secondary EMFs in respective phase such that they maintain their phase angle between them.

- These EMFs drives the currents in the secondary and hence to the load. Depends on the type of connection used and number of turns on each phase, the voltage induced will be varied for obtaining step-up or step-down of voltages.

3.8 Comparison between Single Three Phase and Bank of Three Single Phase Transformers for Three Phase System

- It is found that generation, transmission and distribution of electrical power are more economical in three phase system than single phase system.
- For three phase system three single phase transformers are required. Three phase transformation can be done in two ways, by using single three phase transformer or by using a bank of three single phase transformers.
- Both are having some advantages over other. Single 3 phase transformer costs around 15 % less than bank of three single phase transformers. Again former occupies less space than later.
- For very big transformer, it is impossible to transport large three phase transformer to the site and it is easier to transport three single phase transformers which is erected separately to form a three phase unit.
- Another advantage of using bank of three single phase transformers is that, if one unit of the bank becomes out of order, then the bank can be run as open delta.

3.9 Types of connection of three phase transformer

- A verity of connection of three phase transformer is possible on each side of both a single 3 phase transformer or a bank of three single phase transformers. Marking or Labeling the Different Terminals of Transformer
- Terminals of each phase of HV side should be labeled as capital letters, A, B, C and those of LV side should be labeled as small letters a, b, c. Terminal polarities are indicated by suffixes 1 and 2. Suffix 1's indicating similar polarity ends and so do 2's.

(1) Star-Star Transformer

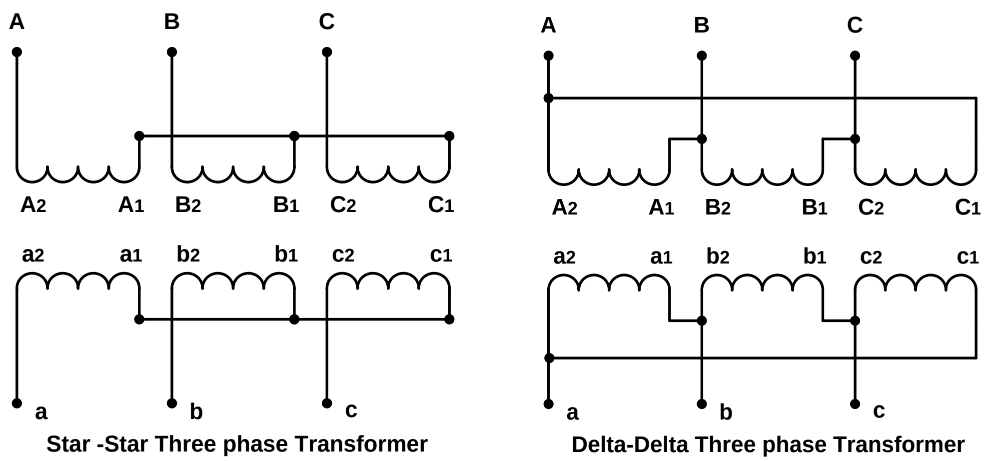


Figure 2.13 3-phase transformer connections

- Star-star transformer is formed in a 3 phase transformer by connecting one terminal of each phase of individual side, together.

- The common terminal is indicated by suffix 1 in the figure below. If terminal with suffix 1 in both primary and secondary are used as common terminal, voltages of primary and secondary are in same phase.
- That is why this connection is called zero degree connection or 0^o - connection. If the terminals with suffix 1 are connected together in HV side as common point and the terminals with suffix 2 in LV side are connected together as common point,
- The voltages in primary and secondary will be in opposite phase. Hence, star-star transformer connection is called 180^o-connection, of three phase transformer.

(2) Delta-Delta Transformer

- In delta-delta transformer, 1 suffixed terminals of each phase primary winding will be connected with 2 suffixed terminal of next phase primary winding.
- If primary is HV side, then A_1 will be connected to B_2, B_1 will be connected to C_2 and C_1 will be connected to A_2. Similarly in LV side 1 suffixed terminals of each phase winding will be connected with 2 suffixed terminals of next phase winding.
- That means, a_1 will be connected to b_2, b_1 will be connected to c_2 and c_1 will be connected to a_2.
- If transformer leads are taken out from primary and secondary 2 suffixed terminals of the winding, then there will be no phase difference between similar line voltages in primary and secondary.
- This delta delta transformer connection is zero degree connection or 0^o-connection.
- But in LV side of transformer, if, a_2 is connected to b_1, b_2 is connected to c_1 and c_2 is connected to a_1.
- The secondary leads of transformer are taken out from 2 suffixed terminals of LV windings, and then similar line voltages in primary and secondary will be in phase opposition. This connection is called 180^o-connection, of three phase transformer.

(3) Star-Delta Transformer

- Here in star-delta transformer, star connection in HV side is formed by connecting all the 1 suffixed terminals together as common point and transformer primary leads are taken out from 2 suffixed terminals of primary windings.
- The delta connection in LV side is formed by connecting 1 suffixed terminals of each phase LV winding with 2 suffixed terminal of next phase LV winding. More clearly, a_1 is connected to b_2, b_1 is connected to c_2 and c_1 is connected to a_2.
- The secondary (here it considered as LV) leads are taken out from 2 suffixed ends of the secondary windings of transformer. The transformer connection diagram is shown in the figure beside.
- It is seen from the figure that the sum of the voltages in delta side is zero. This is a must as otherwise closed delta would mean a short circuit.
- It is also observed from the phasor diagram that, phase to neutral voltage (equivalent star basis) on the delta side lags by -30^o to the phase to neutral voltage on the star side; this is also the phase relationship between the respective line to line voltages.
- This star delta transformer connection is therefore known as -30^o-connection. Star-delta $+30^o$-connection is also possible by connecting secondary terminals in following sequence. a_2 is connected to b_1, b_2 is connected to c_1 and c_2 is connected to a_1.

- The secondary leads of transformer are taken out from 2 suffixed terminals of LV windings,

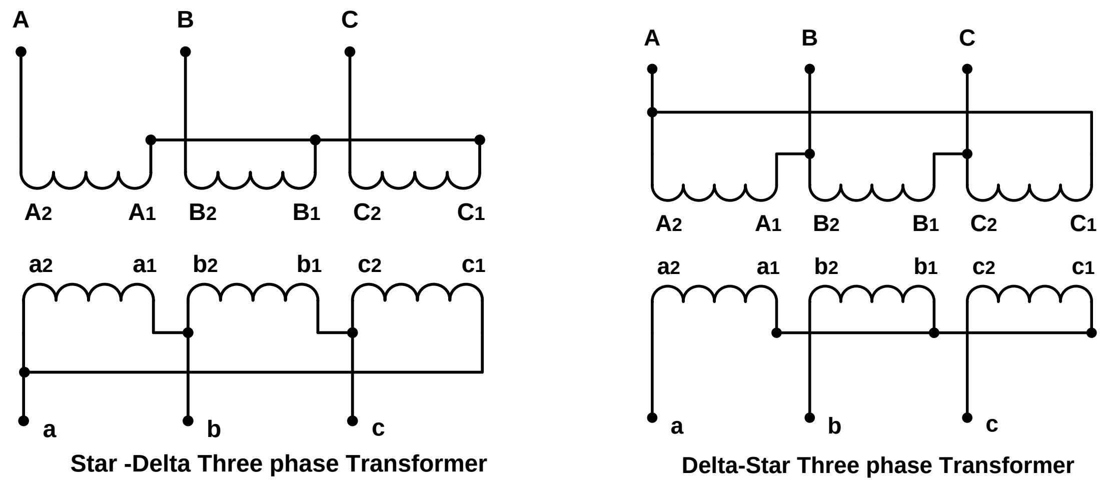


Figure 2.14 3-phase transformer connections

(4) Delta-Star Transformer

- Delta-star transformer circuit diagram shown in above figure.
- Delta-star transformer connection of three phase transformer is similar to star – delta connection. If anyone interchanges HV side and LV side of star-delta transformer in diagram, it simply becomes delta – star connected 3 phase transformer.
- That means all small letters of star-delta connection should be replaced by capital letters and all small letters by capital in delta-star transformer connection

3.10 Voltage and current ratios of transformer

- Voltage and current relation of primary winding and secondary winding is given as below.

$$E_1 = 4.44\, fN_1\phi_m \text{...........(1)}$$
$$E_2 = 4.44\, fN_2\phi_m \text{..........(2)}$$

Taking ratio of eq(1) and eq(2)

At no Load

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

At Load

$$V_1 = E_1 \; and \; V_2 = E_2$$
$$\frac{V_1}{V_2} = \frac{N_1}{N_2} \; or \; \frac{V_2}{V_1} = \frac{N_2}{N_1}$$
$$V_1 = \text{ Primary voltage}$$
$$V_2 = \text{Secondary voltage}$$

If η of transformer 100%

Input power = Output power

$$V_1 I_1 \cos\phi_1 = V_2 I_2 \cos\phi_2$$
$$practically \; , \cos\phi_1 = \cos\phi_2$$
$$V_1 I_1 = V_2 I_2$$
$$\frac{I_1}{I_2} = \frac{V_2}{V_1}$$
$$But, \frac{V_2}{V_1} = \frac{N_2}{N_1} = K$$
$$\frac{I_1}{I_2} = \frac{N_2}{N_1}$$
$$\cos\phi_1 = \text{Power factor of primary side}$$
$$\cos\phi_2 = \text{Power factor of Secondary side}$$

3.11 Explain Ideal Transformer

- An ideal transformer is an imaginary transformer which does not have any loss in it, means no core losses, copper losses and any other losses in transformer. Efficiency of this transformer is considered as 100%.
- Ideal transformer model is developed by considering a transformer which does not have any loss. That means the windings of the transformer are purely inductive and the core of transformer is loss free. there is zero leakage reactance of transformer.
- As we said, whenever we place a low reluctance core inside the windings, maximum amount of flux passes through this core, but still there is some flux which does not pass through the core but passes through the insulation used in the transformer.
- An ideal transformer have the following properties:
  - ✓ Its primary and secondary winding have negligible resistance.
  - ✓ The core has infinite permeability (μ) so that negligible mmf is required to establish the flux in the core.
  - ✓ Its leakage flux and leakage inductances are zero. The entire flux is confined to the core and links both the windings.
  - ✓ There are no losses due to resistances, hysteresis and eddy currents. Thus, the efficiency is 100 %.
- This flux does not take part in the transformation action of the transformer. This flux is called leakage flux of transformer. In an ideal transformer, this leakage flux is also considered nil.
- That means, 100% flux passes through the core and links with both the primary and secondary windings of transformer.

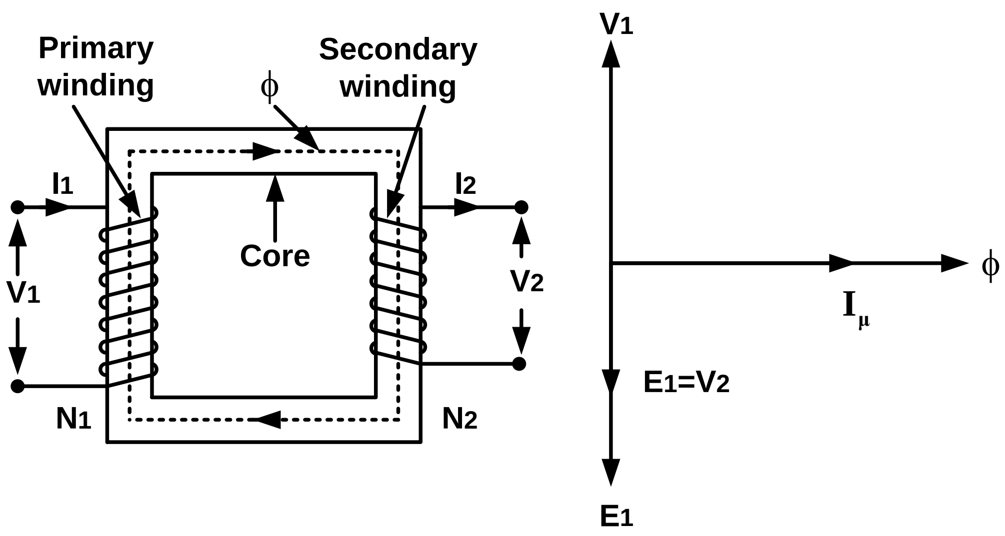


Figure 2.15 Ideal transformer and its vector diagram

- Although every winding is desired to be purely inductive but it has some resistance in it which causes voltage drop and loss in it. In such ideal transformer model, the windings are also considered ideal that means resistance of the winding is zero.

- Now if an alternating source voltage V_1 is applied in the primary winding of that ideal transformer, there will be a counter self emf E_1 induced in the primary winding which is purely 180 degree in phase opposition with supply voltage V_1.
- For developing counter emf E_1 across the primary winding, it draws current from the source to produce required magnetizing flux.
- As the primary winding is purely inductive, that current 90^o lags from the supply voltage. This current is called magnetizing current of transformer $I\mu$.
- This alternating current $I\mu$ produces an alternating magnetizing flux Φ which is proportional to that current and hence in phase with it.
- As this flux is also linked with secondary winding through the core of transformer, there will be another emf E_2 induced in the secondary winding, this is mutually induced emf.
- As the secondary is placed on the same core where the primary winding is placed, the emf induced in the secondary winding of transformer, E_2 is in the phase with primary emf E_1 and in phase opposition with source voltage V_1.

3.12 Explain Practical Transformer

- A practical transformer hasn't 100% efficiency due to losses.

Transformer 'no load' condition

- A transformer is on no load when its secondary winding is open circuited.

  So, the secondary current is zero.
- When AC supply is applied to primary winding, a small amount of current I_o flows in the primary winding.
- The current I_o is called the no load current of the transformer. It is made up with two components I_μ and I_w.
- The component I_μ is called the magnetizing component and it magnetizes the core and it is in phase with ϕ_m. It is also called reactive component or wattles component of no-load current.
- Another component is I_w, it is called active component or working component or wattful component and it is in phase with supply voltage.

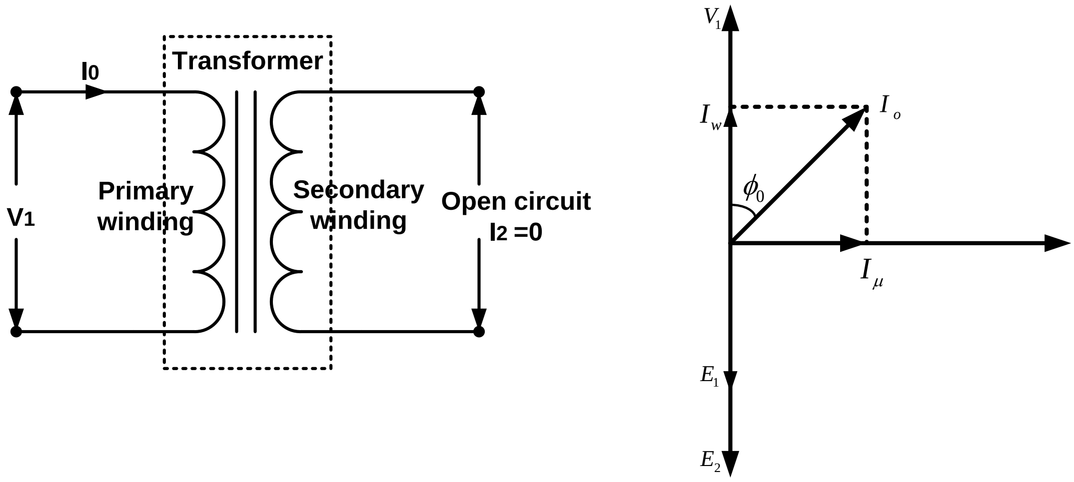


Figure 2.16 Practical transformers on no load and vector diagram

- The no-load current is small of the order of 3 to 5% of the rated current of primary winding.
- Consider the transformer under no-load and take ϕ_m as a reference phasor.
- At no-load we have,

$$\phi = \phi_m \sin \omega t$$
$$e_1 = E_{1m} \sin\left(\omega t - \frac{\pi}{2}\right)$$
$$e_2 = E_{2m} \sin\left(\omega t - \frac{\pi}{2}\right)$$

- Since E_1 and E_2 are induced emf by the same flux ϕ and they will be in phase with each other. E_2 differs from the magnitude of E_1, because E_2 = E_1. E_2 and E_1 are lag behind ϕ by 90^0.
- If the voltage drop in the primary winding are neglected E_1 will be equal and opposite to the applied voltage V_1. I_μ is in phase with ϕ and I_w is in phase with V_1. The phasor sum of I_μ and I_w is I_0 .
- Φ_0 is called the no-load power factor angle, so that the power factor on no load is $\cos\Phi_0$.

$$I_w = I_0 \cos \phi_0$$
$$I_\mu = I_0 \sin \phi_0$$
$$I_0 = \sqrt{I^2{}_w + I^2{}_\mu}$$
$$\cos \phi_0 = \frac{I_w}{I_0}$$

- Also, core loss $= V_1 I_0 \cos \phi_0 = V_1 I_w$ Watt.
- Magnetizing volt-amperes $= V_1 \sin \phi_0 = V_1 I_\mu$ VAr

Transformer on load

- When an electrical load is connected to the secondary winding of a transformer, a current flows in the secondary winding.
- This secondary current is due to the induced secondary voltage that is set up by the magnetic flux created in the core from the primary current.
- The secondary current, I_2 which is determined by the characteristics of the load this secondary current creates a self-induced secondary magnetic field Φ_2 in the transformer core which flows in the exact opposite direction to the main primary field, Φ_1.
- These two magnetic fields oppose each other resulting in a combined magnetic field of less magnetic strength than the single field produced by the primary winding alone when the secondary circuit was open circuited.
- This combined magnetic field reduces the back EMF of the primary winding causing the primary current, I_1 to increase slightly.
- The Primary current continues to increase until the cores magnetic field is back at its original strength and for a transformer to operate correctly.

