CHAPTER 1

DC CIRCUITS

DEFINATIONS

Linear elements :

In an electric circuit, a linear element is an electrical element with a linear relationship between current and voltage. Resistors are the most common example of a linear element; other examples include capacitors, inductors, and transformers.

Nonlinear Elements :

A nonlinear element is one which does not have a linear input/output relation. In a diode, for example, the current is a non-linear function of the voltage.Most semiconductor devices have non-linear characteristics.

Active Elements :

The elements which generates or produces electrical energy are called active elements. Some of the examples are batteries, generators,transistors,operational amplifiers,vacuum tubes etc.

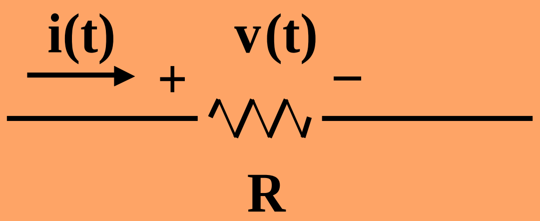
Passive Elements :

All elements which consume rather than produce energy are called passive elements, like resistors,inductors and capacitors.

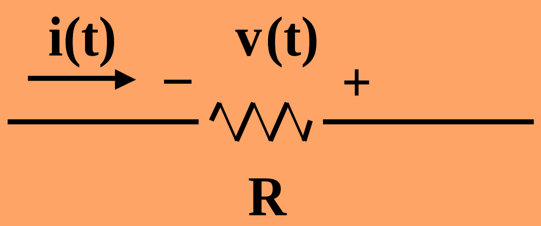
- In unilateral element, voltage – current relation is not same for both the direction. Example: Diode, Transistors.
- In bilateral element, voltage – current relation is same for both the direction. Example: Resistor
- The voltage generated by the source does not vary with any circuit quantity. It is only a function of time. Such a source is called an ideal voltage Source.
- The current generated by the source does not vary with any circuit quantity. It is only a function of time. Such a source is called as an ideal current source.
- **Resistance :** It is the property of a substance which opposes the flow of current through it. The resistance of element is denoted by the symbol "R". It is measured in Ohms. $R = PL / A\ \Omega$

Ohm's Law:

The current flowing through the electric circuit is directly proportional to the potential difference across the circuit and inversely proportional to the resistance of the circuit, provided the temperature remains constant.



$$v(t) = Ri(t) \tag{2.1}$$

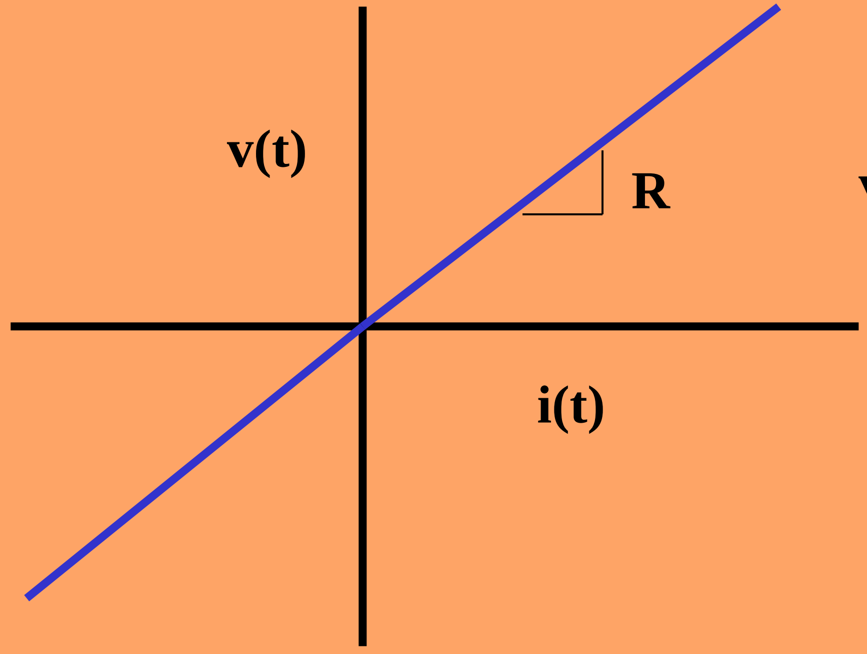


$$v(t) = -Ri(t) \tag{2.2}$$

Basic Laws of Circuits

Ohm's Law:

Directly proportional means a straight line relationship.



v(t) = Ri(t)

The resistor is a model and will not produce a straight line for all conditions of operation.

Basic Laws of Circuits

Ohm's Law: About Resistors:

The unit of resistance is ohms(Ω).

A mathematical expression for resistance is

$$R = \rho \frac{l}{A} \qquad \textbf{(2.3)}$$

$$l : The\ length\ of\ the\ conductor\ (meters)$$

$$A : The\ cross-sectional\ area\ (meters^2)$$

$$\rho : The\ resistivity\ (\Omega \cdot m)$$

Basic Laws of Circuits

Ohm's Law: About Resistors:

We remember that resistance has units of ohms. The reciprocal of resistance is conductance. At one time, conductance commonly had units of mhos (resistance spelled backwards).

In recent years the units of conductance has been established as seimans (S).

Thus, we express the relationship between conductance and resistance as

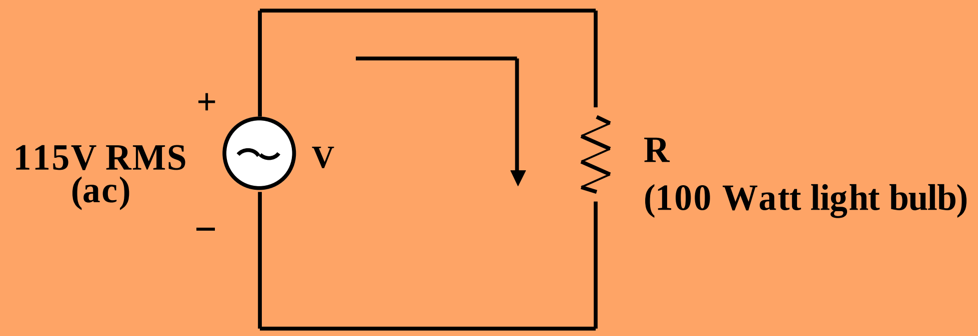
$$G = \frac{1}{R} \quad \text{(S)} \qquad (2.4)$$

We will see later than when resistors are in parallel, it is convenient to use Equation (2.4) to calculate the equivalent resistance.

Basic Laws of Circuits

Ohm's Law: **Ohm's Law: Example 2.1.**

Consider the following circuit.



Determine the resistance of the 100 Watt bulb.

$$P = VI = \frac{V^2}{R} = I^2 R \qquad (2.5)$$

$$R = \frac{V^2}{P} = \frac{115^2}{100} = 132.25 \; ohms$$

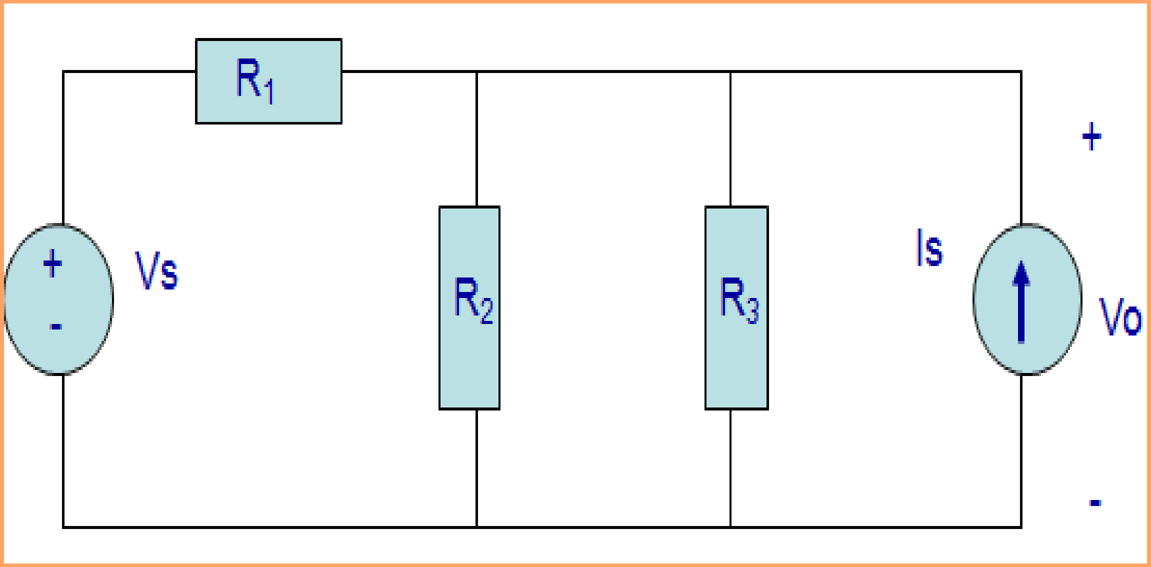
A suggested assignment is to measure the resistance of a 100 watt light bulb with an ohmmeter. Debate the two answers.

Circuit Definitions

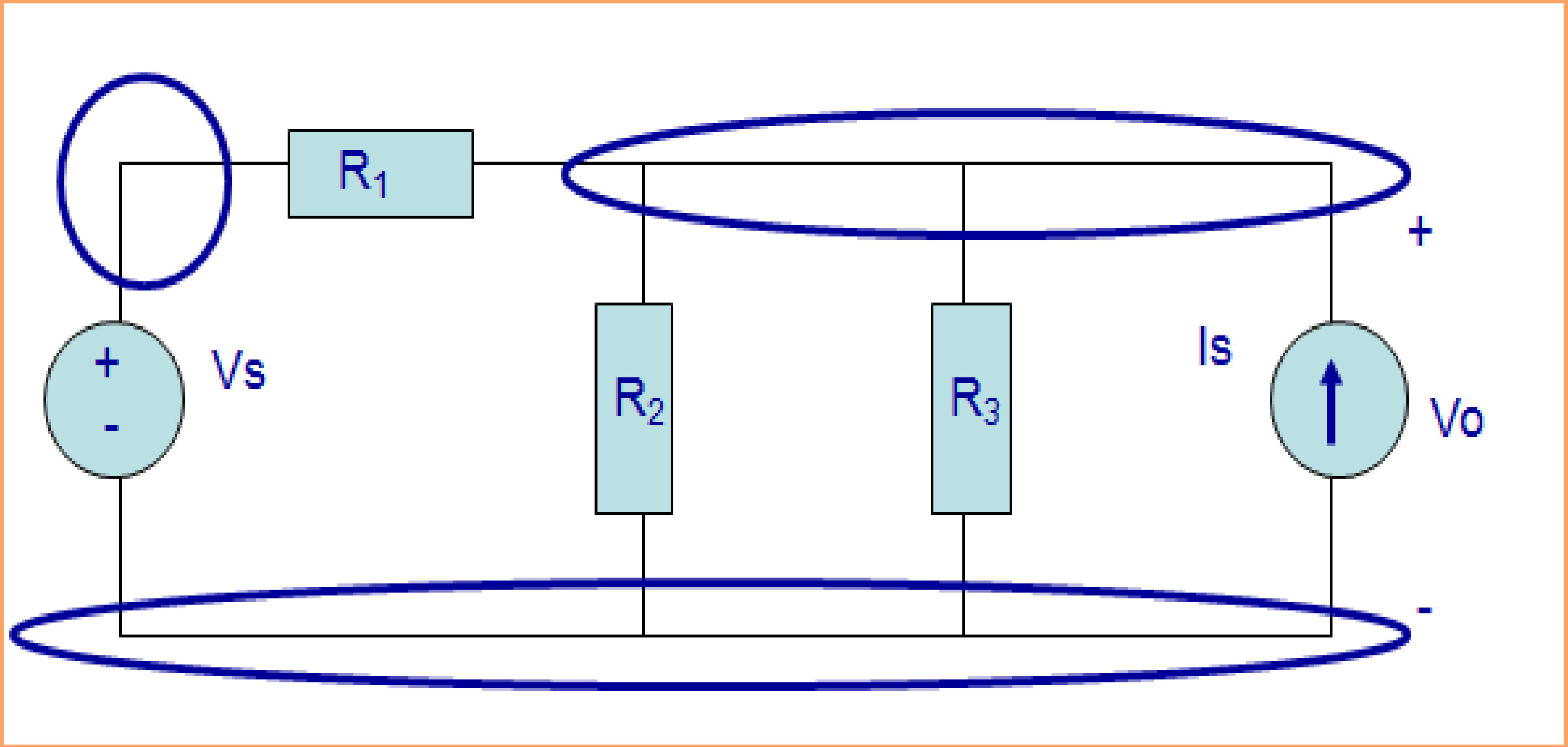
- Node – any point where 2 or more circuit elements are connected together
  - Wires usually have negligible resistance
  - Each node has one voltage (w.r.t. ground)
- Branch – a circuit element between two nodes
- Loop – a collection of branches that form a closed path returning to the same node without going through any other nodes or branches twice

Example

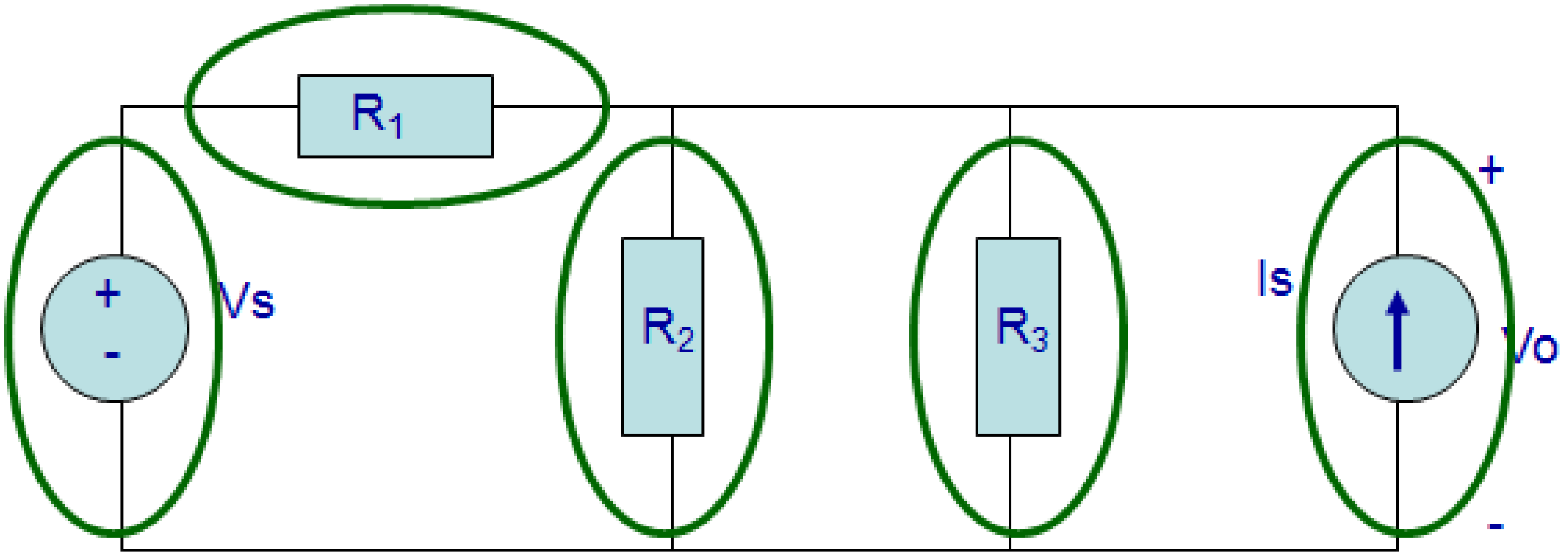
How many nodes, branches & loops?



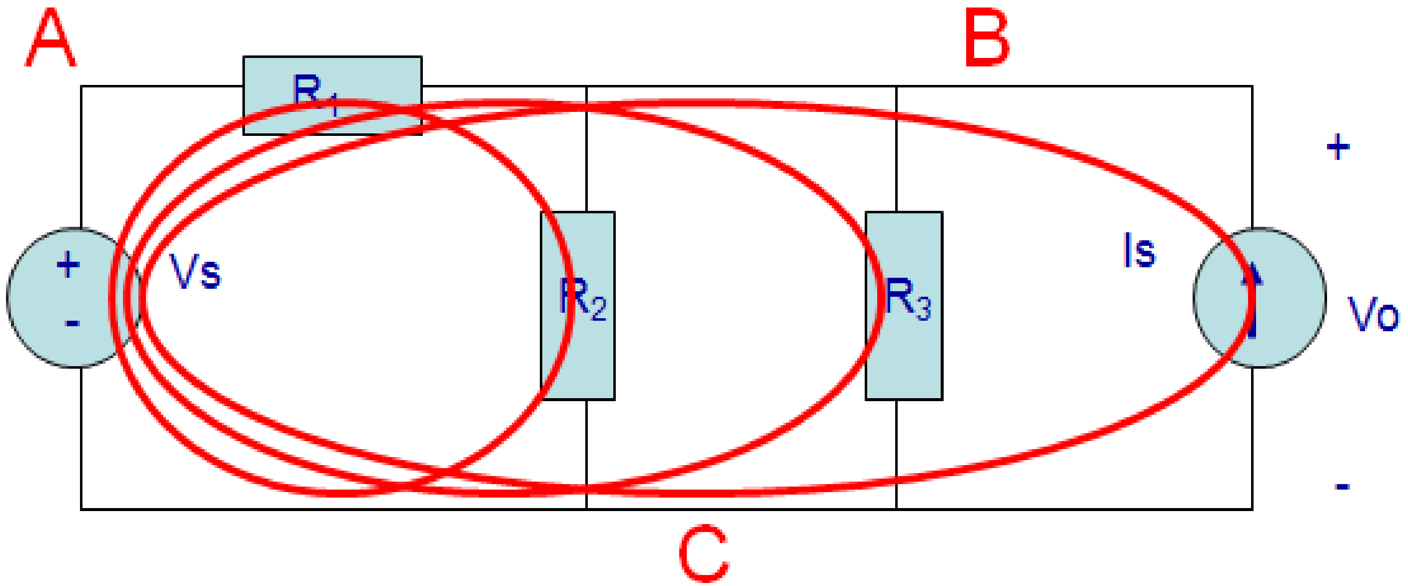
Three nodes



- 5 Branches



Three Loops, if starting at node A

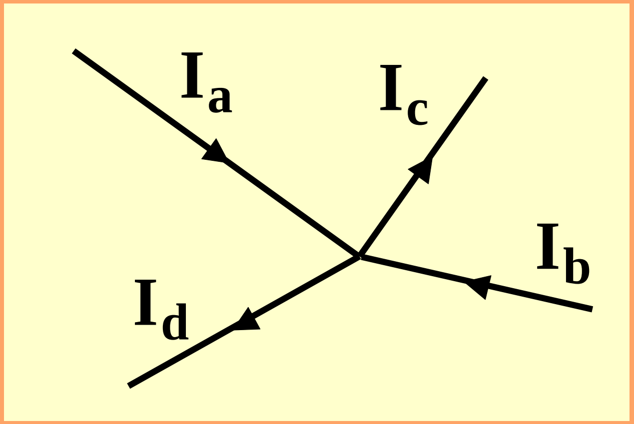


Basic Laws of Circuits

Kirchhoff's Current Law

As a consequence of the Law of the conservation of charge, we have:

- **The sum of the current entering a node (junction point) equal to the sum of the currents leaving.**



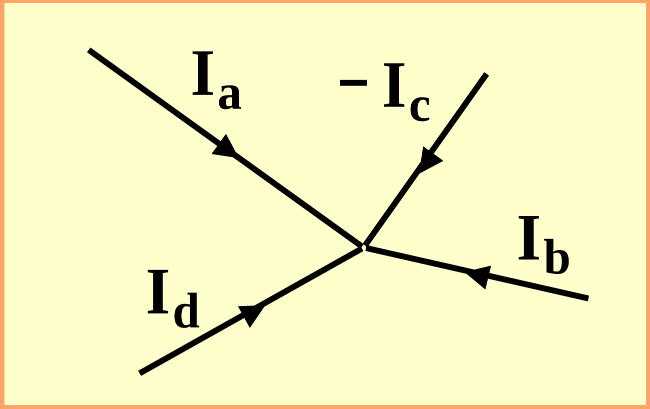
$$I_a + I_b = I_c + I_d$$

I_a, I_b, I_c, and I_d can each be either a positive or negative number.

Basic Laws of Circuits

Kirchhoff's Current Law

- **The algebraic sum of the currents entering a node equal to zero.**



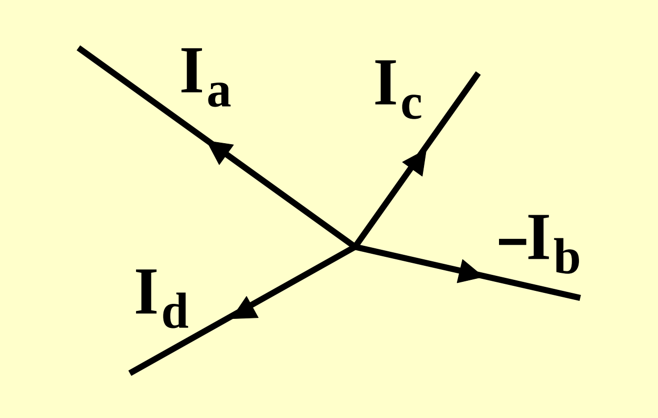
$$I_a + I_b - I_c + I_d = 0$$

I_a, I_b, I_c, and I_d can each be either a positive or negative number.

Basic Laws of Circuits

Kirchhoff's Current Law

- **The algebraic sum of the currents leaving a node equal to zero.**



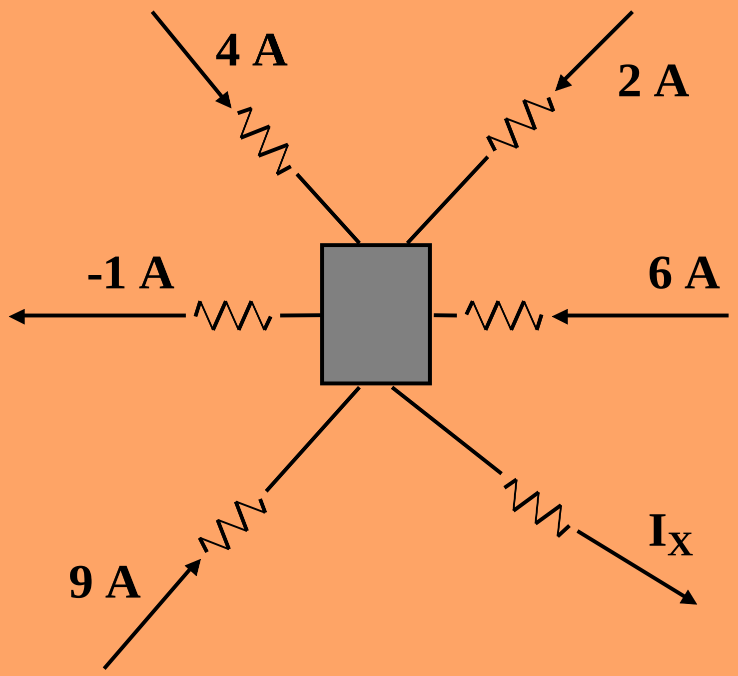
$$I_a - I_b + I_c + I_d = 0$$

I_a, I_b, I_c, and I_d can each be either a positive or negative number.

Basic Laws of Circuits

Kirchhoff's Current Law: Example 2.2.

Find the current I_x.



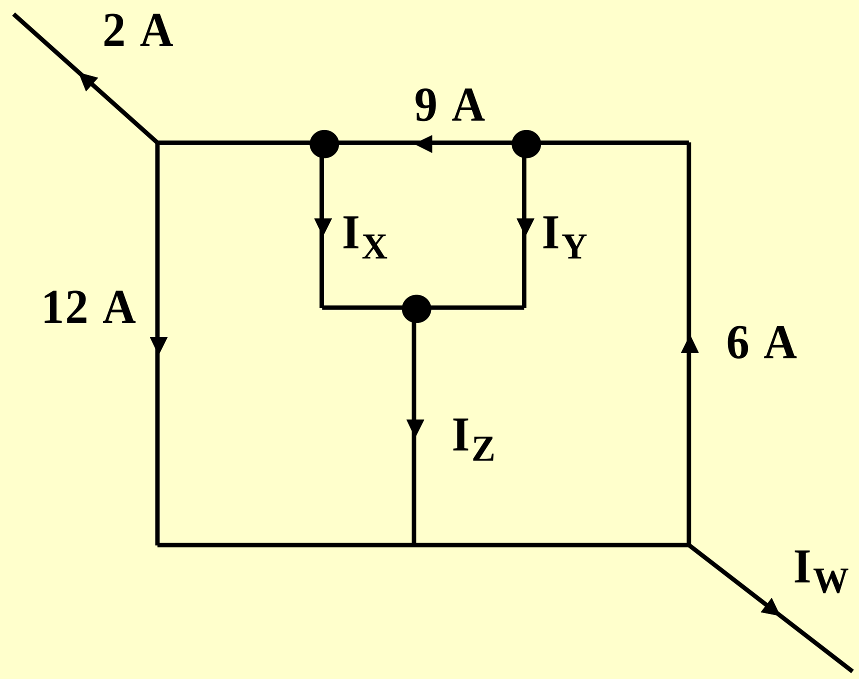
Ans: I_X =

Highlight the box then use bring to front to see answer.

Basic Laws of Circuits

Kirchhoff's Current Law: Example 2.3

Find the currents I_W, I_X, I_Y, I_Z.



I_W =

I_X =

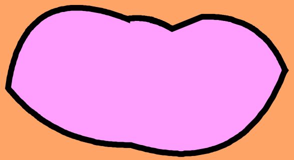
I_Y =

I_Z =

Basic Laws of Circuits

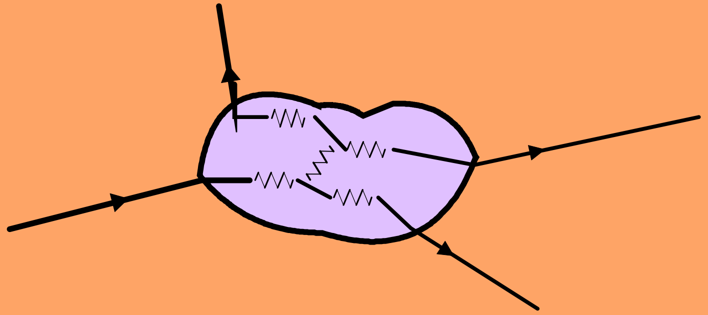
Kirchhoff's Current Law

Kirchhoff's current law can be generalized to include a surface. We assume the elements within the surface are interconnected.



A closed 3D surface

We can now apply Kirchhoff's current law in the 3 forms we discussed with a node. The appearance might be as follows:



Currents entering and leaving a closed surface that contains interconnected circuit elements

Kirchoff's Voltage Law (KVL)

The algebraic sum of voltages around each loop is zero

Beginning with one node, add voltages across each branch in the loop

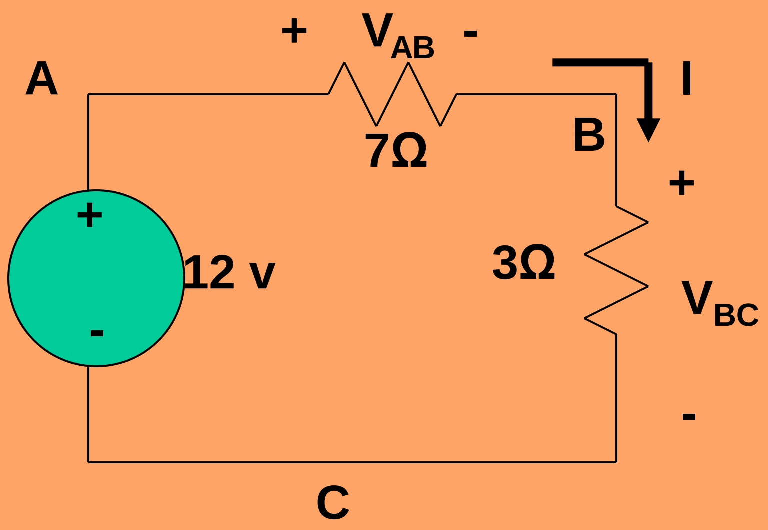
(if you encounter a + sign first) and subtract voltages (if you encounter a – sign first)

Σ voltage drops - Σ voltage rises = 0

Or Σ voltage drops = Σ voltage rises

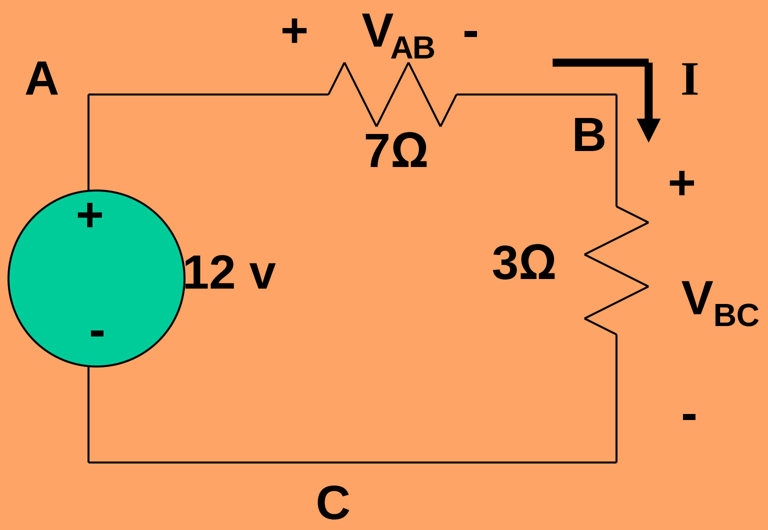
Circuit Analysis

- When given a circuit with sources and resistors having fixed values, you can use Kirchoff's two laws and Ohm's law to determine all branch voltages and currents

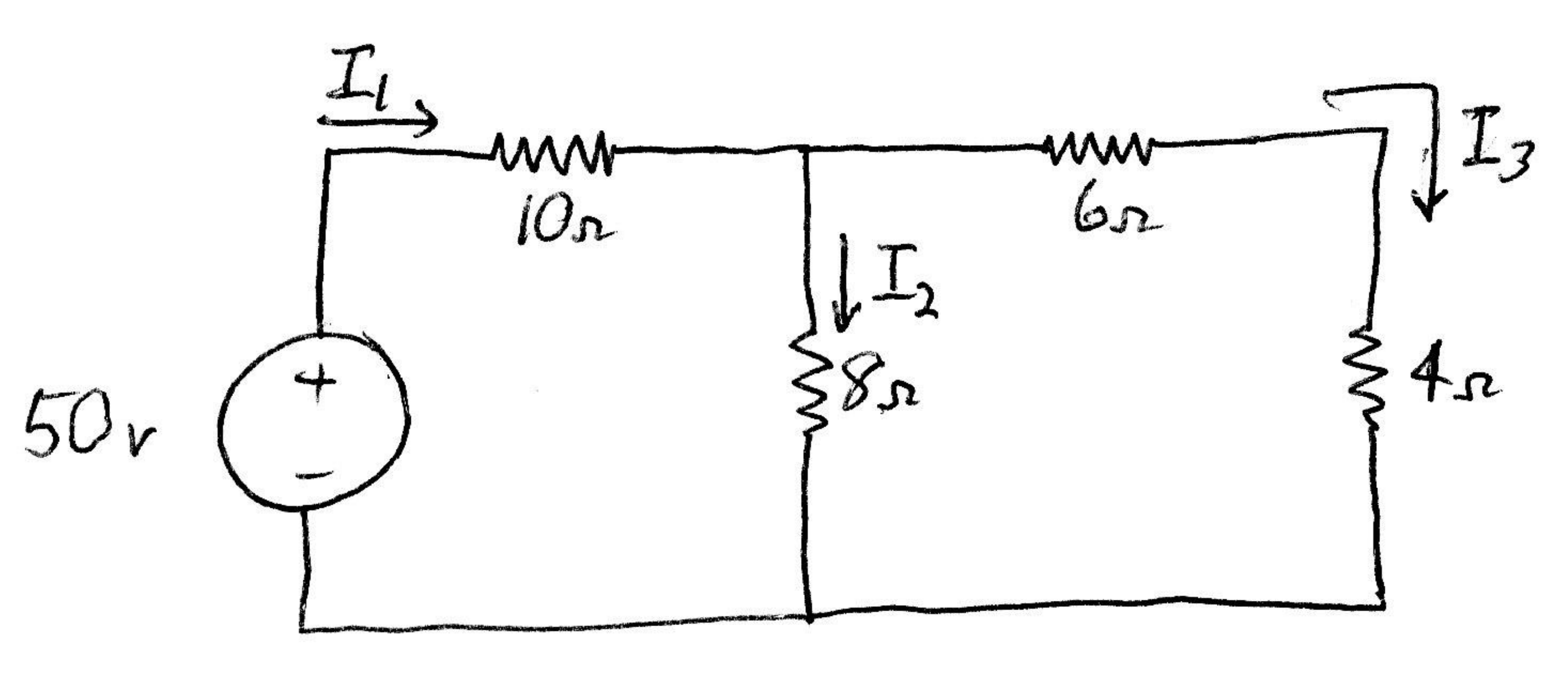


Circuit Analysis

- By Ohm's law: $V_{AB} = I \cdot 7\Omega$ and $V_{BC} = I \cdot 3\Omega$
- By KVL: $V_{AB} + V_{BC} - 12\text{ v} = 0$
- Substituting: $I \cdot 7\Omega + I \cdot 3\Omega - 12\text{ v} = 0$
- Solving: $I = 1.2\text{ A}$

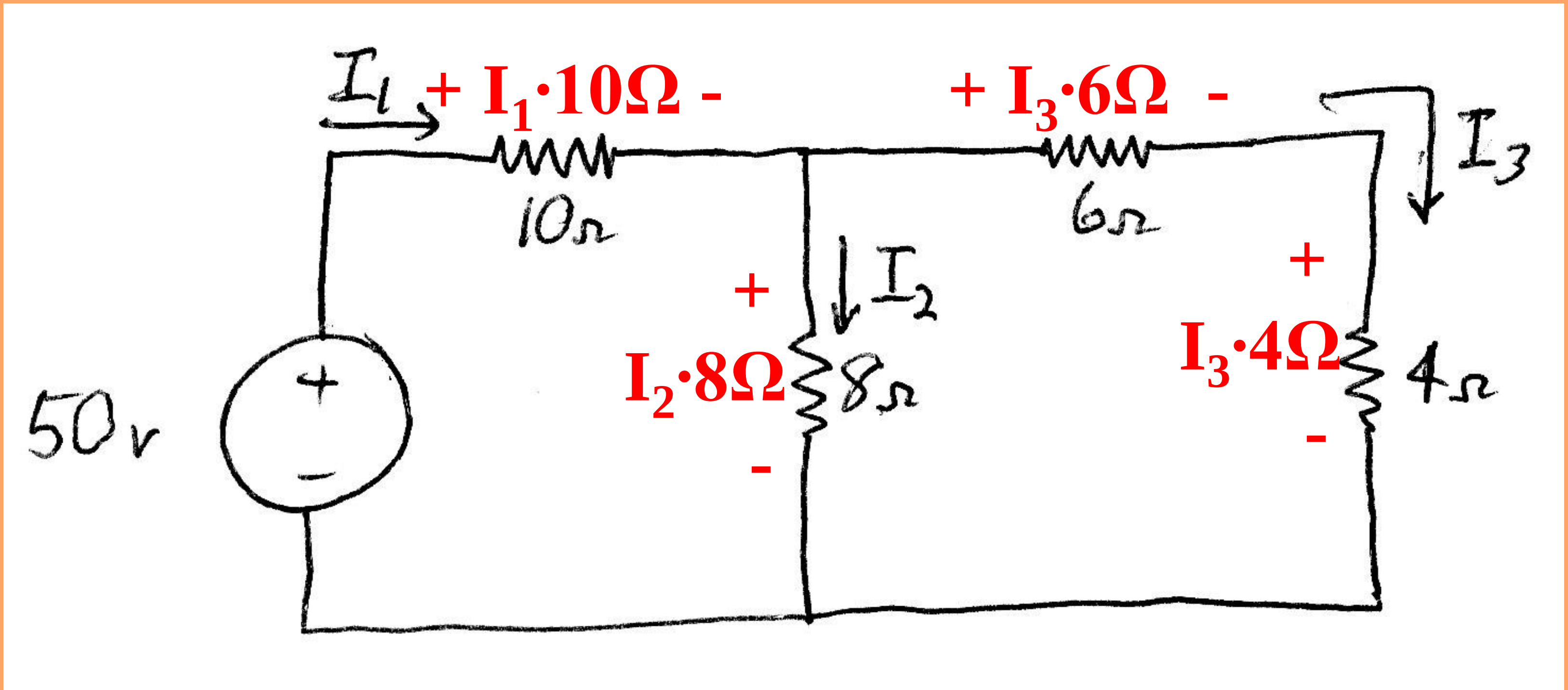


Example Circuit



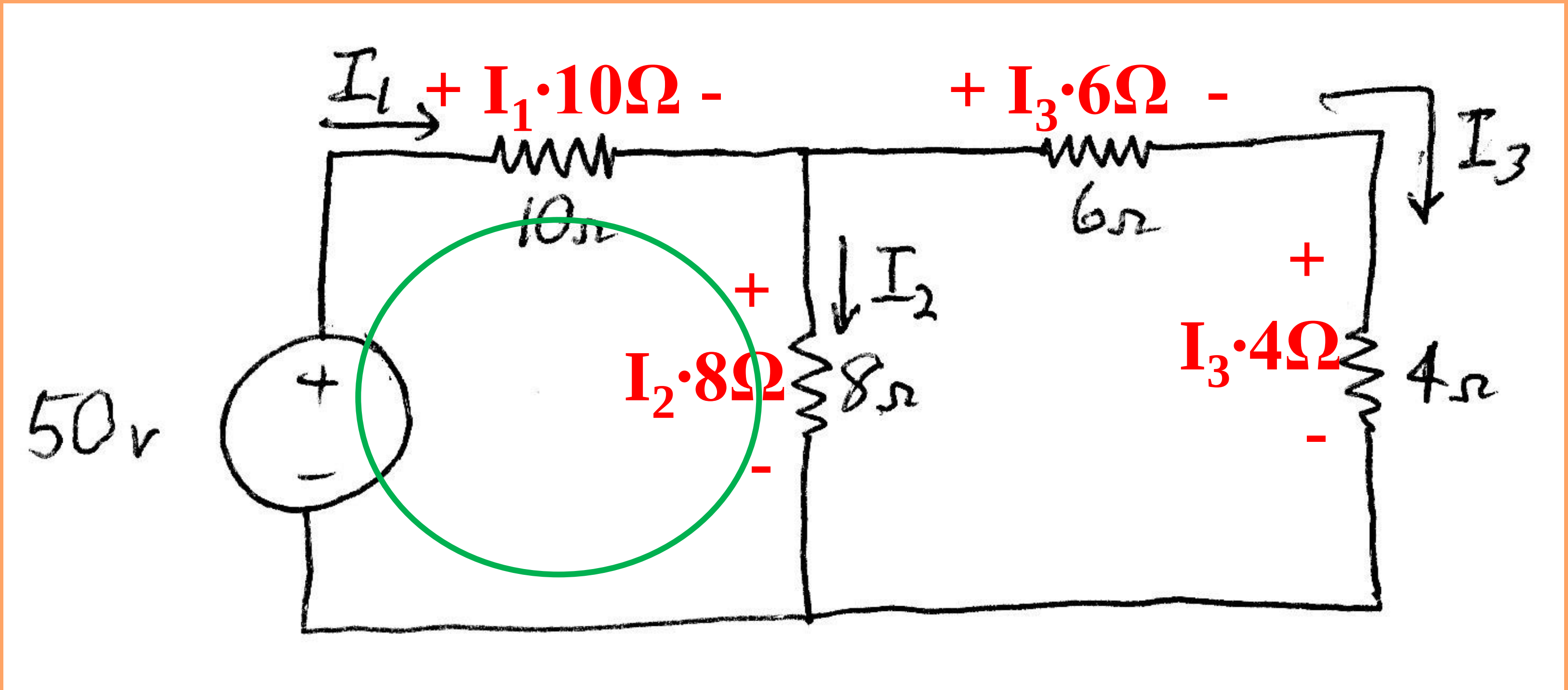
Solve for the currents through each resistor
And the voltages across each resistor

Example Circuit



Using Ohm's law, add polarities and expressions for each resistor voltage

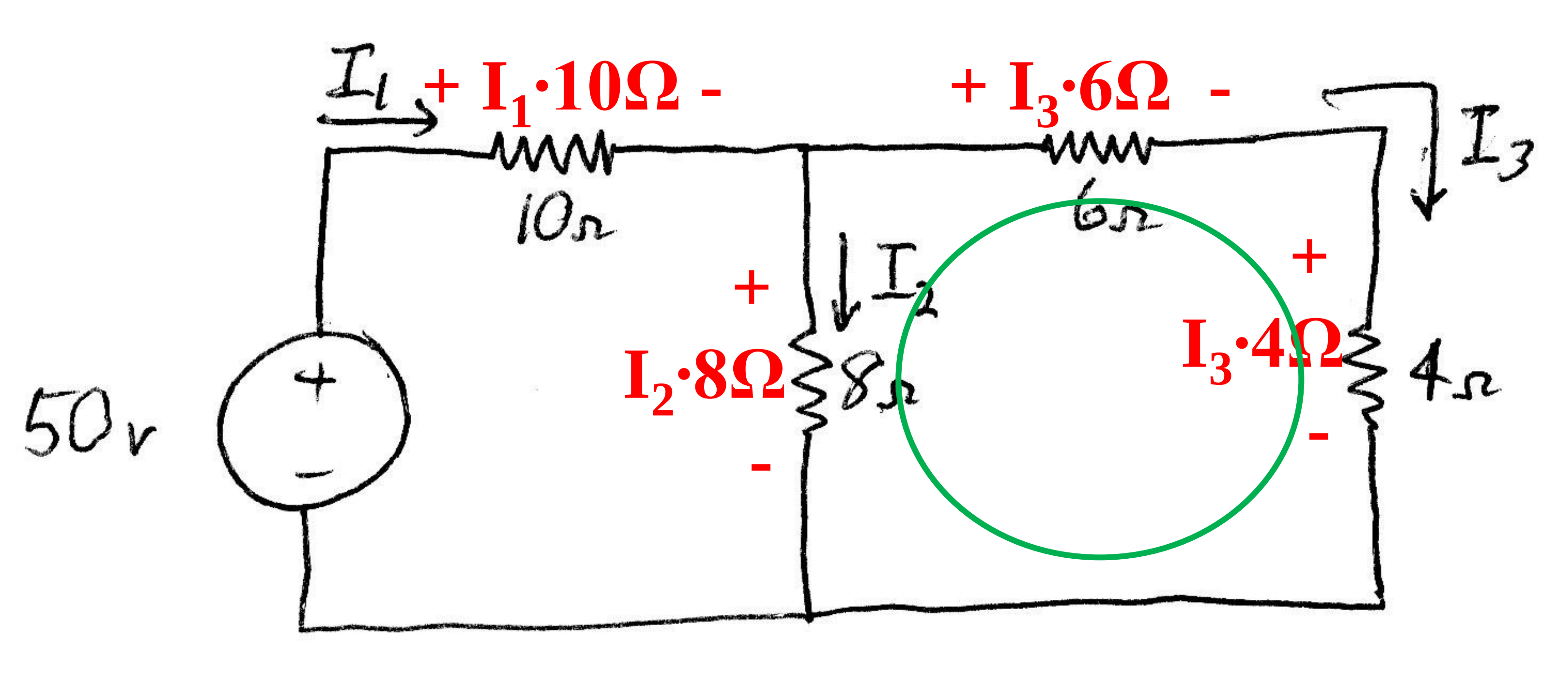
Example Circuit



Write 1st Kirchoff's voltage law equation

$-50\ v + I_1 \cdot 10\Omega + I_2 \cdot 8\Omega = 0$

Example Circuit



Write 2nd Kirchoff's voltage law equation

$$-I_2 \cdot 8\Omega + I_3 \cdot 6\Omega + I_3 \cdot 4\Omega = 0$$

$$\text{or } I_2 = I_3 \cdot (6+4)/8 = 1.25 \cdot I_3$$

Example Circuit

- We now have 3 equations in 3 unknowns, so we can solve for the currents through each resistor, that are used to find the voltage across each resistor
- Since $I_1 - I_2 - I_3 = 0$, $I_1 = I_2 + I_3$
- Substituting into the 1st KVL equation

$$-50\text{ v} + (I_2 + I_3)\cdot 10\Omega + I_2\cdot 8\Omega = 0$$

$$\text{or } I_2\cdot 18\ \Omega + I_3\cdot 10\ \Omega = 50\text{ volts}$$

Example Circuit

- But from the 2nd KVL equation, $I_2 = 1.25 \cdot I_3$
- Substituting into 1st KVL equation:

$(1.25 \cdot I_3) \cdot 18\ \Omega + I_3 \cdot 10\ \Omega = 50$ volts

Or: $I_3 \cdot 22.5\ \Omega + I_3 \cdot 10\ \Omega = 50$ volts

Or: $I_3 \cdot 32.5\ \Omega = 50$ volts

Or: $I_3 = 50$ volts/32.5 Ω

Or: $I_3 = 1.538$ amps

Example Circuit

- Since $I_3 = 1.538$ amps

  $I_2 = 1.25 \cdot I_3 = 1.923$ amps
- Since $I_1 = I_2 + I_3$, $I_1 = 3.461$ amps
- The voltages across the resistors:

  $I_1 \cdot 10\Omega = 34.61$ volts

  $I_2 \cdot 8\Omega = 15.38$ volts

  $I_3 \cdot 6\Omega = 9.23$ volts

  $I_3 \cdot 4\Omega = 6.15$ volts

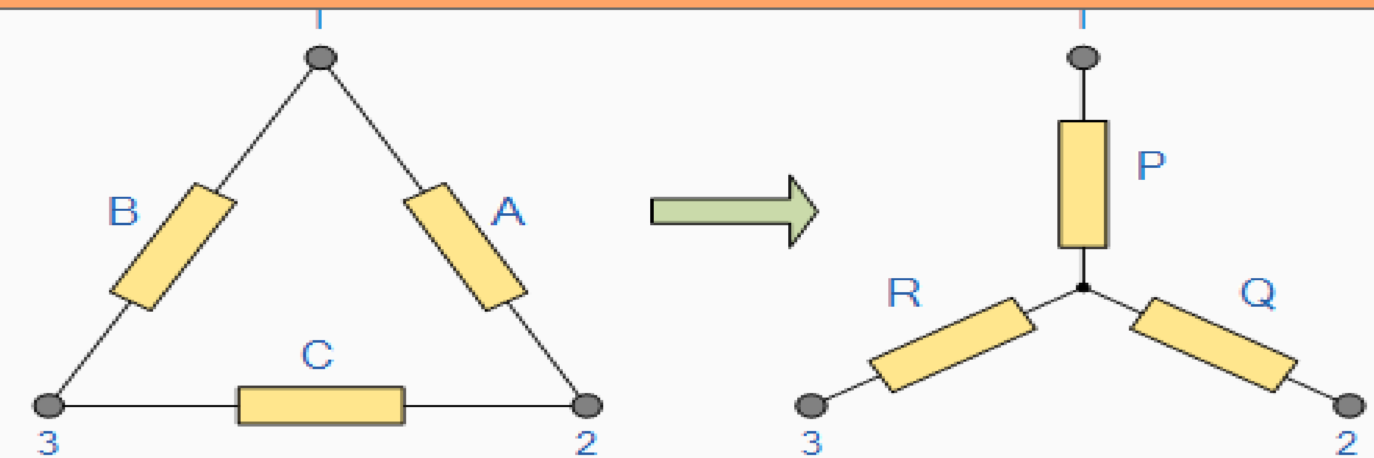
Star Delta Transformation

- We can now solve simple series, parallel or bridge type resistive networks using *Kirchoff´s Circuit Laws*, mesh current analysis or nodal voltage analysis techniques but in a balanced 3-phase circuit we can use different mathematical techniques to simplify the analysis of the circuit and thereby reduce the amount of math's involved which in itself is a good thing.
- Standard 3-phase circuits or networks take on two major forms with names that represent the way in which the resistances are connected, a **Star** connected network which has the symbol of the letter, Y (wye) and a **Delta** connected network which has the symbol of a triangle, Δ (delta). If a 3-phase, 3-wire supply or even a 3-phase load is connected in one type of configuration, it can be easily transformed or changed it into an equivalent configuration of the other type by using either the **Star Delta Transformation** or **Delta Star Transformation** process.
- A resistive network consisting of three impedances can be connected together to form a T or "Tee" configuration but the network can also be redrawn to form a **Star** or Y type network as shown below

Delta Star Transformation

To convert a delta network to an equivalent star network we need to derive a transformation formula for equating the various resistors to each other between the various terminals. Consider the circuit below.

Delta to Star Network.



