BASIC ELECTRICAL ENGINEERING
(EE101/ EE 201)

Online Courseware (OCW)

B.TECH (1ST YEAR – 1ST /2ND SEM)

(2019-20)

Prepared by: Ms. Rikta Majumder

Department of Electrical Engineering

Guru Nanak Institute of Technology
(Affiliated to MAKUT, West Bengal , Approved by AICTE - Accredited by NAAC – 'A+' Grade)
157/F Nilgunj road, Panihati, Kolkata-700114, West Bengal

Paper Name: Basic Electrical Engineering
Paper Code: EE101/EE201
Contacts: 3L
Credit: 3

Course Content

Paper Name: Basic Electrical Engineering
Paper Code: EE101/EE201
Contact hours: 3L per week
Credit: 3

Pre-requisites

- **Basic 12th standard Physics and Mathematics.**
- **Concept of components of electric circuit.**

Course Objective

To introduce the students to basic principles of DC and AC circuits, Electrical Machines and Electrical Systems.

Course Outcome

At the end of this course, students will able

EE101/EE201.1. To understand Basic Electrical circuits, Power distribution and Safety measures.

EE101/EE201.2. To analyze an apply DC network theorems.

EE101/EE201.3. To analyze and apply concept of AC circuits of single-phase and three-phase.

EE101/EE201.4. To analyze and apply concepts of AC fundamentals in solving AC network problems.

EE101/EE201.5. To understand basic principles of Transformers and Rotating Machines.

CO-PO Mapping:

	PO1	PO2	PO3	PO 4	PO5	PO6	PO7	PO8	PO9	P10	P11	P12
EE 101/201. 1	3	1	-	-	-	2	-	-	-	2	2	1
EE 101/201. 2	2	3	-	-	-	-	-	-	-	-	1	1
EE 101/201. 3	2	3	1	-	-	-	-	-	-	-	1	1
EE 101/201. 4	1	2	3	1	-	-	-	-	-	-	-	1
EE 101/201. 5	3	-	-	-	-	-	-	-	-	-	-	1

Course contents

Module I: DC Circuits (8L)

Definition of electric circuit, linear circuit, non-linear circuit, bilateral circuit, unilateral circuit, Dependent source, node, branch, active and passive elements, Kirchhoff's laws, Source equivalence and conversion, Network Theorems - Superposition Theorem, Thevenin's Theorem, Norton Theorem, Maximum Power Transfer Theorem, Star-Delta Conversions.

Module II: AC Fundamentals (8L)

Sinusoidal quantities, Average and RMS values, peak factor, Form factor, Phase and Phase difference, concept of phasor diagram, V-I Relationship in R, L, C circuit, Combination R-L-C in series and parallel circuits with phasor diagrams, impedance and admittance, impedance triangle and power triangle, Power

factor, concept of resonance, Power in AC circuit, simple problems (series and parallel circuit only), Three-phase balanced circuits, Concept of three-phase power measurement.

Module III: Single-Phase Transformer (4L)

Brief idea on constructional parts, classifications, working principle. Problems on EMF equation. Phasor diagram, Equivalent circuit.

Module IV: Electrical Rotating Machines (7L)

a) DC Machines (4L)

Brief idea on constructional features, classifications, working principle of both motor and generator. Simple problems on Voltage equation.

b) Three-Phase Induction Motor (3L)

Basic concept of three phase circuit and production of rotating magnetic field. Working principle of three-phase induction motor and torque-speed characteristics (concept only). No numerical problem.

Module V: General Structure of Electrical Power System (1L)

Power generation to distribution through overhead lines and underground cables with single line diagram.

Module VI: Electrical Installations (2L)

Earthing of Electrical Equipment, ideas of basic components- MCB, MCCB, ELCB, SFU, Megger.

Project Domains:

a) **DC Network Theorem**

b) **R-L-C Circuit**

c) **Transformers**

d) **DC Motors**

Text books:

1. D. P. Kothari & I. J. Nagrath, Basic Electrical Engineering, TMH.
2. V. Mittle & Arvind Mittal, Basic Electrical Engineering, TMH.
3. Ashfaq Hussain, Basic Electrical Engineering, S. Chand Publication.
4. Chakrabarti,Nath & Chanda, Basic Electrical Engineering, TMH.
5. C.L. Wadhwa, Basic Electrical Engineering, Pearson Education.

Reference books

1. E. Hughes, “Electrical and Electronics Technology”, Pearson, 2010.
2. V. D. Toro, “Electrical Engineering Fundamentals”, Printice Hall India, 1989

MODULE I

DC CIRCUITS

Electric Circuit

Anelectric circuit is a closed conducting path through which an electric current either flows or is intended to flow. The basic electric circuit consists of
a)Source of energy
b) Two conductors connecting the source and the load to transfer the energy.

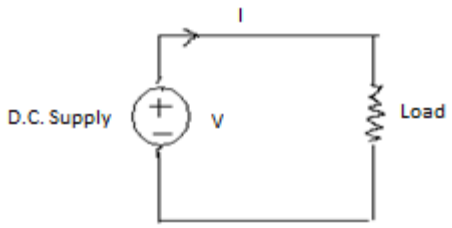


Fig.1.1 Electric circuit with resistive load

Network:

Component of circuit elements are resistor, inductor and capacitor, voltage source and current source. An interconnection of circuit elements is called a network.

Linear Circuit:
The parameters of linear element remains constant i.e the parameters do not change with current or voltage applied to the element(i.e R,L,C).The linear element shows linear characteristics of voltage vs. current (for constant temperature and frequency).

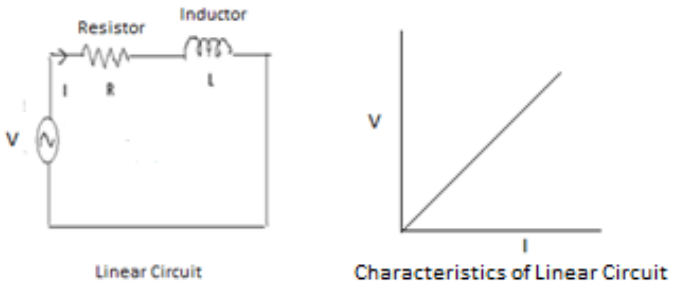


Fig. 1.2

Non Linear Circuit:

In a non linear electric circuit is an electrical element which does not have a linear relationship between current and voltage.Examples are diode, transistors and semiconductor devices. The current I through a diode is a non-linear function.

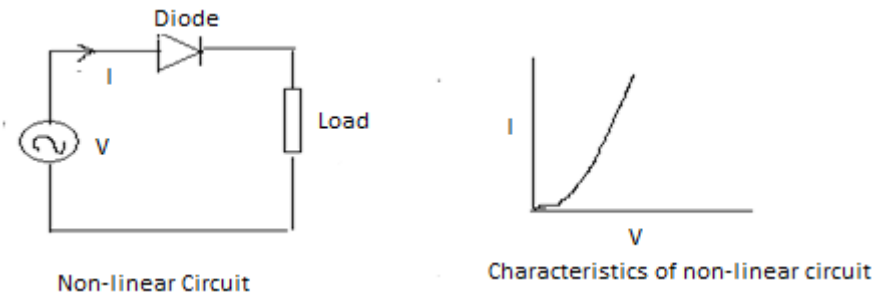


Fig. 1.3

Bilateral circuit:

Bilateral circuit is one whose properties and characteristics are same in either direction. For example, a resistor , if it is connected right to left or left to right whose properties and characteristics are same.

Unilateral Circuit:

Unilateral circuitis the circuit where properties and characteristics change with the direction of operation (direction current). Diode rectifier is the best example of unilateral circuit.

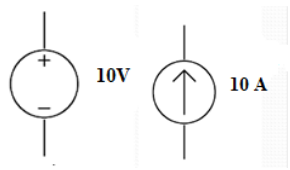
1.1 Electrical Sources

There are two types of electrical sources.

- Independent Sources and
- Dependent sources.

Independent Sources:

The strength of voltage or current is not changed by any variation in the connected network the source is said to be either independent voltage or independent current source. In this, the value of voltage or current is fixed and is not adjustable.



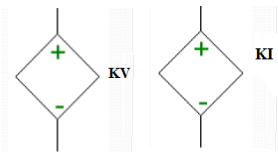
a) Independent Voltage Source Symbolb) Independent Current Source Symbol

Fig.1.4

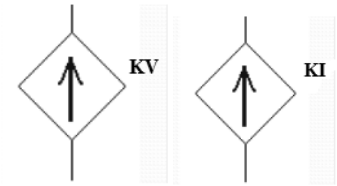
Dependent Sources:

The output voltage or current of a dependent source is determined by one of the parameters associated with another component in the circuit.

Dependent Sources are classified as:



i) Voltage controlled voltage source ii) Current controlled voltage source



iii) Voltage controlled current source iv) Current controlled current source

Fig.1.5

Node:A node is the point of connection between two or more branches. A node is a point where two or more circuit elements meet.

Branch:A branch represents a single element such as a voltage source or a resistor.

Active Element: The active elements generate energy. Batteries, generators, operational amplifiersetc are active elements.

Passive Element:A passive **element** is an electrical component that does not generate power, but instead dissipates, stores, and/or releases it. Passive **elements** include resistances, capacitors and inductors.

Loop: A loop is a closed path in a circuit where two nodes are not traversed twice except the initial point.

Mesh:A mesh is a closed path in a circuit with no other paths inside it, in other words, a loop with no other loops inside it.

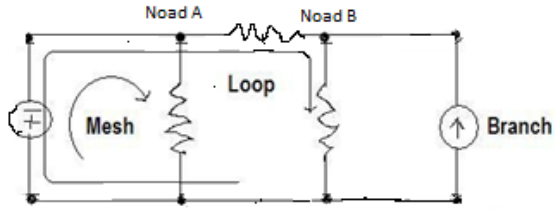


Fig.1.6

In the above fig.1.6, we find that the circuit has ***2 nodes*** and ***3 meshes(independent loops)***

1.3 Kirchoff's Laws

There are some simple relationships between currents and voltages of different branches of an electrical circuit.

Kirchhoff's Current Law (KCL):

If we consider all the currents enter in the junction are considered as positive sign, then convention of all the branch currents leaving the junction are negative.

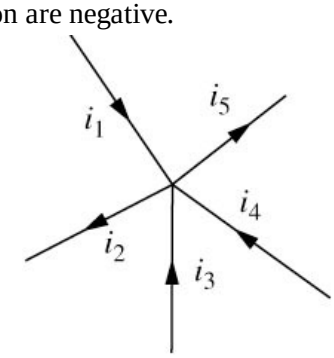


Fig.1.7

Mathematically we can write, $i_1 + (-i_2) + i_3 + i_4 + (-i_5) = 0$

Kirchhoff's Voltage Law (KVL):

This law deals with the voltage drops at various branches.

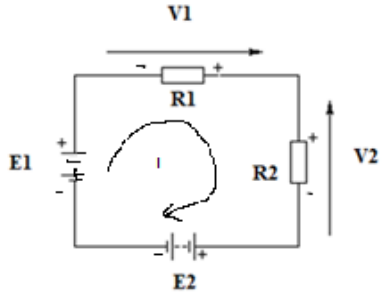


Fig.1.8

Mathematically we can write, E1+ V1-V2-E2 =0

Sign of Battery

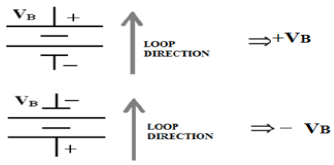


Fig.1.9

For a battery, the polarity is usually indicated on the battery with "+" or "-" near one of the terminals.

Sign of Resistor Voltage Drop Polarity

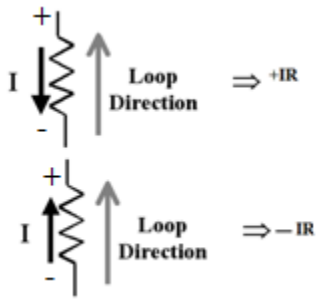


Fig.1.10

The direction of current flow through a resistor determines the polarity of resistors in a circuit.

1.4 Source Equivalence and Conversion

Source transformation is simplifying a circuit solution by transforming a voltage into a current source, and vice versa.

Conversion of voltage source to current source

Convert the constant voltage source shown in figure 1.11 to constant current source.

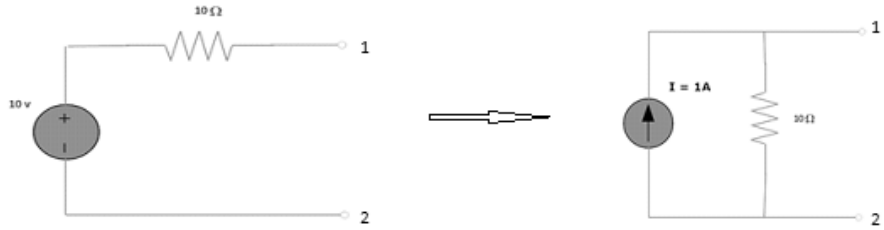


Fig.1.11

Conversion of current source to voltage source

Convert the constant current source shown in figure 1.12 to voltage source.

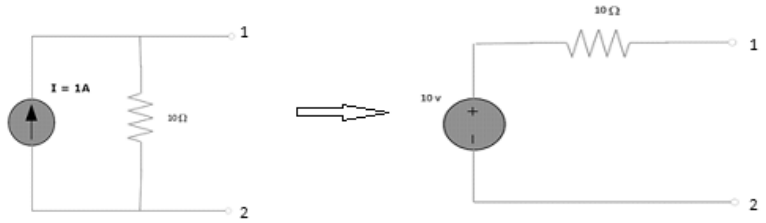


Fig.1.12

We have to do same inverse procedure.