- A balanced condition must always exist between the primary and secondary magnetic fields. This results in the power to be balanced and the same on both the primary and secondary sides.

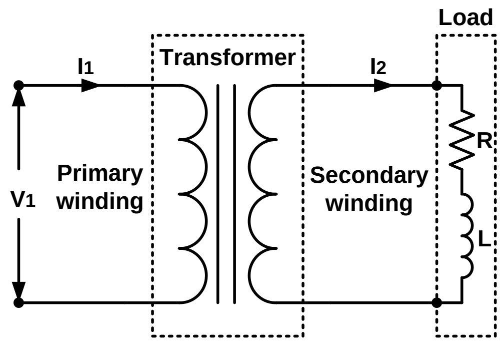


Figure 2.17 Practical transformer on load

- We can calculate the primary current, I_P by the following methods:

$$\text{Horizontal Component } I_x = I_0 \sin\phi_0 + I'_1 \sin\phi_2$$
$$\text{Vertical Component } I_Y = I_0 \cos\phi_0 + I'_1 \cos\phi_2$$
$$I_1 = \sqrt{\left(\sqrt{(I_X{}^2 + I_Y{}^2}\right)}$$
$$\text{p.f} = \cos\phi = \frac{I_Y}{I_X}$$

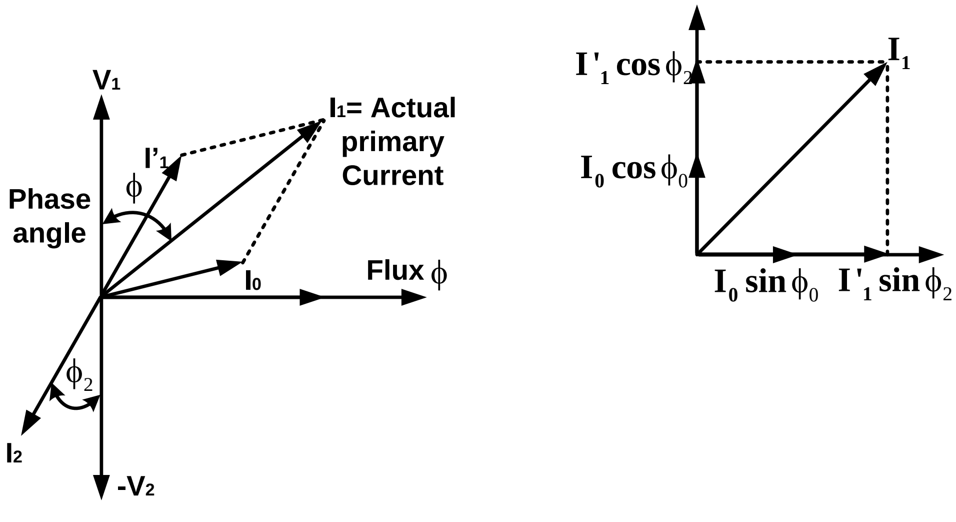


Figure 2.18 Vector diagram of Practical transformer on load and vector diagram

- We know that the turns ratio of a transformer states that the total induced voltage in each winding is proportional to the number of turns in that winding.
- The power output and power input of a transformer is equal to the volts times amperes, (V x I).

  Therefore

Transformer Ratio

$$P_{Primary} = P_{Secondary}$$

$$V_1 I_1 = V_2 I_2$$

$$I_2 = \frac{V_1 I_1}{V_2}$$

$$\therefore \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

But we know that voltage ratio = turns ratio

$$So,\ n = n = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

- Note that the current is inversely proportional to both the voltage and the number of turns.
- This means that with a transformer loading on the secondary winding, in order to maintain a balanced power level across the transformers windings.
- If the voltage is stepped up, the current must be stepped down and vice versa. In other words, "higher voltage — lower current" or "lower voltage — higher current".
- The total current drawn from the supply by the primary winding is the vector sum of the no-load current I_0 and the additional supply current I_1.
- As a result of the secondary transformer loading and which lags behind the supply voltage by an angle of Φ. We can show this relationship as a phasor diagram.

Transformer Equivalent Circuit

- Actual real life, transformer windings have impedances of both X_L and R. These impedances need to be taken into account when drawing the phasor diagrams as these internal impedances cause voltage drops to occur within the transformers windings.
- The internal impedances are due to the resistance of the windings and an inductance called the leakage reactance resulting from the leakage flux. These internal impedances are given as:

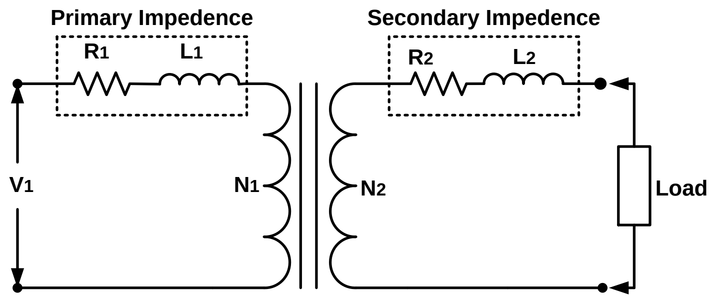


Figure 2.19 equivalent circuit of transformer

- So the primary and secondary windings of a transformer possess both resistance and reactance. Sometimes, it can be more convenient if all these impedances are on the same side of the transformer to make the calculations easier.

- It is possible to move the primary impedances to the secondary side or the secondary impedances to the primary side. The combined values of R and L impedances are called "Referred Impedances" or "Referred Values".
- The object here is to group together the impedances within the transformer and have just one value of R and X_L in our calculations as shown.

3.13 Difference between Ideal transformer and actual transformer

- The windings (both primary and secondary) of an ideal transformer are considered to have zero resistance, hence the transformer is lossless.
- There is no leakage flux in an ideal transformer.
- The permeability of the core material in ideal transformer is considered to be tending to infinity and hence the current needed to set up the flux in the transformer is negligible.
- There is zero hysteresis and eddy current losses in an ideal transformer.

3.14 Losses in Transformer

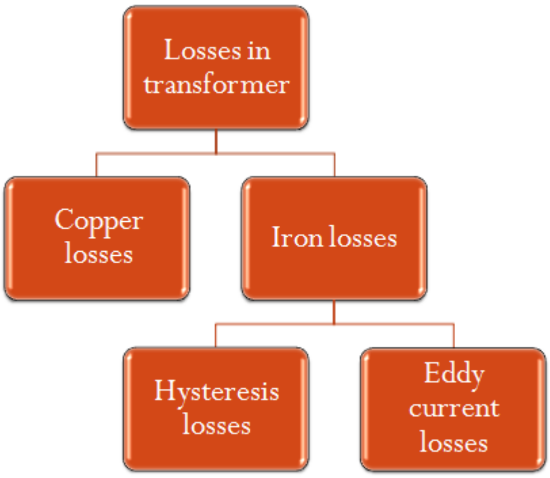


Figure 2.20 Block diagram of types of losses

- As the electrical transformer is a static device, mechanical loss in transformer normally does not come into picture. We generally consider only electrical losses in transformer. Loss in any machine is broadly defined as difference between input power and output power.
- When input power is supplied to the primary of transformer, some portion of that power is used to compensate core losses in transformer i.e. Hysteresis loss in transformer and Eddy current loss in transformer core.
- some portion of the input power is lost as I^2R loss and dissipated as heat in the primary and secondary windings, because these windings have some internal resistances in them.
- The first one is called core loss or iron loss in transformer and the later is known as ohmic loss or copper loss in transformer.
- Another loss occurs in transformer, known as Stray Loss, due to Stray fluxes link with the mechanical structure and winding conductors.

(1) Copper losses

- Transformer Copper Losses are mainly due to the electrical resistance of the primary and secondary windings.
- Most of the transformer coils are made from copper wire which has resistance in Ohms (Ω). This resistance opposes the magnetizing currents flowing through them.
- When a load is connected to the transformers secondary winding, large electrical currents flow in both the primary and the secondary windings, electrical energy and power (or the I^2R) losses occur as heat.
- Generally copper losses vary with the load current, being almost zero at no-load, and at a maximum at full-load when current flow is at maximum.
- A transformers VA rating can be increased by better design and transformer construction to reduce these core and copper losses.
- Transformers with high voltage and current ratings require conductors of large cross-section to help minimize their copper losses.
- Increasing the rate of heat dissipation (better cooling) by forced air or oil, or by improving the transformers insulation so that it will withstand higher temperatures can also increase a transformers VA rating

(2) Iron losses or core losses

- Hysteresis loss and eddy current loss both depend upon magnetic properties of the materials used to construct the core of transformer and its design. So these losses in transformer are fixed and do not depend upon the load current.
- So core losses in transformer which is alternatively known as iron loss in transformer can be considered as constant for all range of load.

(3) Hysteresis loss

- The work was done by the magnetizing force against the internal friction of the molecules of the magnet, produces heat. This energy which is wasted in the form of heat due to hysteresis is called Hysteresis Loss.
- When in the magnetic material magnetization force is applied, the molecules of the magnetic material are aligned in one particular direction, and when this magnetic force is reversed in the opposite direction, the internal friction of the molecular magnets opposes the reversal of magnetism resulting in Magnetic Hysteresis.
- Therefore, cores are made of materials with narrow hysteresis loops so that little energy will be wasted in the form of heat.
- Hysteresis loss in transformer is denoted as,

$$W_h = K_h f \left(B_m\right)^{1.6} \ \ watt$$

$$Where\ K_h = Hysteresis\ constant$$

(4) Eddy current losses

- Whenever a conductor is moving in a magnetic field or conductor is placed in changing magnetic field, an emf is induced in conductor according to faraday's laws electromagnetic induction.

- These emf set up corresponding induced currents. These currents circulate in large number of small concentric paths within the solid mass of the conductor and are known as eddy currents.
- As these eddy currents are not used for doing any useful works and flow within the body, these currents cause power loss. The power loss due to eddy currents is called eddy current loss.
- Eddy current loss in transformer is denoted as,

$$W_h = K_e f^2 K_f^{\,2} B_m^{\,2} \text{ watt}$$

$$K_e = \textit{Eddy current constant.}$$

$$K_f = \textit{form constant.}$$

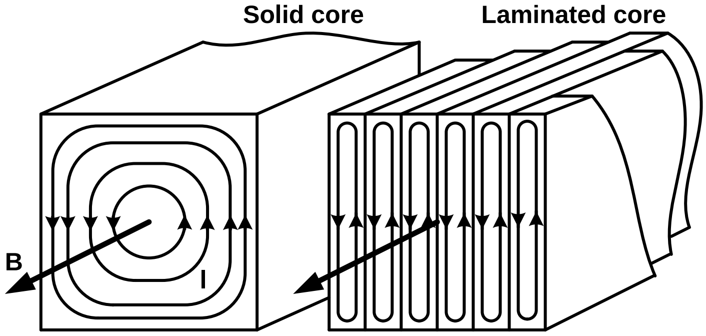


Figure 2.21 Eddy current losses

3.15 Explain Transformer efficiency

- A transformer is a static device this means there are no friction or windage losses associated with other electrical machines.
- A transformer has losses called "copper losses" and "iron losses" but generally these are quite small. Copper losses, also known as I^2R loss. .
- The actual watts of power lost can be determined (in each winding) by squaring the amperes and multiplying by the resistance in ohms of the winding (I^2R).
- Iron losses, also known as hysteresis is the lagging of the magnetic molecules within the core, in response to the alternating magnetic flux.
- The intensity of power loss in a transformer determines its efficiency. The efficiency of a transformer is reflected in power (wattage) loss between the primary (input) and secondary (output) windings.
- The resulting efficiency of a transformer is equal to the ratio of the power output of the secondary winding, to the power input of the primary winding, and is therefore high.
- An ideal transformer is 100% efficient because it delivers all the energy it receives. Real transformers on the other hand are not 100% efficient and at full load, the efficiency of a transformer is between 94% to 96% which is quite good.
- For a transformer operating with a constant voltage and frequency with a very high capacity the efficiency may be as high as 98%. The efficiency, η of a transformer is given as:

$$Efficiency\ \eta = \frac{Output\ power}{Input\ power} \times 100\ \%$$

$$= \frac{Input\ power - Losses}{Input\ power} \times 100\ \%$$

$$= 1 - \frac{Losses}{Input\ power} \times 100\ \%$$

3.16 Explain voltage regulation

- The voltage regulation is the percentage of voltage difference between no load and full load voltages of a transformer with respect to its full load voltage.
- Say an electrical power transformer is open circuited, means load is not connected with secondary terminals. In this situation, the secondary terminal voltage of the transformer will be its secondary induced emf E_2.
- Whenever full load is connected to the secondary terminals of the transformer, rated current I_2 flows through the secondary circuit and voltage drop comes into picture.
- At this situation, primary winding will also draw equivalent full load current from source. The voltage drop in the secondary is I_2Z_2 where Z_2 is the secondary impedance of transformer.
- Now if at this loading condition, any one measures the voltage between secondary terminals, he or she will get voltage V_2 across load a terminal which is obviously less than no load secondary voltage E_2 and this is because of I_2Z_2 voltage drop in the transformer.

$$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100\%$$

3.17 Explain Auto Transformer

- Auto transformer is kind of electrical transformer where primary and secondary shares same common single winding. So basically it's a one winding transformer.

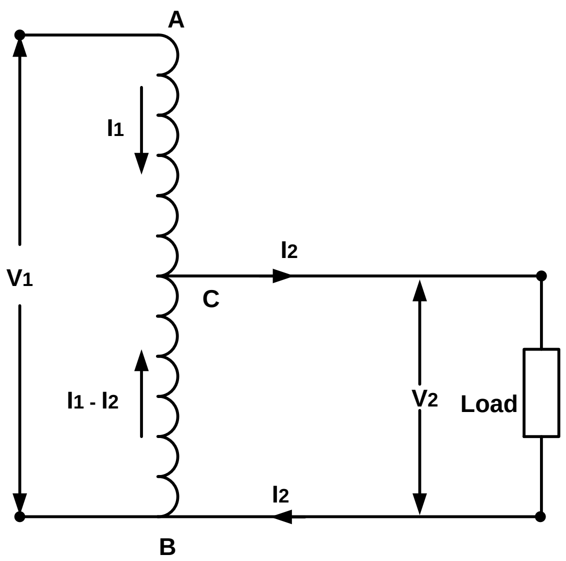


Figure 2.22 Circuit diagram of Auto transformer

- In Auto Transformer, one single winding is used as primary winding as well as secondary winding. But in two windings transformer two different windings are used for primary and secondary purpose.
- The winding AB of total turns N1 is considered as primary winding. This winding is tapped from point ′C′ and the portion BC is considered as secondary. Let's assume the number of turns in between points ′B′ and ′C′ is N2.
- If V1 voltage is applied across the winding i.e. in between ′A′ and ′C′.