Compare the resistances between terminals 1 and 2.

$$P + Q = A \ \text{ in parallel with } (B + C)$$

$$P + Q = \frac{A(B + C)}{A + B + C} \qquad \ldots EQ1$$

Resistance between the terminals 2 and 3.

$$Q + R = C \ \text{ in parallel with } (A + B)$$

$$Q + R = \frac{C(A + B)}{A + B + C} \quad \ldots EQ2$$

Resistance between the terminals 1 and 3.

$$P + R = B \text{ in parallel with } (A + C)$$

$$P + R = \frac{B(A + C)}{A + B + C} \quad \ldots EQ3$$

This now gives us three equations and taking equation 3 from equation 2 gives:

$$EQ3 - EQ2 = (P + R) - (Q + R)$$

$$P + R = \frac{B(A + C)}{A + B + C} - Q + R = \frac{C(A + B)}{A + B + C}$$

$$\therefore P - Q = \frac{BA + CB}{A + B + C} - \frac{CA + CB}{A + B + C}$$

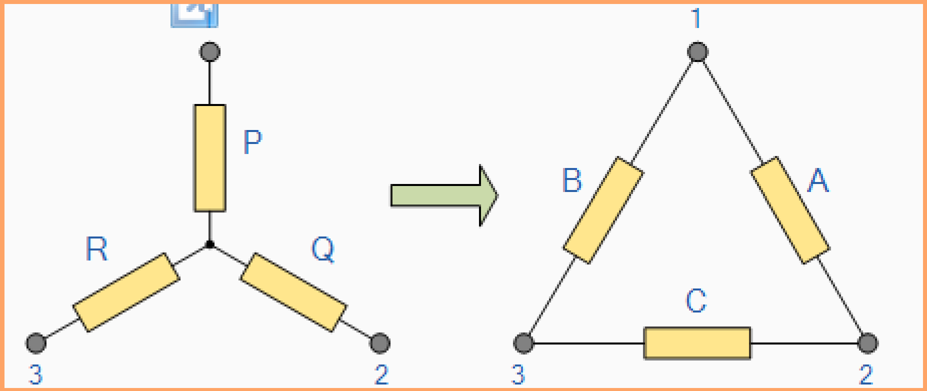
Delta to Star Transformations Equations

$$P = \frac{AB}{A + B + C} \quad Q = \frac{AC}{A + B + C} \quad R = \frac{BC}{A + B + C}$$

Star Delta Transformation

- We have seen above that when converting from a delta network to an equivalent star network that the resistor connected to one terminal is the product of the two delta resistances connected to the same terminal, for example resistor P is the product of resistors A and B connected to terminal 1.
- By rewriting the previous formulas a little we can also find the transformation formulas for converting a resistive star network to an equivalent delta network giving us a way of producing a star delta transformation as shown below.

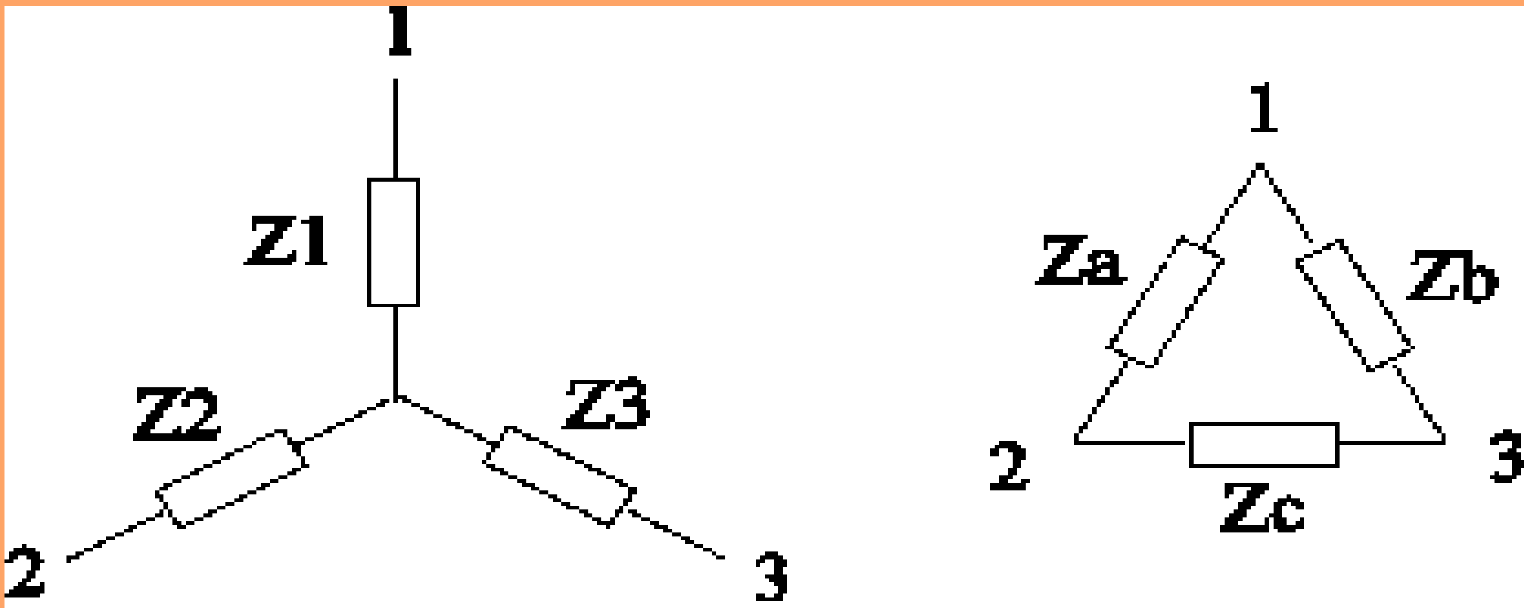
Star to Delta Network.



Star Delta Transformation Equations

$$A = \frac{PQ}{R} + Q + P \quad B = \frac{RP}{Q} + P + R \quad C = \frac{QR}{P} + Q + R$$

Star-Delta Transformation



$$Z1 = ZaZb/(Za+Zb+Zc)$$

$$Z2 = ZaZc/(Za+Zb+Zc)$$

$$Z3 = ZbZc/(Za+Zb+Zc)$$

$$Za = Z1+Z2+(Z1Z2/Z3)$$

$$Zb = Z1+Z3+(Z1Z3/Z2)$$

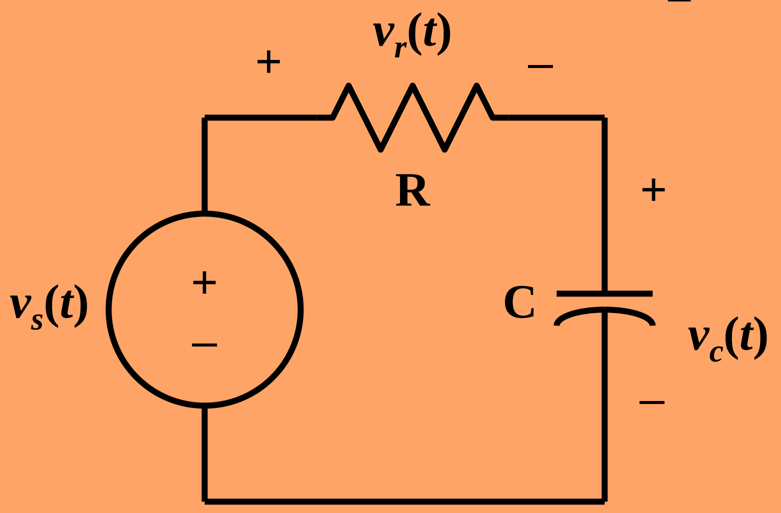
$$Zc = Z2+Z3+(Z2Z3/Z1)$$

STAR/DELTA TRANSFORMATIONS

D.C. Transient response

The storage elements deliver their energy to the resistances, hence the response changes with time, gets saturated after sometime, and is referred to the transient response.

The Differential Equation



KVL around the loop:

$$v_r(t) + v_c(t) = v_s(t)$$

RC Differential Equation(s)

From KVL:

$$R\,i(t) + \frac{1}{C}\int_{-\infty}^{t} i(x)dx = v_s(t)$$

Multiply by C; take derivative

$$RC\frac{di(t)}{dt} + i(t) = C\frac{dv_s(t)}{dt}$$

Multiply by R; note v_r=R·i

$$RC\frac{dv_r(t)}{dt} + v_r(t) = RC\frac{dv_s(t)}{dt}$$

LR Series Circuit

- An **LR Series Circuit** consists basically of an inductor of inductance L connected in series with a resistor of resistance R. The resistance R is the DC resistive value of the wire turns or loops that goes into making up the inductors coil. Consider the LR series circuit below.
- The above *LR series circuit* is connected across a constant voltage source, (the battery) and a switch. Assume that the switch, S is open until it is closed at a time t = 0, and then remains permanently closed producing a "step response" type voltage input. The current, i begins to flow through the circuit but does not rise rapidly to its maximum value of Imax as determined by the ratio of V / R (Ohms Law).

- This limiting factor is due to the presence of the self induced emf within the inductor as a result of the growth of magnetic flux, (Lenz's Law). After a time the voltage source neutralizes the effect of the self induced emf, the current flow becomes constant and the induced current and field are reduced to zero.
- We can use *Kirchoffs Voltage Law*, (KVL) to define the individual voltage drops that exist around the circuit and then hopefully use it to give us an expression for the flow of current.

Kirchoffs voltage law gives us:

Kirchoffs voltage law gives us:

$$V_{(t)} = V_R + V_L = 0$$

The voltage drop across the resistor, R is IR (Ohms Law).

$$V_R = I \times R$$

The voltage drop across the inductor, L is by now our familiar expression L = di/dt

$$V_L = L\frac{di}{dt}$$

Then the final expression for the individual voltage drops around the LR series circuit can be given as:

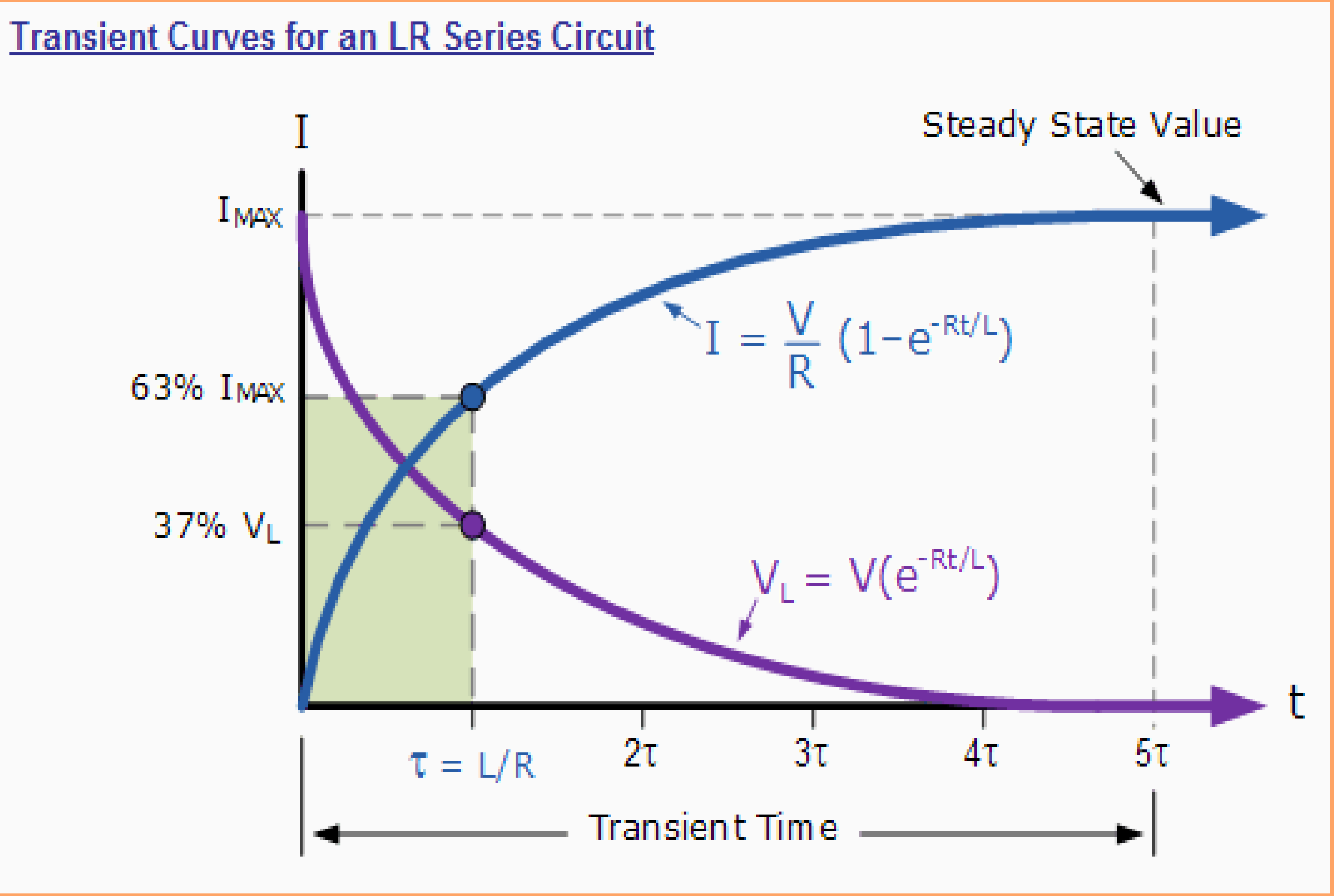
$$V_{(t)} = I \times R + L\frac{di}{dt}$$

We can see that the voltage drop across the resistor depends upon the current, i, while the voltage drop across the inductor depends upon the rate of change of the current, di/dt. When the current is equal to zero, (i = 0) at time t = 0 the above expression, which is also a first order differential equation, can be rewritten to give the value of the current at any instant of time

Expression for the Current in an LR Series Circuit

$$I_{(t)} = \frac{V}{R}\left(1 - e^{-Rt/L}\right) \quad (A)$$

The L/R term in the above equation is known commonly as the Time Constant, (τ) of the LR series circuit and V/R also represents the final steady state current value in the circuit. Once the current reaches this maximum steady state value at 5τ, the inductance of the coil has reduced to zero acting more like a short circuit and effectively removing it from the circuit. Therefore the current flowing through the coil is limited only by the resistive element in Ohms of the coils windings. A graphical representation of the current growth representing the voltage/time characteristics of the circuit can be presented as.



Transient Curves for an LR Series Circuit
I
Steady State Value
I MAX
63% I MAX
37% V L
I = V/R (1-e^-Rt/L)
V L = V(e^-Rt/L)
t
τ = L/R
2τ
3τ
4τ
5τ
Transient Time

Time constant of RC and RL

- The time taken to reach 36.8% of initial current in an RC circuit is called the time constant of RC circuit.

  Time constant (t) = RC.
- The time taken to reach 63.2% of final value in a RL Circuit is called the time constant of RL circuit.
- Time constant (t) = L / R

Important Concepts

- The differential equation for the circuit Forced (particular) and natural (complementary) solutions
- Transient and steady-state responses
- 1st order circuits: the time constant (τ)
- 2nd order circuits: natural frequency (ω_0) and the damping ratio (ζ)

Differential Equation Solution

- The total solution to any differential equation consists of two parts:

$$x(t) = x_p(t) + x_c(t)$$

- Particular (**forced**) solution is $x_p(t)$
  - Response particular to a given source
- Complementary (**natural**) solution is $x_c(t)$
  - Response common to all sources, that is, due to the "passive" circuit elements

ELECTROMECHANICAL SYSTEMS

Unit 2
AC Circuits

Aim and Learning Outcomes

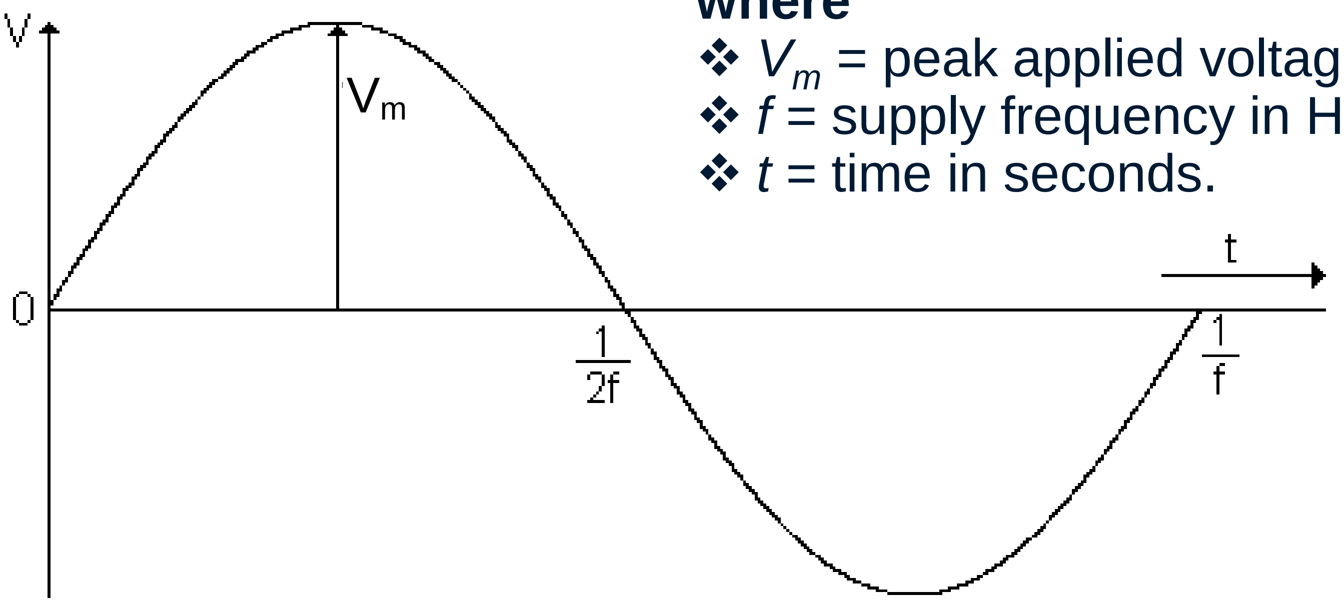
- Most practical applications in electrical engineering involve alternating current and voltages.
- This unit explains
  - analysis of AC circuits and their operations
  - use of capacitance transducers.
- After completing this unit you should be able to
  - Analyse passive AC circuits comprising resistors, inductors and capacitors
  - To determine current flow, voltage distribution and power dissipation.
  - Identify series resonance.
  - Analyse power factor improvement circuits.
  - Describe the operation of capacitance transducers and their use in measuring displacement.

Content

Introduction

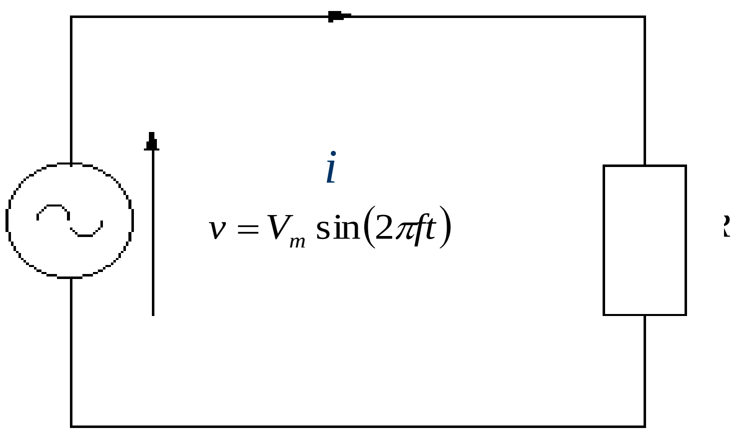
- Electricity supply systems are normally **ac** (alternating current).
- The supply voltage varies sinusoidal
- instantaneous applied voltage, $$v = V_m \sin(2\pi f t)$$

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



where
- V_m = peak applied voltage in volts
- f = supply frequency in Hz
- t = time in seconds.

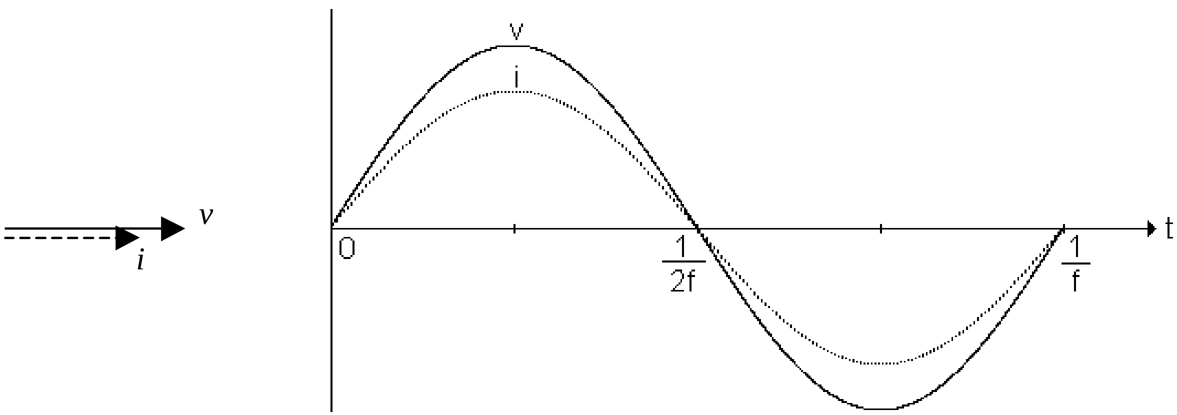
Resistance connected to an AC supply



Instantaneous current, $i = \dfrac{v}{R}$

$$i = \frac{V_m}{R}\sin(2\pi f t)$$

$$i = I_m \sin(2\pi f t)$$



Current and Voltage are in phase

Root Mean Square (rms) Voltage and Current

- The "effective" values of voltage and current over the whole cycle

- rms voltage is $V = \frac{V_m}{\sqrt{2}}$

- rms current is $I = \frac{I_m}{\sqrt{2}}$

"RMS value of an alternating current is that steady state current (dc) which when flowing through the given resistor for a given amount of time produces the same amount of heat as produced by the alternative current when flowing through the same resistance for the same time"

Meters normally indicate rms quantities and this value is equal to the DC value

Other representations of Voltage or Current are

- **maximum or peak value**
- **average value**

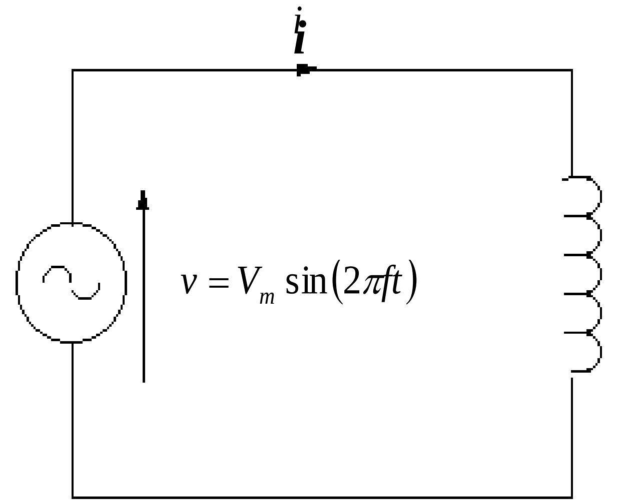
Inductance connected to an AC supply

$$v = L\frac{di}{dt}$$ *i – instantaneous current*

$$v = V_m \sin(2\pi ft) \Rightarrow i = \frac{-V_m}{2\pi fL}\cos(2\pi ft) \qquad \omega = 2\pi f$$

$$i = \frac{-V_m}{\omega L}\cos(\omega t) \Rightarrow I_m = \frac{-V_m}{\omega L}\Big|_{t=0}$$

$$i = \frac{V_m}{\omega L}\sin\left(\omega t - \frac{\pi}{2}\right)$$ ➡ **Current lags Voltage by 90 degree**

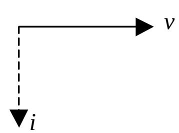


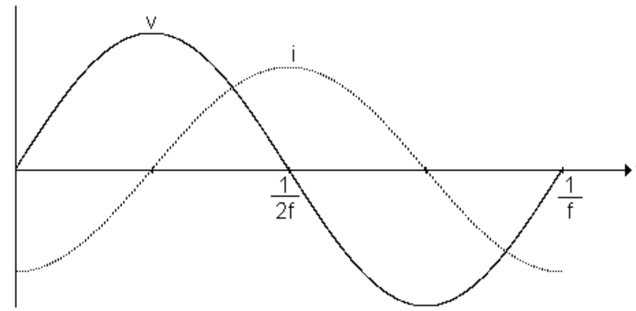
rms current $$I = \frac{V}{\omega L} = \frac{V}{2\pi fL}$$

Using complex numbers and the *j* operator $$I = \frac{-j}{\omega L}V$$

Inductive Reactance $$X_L = 2\pi fL = \omega L$$

$$I = -j\frac{V}{X_L} = \frac{V}{jX_L}$$



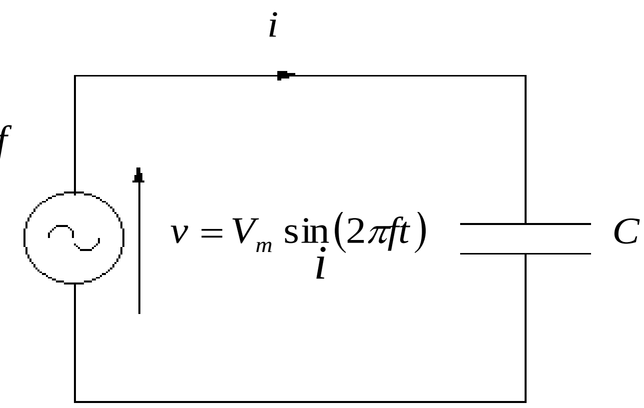


Phasor diagram and wave form

Capacitance connected to an AC supply

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

$$v = V_m \sin(2\pi f t) \Rightarrow i = 2\pi f C V_m \cos(2\pi f t) \qquad \omega = 2\pi f$$



$$i = \omega C V_m \cos(\omega t) \Rightarrow I_m = \omega C V_m$$

$$i = \omega C V_m \sin\left(\omega t + \frac{\pi}{2}\right) \Rightarrow$$ **Current leads Voltage by 90 degrees**

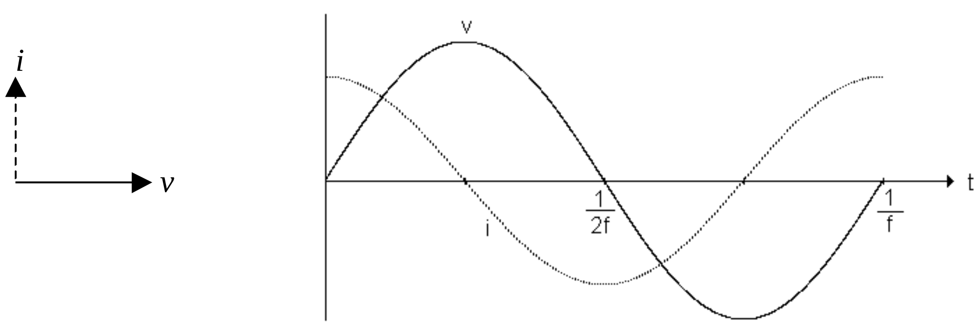
rms current $$\mathrm{I} = \omega \mathrm{CV} = 2\pi \mathrm{fCV}$$

Using complex numbers and the *j* operator $$\mathrm{I} = +j\omega \mathrm{CV}$$

Capacitance Reactance

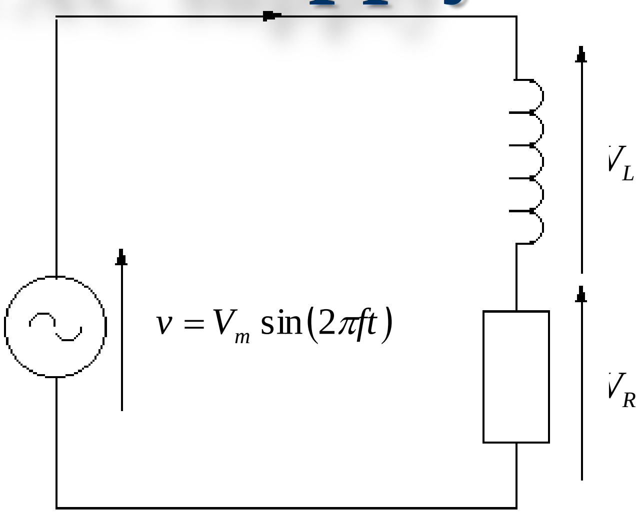
$$X_C = \frac{1}{2\pi f C} = \frac{1}{\omega C}$$

$$I = +j\frac{V}{X_C} = -\frac{V}{jX_C} = \frac{V}{(-jX_C)}$$



Phasor diagram and wave form

R and L in series with an AC supply



$$V = V_R + V_L$$

But $V_R = IR$ **and** $V_L = I \cdot jX_L$

$$\therefore \quad V = I(R + jX_L)$$

And $I = \dfrac{V}{R + jX_L}$ Where, $X_L = \omega L = 2\pi f L$ $\quad \therefore \quad I = \dfrac{V}{R + j\omega L}$

Complex Impedance $\quad Z = R + j\omega L$

Cartesian Form $\quad I = \dfrac{V}{R + j\omega L} \cdot \dfrac{R - j\omega L}{R - j\omega L}$ ➡ $I = \left[\dfrac{VR}{R^2 + \omega^2 L^2}\right] - j\left[\dfrac{V\omega L}{R^2 + \omega^2 L^2}\right]$

-j **indicates that the current <u>lags</u> the voltage**

Complex Impedance: $Z = R + j\omega L$

Cartesian Form: $I = \left[\dfrac{VR}{R^2 + \omega^2 L^2}\right] - j\left[\dfrac{V\omega L}{R^2 + \omega^2 L^2}\right]$

In Polar Form

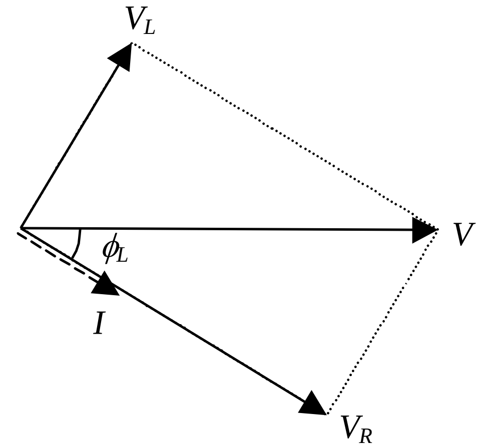
$$I = \frac{V}{\sqrt{R^2 + \omega^2 L^2}} \angle(-\phi_L)$$

$$\phi_L = \tan^{-1}\left(\frac{\omega L}{R}\right)$$

$-\phi_L$ indicates lagging current.

$$|I| = \frac{V}{\sqrt{R^2 + \omega^2 L^2}}$$

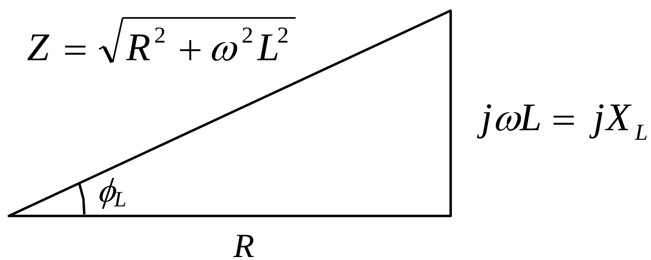
phasor diagram constructed with RMS quantities



Power factor, p.f. $= \cos(\phi_L) = \cos\left(\tan^{-1}\dfrac{\omega L}{R}\right)$

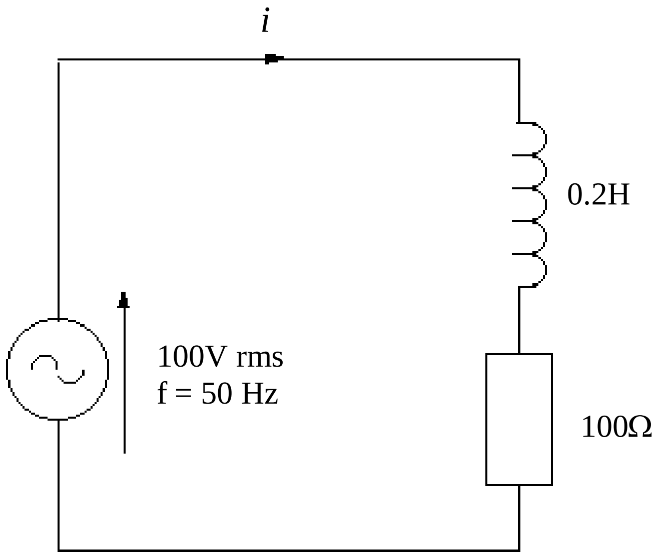
Complex impedance: $Z = R + j\omega L$

$$|Z| = \sqrt{R^2 + \omega^2 L^2}$$



Exercise:

For the circuit shown below, calculate the rms current I & phase angle ϕ_L



Use:

$$I = \frac{V}{\sqrt{R^2 + \omega^2 L^2}} \angle(-\phi_L)$$

$$I = \left[\frac{VR}{R^2 + \omega^2 L^2}\right] - j\left[\frac{V\omega L}{R^2 + \omega^2 L^2}\right]$$

$$\phi_L = \tan^{-1}\left(\frac{\omega L}{R}\right)$$

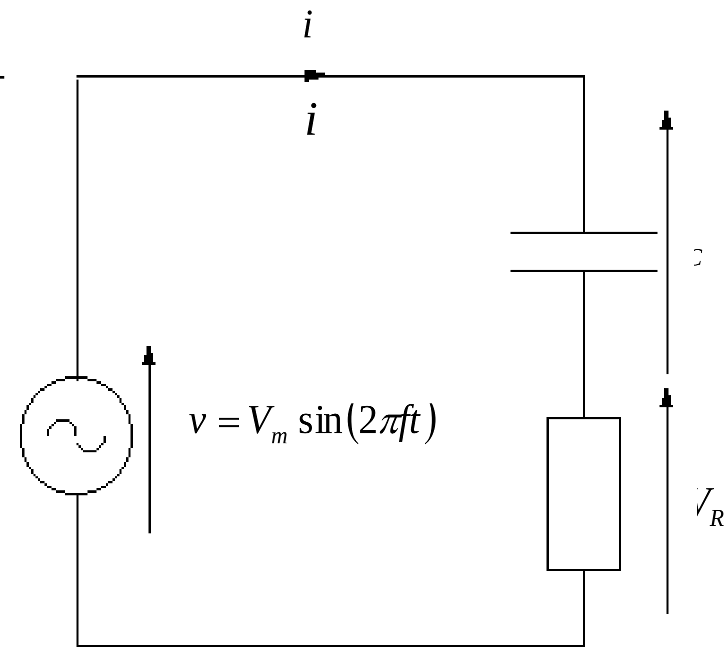
Answer: I = 0.85A $\angle$-32.10

R and C in series with an AC supply

$V = V_C + V_R$ **But** $V_R = IR$ **and** $V_C = I(-jX_C)$

$\therefore \quad V = I(R - jX_C) \Rightarrow I = \dfrac{V}{R - jX_C}$

but $X_C = \dfrac{1}{\omega C} = \dfrac{1}{2\pi f C}$ $\quad \therefore I = \dfrac{V}{R - (j/\omega C)}$



Complex Impedance $Z = (R - j/\omega C)$

***The current, I* in Cartesian form is given by**

$$I = \left[\frac{VR}{R^2 + \dfrac{1}{\omega^2 C^2}}\right] + j\left[\frac{V/\omega C}{R^2 + \dfrac{1}{\omega^2 C^2}}\right]$$

+j signifies that the current **<u>leads</u>** the voltage.

Complex Impedance: $Z = (R - j/\omega C)$

***I* Cartesian form:** $I = \left[\dfrac{VR}{R^2 + \dfrac{1}{\omega^2 C^2}}\right] + j\left[\dfrac{V/\omega C}{R^2 + \dfrac{1}{\omega^2 C^2}}\right]$

In Polar Form

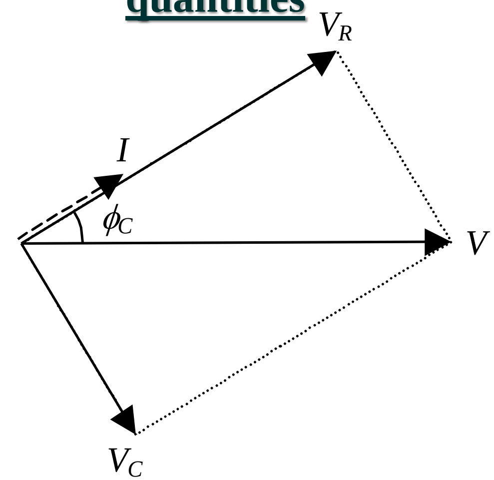
$$I = \frac{V}{\sqrt{R^2 + \dfrac{1}{\omega^2 C^2}}} \angle + \phi_C$$

$+\phi_C$ identifies current **leading** voltage

$$\phi_C = \tan^{-1}\left(\frac{1}{\omega CR}\right)$$

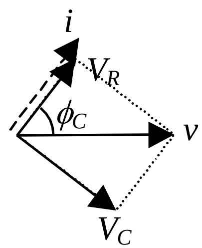
$$|I| = \frac{V}{\sqrt{R^2 + \dfrac{1}{\omega^2 C^2}}}$$

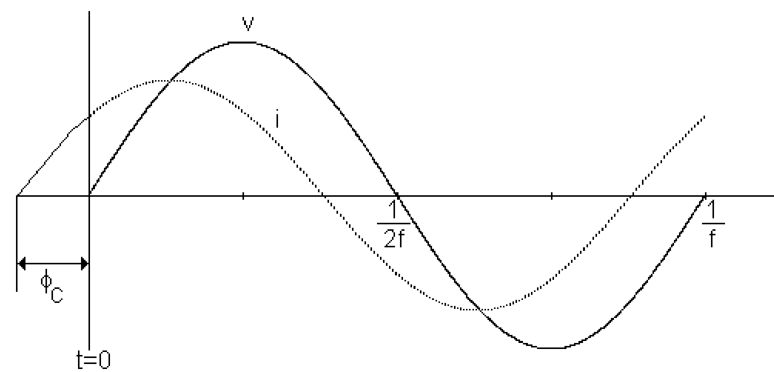
phasor diagram drawn with RMS quantities



Power Factor $= \cos(\phi_C)$

$$= \cos\left(\tan^{-1}\left(\frac{1}{\omega CR}\right)\right)$$

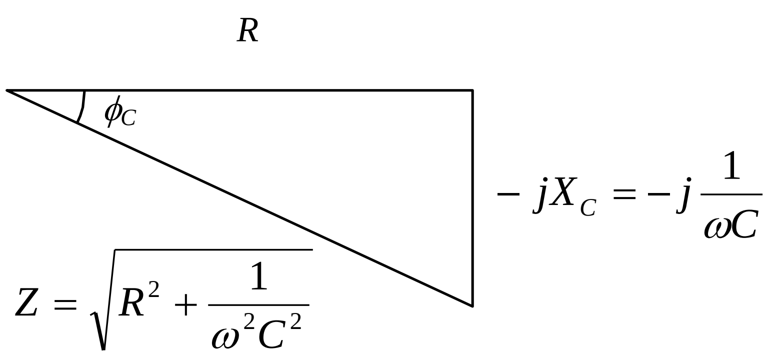




sinusoidal current leading the voltage

$$\therefore \quad Z = R - \frac{j}{\omega C}$$

$$|Z| = \sqrt{R^2 + \frac{1}{\omega^2 C^2}}$$

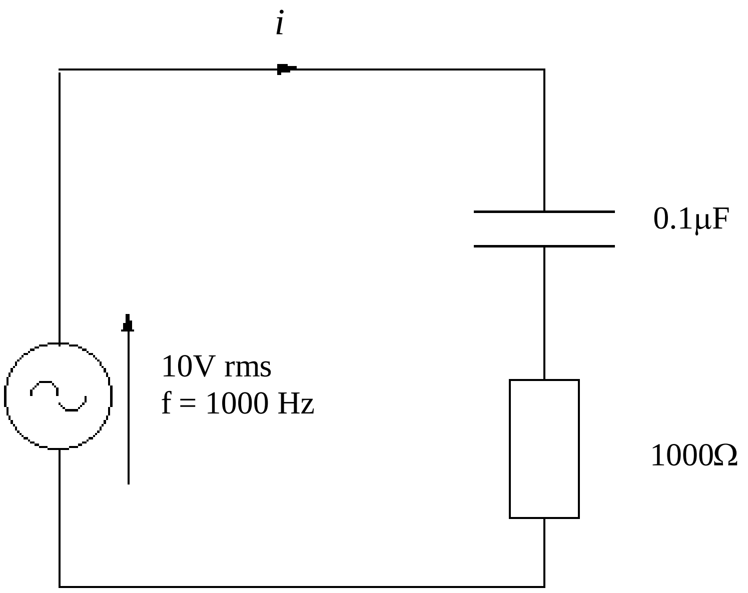


Exercise:

For the circuit shown, calculate the rms current I & phase angle ϕ_L

Use: $$I = \frac{V}{\sqrt{R^2 + \frac{1}{\omega^2 C^2}}} \angle + \phi_C$$

$$I = \left[\frac{VR}{R^2 + \frac{1}{\omega^2 C^2}}\right] + j\left[\frac{V/\omega C}{R^2 + \frac{1}{\omega^2 C^2}}\right]$$



Answer: I = 5.32mA ∠57.90

RLC in series with an AC supply

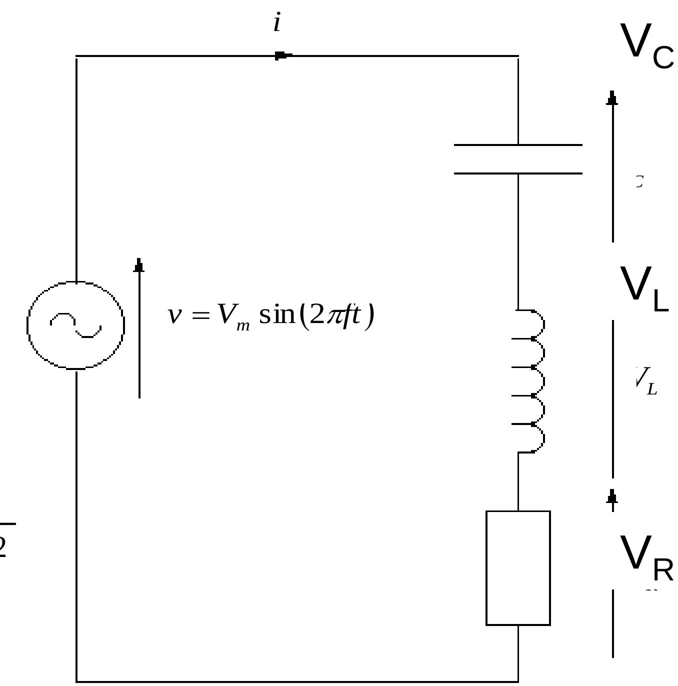
$$V = V_R + V_L + V_C$$

We know that: $V_R = IR$ $\quad V_L = I(jX_L)$ $\quad V_C = I(-jX_C)$

$$\therefore \mathrm{V} = \mathrm{I}[\mathrm{R} + \mathrm{j}\mathrm{X}_\mathrm{L} - \mathrm{j}\mathrm{X}_\mathrm{C}] = \mathrm{I}[\mathrm{R} + \mathrm{j}(\mathrm{X}_\mathrm{L} - \mathrm{X}_\mathrm{C})]$$

But $X_L = \omega L$ **&** $X_C = 1/\omega C$

$$\therefore \mathrm{I} = \frac{\mathrm{V}}{\mathrm{R} + \mathrm{j}(\omega \mathrm{L} - 1/\omega\mathrm{C})}$$



Complex Impedance

$$Z = R + j\left(\omega L - \frac{1}{\omega C}\right) \qquad |Z| = \sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}$$

From previous page ➡ $$I = \frac{V}{R + j\left(\omega L - 1/\omega C\right)}$$

$$I = \frac{VR}{R^2 + \left(\omega L - 1/\omega C\right)^2} - j\frac{V\left(\omega L - 1/\omega C\right)}{R^2 + \left(\omega L - 1/\omega C\right)^2}$$

$$I = \frac{V}{R^2 + \left(\omega L - 1/\omega C\right)^2}\left[R - j\left(\omega L - 1/\omega C\right)\right]$$

$$I = \frac{V}{\sqrt{R^2 + \left(\omega L - 1/\omega C\right)^2}} \angle -\phi_s$$

The phasor diagram (and hence the waveforms) depend on the relative values of ωL and $1/\omega C$. Three cases must be considered

$$\phi_s = \tan^{-1}\left(\frac{\omega L - 1/\omega C}{R}\right)$$

or

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

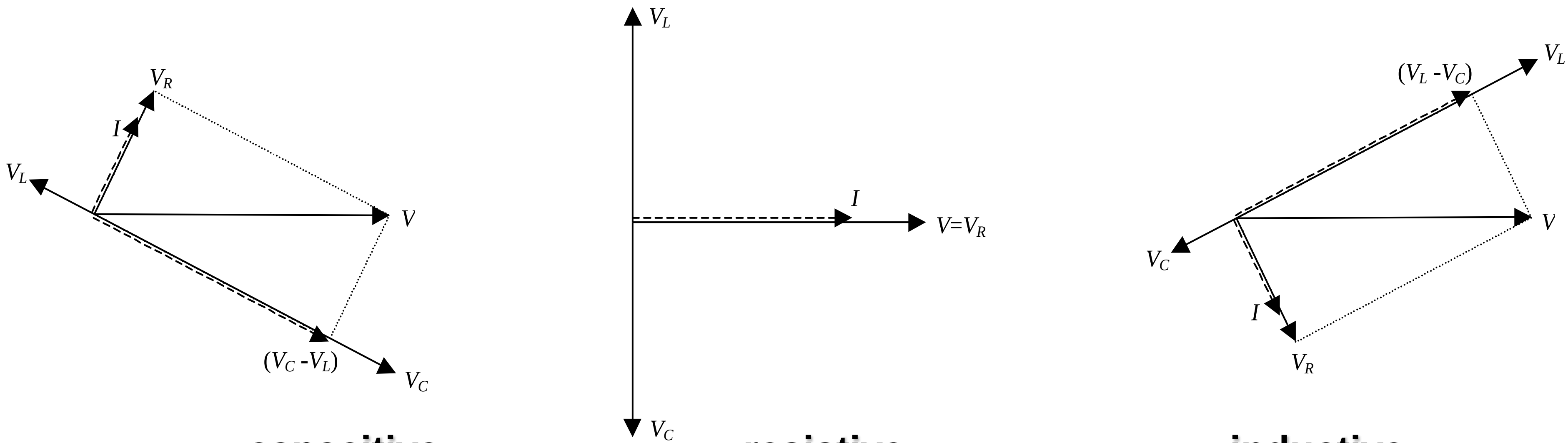
$$\left|I\right| = \frac{V}{\sqrt{R^2 + \left(\omega L - 1/\omega C\right)^2}}$$

From previous page ➡ $$|I| = \frac{V}{\sqrt{R^2 + (\omega L - 1/\omega C)^2}}$$

(i) $\omega L < 1/\omega C \quad V_L < V_C$

(ii) $\omega L = 1/\omega C \quad V_L = V_C$

(iii) $\omega L > 1/\omega C \quad V_L > V_C$



capacitive **resistive** **inductive**

Resonant frequency } $$f_o = \frac{1}{2\pi\sqrt{LC}}$$

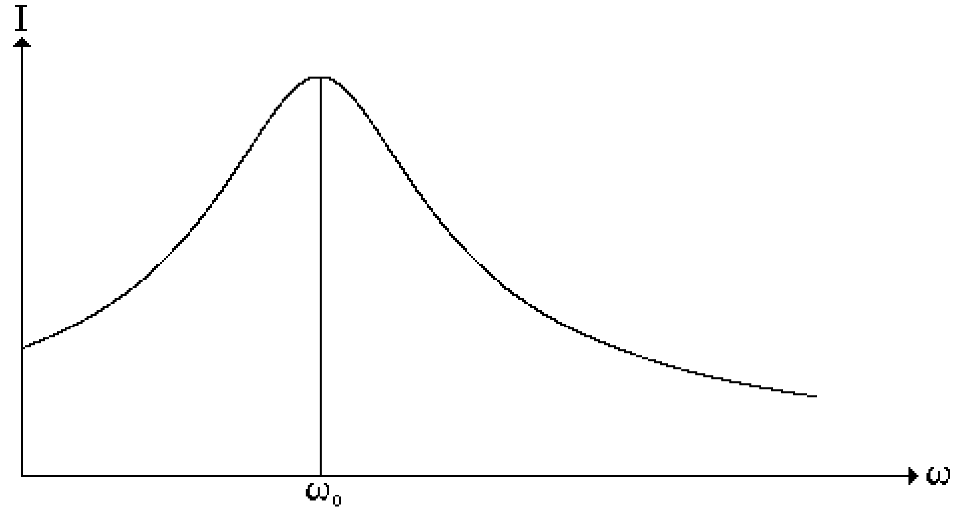
From previous page ➡ $$|I| = \frac{V}{\sqrt{R^2 + (\omega L - 1/\omega C)^2}}$$

From the above equation for the current it is clear that the magnitude of the current varies with ω (and hence frequency, f). This variation is shown in the graph

at ω_o, $$\omega L = 1/\omega C \qquad I = \frac{V}{R}\angle 0°$$

$|V_L| = |V_C|$ and they may be greater than V

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad \& \quad f_0 = \frac{\omega_0}{2\pi} = \frac{1}{2\pi\sqrt{LC}}$$

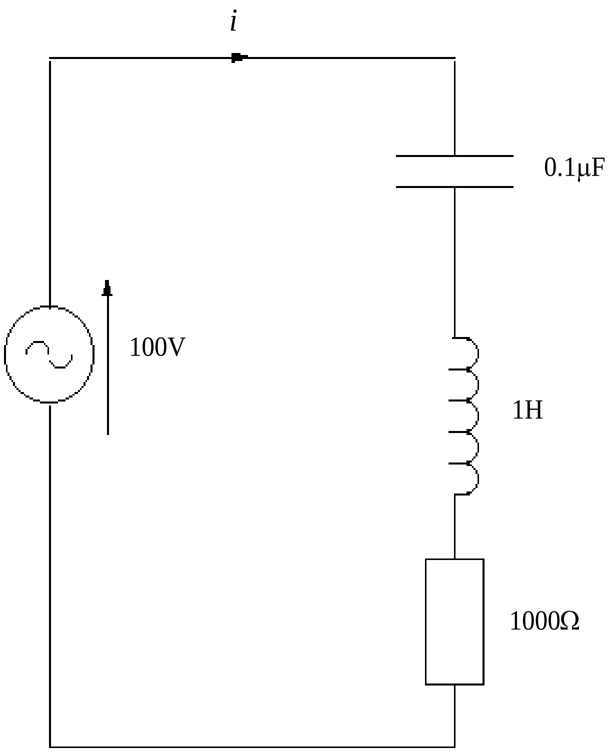


- f_o **is called the series resonant frequency.**
- **This phenomenon of series resonance is utilised in radio tuners.**

Exercise:

For circuit shown in figure, calculate the current and phase angle and power factor when frequency is

(i) 159.2Hz, (ii) 1592.Hz and (iii) 503.3Hz



How about you try this ?