1.5 Network Theorem

Superposition Theorem:

Superposition theorem states that, "In a network of linear resistances containing more than one source of e.m.f., the current which flows at any point is the sum of all the currents which would flow at that point if each source of e.m.f where considered separately and all the other source of e.m.f replaced for the time being by resistances equal to their internal resistances."

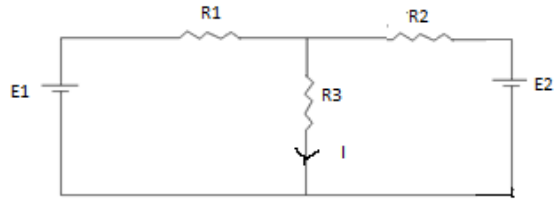


Fig.1.13

- Replace all other independent voltage sources with a short circuitand current sources with an open circuit.
  - Once voltage drops and/or currents have been determined for each individual source working separately, the values are added algebraically to find the actual voltage drops/currents with all sources active.

Step 1 : To find I_1

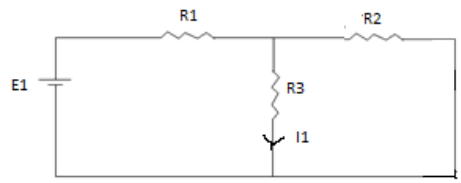


Fig.1.14

Step 2 : To find I_2

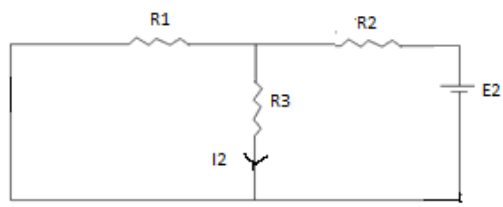


Fig.1.15

Step 3 : Total current I = $I_1 + I_2$

Thevenin's Theorem

Statement: The current flowing through a load resistance R_L connected across any two terminals X and Y of a bilateral, linear network is given by $\frac{V_{TH}}{R_{TH}+R_L}$, where V_{TH} is the open circuit voltage and R_{TH} is the Thevenin's resistance of the network as viewed back into the open circuited network from terminals XY deactivating all the independent sources.

Procedure to solve any network using Thevenin's Theorem:

Step-I:

To findV_{TH}:

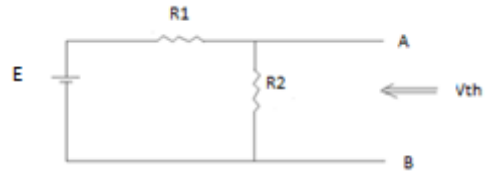


Fig.1.16

Calculation:

$V_{TH}=IR_2$ ..... (i)

Where, $I=\frac{E}{R_1+R_2}$ ……..……...…… (ii)

$V_{TH}=\frac{E}{R_1+R_2}R_2$ …… (iii)

Step-II:

To find R_{TH}:

Calculation:

$R_{TH}=\frac{R_1R_2}{R_1+R_2}$ …….....…….. (iv)

Step-III: To find I_L:

Thevnin's Equivalent Circuit:

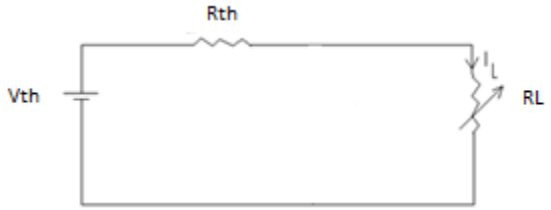


Fig.1.17

Calculation:

$$I_L = \frac{V_{TH}}{R_{TH} + R_L}$$

Norton's Theorem

Statement:

Procedure to solve any network using Norton's Theorem:

Step-I:

To find I_{SC}:

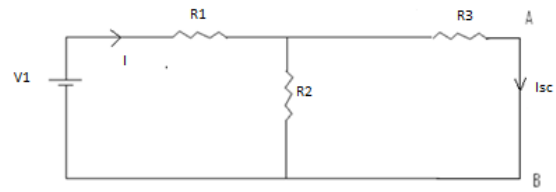


Fig.1.18

Calculation:

$$I = \frac{V1}{R_{eq}} = \frac{V1}{R_1 + \frac{R_2 R_3}{R_2 + R_3}}$$

$$I_{SC} = I \, X \, \frac{R_2}{R_2 + R_3}$$

Step-II:To find R_N:

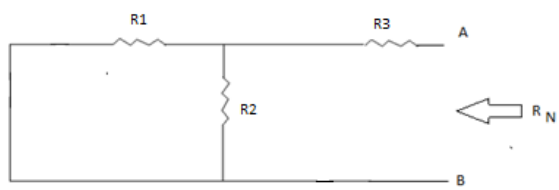


Fig.1.19

Calculation:

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

Norton's Equivalent Circuit:

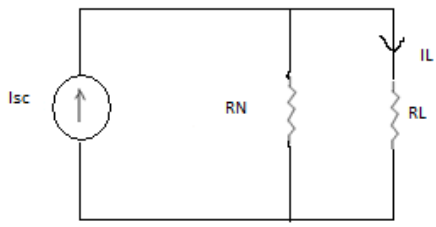


Fig.1.20

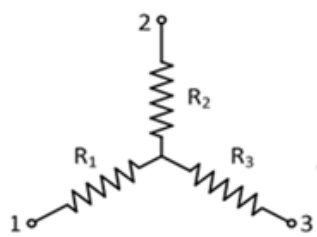
Calculation:

$$I_L = Isc\ X\ \frac{R_N}{R_N + R_L}$$

Star – Delta Conversion:

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).

Star Delta Transformations allow us to convert impedances connected together in a 3-phase configuration from one type of connection to another.These circuit transformations allow us to change the three connected resistances (or impedances) by their equivalents measured between the terminals 1-2, 1-3 or 2-3 for either a star or delta connected circuit



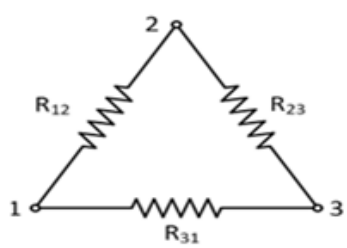


Fig.1.21 Star Connection Fig.1.22Delta Connection

From fig. (1) and fig. (2)

Resistance between terminal 1 and 2 for Star network = resistance between terminal 1 and 2 for Delta network

$R_1 + R_2 = R_{12} || (R_{23} + R_{31})$

$= R_{12} (R_{23} + R_{31}) / (R_{12} + R_{23} + R_{31})$ ……(i)

Similarly ,

$R_2 + R_3 = R_{23} (R_{31} + R_{12}) / (R_{12} + R_{23} + R_{31})$ ……..(ii)

$R_3 + R_1 = R_{31} (R_{12} + R_{23}) / (R_{12} + R_{23} + R_{31})$ ……..(iii)

Equations for the transformation from Δ to Y :

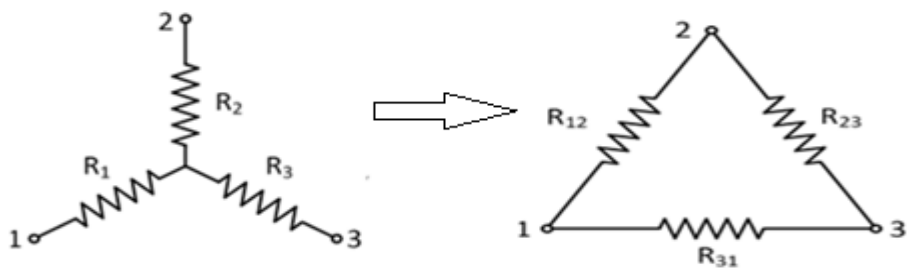


Fig.1.23

Adding the equation (i) , (ii) and (iii)

$(R_1 + R_2 + R_3) = (R_{12} R_{23} + R_{23} R_{31} + R_{31} R_{12}) / (R_{12} + R_{23} + R_{31})$

…….(iv)

Subtraction of equation (ii) from equation (iv)

$R_1 = R_{12} R_{31} / (R_{12} + R_{23} + R_{31})$ …….. (v)

Similarly ,

$R_2 = R_{12} R_{23} / (R_{12} + R_{23} + R_{31})$ …….(vi)

$R_3 = R_{23} R_{31} / (R_{12} + R_{23} + R_{31})$ ……..(vii)

Equations for the transformation from Y to Δ :

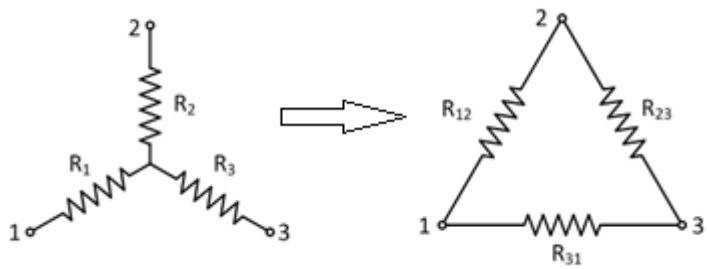


Fig.1.24

From the equation (v) , (vi) and (vii)

We gate,

$R_1 R_2 + R_2 R_3 + R_3 R_1 = R_{12} R_{23} R_{31} / (R_{12} + R_{23} + R_{31})$ …….(viii)

Division of equation (viii) by equation (viii) ,

$R_{12} = (R_1 R_2 + R_2 R_3 + R_3 R_1) / R_3$

Similarly ,

$R_{23} = (R_1 R_2 + R_2 R_3 + R_3 R_1) / R_1$

$R_{31} = (R_1 R_2 + R_2 R_3 + R_3 R_1) / R_2$

Maximum Power Transfer Theorem:

This theorem is used to value of load resistance for which maximum power will be transfer from source to load.

Statements of Maximum Power Transfer Theorem:

A resistive load abstracts maximum power from a network when the load resistance equals to the internal resistance of the network as viewed back to the network from output terminals, with all energy sources removed, leaving behind their internal resistances.

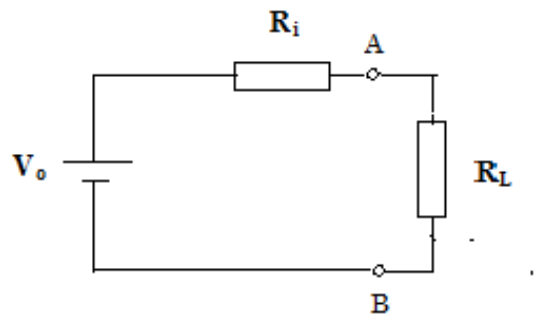


Fig.1.25

Proof of Maximum Power Transfer Theorem:

A variable resistance R_L is connected to a dc source network. The aim is to determine the value of R_L such that it receives maximum power from the dc source.

$I_L = V_0 / (R_i + R_L)$ .....(i)

The power delivered to the resistive load is given by

$P_L = I_{L2} R_L = [V_0 / (R_i + R_L)]^2 R_L$ .....(ii) [substituting IL from equation (i)]

For PL to be maximum,

$dP_L / dR_L = 0$

$R_i = R_L$

Hence, it has been prove that the power transfer from a dc source network to a resistive load is maximum when the internal resistance of the dc source network is equal to the load resistance.

$P_{max} = = V_0^2 / 4 R_{th}$

The maximum power transfer theorem defines the condition under which the maximum power is transferred to the load in a circuit.

Multiple Choice Type Questions:

1. In an electrical network, mesh is defined as
(a)any closed path (b)a loop containing other loops
(c) the shortest possible loop (d) the longest loop

2. Kirchoff's voltage law is concerned with
(a) IR drops (b) battery emfs
(c) junction voltages (d) both (a) and (b)

3.Mesh Analysis is based on

(a) KVL (b)KCL

(c) Ohm's Law (d) Law of conservation of energy

4. Which among the following is also regarded as 'Dual of Thevenin's Theorem'?

a. Norton'sTheorem
b. SuperpositionTheorem
c. Millman'sTheorem
d. Maximum Power Transfer Theorem

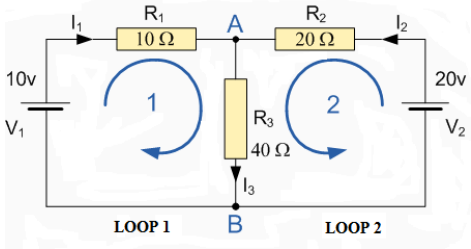
Ans. a

5. Which is the correct sequential order of steps to be undertaken while applying Thevenin's theorem?

A. Calculation of Thevenin's equivalent voltage
B. Removal of branch impedance through which required current is to be estimated
C. Estimation of equivalent impedance between two terminals of the branch
D. Estimation of branch current by schematic representation of Thevenin's equivalent circuit

a. A,C,B,D
b. B,A,C,D
c. D,A,C,B
d. B, C, D, A

6. Determine the values of the current flowing through each of the resistors.



Solution:

At node A by KCL ,we can write $I_1 + I_2 = I_3$ .....(1)

By KVL, in loop 1,we can write $10 - I_1R_1 - I_3R_3 = 0$ ……..(2)

By KVL, in loop 1, we can write $20 - I_2R_2 - I_3R_3 = 0$ ……. (3)

Substituting the value of I_3 from equation (1) to equation (2) we write

$10 - I_1R_1 - (I_1 + I_2)\ R3 = 0$

Or $10 - 10\ I_1 - 40(I_1 + I_2) = 0$ …….(A)

Again substituting the value of I_3 from equation (1) to equation (3) we write

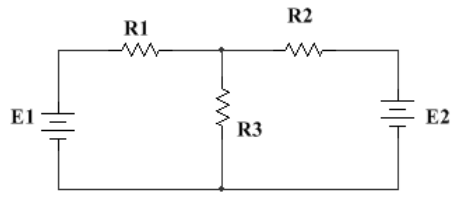
$20 - I_2R_2 - (I_1 + I_2)R_3 = 0$

Or $20 – 20I_2 - 40(I_1 + I_2) = 0$…….(B)

Solving Equation (A) and (B) we get that

I_1= 0.143 Amps and I_2= 0.429 Amps.