So Voltage per turn in this winding is $\frac{V_1}{N_1}$,

Hence, the voltage across the portion BC of the winding, will be,

$$\frac{V_1}{N_1} \times N_2 \text{ and from the above, this voltage is } V_2$$

$$\text{Hence, } \frac{V_1}{N_1} \times N_2 = V_2$$

$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \text{Constant} = K$$

- Hence, the voltage across the portion BC of the winding, will be, as BC portion of the winding is considered as secondary, it can easily be understood that value of constant ′k′ is nothing but turns ratio or voltage ratio of that auto transformer.
- When load is connected between secondary terminals i.e. between ′B′ and ′C′, load current I_2 starts flowing. The current in the secondary winding or common winding is the difference of I_2 and I_1 .

Application of Auto transformer

- Compensating voltage drops by boosting supply voltage in distribution systems.
- Auto transformers with a number of tapping are used for starting induction and synchronous motors.
- Auto transformer is used as variac in laboratory or where continuous variable over broad ranges are required.
- The auto transformer is used as balance coil to give a neutral in a 3-wire ac distribution system

4.1 Introduction

- An **induction motor** or **asynchronous motor** is an AC electric motor in which the electric current in the rotor needed to produce torque is obtained by electromagnetic induction from the magnetic field of the stator winding.
- Three-phase squirrel-cage induction motors are widely used as industrial drives because they are rugged, reliable and economical.
- The induction motor is maintenance free. It has high overloading capacity.
- Single-phase induction motors are used extensively for smaller loads, for household appliances like ceiling fans. Although traditionally used in fixed-speed applications, induction motors are increasingly being used with variable-frequency drives (VFDs) in variable-speed applications like in cranes, lifts, cement plants, ceramic plants, food processing industries etc.
- VFDs offer energy savings opportunities for existing and prospective induction motors in variable-torque centrifugal fan, pump and compressor load applications.

4.2 Construction of Induction Motor

- A three phase Induction motor mainly consists of two parts called as the Stator and Rotor.

(a) Stator

- It is the stationary part of the induction motor.
- The stator is built up of high-grade alloy steel laminations to reduce eddy current losses.
- It has three main parts, outer frame, stator core and a stator winding.

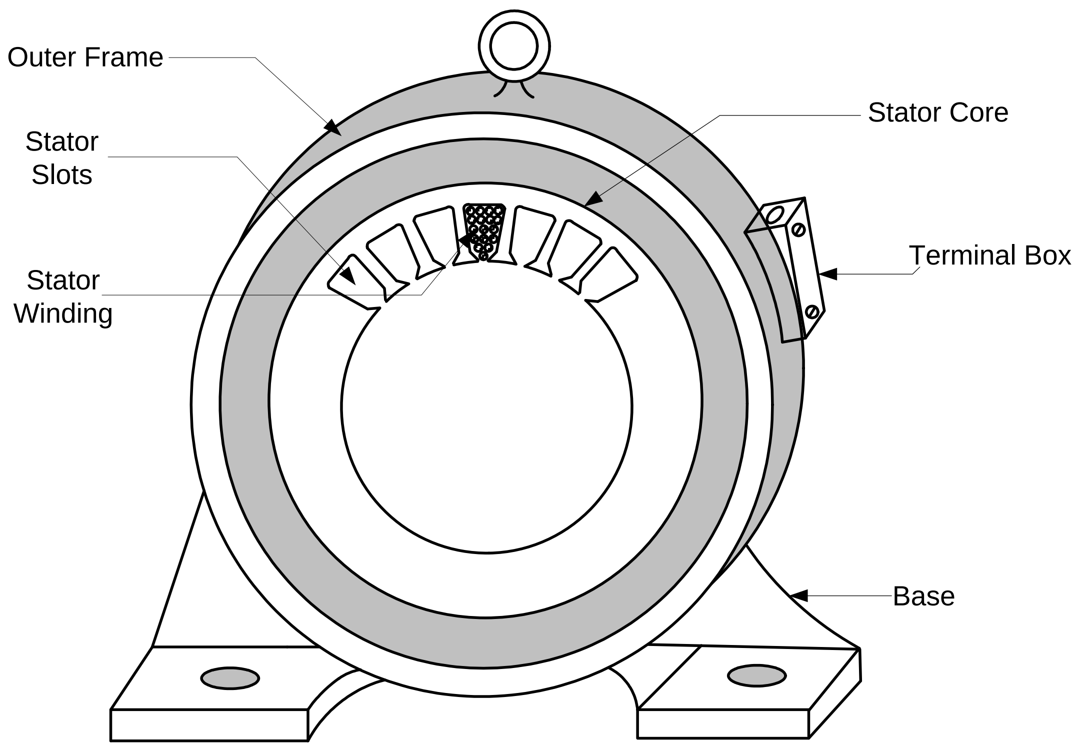


Figure 4.1 Outer frame of an induction motor

- ***Outer frame***

- It is the outer body of the motor. Its main function is to support the stator core and to protect the inner parts of the machine.

- For small machines, the outer frame is casted, but for the large machine, it is fabricated.

- ***Stator Core***
- The core of the stator carries three phase windings which are usually supplied from a three-phase supply system.
- The stator core is built of high-grade silicon steel stampings.
- Its main function is to carry the alternating magnetic field which produces hysteresis and eddy current losses.

- ***Stator windings***
- The stator windings are housed in stator slots with double layer winding.
- These windings are distributed and are mostly short pitched.
- Anyway, the stator of the motor is wound for a definite number of poles, depending on the speed of the motor.
- The windings may be connected in star or delta.
- As the relationship between the speed and the pole of the motor is given as

$$N_S \propto \frac{1}{P} \ or \ N_S = \frac{120f}{P}$$

(b) Rotor

- It is the rotating part of induction motor
- The rotor is also built of thin laminations of the same material as the stator.
- The laminated cylindrical core is mounted directly on the shaft.
- These laminations are slotted on the outer side to receive the conductors. There are two types of rotor:

- ***Squirrel cage rotor***
- A squirrel cage rotor consists of a laminated cylindrical core.
- The circular slots at the outer periphery are semi-closed. Each slot contains uninsulated bar conductor of aluminum or copper.
- At the end of the rotor the conductors the short-circuited by a heavy ring of copper or aluminum.
- Now a days this type of motors are widely used in domestic as well as commercial purposes.
- This type of motors required low maintanance compare to wound rotor type motors.

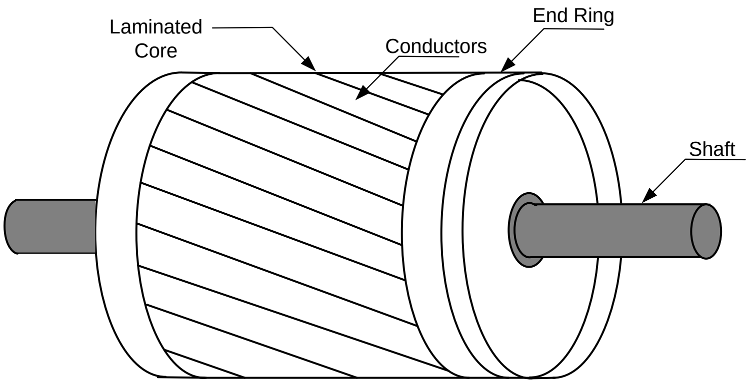


Figure 4.2 Squirrel cage rotor

- ***Wound rotor (Slip ring rotor)***
- A wound rotor is built with a polyphase distributed winding similar to that of stator winding and wound with the same number of poles as, the stator.
- The terminals of the rotor winding are connected to insulated slip rings mounted on the shaft.
- Carbon brushes bearing on these rings make the rotor terminals available external to the motor,
- Wound-rotor induction machines are relatively uncommon, being found only in a limited number of specialized applications.
- This type of motors are widely used where *high starting torque* is required.
- The cost and size of this type motor is more and large respectively.

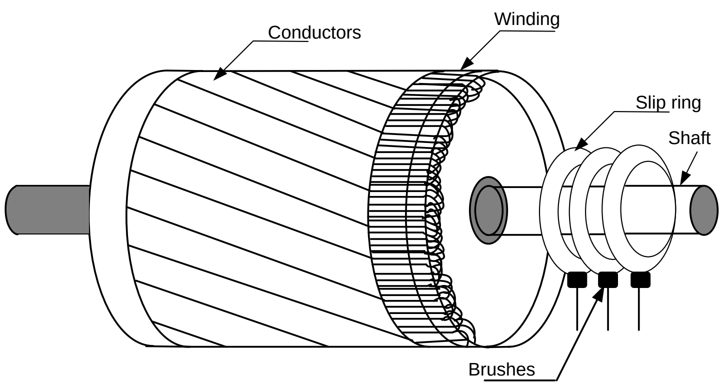


Figure 4.3 Wound rotor

4.3 Production of RMF (Rotating Magnetic Field)

- When stationary three phase winding coils are supplied by an alternating 3-phase supply then uniform Rotating Magnetic Field (or Flux) [RMF] of constant value is produced.
- The principle of a three phase, two pole stator having three identical winding coils are placed by 120^0 electrical (Space) degree apart. The flux (Sinusoidal) due to three phase windings is shown in below *Figure 4.4 (b)*
- The directions of the positive fluxes are shown individually below at different positions.
- Let us say that the maximum value of the flux due to any one of the three phases be $\emptyset_m$. The resultant flux $\emptyset_r$, at any instant is given by the resultant sum of the individual fluxes $\emptyset_1$, $\emptyset_2$and $\emptyset_3$ due to three phases

- We have consider the 1/6th time period apart corresponding to points marked 0, 1, 2 and 3 in *Figure 2.1 (a).*

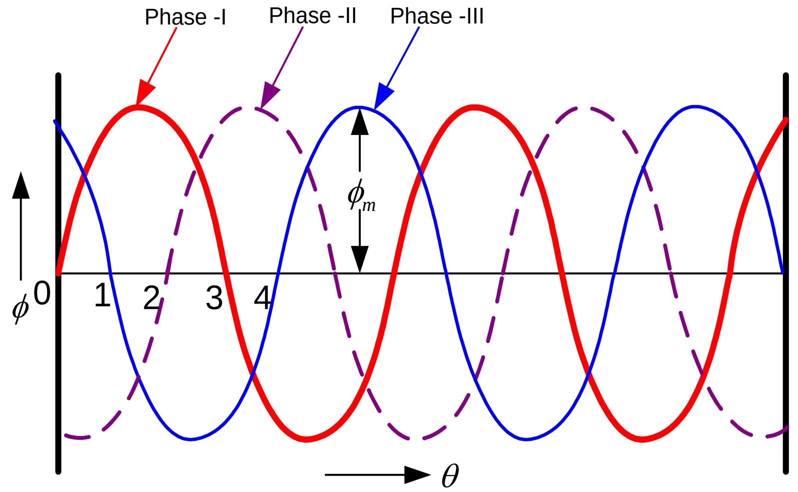


Figure 4.4 (a) Phasor representation

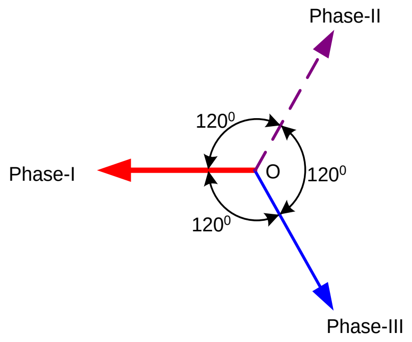


Figure 4.4 (b)

When $\theta = 0^0$ (At point 0)

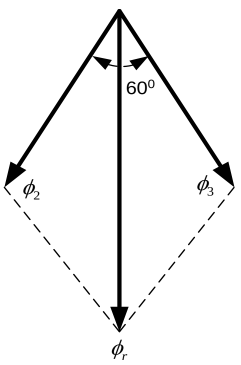


Figure 4.5

$\emptyset_1 = 0$

$$\emptyset_2 = -\frac{\sqrt{3}}{2}\emptyset_m$$

$$\emptyset_3 = \frac{\sqrt{3}}{2}\emptyset_m$$

When $\theta = 60^0$ (At point 1)

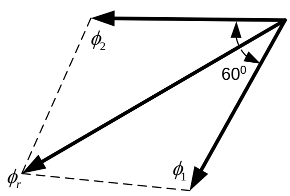


Figure 4.6

$$\emptyset_1 = \frac{\sqrt{3}}{2}\emptyset_m$$

$$\emptyset_2 = -\frac{\sqrt{3}}{2}\emptyset_m$$

$\emptyset_3 = 0$

When $\theta = 120^0$ (At point 2)

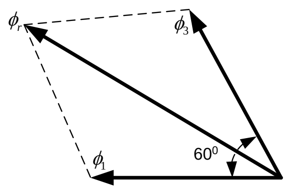


Figure 4.7

$$\emptyset_1 = \frac{\sqrt{3}}{2}\emptyset_m$$

$\emptyset_2 = 0$

$$\emptyset_3 = -\frac{\sqrt{3}}{2}\emptyset_m$$

When $\theta = 180^0$ (At point 3)

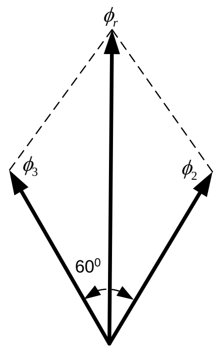


Figure 4.8

$\emptyset_1 = 0$

$$\emptyset_2 = \frac{\sqrt{3}}{2}\emptyset_m$$

$$\emptyset_3 = -\frac{\sqrt{3}}{2}\emptyset_m$$

When θ = 0⁰ (At point 0)

Resultant flux,

$$\phi_r = \sqrt{\phi_2^{\ 2} + \phi_3^{\ 2} - 2\phi_2\phi_3 \cos\theta}$$

$$= \sqrt{\left(-\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 - 2\left(-\frac{\sqrt{3}}{2}\phi_m\right)\left(\frac{\sqrt{3}}{2}\phi_m\right)\cos 60^0}$$

$$= \sqrt{\left[\frac{3}{4} + \frac{3}{4} + \frac{3}{2}\left(\frac{1}{2}\right)\right]\phi_m^{\ 2}}$$

$$= \sqrt{\left[\frac{3+3+3}{4}\right]\phi_m^{\ 2}}$$

$$= \sqrt{\left[\frac{9}{4}\right]\phi_m^{\ 2}}$$

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

When θ = 60⁰ (At point 1)

Resultant flux,

$$\phi_r = \sqrt{\phi_1^{\ 2} + \phi_2^{\ 2} - 2\phi_1\phi_2 \cos\theta}$$

$$= \sqrt{\left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(-\frac{\sqrt{3}}{2}\phi_m\right)^2 - 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(-\frac{\sqrt{3}}{2}\phi_m\right)\cos 60^0}$$

$$= \sqrt{\left[\frac{3}{4} + \frac{3}{4} + \frac{3}{2}\left(\frac{1}{2}\right)\right]\phi_m^{\ 2}}$$

$$= \sqrt{\left[\frac{3+3+3}{4}\right]\phi_m^{\ 2}}$$

$$= \sqrt{\left[\frac{9}{4}\right]\phi_m^{\ 2}}$$

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

When θ = 120⁰ (At point 2)

Resultant flux,

$$\phi_r = \sqrt{{\phi_1}^2 + {\phi_3}^2 - 2\phi_1\phi_3 \cos\theta}$$

$$= \sqrt{\left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(-\frac{\sqrt{3}}{2}\phi_m\right)^2 - 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(-\frac{\sqrt{3}}{2}\phi_m\right)\cos 60^0}$$

$$= \sqrt{\left[\frac{3}{4} + \frac{3}{4} + \frac{3}{2}\left(\frac{1}{2}\right)\right]{\phi_m}^2}$$

$$= \sqrt{\left[\frac{3+3+3}{4}\right]{\phi_m}^2}$$

$$= \sqrt{\left[\frac{9}{4}\right]{\phi_m}^2}$$

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

When θ = 180⁰ (At point 3)

Resultant flux,

$$\phi_r = \sqrt{{\phi_2}^2 + {\phi_3}^2 - 2\phi_1\phi_3 \cos\theta}$$

$$= \sqrt{\left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(-\frac{\sqrt{3}}{2}\phi_m\right)^2 - 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(-\frac{\sqrt{3}}{2}\phi_m\right)\cos 60^0}$$

$$= \sqrt{\left[\frac{3}{4} + \frac{3}{4} + \frac{3}{2}\left(\frac{1}{2}\right)\right]{\phi_m}^2}$$

$$= \sqrt{\left[\frac{3+3+3}{4}\right]{\phi_m}^2}$$

$$= \sqrt{\left[\frac{9}{4}\right]{\phi_m}^2}$$

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

4.4 Working Principle

- For simplicity, consider one conductor on the stationary rotor as shown in *Figure 4.9 (a).*
- This conductor be subject to the rotating magnetic field produced when a three phase supply is connected to the three phase winding of the stator.
- Consider the rotation of the magnetic field be clockwise.
- A magnetic field moving clockwise has the effect as a conductor moving anticlockwise in a stationary field.
- According to Faraday's law of electromagnetic induction, emf will be produced in the conductor.