Answer:

(i) 11.04 mA + 83.6^o, 0.111 leading
(ii) 11.04mA, -83.6^0, 0.111 lagging
(iii) 100mA, 00, 1.0 (in phase)

AC Supply in Parallel with C, and in Series R &L

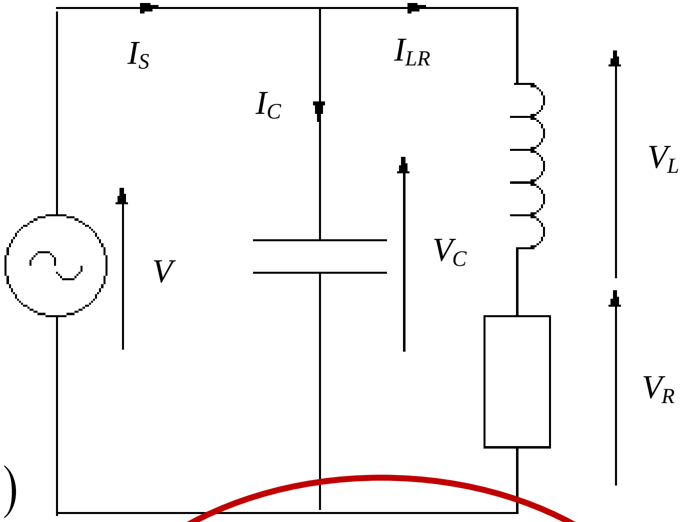
$$I_S = I_C + I_{LR} \qquad V = V_C = V_R + V_L$$

Can U name the Laws?

We know that: $V_C = I_C(-jX_C) = I_C(-j/\omega C) = V \Rightarrow I_C = j\omega CV$

$$V_R = I_{LR}R$$

$$V_L = I_{LR}(jX_L) = I_{LR}(j\omega L)$$

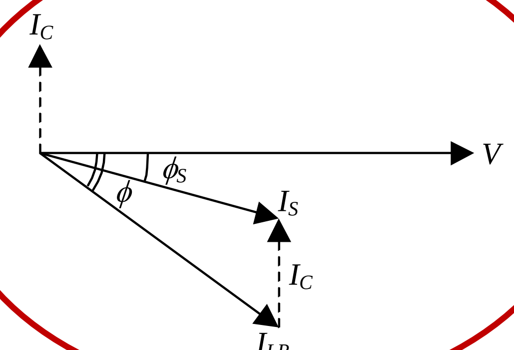


Substituting for the different Voltage components gives:

$$V = I_{LR}(R + j\omega L) \Rightarrow I_{LR} = \frac{V}{R + j\omega L} = \frac{V}{R^2 + \omega^2 L^2}(R - j\omega L)$$

and $I_S = I_C + I_{LR} \Rightarrow I_S = j\omega CV + \frac{V}{R^2 + \omega^2 L^2}(R - j\omega L)$

Hence, $I_S = \frac{V}{R^2 + \omega^2 L^2}\left[R + j\omega\left(CR^2 + \omega^2 CL^2 - L\right)\right]$

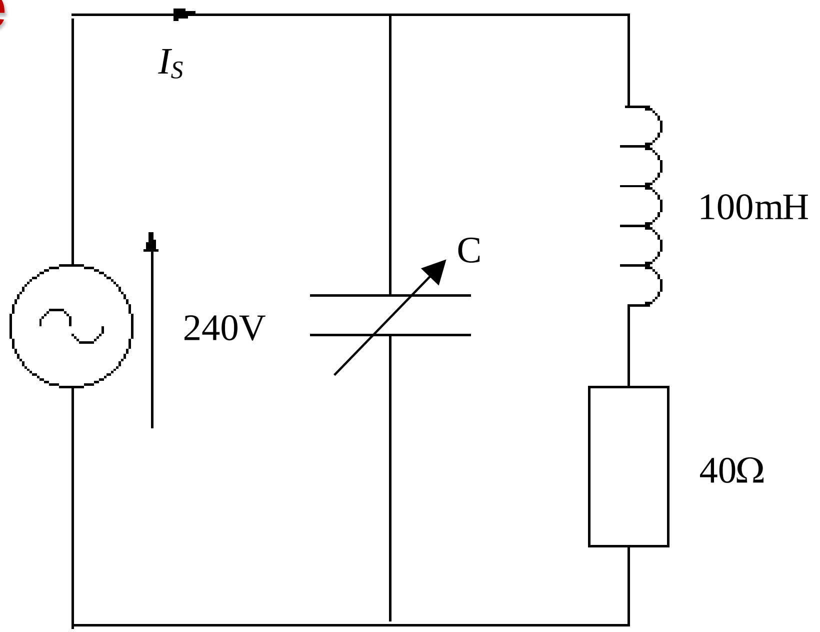


Exercise:

For the circuit shown calculate the minimum supply current, I_s and the corresponding capacitance C. Frequency is 50 Hz.

How about you try this one too?

😊



Answer: I_{Smin} = 3.71A C = 38.6μF

Power Dissipation

We know that: ***power dissipation*** $|_{instantaneous}$ = ***voltage*** $|_{instantaneous}$ × ***current*** $|_{instantaneous}$

$$\therefore \mathrm{p} = \mathrm{v} \times \mathrm{i}$$

Hence, **instantaneous voltage,** ➡ $v = V_m \sin(\omega t)$

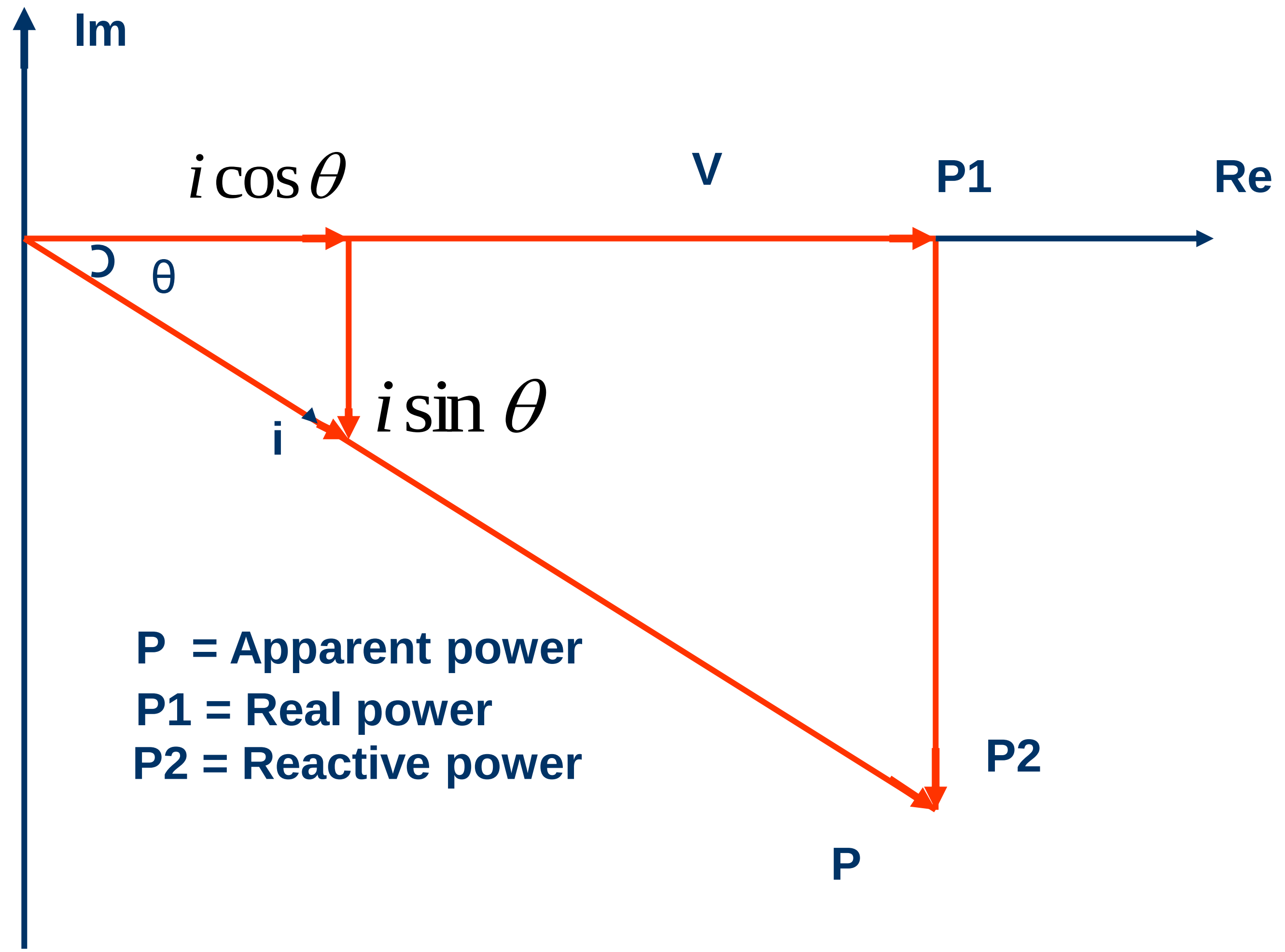
instantaneous current, ➡ $i = I_m \sin(\omega t \pm \phi)$

$$p = vi = V_m \sin(\omega t) I_m \sin(\omega t \pm \phi) \qquad p = \frac{V_m I_m}{2}\left[\cos(2\omega t \pm \phi) - \cos(\pm \phi)\right]$$

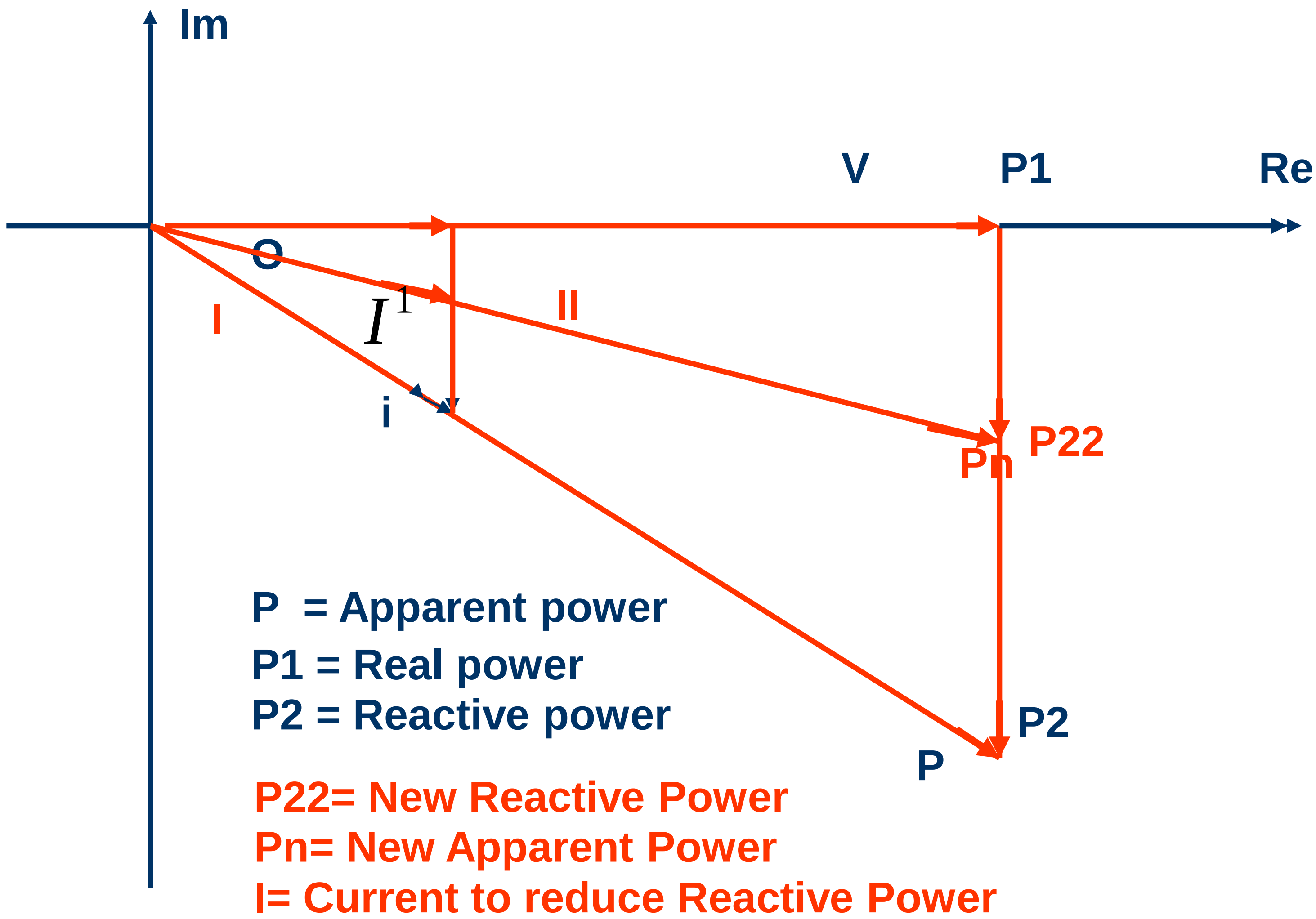
$P = \dfrac{V_m I_m}{2} \cos\phi$ **but** $V = \dfrac{V_m}{\sqrt{2}}$ **&** $I = \dfrac{I_m}{\sqrt{2}}$

Therefore, **net power transfer** ➡ $P = VI\cos(\phi)$

Real, Apparent and Reactive Power

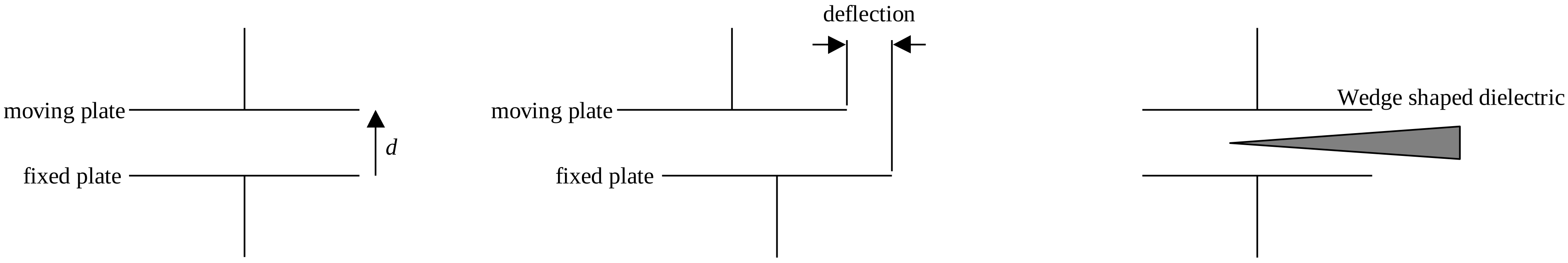


Power Factor Correction



Capacitance Transducers

- Displacement transducers are often variable capacitors,
- Their capacitance varies with movement.
- The value may be adjusted by varying either
  - the distance between the capacitance plates, or
  - the effective plate area, or
  - the effective dielectric between the plates



1. Changing the spacing   2. Adjusting the plate overlap   3. Varying the dielectric between the plates

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

Where

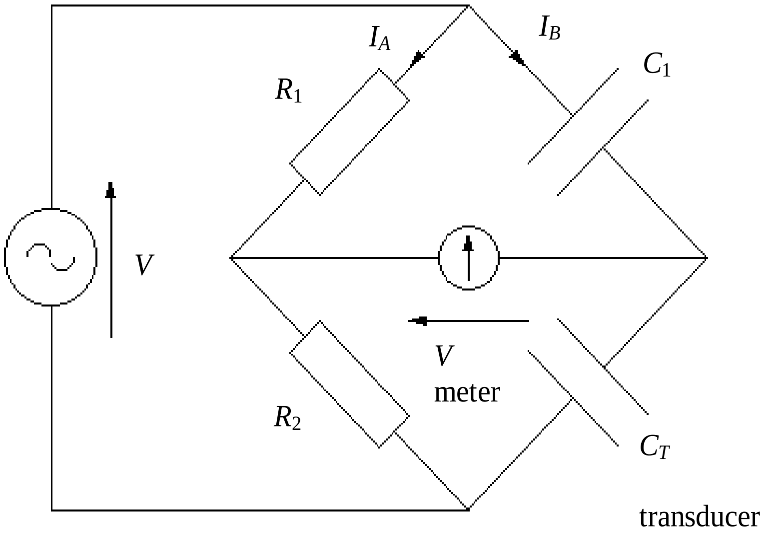
ε_0 = permittivity of free space

ε_r = relative permittivity of dielectric

A = area of overlap between the plates

d = distance between the plates

To determine the displacement by measuring the capacitance accurately. When the bridge is balanced,



$$I_A R_1 = I_B \cdot \frac{1}{j\omega C_1} \qquad I_A R_2 = I_B \cdot \frac{1}{j\omega C_T}$$

$$C_T = C_1 \frac{R_1}{R_2}$$

To achieve the maximum bridge sensitivity:

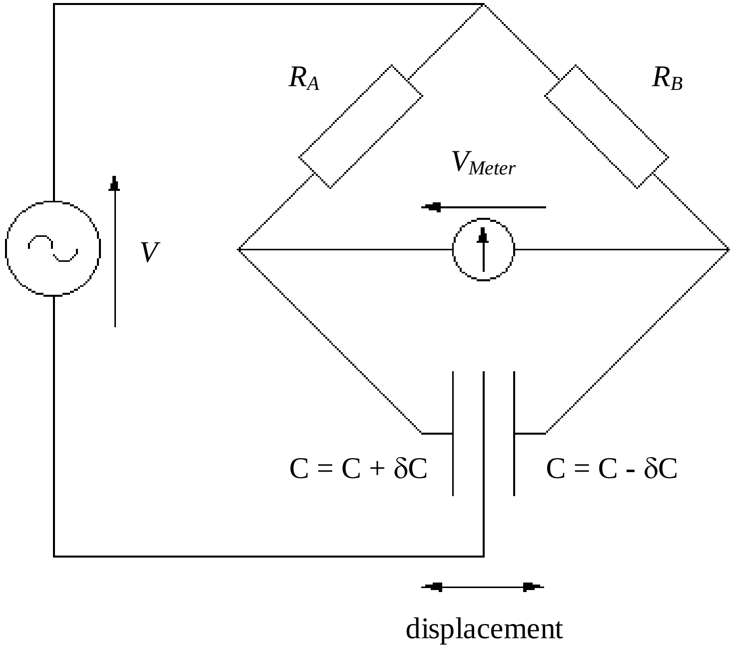
- the two capacitors should be equal
- the resistances equal to the capacitive reactance at the measuring frequency.

For accurate measurements prevent or minimise:-

- stray capacitance between leads and earth
- transducer lead inductance
- transducer dielectric losses
- harmonic distortion (undesired components) in voltage supply

Linearity of the transducer may be improved by using a differentially connected displacement device

The transducer is connected to adjacent arms of an ac bridge.
Movement of the central plate increases the capacitance on one side and reduces it on the other.



Conclusion

1. **AC supply with resistive load, RL in series, RC in series, RLC in series, and RLC in parallel.**
2. **Phasor & Cartesian representations.**
3. **Phase angle and power factor.**
4. **Dissipated Power.**
5. **Applications: Capacitance transducer**

Problem Sheet

Q_1. A 20V 50Hz supply feeds a 20 Resistor in series with a 100mH inductor. Calculate the circuit (complex) impedance and current.

Q_2. A 200V supply feeds a series circuit comprising 250 resistor, 100mH inductor and a 159nF capacitor. Calculate the resonant frequency f_o and the corresponding current. Also calculate the current when the frequency is:- $f_o/3$ $3f_o$

Q_3. A small company connected to 240V, 50Hz single-phase supply draws a current of 40A at 0.8 power factor lagging. A capacitance is connected across the supply to improve the power factor of the supply current to:

i) unity ii) 0.95 lagging

Calculate the supply current and capacitance in each case.

Q_4. The central plate of a differentially connected displacement transducer shown in Fig 2.10c is initially midway between the outer plates. Show that if the central plate is displaced δd that the fractional change in the capacitances ($\delta C/C$) is given approximately by:

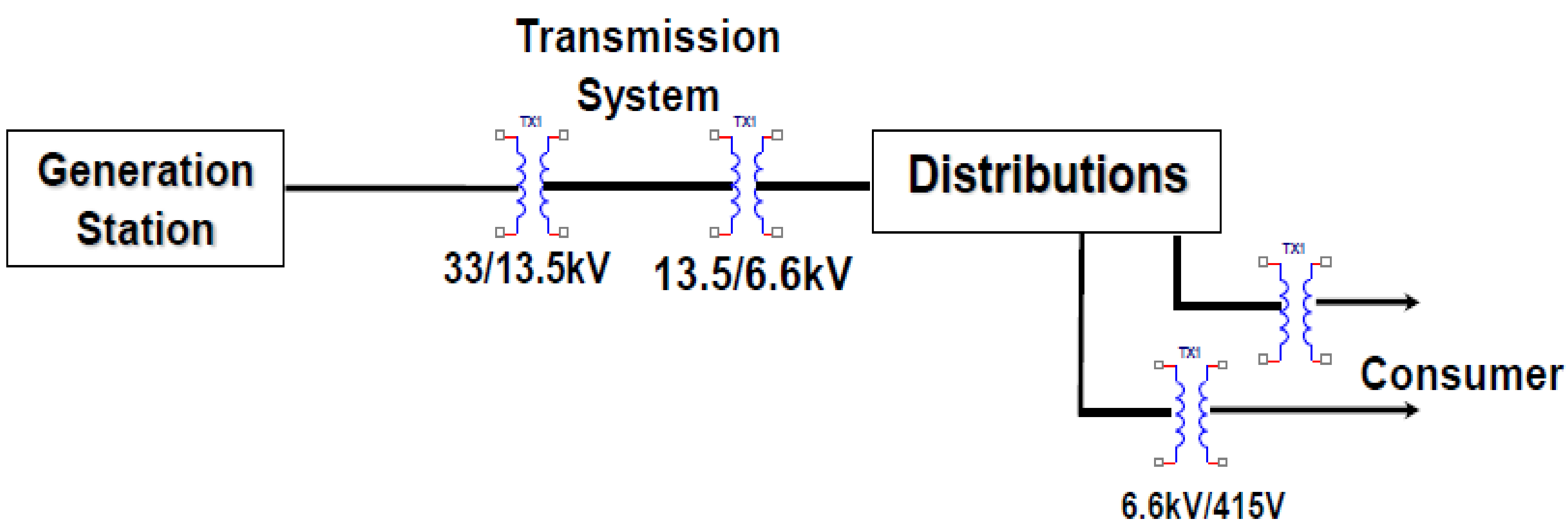
$$\frac{\delta C}{C} = \frac{\delta d}{d}$$

PRESENTATION ON TRANSFORMER

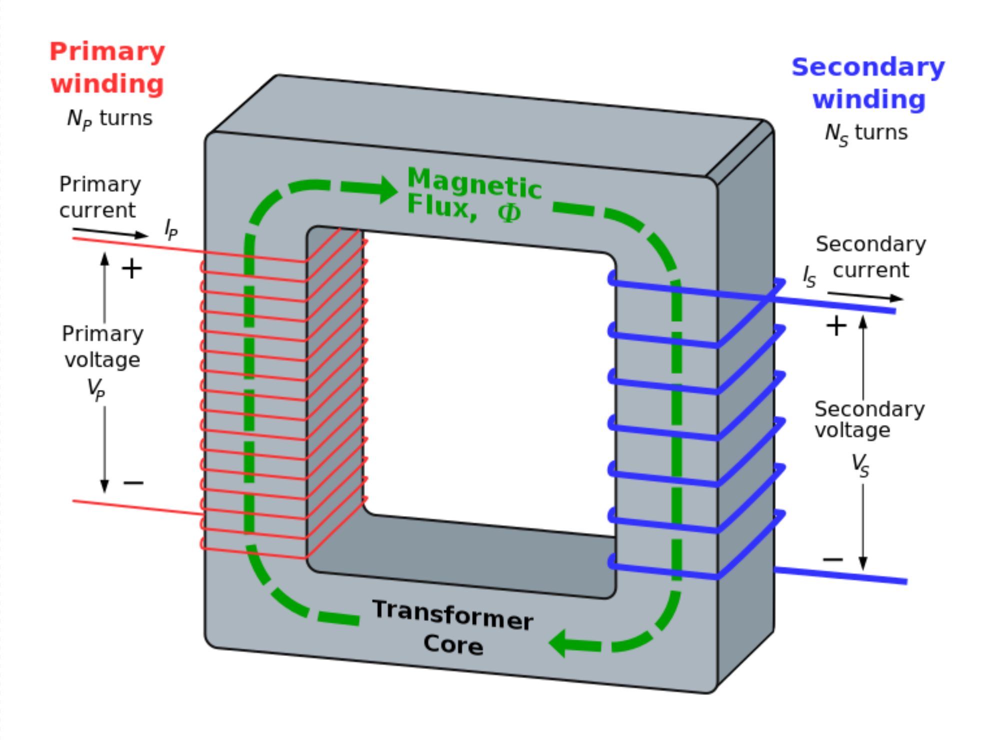
INTRODUCTION

- The transformer is a static device which is used to transfer electrical energy from one ac circuit to another ac circuit.
- Input to a transformer and output from a transformer both are alternating quantities (AC).
- Electrical energy is generated and transmitted at an extremely high voltages. The voltage is to be then reduced to a lower value for its domestic and industrial use.
- This is done by using a transformer.

- The power transmission system using transformers is shown in figure.
- When the transformer changes the voltage level, it changes the current level also.



Basic Principle



- The primary winding is connected to the single – phase ac supply, an ac current starts flowing through it.

- The ac primary current produces an alternating flux (Φ) in the core.
- Most of this changing flux gets linked with the secondary winding through the core.
- The varying flux will induce voltage into the secondary winding according to the faraday's laws of electromagnetic induction.
- Voltage level change but frequency i.e. time period remains same.
- There is no electrical contact between the two winding, an electrical energy gets transferred from primary to the secondary.

- A simple transformer consists of two electrical conductors called the primary winding and the secondary winding.
- Energy is coupled between the windings by the time varying magnetic flux that passes through(links) both primary and secondary windings.

Can the transformer operate on DC?

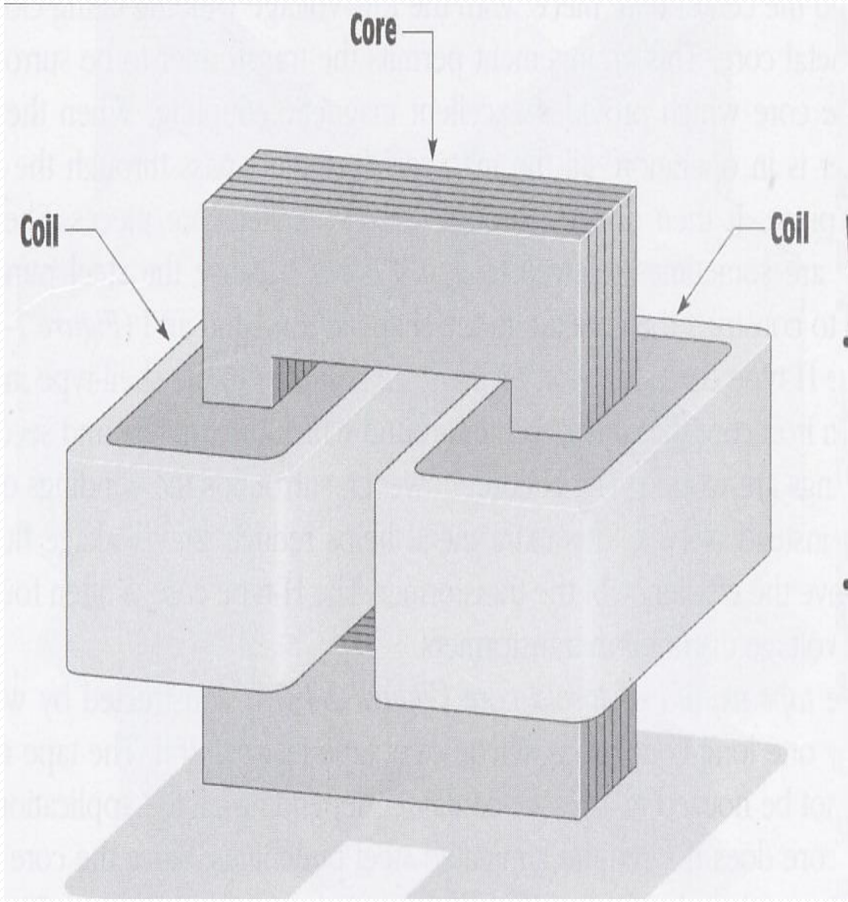
- Answer: **NO**
- The transformer action does not take place with a direct current of constant magnitude.
- Because with a DC primary current, the flux produced in the core is not alternating but it is of constant value.
- As there is no change in the flux linkage with the secondary winding, the induced emf in the secondary is zero.

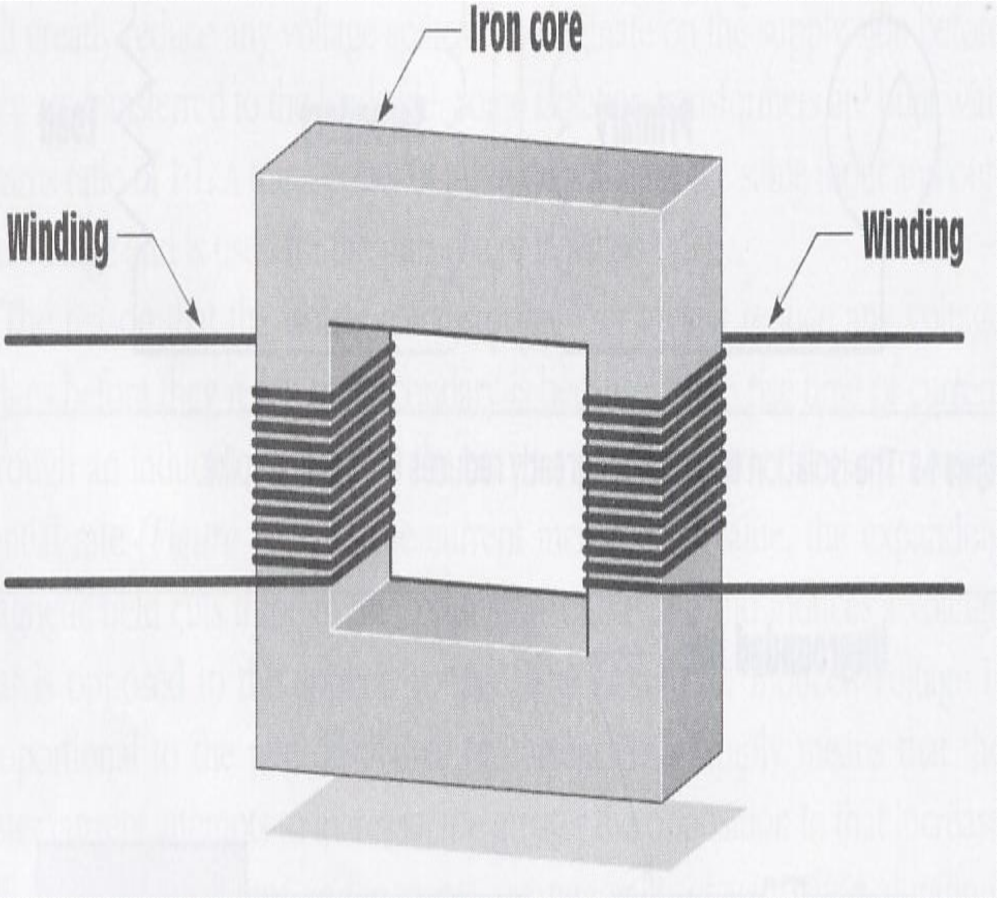
- If DC is applied to the primary then there is a possibility of transformer core saturation.
- If core saturates the primary will draw excessively large current. Therefore application of DC should be avoided.

Transformer Types

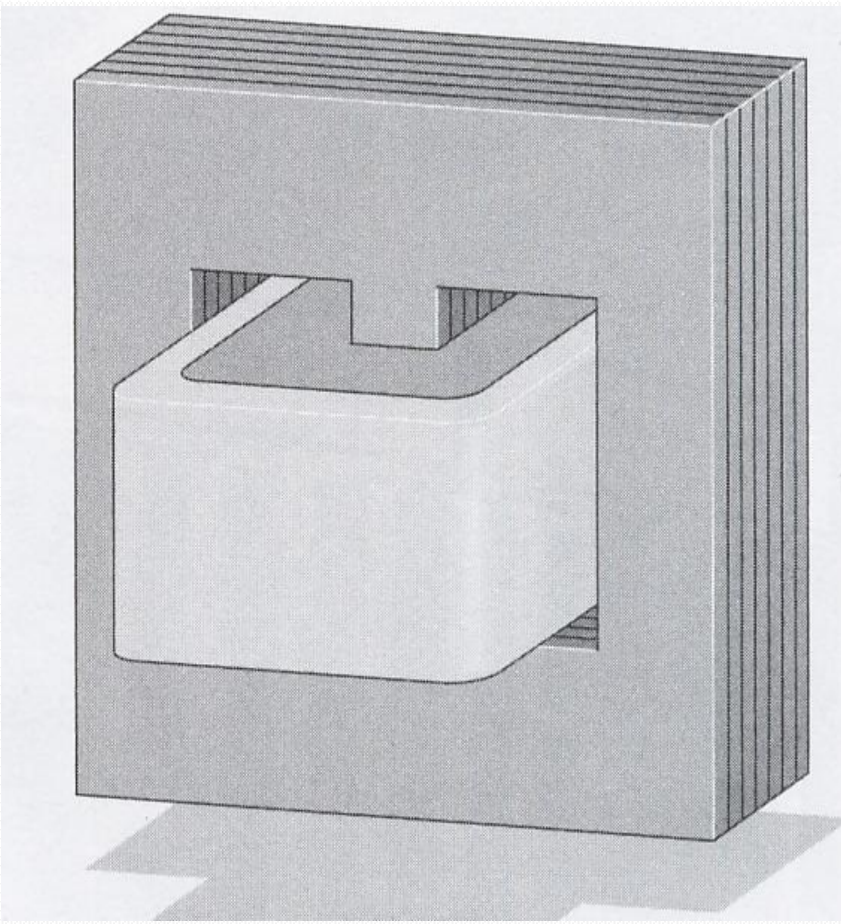
- The transformer are of different types depending on the arrangement of the core and the winding as follows.
- Core Type
- Shell Type
- Berry Type
- The magnetic core is a stack of thin silicon-steel laminations about 0.35 mm thick for 50 Hz transformer. In order to reduce the eddy current losses, these laminations are insulated from one another by thin layers of varnish.

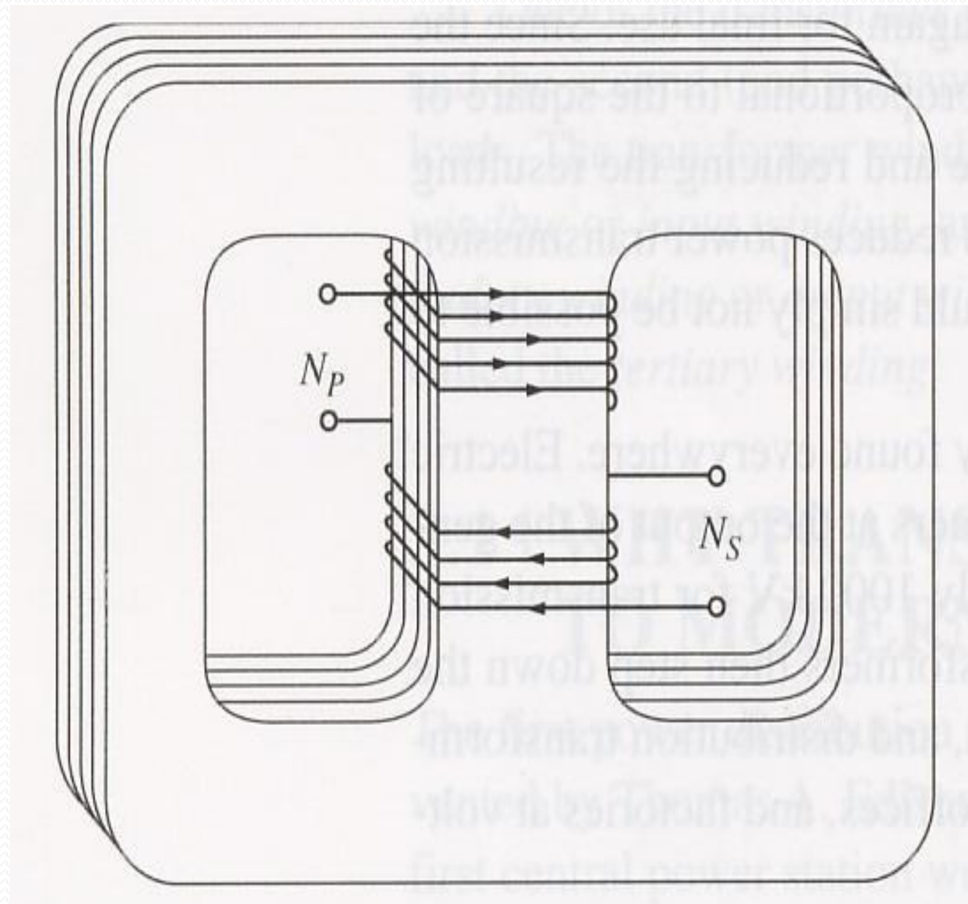
Core Type Transformer





Shell Type Transformer

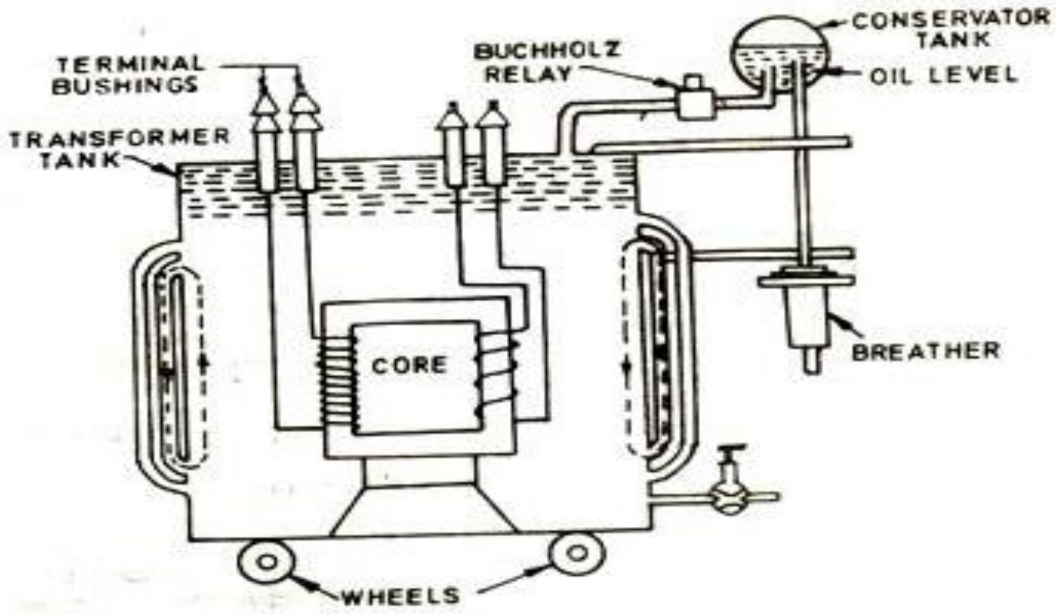




Sr. No	Core Type Transformer	Shell Type Transformer
1.	The core has only one window.	The core has two windows.
2.	Winding encircles the core.	Core encircles the windings.
3.	Cylindrical windings are used.	Sandwich type windings are used.
4.	Easy to repair.	It is not so easy to repair.
5.	Better cooling since more surface is exposed to the atmosphere.	Cooling is not very effective.

Construction of Transformer

- The Most important parts of a transformer are the windings (coils) and the core.
- Some other parts such as suitable tank, conservator, bushings, breather, explosion vent etc. are also used along with the core and windings.



Applications

- Step – up and Step – down Voltage
- Measurement of current in single and three phase system
- Measurement of voltage in single and three phase system
- Measurement of power
- Measurement of Energy

Thank You

UNIT 5

Electrical Installations

Contents: Components of LT Switchgear: Switch Fuse Unit (SFU), MCB, ELCB, MCCB, Types of Wires and Cables, Importance of earthing. Types of Batteries, Important characteristics for Batteries. Elementary calculations for energy consumption and savings.

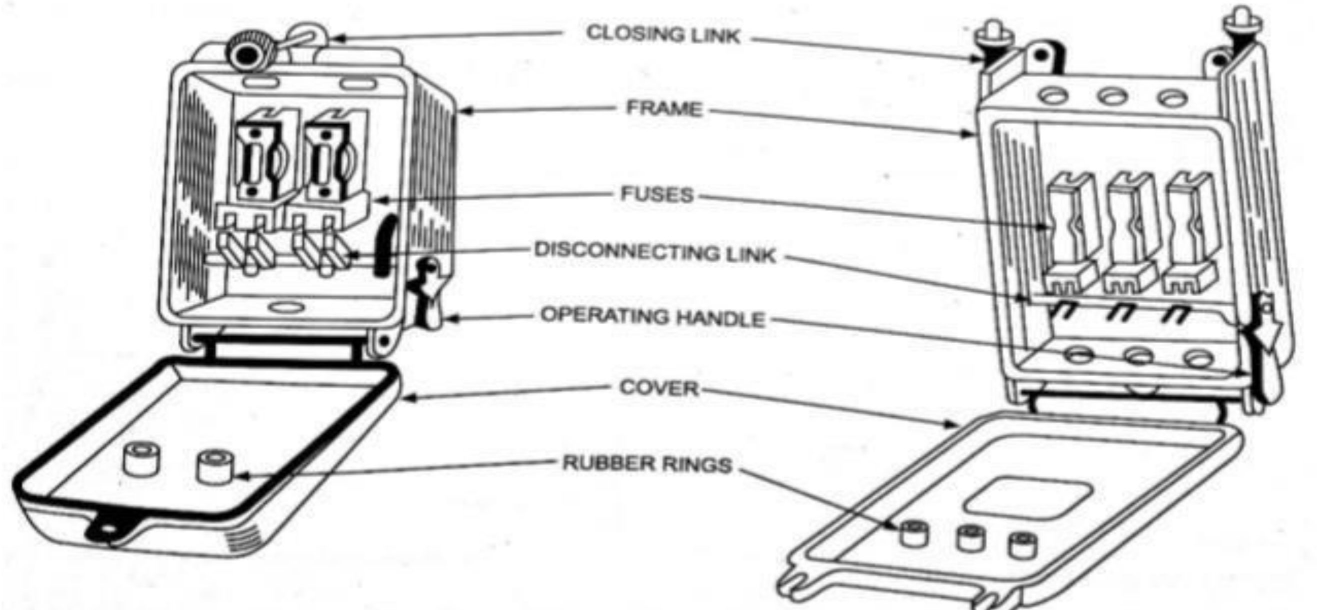
Classification of Switchgear:

Switchgear can be classified on the basis of voltage level into the following:

1. Low voltage (LV) Switchgear: upto 1KV
2. Medium voltage (MV) Switchgear: 3 KV to 33 KV
3. High voltage (HV) Switchgear: Above 33 KV

Switch Fuse Unit (SFU):

Switch fuse is a combined unit and is known as an iron clad switch, being made of iron. It may be double pole for controlling single phase two-wire circuits or triple pole for controlling three- phase, 3-wire circuits or triple pole with neutral link for controlling 3-phase, 4-wire circuits. The respective switches are known as double pole iron clad (DPIC), triple pole iron clad (TPIC), and triple pole with neutral link iron clad (TPNIC) switches.



(a) DPIC Switch

(b) TPIC Switch

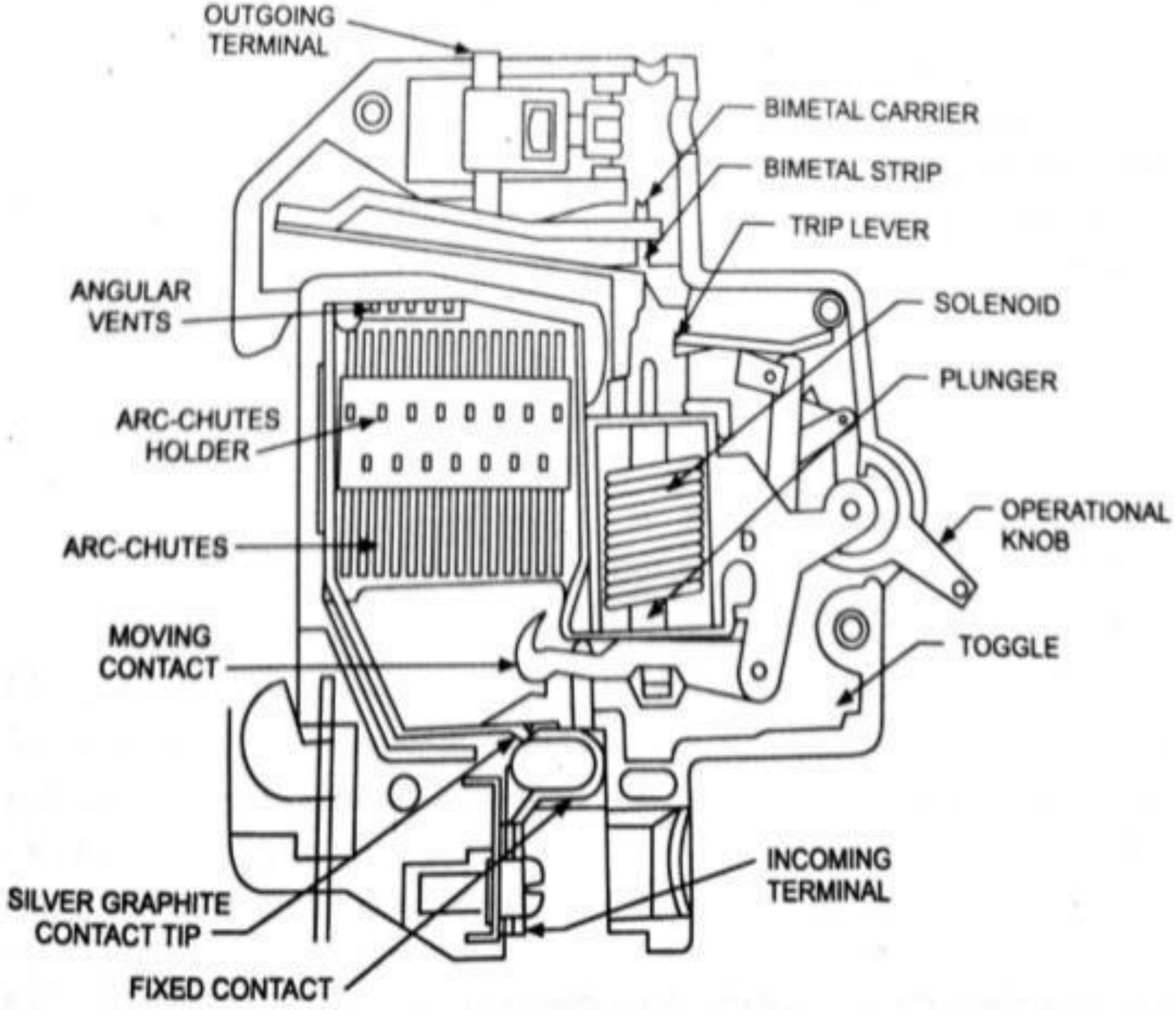
Miniature Circuit Breaker (MCB):

A device which provides definite protection to the wiring installations and sophisticated equipment against over-currents and short-circuit faults

Thermal operation (overload protection) is achieved with a bimetallic strip, which deflects when heated by any over-currents flowing through it. In doing so, releases the latch mechanism and causes the contacts to open.