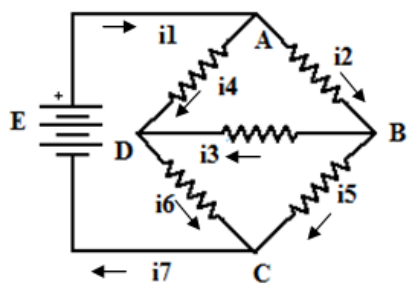
7. Find out the value of current in resistance R3 in the given diagram:



Given: E_1=10V,E_2= 5V, R_1= 50 ohm,R_2= 75 ohm,R_3= 20ohm.(**Ans: Current in R3= 0.16 Amp**)

8. Find the magnitude and direction of unknown currents in the given figure:

Given i_1= 10A, i_2=6A, i_5= 4 A



Solution:

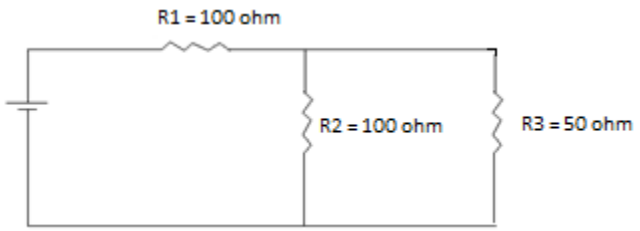
By observation, we findthat i_1=i_7 = 10 A
At node A, by KCL, i1 = i2+i4
Or 10= 6+ i4
Or i4= 4A

At node B, by KCL, i2 = i3+i5
Or i3 = i2 – i5 = 6 - 4 =2A

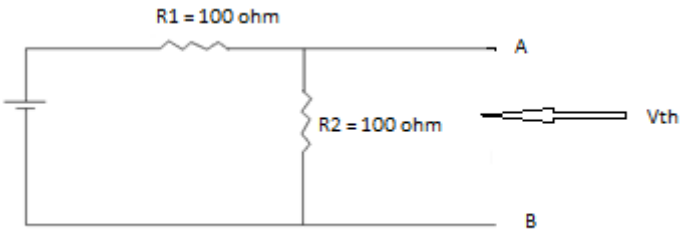
At node C, by KCL, i7= i5 +i6
Or i6= i7 – i5 = 10- 4=6A
All unknown branch currents of the network are given as: i2= 6A, i4= 4A, i6= 6A (Ans)

Example: 9

Find the current possesses through 50 Ω resistance from the given circuit diagram using Thevenin's theorem.



Solution:



Calculation:

$V_{TH}=IR_2$ ..... (i)

Where, $I = \frac{E}{R_1+R_2}$ ……..……..…… (ii)

$V_{TH} = \frac{E}{R_1+R_2} R_2$ …… (iii)

$V_{TH} = \frac{4}{100+100}$ X 100

V_{TH}= 2 Volt

Step-II:

To find R_{TH}:

Calculation:

$R_{TH} = \frac{R_1 R_2}{R_1+R_2}$ …….....…….…….. (iv)

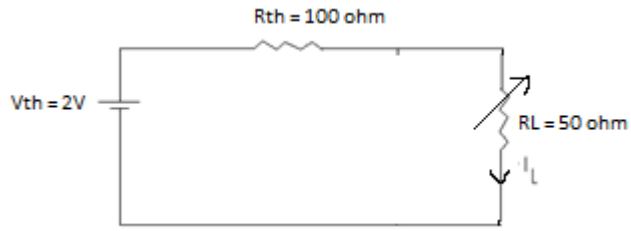
$R_{TH} = \frac{100x100}{100+100}$

R_{TH}= 50 ohm

Step-III:

To find I_L:

Thevnin's Equivalent Circuit:



Calculation:

$$I_L = \frac{V_{TH}}{R_{TH} + R_L}$$

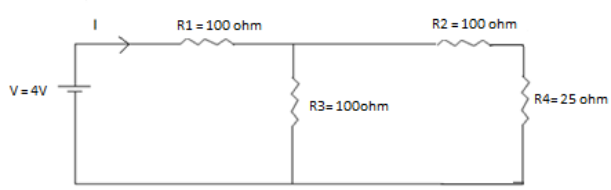
$$I_L = \frac{2}{50 + 100}$$

$I_L = 0.01333 \text{ mA}$.

$$I_L = 13.33 \text{ A}$$

Example .10

Find current passes through 25 Ω resistance using Norton's theorem from the given circuit diagram.



Ans. I_L = 0.857 A

AC FUNDAMENTALS

2.1 Introduction:

Electrical voltage can be generated in two forms, i.e. DC and AC. Pure DC signals have

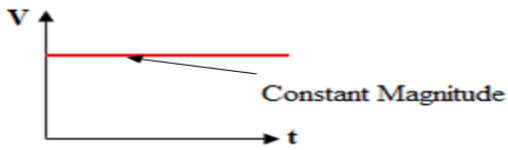


Fig.1 DC Voltage

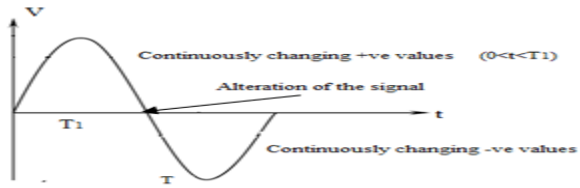


Fig.2 AC Voltage

constant magnitude that does not vary with time. But, alternating voltages have continuously changing magnitude with respect to time and these voltages alter their polarity (+ve/ -ve) after certain interval of time. Fig. 1 and fig.2 below shows a dc and ac signals respectively. Due to its own advantages over dc voltage ac voltages are widely used to generate, transmit, and distribute electric power. In Indian standard alternating voltage is generated at 50Hz frequency.

2.2 Generation of Sinusoidal (AC) Voltage:

Whenever there is a relative motion between a coil, placed in a magnetic field and the magnetic field an alternating voltage may be generated.

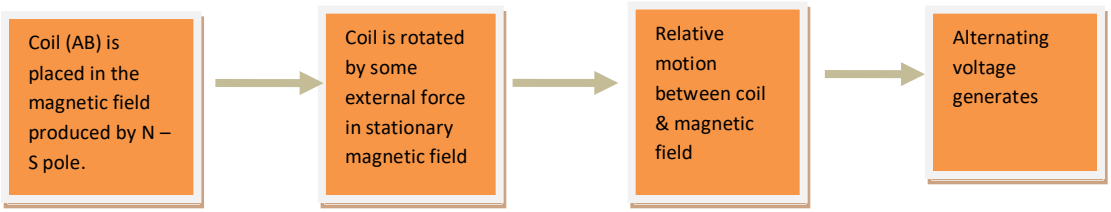


Fig. 3 Block Diagram representation of AC voltage generation

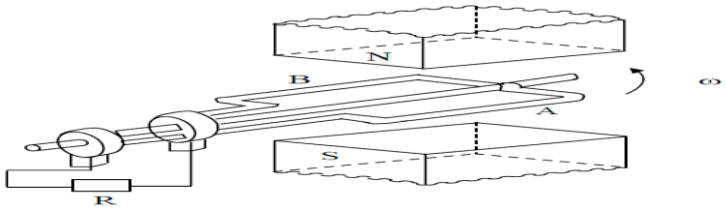


Fig. 4 Schematic Diagram

secs the coil rotates an angle θ from horizontal axis (Fig.5). At this position the component of flux $\Phi = \Phi_m \text{Sin}\omega t$ is perpendicular to the coil plane.

According to Faraday's laws of electromagnetic induction, At any time t instantaneous voltage generated (EMF) in coil

$$\mathbf{e = -T\frac{d\Phi}{dt}} \quad \text{.....(i)}$$

By substituting, $\Phi = \Phi_m \text{Sin}\omega t$ and solving above equation

$$\mathbf{e = E_m \text{Sin}\omega t = E_m \text{Sin}\theta \text{.....(ii)}}$$

Where, $\mathbf{E_m = \omega T \Phi_m}$..... (iii)

When coil is rotated by 90°, i.e, $\boldsymbol{\theta = 90°}$, voltage is maximum.

Fig. 5 Coil position at any time t

2.3 Basic Terms:

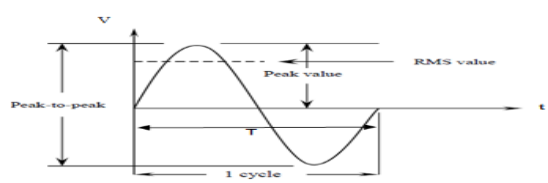


Fig. 5 Sinusoidal AC Waveform

Amplitude: Peak value attained by an alternating wave.

Cycle: A complete set of positive and negative values of an alternating wave**.**

Time Period (T): Time taken to complete one full cycle by an alternating wave.

Frequency (f): Number of cycles completed in one sec. Unit is Hz**.**

Phase angle (θ): Fraction of time period of alternating quantity that has elapsed since the cycle has started. Phase angle is expressed in rad or degree.

Phase Difference: Difference in phase angle between positive zero crossing of any two alternating quantities. If waveform A passes through positive zero crossing earlier than waveform B, it is said that A is leading or B is lagging behind A.

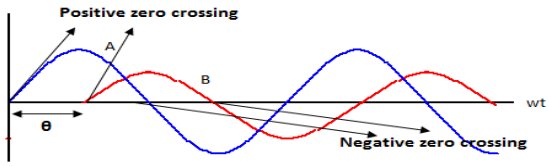


Fig. 7 Phase difference between two alternating waveforms

2.4 Relation between frequency (f) & Time period (T):

f cycles are completed in 1 sec

1 cycle is completed in $\frac{1}{f}$ sec

Hence, $T = \frac{1}{f}$

2.5 Different forms of EMF equation:

Instantaneous voltage generated,

$$e = E_m \sin\omega t = E_m \sin\theta = E_m \sin 2\pi ft = E_m \sin\frac{2\pi}{T} \text{.....(iv)}$$

2.6 Average value or Mean value of a Sinusoidal waveform:

It is the amount of steady or direct current of an alternating current that transfer same amount of charge as transferred by that alternating current during same time.
Mathematically,

$$\text{Average value} = \frac{\text{Total Area covered by an alternating wave during certain period}}{\text{Total Time Period}}$$

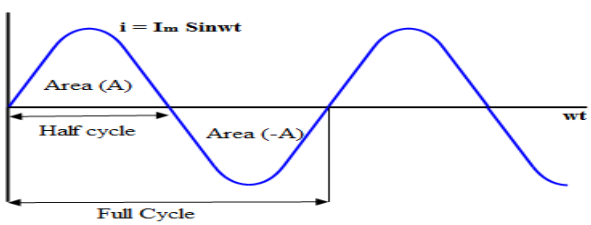


Fig 8

Average value of alternating wave is calculated over full cycle for unsymmetrical waves. For symmetrical waves average value is zero over a full cycle. Hence, for such waves it should be calculated over positive half cycle / negative half cycle.

The average value of sinusoidal alternating current is given by**:**

$$I_{av} = \frac{1}{\pi}\int_0^{\pi} i\, d(wt) = 0.637\, I_m \text{[Substitute, } i = I_m \text{Sinwt].....(v)}$$

2.9 RMS value or Effective value of a Sinusoidal waveform

It is the steady or direct current of an alternating quantity which produces same heat when passed through a circuit for certain period of time as produced by the alternating quantity.

Fig. 9

Let, direct current I current passes through R resistance for t time and produces H_1 heat. Alternating current i_{ac} passes through the same circuit for same time and produces H_2 heat.

If, $H_1 = H_2$, then I is the RMS value of i_{ac}.

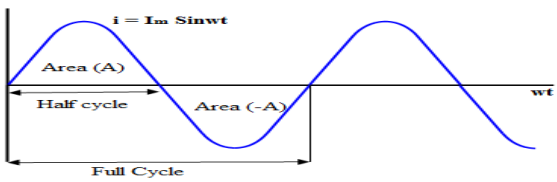


Fig. 10 AC waveform

$$\mathbf{I = I_{rms}} = \frac{\sqrt{i_1^2+i_2^2.....+i_n^2}}{2\pi} = \frac{\sqrt{\int_0^{2\pi} i^2 d(wt)}}{2\pi} = I_m/\sqrt{2} = \mathbf{0.707\ I_m}$$ [Substitute i= I_m Sinwt]……. (vi)

RMS value for any wave (symmetrical/ Unsymmetrical) is calculated over a full cycle. Although for the sinusoidal wave shown in above figure has zero average value over a full cycle, but rms value will have a positive value (As for RMS value we need to find squared values of area covered in a full cycle)

Form Factor: Ratio of RMS value and average value of an alternating quantity.

$$\text{Form Factor(FF)} = \frac{I_{rms}}{I_{av}} = 1.11 \text{(For sine wave)}$$

More closer the FF to unity (1), better is waveform quality.

Crest Factor/ Peak Factor: Ratio of peak value and RMS value of an alternating quantity.

$$\text{Crest Factor(CF)} = \frac{I_m}{I_{rms}} = 1.414$$

Phase Difference of a Sinusoidal Waveform

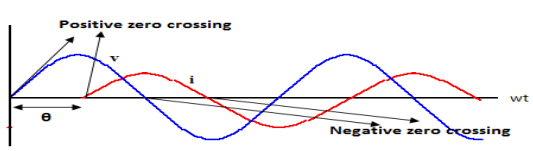


Fig. 11 Phase difference between voltage & current

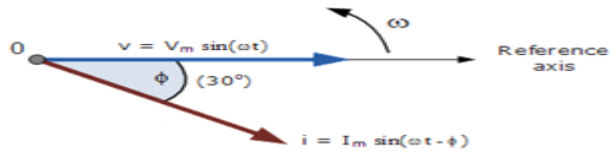
The generalized mathematical expression to define these two sinusoidal quantities will be written as:

$$v = V_m \text{Sin } wt$$

$$i = I_m \text{Sin } (wt - \theta)$$

From above two equations, it is found that phase difference between v & i is θ and –ve sign indicates i lags behind v.