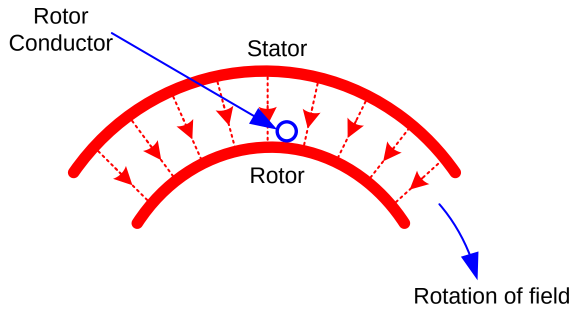


Figure 4.9 (a)

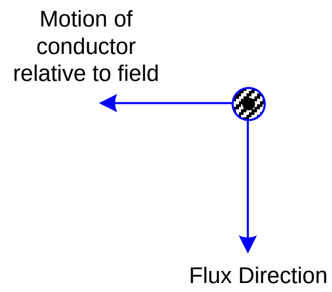


Figure 4.9 (b)

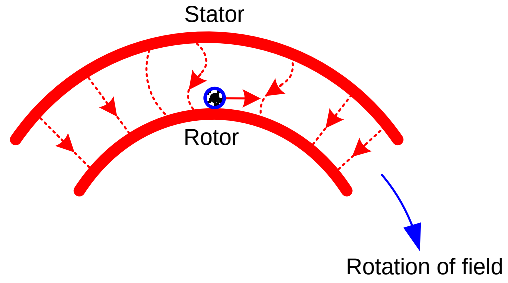


Figure 4.9 (c)

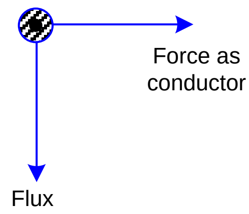


Figure 4.9 (d)

- By completing the rotor circuit either using end rings or external resistances the induced emf causes current to flow in the conductor.
- By using right hand rule we can determine the direction of induced current in the conductor.
- By using right hand rule the direction of the induced current is outwards (shown as dot) in *Figure 4.9 (b).*
- The current in the rotor conductor produces its own magnetic field as shown in *Figure 4.9 (a).*
- We know that when a current carrying conductor put in a magnetic field a force is produced. This force is produced on the rotor conductor.
- The direction of this force can be calculated by using left-hand rule as shown in *Figure 4.9 (d).*
- It is seen that the force acting on the conductor is in the same direction as the direction of the rotating magnetic field.
- The rotor conductor is in a slot on the circumference of the rotor, the force acts in a tangential direction to the rotor and develops a torque in a rotor.
- Similarly, torque produces in all the rotor conductors.
- Since, the rotor is free to move then it rotates in the same direction as the rotating magnetic field. Thus, three phase induction motor is self-starting motor.

4.5 Construction and working of Single phase induction motor:-

- Single phase motors are very widely used in home, offices, workshops etc. as power delivered to most of the houses and offices is single phase.
- In addition to this, single phase motors are reliable, cheap in cost, simple in construction and easy to repair.

- Single phase electric motors can be classified as:

  1. Single phase induction motor (Split phase, Capacitor and shaded pole etc)
  2. Single phase synchronous motor
  3. Repulsion motor etc.

4.6 Single phase Induction motor

o Construction

- Construction of a single phase induction motor is similar to the construction of three phase induction motor having squirrel cage rotor, except that the stator is wound for single phase supply.
- Stator is also provided with a 'starting winding' and 'running winding'.

Figure 4.10 Single phase induction motor

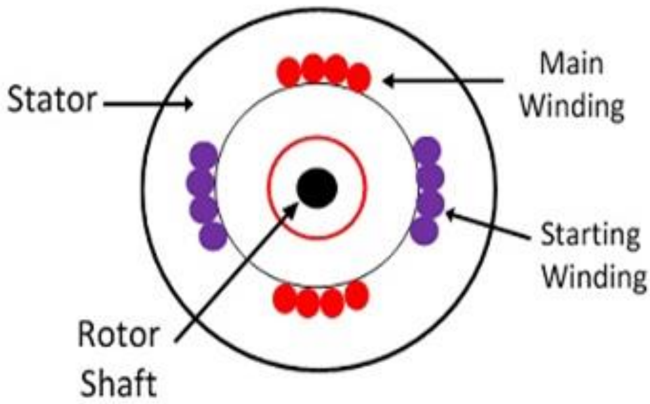


Figure 4.11 Single phase induction motor Construction

o Working principle of single phase induction motor

- We know that when the stator of a single phase motor is fed with single phase supply, it produces alternating flux in the stator winding.

- The alternating current flowing through stator winding causes induced current in the rotor bars (of the squirrel cage rotor) according to Faraday's law of electromagnetic induction.
- This induced current in the rotor will also produce alternating flux. Even after both alternating fluxes are set up, the motor fails to start (the reason is explained below).
- However, if the rotor is given a initial start by external force in either direction, then motor accelerates to its final speed and keeps running with its rated speed. This behavior of a single phase motor can be explained by double-field revolving theory.

○ Double-field revolving theory

- The double-field revolving theory states that, any alternating quantity (here, alternating flux) can be resolved into two components having magnitude half of the maximum magnitude of the alternating quantity, and both these components rotating in opposite direction.
- Following figures will help you understanding the double field revolving theory.

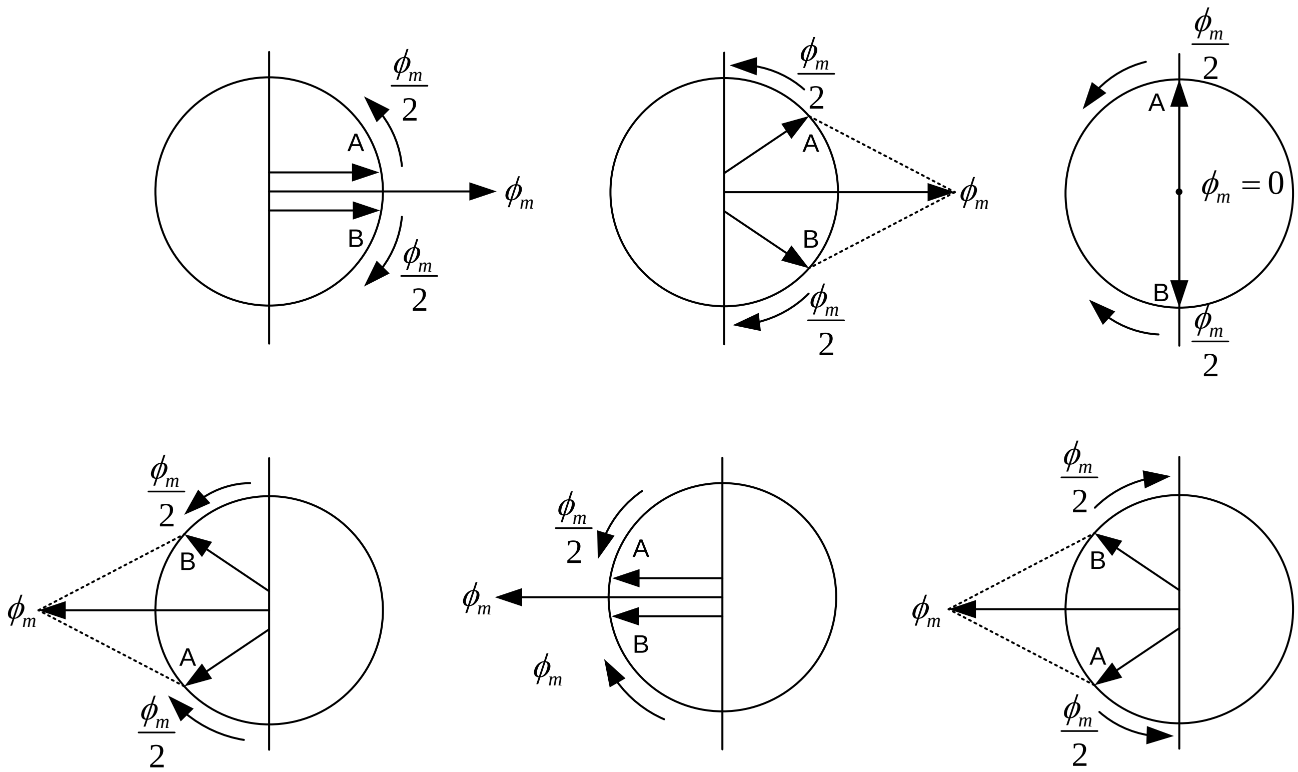


Figure 4.12 Double field revolving theory

4.7 Why single phase induction motor is not self-starting?

- The stator of a single phase induction motor is wound with single phase winding.
- When the stator is fed with a single phase supply, it produces alternating flux (which alternates along one space axis only).
- Alternating flux acting on a squirrel cage rotor cannot produce rotation, only revolving flux can. That is why a single phase induction motor is not self-starting.

4.8 How to make single phase induction motor self-starting?

- As explained above, single phase induction motor is not self-starting. To make it self-starting, it can be temporarily converted into a two-phase motor while starting.
- This can be achieved by introducing an additional 'starting winding' also called as auxiliary winding.
- Hence, stator of a single phase motor has two windings:
    - Main winding and
    - Starting winding (Auxiliary winding).
- These two windings are connected in parallel across a single phase supply and are spaced 90 electrical degrees apart.
- Phase difference of 90^0 can be achieved by connecting a capacitor in series with the starting winding.
- Hence the motor behaves like a two-phase motor and the stator produces revolving magnetic field which causes rotor to run.
- Once motor gathers speed, say upto 80 or 90% of its normal speed, the starting winding gets disconnected form the circuit by means of a centrifugal switch, and the motor runs only on main winding.

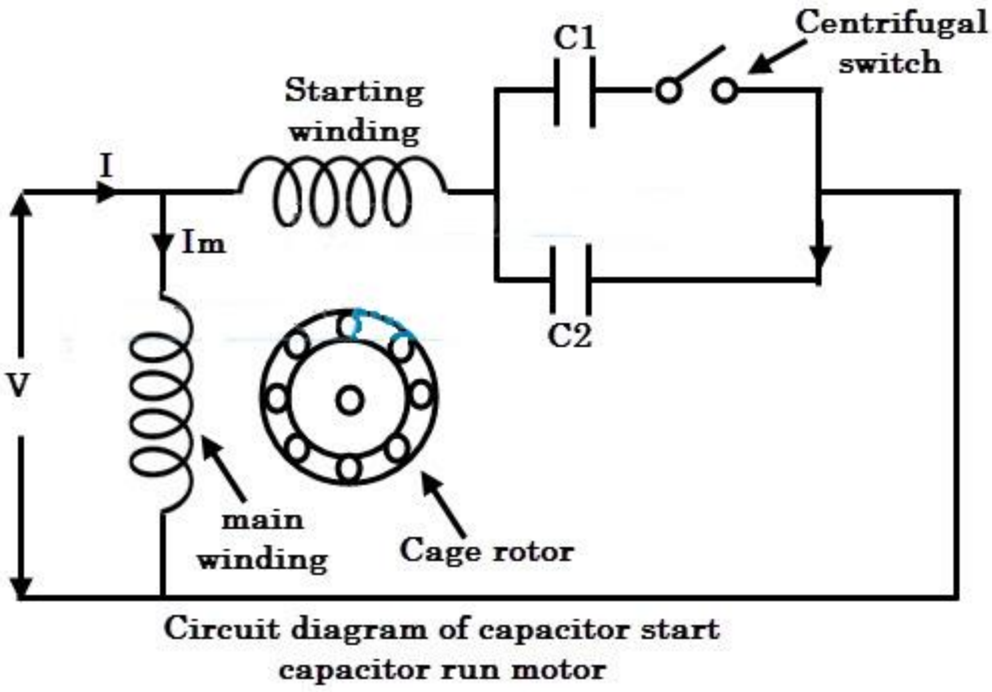


Figure 4.13 Single phase induction motor circuit diagram

Applications of Induction motors

- Deep Well Water Pumps
- Refrigerator and Compressors
- Small water pumps
- Ceiling fan
- Washing machines

4.9 DC Motor

DC motors are classified as

- **Separately Excited DC motor**
  An extra dc supply or excitation need to start this type of motor.
- **Self-excited DC motor**
  No need of extra dc supply to start this type of dc motor

Construction and working of Separately Excited DC motor:

- The DC motor is the device which converts the direct current into the mechanical work. It works on the principle of Lorentz Law, which states that ***"the current carrying conductor placed in a magnetic and electric field experience a force".*** And that force is called the Lorentz force.
- The Fleming's left-hand rule gives the direction of the force.

4.10 Construction of Separately Excited DC motor

- The construction of DC motor is same as that of DC generator. Construction of DC motor is given below:

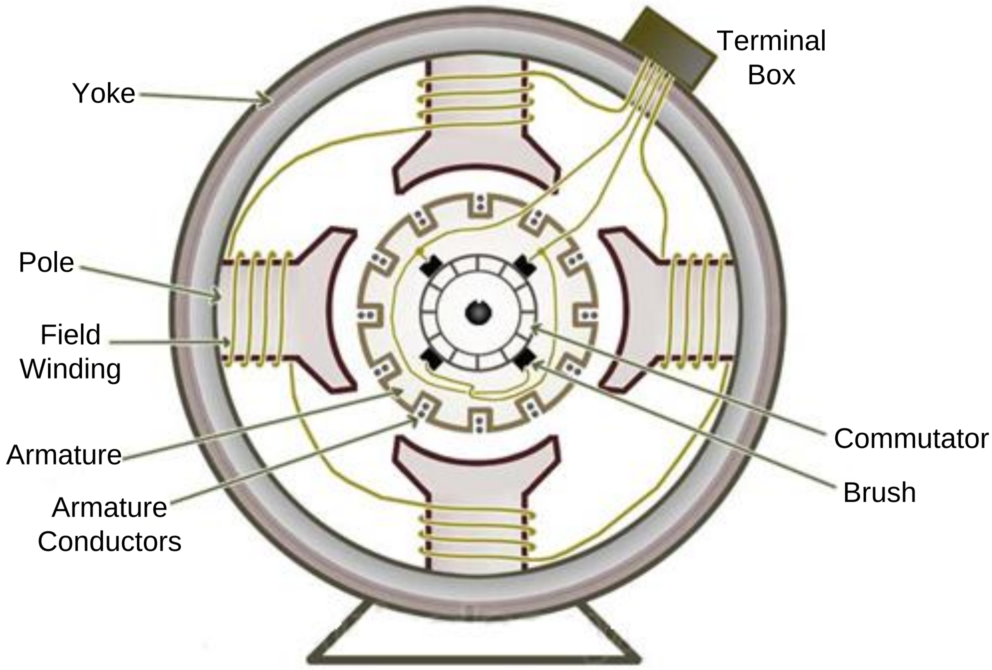


Figure 4.14 Construction of DC motor

Main parts of a DC motor are:

- ***Yoke***

- Yoke is also called as frame. It provides the protection to the armature, commutator, windings and other and other parts from moisture and dust.
- It also provide mechanical support to field poles.
- It is made from law reluctance material like cast iron, silicon steel etc.
- For small DC machines it is made from cast iron while for large machines it is made from silicon steel.
- The steel frame of yoke is affix at the bottom of the frame.

- *Field Winding*

- The winding wound around the poles are known as field winding.
- In this type of motor field winding supplied with extra DC (Excitation).
- The field coils are connected series each other from the field windings.
- The field winding also known as exciting windings and it is made from the pure copper.
- Due to the flow of current through the field winding alternate N and S poles are produced. Which pole is produce at a particular core is decided by the right hand thumb rule for a current carrying circular conductors.