MCBs are available with different current ratings of 0.5, 1.2, 2.5, 3, 4, 5, 6, 7.5, 10, 16, 20, 25, 32,35, 40, 63, 100, 125, 160 A and voltage rating of 240/415 V AC and up to 220 V DC. Operating time is very short (less than 5 ms).

They are suitable for the protection of important and sophisticated equipment, such as air- conditioners, refrigerators, computers etc.


OUTGOING TERMINAL
BIMETAL CARRIER
BIMETAL STRIP
TRIP LEVER
ANGULAR VENTS
SOLENOID
PLUNGER
ARC-CHUTES HOLDER
ARC-CHUTES
OPERATIONAL KNOB
MOVING CONTACT
TOGGLE
INCOMING TERMINAL
SILVER GRAPHITE CONTACT TIP
FIXED CONTACT

Earth Leakage Circuit Breaker (ELCB):

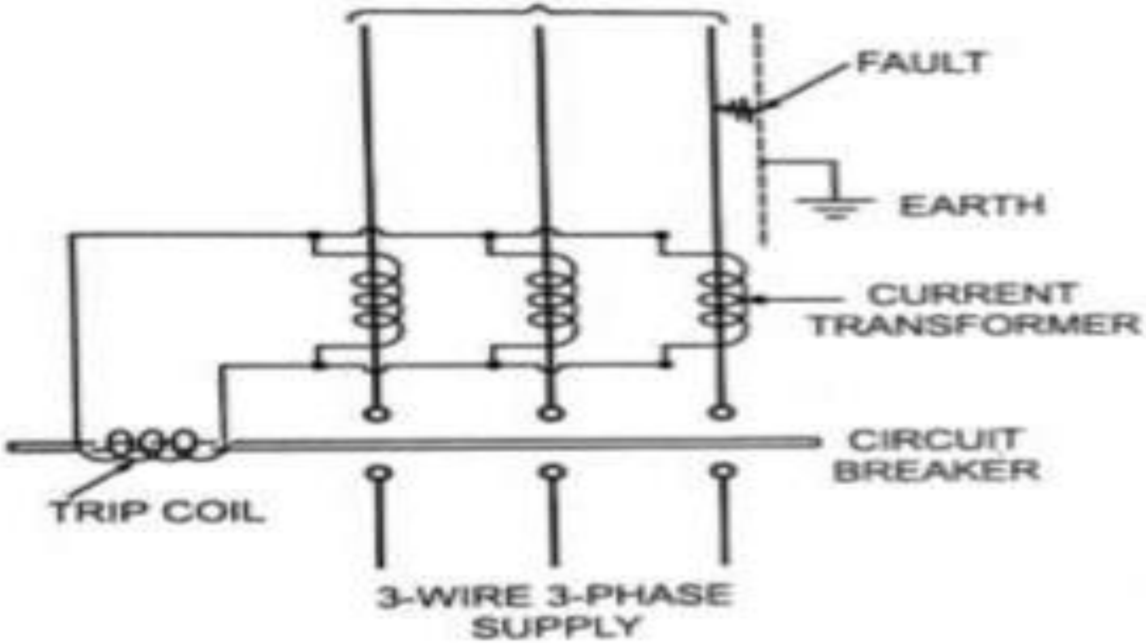
It is a device that provides protection against earth leakage. These are of two types.

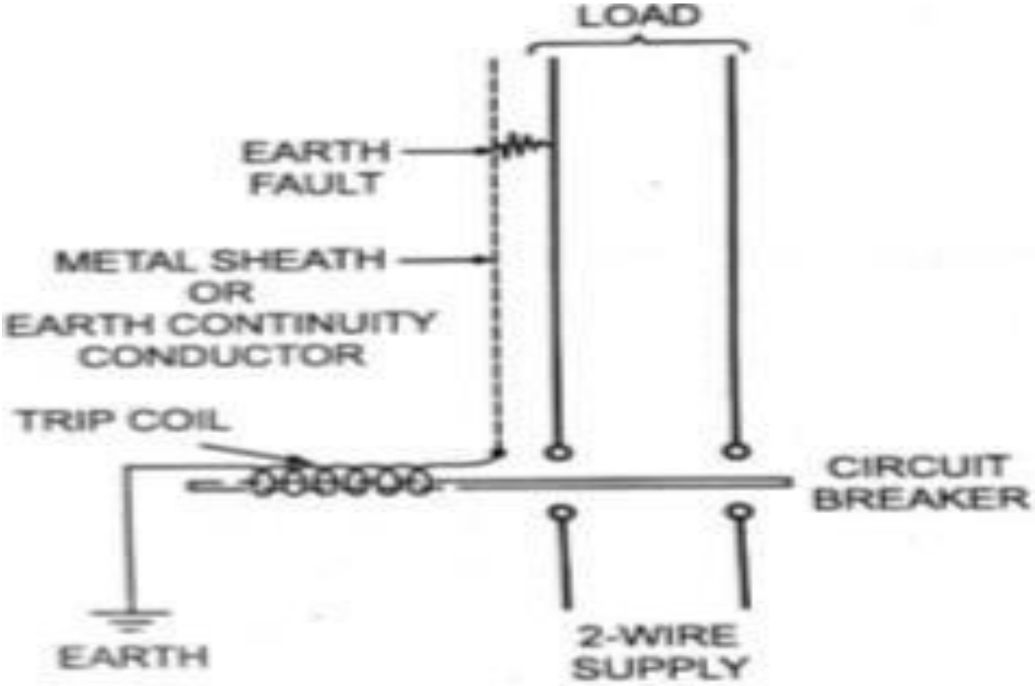
1. **Current operated earth leakage circuit breaker:**
2. **Voltage operated earth leakage circuit breaker.**

1. **Current operated earth leakage circuit breaker:** It is used when the product of the operating current in amperes and the earth-loop impedance in ohms does not exceed 40. such circuit breakers is used where consumer's earthing terminal is connected to a suitable earth electrode. A current-operated earth leakage circuit breaker is applied to a 3-phase, 3-wire circuit.

In normal condition when there is no earth leakage, the algebraic sum of the currents in the three coils of the current transformers is zero, and no current flows through the trip coil. In case of any earth leakage, the currents are unbalanced and the trip coil is energized and thus the circuit breaker is tripped.

1. **Voltage operated earth leakage circuit breaker:** It is suitable for use when the earth–loop impedance exceeds the values applicable to fuses or excess-current circuit breaker or to current operated earth leakage circuit breaker. When the voltage between the earth continuity conductor (ECC) and earth electrode rises to sufficient value, the trip coil will carry the required current to trip the circuit breaker. With such a circuit breaker the earthing lead between the trip coil and the earth electrode must be insulated; in addition, the earth electrode must be placed outside the resistance area of any other parallel earths which may exist.


FAULT
EARTH
CURRENT
TRANSFORMER
CIRCUIT
BREAKER
TRIP COIL
3-WIRE 3-PHASE
SUPPLY


LOAD
EARTH
FAULT
METAL SHEATH
OR
EARTH CONTINUITY
CONDUCTOR
TRIP COIL
CIRCUIT
BREAKER
EARTH
2-WIRE
SUPPLY

Molded Case Circuit Breaker (MCCB) :

It is a type of electrical protection device that can be used for a wide range of voltages, and frequencies of both 50 Hz and 60 Hz, the main distinctions between molded case and miniature circuit breaker are that MCCB can have current rating up to 2500 amperes, and its trip setting are normally adjustable. MCCBs are much larger than MCBs. An MCCB has three main functions:

- **Protection against overload.**
- **Protection against electrical faults.**
- **Switching a circuit ON and OFF.** This is a less common function of circuit breakers, but they can be used for that purpose if there is not an adequate manual switch.

Operating Mechanism: At its core, the protection mechanism employed by MCCBs is based on the same physical principles used by all types of thermal-magnetic circuit breakers.

- Overload protection is accomplished by means of a thermal mechanism. MCCBs have a bimetallic contact what expands and contracts in response to changes in temperature. Under normal operating conditions, the contact allows electric current through the MCCB. However, as soon as the current exceeds the adjusted trip value, the contact will start to heat and expand until the circuit is interrupted.
- The thermal protection against overload is designed with a time delay to allow short duration overcurrent, which is a normal part of operation for many devices. However any over current conditions, that lasts more than what is normally expected represent an overload, and the MCCB is tripped to protect the equipment and personnel. On the other hand, fault protection is accomplished with electromagnetic induction, and the response is instant. Fault currents should be interrupted immediately, no matter if their duration is short or long. Whenever a fault occurs, the extremely high current induces a magnetic field in a solenoid coil located inside the breaker-this magnetic induction trips a contact and current is interrupted. As a complement to the magnetic protection mechanism, MCCBs have internal arc dissipation measures to facilitate interruption.

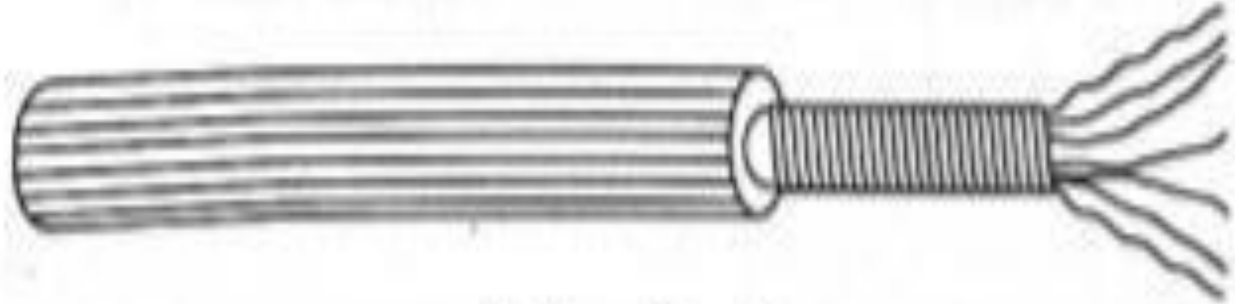
Types of Wires and Cables:

For internal wiring of any building, wires and cables may be categorized into following groups:

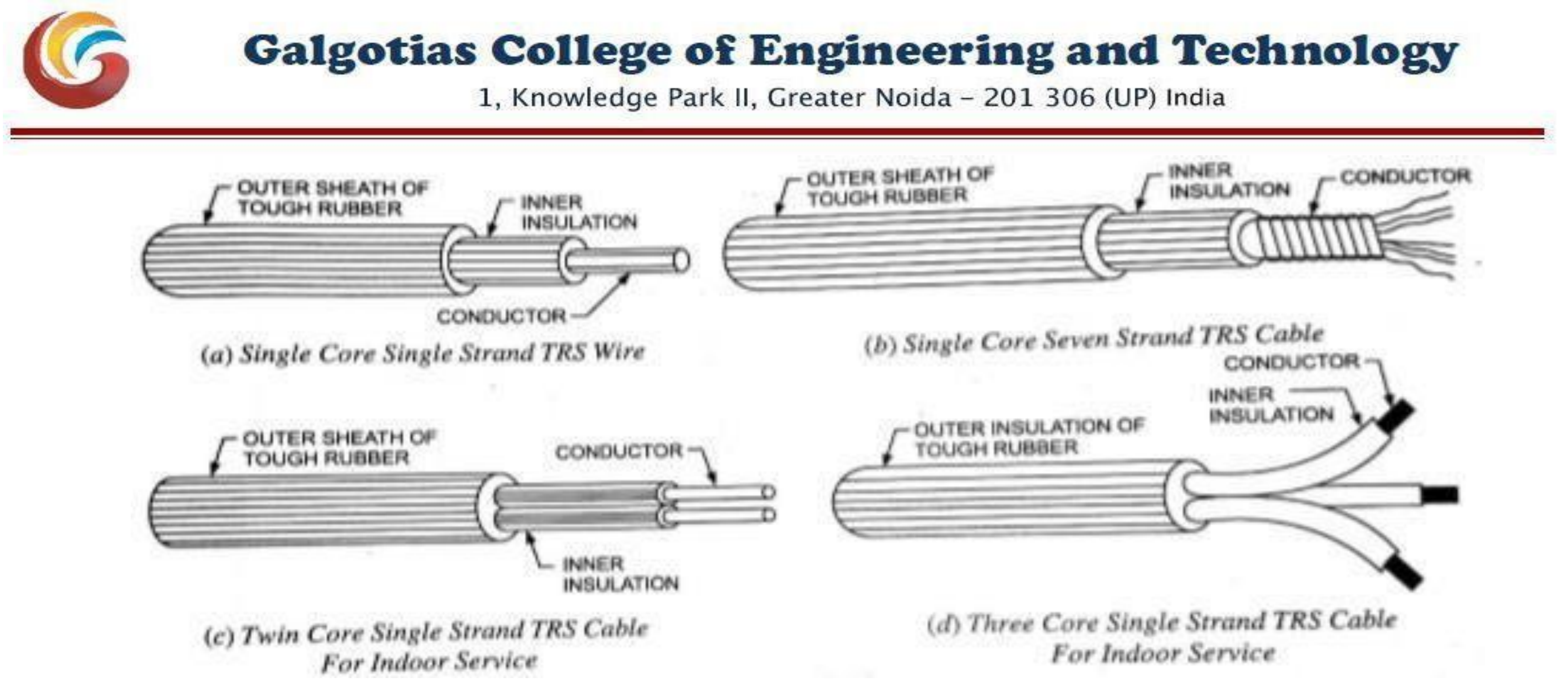
1. **Conductor Used:** According to conductor material used in the cables, these may be divided into two classes known as **copper conductor** cables and **aluminium conductor** cables.
2. **Number of Cores Used:** It may be divided into different classes known as: single core cables, twin core cables, three core cables, two core with ECC (Earth Continuity Conductor) cables etc.
3. **Voltage Grading:** According to voltage grading the cables may be divided into two classes (i) 250/440 Volt cables and (ii) 650/1100 volt cables
4. **Types of Insulation Used:** According to type of insulation the cables are of following types:
   - Vulcanized Indian Rubber (VIR) insulated cables
   - Tough Rubber Sheathed (TRS) or Cab Tyre Sheathed (CTS) cables.
   - Lead Sheathed Cables.
   - Polyvinyl Chloride (PVC) Cables.
   - Weatherproof cables.
   - Flexible cords and cables.
   - XLPE cables.
   - Multi-strand cables.

- **Vulcanized Indian Rubber (VIR) insulated cables:** VIR cables are available in 240/415 volts as well as in 650/1100 volt grades. VIR cables consists of either Tinned copper conductor Covered with a layer of VIR insulation. Over the rubber Insulation cotton tape sheathed Covering is provided with Moisture resistant compound bitumen wax or some other insulating material for making the cables moisture proof.

(a) Single Strand


(b) Seven Strand

Tough Rubber Sheathed (TRS) or Cab Tyre Sheathed (CTS) cables: These cables are available in 250/440 volt and 650/1100 volt grades and used in CTS (or TRS) wiring. TRS cable is nothing but a VIR conductor with an outer protective covering of tough rubber, which provides additional insulation and protection against wear and tear.



(a) *Single Core Single Strand TRS Wire*

(b) *Single Core Seven Strand TRS Cable*

(c) *Twin Core Single Strand TRS Cable For Indoor Service*

(d) *Three Core Single Strand TRS Cable For Indoor Service*

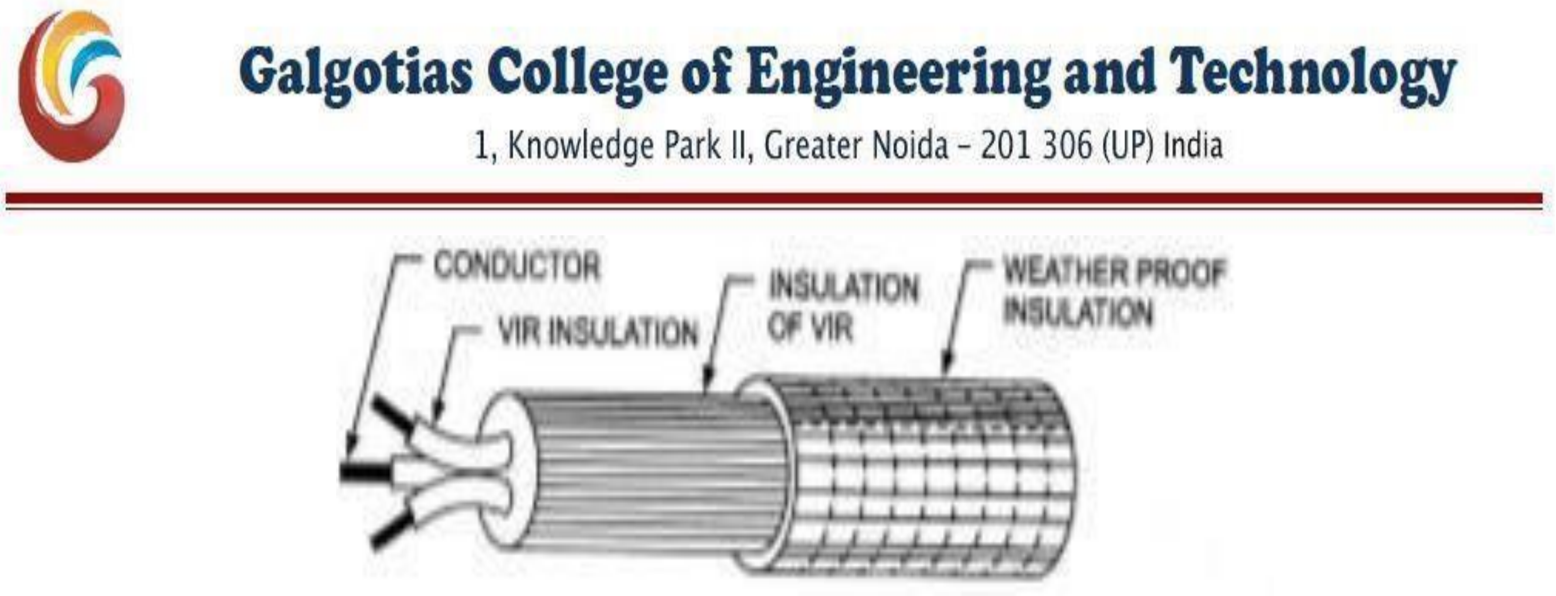
Lead Sheathed Cables: These cables are available in 240/415 volt grade. The lead sheathed cable is a vulcanized rubber insulated conductor covered with a continuous sheath of lead. The lead sheath provides very good protection against the absorption of moisture and sufficient protection against mechanical injury and so can be used without casing or conduit system.

Polyvinyl Chloride Insulated Cables: These cables are available in 250/440 volt and 650/1100 volt grades

- PVC insulation has better insulating qualities.
- PVC insulation provides better flexibility.
- PVC insulation has no chemical effect on metal of the wire.
- Thin layer of PVC insulation will provide the desired insulation level.
- PVC coated wire gives smaller diameter of cable and, therefore, more no. of wires can be accommodated in the conduit of a given size in comparison to VIR or CTS wires.

Weather Proof Cables:

i. These cables are used for outdoor wiring and for power supply or industrial supply
ii. These cables are either PVC insulated or vulcanized rubber insulated conductors being suitably taped braided and then compounded with weather resisting material.
iii. These cables are available in 240/415 volt and 650/1100 volt grades.



EARTHING

1. The main objective of earthing is to provide safety of operation.
2. Another objective of the earthing, though not widely used nowadays, is to save conducting material.

- **Methods of Earthing:** Earthing should be done in a way so that on a short circuit, the earth loop impedance is low enough to pass 3 times the current if fuses are used, and 1.5 times the current if MCBs are used. The metal work should be solidly earthed without using any switch or fuse in the circuit.

There are different types of earthing methods are used:

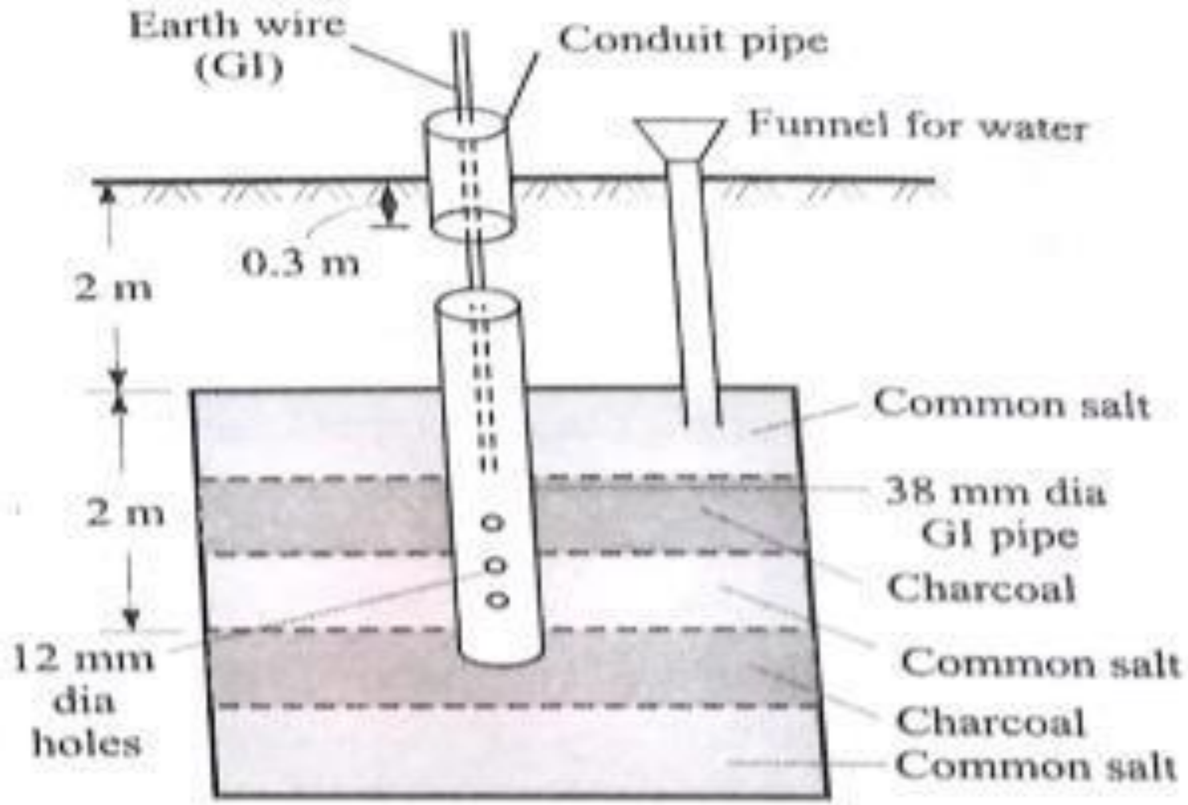
1. Strip or Wire Earthing.
2. Rod Earthing.
3. Pipe Earthing.
4. Plate Earthing.

Pipe and Plate Earthings are commonly used.

Strip or Wire Earthing: In this system of earthing, strip electrodes of cross section not less than 25 mm X 1.6 MM if of copper and 25 mm X 4 mm if of galvanized iron or steel are buried in horizontal trenches of minimum depth 0.5 metre. If round conductors are used

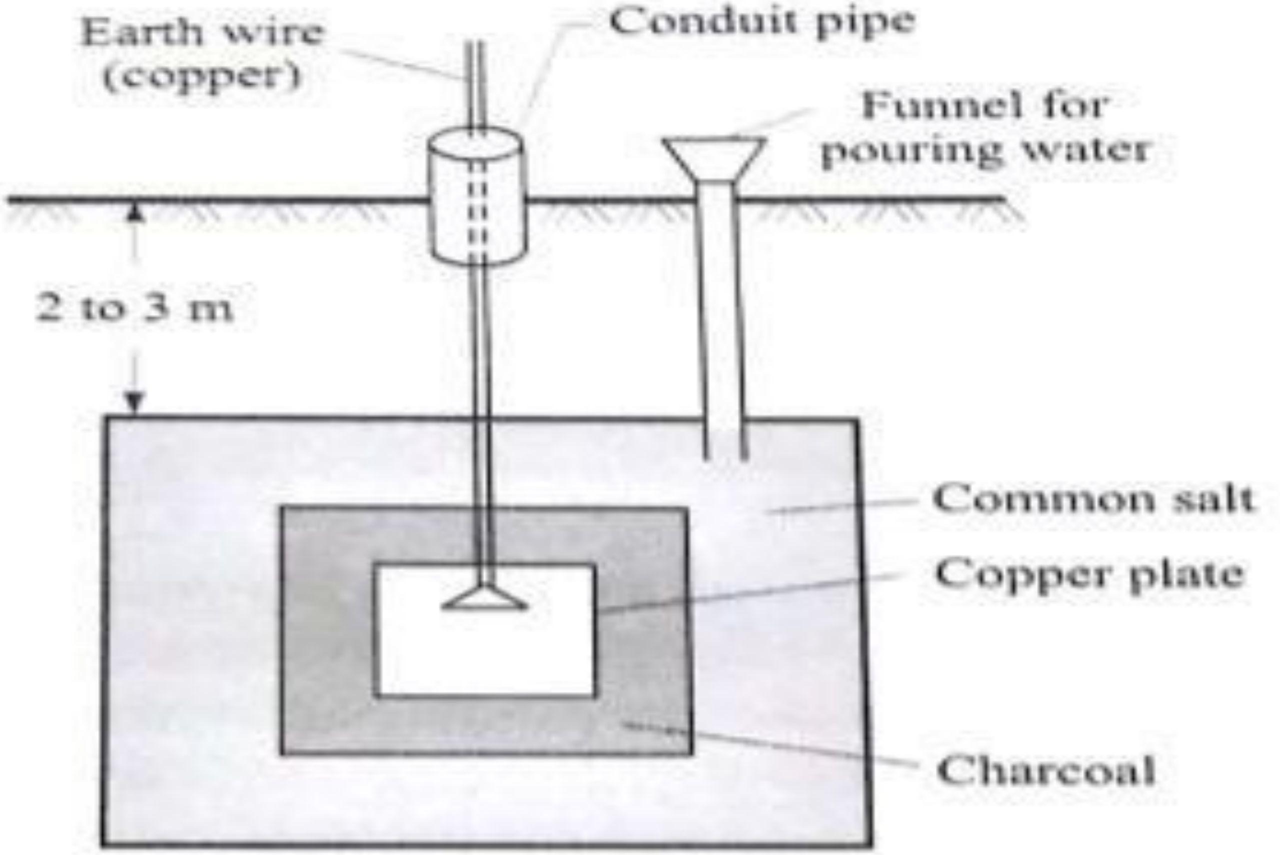
Rod Earthing: In this type of earthing, 12.5 mm diameter solid rods of copper or 16 mm diameter solid rods of galvanized iron or steel or hollow section 25 mm GI pipes of length not less than 2.5 metres are driven vertically into the earth either manually or by pneumatic hammer.

Pipe Earthing:



(*b*) Pipe earthing.

Plate Earthing:



(*a*) Plate earthing.

Batteries

Types of Batteries: There are two types of batteries which are given below:

Primary Battery

Secondary Battery

Important characteristics for Batteries:

Electrical Characteristics:

There are three important characteristics of an accumulator (or storage battery) namely,

- Voltage
- Capacity and
- Efficiency

Voltage: Average emf of cell is approximately 2.0 volts. The value of emf of a cell does not remain constant but varies with the change in specific gravity of electrolyte, temperature and the length of time since it was last charged.

Capacity: The quantity of electricity which a battery can deliver during single discharge until its terminal voltage falls to 1.8 V/cell is called the capacity of a battery.

$$Capacity\ of\ Battery\ or\ Cell = I_d T_d$$

1. **Efficiency:** The efficiency of the cell can be given in two ways:

1. ***The Quantity or Ampere – Hour (A-H) Efficiency:*** The ratio of output ampere-hour during discharging to the input ampere-hour during charging of the battery is called ***quantity or ampere-hour*** efficiency of the battery.

$$\eta AH = \frac{I_d T_d}{I_c T_c}$$

Where I_d=Discharging Current in Ampere

I_c=Charging Current in Ampere

T_d= Discharging Time of cell or battery in hours

T_c= Charging Time of cell or battery in hours

1. ***Energy or Watt – Hour (W-H) Efficiency:*** The ratio of output watt-hour during discharging to the input watt-hour during charging of the battery is called ***energy or watt-hour*** efficiency of the battery.

$$\eta WH = \frac{V_d I_d T_d}{V_c I_c T_c}$$

Where V_d= Average Terminal Voltage during Discharging

V_c=Average Terminal Voltage during Charging

I_d=Discharging Current in Ampere

I_c=Charging Current in Ampere

T_d= Discharging Time of cell or battery in hours

T_c= Charging Time of cell or battery in hours

AC CIRCUITS

BY- Dr R ISAAC

Mr M.A.NABI

Contents

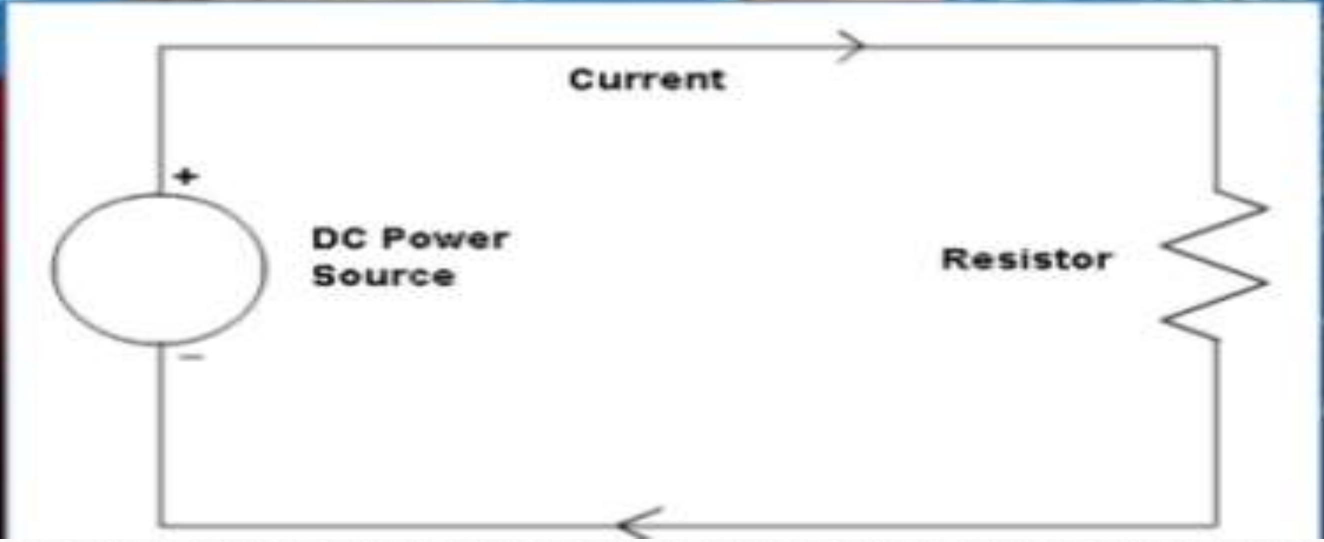
DC Circuits

- **Ohms Law**
- **Definitions of Node, Mesh**
- **KVL & KCL.**
- **Series R-L Circuits.**
- **Series R-C Circuits.**
- **Series R-L-C Circuits.**
- **Series Reasonance Circuit**

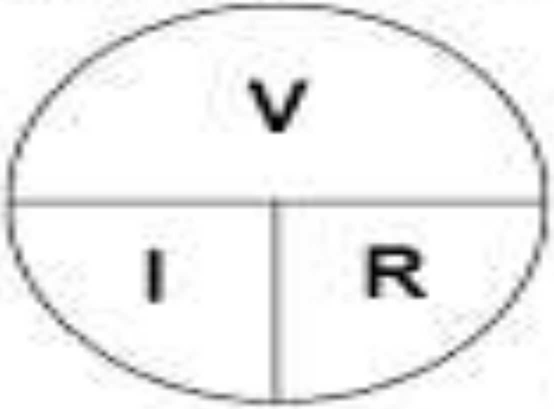
OHM'S LAW

OHM'S LAW

- One of the most fundamental law in electrical circuits relating voltage, current and resistance
- Developed in 1827 by German physicist **Georg Simon Ohm**



Ohm's Law Mnemonic



Definitions

Current: the number of electrons that go through a wire in one second

Voltage: the pressure that pushes the electrons

Resistance: the material property that makes it hard to push an electron through a wire

Power: the rate at which energy is used up. The more power, the brighter a light bulb.

$V = IR$

$R = V/I$

$I = V/R$

ELECTRICAL NETWORKS

PART
S

Node

- A junction in a circuit where two or more circuit elements and/or branches are connected together.

Branch

- Part of a network which lies netween two junctions.

Loop

- A closed path in a circuit in which no element or node is encountered more than once.

Mesh

- A loop that contains no other loop within it.

Resistor, Capacitor, and Inductor

- Resistor: the ability to resist the flow of electric current through it.
- Capacitor: the ability to oppose the change of voltage across it.
- Inductor: the ability to oppose the change of current flowing through it.

R,L,C in Series/Parallel

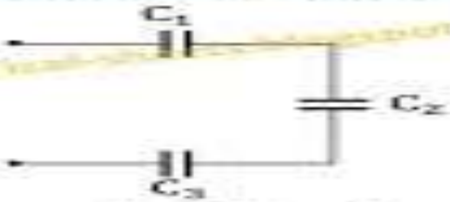
Resistors in Series

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

Resistors in Parallel

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

Capacitors in Series



$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Capacitors in Parallel

$$C_{eq} = C_1 + C_2 + C_3$$

Inductors in Series

$$L_{eq} = L_1 + L_2 + L_2$$

Inductors in Parallel

$$\frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3}$$

SERIES CIRCUITS

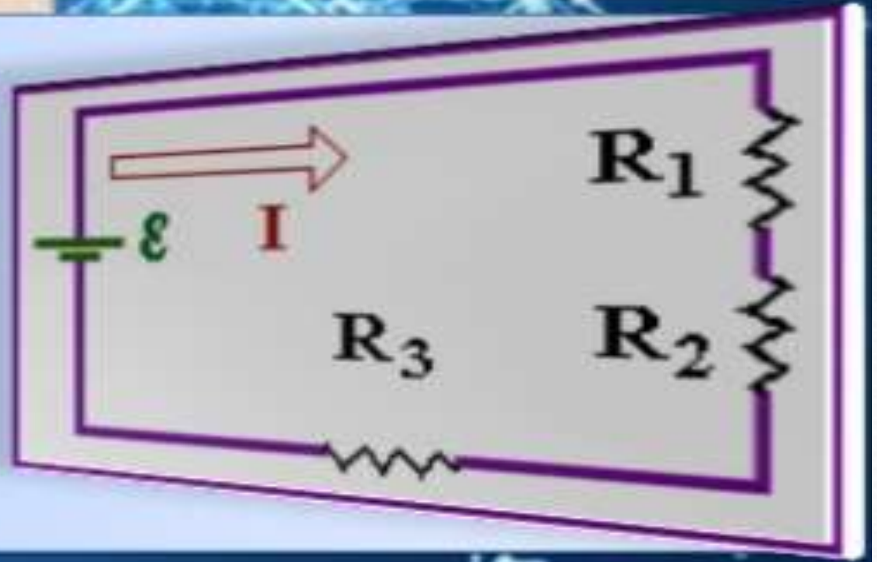
SERIES circuits

- A circuit connection in which the components are connected to form one conducting path

$$R_{equivalent} = R_1 + R_2 + R_3$$

$$V_{total} = V_1 + V_2 + V_3$$

$$I = I_1 = I_2 = I_3$$



PARALLEL CIRCUITS

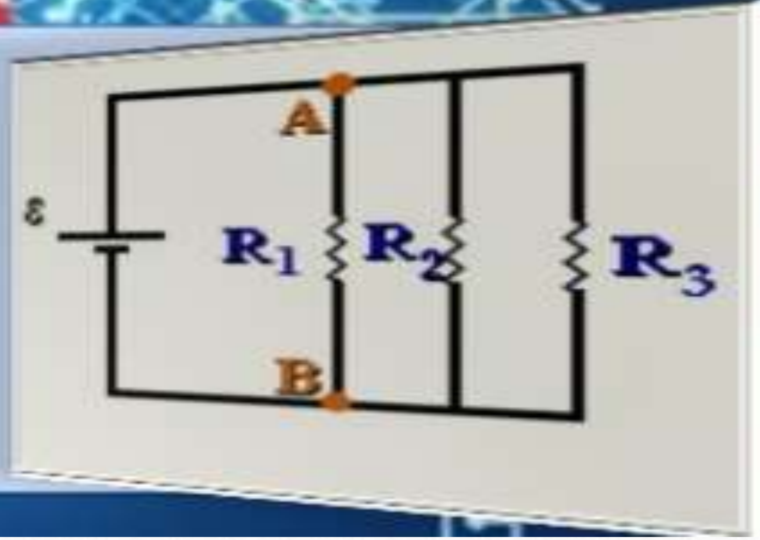
PARALLEL circuits

- A circuit connection in which the components are connected to form more than 1 conducting path

$$\frac{1}{R_{equivalent}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$V_1 = V_2 = V_3 = V$$

$$I = I_1 + I_2 + I_3$$



KIRCHHOFF'S LAW

KIRCHHOFF'S LAW

- More comprehensive than Ohm's Law and is used in solving electrical
- Termed as "Laws of Electric Networks"
- Formulated by German physicist **Gustav Robert Kirchhoff**

Kirchhoff's Current Law (KCL)

"In any electrical network, the algebraic sum of the current meeting at a point (or junction) is zero."

$$\sum I = 0$$

Clip slide

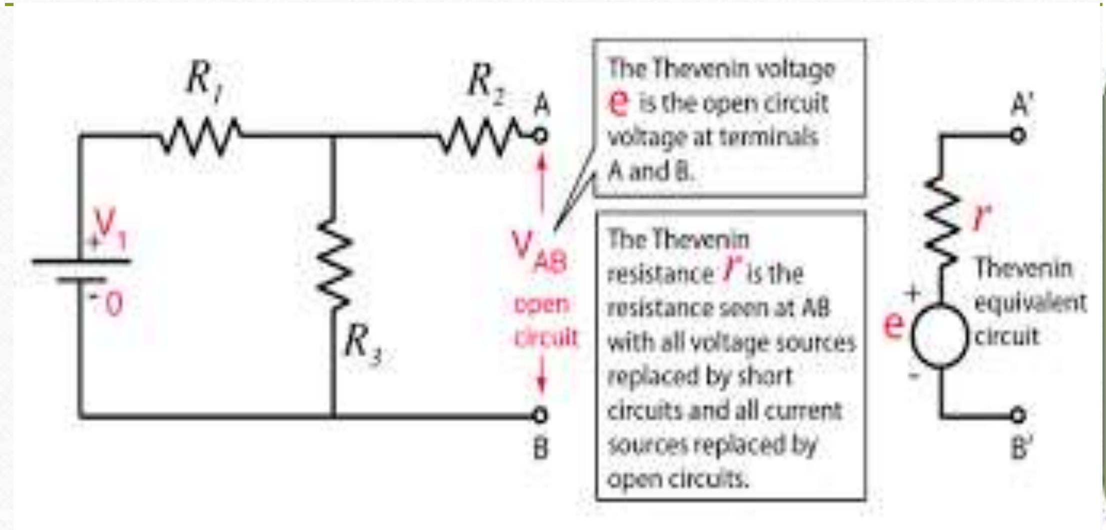
KIRCHHOFF'S VOLTAGE LAW

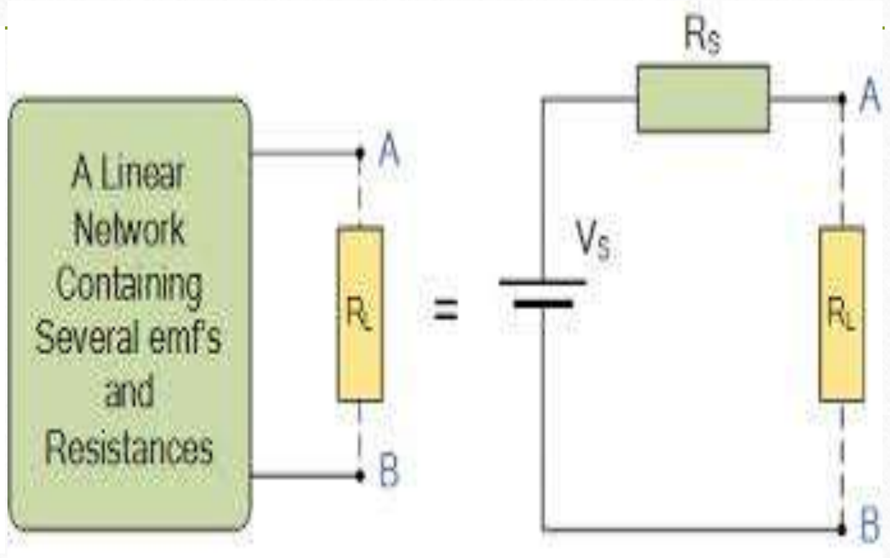
Kirchhoff's Voltage Law (KVL)

"The algebraic sum of the products of currents and resistances in each of thr conductors in any closed path (or mesh) in a network PLUS the algebraic sum of the emfs in the path is zero."

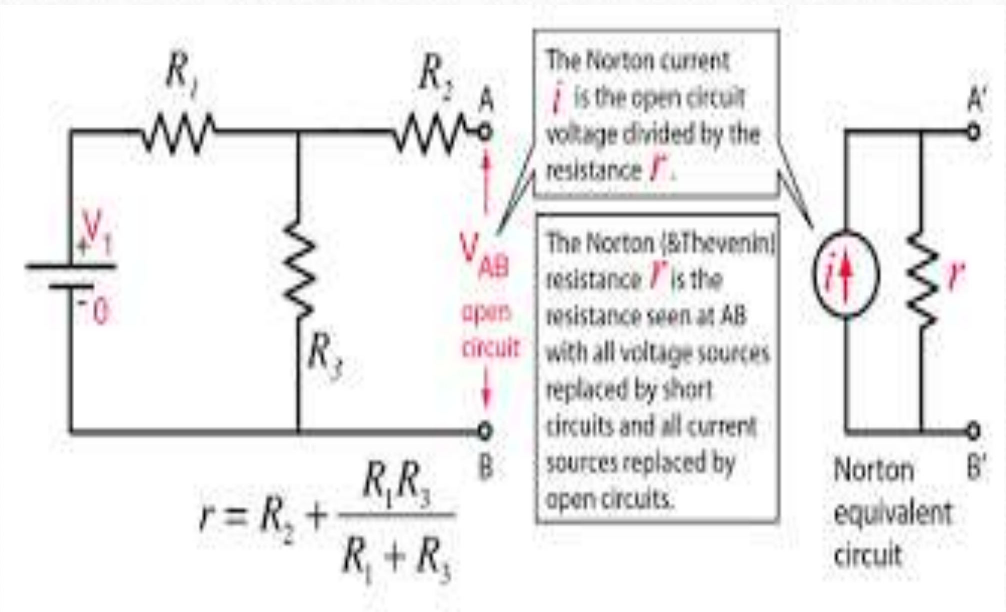
$$\sum V = 0$$

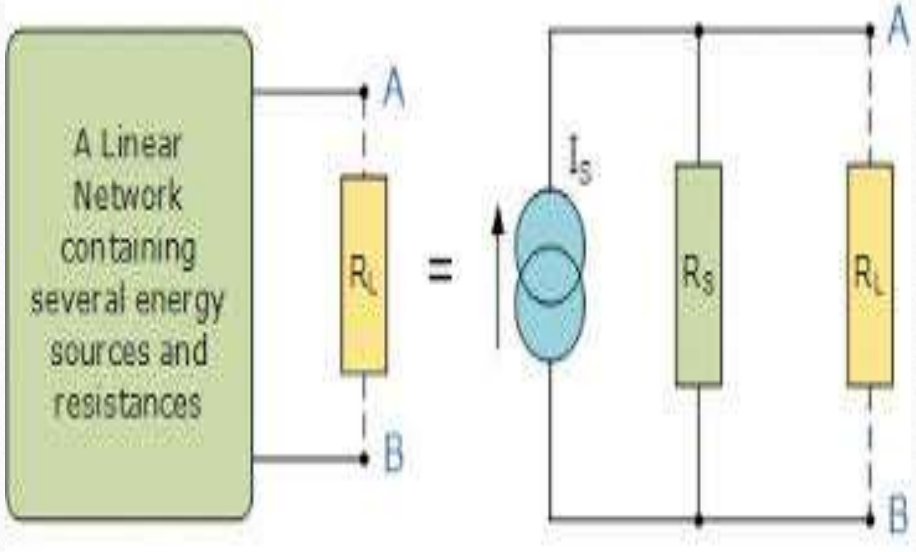
THEVENINS THEOREM





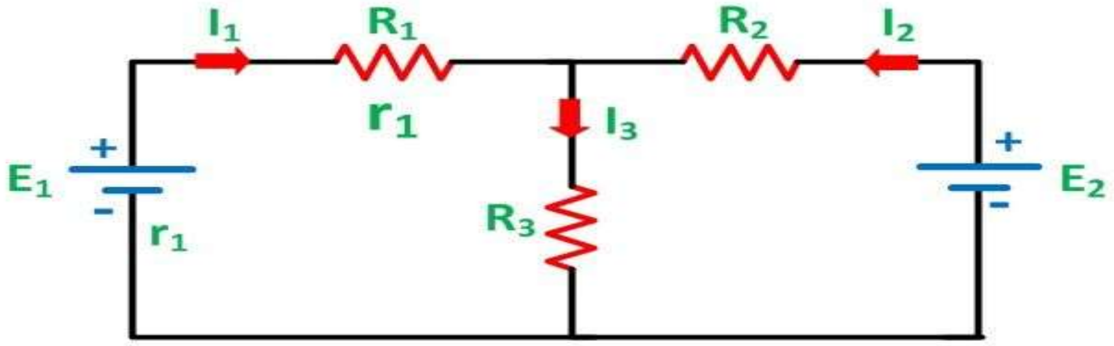
NORTONS THEOREM



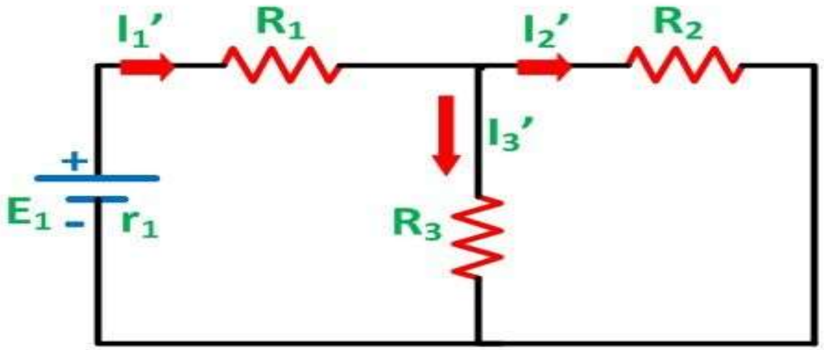


Superposition Theorem

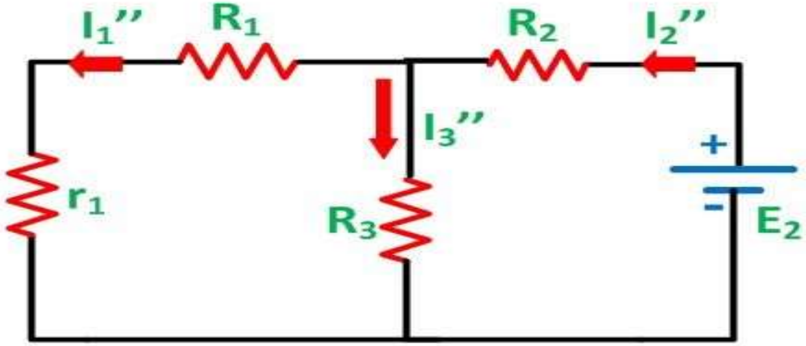
- The superposition theorem extends the use of Ohm's Law to circuits with multiple sources.
- ***Statement:-*** ***"The current through, or voltage across, an element in a linear bilateral network equal to the algebraic sum of the currents or voltages produced independently by each source."***
- Superposition theorem is very helpful in determining the voltage across an element or current through a branch when the circuit contains multiple number of voltage or current sources.