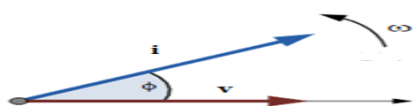
Phasor Diagram representing above equations:



Similarly, if current i leads voltage v, the phasor diagram can be written as:

$$v = V_m \text{Sin } wt$$

$$i = I_m \text{Sin } (wt + \theta)$$



2.10 Complex Number:

Any phasor quantity can be represented in different forms.
i. Trigonomatric form, ii. Exponential form,iii. Polar form.

Trigonomatric form: V = V(cosΦ+sinΦ)
Polar form: V = V ∠ +Φ°
Rectangular form: V = a+jb

2.10.1 Mathematical Operation of Phasors:

- For addition and subtraction operation, rectangular forms are used. Such operations can't be performed in polar form.
- For multiplication and division operation, rectangular forms can be used, but not preferred. Such operations are performed in polar form.
- Let, A = X ∠ +Φ° & B = Y ∠ +α°

Then, A*B = XY ∠ +(Φ°+ α°) ; A/B = X/Y ∠ +(Φ°- α°)

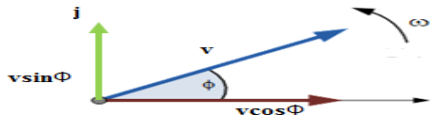
Let, A = a+jb & C = c+jd

Then, A+C = (a+c) + j(b+d)

2.10.2 Conversion of POLAR form into RECTANGULAR form

Let, **v** = v∠ +Φ° = v(cosΦ + j sinΦ) = a+jb

Where, a = vcosΦ b= vsinΦ



2.10.3 Conversion of RECTANGULAR form into POLAR form

Let, A = a+jb

Magnitude of A , X = $\sqrt{a^2 + b^2}$ **;** Angle of A, Φ = $\tan^{-1}\frac{b}{a}$

2.11 Significance of j operator:

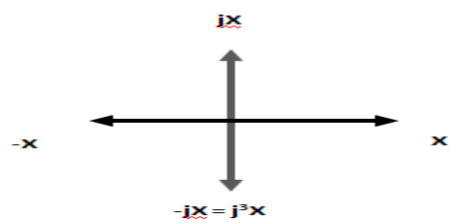


Fig. 12

Hence, if X is multiplied by j twice, the quantity will be rotated through 180° in anticlockwise direction. if X is multiplied by j once, the quantity will be rotated through 90° in anticlockwise direction. if X is multiplied by j thrice, the quantity will be rotated through 270° in anticlockwise direction.

Let, Z = R+jX, this indicates R and X are 90° apart and X leads R.

Z = R-jX, this indicates R and X are 90° apart and X lags behind R.

EXAMPLE I: An alternating voltage is given by the equation v = 10 sin (628 t + $\frac{\pi}{6}$) .Find theRms value ,(b) frequency, (c)time period (d) form factor (e) peak factor (f) average value.

We know, $v = V_m Sin\,(wt + \theta)$

By comparison, V_m = 10 V; ω= 2πf = 628; θ = $\frac{\pi}{6}$

So, (a) $V_{rms} = \frac{V_m}{\sqrt{2}}$ = 7.07 V (f) V_{av} = 0.637* V_m = 6.37 V (b) f = $\frac{\omega}{2\pi}$ = 100Hz ,

(c) T = $\frac{1}{f}$ = 0.01 secs (d) FF = $\frac{V_{rms}}{V_{av}}$ = 1.11 (e) Peak factor = $\frac{I_m}{I_{rms}}$ =1.414

KEY POINTS:

- DC has no frequency, constant magnitude.
- AC has specific frequency, changing magnitude.
- Average value of a sinusoidal ac signal should be calculated over a half cycle.
- RMS value of a sinusoidal ac signal should be calculated over a full cycle.
- All electrical machines, devices operate at 50Hz signal in India and rated in RMS value.
- For a better quality waveform, FF should be close to unity.
- Phasor addition & subtraction is not possible in polar form. Hence, POLAR to RECTANGULAR form conversion is necessary.
- Phasor multiplication and division is possible in rectangular form. But it is preferred to perform such operations in rectangular form. Hence, RECTANGULAR to POLAR form conversion is necessary.
- To rotate any quantity by 90º in anticlockwise direction, multiply that quantity by j.

Multiple Choice Type Questions:

1. The peak value of a sine wave is 100V. The average and RMS values are……. Respectively.
   (i) 63.7 V & 70.7 V (ii) 6.37 V & 7.07 V (iii) 0.637 V & 0.707 V (iv) none
2. Two alternating waveforms A & B have 10 secs & 20 secs time period. A has……. Than B.
   (i) Less (ii) more (iii) equal (iv) none of these

Long Questions:

1. An alternating voltage is given by the equation v = 100 sin (314 t + $\frac{\pi}{3}$) .Find the
(a) Rms value ,(b) frequency, (c)time period (d) form factor (e) peak factor (f) average value
2. A = 10 $\angle$ 30º & B = 20 $\angle$ 60º. Find A+B.
3. An alternating voltage has amplitude of 100V at 50 Hz frequency. Write down equation of instantaneous voltage. Also find the magnitude of voltage at0.01 sec.

AC through Electric Circuit

2.12 Purely resistive circuit (R only)

Let, a pure sinusoidal voltage v is applied to a purely resistive circuit having resistance R.

$$\boldsymbol{i} = \frac{\boldsymbol{v}}{\boldsymbol{R}} = \frac{\boldsymbol{V_m}}{\boldsymbol{R}} \boldsymbol{Sinwt} \ldots\ldots\ldots\ldots\ldots \text{(vii)}$$

Where, Instantaneous supply voltage,

$$v = V_m Sinwt \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(viii)}$$

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

I_m and V_m are the maximum values of current and voltage respectively.
V & I are RMS values of voltage & current respectively.

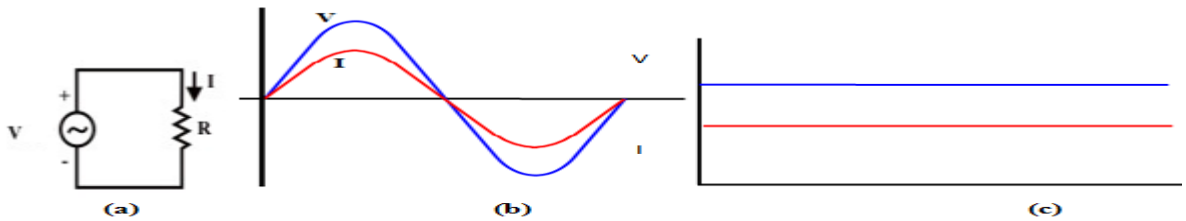


Fig. 13 (a) Purely resistive circuit with ac voltage
(b) voltage & current waveforms
(c) Phasor Diagram

- From equation (vii) & (viii), it is observed that phase angle between voltage (V) & current (I) is, $\Phi = 0^o$. In other words, V & I are in same phase.
- Hence, power factor, **cosΦ = 1 (Unity).**

2.13 Purely inductive circuit (L only)

If pure sinusoidal alternating voltage is applied to the circuit, the instantaneous voltage is given by,

$$v = V_m Sinwt \ldots\ldots\ldots\ldots\ldots\ldots(ix)$$

As we know, $v = L\frac{di}{dt}$,

$i = \frac{1}{L}\int v = V_m Sinwt$

Sol

$i = \frac{V_m}{wL} Sin(wt - 90^o) = I_m \text{ Sin } (wt\text{-}90^o)$ ……..(x)

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

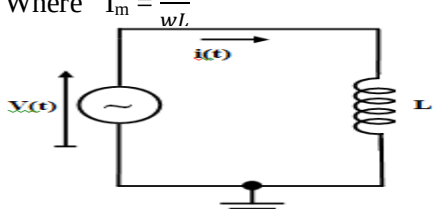


Fig . 14 Purely Inductive circuit Diagram

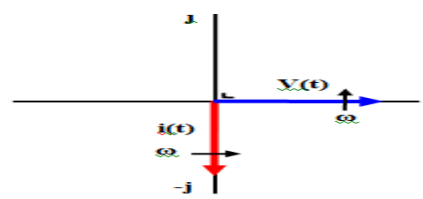


Fig 15 . Phasor

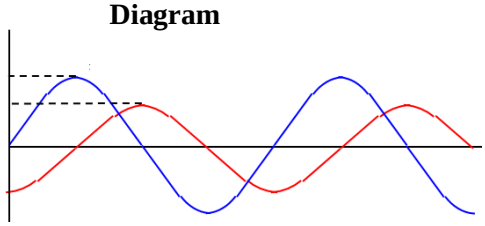


Fig. 16 Voltage & Current Waveforms

For purely inductive circuit, the term inductive reactance, $X_L = wL = 2\prod fL$ offers opposition to the flow of current. Its unit is ohm.

- For DC voltage source as frequency is zero, inductor behaves as a short circuit.
- From equation (ix) & (x), it is observed that phase angle between voltage (V) & current (I) is, $\Phi = 90^o$. **(-ve) sign indicates current is lagging**. Hence, power factor, **cosΦ = 0.**

2.14 Purely capacitive circuit (C only)

If pure sinusoidal alternating voltage is applied to the circuit, the instantaneous voltage is given by,

$$v = V_m Sinwt \ldots\ldots\ldots\ldots\ldots\ldots (xi)$$

As we know, $i = C\frac{dv}{dt}$

Solving this equation, we get ;

$i = \frac{V_m}{(1/wc)} Sin(wt + 90^o) = I_m \text{ Sin } (wt+90^o)$ ……..(xii)

Where, $I_m = \frac{V_m}{(1/wc)} = wcV_m$

For purely capacitive circuit, the term inductive reactance, $X_c = \frac{1}{wc} = \frac{1}{2\Pi fC}$ offers opposition to the flow of current. Its unit is ohm.

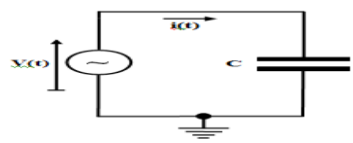


Fig. 17 Purely capacitive circuit

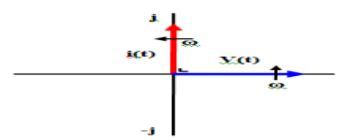


Fig. 18 Phasor

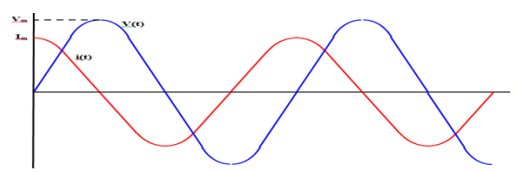


Fig. 19 Voltage & current waveforms

- Capacitive reactance decreases with increasing frequency.
- For DC voltage source as frequency is zero, capacitor behaves as an open circuit.
- From equation (xi) & (xii), it is observed that phase angle between voltage (V) & current (I) is,

  $\Phi = 90^o$. **(+ve) sign indicates current is leading voltage by 90 degree**.

- Hence, power factor, cosΦ = 0.

2.15 Series Circuits (Series RL, RC, RLC circuits)

2.15.1 Inductive circuit (R and L in series)

In the following circuit diagram,

Let, V = RMS value of supply voltage; I = RMS value of supply current

V_R = RMS value of voltage drop across resistance R ; V_L = RMS value of voltage across inductor L.

If current I is taken as reference phasor, then V_R must be in phase with I & V_L must lead I by 90º.

The supply voltage, V is phasor sum of V_R & V_L. The phasor diagram of RL series circuit is shown below.

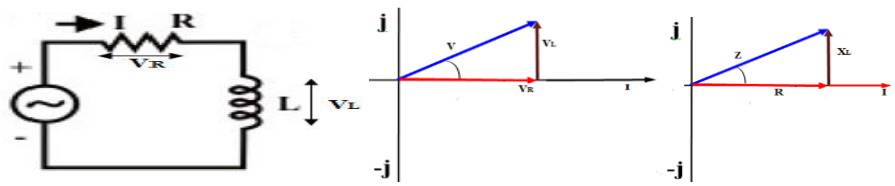


Fig. 20 Circuit Diagram **Fig. 21 Voltage Triangle** **Fig. 22 Impedance triangle**

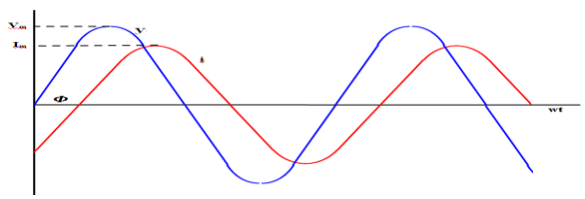


Fig. 23 Voltage & current waveforms

From Phasor diagram,

Magnitude of supply voltage, $$\mathbf{V} = \sqrt{V_R^{\,2} + V_L^{\,2}} = \mathbf{I}\sqrt{R^2 + X_L^{\,2}}$$

In ac circuit, the ratio of V& I is known as impedance of the circuit. It is denoted by Z.

$$\mathbf{Z} = \frac{V}{I} = \sqrt{R^2 + X_L^{\,2}}$$

Note that, if each side of voltage triangle is divided by I, impedance triangle is obtained.

And Phase angle, $$\mathbf{\Phi} = tan^{-1}\left(\frac{X_L}{R}\right)$$

Power factor, $$\mathbf{cos\Phi} = \frac{R}{Z}$$

Using phasor algebra,

I = I$\angle$ 0º.

V= V$\angle$ +Φº.