- *Poles, Pole shoe and Pole core*

- The main parts of the pole are:
- The poles of a DC machine are an electromagnet. The field winding wound on pole.
- Poles produce the magnetic flux when the field winding is excited.
- Pole shoe is the extended curved part of pole and it enlarges the area of pole.
- By curves shape of pole shoe more flux can pass through the air gap to armature.
- A law reluctance magnetic materials are used to made it.
- Poles are made with laminations to reduce the eddy current loss.

- *Armature*

An armature is the rotating part of DC machine it consists of :

Armature core

- It is the cylindrical part mounted on rotating shaft.
- It is provided with large number of slots all over its periphery and all these slots are parallel with rotating shaft.

Armature windings

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

- *Commutator and brushes*

- Physical connection to the armature winding is made through a commutator-brush arrangement.
- The function of a commutator, in a dc generator, is to collect the current generated in armature conductors. Whereas, in case of a dc motor, commutator helps in providing current to the armature conductors.
- A commutator consists of a set of copper segments which are insulated from each other.
- The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed to the shaft.
- Brushes are usually made from carbon or graphite.

- They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

- ***Bearings***
- It is provided to reduce friction loss in DC machines.
- It is mounted on driving end and non-driving end of the shaft.

Working of DC motor

Fleming's Left Hand Rule

- The Fleming's left hand rule is used to find out the direction of force acting on the armature conductors of dc motor.
- If the thumb, middle finger and the index finger of the left hand are displaced from each other by an angle of 90°, the middle finger represents the direction of the magnetic field. The index finger represents the direction of the current, and the thumb shows the direction of forces acting on the conductor.

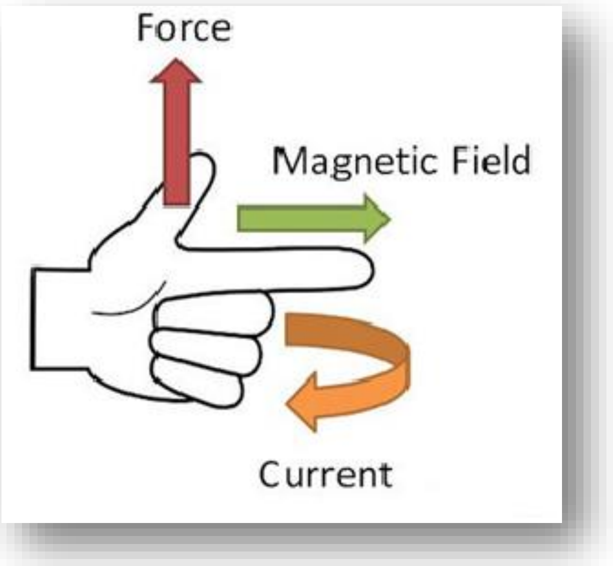


Figure 4.15 Fleming's left hand rule

- The force can be calculated by following formula:

$$F = BIL \quad (Newton)$$

- There is no difference between a dc motor and a dc generator. The same machine we can use as a motor or generator.
- When the machine is operated as a generator, it is driven by the mechanical machine (prime mover) and it develops voltage which produces a flow of current in an electric circuit.
- When a machine is operated as a motor, it is supplied electric current and it develops torque (force) which produces mechanical action.

- *Back EMF*

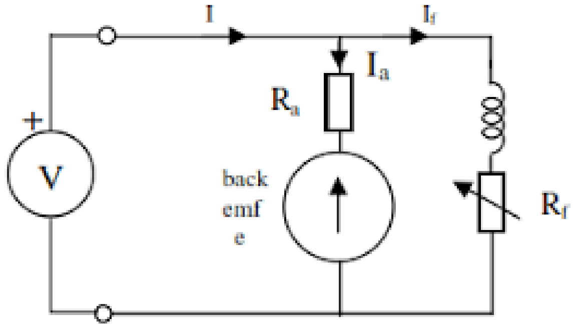


Figure 4.16 DC shunt motor

- When the armature of DC motor rotates, in a magnetic field, armature conductors cut the magnetic flux. Therefore an emf is induced according to Faraday's law of electromagnetic induction in it, whose direction is in the opposition to the applied voltage (according to Len'z law).
- Because of the opposite direction it is called the counter emf or Back emf. It's value is always less than the applied voltage.
- It can be calculated by,

$$E_b = \frac{\phi Z N}{60} \times \left(\frac{P}{A}\right) \quad Volt$$

- The applied voltage (V) has to force current through the armature conductors against this back emf.
- The electric work done in overcoming this opposition is converted into mechanical energy developed in the armature.
- Energy conversion is not possible unless there is some opposition. In DC generators, the opposition is provided by magnetic force and in dc motors, back emf does this job.

4.11 Synchronous Generator

Synchronous machines are classifies as:

- Synchronous Generator and
- Synchronous motor

- Synchronous generators are widely used to generate constant voltage output, that is why synchronous generators are used in power plants (for examples- Thermal power plants and hydro power plans, Diesel power plants etc.)

Construction of Synchronous generator

- Construction wise, an alternator consists of field poles placed on the rotating fixture of the machine i.e. rotor as shown in the *Figure 4.17* below.
- All modern electrical power generating stations use this technology for generation of three-phase power, and as a result, the alternator or synchronous generator has become a subject of great importance and interest for power engineers.
- An alternator is basically a type of AC generator which also known as synchronous generator. The field poles are made to rotate at synchronous speed Ns = 120 f/P for

effective power generation. Where, f is the alternating current frequency and the P represents the number of poles.

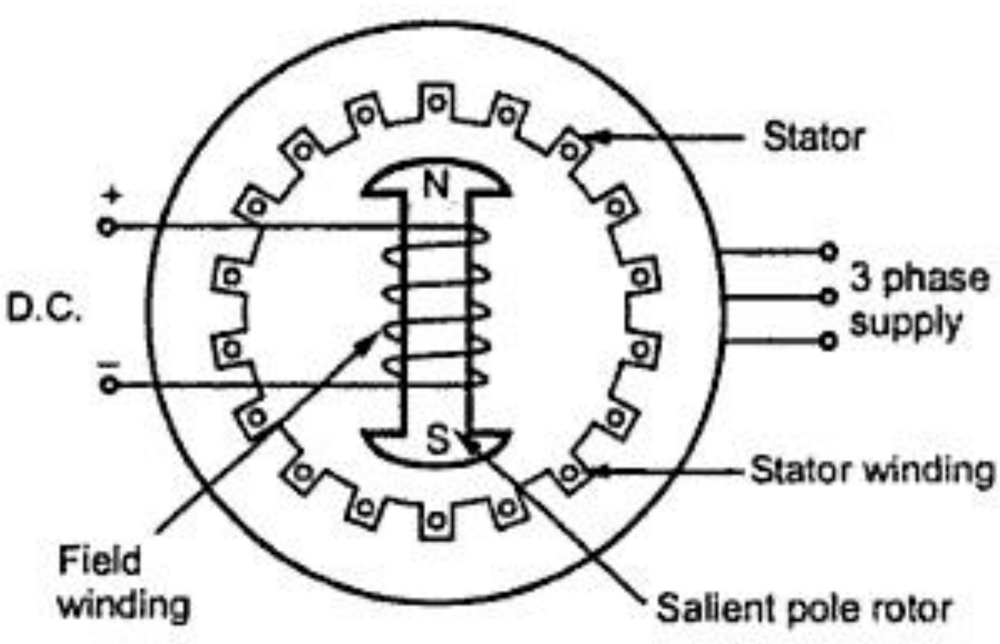


Figure 4.17 Synchronous generator construction

- In most practical construction of alternator, it is installed with a stationary armature winding and a rotating field unlike in the case of DC generator where the arrangement is exactly opposite.
- This modification is made to cope with the very high power of the order of few 100 Megawatts produced in an AC generator contrary to that of a DC generator.
- To accommodate such high power the conductor weighs and dimensions naturally have to be increased for optimum performance.
- For this reason is it beneficial to replace these high power armature windings by low power field windings, which is also consequently of much lighter weight, thus reducing the centrifugal force required to turn the rotor and permitting higher speed limits.
- There are mainly two types of rotor used in construction of alternator,
    - Salient pole type.
    - Cylindrical rotor type.

○ **Salient Pole Type**

- The term salient means protruding or projecting.
- The salient pole type of rotor is generally used for slow speed machines having large diameters and relatively small axial lengths.
- The poles, in this case, are made of thick laminated steel sections riveted together and attached to a rotor with the help of joint.

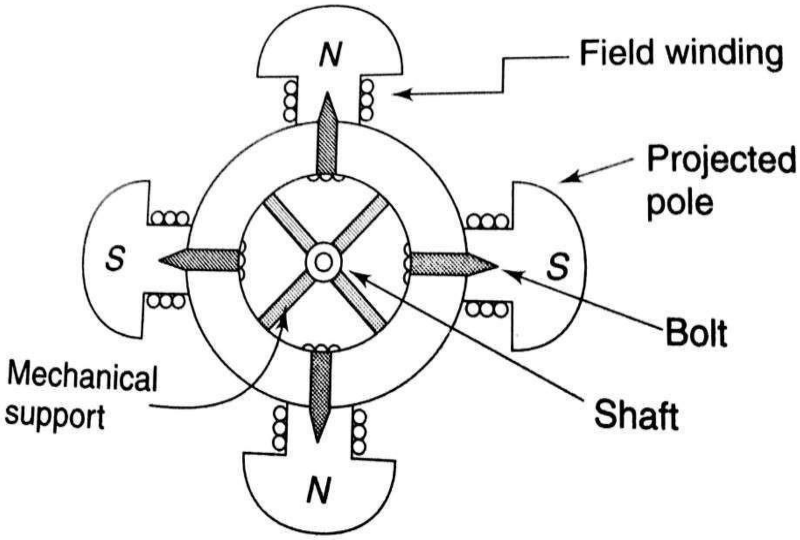


Figure 4.18 Salient pole type rotor

- An alternator as mentioned earlier is mostly responsible for generation of very high electrical power.
- To enable that, the mechanical input given to the machine in terms of rotating torque must also be very high. This high torque value results in oscillation or hunting effect of the alternator or synchronous generator.
- To prevent these oscillations from going beyond bounds the damper winding is provided in the pole faces as shown in the *Figure 4.18*.
- The damper windings are basically copper bars short-circuited at both ends are placed in the holes made in the pole axis.

- When the alternator is driven at a steady speed, the relative velocity of the damping winding with respect to the main field will be zero.
- But as soon as it departs from the synchronous speed there will be relative motion between the damper winding and the main field which is always rotating at synchronous speed.
- This relative difference will induce the current in them which will exert a torque on the field poles in such a way as to bring the alternator back to synchronous speed operation.

- The salient pole type motor is generally used for low-speed operations of around 100 to 400 rpm, and they are used in power stations with hydraulic turbines or diesel engines.
- Salient pole alternators driven by water turbines are called hydro-alternators or hydro generators.

- **Cylindrical Rotor Type**
- The cylindrical rotor is generally used for very high speed operation and employed in steam turbine driven alternators like turbo generators.
- The machines are built in a number of ratings from 10 MVA to over 1500 MVA.

- The cylindrical rotor type machine has a uniform length in all directions, giving a cylindrical shape to the rotor thus providing uniform flux cutting in all directions.
- The rotor, in this case, consists of a smooth solid steel cylinder, having a number of slots along its outer periphery for hosting the field coils.

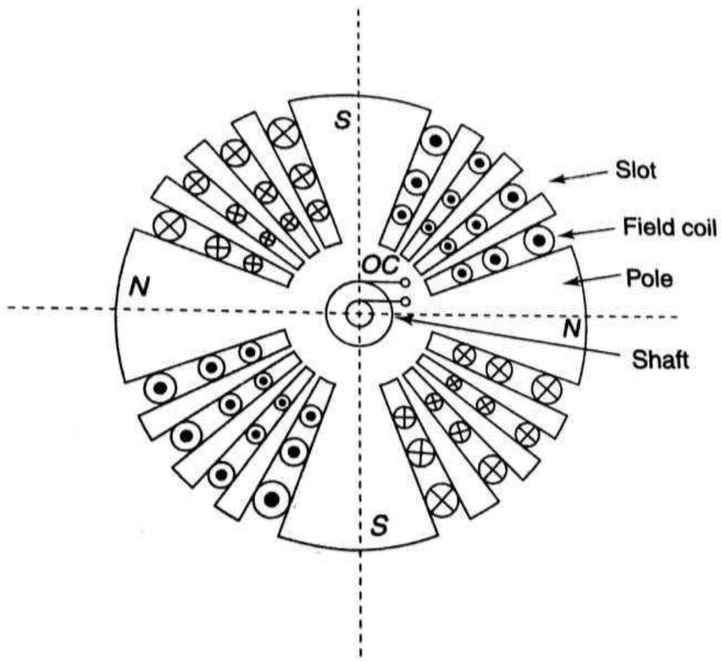


Figure 4.19 Cylindrical Rotor

The cylindrical rotor alternators are generally designed for 2-pole type giving very high speed of

$$N_s = \frac{(120 \times f)}{P} = \frac{(120 \times 50)}{2} = 3000\ rpm$$

- Where, f is the frequency of 50 Hz. The cylindrical rotor synchronous generator does not have any projections coming out from the surface of the rotor, rather central polar area is provided with slots for housing the field windings as we can see from the diagram above.
- The field coils are so arranged around these poles that flux density is maximum on the polar central line and gradually falls away as we move out towards the periphery.
- The cylindrical rotor type machine gives better balance and quieter-operation along with lesser windage losses.

○ Working Principle of Synchronous generator

Operate on principle of electromagnetic induction

• Stationary armature and rotating field
• Rotor is rotated using a prime mover
• When the rotor rotates, the stationary conductors are cut by the magnetic flux
• Hence emf is induced in three phase alternators, the rotor flux will induce 3-phase voltages displaced in time by 120^0 emf induced is AC in nature
• AC voltage will give rise to AC current when a load is connected to stator

- **Applications**
  - Salient pole generator is used for law speed upto 1000 rpm maximum.
  - Salient pole generator is used in hydro-power plant.
  - Cylindrical rotor type synchronous generators are high speed machine upto 3000 rpm.
  - Cylindrical rotor type synchronous generators are used mostly in thermal power plant.

****

5.1 What is fuse? Define its characteristic.

- Fuse is the simplest device, which break the circuit under abnormal condition.
- It is only a current interrupting device under fault condition.
- It is not able to make or brake the circuit under normal condition.
- A fuse consists of a metal strip of mounted between a pair of electrical terminals, and enclosed by a non-conducting and non-combustible housing.
- The fuse is arranged in series to carry all the current passing through the protected circuit.

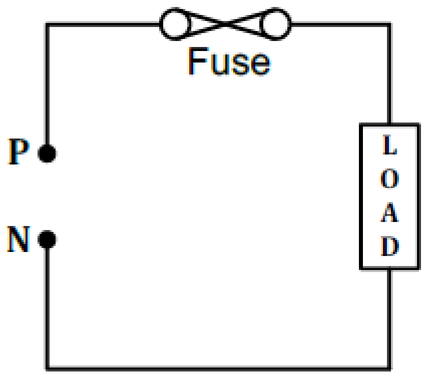


Figure 5.1 Fuse connected in circuit

- The fuse element is made of zinc, copper, silver, aluminum, or alloys.
- The fuse element may be surrounded by air or by materials to quench the arc. Silica sand or non-conducting liquids may be used.
- It is used for overload short circuit protection in medium voltage (up to 33 kv) and low voltage (up to 400v) installation.
- Fuse characteristics are drawn between current and time scale. The curve shows that fault current and operating time is inversely proportional to each other.
- The time considered is précising time and current is prospective current.
- The fuse characteristics become asymptotic and there is a minimum current below which the fuse does not operate. This is called minimum fusing current.