Circuit Diagram A

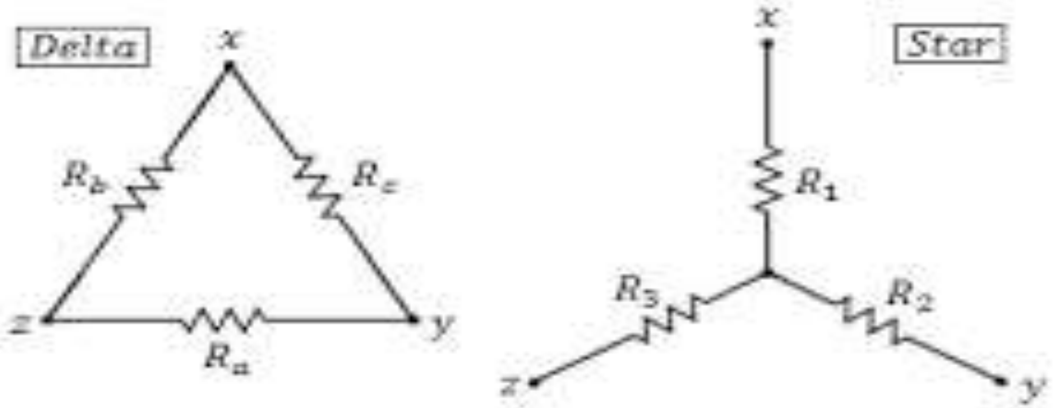


Circuit Diagram B



Circuit Diagram C

STAR TO DELTA



$$R_a = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_1}$$

$$R_b = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_2}$$

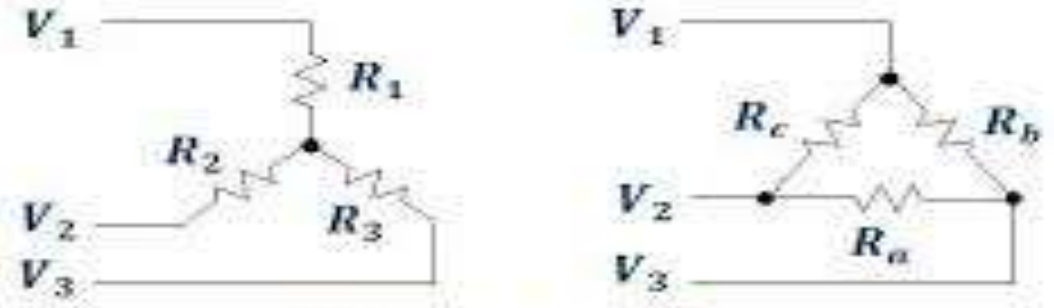
$$R_c = \frac{R_1R_2 + R_2R_3 + R_3R_1}{R_3}$$

$$R_1 = \frac{R_bR_c}{R_a + R_b + R_c}$$

$$R_2 = \frac{R_aR_c}{R_a + R_b + R_c}$$

$$R_3 = \frac{R_aR_b}{R_a + R_b + R_c}$$

Star to Delta (Y to Δ) Resistance Conversion Formula

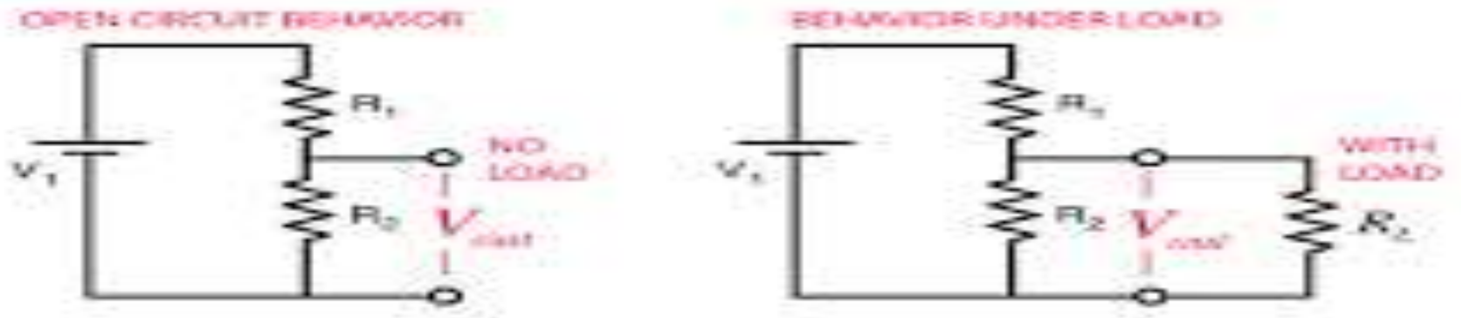


$$R_a = \frac{R_1R_2 + R_1R_3 + R_2R_3}{R_1}$$

$$R_b = \frac{R_1R_2 + R_1R_3 + R_2R_3}{R_2}$$

$$R_c = \frac{R_1R_2 + R_1R_3 + R_2R_3}{R_3}$$

Voltage Divison Formula



$$V_{out} = V_1 \frac{IR_2}{I(R_1 + R_2)} = \frac{V_1 R_2}{(R_1 + R_2)}$$

OUTPUT VOLTAGE UNDER "NO LOAD" CONDITION (open circuit)

OUTPUT VOLTAGE UNDER LOAD

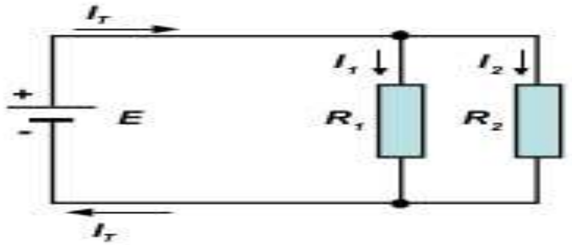
$$V_{out} = V_1 \frac{IR_2}{I(R_1 + R_2)} = \frac{V_1 (R_2 \parallel R_L)}{(R_1 + R_2 \parallel R_L)}$$

Current Division Formula

Current Divider Principle

In parallel circuits the current I_T divides up through the various branch networks, I_1, I_2.

The ratio between any two branch currents is the inverse ratio of the branch resistances.



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

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

This procedure is only suitable where there are two parallel branches.

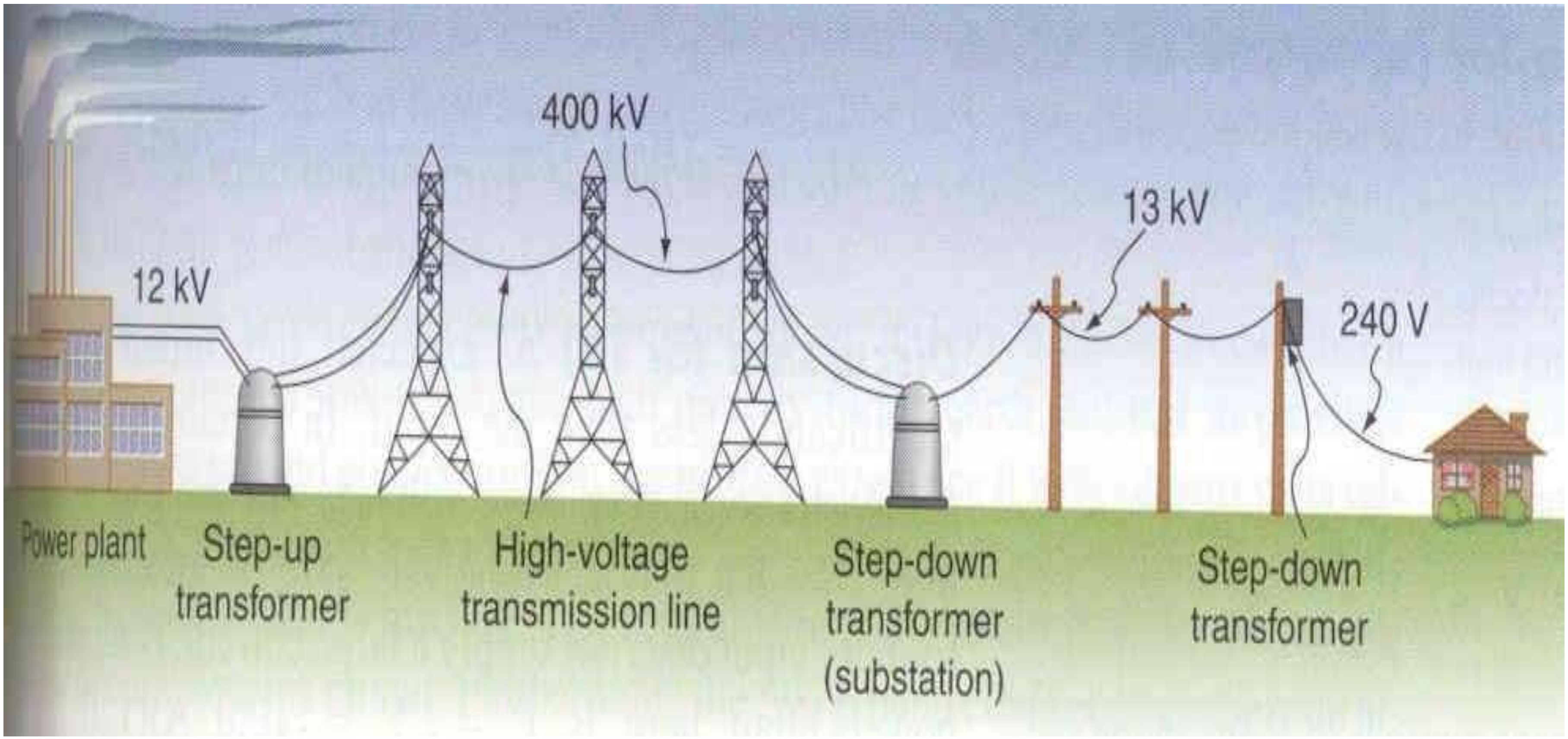
THANK U

Unit – III

TRANSFORMERS

BY- Dr R ISAAC
Mr M.A.NABI

Overview of Electrical Power System



SINGLE PHASE TRANSFORMER

INTRODUCTION

- A transformer is a static machine.

- The word “transformer” comes from the word “transform”.

- Transformer is not an energy conversion device, but is a device that changes AC electrical power at one voltage level into AC electrical power at another voltage level through the action of magnetic field, without a change in frequency.

- It can be used either to step-up or step-down Voltage at constant frequency

Working Principle of Transformers

- The transformer works on the principle of Mutual Induction between two magnetically coupled coils

- Is based on Faraday's laws of Electromagnetic Induction

Faradays Laws

1st law: Whenever magnetic flux linking with a coil changes with time an EMF is induced in that coil or whenever a moving conductor cuts the magnetic flux, an EMF is induced in the conductor.

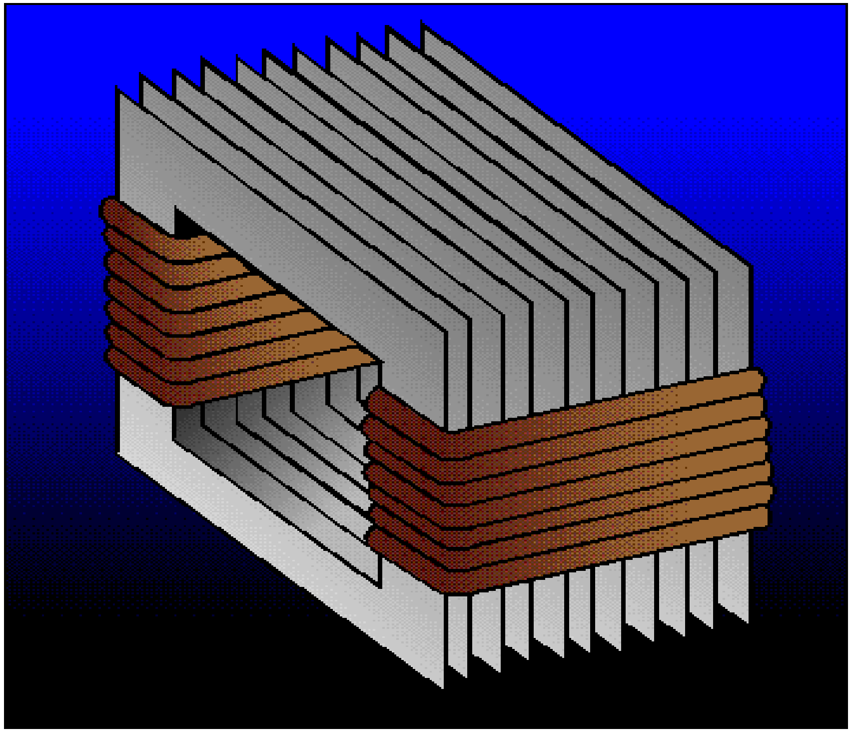
2nd law: The magnitude of the induced emf is equal to the product of the number of turns of the coil and the rate of change of flux linkage.

Lenz's Law

The direction of the induced EMF by electromagnetic induction is in a direction to oppose the main cause producing it.

What are the basic parts of a transformer?

Transformer Construction



The basic parts of a transformer are

- **Magnetic Core**
- **Windings** or **Coils**

Transformer Construction

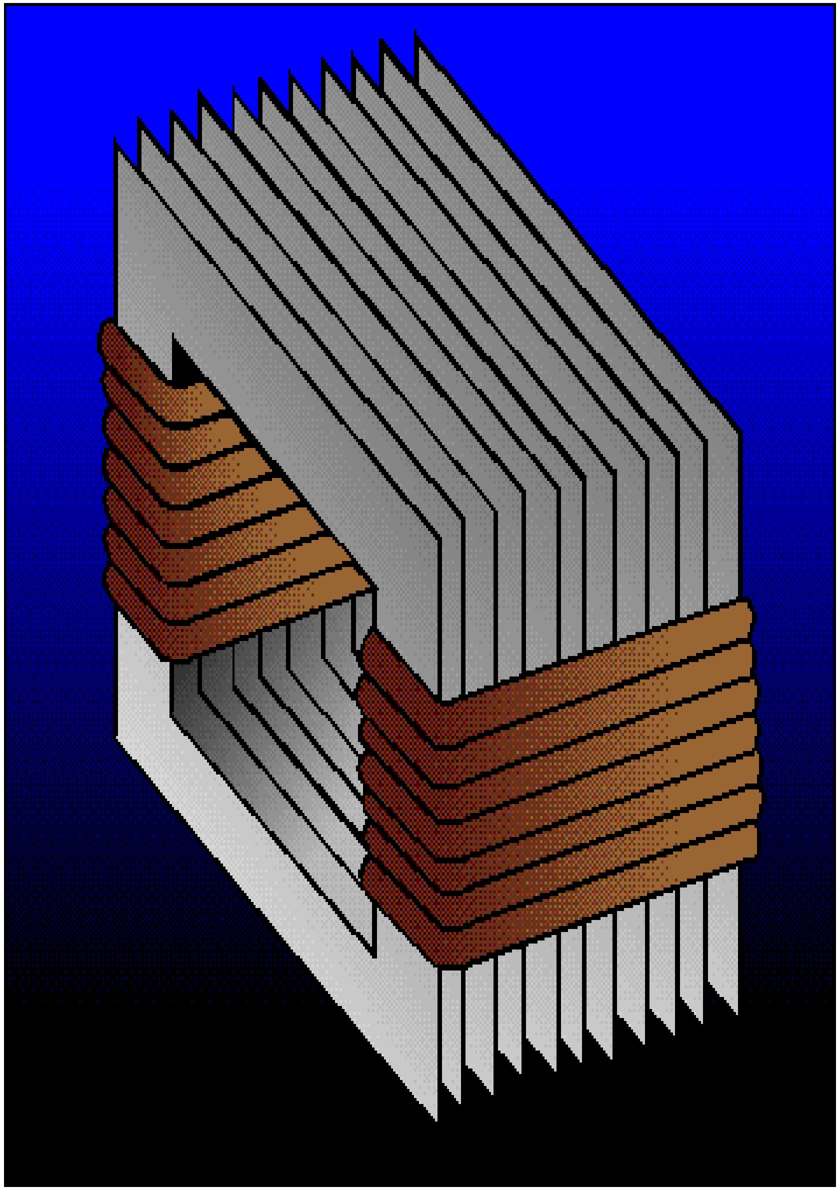
Magnetic Core consists of two parts

- **Limbs or legs**

  The vertical portion on which windings or coils are wound are called limbs

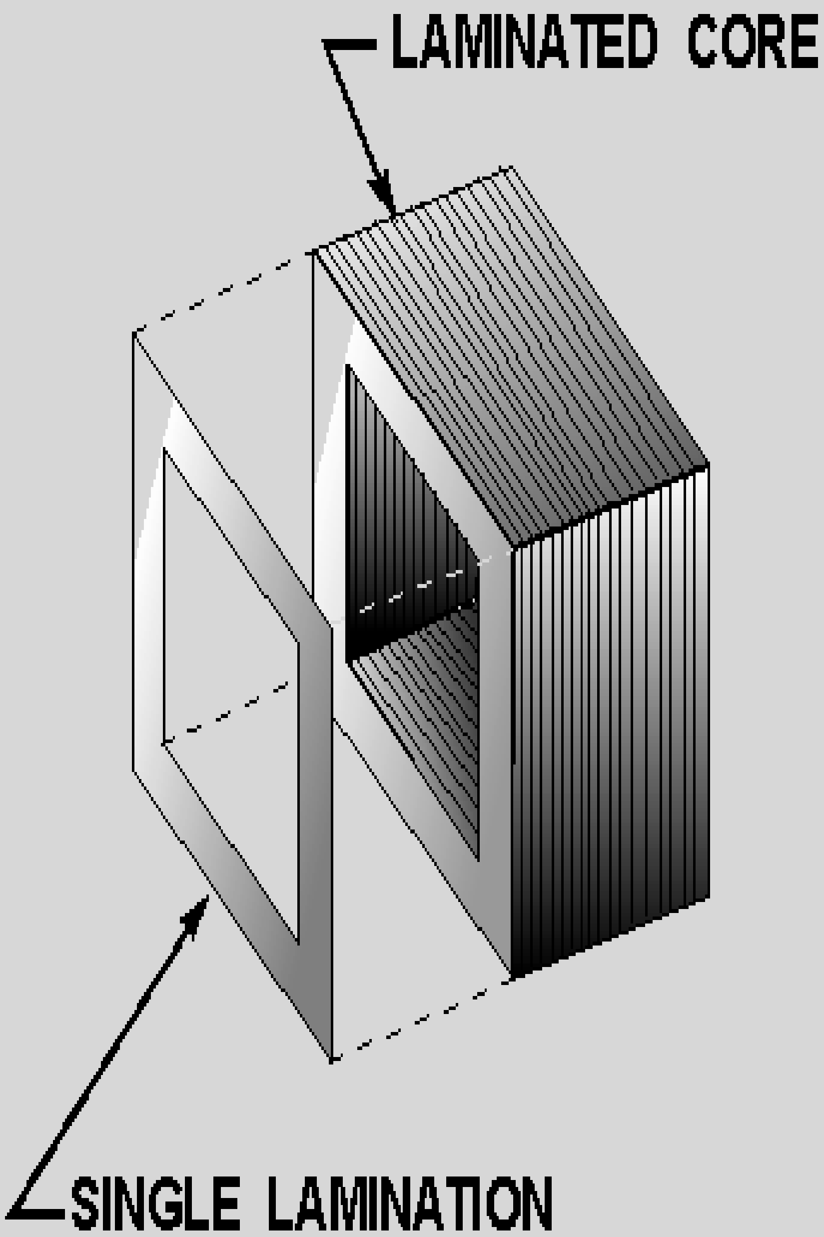
- **Yokes**

  The top and bottom horizontal portions are called as yokes of the core



Transformer construction

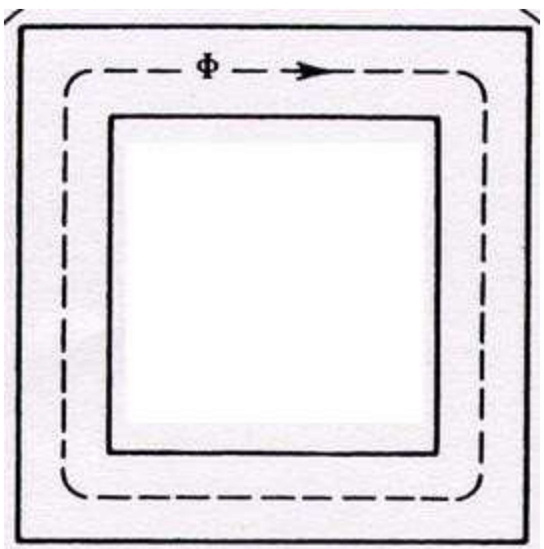
- In all types of transformers the core is made of steel having silicon content
- High silicon content reduces the hysteresis loss
- Core is laminated to reduce the eddy current losses
- Laminations are insulated from each other by light coat of varnish or by an oxide layer

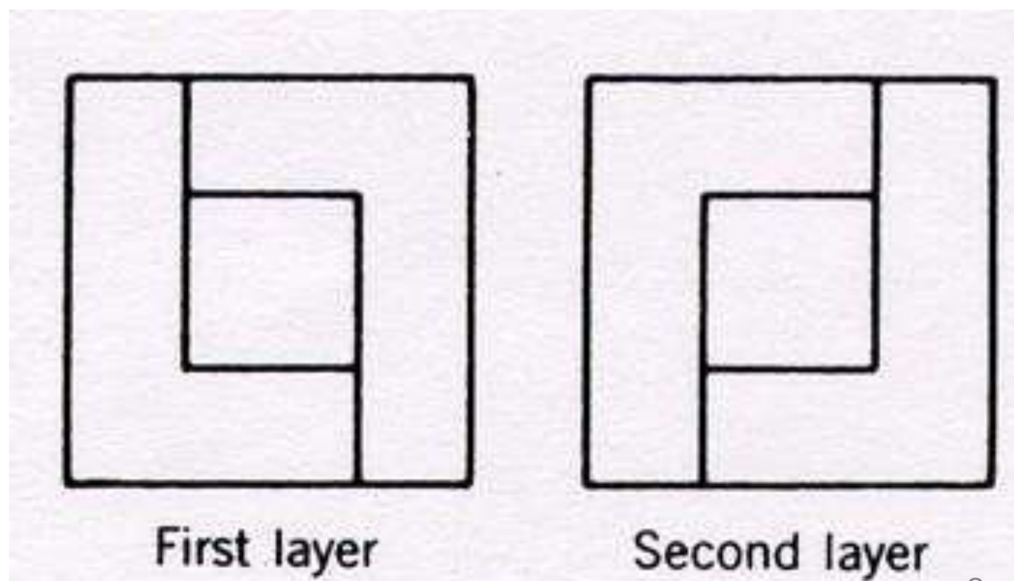


Magnetic Core(2 types)
1. Core type 2. Shell type

Core type

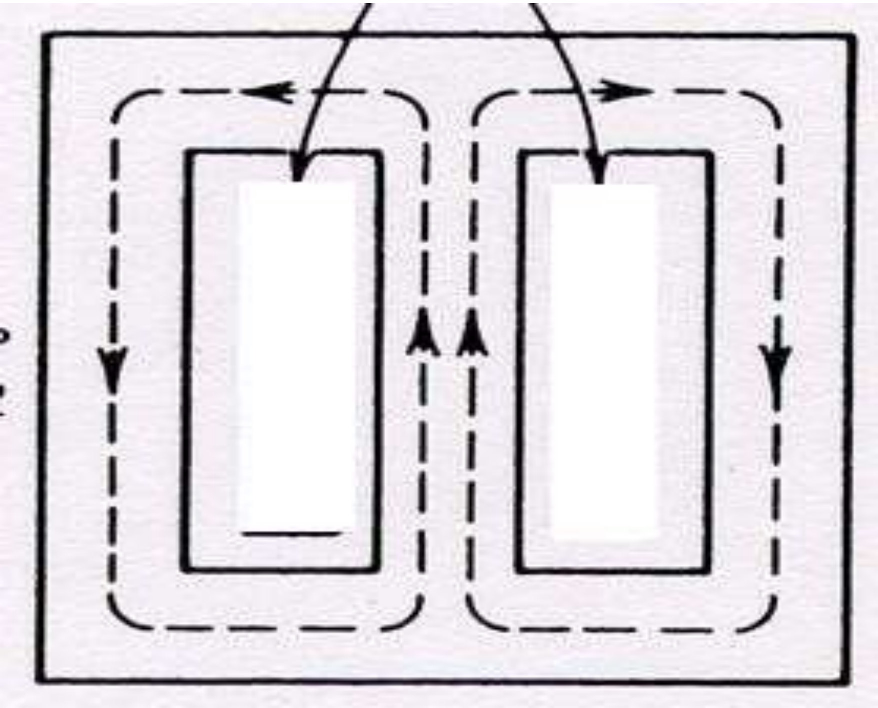
- The core is made up of silicon steel laminations which are either rectangular or L- shaped(0.3 - 0.5mm thick)

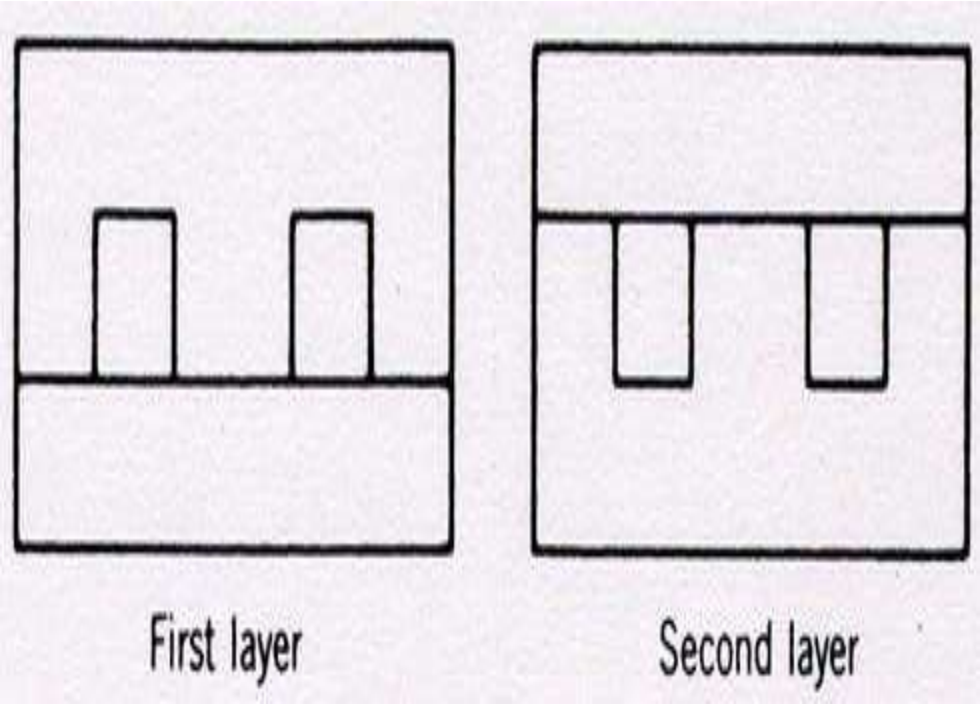




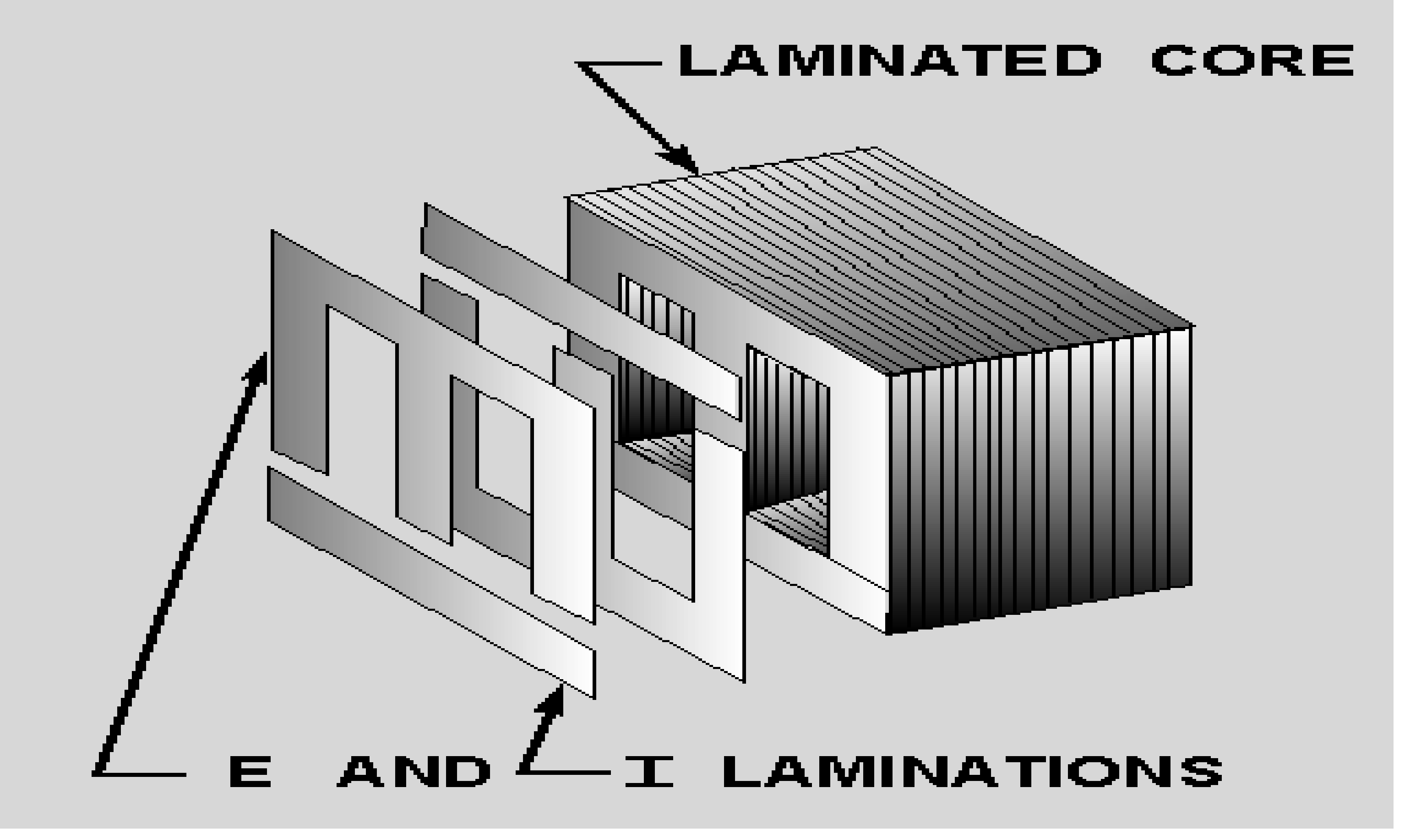
Shell type

- The core is made up of E-shaped or F- shaped laminations which are stacked to give a reactangular shape.

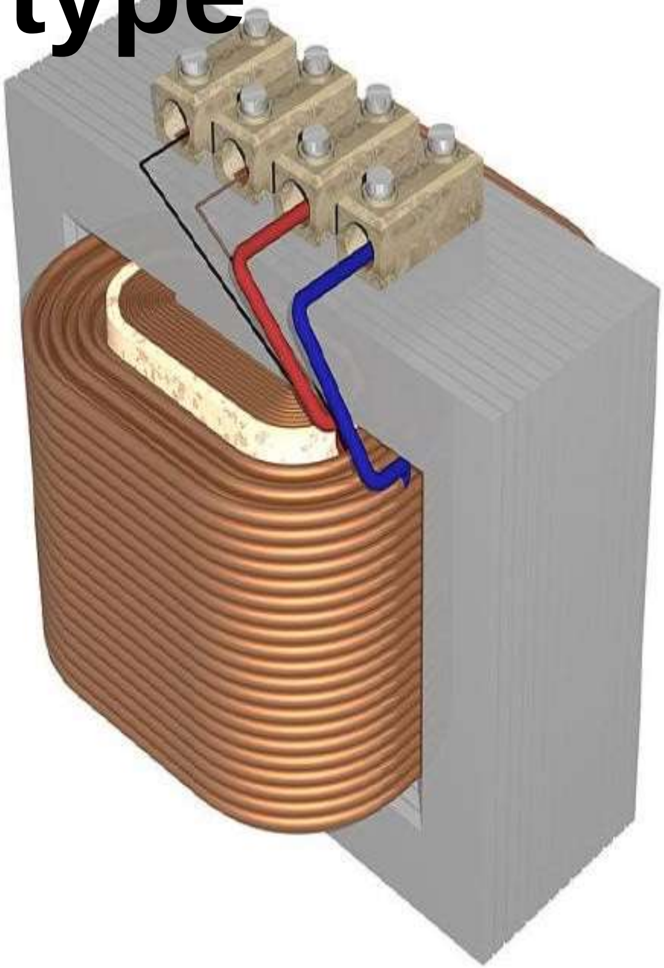




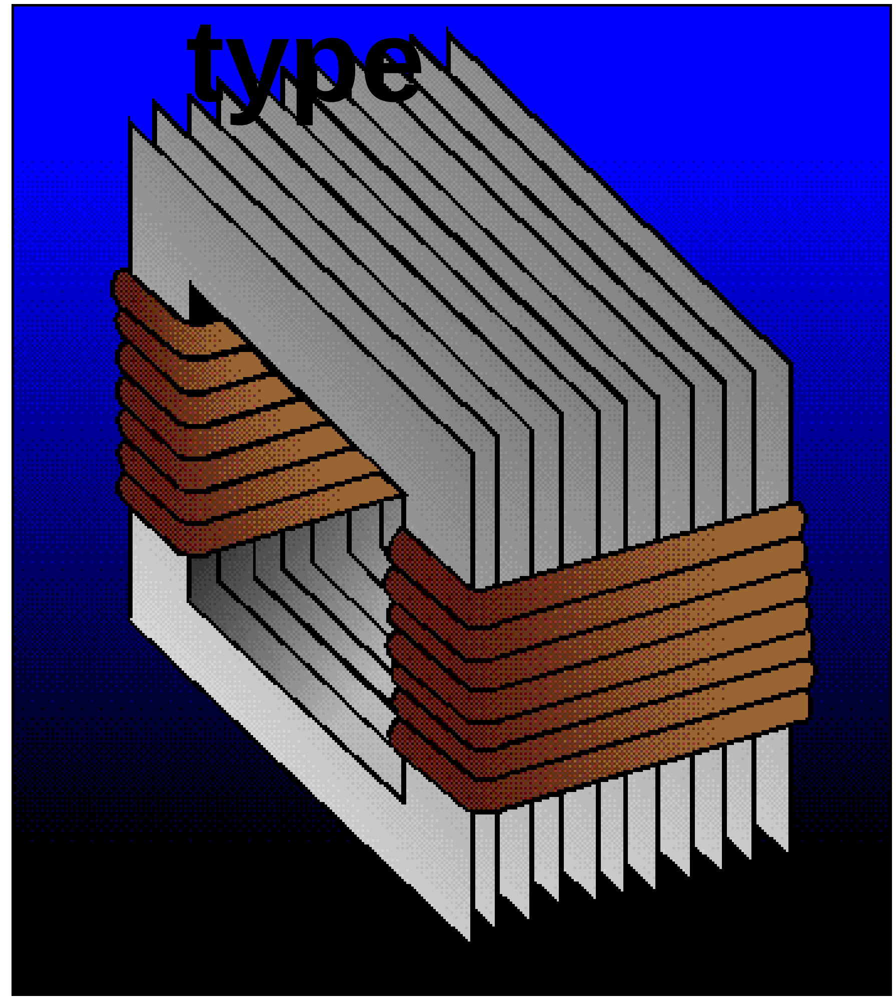
Shell



Shell type



Core type



Core type	Shell type
The winding encircles the core	The core encircles most part of winding
It has single magnetic circuit	Has double magnetic circuit
Cylindrical coils are used	Multilayer disc or sandwich type coils are used
Simple in design and permit easier assembly and Insulation of winding , also easier to dismantle for repair work	Assembly and repair work is difficult
winding of core type have poorer mechanical strength , because they are not braced or supported	winding are surrounded and braced by the core, hence have greater capability of withstanding forces produced under short ckt conditions.
Wdg are uniformly distributed on two limbs hence natural cooling is effective	Natural cooling is not effective as the wdgs are surrounded by core
Preferred for low voltage transformers	Preferred for high voltage transformers

Windings or Coils

- A single phase transformer may be designed with primary winding on one limb and secondary winding on the other limb. This arrangement results in a large separation between the primary and secondary winding s and large leakage reactance

- Hence each limb carries one half of primary winding & one half of secondary winding so that the two windings can be closely coupled to keep reactance low

- The low voltage winding is wound on the inside nearer to core while high voltage winding away from core to reduce the amount of insulating materials

Windings or Coils

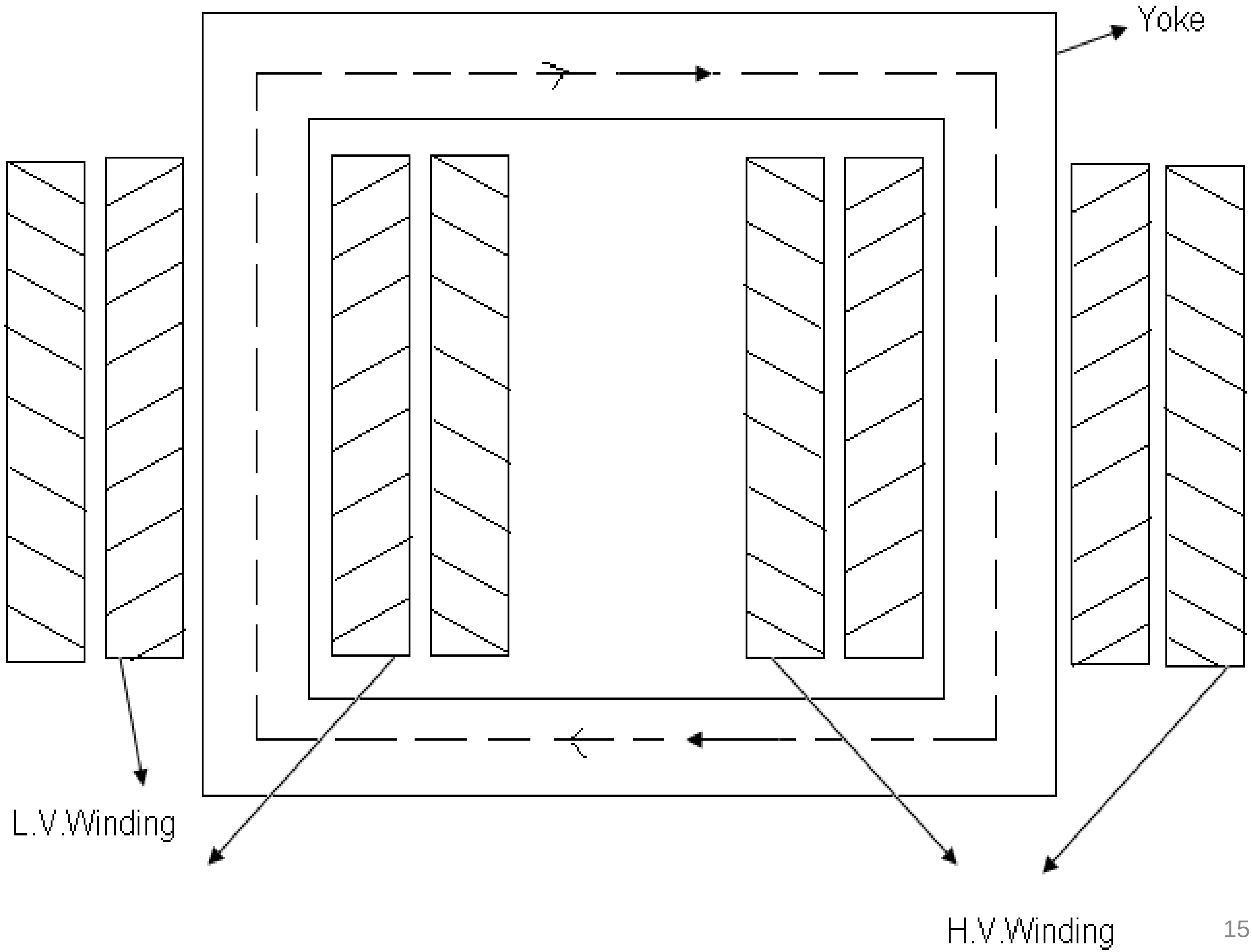
- Windings are of 2 types

  1. Concentric windings 2. Sandwich windings

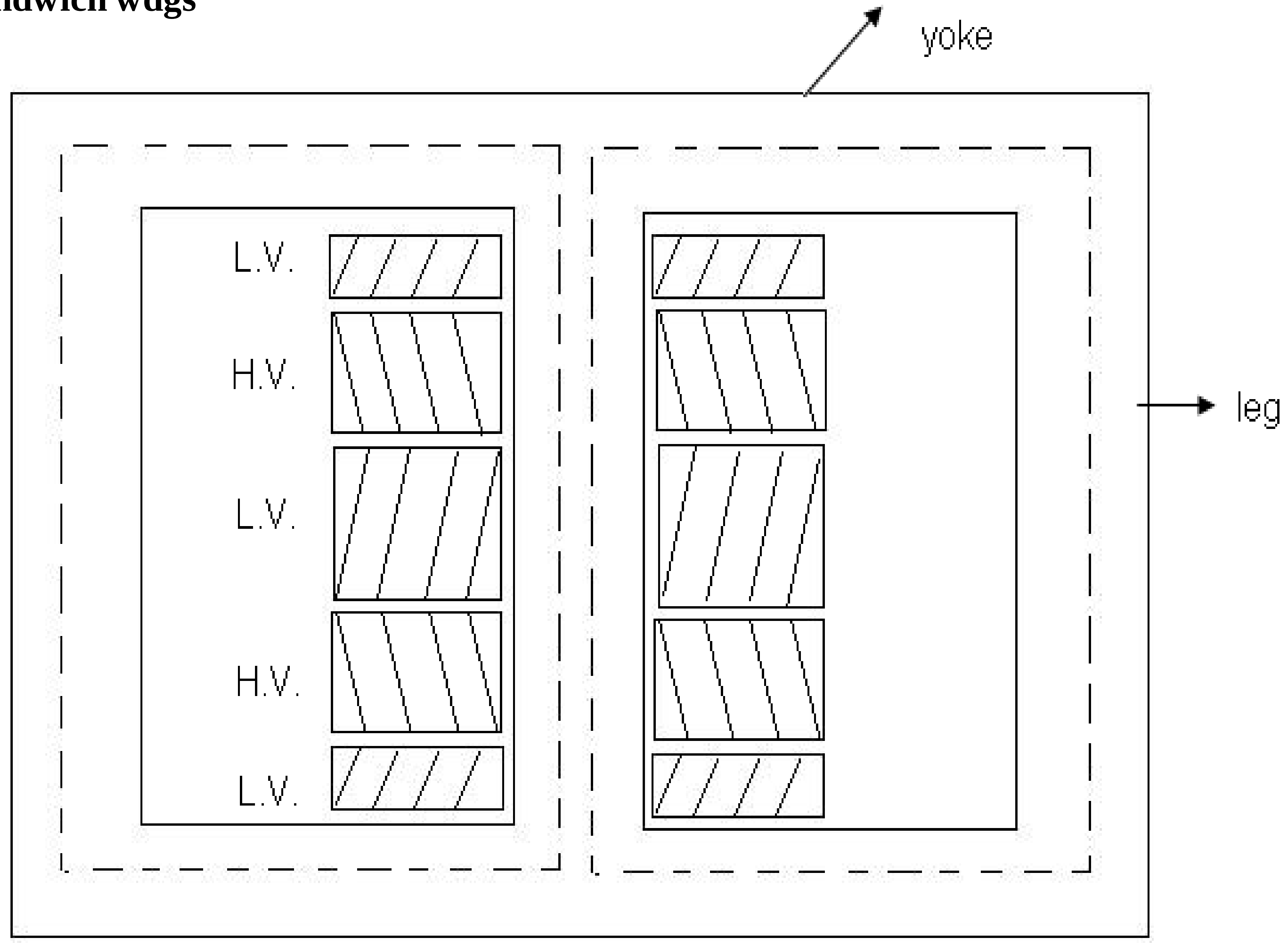
- Concentric winding are used for core type transformers

- Sandwich coils are used for shell type , both HV and LV sections are split into a number of sections . Each HV section lies between the LV sections

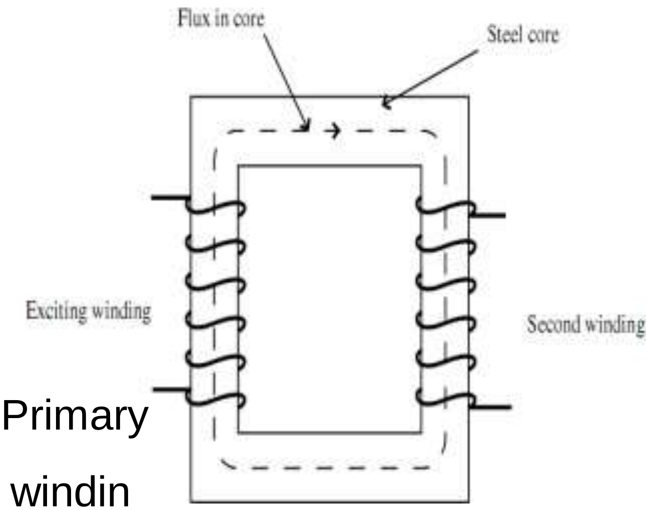
Concentric wdgs



Sandwich wdgs



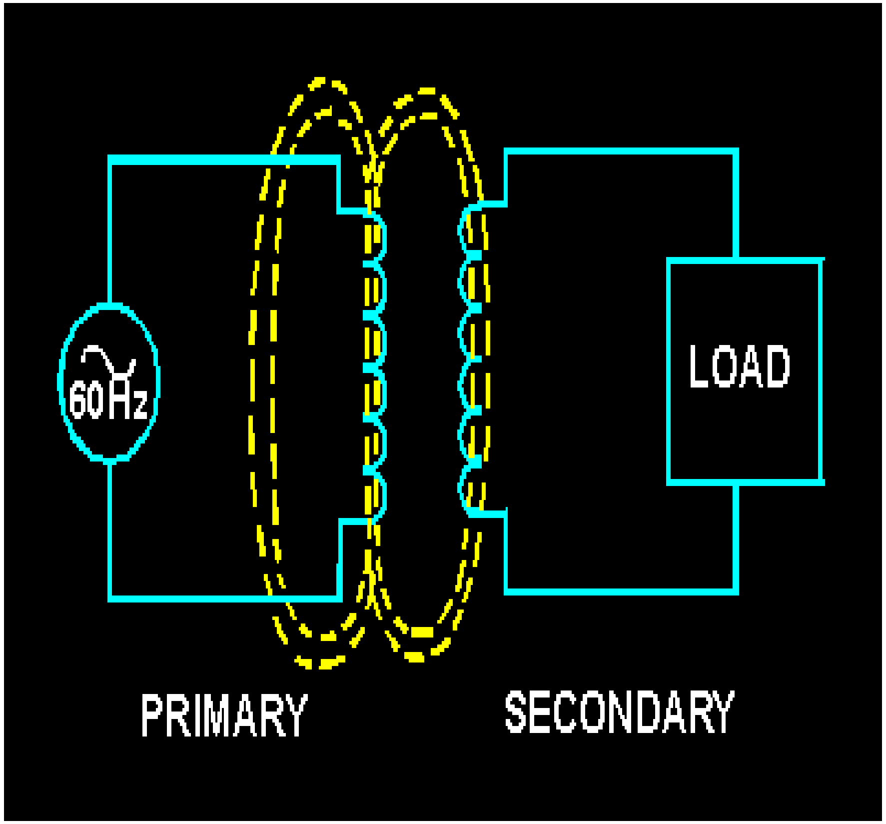
Transformer and its Operation



Primary winding

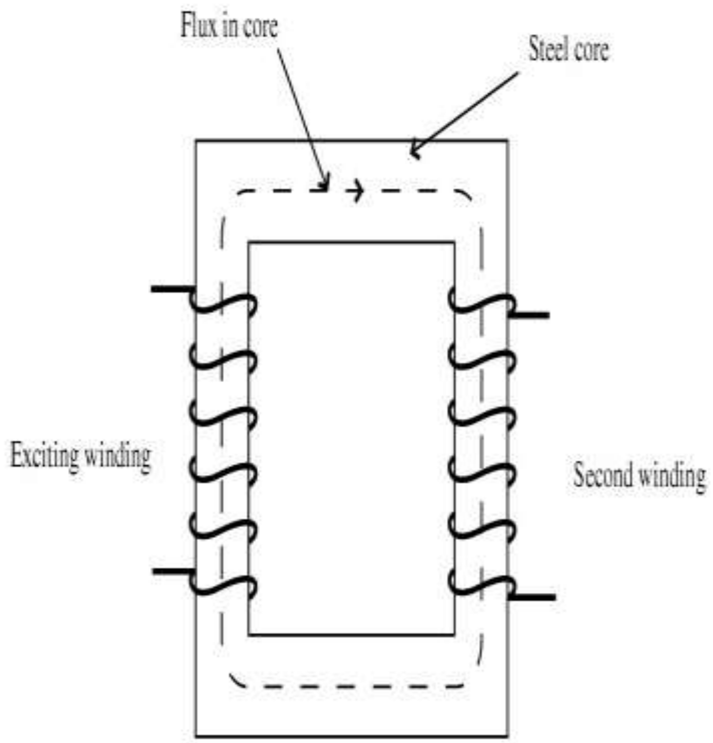
- No electrical connection is present between the two winding
- Magnetic linkage exists between the two windings
- The magnetic linkage is provided through a path of low reluctance with the help of core
- A transformer basically consists of two windings which are wound on a silicon steel core
- The winding which is connected to the supply mains is known as primary winding
- The winding which is connected to the load is known as secondary winding