Z = Z$\angle$ +Φº

- Hence it is observed that in series RL circuit current lags behind supply voltage by an angle Φº.
- For a RL series circuit,
  With R resistance and very negligible inductance (L≈ 0)
  Φ = 0º.
- With Rresistance and very high inductance (L≈ infinite)
  Φ = 90º.
- So, with increase in L value, current drawn from supply will be delayed more.

- **The range of phase angle variation is**

  $0^o < \Phi < 90^o$.

- **The range of power factor,**

  $0 < \cos\Phi < 1$.

2.15.2 Capacitive circuit (R and C in series)

In the following circuit,

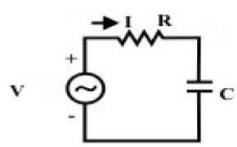
Let, V = RMS value of supply voltage; I = RMS value of supply current

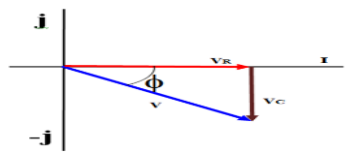
V_R = RMS value of voltage drop across resistance R ; V_c = RMS value of voltage across capacitor C.

If, current I is taken as reference phasor, then V_R must be in phase with I & V_C must lag behind I by 90°.

The supply voltage, V is phasor sum of V_R & V_L.

The phasor diagram of RC series circuit is shown below.





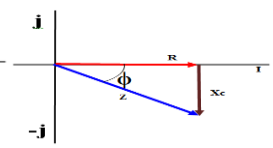


Fig. 24 Circuit Diagram **Fig. 25 Voltage Triangle** **Fig. 26**

From Phasor diagram,

Magnitude of supply voltage, $V = \sqrt{{V_R}^2 + {V_c}^2} = I\sqrt{R^2 + {X_c}^2}$

In ac circuit, the ratio of V& I is known as impedance of the circuit. It is denoted by Z.

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

And Phase angle, $\Phi = tan^{-1}(\frac{X_c}{R})$

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

Using phasor algebra,

I = I$\angle 0^o$.

V= V$\angle -\Phi^o$.

Z = $Z\angle -\Phi^o = R - j\,Xc$

Hence it is observed that in series RC circuit current leads supply voltage by an angle Φ^o.

The range of phase angle variation is

$0^o < \Phi < 90^o$

The range of power factor,

$0 < \cos\Phi < 1$

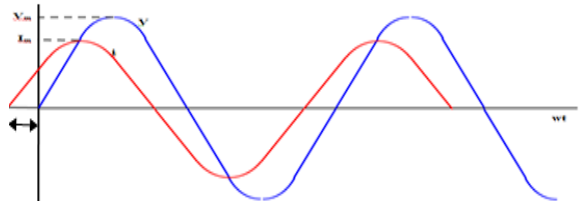


Fig. 27 Voltage & Current waveforms

- Hence it is observed that in series RC circuit current leads supply voltage by an angle Φ°.
- . **The range of phase angle variation is**

$$0^\circ < \Phi < 90^\circ.$$

- **The range of power factor,**

$$0 < \cos\Phi < 1.$$

2.15.3 Series (R-L-C) circuit

In series RLC circuit, if voltage across inductor is greater than that across capacitor, the circuit is inductive.if voltage across inductor is less than that across capacitor, the circuit is capacitive.

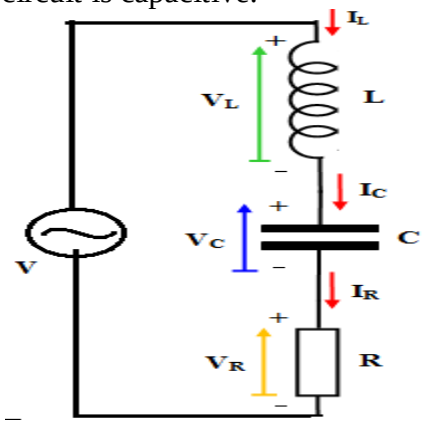


Fig. 28 RLC Series Circuit

V = RMS value of supply voltage

$I = I_L = I_R = I_C$ = RMS value of supply current

V_L = RMS value of inductor voltage

V_R = RMS value of resistor voltage

V_L = RMS value of capacitor voltage

X_L = inductive reactance

X_C = capacitive reactance

CASE I. Inductive : ($V_L > V_C$) OR ($X_L > X_C$)

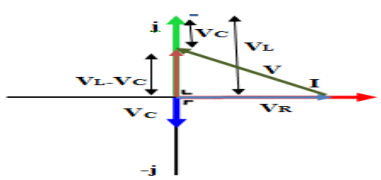


Fig. 29 Voltage Triangle

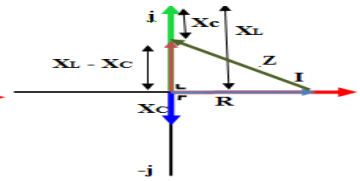


Fig. 30 Impedance Triangle

Magnitude of supply voltage, $\mathbf{V} = \sqrt{V_R^2 + (V_L - V_C)^2} = \mathbf{I}\sqrt{R^2 + (X_L - X_C)^2}$

So, impedance, $\mathbf{Z} = \sqrt{R^2 + (X_L - X_C)^2} = \mathbf{R} + \mathbf{jX}$

Phase Angle, $\boldsymbol{\Phi} = \tan^{-1}\frac{X_L - X_C}{R}$

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

Using phasor algebra,

I = **I** ∠ 0º.
V= **V** ∠ +Φº.
Z = Z ∠ +Φº = R + j X

CASE II. Capacitive: (V_L<V_C) OR (X_L <X_C)

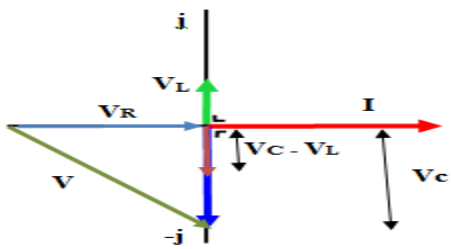


Fig. 31 Voltage Triangle

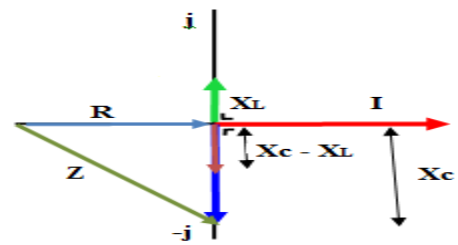


Fig. 32 Impedance Triangle

Magnitude of supply voltage, **V** = $\sqrt{V_R^2 + (V_c - V_L)^2}$ = **I** $\sqrt{R^2 + (X_C - X_L)^2}$

So, impedance, **Z** = $\sqrt{R^2 + (X_c - X_L)^2}$ = **R – jX**

Phase Angle, $\boldsymbol{\Phi} = \tan^{-1}\frac{X_C - X_L}{R}$

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

Using phasor algebra,

I = **I** ∠ 0º.
V= **V** ∠ -Φº.
Z = Z ∠ -Φº = R – j X

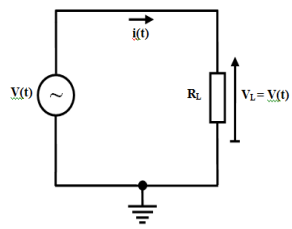
- For series RLC circuit, if $X_L > X_c$ then circuit is inductive and pf is lagging.
- For series RLC circuit, if $X_c > X_L$ then circuit is capacitive and pf is leading.
- For series RLC circuit, if $X_L = X_c$ then circuit is resistive and pf is zero.
- **The range of phase angle variation is**

  0º< Φ<90º.
- **The range of power factor,**

  0< cos Φ <1.

Power in AC circuits

2.16.1 Purely resistive circuit:



$V(t) = V_m \text{Sin } \omega t$

$i(t) = I_m \text{Sin } \omega t$

Fig.33Resistive Circuit

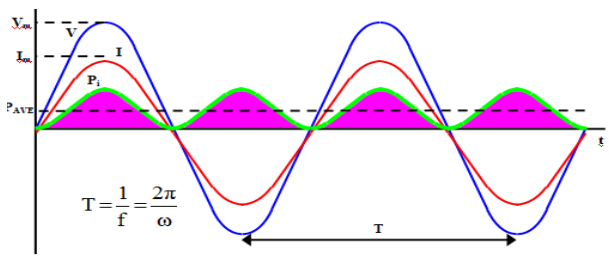


Fig. 34 voltage, current, power waveform

Instantaneous Power:

Instantaneous power is product of the instantaneous voltage across and the instantaneous current flowing through a load

p(t) = V(t)*I(t)

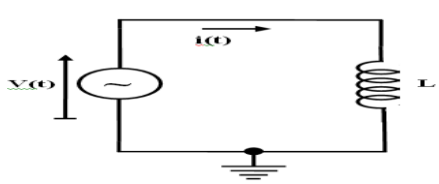
As, $V(t) = V_m \text{Sinwt}$ & $I(t) = I_m \text{Sinwt}$

So, $P(t) = V_m \text{Sinwt} * I_m \text{Sinwt} = \frac{V_m I_m}{2}(1 - \text{Cos } 2wt)$

Average Power:

$$P_{av} = \frac{1}{2\pi}\int_0^{2\pi} P(t)dt = \frac{V_m I_m}{2} = VI$$

2.16.2 Purely Inductive circuit:



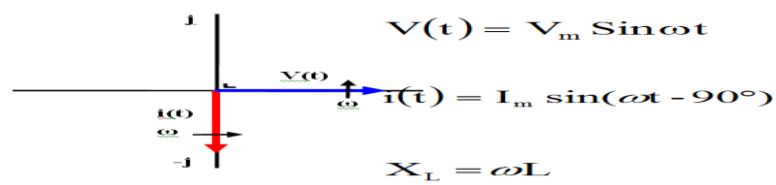


Fig.35 Circuit Diagram **Fig. 36 Phasor Diagram**

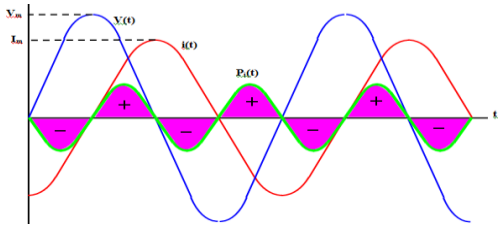


Fig. 37voltage, current, power curve

Instantaneous Power, P(t) = P(t) = V(t)*I(t)

As V(t) = V_mSinwt & I(t) = I_mSinwt

So, P(t) = V_mSinwt * I_mSin(wt - 90º)

Average Power, $\mathbf{P_{av}} = \frac{1}{2\pi}\int_0^{2\pi} P(t)dt = 0$

From power curve it is seen that power is negative in 1st quarter cycle, positive in 2nd quarter cycle and so on. Hence total power consumed by an inductor is zero. Practically, in one quarter cycle inductor consumes power from source and in next quarter cycle it releases power to source. Hence, net power consumed over a full cycle is zero.

2. 16.3 Purely Capacitive Circuit

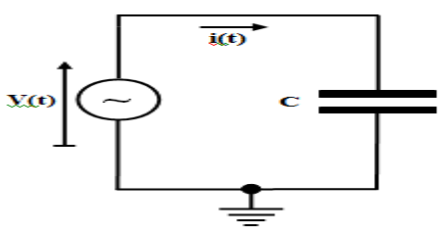
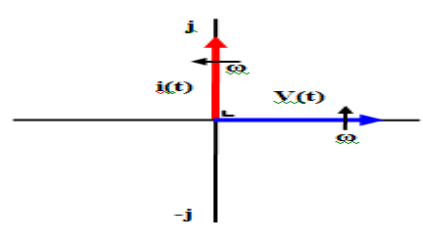


Fig. 38 Circuit Diagram



$$V(t) = V_m \, Sin\omega t$$

$$i(t) = I_m \sin(\omega t + 90°)$$

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

Fig. 39 Phasor Diagram

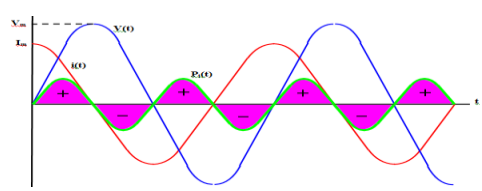


Fig. 40 Power curve

Instantaneous Power, P(t) = P(t) = V(t)*I(t)

As V(t) = V_mSinwt & I(t) = I_mSinwt

So, **P(t) = V_mSinwt * I_mSin(wt + 90º)**

Average Power, $P_{av} = \frac{1}{2\pi}\int_0^{2\pi} P(t)dt = 0$

From power curve it is seen that power is positive in 1st quarter cycle, negative in 2nd quarter cycle and so on. Hence total power consumed by a capacitor is zero. Practically, in one quarter cycle capacitor consumes power from source and in next quarter cycle it releases power to source. Hence, net power consumed over a full cycle is zero.

2.16.4 Power in RLC circuit

It is seen that among R, L, C only R can consume power. This power is dissipated in the circuit and utilized to do the useful work. It is termed as **active power**.

The power transferred to the inductor and capacitor is energy which is temporarily stored and then returned to the source. This power is not dissipated and can therefore be considered as **reactive power**.

Hence in AC circuits containing R, L, C , the total power delivered by source can be divided in two parts.

(i) Active power (ii) Reactive power.

Total power delivered by source is known as **apparent power**.