FUSE Characteristics

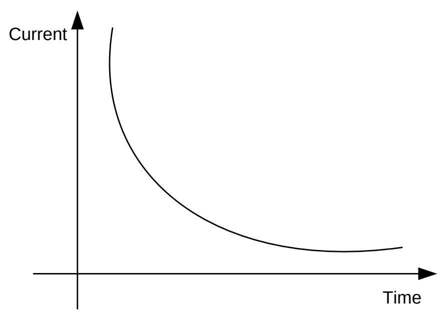


Figure 5.2 Fuse Characteristics

They should have a following desirable characteristic:-

- Low melting point
- High conductivity
- Free from deterioration from oxidation
- Low cost

5.2 Write short note on HRC fuse.

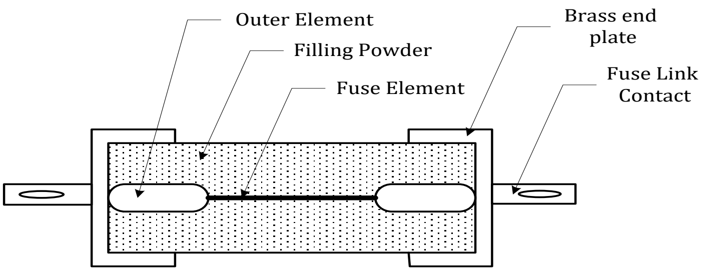


Figure 5.3 HRC Fuse

- When the load capacity is very high the level of fault current will also increase. So faulty clearing device will be under heavy stress.
- HRC fuse is preferred for heavy duty and rapid operation.
- It consists of heat resisting ceramic cylindrical body having low co-efficient of thermal expansion.
- The fuse element is made up of silver or silver alloy to improve fuse life.
- It is filled with incombustible powder which absorbs the arc produced at the time of blowing.
- The rating is much more accurate. It is widely used because of silent operation and non-deteriorating characteristics.
- It is maintenance free and easy to install.

Advantages:-

- Speed of operation is very high.
- Maintenance cost is practically is zero.
- They deteriorate with age.
- They provide reliable operation.
- They cheaper than other protecting devices.

Disadvantages:-

- Heat produced by arc may affect the associate switches.
- They have to be replaced after each operation.

5.3 Compare Fuse with MCB.

Fuse	MCB
○ Melts the wire when fault occurs	○ Cut-off circuit when the fault occurs
○ Fuse wire available may not be standard rating	○ MCB available is of standard rating
○ Operated at 50 to 100 % over load capacity	○ Operated at 5 to 15 % over load capacity
○ Hand tools are required to re-wire the fuse when blown off	○ No hand tool required to reset
○ Cheapest among all safety device	○ Initial cost is very high
○ Fuse board (mounting arrangement) is not compact	○ MCB board (mounting arrangement) is compact

5.4 Compare MCB with ELCB.

MCB	ELCB
○ MCB is an electromechanical device which protects an electrical circuit from an over current and in short circuit condition.	○ The ELCB is used to protect the circuit from the electrical leakage.
○ MCB has slower operation time than ELCB.	○ ELCB has rapid operation compare to MCB.
○ The operating principle of MCB is simple.	○ The operating principle of ELCB is complicated.
○ MCB does not give human protection.	○ ELCB gives human protection.
○ MCB is cheaper than ELCB.	○ ELCB is costlier than MCB.
○ Rated current is not more than 100 Ampere.	○ The range of rated current us up to 1000 Ampere.
○ This circuit breaker connects the phase and neutral terminal.	○ This circuit breaker connects the phase, earth wire and neutral terminal.
○ **Applications:** ○ Domestic and commercial purposes.	○ **Applications:** ○ Mostly in Domestic purposes.

5.5 Write short notes on MCB.

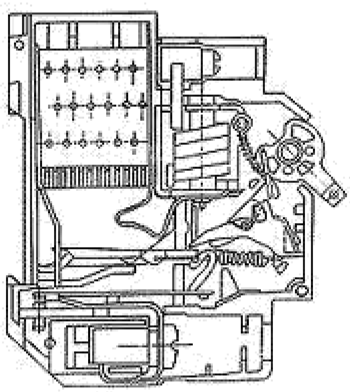


Figure 5.4 MCB Construction

- MCB have the features of good HRC fuse and a good switch.
- These are used for switching purpose under normal condition and circuit break under overloading and short circuit condition.
- It is normally operated at 1.25 times its rated current.
- It is manufactured with quick reset hand operated facility.
- It is basically operated on two type of working principles:
    - ❖ **Thermal operation:**
- It is achieved by bimetallic strip which deflects when heated by any over current flowing through it.
    - ❖ **Magnetic operation:**
- When short circuit occurs the rising current energizes the solenoid further operating plunger to strike the trip lever immediately releasing of latch mechanism.

Construction of MCB

- The casing of MCB is made of moulded thermoplastic polyester. This material is fire retardant and non-hygroscopic. They are installed directly on Rail in distribution boards, control panels simply by fixing.
- The contacts are made of Silver- Copper alloy which ensure longer life of contacts. These have low resistance resulting in low watt loss. The contacts are designed to have zero Bounce during closing operation.
- Operating Mechanism of MCB has quick make, quick break, and trip-free mechanism.

Application:-

- MCB are used extensively in low voltage domestic, commercial and industrial.

5.6 Write short notes on MCCB.

Definition

- MCCB is a switching device which is used in LT electrical system. It provides protection against overload & short circuit. Fault sensing arrangements are installed inside MCCBs & shunt release is provided for remote tripping of MCCB.
- It is available between 100A & 630Acurrent.

Working Principle

- MCCB provides **protection against overload** through thermal mechanism.
- It has bimetallic contacts which expand & contract on temperature changes *(same like an automatic iron).*
- Under normal condition these contacts allow normal current to flow but when current exceeds its trip limit, the bimetallic contacts start heating up & expand until the circuit is isolated/tripped.
- When MCCB is tripped, faulty circuit is isolated from circuit & the temperature of bimetallic contacts starts getting normal & MCCB again is ready for next operation.
- MCCB provides protection against short circuit – if current is very high, fault current should be interrupted immediately.
- This is achieved by electromagnetic induction. Whenever fault occurs, the high current induces a magnetic field in a solenoid coil located inside the breaker, this magnetic induction trips a contact & current is interrupted.
- In the tripping process, arc is produced & that is dissipated by taking suitable measures inside the breaker.
- These breakers can be manually switched off or on also which is required during maintenance or other purpose.

Figure 5.5 MCCB

- **Current rating of MCCB**
- A typical range of **Three phase MCCB** are – 100A, 125A, 150A, 200A, 250A, 315A, 400A, 630A (These ranges are standard rating that available in the market)
- **Application:**
- Especially for industrial purposes where load current are more than 100A.
- It is used in cement industries, ceramic industries, food processing industries etc.

5.7 List various device used in Electrical Circuit. Write the brief note on ELCB.

Followings Protective Device used in Electrical Circuit:-

(1) Fuse
(2) Miniature Circuit Breaker (MCB)
(3) Earth Leakage Circuit Breaker (ELCB)
(4) Relay

ELCB:-

- Earth Leakage Circuit Breaker (ELCB). An Earth Leakage Circuit Breaker (ELCB) is a device used to directly detect currents leaking to earth from an installation and cut the power and mainly used in TT earthing systems.
- For the protection of human body from the electric shock protective device like fuse or MCB are used.
- But generally this device are incapable of measuring small current flowing in human body, so requirement is to have a device which can sense small current and cut-off the supply instantly.
- The device used for this purpose is known as Earth Leakage Circuit Breaker (ELCB).

There are two types of ELCBs:

- 1. Voltage Earth Leakage Circuit Breaker (Voltage-ELCB)
- 2. Current Earth Leakage Current Earth Leakage Circuit Breaker (Current-ELCB).

Circuit Diagram:-

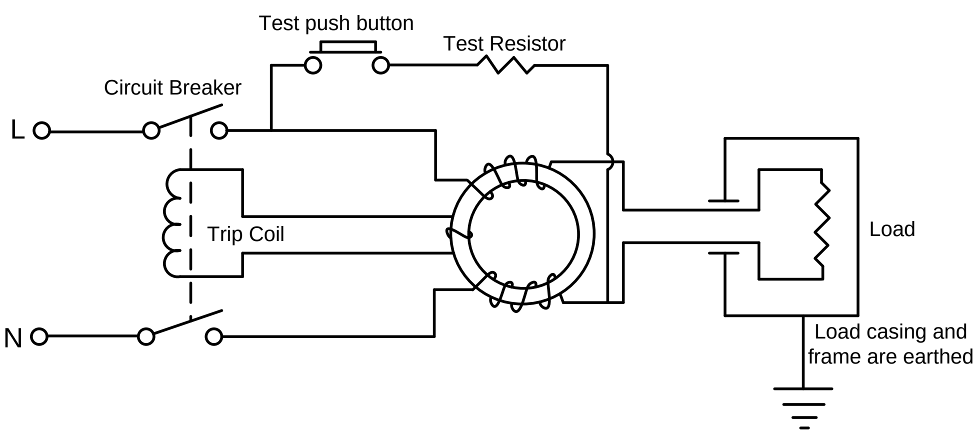


Figure 5.6 ELCB Circuit Diagram

Working of ELCB

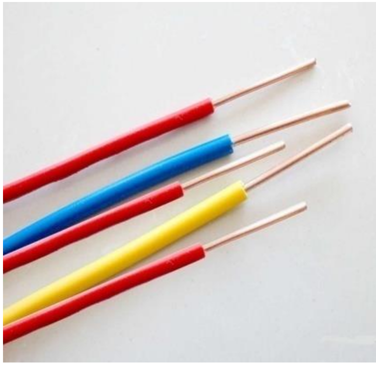
- It is current operated device designed to operate when a leakage current exceeds the predefined value.
- It consists of a operating coil and a trip mechanism which operated the circuit when required.
- The coil is supplied through 1-Φ supply so current in phase & neutral wire will be same.
- This current will produce flux linkages same in magnitude but of opposite direction. This will result zero net flux in tripping coil of relay.
- When fault or leakage current exceeds the limit higher current will flow in phase conductor than neutral current.
- Resultant flux now is out of balance in tripping coil of relay. Difference of flux will induce emf in the coil which opens the contact of ELCB and isolate the circuit from the supply.

5.8 Explain types of wire

- There are different types of wire are listed below:
- Triplex wire: Triplex wires are usually used in single-phase service drop conductors, between the power pole and weather heads. They are composed of two insulated aluminum wires wrapped with a third bare wire which is used as a common neutral.
- **Non-metallic sheathed wires:** Non-metallic sheath wire is used in most homes and has 2-3 conductors, each with plastic insulation, and a bare ground wire. The individual wires are covered with another layer of non-metallic sheathing. Since it's relatively cheaper and available in ratings for 15, 20 and 25 amps, this type is preferred for in-house wiring.

Triplex wire

Non-metallic sheathed wire



Single strand wire

Figure 5.7 Types of wire

- **Single Strand Wire**: Single strand wire also uses THHN (Thermoplastic High Heat-resistant Nylon-coated) wire, though there are other variants. Each wire is separate and multiple wires can be drawn together through a pipe easily. Single strand wires are the most popular choice for layouts that use pipes to contain wires.

5.9 Explain types of Cable

Under ground cable are classified as follow:

(1) According to voltage level:

- **Low voltage (L.T.) cable:** It consist of one circular core of tinned stranded copper (or aluminum) insulated by layers of impregnated paper. These cable are used up to 1 kV.
- **High voltage (H.T.) cable:** It consist of either circular shaped or oval or sector shaped 3 core stranded copper or aluminum. These cable are used up to 11 kV.
- **Super tension (S.T.) cable:** The insulation on each core is covered with aluminum foil or own lead sheath or metallized paper. These cable are used up to 33 kV.
- **Extra high tension (E.H.T.) cable:** oil filled cable and gas pressure cable are types of E.H.T. cable. Oil filled cable is consist of oil channel at the center of core by stranding the conductors wire around the hollow cylindrical steel spiral tape.Gas pressure cable is laid in a gas tight steel pipe which is filled with dry nitrogen at 12 to 15 atmosphere pressure produces radial compression and closes the voids. These cable are used up to 66 kV.
- **Extra super voltage cable:** These cable are used up to 132 kV and above.

(2) According to insulating material :

- Insulation is provided on conducting material to block the path of leakage current from the conductor,thus minimizing the risk shock and fire. Normally cables are classified according to the insulation used over the conductor. The various classification of cable commonaly used for domestic wiring are as follow:
- **Vulcanized rubber sheathed (V.I.R.) insulated cables:** These consists of a copper conductor covered with a insulation layer of Vulcanized Indian Rubber (VIR). A cotton tape covering is provided over this insulation layer to protect the wire from moisture and to provide mechanical strength to the wire. The thickness of the Vulcanized Indian Rubber depends on the voltage.
- **Cab Type sheathed (T.R.S.) cables:** These C.T.S or T.R.S wires consists of vulcanized rubber insulated conductor. This insulation layer is covered by a layer made of tough rubber (or) tough rubber sheathed covering is provided over this insulation layer. This covering will be very hard and protects the wire from moisture and provides mechanical strength to the wire. These wires are available in single core, twin core, triple core etc. As these wires have tough rubber covering no additional protection or strength is required.
- **Weather –proof cables:** These wires consists of conductor provided with an insulation layer made up of hard rubber. Over this cotton sheathed and cotton tape covering is provided especially to protect the wire from moisture. These wires are used where the moisture is present.
- **Polyvinyl chloride (P.V.C.) insulated cables:** These wires consists of a conductor over which an insulation layer made up of Polyvinyl Chloride is provided. These wires cannot resist much heat and they have relatively low melting points, so they aren't used in hot places and also these wires are not used with heating appliances. PVC wires are available in almost all colors.
- **Lead sheathed cables:** These wires consists of vulcanized Indian rubber insulated conductor over which a Lead sheath is provided which gives mechanical strength to the

wire and it also protects the wire from moisture. These wires are generally used where there is chances of moisture like in snowy places. As Lead is a good conductor of electricity the Lead covering may give electric shock to us so to prevent this the Lead covering is provided with earth wire. These wires are available in single core, twin core, triple core etc size.

(3) According to number of conductor :

- **Single core:** Single core cable means,it consists of one conductor only.
- **Multi core:** Multi core cable has more than one core.
  - **2 core cable:** In 2 core cable, one conductor act as a phase and another act as a neutral. Both conductor have a equal cross sectional area.
  - **3 core cable:** In 3 core cable, all the conductors have a equal cross sectional area. Three strand carry R,Y and B phases respectively.
  - **3 ½ core cable:** In 3 ½ core cable, 3 conductors have a equal cross sectional area. Three strand carry R,Y and B phases respectively. Fourth core having cross sectional are half than that the other. Fourth core are used as a neutral.
  - **4 core cable:** In 4 core cable, all the conductors have a equal cross sectional area. All strand carry R,Y ,B phases and neutral respectively.

5.10 Cable construction with neat sketch diagram

- Construction of cable as shown in figure. Different parts of cable are given below.
- **Conductor:** Conductors used for cables are generally made up of tinned copper or aluminium.To provides the sufficient flexibility conductors are used in stranded form. Cable may consist of one, two, three of four conductors depending upon the service required.
- **Paper insulation:** The type and thickness of insulation depends upon the voltage level. Insulating materials should provide the following properties: High insulation resistance, High mechanical strength, Non-porous, Chemically inert, high die-electric strength, Non-inflammable etc.
- Following are the different materials used for cable insulation: Rubber, Vulcanized India Rubber, Impregnated paper, PVC etc.

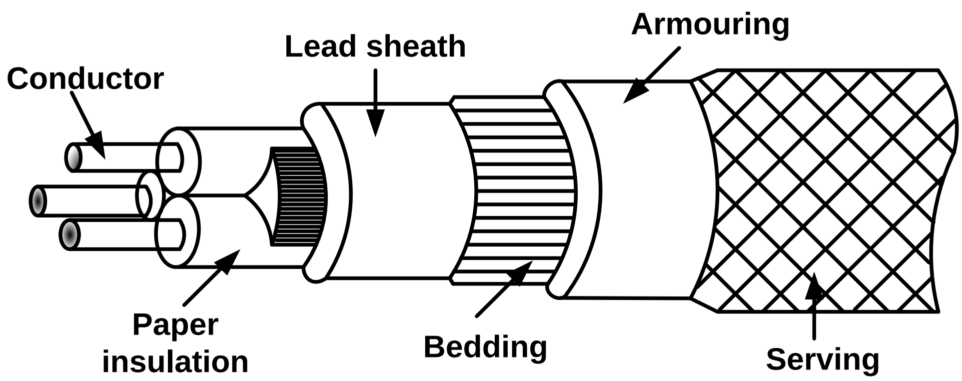


Figure 5.8 Construction of cable

- **Lead Sheath:** As the cable is placed under ground, soil may present moisture, gases and some other liquids. Therefore, to protect the cable metallic sheath made up of lead or aluminum is provided over the insulation.
- **Bedding:** To protect the metallic sheath from corrosion and some mechanical injury, bedding is provided. It is made up of some fibrous material such as jute.
- **Armoring:** Armoring is used to protect the cable from mechanical injury while handling. It consists of one or two layers of galvanized steel wire or steel tape.
- **Serving:** Serving is provided to protect the armoring from atmospheric conditions. It is made up of some fibrous material like jute.