Transformer and its Operation



- When primary winding is connected to AC supply mains a current flows through it
- This current produces an alternating flux in the core
- This flux links with primary winding and produces self induced emf in the primary winding which opposes the applied voltage (Lenz's law)

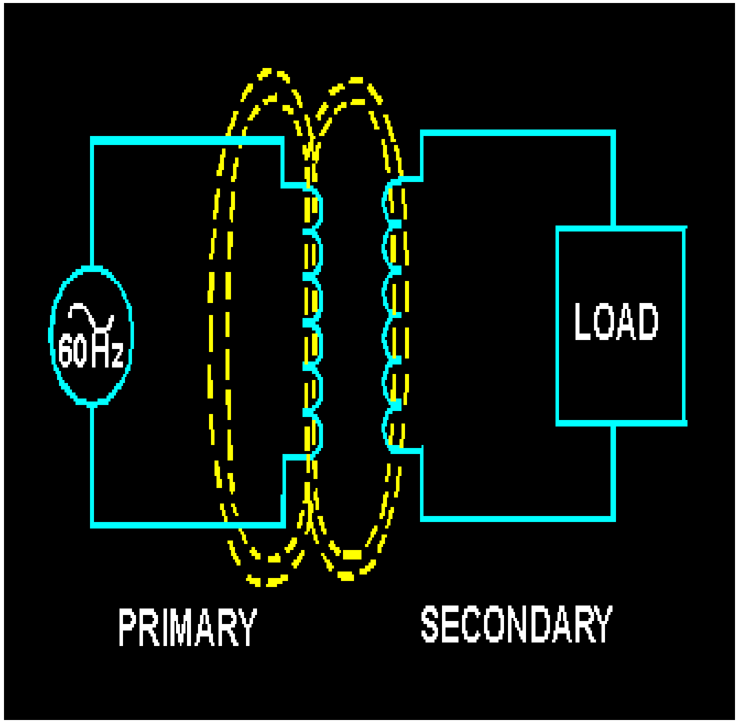
Transformer and its Operation



- This flux passes through the core and links with the secondary windings to induce an emf called mutually induced emf in the secondary winding

- The frequency of the emf induced in the secondary is same as that of the flux or that of the supply voltage

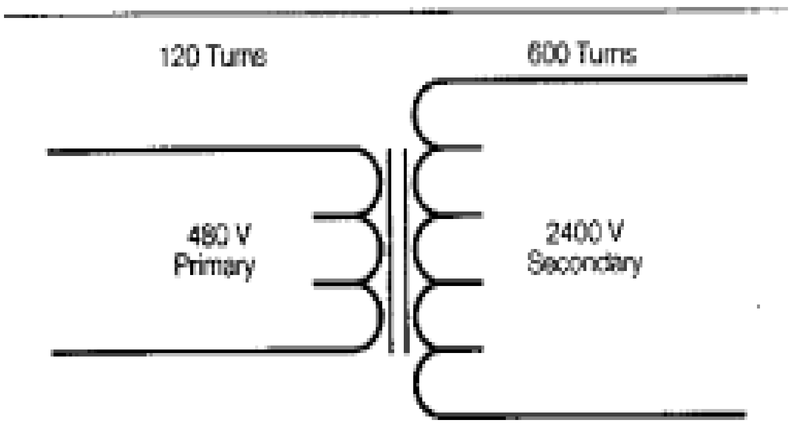
Transformer and its Operation



- The induced emf in the secondary winding will be able to circulate the current in the external load connected to it

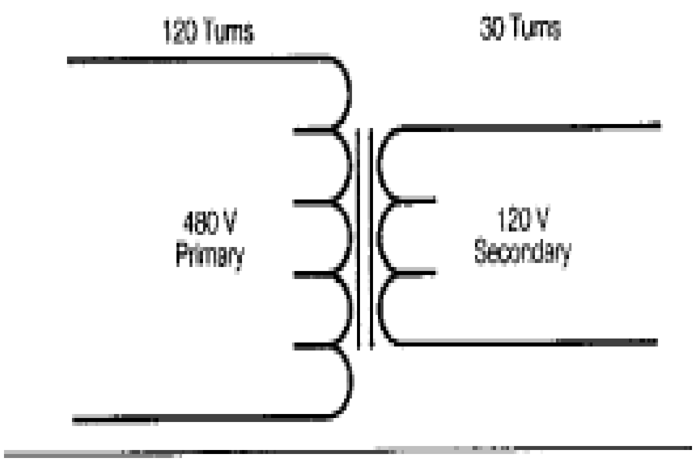
- Energy is transferred from primary winding to the secondary winding by electro-magnetic induction principle without change of frequency

Step up transformer



- When the transformer rises the voltage it is called step-up transformer
- In step up transformer the output voltage is higher than input voltage

Step down transformer



- When the transformer reduces the voltage it is called step-down transformer
- In step-down transformer the output voltage is less than input voltage

Theory of an Ideal Transformer

- An ideal transformer is one whose output is equal to the input i.e., loss free transformer
- Transformer is called an ideal transformer if it satisfies the following properties:

a) Has no iron losses i.e., hysteresis & eddy current losses in a transformer core are zero

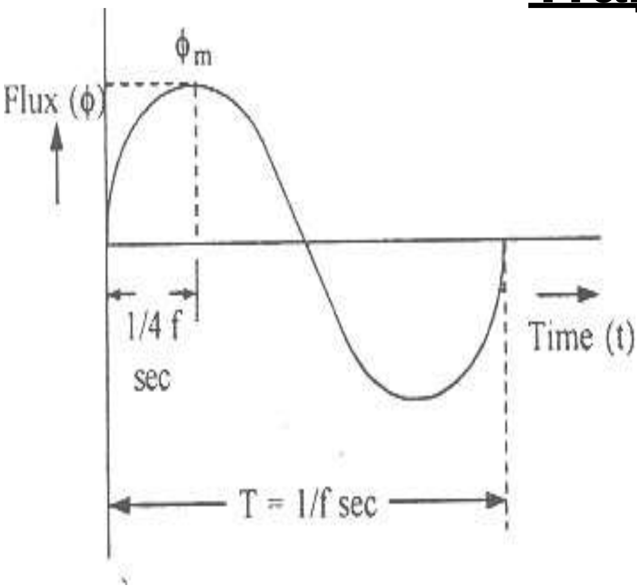
b) Windings have zero resistance i.e., there is no ohmic power loss and no resistive voltage drop

c) Leakage flux is zero i.e., 100 % flux produced by primary windings links with secondary windings

d) Permeability of core is high i.e., negligible current is required to establish flux

e) Efficiency is 100 % i.e., power output = power

E M F Equation of a Transformer



- Primary windings is excited with alternating current or AC supply
- This produces alternating flux and current as
shown in the fig.
- Let N_1 =Number of turns of primary winding

N_2 = Number of turns of secondary

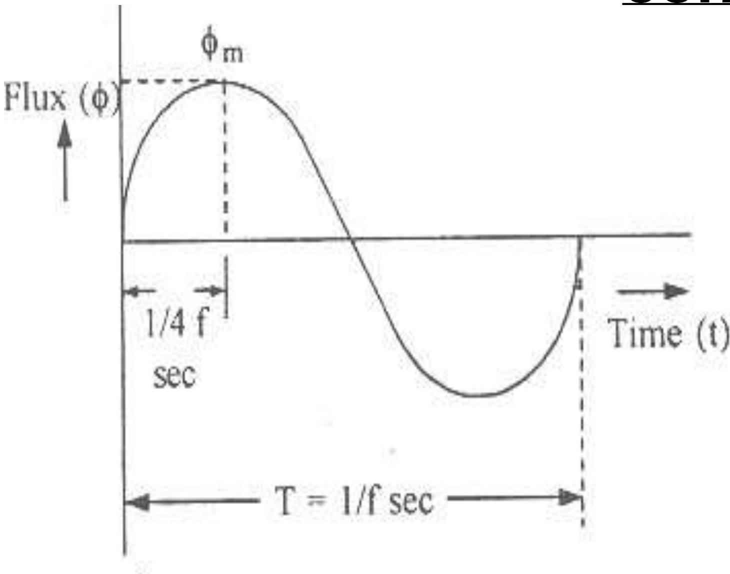
wdgs V_1 = Primary voltage

(applied voltage) V_2 =

Secondary voltage (load voltage)

E_1= Induced e.m.f.'s in primary windings (Volts)
E_2 = Induced e.m.f.'s in secondary windings
(Volts) $Ø_m$ = Maximum value of flux in the core in
Weber's

E M F Equation contd..



- As shown in fig. the flux increases from its zero value to maximum value $Ø_m$ in one quarter of the cycle i.e. in 1/4f seconds.

Average rate of change of flux $= dØ/dt$

$= Ø_m/(1/4f)$

$= 4fØ_m$ volt

According to faraday's laws of electromagnetic induction rate of change of flux means induced e.m.f in volts

Average e.m.f. per turn = $4fØ_m$ volt

Since flux varies sinusoidally

Form factor = RMS value/Average value

= 1.11

E M F Equation contd..

- RMS value of e.m.f. per turn = 1.11x4f$Ø_m$ volt

  = 4.44f$Ø_m$

- RMS value of induced e.m.f. in primary winding

  E_1 = N_1x4.44 f $Ø_m$ volt

  E_1 = 4.44 f $N_1Ø_m$ volt

  or

  E_1 = 4.44 f N_1B_mA volt

- Similarly RMS value of induced e.m.f. in secondary winding

  E_2 = 4.44 f $N_2Ø_m$ volt

  or

  E_2 = 4.44 f N_2B_mA volt

Transformation Ratio

- **Voltage Transformation ratio (K):** The ratio of secondary voltage to primary voltage is known as Transformation ratio. It is represented by the letter K

$$K = V_2/V_1$$

In an Ideal Transformer

$V_1=E_1$

$V_2=E_2$

hence voltage ratio $V_2 / V_1 = E_2 / E_1$

$= 4.44fN_2Ø_m/4.44fN_1Ø_m$

$= N_2/N_1$

therefore $K = V_2/V_1 = E_2/E_1 = N_2/N_1$

- If V2 > V1 or N2 > N1 , then K > 1 then the transformer is called STEP-UP transformer
- If $V_2 < V_1$ or $N_2 < N_1$, then K < 1 then the transformer is called STEP-DOWN transformer

Transformation ratio cond….

- In an IDEAL transformer losses are negligible hence OUTPUT = INPUT

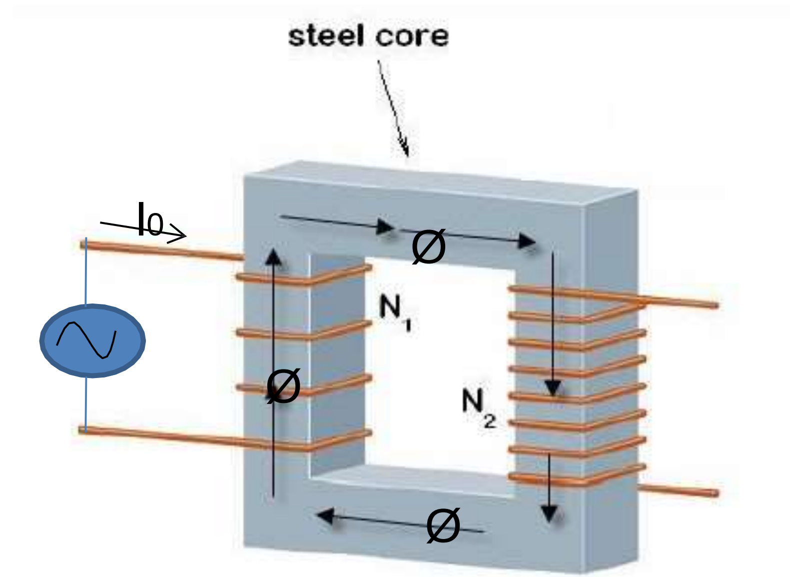
$$V_2 I_2 = V_1 I_1$$

i.e.

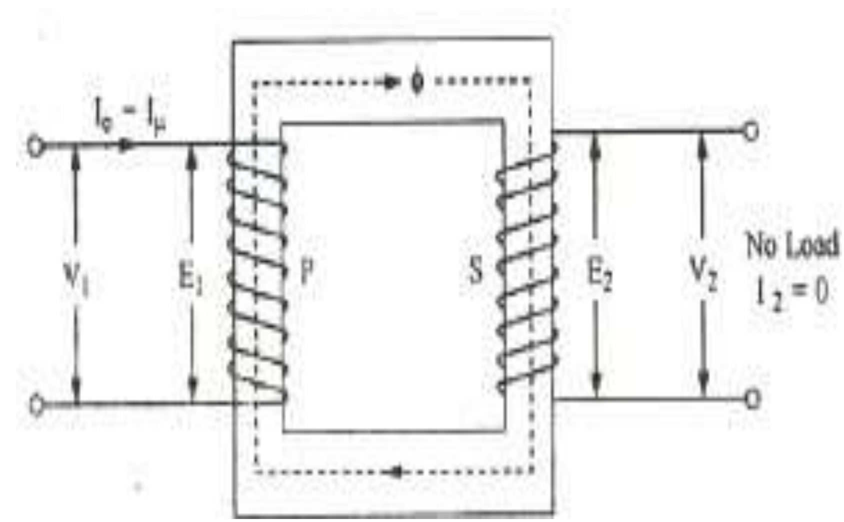
$$E_2/E_1 = V_2/V_1 = N_2/N_1 = I_1/I_2 = K$$

Ideal transformer on No load

- Consider an ideal transformer as shown in the figure.



- Let the primary Supply voltage be V_1
- As there is no load the secondary current $I_2 = 0$ (i.e., secondary is open circuit)



- A small current flows on primary side which produces flux
- As windings are purely reactive this current I_o lags V_1 by 90^0.
- I_o current has two components

Ideal transformer on No load contd…

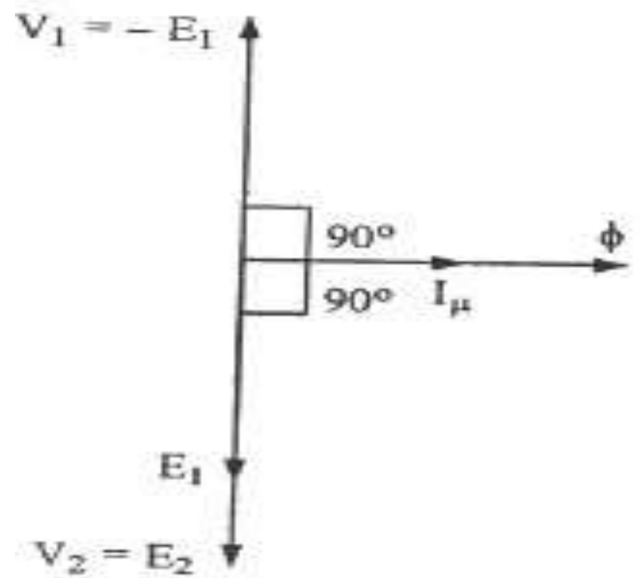
- The no-load component of current which magnetizes the core is called magnetizing current Iµ

- There is also another component of current called the core loss component I_c or I_w used to supply core loss

- So the No-load current of a transformer is the
vector or phasor sum of Iµ and I_c

- The magnetizing current Iµ is always in phase with the flux Ø

- The varying flux is linked with both the windings and so induces e.m.f in both primary winding E_1 & Secondary winding E_2, E_1 & E_2 will lag behind the flux by 90^0



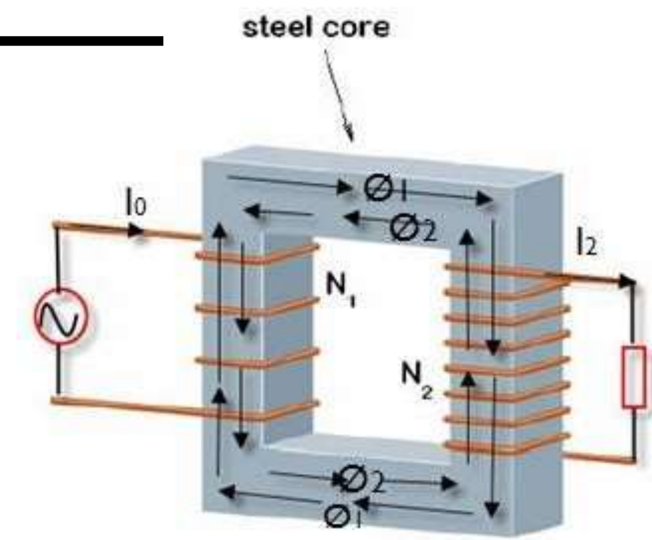
Ideal transformer on No load contd…

- The e.m.f's E_1 & E_2 are in phase with each other

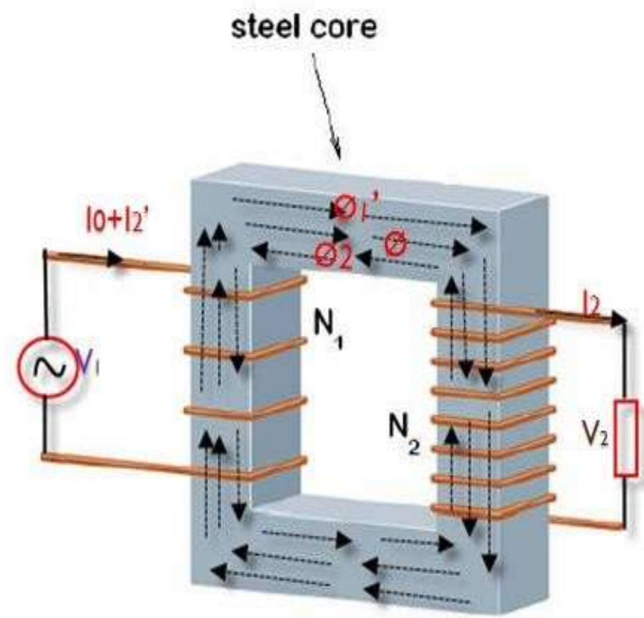
- Magnitude of induced e.m.f in the primary winding E_1 will be approximately equal but opposite to applied voltage V_1 and is known as counter e.m.f or back e.m.f. and $E_2=V_2$

Ideal transformer On Load

- When transformer is loaded, the secondary current I_2 is set up. The I_2 current sets up its own flux $Ø_2$ opposing the main primary flux $Ø_1$ as shown in figure



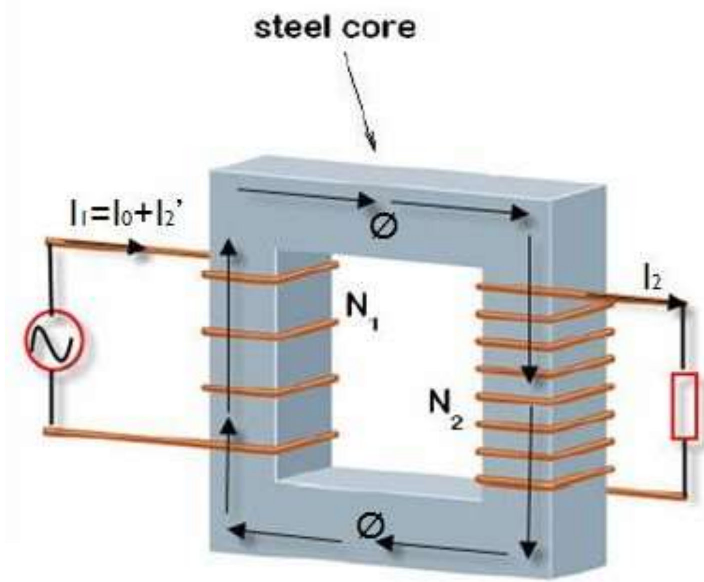
- When the secondary flux opposes the primary flux, the reduction in the net flux in the core causes to draw an extra current from the supply known as load component of primary current I_2'



- The additional primary mmf (N_1I_2') set up a flux $Ø_2$' which is equal and opposite to $Ø_2$ as shown in fig

Ideal transformer On Load

Since $\varnothing_2 = \varnothing_2'$, the net flux in the core is, therefore, the same as at no-load flux i.e, Ø as shown in figure



Therefore , $I_1=I_0+I_2'$

- Since $\varnothing_2 = \varnothing_2'$

Secondary mmf = Additional primary mmf

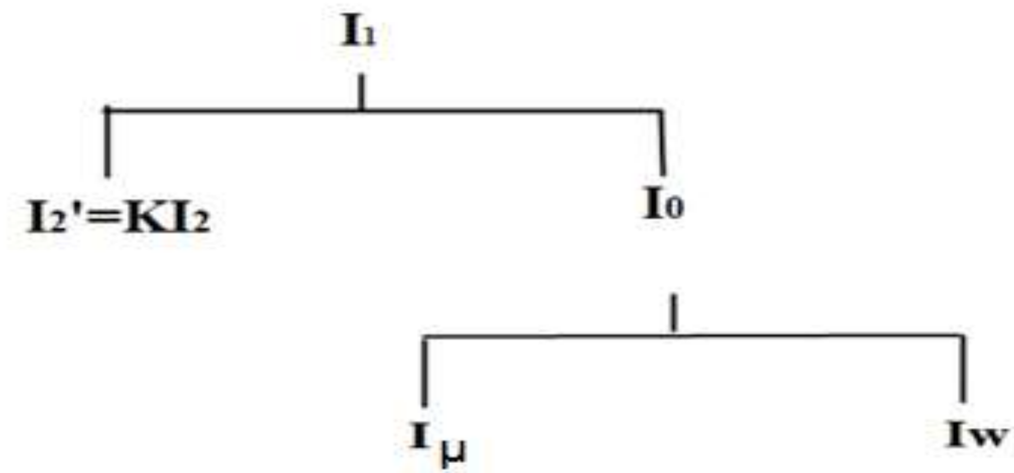
$N_2 I_2 = N_1 I_2'$ — Since the reluctance for the two windings is same

$I_2' = (N_2/N_1) I_2$

$I_2' = K\, I_2$

$\bar{I}_1 = \bar{I}_0 + \bar{I}_2'$

The total primary current I_1 is the vector sum of I_0 and I_2' as shown below:



Where

I_2' - is the load component of primary current

I_0 - no-load current

$I\mu$ - the magnetizing or wattless component of no-load current

I_w - the working or active or iron loss component of no-load current

Practical Transformers

Factors Need to be Considered

The ideal transformer is not a sufficiently accurate model for all purposes. A better model should include:

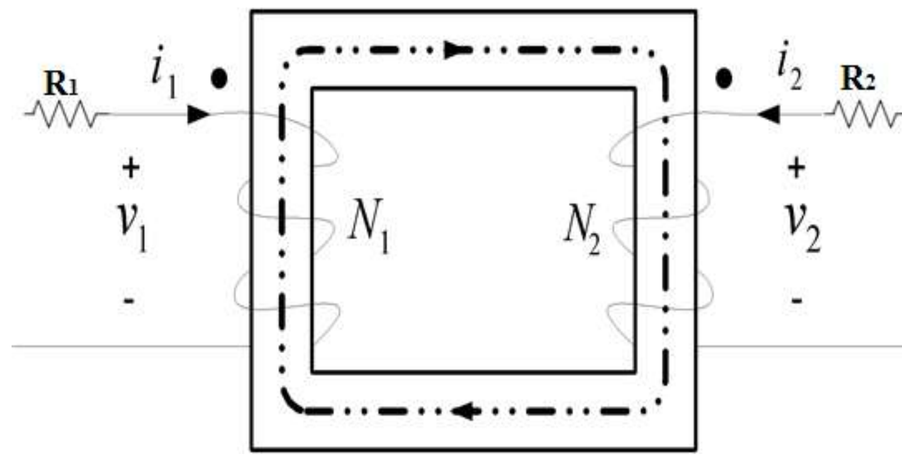
- ✓ Winding resistances,
- ✓ Leakage fluxes,
- ✓ Core losses,
- ✓ Effects of limited magnetic permeability of the core material,
- ✓ Stray capacitancesdue to the electrical coupling between windings (significant at high frequency)

Real or Practical Transformer
{ with winding resistances only}

- A practical transformer has coils of finite resistance. The effect of resistance is to cause voltage drops in the two windings.

- Let R_1 and R_2 be the resistances of the primary winding and secondary winding respectively. Hence, the I_1R_1 and I_2R_2 represent the corresponding voltage drops in the windings

Writing the KVL equations for the primary and secondary loops we have



Primary induced e.m.f. is given by $\bar{E}_1 = \bar{V}_1 - \bar{I}_1 R_1$

Similarly the Secondary induced e.m.f. is given by, $\bar{E}_2 = \bar{V}_2 + \bar{I}_2 R_2$

Equivalent Resistance

- To model a transformer, it is important to understand how resistances or impedances are transferred from one side to another, that is primary to secondary or secondary to primary. Resistance or impedance transfer helps to calculate the current/voltage easier and get rid of the ratio for the rest of the calculation.

- The resistances of the windings can be transferred from LV to HV or vise versa on the basis of equal power loss i.e. copper losses
- The copper loss in the secondary winding is $I_2^2 R_2$. This loss is supplied by primary winding current I_2 . If $R_2^{'}$ is the equivalent resistance in the primary which would have the same loss as with R_2 in the secondary,

Equivalent Resistance

Then

$$I_2^2 R_2 = I_1^2 R_2^1$$

$$\therefore \quad R_2^1 = \frac{I_2^2}{I_1^2} R_2$$

$$R_2^1 = \frac{R_2}{K^2} \qquad \text{where} \quad K = \frac{I_1}{I_2}$$

Then R_2^1 is called the secondary resistance referred to primary.

The total resistance of the primary ,

$$\Rightarrow \quad R_{01} = R_1 + R_2^1$$

$$= R_1 + R_2 / K^2$$

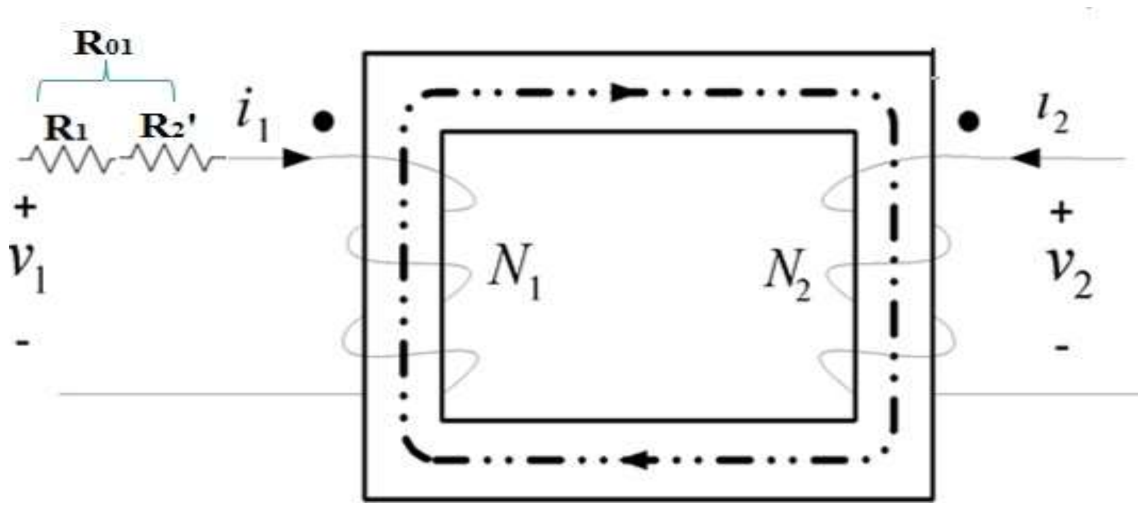
Similarly, if we proceed in the same way, the equivalent primary resistance referred to secondary is obtained.

where

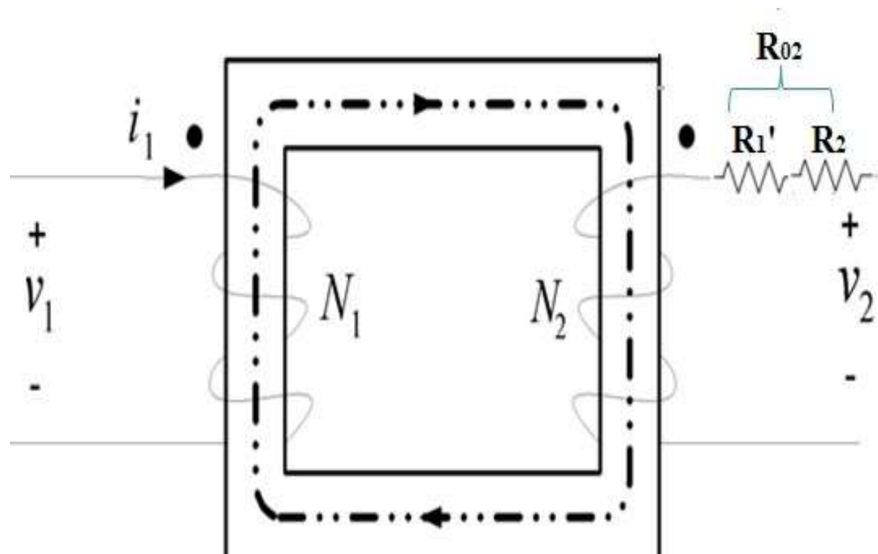
$$\Rightarrow \quad R_{02} = R_1^1 + R_2$$

$$= K^2 R_1 + R_2$$

Total resistance of the transformer referred to primary is shown below



Total resistance of the transformer referred to secondary is shown below



Leakage Flux

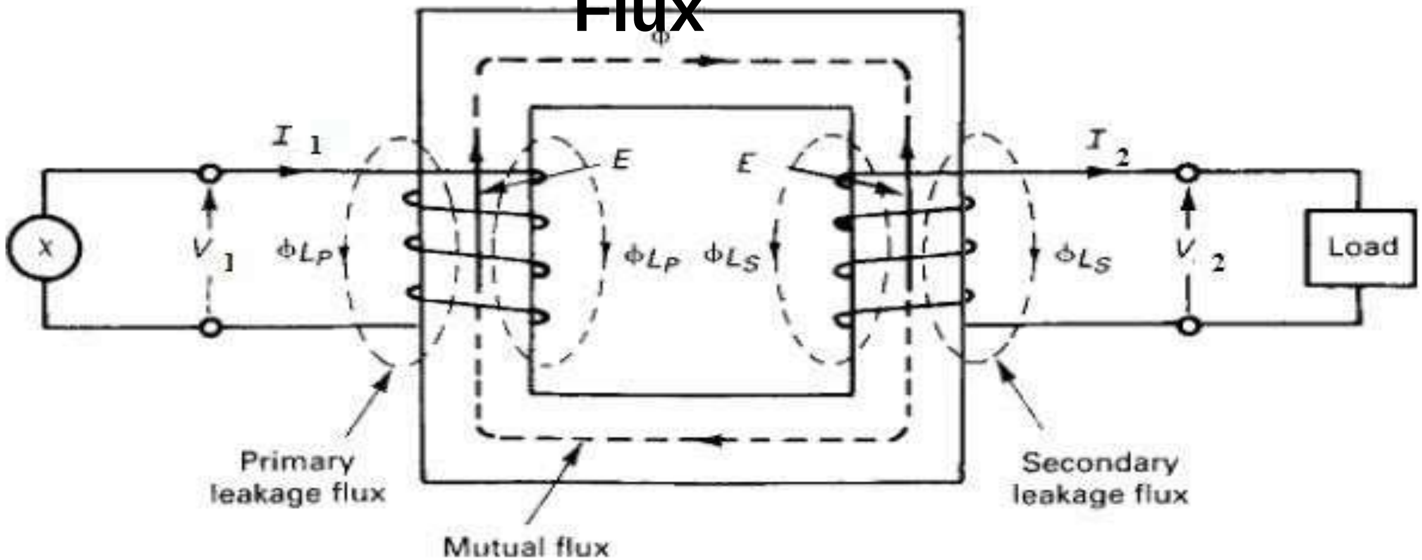
- The ideal transformer model assumes that all flux generated by the primary winding links all the turns of every winding, including itself. In practice, some flux traverses paths that take it outside the windings.

- Not all of the flux produced by the primary current links the winding, but there is leakage of some flux into air surrounding the primary.

- Similarly, not all of the flux produced by the secondary current (load current) links the secondary, rather there is loss of flux due to leakage. These effects are modeled as leakage reactance in the equivalent circuit representation.

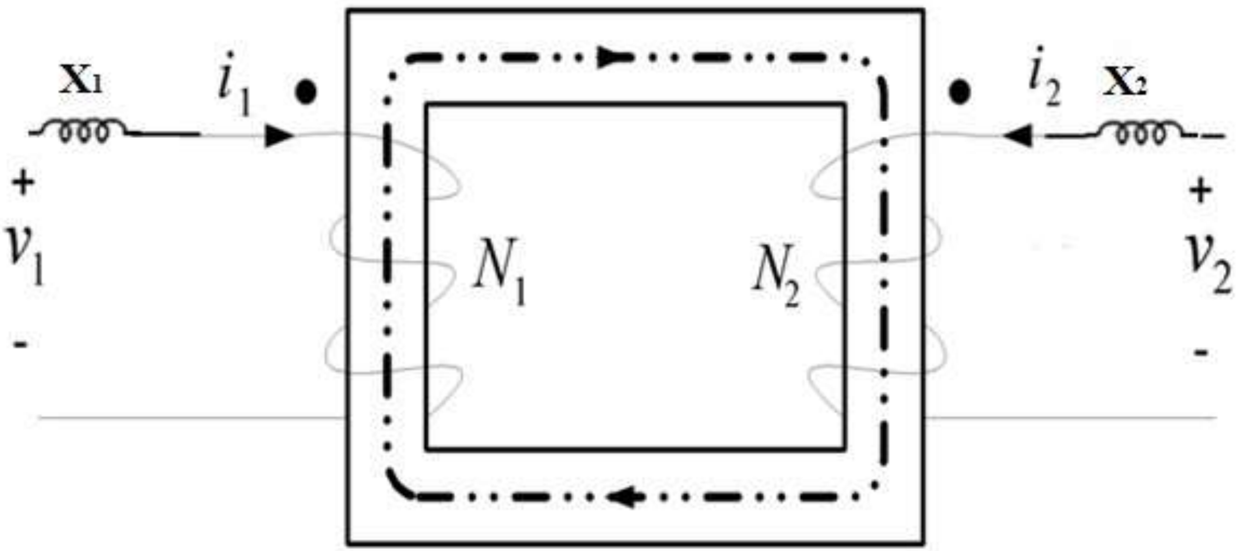
- Such flux is termed leakage flux, and manifests itself as self-inductance in series with the mutually coupled transformer windings

Leakage Flux



- Leakage results in energy being alternately stored in and discharged from the magnetic fields with each cycle of the power supply. It is not itself directly a source of power loss, but results in poorer voltage regulation, causing the secondary voltage to fail to be directly proportional to the primary, particularly under heavy load.

Practical Transformer with winding leakage rea



Writing the KVL equations for the primary and secondary loops we have

Primary induced e.m.f.

$$\overline{E_1} = \overline{V_1} - j\bar{I_1} X_1$$

Similarly,
Secondary induced e.m.f.

$$\overline{E}_2 = \overline{V}_2 + j\bar{I}_2 X_2$$

Leakage Reactance Transfer:

- The leakage reactance of secondary referred to primary,

$$X_2^1 = \frac{X_2}{K^2}$$

The total leakage reactance referred to primary,

$$X_{01} = X_1 + X_{2}^{1}$$

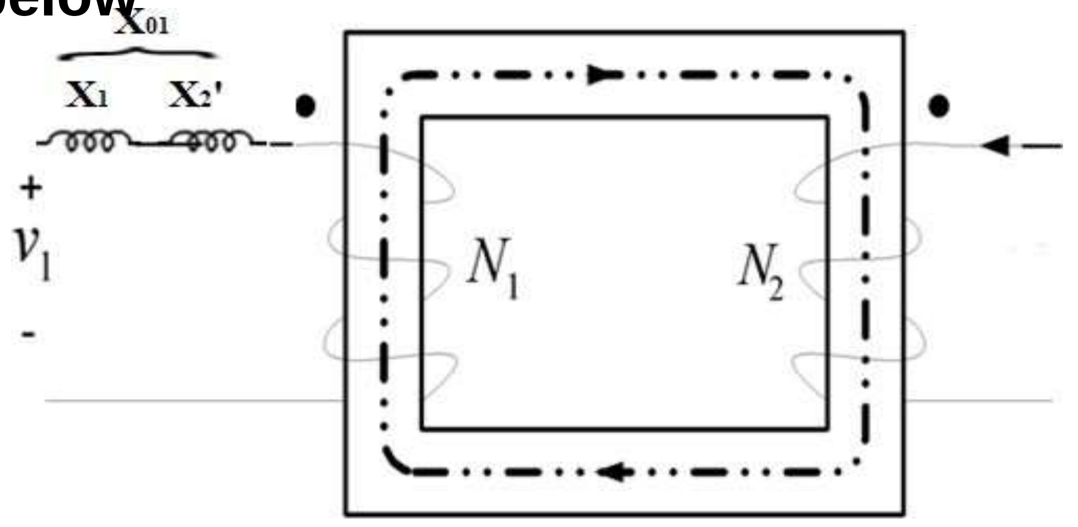
- Similarly, the leakage reactance of primary referred to secondary,

$$X_1^1 = k^2 X_1$$

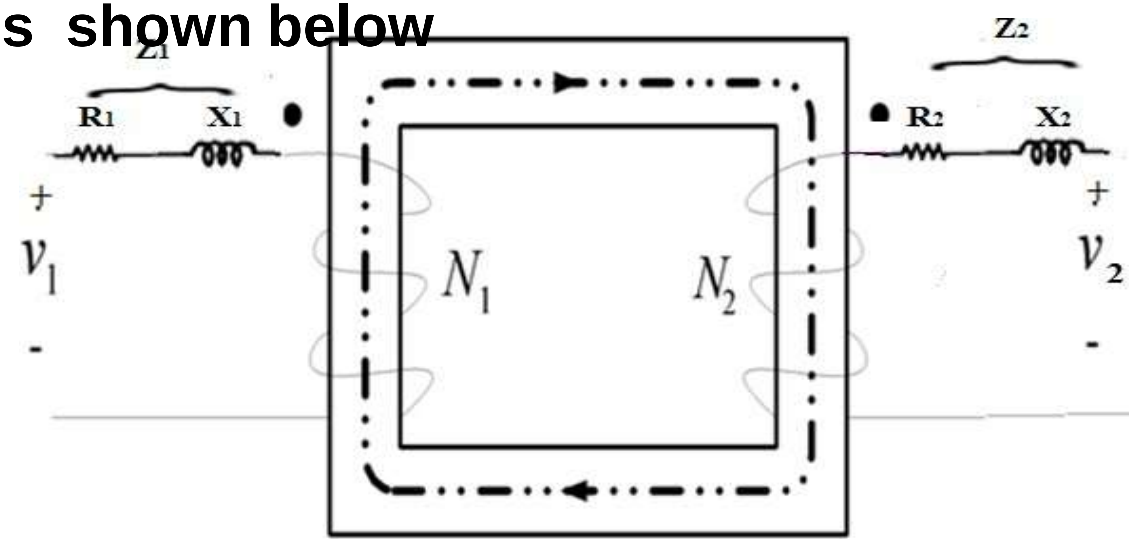
The total leakage reactance referred to secondary,

$$X_{02} = X_2 + X_1^1$$

Effective Reactance of Transformer in primary circuit is shown below



Resistance and Reactance of Transformer in primary and secondary is shown below



The impedance of the primary winding is $Z_1 = R_1 + jX_1$

Similarly, impedance of the secondary winding is $Z_2 = R_2 + jX_2$

Therefore, the voltage drop in the primary winding is due to its

resistance and leakage reactance.

Hence $V_1 = E_1 + I_1(R_1 + jX_1)$

$$\overline{V_1} = \overline{E_1} + \overline{I_1}\,\overline{Z_1}$$

Similarly, in the secondary winding, we have

$$E_2 = V_2 + I_2(R_2 + jX_2)$$

$$\overline{V_2} = \overline{E_2} - \overline{I_2}\,\overline{Z_2}$$

Total impedance referred to primary

$$Z_{01} = Z_1 + Z_2^1$$

$$Z_{01} = R_{01} + jX_{01}$$

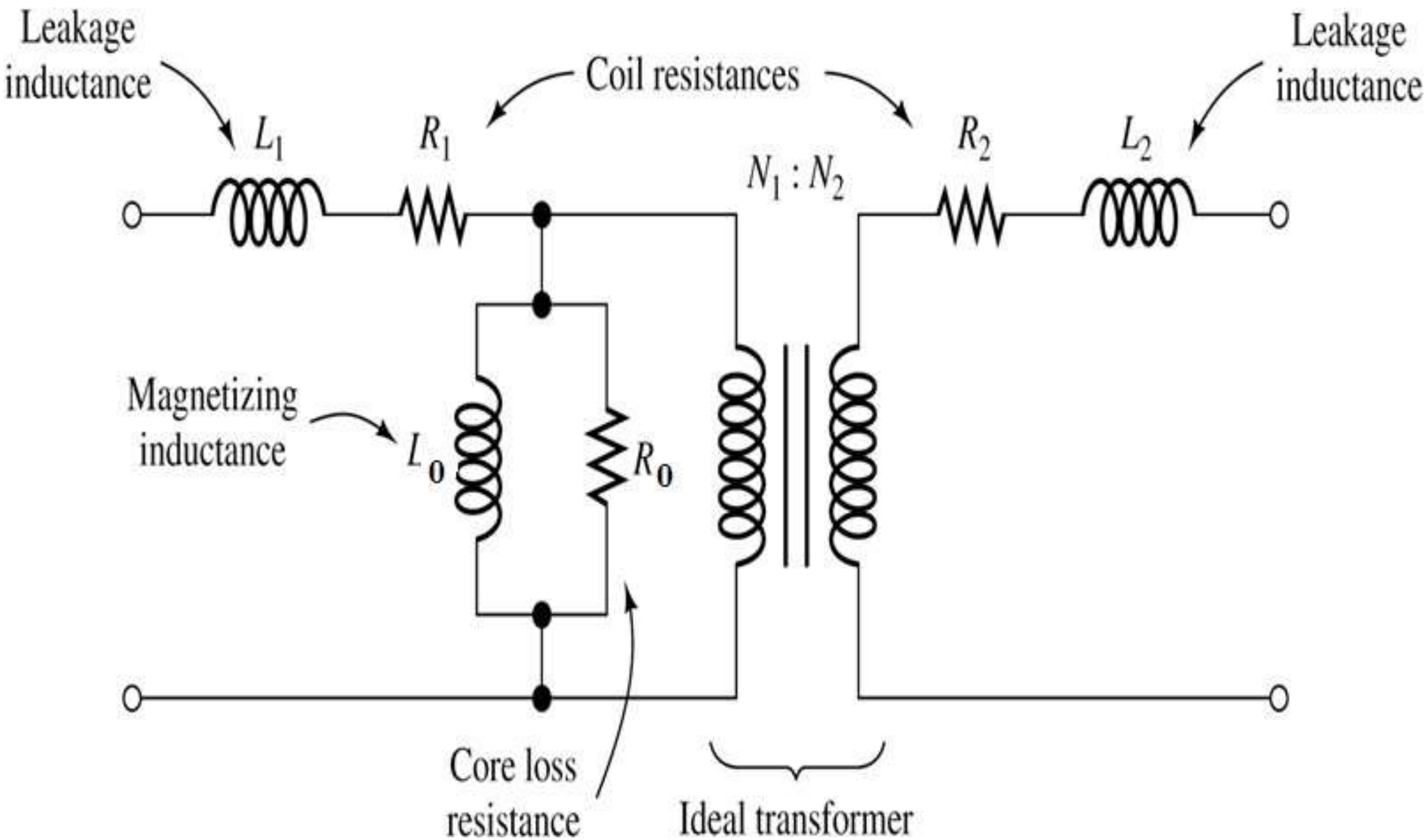
Equivalent Circuit of a Real Transformer

Equivalent Circuit of a Real Transformer

Equivalent Circuit of a Two-winding, 1-phase Transformer:

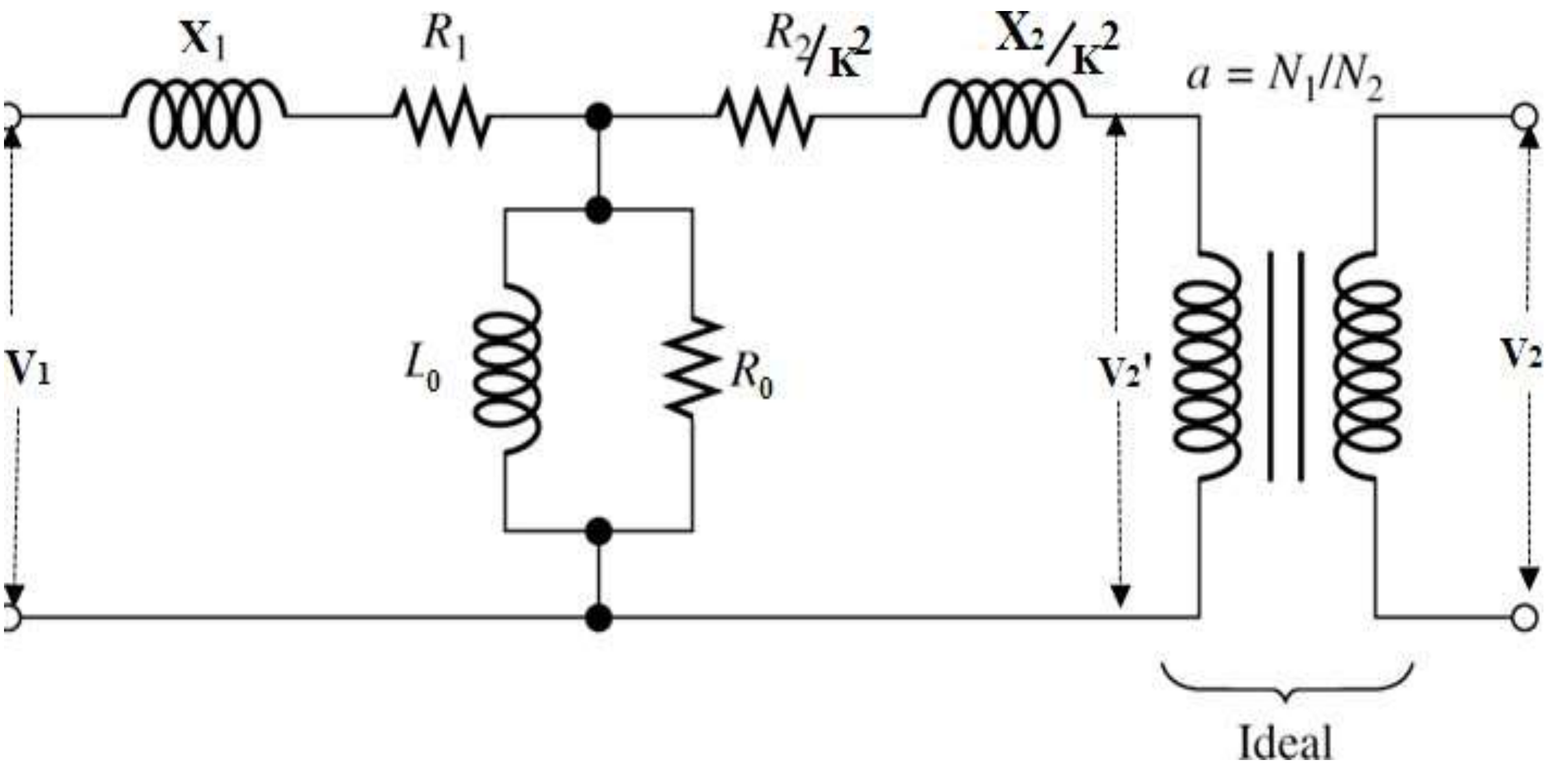
- R_0 core loss component, This resistance models the active loss of the core
- X_0 :magnetization component, This reactance models the reactive loss of the core
- R_1 and X_1 are resistance and reactance of the primary winding
- R_2 and X_2 are resistance and reactance of the secondary winding