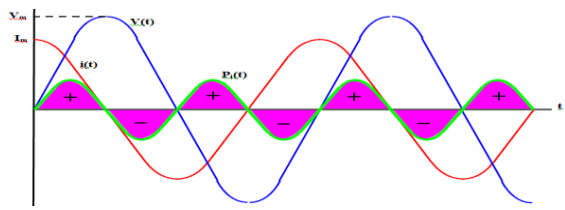


Fig. 43Power Curve

Instantaneous Power

Instantaneous Power, P(t) = P(t) = V(t)*I(t)

For inductive circuit,

As $V(t) = V_m Sinwt$ & $I(t) = I_m Sin(wt-\Phi)$

So, $\mathbf{P(t) = V_m Sinwt * I_m Sin(wt - \Phi^o)}$

Average Power, $\mathbf{P_{av} = \frac{1}{2\pi}\int_0^{2\pi} P(t)dt = VI\ Cos\Phi}$

For capacitive circuit,

As $V(t) = V_m Sinwt$ & $I(t) = I_m Sin(wt+\Phi)$

So, $\mathbf{P(t) = V_m Sinwt * I_m Sin(wt + \Phi^o)}$

Average Power, $\mathbf{P_{av} = \frac{1}{2\pi}\int_0^{2\pi} P(t)dt = VI\ Cos\Phi}$

Where, V & I denotes RMS voltage & current respectively

Power Triangle

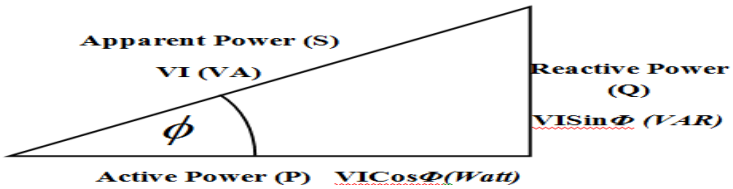


Fig. 44 Power Triangle

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

2.17 Comparative Study of R,L,C,RL,RC,RLC circuits

Element	Φ	Cos φ	Formulas
Resistor(R)	0	1	P=VI,Z=R
Inductor(L)	90(Lagging)	0	P=0,Z=JX_L
Capacitor (C)	90(Leading)	0	P=0,Z=JX_C
Series R-L	0< φ<90(Lagging)	0< Cos φ<1	P=VI Cos φ,Z=R+JX_L
Series R-C	0< φ<90(Leading)	0< Cos φ<1	P=VI Cos φ,Z=R+JX_C
Series R-L-C	0< φ<90(Lagging/Leading)	0< Cos φ<1	P=VI Cos φ,Z=R+J(X_L-X_C)

2.18 Resonance in Series RLC Circuit

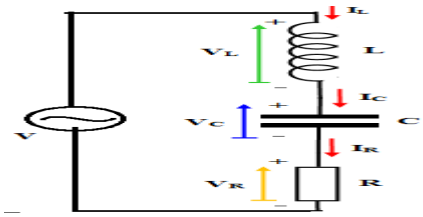


Fig. 45 Circuit Diagram

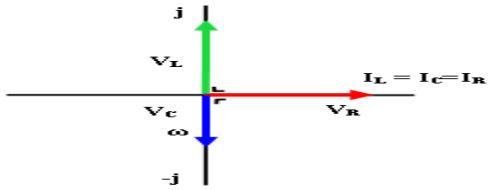


Fig 46. Phasor Diagram

capacitive reactance of the circuit. Hence at resonance,

- $X_L = X_C$
- $V_L = V_C$
- Z = R (Circuit behaves like a purely resistive circuit)
- $\Phi = 0^o$ (Supply voltage & current are in same phase)
- $\cos\Phi = 1$ (Unity)

When, $X_L = X_C$

$f = f_0 = \frac{1}{2\pi\sqrt{LC}}$

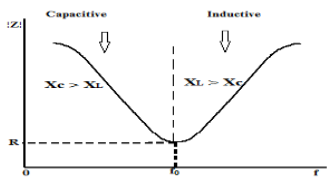


Fig. 47 Impedance Vs Freq

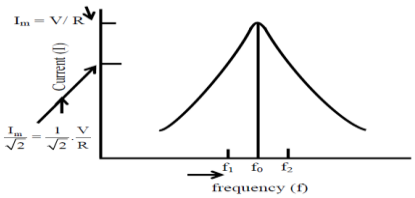


Fig 48. Current Vs Freq

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

When, f is very low,

$X_L = 2\pi fL$ (Very low), $X_C = \frac{1}{2\pi fC}$ (Very high)

As, $X_C > X_L$ circuit behaves as capacitive circuit.

The difference (X_C - X_L) is very high, hence Z is large.

As frequency increases, X_L increases from very low value and X_C decreases from very high value. So, the difference

(X_C - X_L) goes on decreasing, which reduces impedance Z.

At certain frequency, f_0 (resonant frequency), (X_C - X_L) = 0 and Z = R is minimum, Current I $= \frac{V}{Z}$ is maximum.

If frequency is increased beyond f_0, (X_C - X_L) < 0, or $X_L > X_C$. Hence the circuit becomes inductive and the difference (X_L - X_C) goes on increasing. Which in turn increases Z and reduces I.

2.18.1 Effect of resistance on resonance

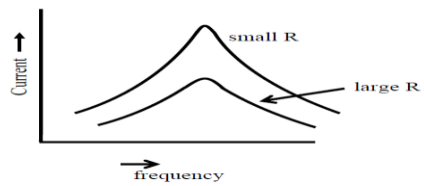


Fig. 49 Effect of resistance on resonance

2.18.2 Q factor or Quality factor of a coil

It is defined as the ratio of voltage drop across reactive elements (inductor/ capacitor) to the voltage drop across resistor.

Q factor = $\frac{V_L}{V_R} = \frac{wL}{R} = \frac{1}{wCR}$

At resonance, $\omega = \omega_0$, **Q factor** = $\frac{1}{R}\sqrt{\frac{L}{C}}$

2.18.3 Half power frequency: The frequency at which power consumed by the circuit is half of the power consumed at resonance, is known as half power frequency.

In the fig below f_1 is lower half power frequency and f_2 is upper half power frequency. It is seen at half power frequency current, $I = \frac{I_m}{\sqrt{2}}$.

Hence, power consumed at f_1 = power consumed at f_2 = $\left(\frac{I_m}{\sqrt{2}}\right)^2 R = \frac{1}{2} I_m^2 R = \frac{1}{2}$ x power consumed at resonance.

$$f_1 = f_0 - \frac{R}{4\pi L} \qquad f_2 = f_0 + \frac{R}{4\pi L}$$

2.18.4 Bandwidth: It is defined as the band of frequencies which lies between two points on either side of resonant frequency where current is 70.7 % of current at resonance.

Bandwidth = $f_2 - f_1 = \frac{R}{2\pi L}$

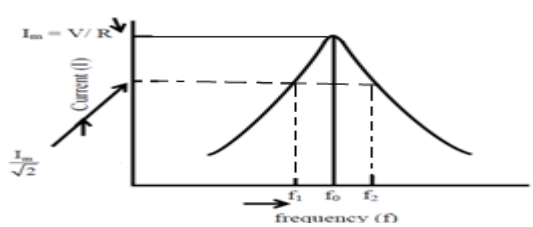


Fig. 50 Bandwith frequency

Power is consumed in resistors only. This power is known as ACTIVE POWER.

- Reactive elements (L/C) can't consume any power. This power is known as REACTIVE POWER.
- Power delivered by a source is known as total power or APPARENT POWER.
- At resonance, inductive reactance and capacitive reactance are same.
- At resonance, power factor is unity.
- At half power frequencies power consumed by circuit is half of power consumed at resonance.

Example III.

A series RLC circuit has R = 20 Ω, L = 0.1 H, C = 50μF and supplied with 220V, 50 Hz voltage source.

Find (i) Impedance (ii) current (iii) voltage across each element (iv) power factor (v) power delivered by source (vi) Power drawn by the circuit & reactive power (vii) Active & reactive component of current.

Solution: we know, (i) **Z** = $\sqrt{R^2 + (X_L - X_c)^2}$

Where, $X_L = 2\pi fL = 31.4\ \Omega$, $X_c = \frac{1}{2\pi fc} = 63.6\ \Omega$

So, $Z = 73.7\Omega$

Given: R = 20Ω, L = 0.1 H, C = 50μF

V =220V, f = 50HZ

(ii) $I = \frac{V}{Z} = 2.98$ A

(iii) Voltage across R, $V_R = IR = 59.7$ V

Voltage across L, $V_L = IX_L = 93.572$ V

Voltage across C, $V_C = IX_C = 189.53$ V

(iv) $\cos\Phi = \frac{R}{Z} = 0.27$

(v) Power delivered by source = Total power = Apparent power, S = VI = 655.6 VA

(vi) Power drawn by circuit = power consumed by circuit = Power loss in R = Active power = $VI\cos\Phi$=177Watt

Reactive power = Imaginary power = Circulating Power , Q = $VI\sin\Phi$ = 631.25 VAR

(vii) Active component of current = $I\cos\Phi$ = 0.804 A

Reactive component of current = $I\sin\Phi$ = 2.87 A

2.19 Parallel RLC Circuit

Parallel circuits can be solved using (i) Phasor method (ii) Admittance method.

(i) Phasor method:

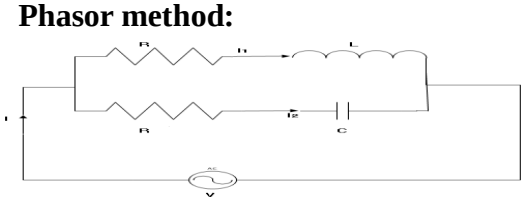


Fig. 51 Circuit Diagram

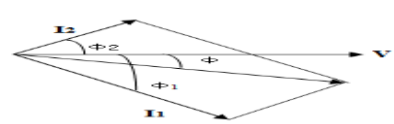


Fig 52. Phasor diagram

Impedance of RL branch, $Z_1 = \sqrt{R^2 + X_L^2}$; Cos $\Phi_1 = \frac{R}{Z_1}$; $I_1 = \frac{V}{Z_1}$

Impedance of RC branch, $Z_2 = \sqrt{R^2 + X_c^2}$; Cos $\Phi_2 = \frac{R}{Z_2}$; $I_2 = \frac{V}{Z_2}$

Horizontal component of $I_1 = I_1$ Cos Φ_1; Horizontal component of $I_2 = I_2$ Cos Φ_2

Resultant Horizontal component = I_1 Cos $\Phi_1 + I_2$ Cos Φ_2;

Vertical component of $I_1 = - I_1$ Sin Φ_1; Vertical component of $I_2 = I_2$ Sin Φ_2

Resultant Vertical component = I_1 Sin $\Phi_1 + I_2$ Sin Φ_2;

Resultant current,

$$I = \sqrt{(ResultantHorizontalcomponentsofI_1\&I_2)^2 + (ResultantVerticalcomponentsofI_1\&I_2)^2}$$

$$= (I_1 \text{ Cos } \Phi_1 + I_2 \text{ Cos } \Phi_2)^2 + (I_1 \text{ Sin } \Phi_1 + I_2 \text{ Sin } \Phi_2)^2$$

Phase Angle, $\Phi = \tan^{-1} \frac{(I1 \text{ Sin } \Phi_1 + I2 \text{ Sin } \Phi_2)}{(I1 \text{ Cos } \Phi_1 + I2 \text{ Cos } \Phi_2)}$

(ii) Admittance Method:

Admittance is reciprocal of impedance. Its unit is mho or Siemens.

Mathematically, $Y = \frac{1}{Z} = \frac{I}{V}$

Conductance (g): Reciprocal of resistance.

Susceptance (b): Reciprocal of reactance.

If n resistances are connected in parallel having R_1, R_2, R3 ,……., $R_n$resistances, then,

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots\ldots + \frac{1}{R_n}$$

Or, $g = g_1 + g_2 + \ldots\ldots\ldots + g_n$

Hence, if nresistances are connected in parallel, the total conductance of the circuit will be addition of individual conductance.

If n elements are connected in parallel having X_{L1}, X_{L2} , X_{L3} ,…,X_{Ln},X_{C1},$X_{C2,}$…., X_{Cn}reactance, then,

$$\frac{1}{X} = \frac{1}{XL1} + \frac{1}{XL2} + \ldots\ldots + \frac{1}{XLn} - \frac{1}{Xc1} - \frac{1}{Xc2} - \ldots\ldots - \frac{1}{Xcn}$$

Or, $b = b_{L1} + b_{L2} + \ldots\ldots\ldots + b_{Ln} - b_{c1} - b_{c2} - \ldots\ldots\ldots - b_{cn}$

Hence, if nelements are connected in parallel,

total susceptance of the circuit = addition of individual inductive susceptance – (addition of individual capacitive susceptance)

If n elements are connected in parallel having Z_1, Z_2 , Z3 ,……., Z_n impedances, then,

$$\frac{1}{z} = \frac{1}{z_1} + \frac{1}{z_2} + \ldots\ldots\ldots + \frac{1}{z_n}$$

Or, $Y = Y_1 + Y_2 + \ldots\ldots\ldots + Y_n$

Hence, if nelements are connected in parallel, the total admittance of the circuit will be addition of individual admittance.