5.11 Eatrhing System

❖ **What is Eatrhing? Explain the purpose of Earthing. *OR* Grounding.**

- "The earthing is the connection of general mass of earth to electrical apparatus in such a manner as to ensure all time an immediate energy discharge without danger".
- The earth is made up of a material that is electrically conductive. A fault current will flow to earth through the live conductor, provided it is earthed.
- The Conventional system of Earthing is done by digging of a large pit into which a GI pipe or a Copper plate is positioned with the layers of charcoal and salt.
- When system is without earthing and if short circuit occurs and human body touches the metal part, current will get return path through human body.
- When system is properly earthed and if short circuit occurs and human body touches the metal part, current will not get path through human body. Because circuit is already provided with low resistance path through earthing.
- An effective earthing is made through any wire, pipe, rod or metal plate known as earth electrode.
- The connecting wire between electrical apparatus and earth electrode is known as earthing lead or main earthing conductor.

Purpose of Earthing

- To avoid electric shock to human body.
- To avoid risk of fire due to earth leakage current through unwanted path.
- Ensure that all exposed conductive parts do not reach a dangerous potential
- Maintain the voltage at any part of an electrical system.

The qualities of a good Earthing

- Must be of low electrical resistance
- Must be of good corrosion resistance
- Must be able to dissipate high fault current repeatedly

5.12 State the different method of earthing and explain one.

Following are the different methods of earthing.

- Pipe earthing
- Plate earthing
- Coil earthing

Pipe Earthing:-

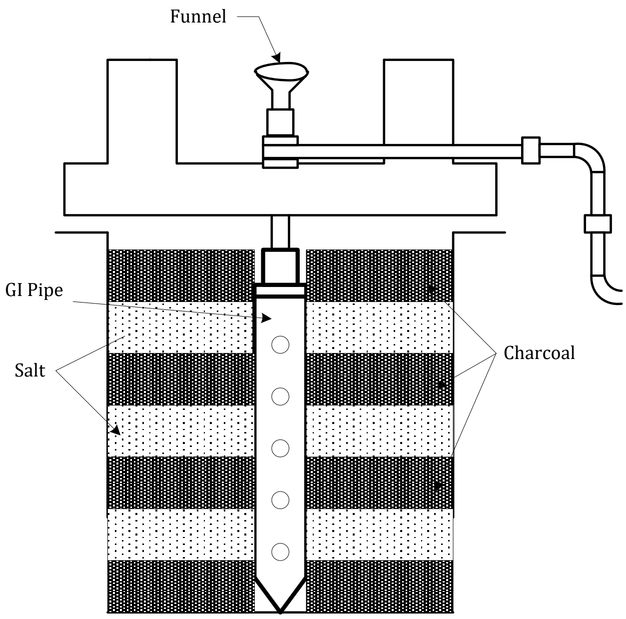


Figure 5.9 Pipe Earthing

- Pipe earthing is the most commonly adopted method and is a best system of earthing compared to the others system.
- In this method of earthing pipe of sufficient diameter is selected whose size is depend upon (a) Maximum earth current of that installation (b) Type of Soil
- As per IS-732-1963, The GI pipe shall not be less than 38mm diameter and 2 meter long for ordinary soil.
- If Cast Iron is used then internal diameter should be 10 mm.
- The depth at which pipe should be buried depends upon condition of soil and moisture.
- For pipe earthing at pit of 40sq.mm is dug in the soil and the pipe having tapered at the bottom is placed vertical in the pit.
- The charcoal and salt are filled in that pit alternately in layers about 2 meters from bottom and for a distance of about 15cm around the pipe. This is done to increase the dampness and moisture of soil surrounding pipe.
- The pipe placed has 12mm diameter holes drilling in it so that water poured from top is easily spread in the media surrounding the pipe which helps in maintaining the resistance of earth.
- At a top a cement concrete work is done to provide protection against mechanical damage.
- A water pouring arrangement is provided by a funnel with wire mesh at the top.

Plate Earthing:-

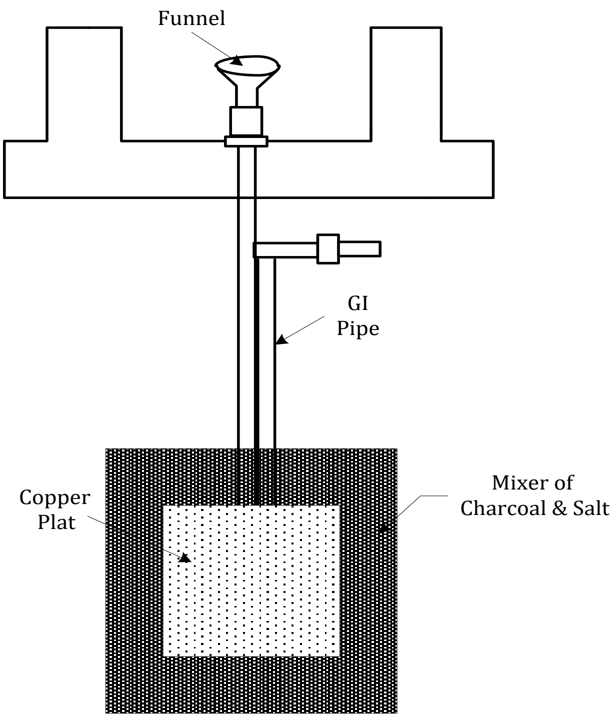


Figure 5.10 Plate Earthing

- In case of plate earthing electrodes may made of GI or steel or copper.
- For copper plate thickness is not less than 3.15mm and for GI or steel plate thickness is not less than 6.30mm.
- The size of plate electrode should be 60×60 cm.
- Plate electrode should be buried such that top edge is a depth of not less than 1.5 meter below the surface of the ground.
- For the plate earthing a pit of a 4 meter dug in to the ground and the earthing plate is placed vertical in that pit.
- The space around the plate is filled with layers of charcoal and salt for a minimum thickness of 15 cm.
- For connection of earth wire to the earth electrode a GI pipe of 12.7 mm diameter is connected to the electrode (earthing plate).
- Earth wire is properly secured to earth electrode with the help of nut, bolt and washer.
- The pit filled with charcoal and salt is also connected with a pipe for carrying water from concrete work that area.
- This will help in increasing the dampness and moisture surrounding the plate.
- No earth electrode should have a resistance more than 3 ohm measured by an earth resistance meter. In rocky soil the resistance may be up to 8 ohm. Copper plate earthing needs to be changed every 12 years due to corrosion attacks.

5.13 Write short note on Neutral Earthing.

- Neutral Earthing is the process of connecting a star point of transformer, generator and motor to ground.
- Protects system against arcing ground
- Keeps balanced voltage with respect to earth
- Greater safety to lightning
- Maintenance and operating cost is low
- Reliable in operation

Types of Neutral Earthing

- All A.C. power system of today is operated with neutral grounded. It is classified as per voltage level as below.

1. Solid Earthing

- Neutral point is connected to earth without intentional resistance or reactance.
- It is used below 660 V.

2. Resistance Earthing

- Neutral point is connected to earth through resistance.
- It is used between 3.3 KV to 11 KV.

3. Reactance Earthing

- Neutral point is connected to earth through resistance.
- It is good as compared to resistance earthing for same voltage level (i.e. 3.3 KV to 11 KV)

4. Resonant Earthing

- The value of reactance is selected so as to neutralise the power frequency capacitive current between line and earth.
- It is used for medium voltage transmission line which connected to generator with intervening power transformer.

5.14 Safety precautions for electrical appliances

- It is extremely important to take safety precautions when working with electricity. Safety must not be compromised and some ground rules must be followed.
- The basic guidelines regarding safe handling of electricity are as given below:
  - Avoid water at all times when working with electricity. Never touch or try to repair any electrical equipment with wet hands, as it increases the possibility of shock.
  - Never use any equipment with frayed cords, damaged insulation or broken plugs.
  - Never work on any receptacle at your home with mains supply ON. Always turn it OFF before working.
  - Always use insulated tools while working.
  - Always use standard pins to tap the supply of power from any plug.
  - Always use the standard ISI marked materials and equipments even though they cost a little more.

- Avoid electrical hazards by not letting the energized parts and unguarded electric equipment exposed because they are a shock risk especially for children in the house.
- Never use an aluminum or steel ladder to work on any appliance at height. Instead use a bamboo, wooden or fiberglass ladder.
- Know the wire code of your country.
- Always check all your GFCIs (Ground Fault Circuit Interrupters) once a month. These devices are commonly used nowadays to avoid electric shock hazards.
- Plug points of high power appliances like refrigerators, wet grinders, washing machine, water heaters etc must have a proper earthing and power should be drawn only through the three pin plugs.
- Always use .a circuit. breaker (MCB) with the appropriate current rating, in each electrical circuit.
- Take care while removing a capacitor from a circuit. A capacitor stores energy and if not removed properly then it may cause an electric shock.

5.15 Basic introduction of Battery

- It is known that the electrical current can easily flow through the metallic conductors. Current can also flow through same liquids called electrolytes.
- When current passes through an electrolytic solution chemical action occur and produced chemical charges.
- Thus in this process electrical energy is converted into chemical energy and chemical energy also converted into electrical energy. The device which is converting chemical energy into electrical energy is called electrical cell.

5.16 Explain following terms

(1) Cells

- The smallest element of a battery is a cell. A cell is defined as a source of emf in which chemical energy is converted into electrical energy.
- A cell consists of two metal plates of different materials. These plates are immersed in a suitable solution. The value of emf produced by a cell depends on: (1) Material used for the plates or electrodes (2) Types of electrolyte

(2) Battery

- A battery is a group of cells. Depending on the voltage and current requirements, the cells are suitably connected in series parallel configurations. Batteries absorb electrical energy at the time of charging and release it at the time of discharging.
- The batteries give out electrical energy due to chemical reaction taking place, while discharging. During the charging process, the batteries chemical changes take place, which absorb the energy.
- The entire resistance encountered by a current as if it flows through a battery from the negative terminal to the positive terminal is known as internal resistance of battery.

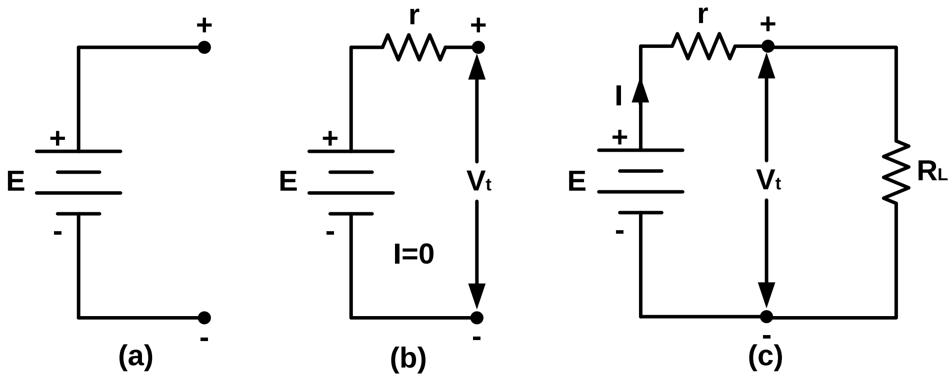


Figure 5.11 Battery

When load (R_L) is connected to battery,

$$E = V_t + I\,r$$

Where, $E =$ Emf of battery

$V_t =$ Terminal voltage of battery

$I =$ Current delivered by battery

$r =$ Internal resistance of battery

5.17 Classification of Cells

- The cells are classified into two categories: (1) Primary cells (2) Secondary cells

(1) Primary Cells

- The chemical action taking place in the primary cells is irreversible (permanent). Hence once the terminal voltage goes down, we have to replace the primary cell by a new one. The energy producing capacity of primary cells is limited. Examples: Dry cell, alkaline cell, mercury cell, zinc-chloride cell etc.

(2) Secondary Cells

- The secondary cells are also called as storage cells or rechargeable cells. The chemical action taking place in secondary cell.
- The secondary cells are reversible (No permanent). So, it is possible to recharge the cell if it is in the discharged state. The electrical energy is stored in the form of chemical form, when the charging current is passed.
- Secondary cells are capable of producing large amount of energy. Examples: Lead-acid cell, Nickel iron alkaline cell, Nickel cadmium-alkaline cell etc.

5.18 What is Requirements of Batteries?

Requirements:

- It should be capable of supplying large current at constant output power.
- Its output voltage should remain constant for all the load currents.
- Storage time should be as long as possible.
- The battery should be compact and occupy less space.
- It should be rechargeable and maintenance free.
- It should be cost effective.

5.19 Explain A-h Capacity and W-h Capacity

(a) A-h Capacity

- An ampere hour (abbreviated Ah, or sometimes amp hour) is the amount of energy charge in a battery that will allow one ampere of current to flow for one hour. An ampere is a unit of measure of the rate of electron flow or current in an electrical conductor.

  $$A\text{-}h\,capacity = I_d T_d$$

  Where,

  I_d = Rated current during discharging

  T_d = discharging time in hour

(b) W-h Capacity

- The watt-hour (symbolized Wh) is a unit of energy equivalent to one watt (1 W) of power expended for one hour (1 h) of time. The watt-hour is not a standard unit in any formal system, but it is commonly used in electrical applications.

  $$W\text{-}h\,capacity = I_d T_d V_d$$

  Where,

  I_d = Rated current during discharging

  T_d = Discharging time in hour

  V_d = The average voltage during discharging

5.20 Give the classification of Battery

(i) Non-rechargeable batteries

- Zinc-chloride batteries
- Zinc-Carbon
- Mercuric Oxide Batteries
- Zinc Silver Oxide Batteries

(ii) Rechargeable batteries

- Lead-acid batteries
- Li-ion batteries
- Nickel-cadmium batteries
- Nickel hybrid batteries

5.21 Explain Lead acid battery with charging & discharging equations

Working of Lead Acid Battery

- The storage battery or secondary battery is such battery where electrical energy can be stored as chemical energy and this chemical energy is then converted to electrical energy as when required. The conversion of electrical energy into chemical energy by applying external electrical source is known as charging of battery.
- Whereas conversion of chemical energy into electrical energy for supplying the external load is known as discharging of secondary battery. During charging of battery, current is passed through it which causes some chemical changes inside the battery. This chemical changes absorb energy during their formation.

- When the battery is connected to the external load, the chemical changes take place in reverse direction, during which the absorbed energy is released as electrical energy and supplied to the load.
- Now try to understand working principle of lead acid battery and for that we will first discuss about lead acid battery which is very commonly used as storage battery or secondary battery.

Materials used for Lead Acid Storage Battery Cells

- The main active materials required to construct a lead acid battery are
  - Lead peroxide (PbO_2).
  - Sponge lead (Pb) and
  - Dilute sulfuric acid (H_2SO_4).

(i) Lead Peroxide (PbO_2)

- The positive plate is made of lead peroxide. This is dark brown, hard and brittle substance.

(ii) Sponge Lead (Pb)

- The negative plate is made of pure lead in soft sponge condition.

(iii) Dilute Sulfuric Acid (H_2SO_4)

- Dilute sulfuric acid used for lead acid battery has ration of water: acid = 3:1.