Complete equivalent circuit



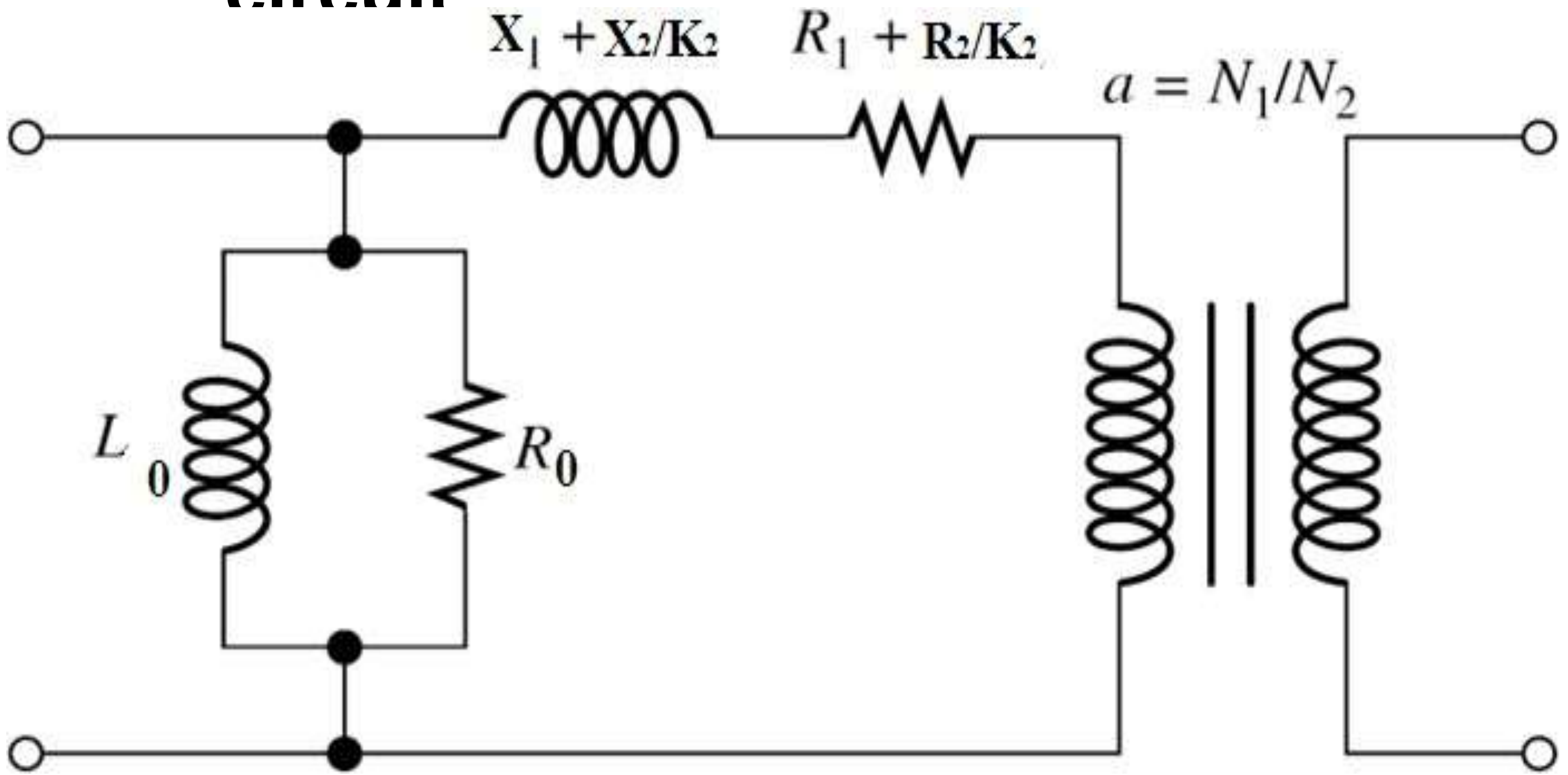
Equivalent Circuit of a Two-winding, 1-phase Transformer

- In transformer analysis, it is usual practice to transfer the secondary quantities to primary side or vice versa

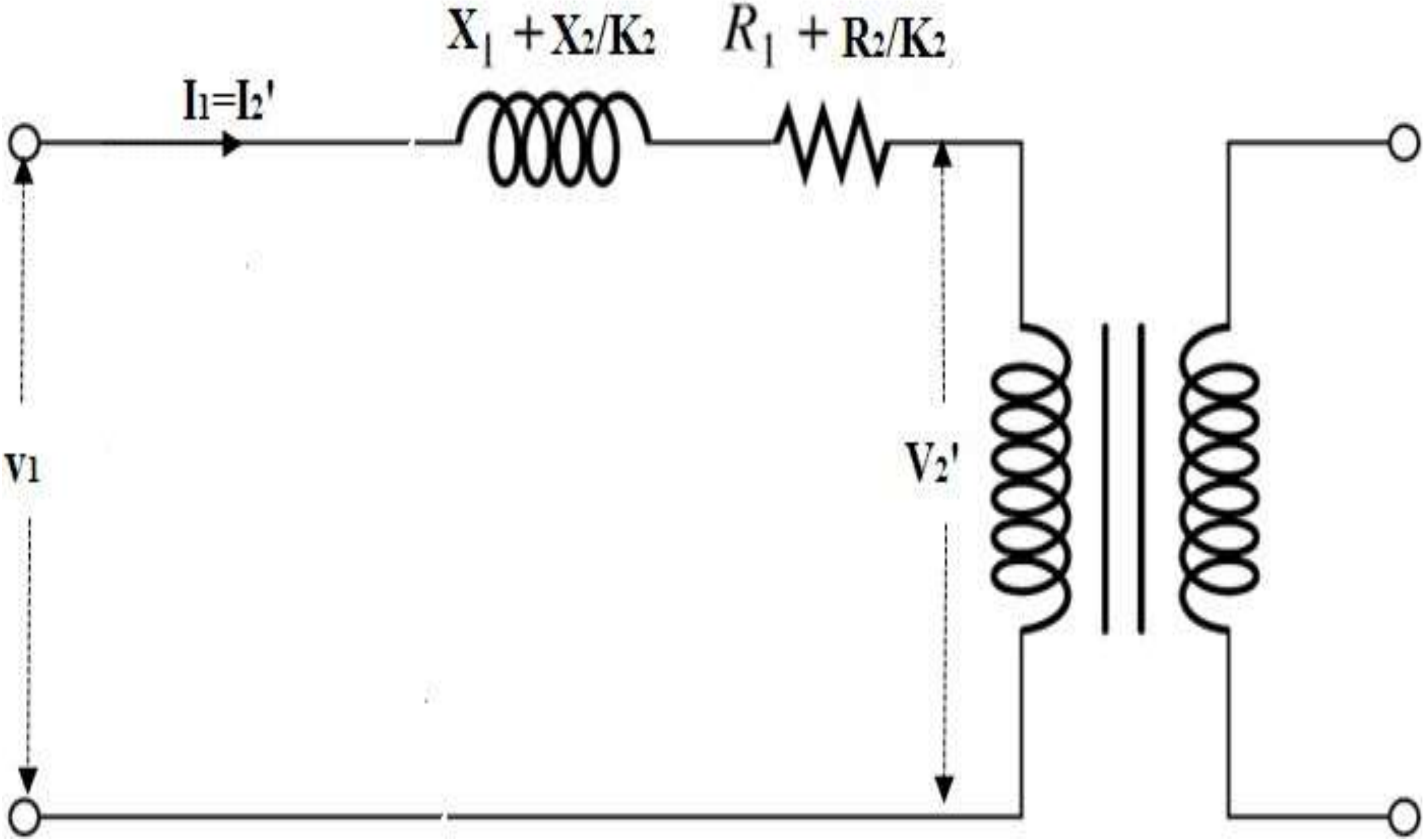


Exact equivalent circuit: All elements referred to Primary

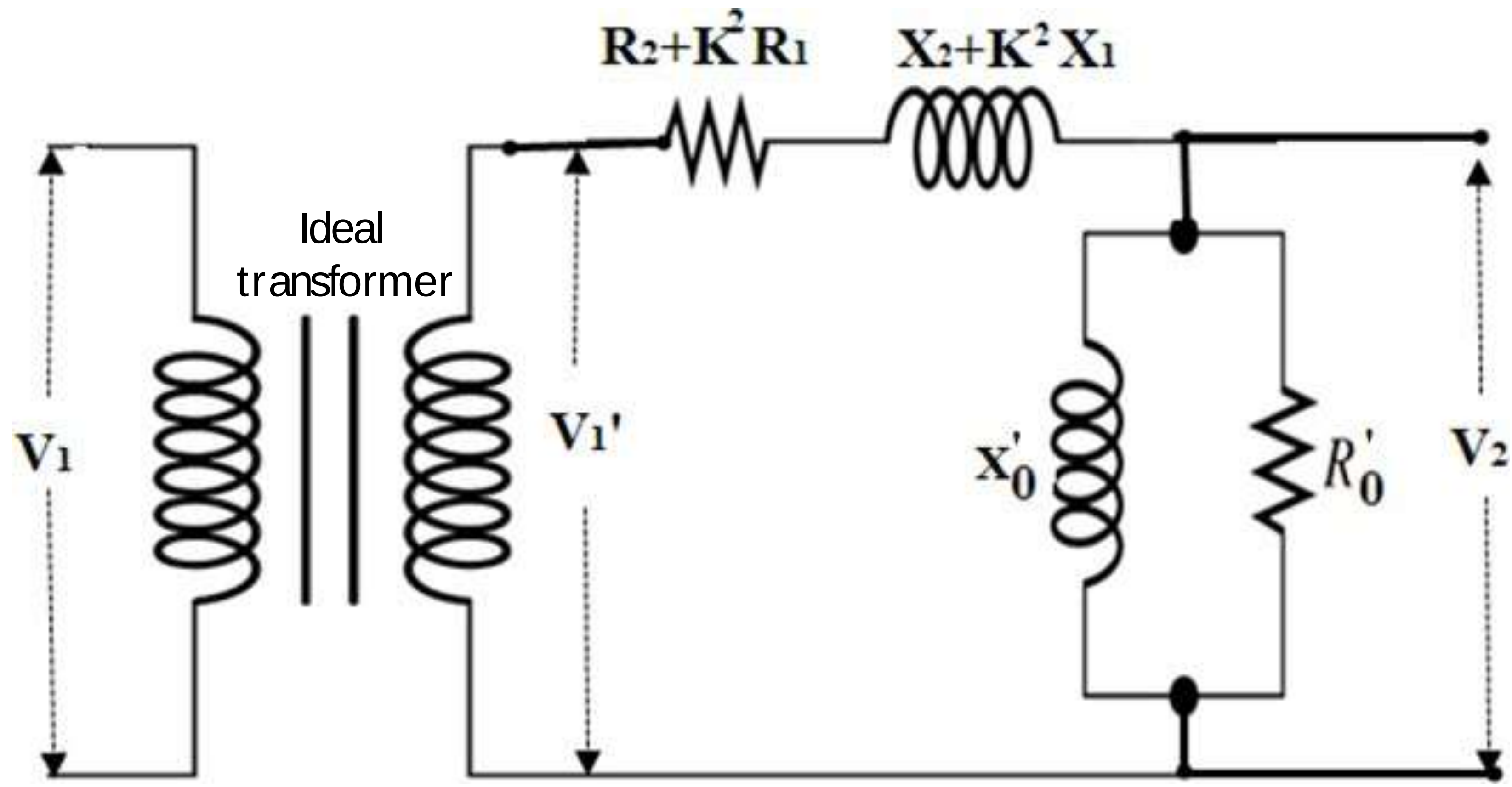
Approximate equivalent circuit



Approximate equivalent circuit : Sufficiently accurate for practical applications



Simplified form of approximate equivalent circuit reffered to primary



Approximate equivalent circuit referred to secondary

Voltage Regulation of a Transformer

- It is defined as the change in secondary terminal voltage from no-load to full-load expressed as a secondary rated voltage with primary applied voltage held constant

Let V_2 be the secondary terminal voltage at any load.
E_2 be the secondary terminal voltage at no-load (rated voltage)

Then at a given power factor and specified load, the voltage regulation is given by:

$$\%\ \text{Voltage Regulation} = \frac{E_2 - V_2}{E_2} \times 100$$

- Thus the voltage drop in the secondary terminal voltage

$$E_2 - V_2 = I_2 R_{o2} \cos\varphi_2 + I_2 X_{o2} \sin\varphi_2$$

- In general, the voltage drop in the secondary terminal voltage for any load power factor

$$E_2 - V_2 = I_2 R_{o2} \cos\varphi_2 \pm I_2 X_{o2} \sin\varphi_2$$

Where +ve sign for lagging power factor load

Transformer Testing

There are two test conducted on transformer

1. **Open Circuit Test**
2. **Short Circuit Test**

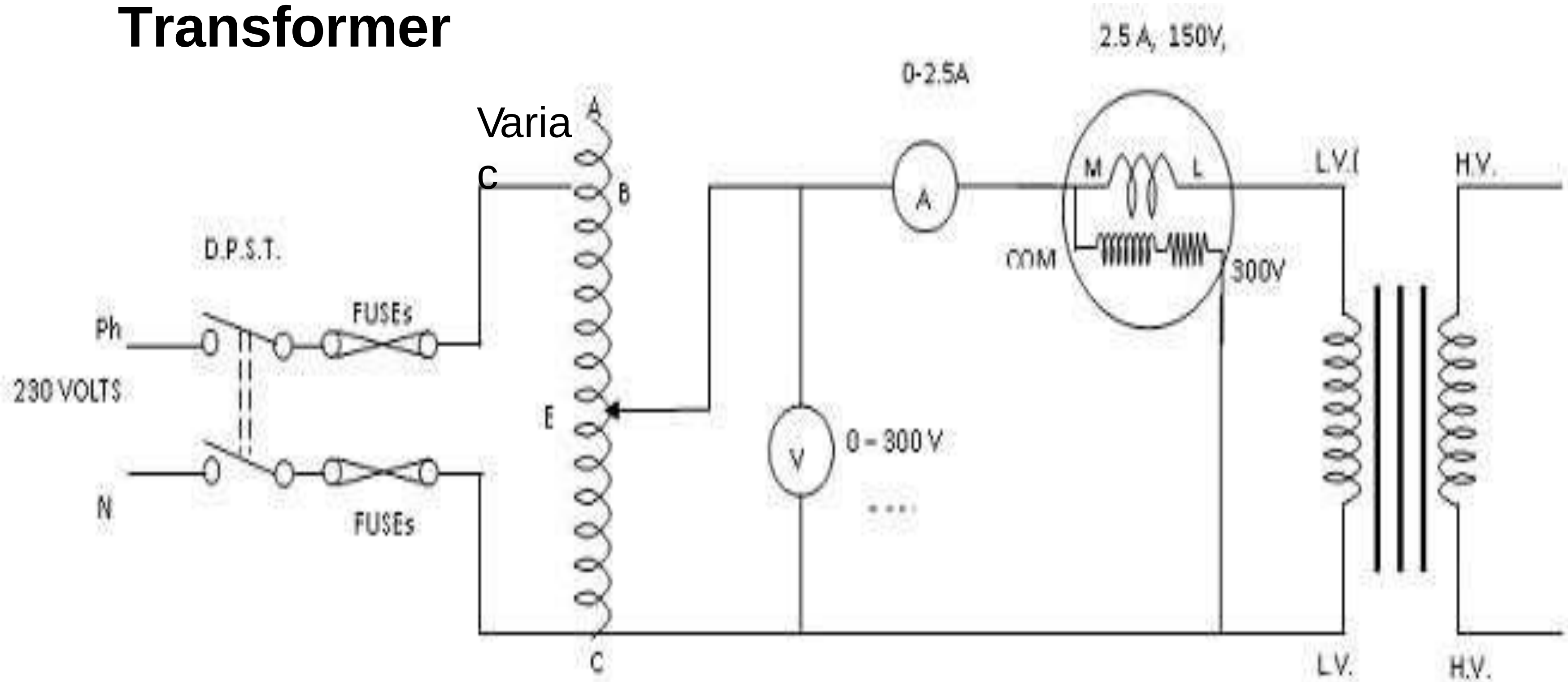
The test are conducted to determine the parameters of the transformer.

- Open circuit test is conducted to determine magnetism parameter,

  R_o and X_o

- Short circuit test is conducted to determine the copper parameter (R_{01}, X_{01} or R_{02},X_{02})depending on which side the test is performed

Open Circuit (OC) Test on single phase Transformer



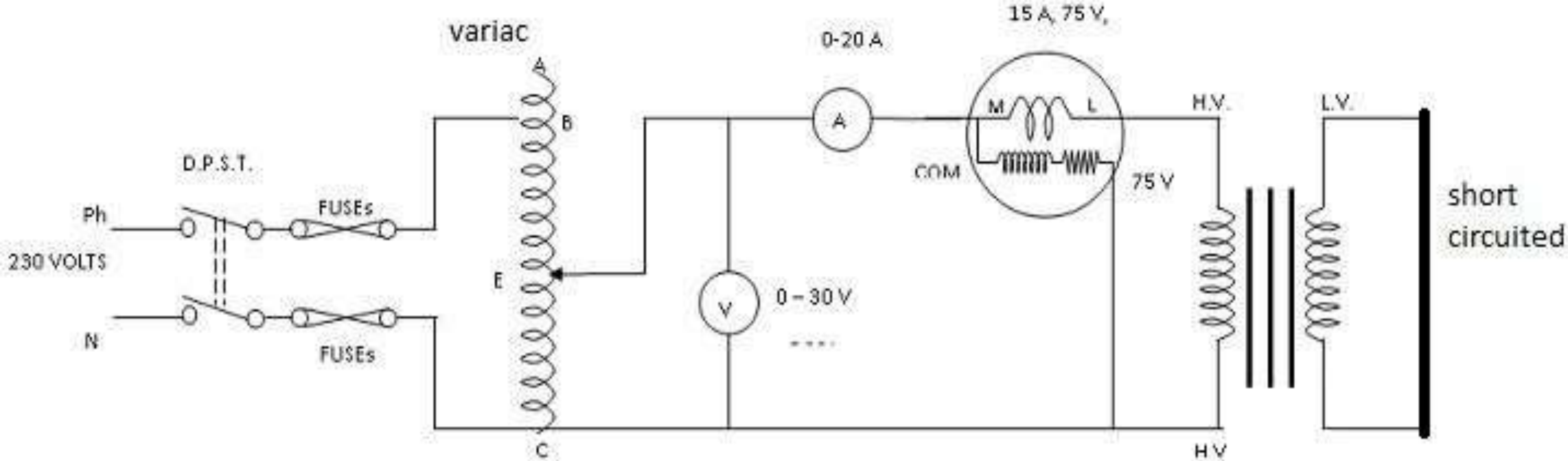
•Give connections as per the circuit diagram, for open circuit test.
•Keep the variac to zero position and switch on the supply.
•Gradually increase the voltage till the voltmeter reads rated voltage of the
primary winding (Note: Secondary is kept open)
•Note down the readings of Ammeter, Voltmeter and wattmeter. Bring the variac to zero position and switch off the supply.

Open Circuit (OC) Test on single phase Transformer

Let the reading of Ammeter be I_{OC} Let the reading of Voltmeter be V_{OC} Let the reading of Voltmeter be W_{OC}

- $W_{OC} = V_{OC} I_{OC} \cos \phi_O$
- Magnetizing current $I_\mu = I_{OC} \sin\phi_O$
- Active component of no load current $= I_W = I_{OC} \cos \phi_O$
- Magnetizing reactance $X_O = V_{OC} / I_\mu$
- Core loss resistance $R_O = V_{OC} / I_W$

Short Circuit (SC) Test on single phase Transformer



- Give connections as per the circuit diagram, for short circuit test.
  (Note: The LV side must be short circuited
- Keeping the variac position at zero, switch on the supply.
- Increase the voltage applied to the transformer slowly till rated current passes through the windings.
- Note down the readings of all the meters.

Short Circuit (OC) Test on single phase Transformer

Let the reading of Ammeter be I_{sc} Let the reading of Voltmeter be V_{sc} Let the reading of Voltmeter be W_{sc}

- $W_{SC} = I_{SC}^2$ R_{02} $R_{02} =$
- W_{SC} / I_{SC}^2
- $Z_{02} = V_{SC} / I_{SC}$

Hence

$$X_{02} = \sqrt{Z_{02}^2 - R_{02}^2}$$

EXAMPLE # 1

A 5KVA, 200/400V,50Hz, single phase transformer gave the following data:

O.C. Test : 200V, 0.7A, 60W on L.V. side
S.C. Test : 22V, 12.5A, 120W on H.V. side

If the transformer operates on full-load determine the percentage regulation at 0.9 lagging power factor

Solution: Given data:

VA rating = 5KVA,
E_1= 200V
E_2= 400V
f = 50Hz

$$K = \frac{E_2}{E_1} = \frac{400}{200} = 2$$

Full load secondary current,

$$I_2 = \frac{VA\ rating}{E_2} = \frac{5x10^3}{400} = 12.5A$$

From S.C. test

Full load Cu losses $W_{Cu} = 120\,W$

$$\therefore \quad W_{Cu} = I_{SC}^2 R_{02}$$

$$\Rightarrow \quad R_{02} = \frac{W_{Cu}}{I_{SC}^2} = \frac{120}{12.5^2} = 0.768\,\Omega$$

$$Z_{02} = \frac{V_{SC}}{I_{SC}} = \frac{22}{12.5} = 1.76\,\Omega$$

$$X_{02} = \sqrt{(Z_{02})^2 - (R_{02})^2}$$

$$X_{02} = \sqrt{(Z_{02})^2 - (R_{02})^2}$$

$$= \sqrt{(1.76)^2 - (0.768)^2}$$

$$= 1.583\,\Omega$$

$$\cos\varphi = 0.9 \Rightarrow \varphi = \cos^{-1} 0.9 = 25.84^0$$

$$\sin\varphi = \sin 25.84^0 = 0.435$$

Solution
:

% Voltage Regulation

$$= \frac{I_2 R_{02} \cos\varphi + I_2 X_{02} \sin\varphi}{E_2} x100$$

$$= \frac{(12.5x0.768x0.9) + (12.5x1.583x0.435)}{400} x100$$

$$= 4.28\%$$

EXAMPLE # 2

A 100KVA, 2400/240V, 50Hz transformer has the following parameters: $R_1 = 0.42\Omega$; $X_1 = 0.72\ \Omega$; $R_2 = 0.0038\ \Omega$; $X_2 = 0.0068\ \Omega$

Calculate the percentage regulation at
(i) Unity p.f.
(ii) 0.8 power factor lagging and
(iii) 0.8 power factor leading

Transformer Efficiency

$$Efficiency \quad \eta = \frac{Output}{Input} X 100$$

$$\text{Efficiency } \eta = \frac{\text{Input power - losses}}{\text{Input power}} \text{ x } 100$$

(or)

$$\eta = \frac{\text{Output power}}{\text{Output power + losses}} \text{ x } 100$$

Transformer Efficiency

- If W_o = iron loss
- W_{Cu} = copper loss
- $\cos\varphi_2$ = load power factor and
- $V_2 I_2$ = output in VA then

$$\text{Efficiency } \eta = \frac{\text{Output power}}{\text{Output power} + \text{losses}} \times 100$$

$$= \frac{V_2 I_2 \cos\varphi_2}{V_2 I_2 \cos\varphi_2 + (W_o + W_{Cu})} \times 100$$

$$= \frac{V_2 I_2 \cos\varphi_2}{V_2 I_2 \cos\varphi_2 + (W_o + I_2^2 R_{o2})} \times 100$$

- Since $W_{Cu} = I_1^2R_1 + I_2^2R_2 = I_1^2R_{01} = I_2^2R_{02}$

- The core losses can be assumed constant at all loads. But the ohmic losses depend on the load current.

- For example, if $I_2^2 R_{02}$ is the ohmic loss at full load, then at half full-load, the ohmic loss will be $^{1}/_{4}\, I_2^2R_{02}$ (one-fourth of that at full-load Cu loss)

- The transformer has maximum efficiency when **Iron loss = copper loss**

EXAMPLE #3

A single phase 10KVA, 450/120V,50Hz transformer gave the following data:

O.C. Test : 120V, 4.2A, 80W on L.V. side
S.C. Test : 9.65V, 22.2A, 120W on H.V. side

Calculate the efficiency and voltage regulation for 0.8 power factor lagging at full load.

Solution:

Given data:

VA rating = 10KVA,
E_1= 450V
E_2= 120V
f = 50Hz

$$K = \frac{E_2}{E_1} = \frac{120}{450} = 0.267$$

Full load secondary current,

$$I_2 = \frac{VA\ rating}{E_2} = \frac{10x10^3}{120} = 83.34A$$

Solution

:

Full load primary current,

$$I_1 = \frac{VA\ rating}{E_1} = \frac{10x10^3}{450} = 22.22A$$

From S.C. test

Full load Cu losses $W_{Cu} = 120W$

$$\therefore \quad W_{Cu} = I_{SC}^2 R_{01}$$

$$\Rightarrow \quad R_{01} = \frac{W_{Cu}}{I_{SC}^2} = \frac{120}{22.2^2} = 0.243\Omega$$

$$Z_{01} = \frac{V_{SC}}{I_{SC}} = \frac{9.65}{22.2} = 0.434\Omega$$

$$X_{01} = \sqrt{(Z_{01})^2 - (R_{01})^2}$$

Solution

:

$$X_{01} = \sqrt{(Z_{01})^2 - (R_{01})^2}$$

$$= \sqrt{(0.434)^2 - (0.243)^2}$$

$$= 0.359\Omega$$

$$\cos\varphi = 0.8 \Rightarrow \varphi = \cos^{-1} 0.8 = 36.86^0$$

$$\sin\varphi = \sin 36.86^0 = 0.6$$

$\therefore$ % Voltage Regulation

$$= \frac{I_1 R_{01}\cos\varphi + I_1 X_{01}\sin\varphi}{E_1} x100$$

$$= \frac{(22.2x0.243x0.8) + (22.2x0.359x0.6)}{450} x100$$

$$= 2.02\%$$

Solution:

From O.C. test

Constant Iron loss $W_O = 250W$

$$\text{Power output at 0.8 p.f. lag} = \text{VA rating x } \cos\varphi$$

$$= 10 \times 10^3 \times 0.8$$

$$= 8000W$$

$$\text{Power Input} = \text{output} + \text{losses}$$

$$= \text{output} + W_{Cu} + W_O$$

$$= 8000 + 120 + 80$$

$$= 8200W$$

$$\therefore \quad \%\ \text{Efficiency} = \frac{\text{Output power}}{\text{Input power}} \times 100$$

$$= \frac{8000}{8200} \times 100$$

$$= 97.56\%$$

EXAMPLE # 4

A 50KVA, 2400/240V,50Hz single phase transformer gave the following data:

O.C. Test : 240V, 5.41A, 186W on L.V. side
S.C. Test : 48V, 20.8A, 617W on H.V. side

Determine the efficiency and the voltage regulation at full load, 0.8 power factor lagging.

Solution:

Given data:

VA rating = 50KVA,
E_1= 2400V
E_2= 240V
f = 50Hz

$$K = \frac{E_2}{E_1} = \frac{240}{2400} = 0.1$$

Full load secondary current,

$$I_2 = \frac{VA\ rating}{E_2} = \frac{50x10^3}{240} = 208.34A$$

Solution

:

Full load primary current,

$$I_1 = \frac{VA\ rating}{E_1} = \frac{50x10^3}{2400} = 20.8A$$

From S.C. test

Full load Cu losses $W_{Cu} = 617W$

$$\therefore \quad W_{Cu} = I_{SC}{}^2 R_{01}$$

$$\Rightarrow \quad R_{01} = \frac{W_{Cu}}{I_{SC}{}^2} = \frac{617}{20.8^2} = 1.426\Omega$$

$$Z_{01} = \frac{V_{SC}}{I_{SC}} = \frac{48}{20.8} = 2.3\Omega$$

$$X_{01} = \sqrt{(Z_{01})^2 - (R_{01})^2}$$

Solution

:

$$X_{01} = \sqrt{(Z_{01})^2 - (R_{01})^2}$$

$$= \sqrt{(2.3)^2 - (1.426)^2}$$

$$= 1.8\,\Omega$$

$$\cos\varphi = 0.8 \Rightarrow \varphi = \cos^{-1} 0.8 = 36.86^0$$

$$\sin\varphi = \sin 36.86^0 = 0.6$$

$\therefore$ % Voltage Regulation

$$= \frac{I_1 R_{01}\cos\varphi + I_1 X_{01}\sin\varphi}{E_1} x100$$

$$= \frac{(20.8x1.426x0.8) + (20.8x1.8x0.6)}{2400} x100$$

$$= 1.92\%$$

Solution :

From O.C. test

Constant Iron loss $W_O = 186\text{W}$

$$\text{Power output at 0.8 p.f. lag} = \text{VA rating x } \cos\varphi$$

$$= 50 \times 10^3 \times 0.8$$

$$= 40000\text{W}$$

$$\text{Power Input} = \text{output} + \text{losses}$$

$$= \text{output} + W_{Cu} + W_O$$

$$= 40000 + 617 + 186$$

$$= 40803\text{W}$$

$$\therefore \quad \% \text{ Efficiency} = \frac{\text{Output power}}{\text{Input power}} \times 100$$

$$= \frac{40000}{40803} \times 100$$

$$= 98\%$$

Classification of Transformers

Transformers are classified based upon

- **Number of Phases**

i)Single Phase Transformers ii)Poly-Phase Transformers

a) 2-phase Transformers
b)3-Phase Transformers

- **Based on construction**

i) core type
ii) shell type
iii) Berry-type

- **Based on Function**

i) Power transformer

a)Setup up transformer
b)Step down transformer

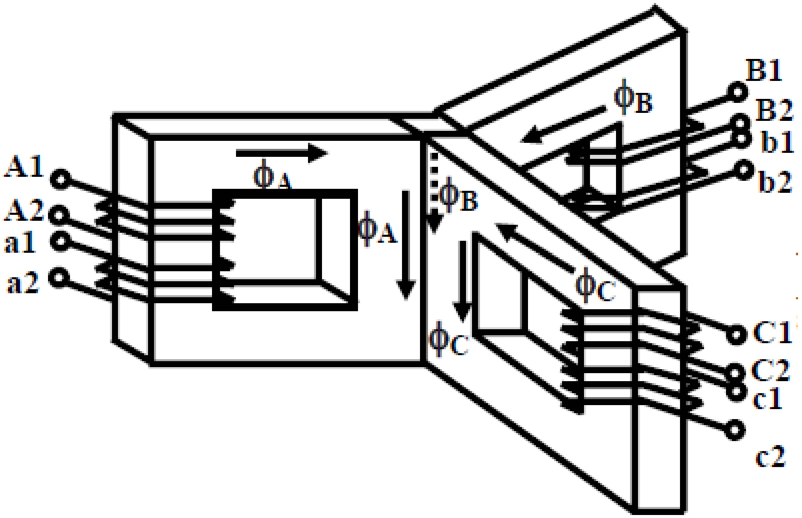
ii) Distribution transformer is always step down

iii) Instrument transformers

3 Phase Transformers

- Almost all major Generation & Distribution Systems in the world are three phase ac systems
- Three phase transformers play an important role in these systems
- Transformer for 3 phase transformer is either:
  - (a) constructed from 3 single phase transformers, or
  - (b) another approach is to employ a common core for the three sets of windings of the three phases

- The construction of a single three phase transformer is the preferred today, it is l slightly more efficient

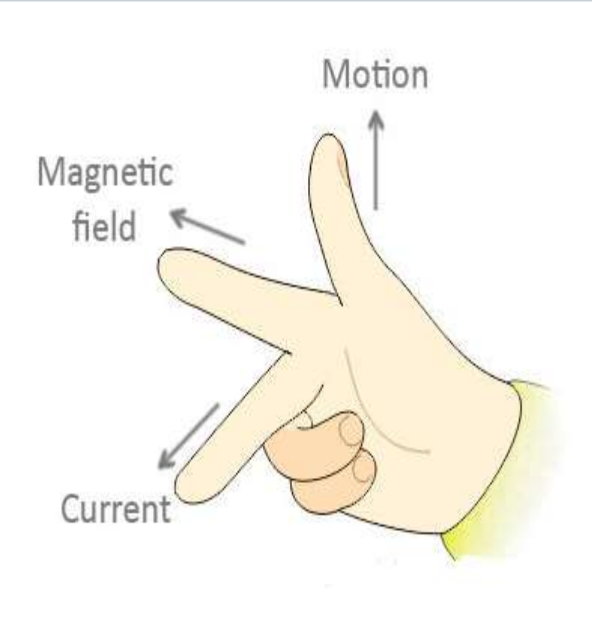


UNIT-4
ELECTRICAL MACHINES

-BY
DR R ISAAC
M A NABI

FARADAYS LAW

- If a current carrying conductor placed in a magnetic field, it experiences a force due to the magnetic field. On the other hand, if a conductor moved in a magnetic field, an emf gets induced across the conductor (Faraday's law of electromagnetic induction).
- FLEMINGS RIGHT HAND RULE



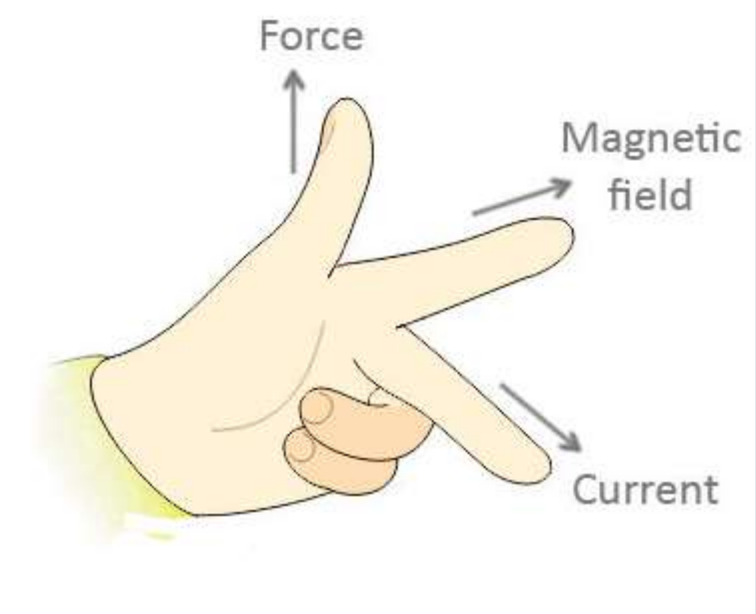
- If angle between the plane of rotation and the plane of the flux is ' θ ' as measured from the axis of the plane of flux then the induced e.m.f. is given by,

$$E = B\,l\,(v \sin \theta) \text{ volts}$$

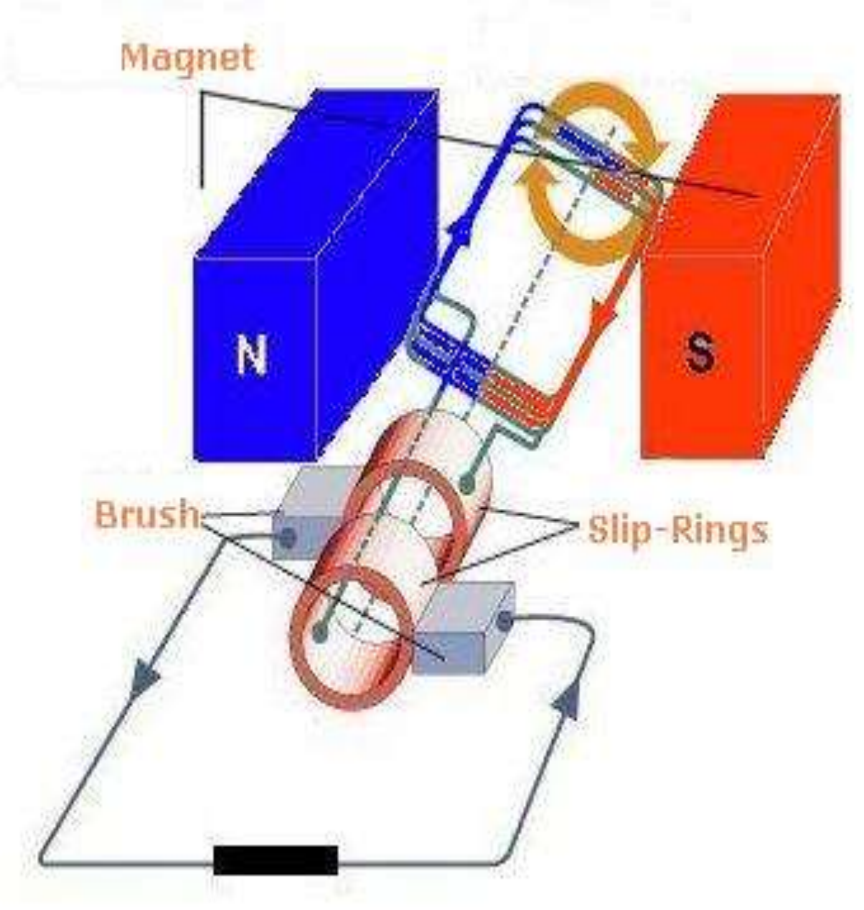
- where $v \sin \theta$ is the component of velocity which is perpendicular to the plane of flux and hence responsible for the induced e.m.f.

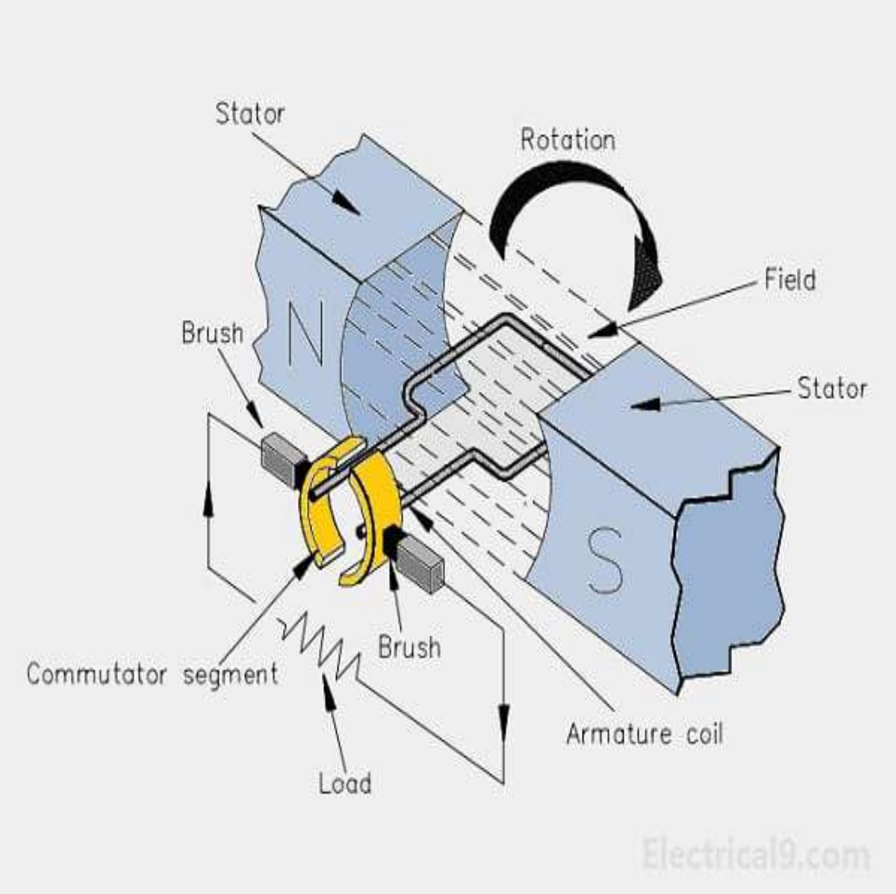
FLEMINGS LEFT HAND RULE

- Whenever a current carrying conductor is placed in a magnetic field, the conductor experiences a force which is perpendicular to both the magnetic field and the direction of current. According to **Fleming's left hand rule**,

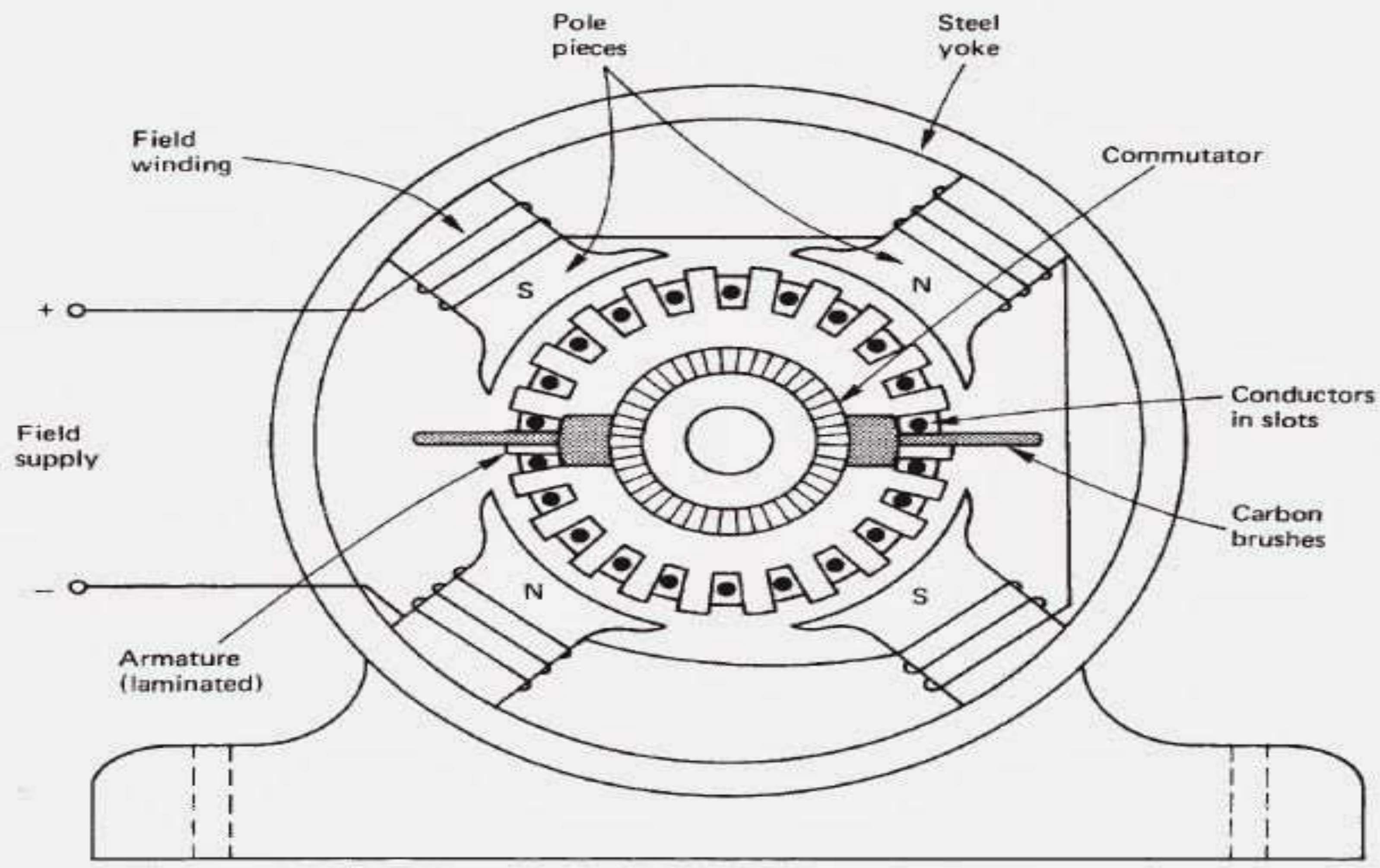


AC AND DC GENERATOR WORKING



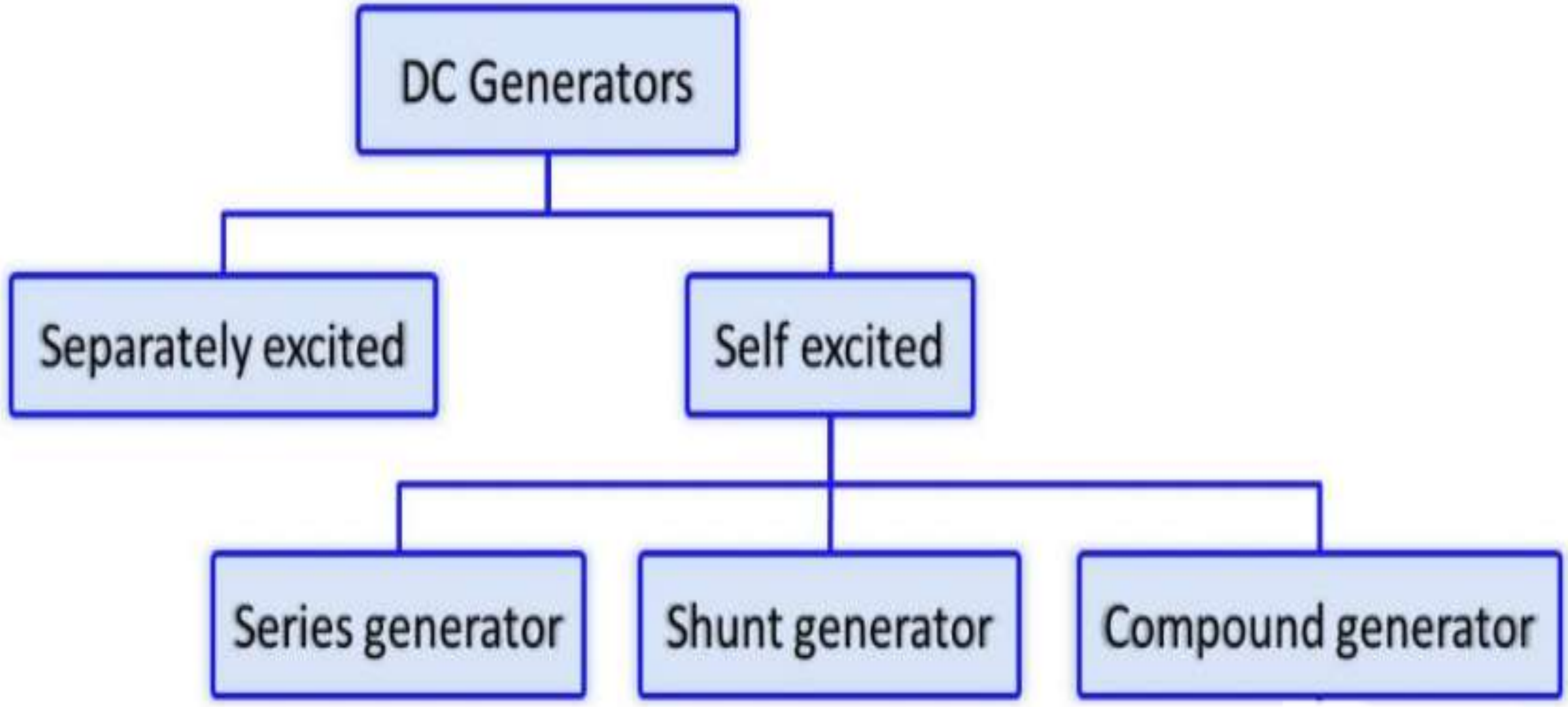


DC GENERATOR CONSTRUCTION



Sr. No.	Lap winding	Wave winding
1.	Number of parallel paths (A) = Poles (P)	Number of parallel paths (A) = 2 (always)
2.	Number of brush sets required is equal to number of poles.	Number of brush sets required is always equal to two.
3.	Preferable for high current, low voltage capacity generators.	Preferable for high voltage, low current capacity generators.
4.	Normally used for generators of capacity more than 500 A.	Preferred for generators of capacity less than 500 A.