2.20Impedance and Admittance triangle:

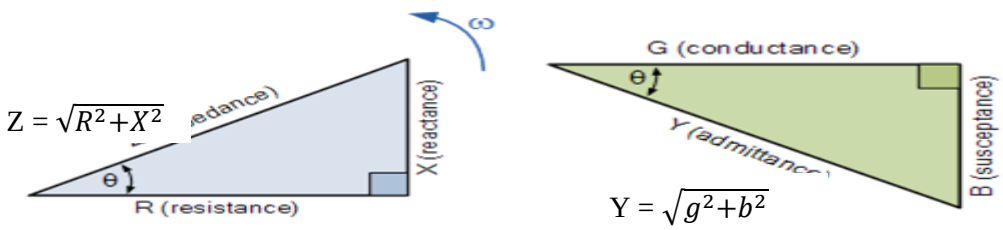


Fig. 53. Impedance & Admittance triangle

2.21 How to find circuit current using Admittance method?

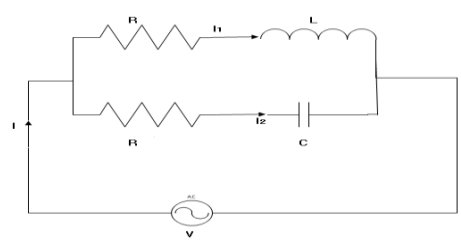


Fig. 54

$Y = Y_1 + Y_2$

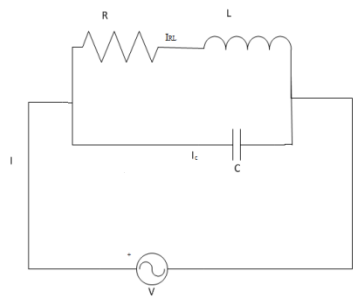
Net conductance, $g = g_1 + g_2$

Net Susceptance, $b = b_L - b_C$

$Y = g + jb = \sqrt{g^2 + b^2}$

$I = VY$

2.22 Resonance in Parallel RLC circuit



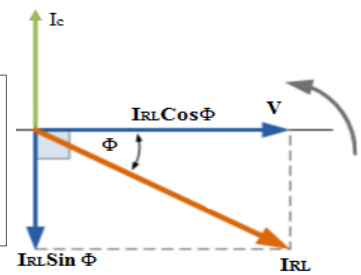


Fig. 55 Circuit Diagram **Fig 56 Phasor Diagram**

We know, at resonance power factor is unity or voltage and current must be in same phase. This is possible if reactive component of current is zero.

So, $I_c - I_{RL}\text{Sin}\Phi=0$

From circuit diagram, $I_C = \frac{V}{X_c}$; $I_{RL} = \frac{V}{Z_L}$; $\text{Sin}\Phi = \frac{X_L}{Z_L}$

Substituting I_C, I_{RL}, SinΦ in above equation, we get

$$\mathbf{f_0} = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}$$

If resistance is neglected,

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

Hence, if resistance value is neglected then resonant frequency for series circuit is same as resonant frequency for parallel circuit.

At resonance, $I_c - I_{RL}\text{Sin}\Phi=0$. Hence, $I = I_{RL}\text{Cos}\Phi = \frac{V}{L/CR}$

Hence at resonance, $\mathbf{I} = \frac{V}{L/CR}$ **(Minimum)**

At resonance, $\mathbf{Z} = L/CR$ **(Maximum)**

At resonance

- Current is minimum, hence such circuit is also termed as rejector circuit.
- Impedance is maximum
- Power factor is unity
- Voltage & current are in same phase
- Net susceptance is zero

2.23 Frequency response curve:

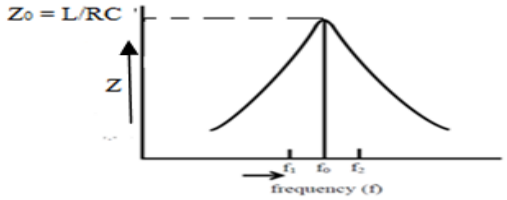


Fig. 57 Impedance Vs Frequency

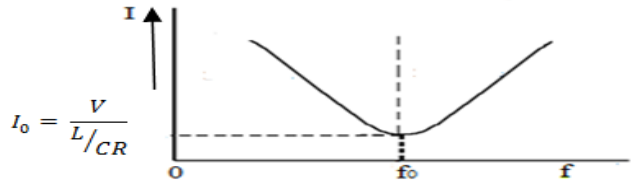


Fig. 58 Current Vs Frequency

Impedance increases and current decreases with increase in frequency till f_0. At f_0 impedance is maximum and current is minimum. Iffrequency is increased beyond f_0 impedance decreases and current increases with increase in frequency.

Q – factor = $\frac{\omega CL}{CR} = \frac{\omega L}{R}$

Q – factor at resonance = $\frac{1}{R}\sqrt{\frac{L}{C}}$

- At resonance reactive component of current is zero
- At resonance net susceptance is zero
- At resonance impedance is maximum
- At resonance current drawn by circuit is minimu

Multiple Choice Questions:

1. A 0.5-H inductor is connected into a 110 V-rms 60-Hz voltage source, with an ammeter in series. What is the rms value of the current through the inductor?

(i) 0.189 A (ii) 0.292 A (iii) 0.584 A (iv) none of these

2. If an R = 1-kΩ resistor, a C = 1-μF capacitor, and an L = 0.2-H inductor are connected in series with a V = 150 sin (377t) volts source, what is the maximum current delivered by the source?

(i) 27 mA (ii)7 mA (iii) 54 mA (iv) none of these

Long Questions:

1. How many degrees are the current and voltage out of phase with each other in a pure inductive circuit?

2. To what is inductive reactance proportional?
3. What is power factor and reactive factor?
4. What is meant by a leading and lagging power factor?

Numerical Problems:

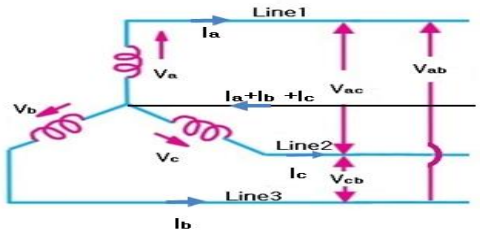
1. An 5 microF capacitor is connected to the terminals of an AC generator with an rms voltage of 100 V and a frequency of 50 Hz. Find the capacitive reactance and the rms current in the circuit.
2. Analyze a series *RLC* AC circuit for which R = 150, L= 0.2 H, C= 20μF, f = 50 Hz, and Vm= 325 V. Find (a) the impedance, (b) the maximum current, (c) the phase angle, and (d) the maximum voltages across the elements.

Three-phase balanced circuits:

2.23 Introduction:

In power generating stations ac power is generated by using 3- phase ac generators. A 3 – ph generator has three coils (3-ph) separated by 120º electrical from each other produces balanced three phase EMF.

For a balanced 3 – ph supply, EMF in each coil or in each phase has same magnitude but separated by 120º electrical from each other.



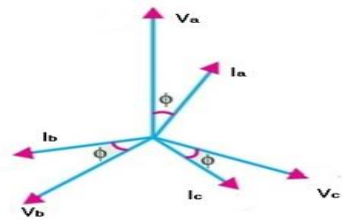


Fig. 1 Phase Connection **Fig.2 Phasor diagram of Phase voltages & currents**

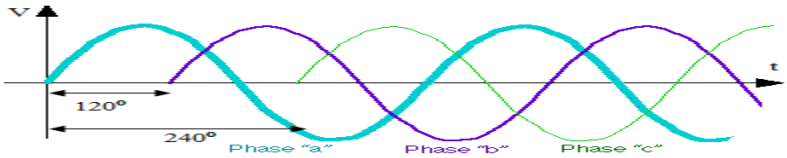


Fig. 3 Balanced 3 – phase voltage waveforms

Mathematically, three phase balanced voltages can be expressed as

$$V_a = V_m \sin\omega t$$

$$V_b = V_m \sin(\omega t - 120^o)$$

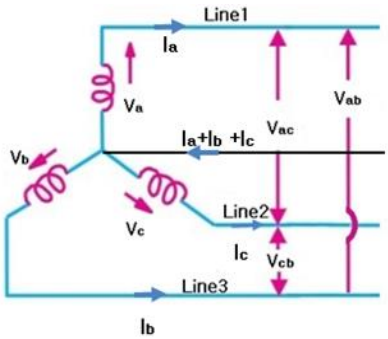
$$V_c = V_m \sin(\omega t - 240^o)$$

2.24 Methods of interconnecting three phases: (i) STAR

(ii) DELTA

2.24.1 STAR Connection:

In such connection one terminal of each coil is connected to a common point, termed as NEUTRL POINT and other terminal of each phase is connected to corresponding phases of 3 – phase load.



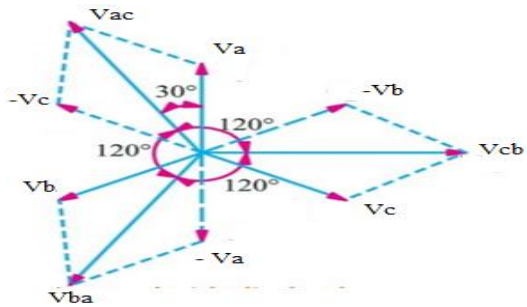


Fig. 4 STAR Connection **Fig. 5 Phasor**

Line voltage: It is the voltage between any two phases.
Phase voltage: It is the voltage between one phase and neutral.
For a balanced system, $V_a = V_b = V_c = V_{ph}$
Line voltage, $V_L = V_{ab} = V_a - V_b$

$V_L = V_{bc} = V_b - V_c$

$V_L = V_{ca} = V_c - Va$

From phasor diagram,

$V_L = V_{ab} = V_a - V_b = \sqrt{3}V_{ph}$ (substituting values of voltages)

$I_{ph} = I_a = I_b = I_c$

$I_L = I_{ph}$

Three phase power, $P_{3\,ph} = 3\, V_{ph} I_{ph} \cos\Phi = \sqrt{3}\, V_L I_L \cos\Phi$

Note: For STAR Connection

- Neutral point must be provided.
- Line voltages(V_{ab}, V_{bc}, V_{ca}) are 120º apart from each other.
- Phase voltages(V_a, V_b, V_c) are 120º apart from each other.
- Line voltages are 30º apart from their respective phase voltages.

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

Example I

Find the line voltage, phase voltage, line current phase current and power factor of the load if a balanced star-connected load of 10Ω per phase is connected to a balanced 3-phase 400V supply.

Line voltage, $V_L = 400V$

Phase voltage, $V_P = V_L/\sqrt{3} = \frac{400}{\sqrt{3}} = 231$ V

Phase Current, $I_p = V_P/Z_P = \frac{231}{10} = 23.1$ A

Line Current, I_L= Phase Current, $I_P = 23.1$ A

Power factor, $\cos\phi = \frac{R}{Z} = \frac{R}{R} = 1.0$

2.24.2 DELTA Connection:

For a balanced system, $V_a = V_b = V_c = V_{ph}$

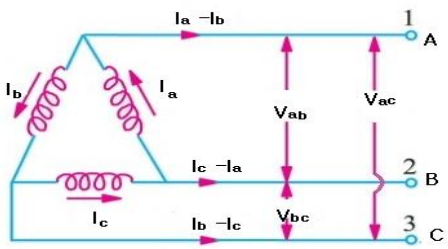


Fig. 6 DELTA Connection

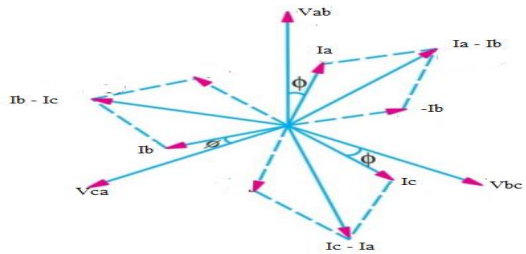


Fig. 7 Phasor diagram

Relation between Line & Phase voltages:

From fig. it is seen that a coil/ phase is connected between any two lines. Hence voltage in each phase equals to voltage between two lines.

Hence, $V_L = V_{ph}$

Relation between Line & Phase currents:

From fig,

Current in line A $= I_a - I_b$

Current in line B $= I_c - I_a$

Current in line C $= I_b - I_c$

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

Three phase power, $P_{3\,ph} = 3\, V_{ph} I_{ph} \cos\Phi = \sqrt{3}\, V_L I_L \cos\Phi$

Note: For DELTA Connection

- Line currents are 120º apart from each other.

  $V_L = V_{ph}$ $\quad I_L = \sqrt{3} I_{ph}$

2.25 Power Measurement in 3 – Phase Circuits:

Two Wattmeter Method:

In this method two watt meter are connected suitably as shown in figure. Let, P_1 & P_2 be reading of two watt meters, then total power consumed by a 3 phase load,

$$P_{3\,ph} = P_1 + P_2 = \sqrt{3}\, V_L I_L \cos\Phi$$

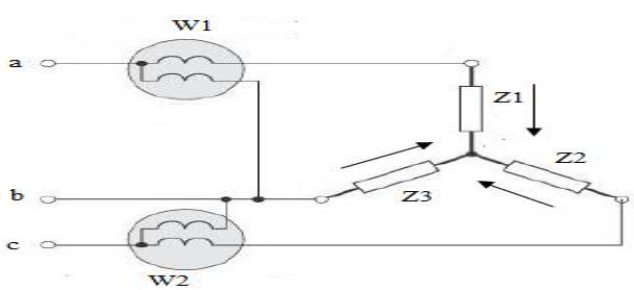


Fig. 8 Two watt meter connection

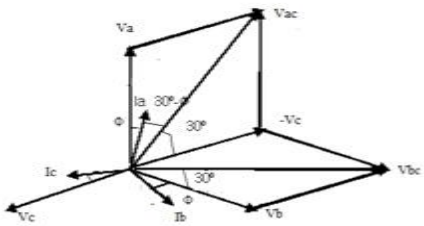


Fig. 9 Phasor Diagram

From fig.