Discharging process

- The lead acid storage battery is formed by dipping lead peroxide plate and sponge lead plate in dilute sulfuric acid. A load is connected externally between these plates. In diluted sulfuric acid the molecules of the acid split into positive hydrogen ions (H+) and negative sulfate ions (SO_4−−).
- The hydrogen ions when reach at PbO_2 plate, they receive electrons from it and become hydrogen atom which again attack $PbO_2$and form PbO and H_2O (water). This PbO reacts with $H_2SO_4$and forms $PbSO_4$ and H_2O (water).

$$PbO_2 + 2H \rightarrow PbO + H_2O$$

$$PbO_2 + H_2SO_4 + 2H \rightarrow PbSO_4 + 2H_2O$$

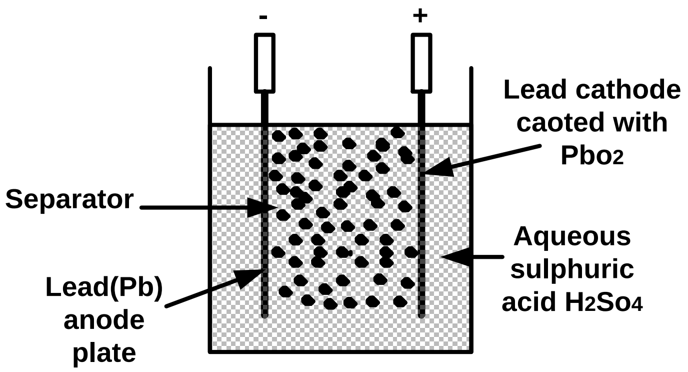


Figure 5.12 Lead acid battery

- SO_4 −− ions are moving freely in the solution so some of them will reach to pure Pb plate where they give their extra electrons and become radical SO_4.
- As the radical SO_4 cannot exist alone it will attack Pb and will form $PbSO_4$. As H+ ions take electrons from PbO_2 plate and SO_4 −− ions give electrons to Pb plate, there would be an inequality of electrons between these two plates.
- Hence there would be a flow of current through the external load between these plates for balancing this inequality of electrons. This process is called discharging of lead acid battery. The lead sulfate ($PbSO_4$) is whitish in color.

Charging process

- Both of the plates are covered with $PbSO_4$.Specific gravity of sulfuric acid solution falls due to formation of water during reaction at PbO_2 plate.
- As a result, the rate of reaction falls which implies the potential difference between the plates decreases during discharging process.
- Now we will disconnect the load and connect $PbSO_4$ covered PbO_2 plate with positive terminal of an external DC source and PbO_2 covered Pb plate with negative terminal of that DC source.
- During discharging, the density of sulfuric acid falls but there still sulfuric acid exists in the solution. This sulfuric acid also remains as H+ and SO_4 −− ions in the solution. Hydrogen ions being positively charged, move to the electrode (cathode) connected with negative terminal of the DC source.
- Here each H+ ion takes one electron from that and becomes hydrogen atom. These hydrogen atoms then attack $PbSO_4$ and form lead and sulfuric acid.

$$PbSO_4 + 2H \rightarrow H_2SO_4 + Pb$$

- SO_4 −− ions move towards the electrode (anode) connected with positive terminal of DC source where they will give up their extra electrons and become radical SO_4. This radical SO_4 cannot exist alone
- Hence reacts with $PbSO_4$ of anode and forms lead peroxide (PbO_2) and sulfuric acid (H_2SO_4)

$$PbSO_4 + 2H_2O + SO_4 \rightarrow PbO_2 + 2H_2SO_4$$

- Hence by charging the lead acid storage battery cell,
    - Lead sulfate anode gets converted into lead peroxide.
    - Lead sulfate of cathode is converted to pure lead.
    - Terminal potential of the cell increases.
    - Specific gravity of sulfuric acid increases.

5.22 Nickel cadmium battery with charging & discharging equations

Construction of Ni-Cd Battery:

- The construction of a nickel - cadmium cell is shown in Figure. The positive plate is made of nickel hydroxide Ni(OH)4 and the negative plate is of spongy cadmium (Cd).

- A 21% solution of potassium hydroxide (KOH) in distilled water is used as the electrolyte. The specific gravity is approximately 1.2.
- The construction of Ni-Cd battery is very similar to that of the nickel-iron battery.
- The positive plates are of nickel hydroxide. The negative plates are made of a mixture of cadmium and iron. KOH (potassium hydroxide) is used as electrolyte in this battery.
- The internal resistance of Ni-Cd batteries is low due to the use of cadmium. Electrical characteristics are almost same as those of the nickel-iron batteries.

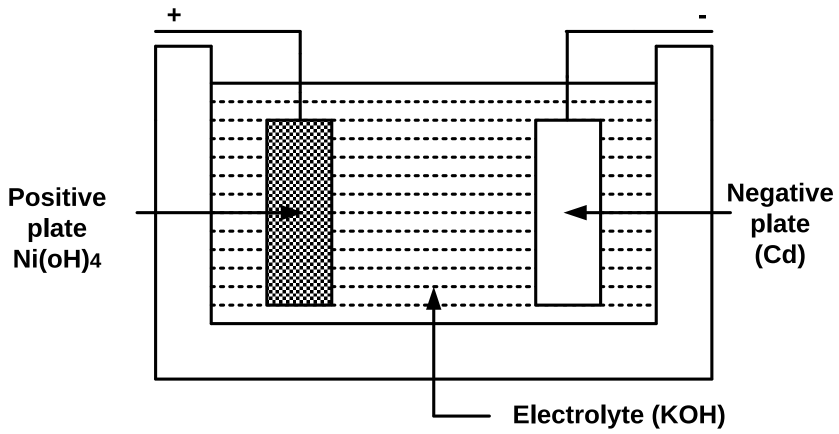


Figure 5.13 Nickel cadmium battery diagram

Action during discharging

At anode

$$Ni(OH)_4 + 2K \rightarrow Ni(OH)_2 + 2KOH$$

At cathode

$$Cd + 2OH \rightarrow Cd(OH)_2$$

Discharging action can be collectively given as,

$$\underbrace{2Ni(OH)_4}_{\substack{Positive\\plate}} + 2KOH + \underbrace{Cd}_{\substack{Negative\\plate}} \rightarrow \underbrace{2Ni(OH)_2}_{\substack{Positive\\plate}} + 2KOH + \underbrace{Cd(OH)_2}_{\substack{Negative\\plate}}$$

- The electrolyte i.e. KOH splits into the positive K ions and negative OH ions. During discharging, ions from negative plate force free electrons to positive plates.
- When the cell is discharged the positive element becomes nickelous hydroxide while negative element becomes cadmium hydroxide.

Action during charging

- During charging of the cell, positive element becomes nickelic hydroxide and negative element becomes metallic cadmium.
- When cell is fully charged it generates oxygen gas at positive element and hydrogen gas at negative element.

The charging equation is collectively given as,

$$\underbrace{2Ni(OH)_2}_{\substack{Positive\\plate}} + 2KOH + \underbrace{Cd(OH)_2}_{\substack{Negative\\plate}} \rightarrow \underbrace{2Ni(OH)_4}_{\substack{Positive\\plate}} + 2KOH + \underbrace{Cd}_{\substack{Negative\\plate}}$$

Applications of Ni-Cd Batteries:

- Following are some of the important applications of Ni-Cd batteries:
  - In helicopters, aeroplanes as auxiliary turbines.
  - For the traction applications.
  - For lighting, air conditioning etc. in trains.
  - In the automobiles.
  - In the movie cameras, electric shavers, photoflash etc.

5.23 Charging and its methods of Battery

- To charge a lead-acid battery, the following important points should be kept in mind.
  - A dc source should be used for charging. If ac source is available it should be first rectified.
  - The dc source should be connected with proper polarities to the battery to be charged.
  - The dc source voltage should be higher than the maximum terminal voltage of the battery. Typically, the charging voltage should be 2.5 V per cell.
  - The value of charging current I should be set properly.
- The charging current should not be too high in order to avoid 'excessive gassing' and heat during the charging process.
- The charging current can be set by taking one of the following two rules:
  - The charging current should be equal to number of positive plates in a single cell.
  - The charging current should be such that the full charging be achieved in 8-hours.

Charging of battery with AC Supply

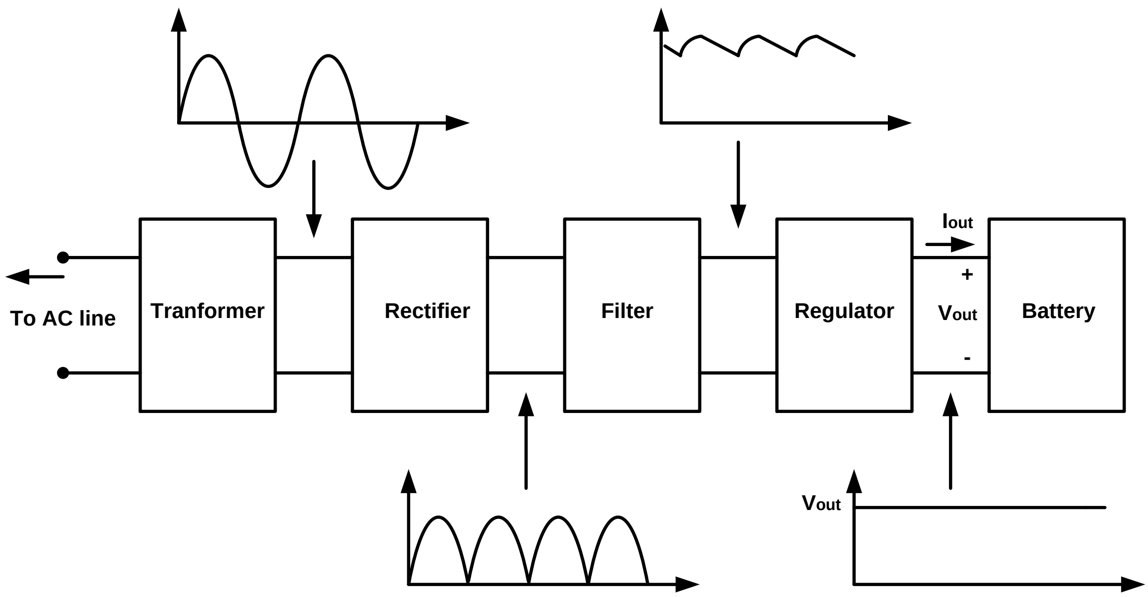


Figure 5.14 Charging of battery from AC supply

- If the source of energy is alternating then the dc voltage required for the charging of a battery is derived from the ac source by using a rectifier.
- The step down transformer reduces the high ac supply voltage to a low ac voltage. The rectifier converts this ac voltage into a dc voltage.
- Filter is use to get pure dc voltage and the output voltage of filter is given to regulator. Regulator is device which gives regulated voltage at input of battery.

Charging Methods:

(1) Constant current charging method

- The completely discharged battery is first charged at a constant charging rate. This will cause the terminal voltage of the battery to increase considerably.
- The charging current is kept constant by varying the supply voltage for overcoming the increased cell voltage. The value of charging current is adjusted carefully to avoid excessive "gasing".

(2) Constant voltage charging method

- When cell voltage reaches sufficiently high value, the constant current charging is stopped and constant voltage charging is adopted. The charging current then decreases.
- This mode of charging is known as the float or trickle charging. Typically, the voltage at which changeover from constant current to constant voltage takes place at 2.15 volts.

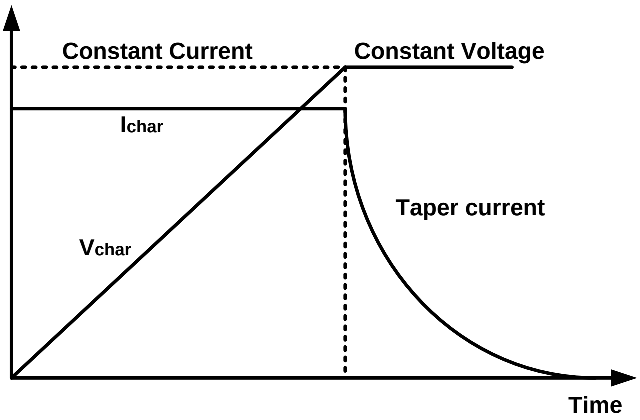


Figure 5.15 Charging modes of battery

(3) Trickle charging

- The Trickle charging is necessary to keep the battery fully charged always. It is used to compensating the charge lost due to internal discharge of the battery. The Trickle charging current is very low.
- When battery is kept as an emergency service, it is necessary to ensure that it is fully charged all the time and ready for the service any time.
- The charged battery always loses some of its charge due to internal leakage and other open circuit losses. To compensate for such loss of charge the battery is kept on trickle charging.

(4) Boost charging

- When the battery is being charged for the first time, or when it is being used after a long time, the boost charging mode is used, where the cell voltage is raised above 2.4 V up to 2.6 V.
- The boost charging is used for breaking down the crystalline PbSO4 which is formed when the battery is not in use for a long time.

5.24 Elementary Calculation of Energy Consumption

Energy consumption (E):

- The electric energy is defined as the product of power and time.

$$Energy = Power(P) x Time(t)$$

The alternate expression for energy is,

$$E = V \ x \ I \ x \ t \ Joules$$

- The S.I. units of energy are Watt-second or Joules. Practically the electrical energy is expressed in watt hour or kWh.
- The electricity meters installed by the electricity board are basically the energy meters which. Measure the electricity consumption in kWh.

Electricity bill for energy consumption:

- The monthly electricity bill is charged on the basis of monthly energy consumption in terms of number of units. (e.g. ~ 7.5 per unit for a domestic customer).

$$1 \ Unit = kWh = 1000 \ Wh$$

- The per unit rates of electricity consumption are different for different types of customers such as domestic, farmers, industrial units etc.

5.25 What is power factor? Explain the methods for power factor improvement.

Power Factor

- It is the measurement of how incoming power is being effectively used in electrical power system.

Methods for power factor improvement

- By the following methods we can improve the power factor:

1. Static Capacitor(Capacitor Bank)
2. Synchronous Condenser
3. Phase Advancer

1. Static Capacitor (Capacitor Bank)

- We know that most of the industries and power system loads are inductive that take lagging current which decrease the system power factor.
- For Power factor improvement purpose, Static capacitors are connected in parallel with those devices which work on low power factor.
- These static capacitors provides leading current which neutralize (totally or approximately) the lagging inductive component of load current (i.e. leading component

neutralize or eliminate the lagging component of load current) thus power factor of the load circuit is improved.

- These capacitors are installed in Vicinity of large inductive load e.g Induction motors and transformers etc, and improve the load circuit power factor to improve the system or devises efficiency.

Advantages:

- Capacitor bank offers several advantages over other methods of power factor improvement.
- Losses are low in static capacitors
- There is no moving part, therefore need low maintenance
- It can work in normal conditions (i.e. ordinary atmospheric conditions)
- Do not require a foundation for installation
- They are lightweight so it is can be easy to installed

Disadvantages:

- The age of static capacitor bank is less (8 – 10 years)
- With changing load, we have to ON or OFF the capacitor bank, which causes switching surges on the system.
- If the rated voltage increases, then it causes damage it.
- Once the capacitors spoiled, then repairing is costly

2. Synchronous Condenser

- When a Synchronous motor operates at No-Load and over-exited then it's called a synchronous Condenser.
- Whenever a Synchronous motor is over-exited then it provides leading current and works like a capacitor.
- When a synchronous condenser is connected across supply voltage (in parallel) then it draws leading current and partially eliminates the re-active component and this way, power factor is improved. Generally, synchronous condenser is used to improve the power factor in large industries.

Advantages:

- Long life (almost 25 years)
- High Reliability
- Step-less adjustment of power factor.
- No generation of harmonics of maintenance
- The faults can be removed easily
- It's not affected by harmonics.
- Require Low maintenance (only periodic bearing greasing is necessary)

Disadvantages:

- It is expensive (maintenance cost is also high) and therefore mostly used by large power users.
- An auxiliary device has to be used for this operation because synchronous motor has no self-starting torque

- It produces noise

3. Phase Advancer

- Phase advancer is a simple AC exciter which is connected on the main shaft of the motor and operates with the motor's rotor circuit for power factor improvement.
- Phase advancer is used to improve the power factor of induction motor in industries.
- As the stator windings of induction motor takes lagging current 90° out of phase with Voltage, therefore the power factor of induction motor is low.
- If the exciting ampere-turns are excited by external AC source, then there would be no effect of exciting current on stator windings.
- Therefore the power factor of induction motor will be improved. This process is done by Phase advancer.

Advantages:

- Lagging kVAR (Reactive component of Power or reactive power) drawn by the motor is sufficiently reduced because the exciting ampere turns are supplied at slip frequency (fs).
- The phase advancer can be easily used where the use of synchronous motors is Unacceptable.

Disadvantage:

- Using Phase advancer is not economical for motors below 200 H.P. (about 150kW)

****