TYPES OF DC GENERATORS



EMF EQUATION

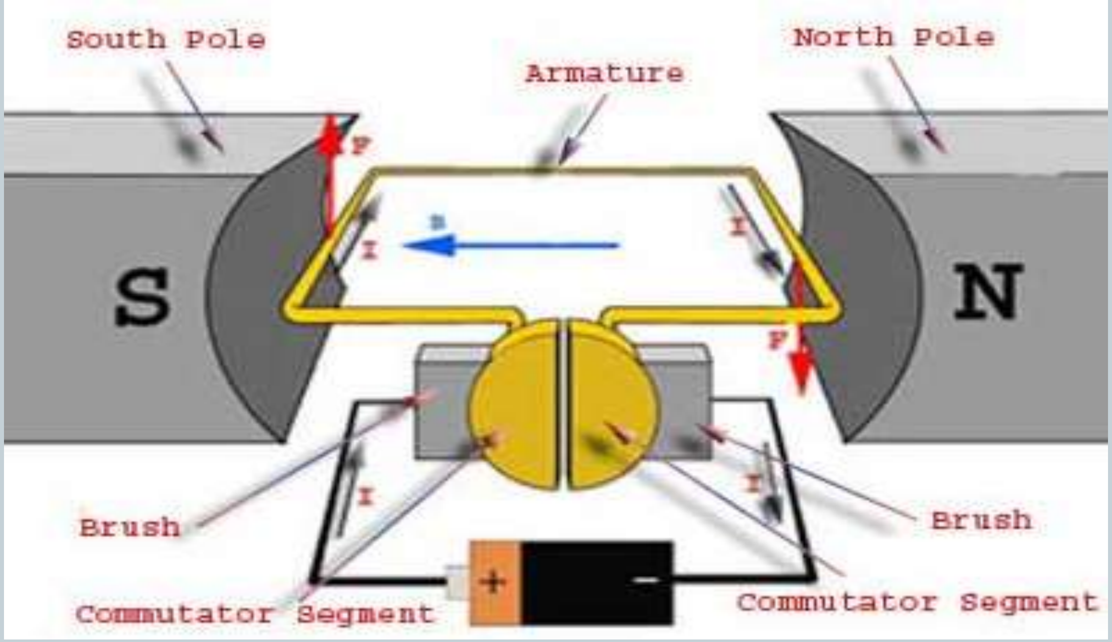
- The **emf equation of dc generator** according to Faraday's Laws of Electromagnetic Induction is

$$\mathbf{Eg = PØZN/60\ A}$$

- Where **Φ** is a flux or pole within Webber
  Z is a total no.of armature conductor
  P is a number of poles in a generator
  A is a number of parallel lanes within the armature
  N is the rotation of armature in r.p.m (revolutions per minute)
  E is the induced e.m.f in any parallel lane within the armature
  Eg is the generated e.m.f in any one of the parallel lanes
  N/60 is the number of turns per second
  Time for one turn will be dt = 60/N sec

DC Motor's Working Principle

- A simple DC motor works on the principle that when a current carrying conductor is placed in a magnetic field, it experiences a mechanical force.



TORQUE EQUATIONS

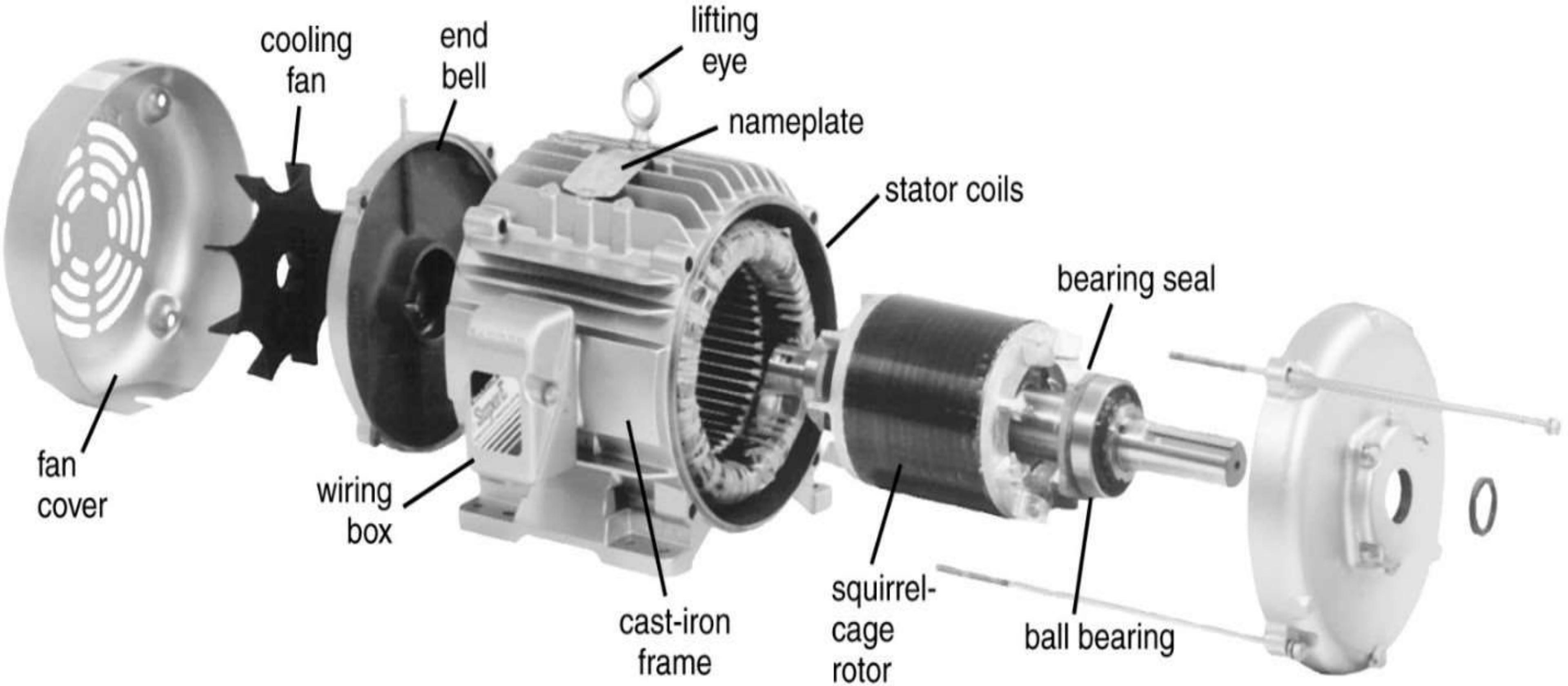
$$Ta = (PZ / 2\pi A) \times \Phi . Ia \text{ (N-m)}$$

$$Tsh = \text{output in watts} / (2\pi N/60)$$

SPEED CONTROL

- ARMATURE VOLTAGE CONTROL
- FLUX CONTROL

Three phase Induction motor construction



Stator and rotor

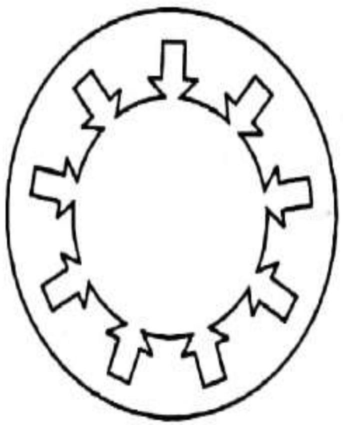
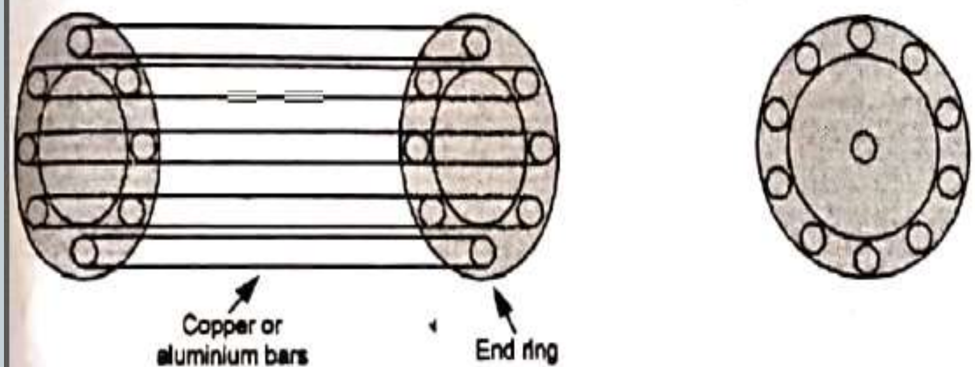


Fig. Stator lamination



(a) Cage type structure of rotor

(b) Symbolic representation

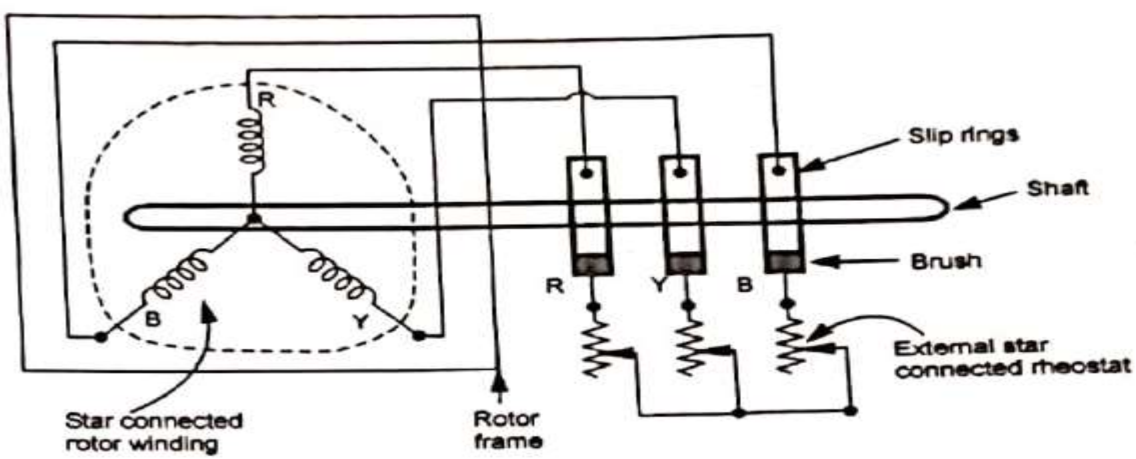


Fig. Slip rings or wound rotor

Synchronous generator

- Stator

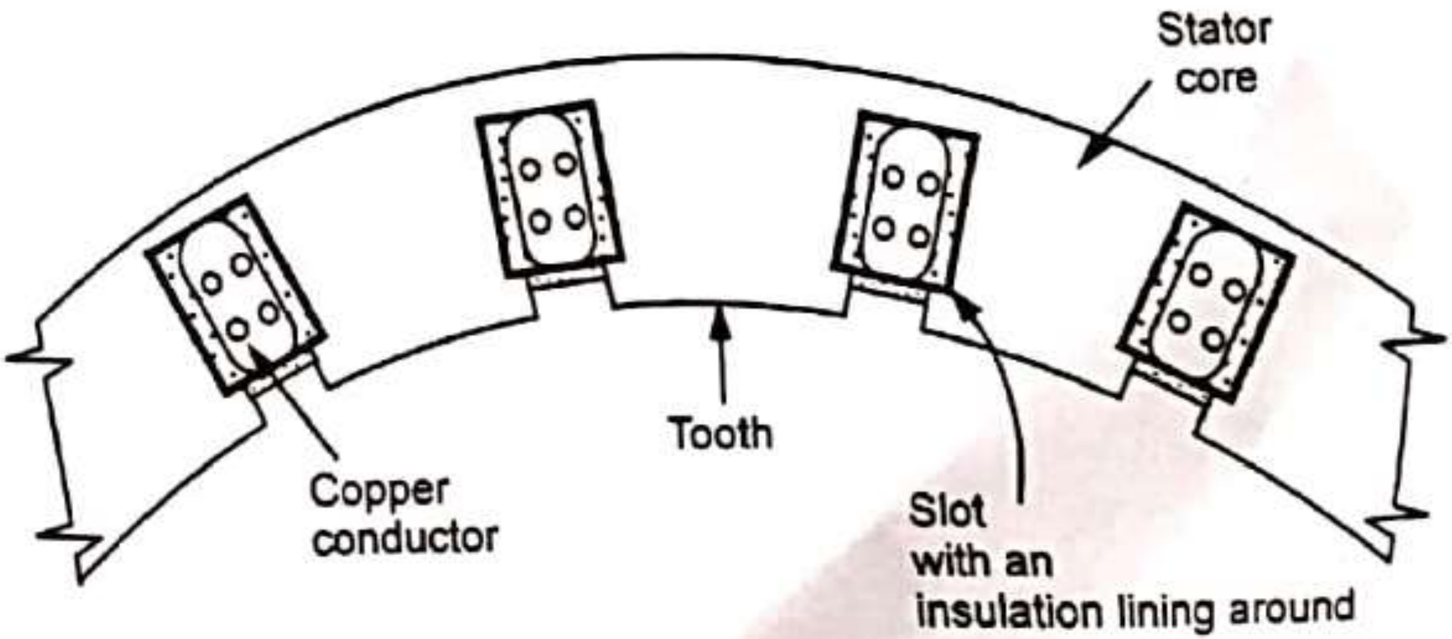


Fig. Section of an alternator stator

Rotor

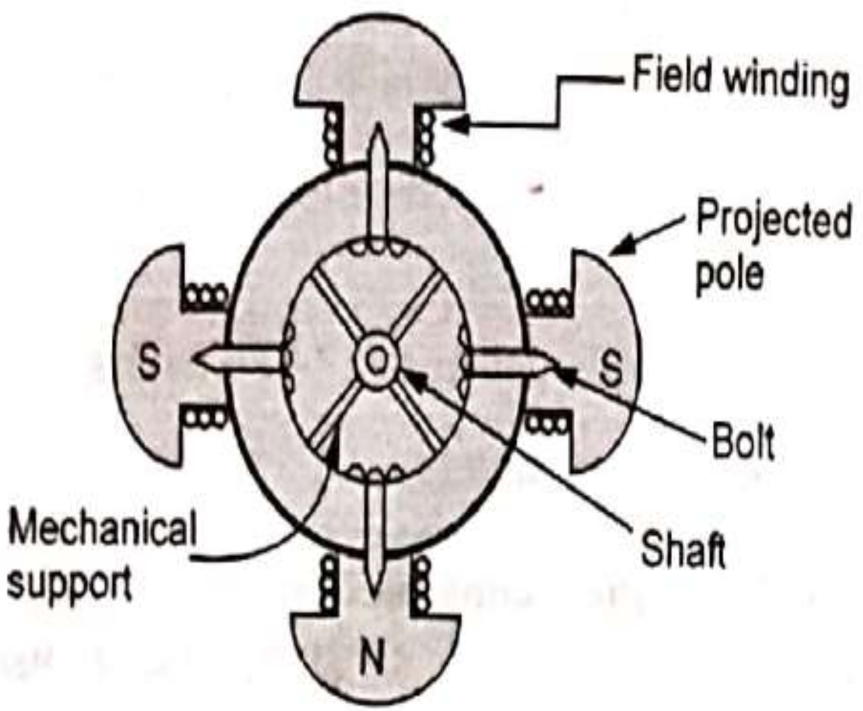


Fig. Salient pole type rotor

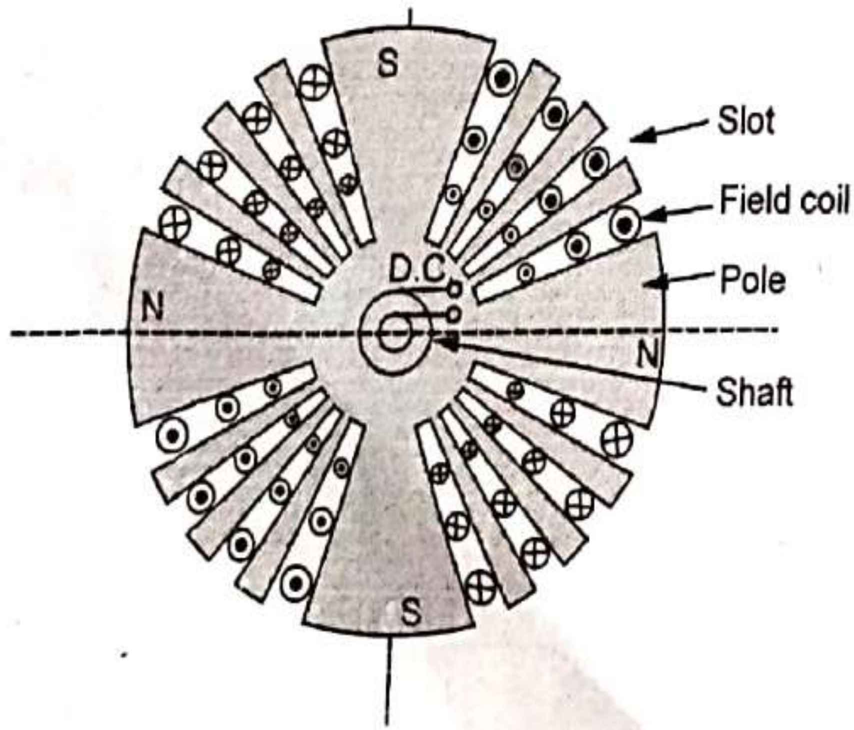


Fig. Smooth cylindrical rotor

ELECTRICAL INSTALLATIONS

Components of LT Switchgear:

- Switch Fuse Unit (SFU)
- MCB, ELCB.
- Types of Wires and Cables.
- Earthing.
- Elementary calculations for energy consumption and battery backup.

- **Wire and cable:**
- The use of Conductors and their insulation is regulated by Indian Electricity (IE) regulation
- and Indian Standard (IS) Code of Practice. Wires and cables are the most common forms of conductors.
- They carry electric current through all types of circuits and systems. A conductor is a wire or cable or any
- other form of mental, suitable for carrying current from generating station the point where it is used.

SFU

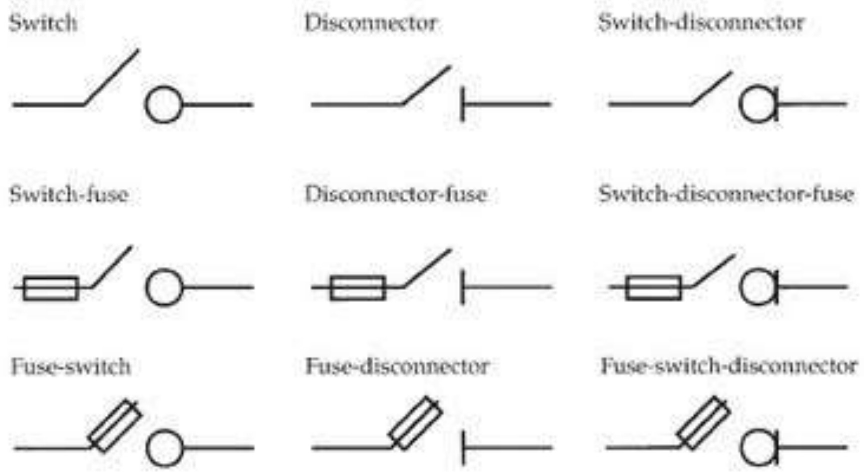
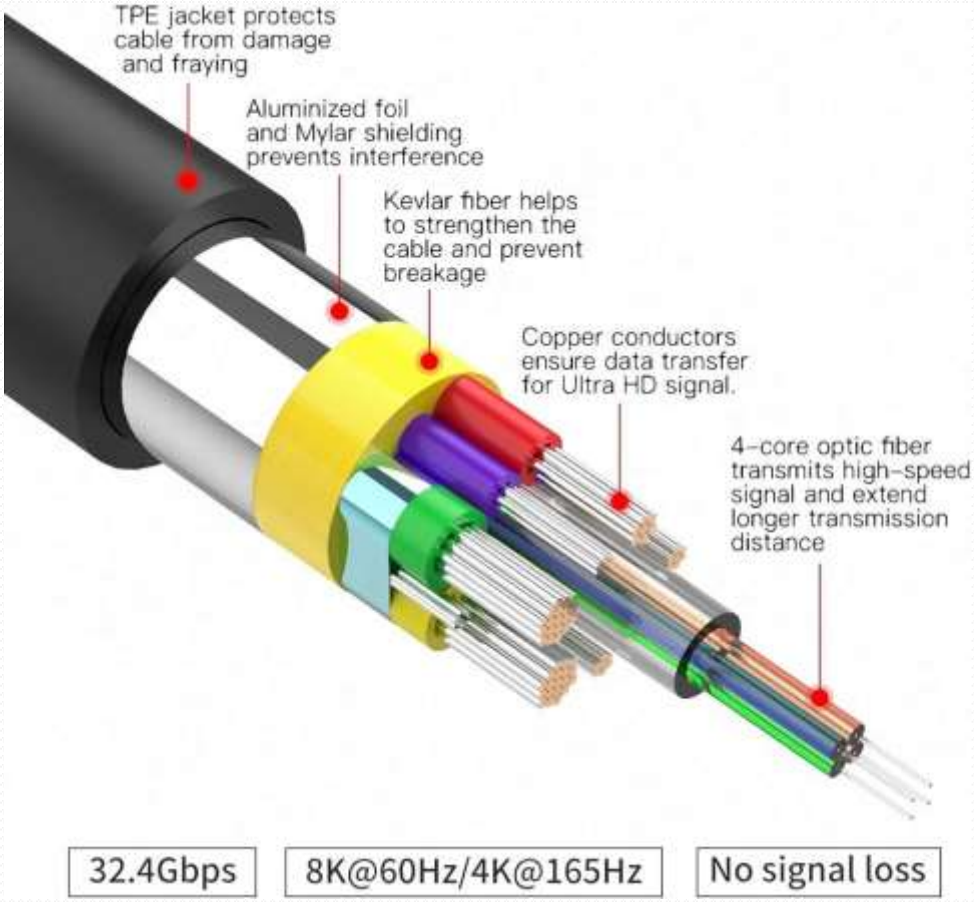
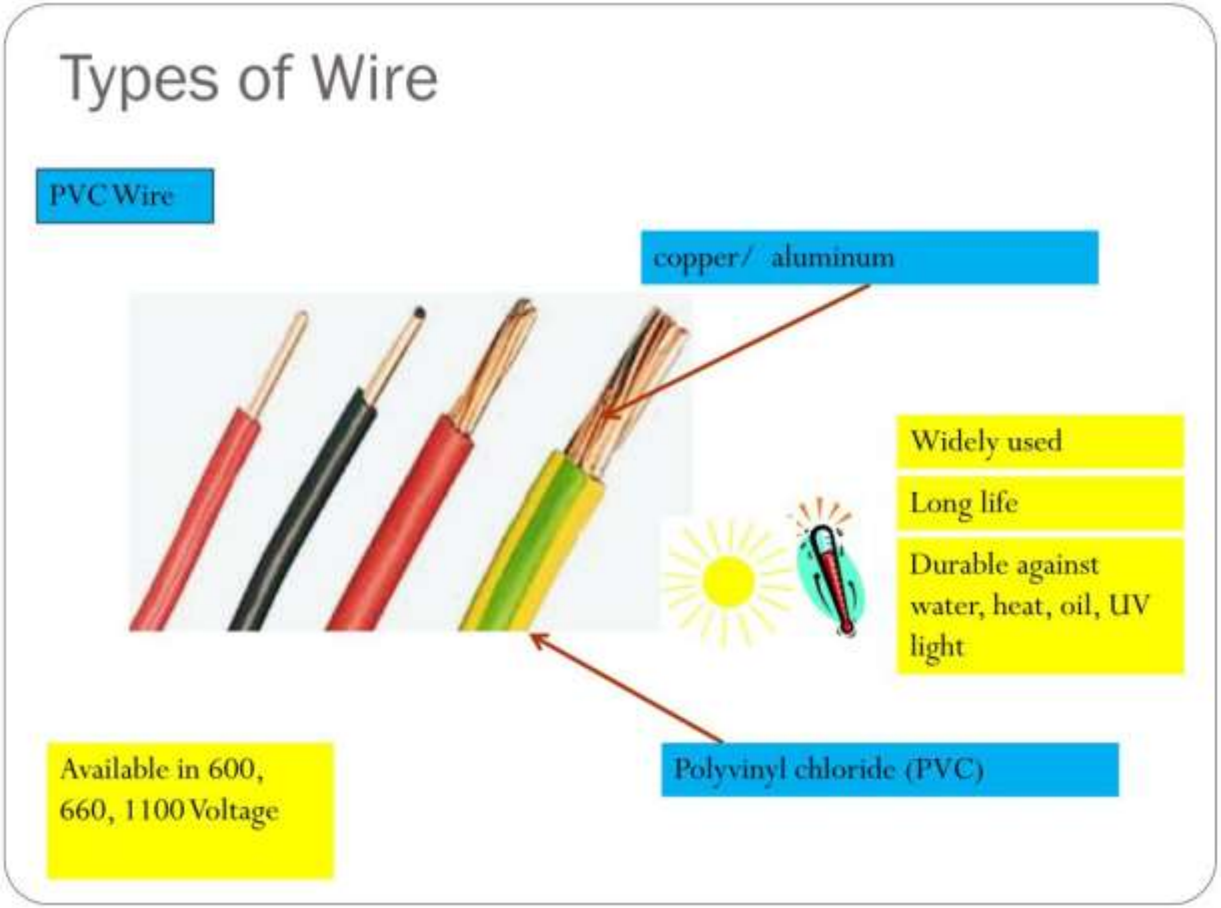


Diagram courtesy of E.I.E.M.A.

CABLE


TPE jacket protects cable from damage and fraying
Aluminized foil and Mylar shielding prevents interference
Kevlar fiber helps to strengthen the cable and prevent breakage
Copper conductors ensure data transfer for Ultra HD signal.
4-core optic fiber transmits high-speed signal and extend longer transmission distance
32.4Gbps
8K@60Hz/4K@165Hz
No signal loss

WIRE


Types of Wire
PVC Wire
copper/ aluminum
Widely used
Long life
Durable against water, heat, oil, UV light
Available in 600, 660, 1100 Voltage
Polyvinyl chloride (PVC)

- **Classifications of Wire / Cables:**
- The wires/ cables used for domestic or industrial wiring are classified into different groups as follows :
- (i) According to the conductor material used
- (a) Copper conductor cables
- (b) Aluminum conductor cable
- (ii) According to number of cores
- (a) Singles core cable (SCC)
- (b) Double core or twin core cables (DCC)
- (c) Three core cables

iii) According to type of insulation
(a) Vulcanized Indian rubber (VIR) insulated wires/cables
(b) Tough rubber sheathed (TRS) or cable tyre sheathed (CTS) cables
(c) Polyvinyl chloride (PVC) cables
(b) Lead sheathed cables
(e) Weather proof cables
(f) Flexible cords and cables
(g) XLPE cables
(IV) According to the voltage at which they are manufactured
(a) Low tension (LT) cables – up to 1000V
(b) High tension (HT) cables – up to 11kV
(c) Super tension (ST) cables – from 22-33kV
(d) Extra high tension (EHT) cables – from 33-66kV
(e) Extra super voltage cables – beyond 132 kV

Earthing of Grounding:

The process of connecting the metallic frame (i.e., non- current carrying part) of electrical equipment or some electrical part of the system (e.g., neutral point in a star-connected system, one conductor of the secondary of a transformer, etc.) to the earth (i.e., soil) is called grounding or Earthing. The potential of the earth is to be considered zero for all practical purposes. Earthing is to connect any electrical equipment to earth with a very low resistance wire, making it to attain earth's potential, This ensures safe discharge of electrical energy due to failure of the insulation line coming in contact with the casing, etc. Earthing brings the potential of the body of the equipment to zero i.e., to the earth's potential, thus ptotecting the operating personnel against electrical shock.

The earth resistance is affected by the following factors :

(a) Material properties of the earth, wire and the electrode

(b) Temperature and moisture content of the soil

(c) Depth of the pit

(d) Quantity of the charcoal used

S.No	Type of Earthing	Application
01	Plate earthing	Large installations such as transmission towers, all sub-stations generating stations
02	Pipe earthing	• For domestic installations such as heaters, coolers, refrigerators, geysers, electric iron, etc. • For 11kV/400V distribution transformers • For induction motors rating upto 100HP • For conduit pipe in a wall, all wall brackets
03	Rod earthing	In areas where the soil is loose or sandy
04	Strip of wire earthing	In rocky ares

(a) Desirable characteristics of a Fuse Element:

The material used foe fuse wires must have the following characteristics:

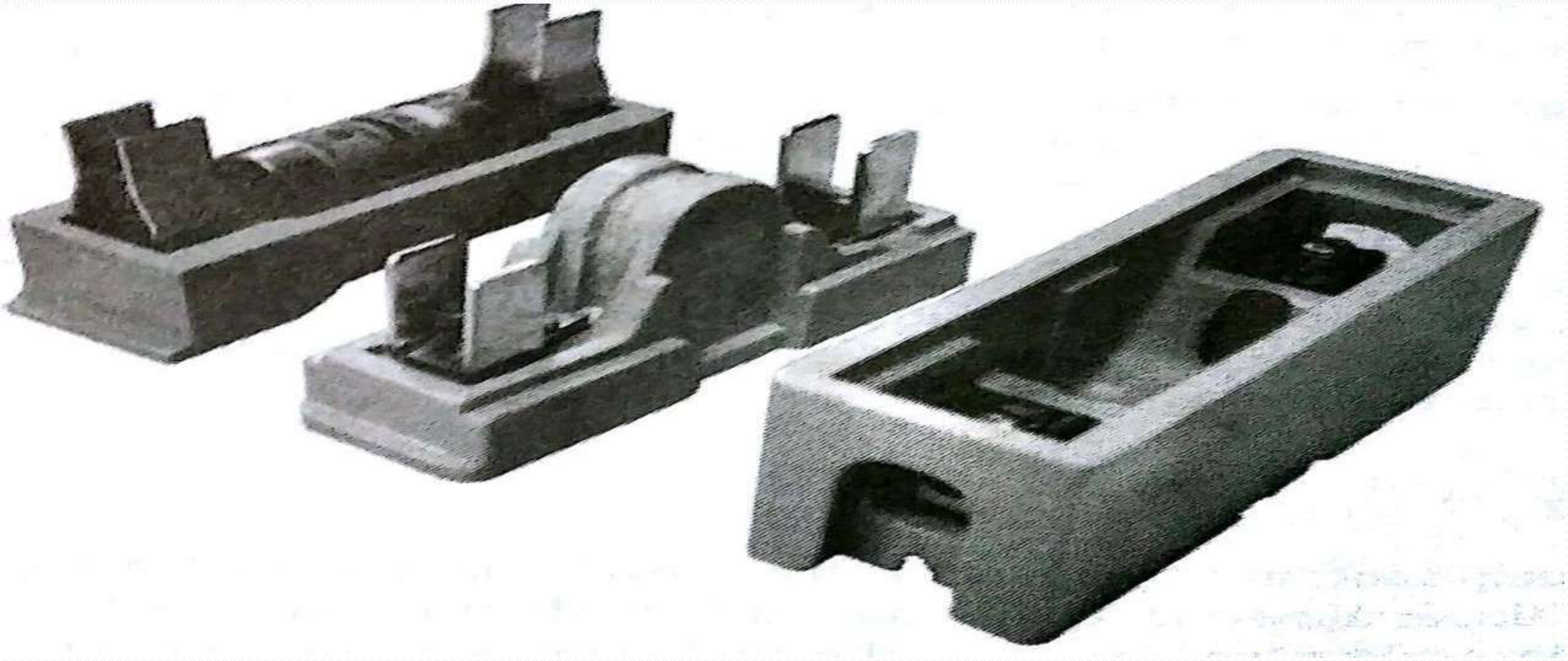
i. Low melting point e.g., tin, lead.

ii. High conductivity e.g., copper.

iii. Free from deterioration due oxidation e.g., silver.

iv. Low cost e.g., tin, copper.

Re-wireable or Kit-Kat Fuse:



High Rupturing Capacity (HRC) Cartridge Fuse:

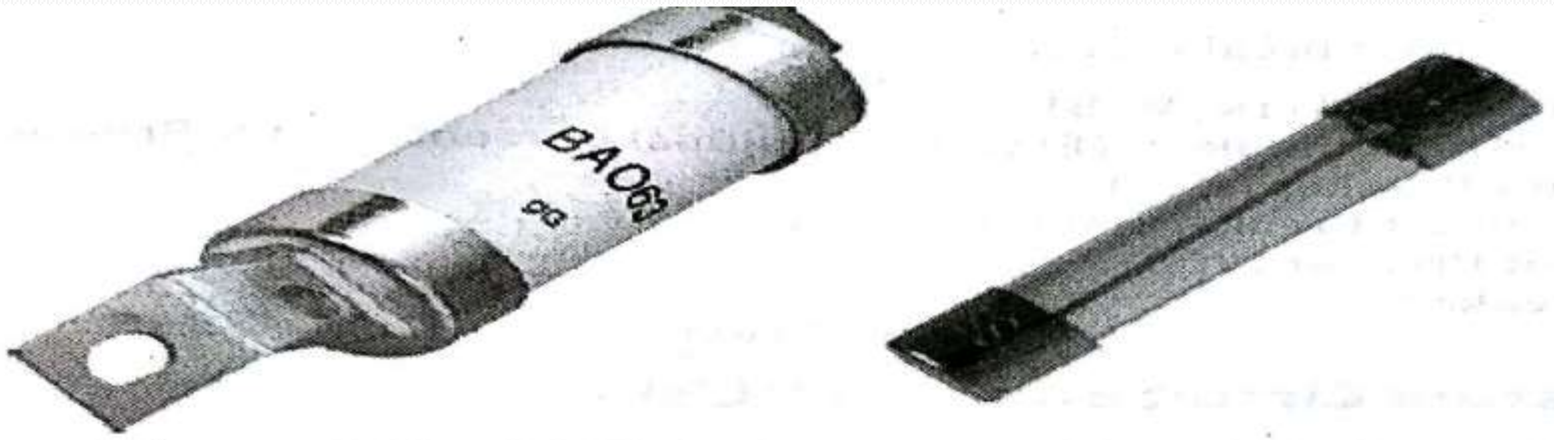
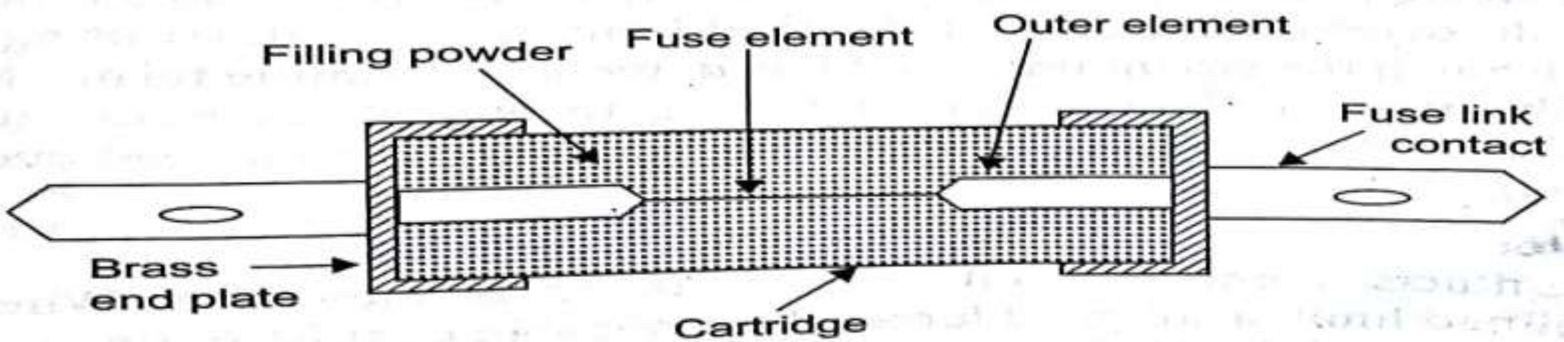


Figure (12.8): *HRC cartridge fuse*



Miniature Circuit Breaker (MCB):

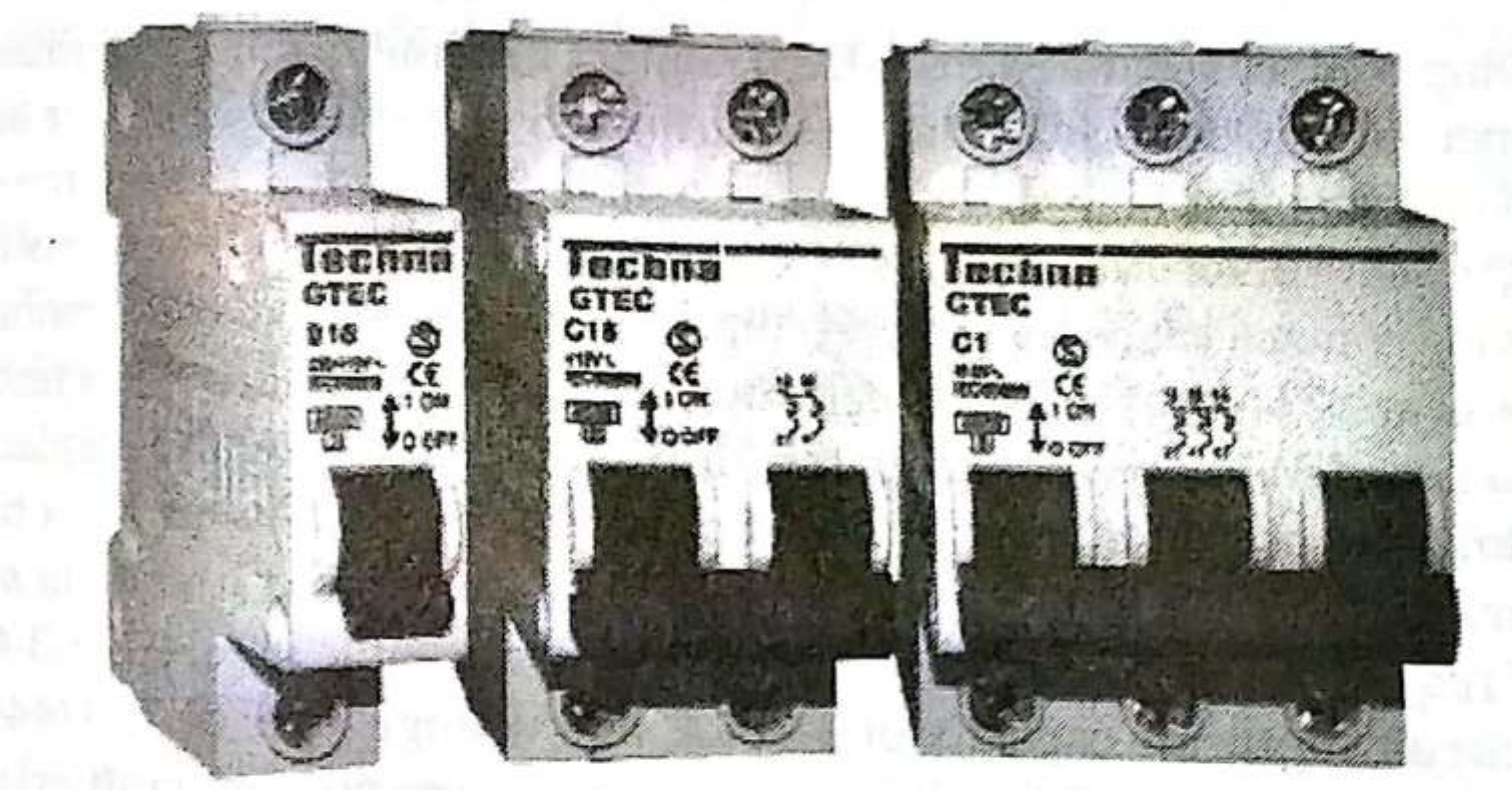


Figure (12.10): *Miniature circuit breaker*

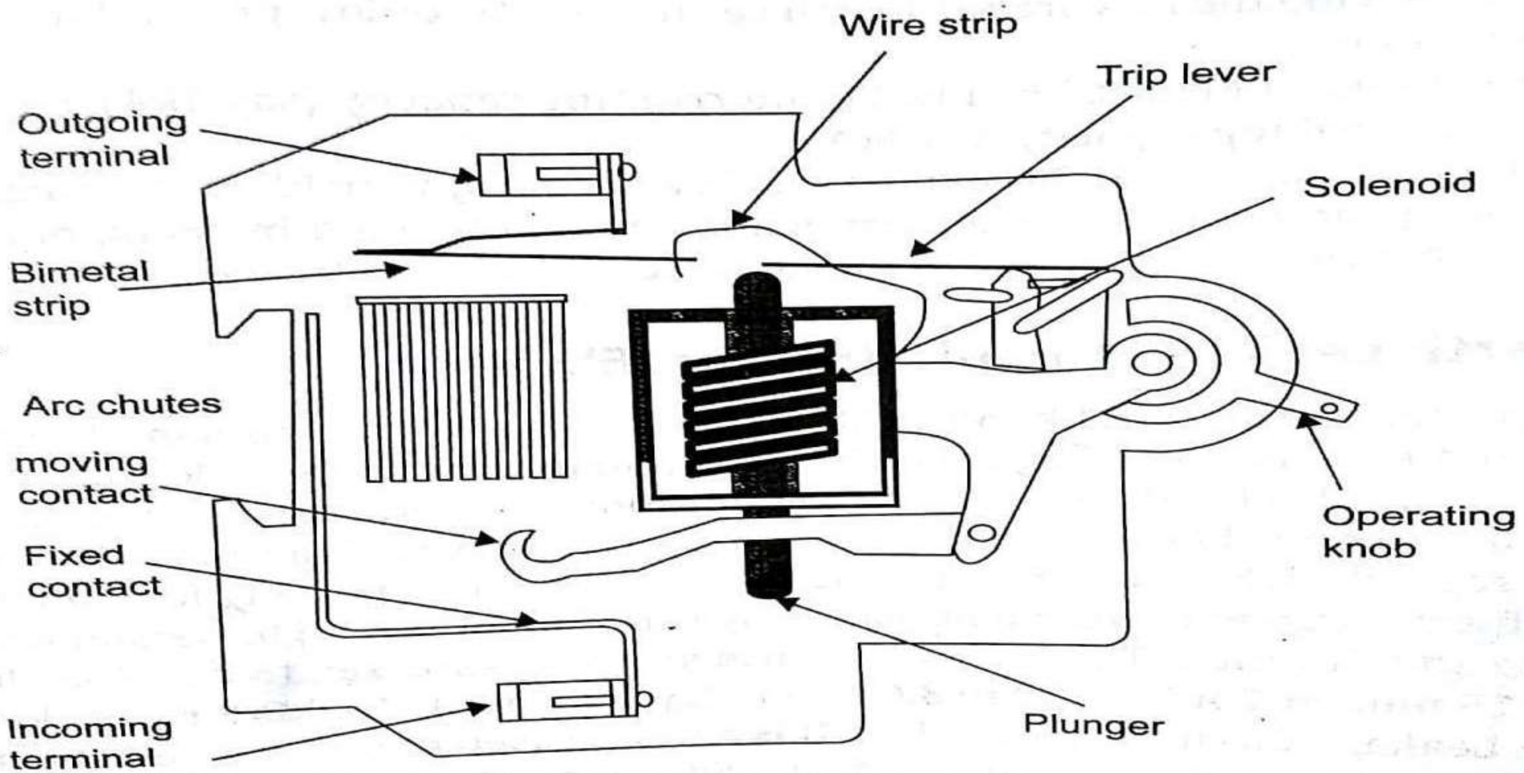
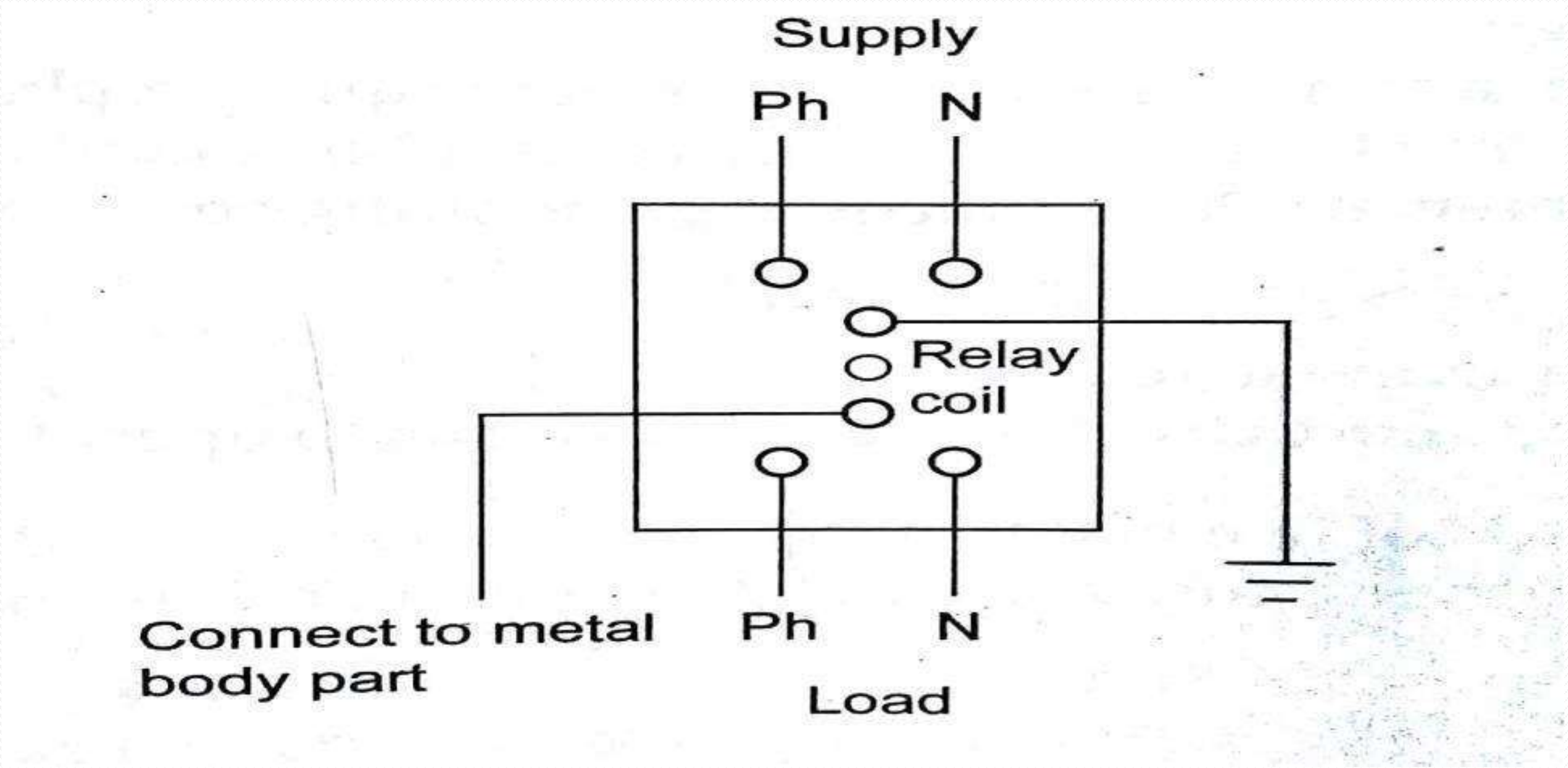


Figure (12.11): *Cross-section of MCB*

(ELCB):
VOLTAGE TYPE ELCB



Earth Leakage Circuits Breaker (ELCB):
CURRENT TYPE ELCB

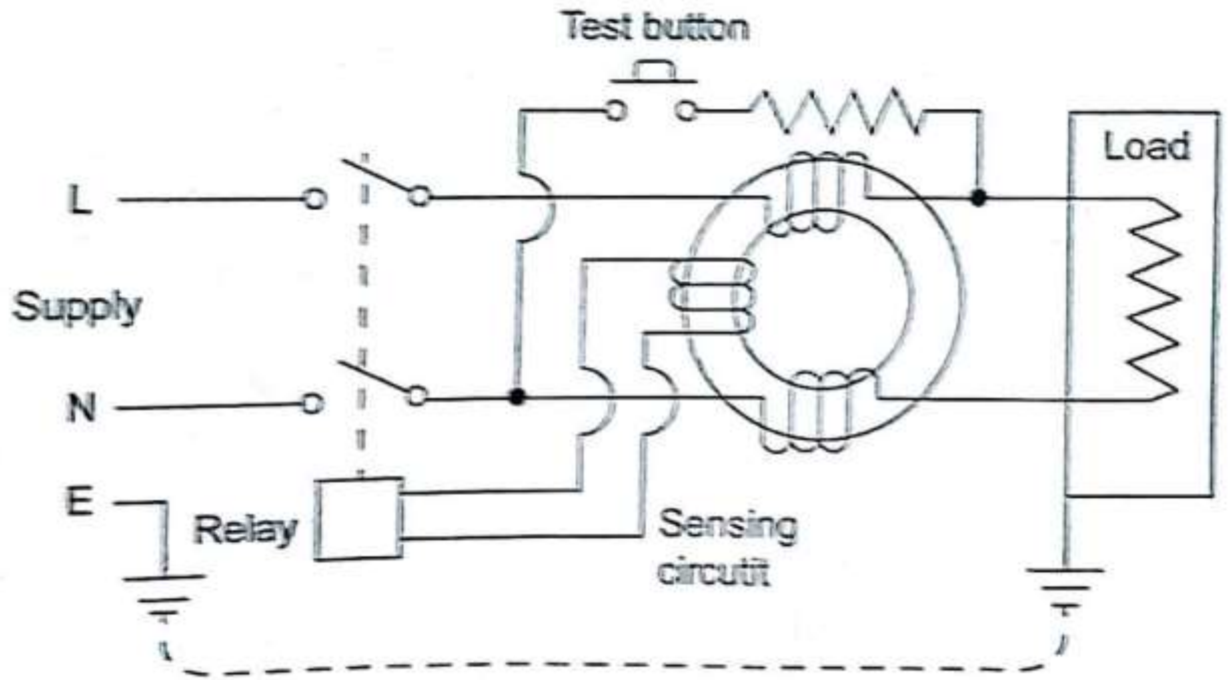


Figure (12.13): *Current earth leakage circuit breaker*