Current through CC of wattmeter, $W_1 = i_a$

Voltage across PC of wattmeter, $W_1 = V_{ac} = V_a - V_c$

From Phasor diagram, Phase angle between V_{ac} & $i_a = (30^o - \Phi)$

Current through wattmeter, $W_2 = i_b$

Voltage across PC of wattmeter, $W_2 = V_b - V_c$

From Phasor diagram, Phase angle between V_{bc} & $i_b = (30^o + \Phi)$

So, power measured by $W_1 = P_1 = V_{ac}\, i_a \cos(30^o - \Phi) = V_L\, I_L \cos(30^o - \Phi)$

Similarly,

power measured by $W_2 = P_2 = V_{bc}\, i_b \cos(30^o + \Phi) = V_L\, I_L \cos(30^o + \Phi)$

Total power measured by two wattmeter $= P_1 + P_2$

$$= V_L\, I_L \cos(30^o - \Phi) + V_L\, I_L \cos(30^o + \Phi)$$

$$= \sqrt{3}\, V_L I_L \cos\Phi = \text{power consumed by 3 phase load}$$

Effect of Power factor in wattmeter reading

Power factor Angle(Φ)	Power factor (Cos Φ)	$W_1 = V_L I_L \cos(30^o - \Phi)$	$W_2 = V_L I_L \cos(30^o + \Phi)$
0°	1	$V_L I_L \cos(30^o)$	$V_L I_L \cos(30^o)$
60°	0.5	$V_L I_L \cos(30^o)$	0
$60^o < \Phi < 90^o$	$0 < \Phi < 0.5$	+ve	-ve
90°	0	$V_L I_L \sin 30^o$	$-V_L I_L \sin 30^o$

$P_1 + P_2 = V_L\, I_L \cos(30^o - \Phi) + V_L\, I_L \cos(30^o + \Phi) = \sqrt{3}\, V_L I_L \cos\Phi$……

$P_1 - P_2 = V_L\, I_L \cos(30^o - \Phi) - V_L\, I_L \cos(30^o + \Phi) = V_L I_L \sin\Phi$……

$$\tan\Phi = \frac{\sqrt{3}(P_1 - P_2)}{(P_1 + P_2)}$$

Multiple Choice Questions:

1. 3 – phase voltages in a balanced 3 –ph system are……. Separated from each other.

(i) 0º (ii) 90º (iii) 120º (iv) 180º

2. Phase difference between line voltage & phase voltage for star connected system is

(i) 0º (ii) 30º (iii) 60º (iv) 90º

3. Line current & phase current are same in

(i) Delta (ii) star (iii) both (iv) none of these

4. Line current in delta system is …….. times of phase current

(i) $\sqrt{3}$ (ii) $\frac{1}{\sqrt{3}}$ (iii) same (iv) none of these

5. In two watt meter method both watt meter have same reading at ……..... power factor.

(i) 1 (ii) 0.5 (iii) 0 (iv) none of these

Long Questions:

1. Prove that, in two watt meter method total power consumed by two watt meter = $\sqrt{3}V_L I_L \cos\Phi$
2. Draw & Explain circuit & phasor diagram of star connection.
3. A balanced delta connected load of (3 + j4) Ω per phase is connected to a three phase ,200V, 50 Hz supply . Find the line current ,phase current,phase voltage,p.f,reactive VA and total VA.
4. The power in a 3 - phase circuit is measured by two watt meters . If the total power is 20kw ,power factor being 0.8 leading ,what will be the reading of each wattmeter ? At which p.f. will one of the wattmeter reading will be zero ?
5. Power is measured in a 3 – ph system by two watt meter method. Reading of the wattmeters are 8kw & 2kw. Find the power factor. If the supply voltage is 200 V, then find line current.

MODULE III

SINGLE PHASE TRANSFORMER

Objective:

The following topics will be covered:

A comprehensive overview of transformer, essentials and how does it operate

- Construction parts, Types of transformers, EMF equation, No load, on load operation, equivalent circuit, phasor diagrams
- Transformer Design Equations, Performance of transformers
- Solving examples on these topics

3.1 Introduction:

Definition:

A transformer is a static piece of apparatus used for transferring power from one circuit to another at a different voltage, but without change in frequency as shown in fig. 6.1

Operation of Transformer:

- Step up and step down
- Isolation Transformer and

- Impedance matching

Transformer Uses:

- √ Power transmission and distribution
- √ TV sets to provide high voltage to picture tubes
- √ Communication Circuitry
- √ Current and Voltage measurement
- √ Supply to arc furnaces etc.

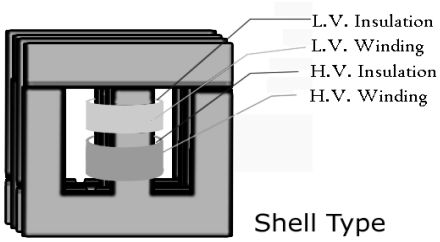
Basic Structure:

1. Electric circuit
2. Magnetic circuit

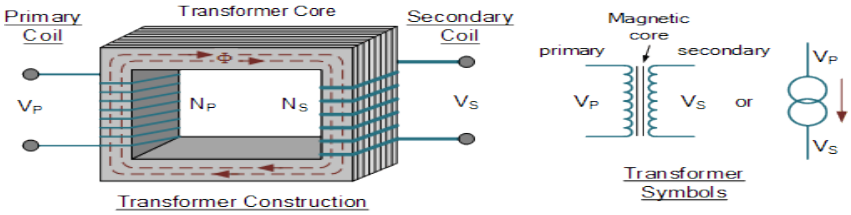
Electric circuit: It consists of primary and secondary windings.

Magnetic circuit: Provides the flux path. It consists of limbs and yoke (Top & Bottom).

Shell type:



Core type:



Electrically it is same for both types of transformers.

3.2 Constructional Parts:

A single phase transformer consists of primary and secondary windings placed on a magnetic core. It works on the principle of mutual induction between two coils as shown in fig. 6.1.

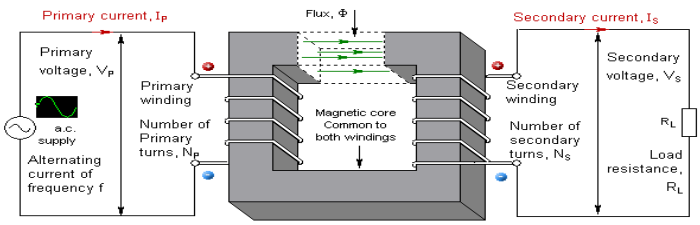


Fig. 3.2

Where

V_p = Primary terminal Voltage

V_s = Secondary terminal Voltage

I_p = Primary Current

I_s = Secondary Current

N_p = Primary Windings

N_s = Secondary Windings

E_p = Primary Induced Voltage

E_s = Secondary Induced Voltage

Transformer Ratio:

Transformer Ratio (turns ratio), this is the most important relationship and it is denoted (k)

$$K = \frac{\text{Number of Turns in the Primary Coil}}{\text{Number of Turns in the Secondary Coil}}$$

$$K = \frac{Np}{Ns}$$

Voltage and Current relationships:

$$\frac{V_p}{V_s} = \frac{i_s}{i_p} = \frac{N_p}{N_s} = K = turns \cdot ratio$$

Where:

V_p = Primary Voltage

V_s = Secondary Voltage

N_p = Primary Turn

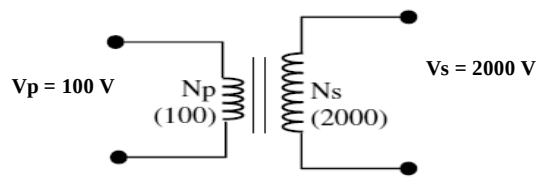
N_s = Secondary Turn

I_p = Primary Current

I_s = Secondary Current

$$\frac{100}{2000} = \frac{1}{20}$$

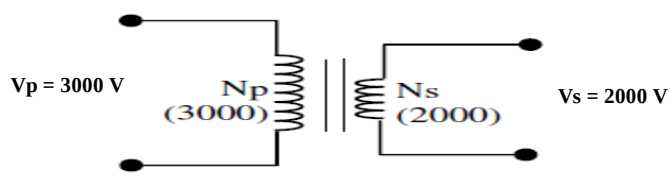
$$tep\,up \quad transformer$$



If K <1 i.e $N_P < N_S$: The above transformer is called step up transformer

$$K = \frac{Vp}{Vs} = \frac{3000}{2000} = 1.5$$

$$K > 1 \rightarrow step\,down \quad transformer$$



If K > 1 i.e $N_P > N_s$: The above transformer is called step down transformer

Transformers: Operating Principle:

E.M.F Equation

Voltage induced in a coil (flux linking equation):

$V = 4.44fN\Phi max$

$$Bm = \frac{\phi_m}{A} \qquad 1tesla(\tau) = \frac{w_b}{m^2}$$

Where

V = induced voltage (V)

f = flux frequency (H_z)

N = number of turns in coil

Φ_{max} = peak value of flux (W_b)

B_m = maximum flux density in the magnetic circuit

A = area of cross section

Types and construction:

Core type: Each limb normally carries one winding (primary or secondary). However part of primary and secondary windings can be wound on both the limbs.

Shell type: Both the windings are wound on the central limb. Shell type construction gives a lesser value of leakage reactance.

Small transformers are all shell type construction and big transformers are of core type construction.The basic circuit as illustrated in fig. 6.3

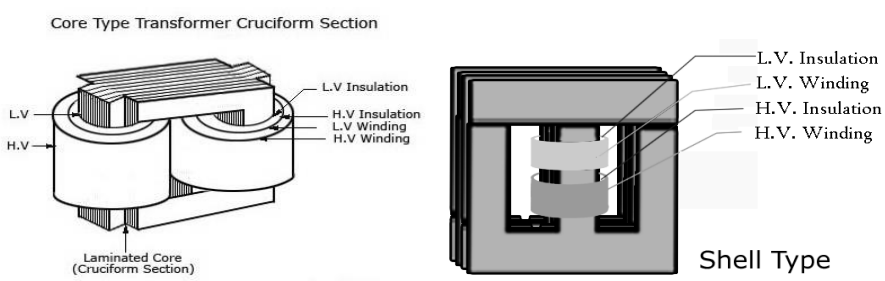


Fig. 3.3

Windings are wrapped around the center leg of a laminated core.

Windings are wrapped around two laminated square core.

Both windings are wrapped around the central core

Different between Ideal & Actual or Real Transformers:

A Transformer is ideal if:

- There is no leakage of flux from the windings.
- The windings will have zero resistance. Coils are lossless (R_1=R_2=0)
- Unity magnetic coupling between primary and secondary coils.

Actual or Real transformer

- There is leakage of flux from the windings.
- Magnetic core has finite permeability and has hysteresis & eddy current loss.
- The windings have finite resistance and there is copper loss (I^2R) in the winding.

Rating of Transformer:

The rating is generally expressed in KVA:

KVA rating of Transformer = $\frac{V_p I_p}{1000} = \frac{V_s I_s}{1000}$

Full load primary current $I_p = \frac{KVA \cdot rating \times 1000}{Vp}$

Full load secondary current $I_s = \frac{KVA \cdot rating \times 1000}{V_s}$

3.3 Transformer on No Load

When the Transformer is operating at no load, there is iron loss in the core and copper loss in the primary winding. Thus primary input current I_0 (no load current) has to supply iron loss in the core and a very small amount of copper loss in primary (which is normally neglected) and a magnetizing current to produce flux ∅. Hence current I_0 has two components:

1) Ic = power or active component. It is in phase with voltage. So $I_c = I_o \cos\theta$

2) Im = magnetizing component. It is phase with flux φ and is lagging the voltage by 90°.So $I_m = I_o \sin\theta$

Hence no load current Io is phasor sum of Ic and Im

$$\bar{I}_0 = \bar{I}_c + \bar{I}_m \qquad I_0 = \sqrt{I_c^{\,2} + I_m^{\,2}}$$

The no load input power is given by:

$$W_0 = V_1 I_0 \cos\theta$$

Where cosθ is power factor at no load

Transformer on Load:

When the Transformer is loaded, a current I_2 will flow in the secondary winding. The secondary current I_2 sets up a secondary flux φ_2 that tends to reduce the flux φ produced by primary current. Hence induced emf E_1 in primary reduces. This causes more current to flow in the primary. Let the additional current in primary be I_2'. This current I_2' is anti phase with I_2 and sets up its own flux φ'_2 which cancels the flux φ_2 produced by I_2.

$$\phi_2 = \phi_2'$$

$$N_2 I_2 = N_1 I_2'$$

$$I_2' = \frac{N_2}{N_1} I_2 = aI_2$$

$$= \frac{I_2}{k}$$

Where k is the turns ratio $= \frac{N_1}{N_2}$

Hence the primary current I_1 is the phasor sum of no load current Io and current I'_2.

3.4 Development of Equivalent Circuit

The equivalent circuit of a single phase transformer is shown in fig. 6.4.

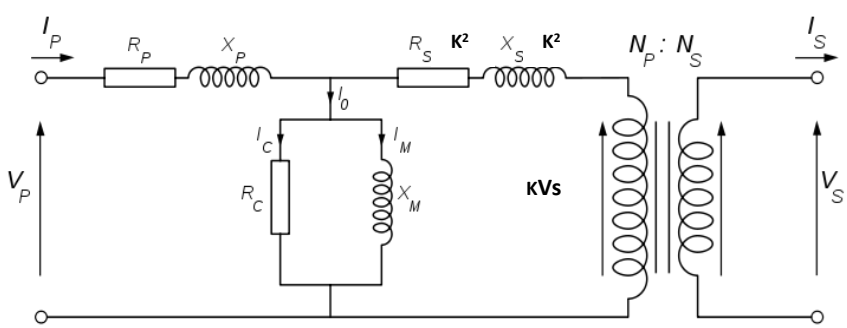


Fig. 3.4

The parameters are:

V_P=Applied voltage in primary
E_1 = Induced emf in primary winding
I_P = Primary current
R_P = Resistance of primary winding
X_P = Leakage reactance of primary winding
I'_2 = Load component of current in primary
I_0 = No load current

R_C = Equivalent Resistance of core loss at rated voltage.
X_M = Equivalent Reactance of the core to produce rated flux at rated voltage
I_C = Core loss component no load current
I_M = Magnetizing component of no load current
V_S= Outputvoltage in secondary
E_S = Induced emf in secondary winding
I_S = Secondary current
R_S = Resistance of secondary winding
X_S = Leakage reactance of secondary winding

Phasor Diagram:

When a transformer is loaded, current I_2 flows in secondary winding and voltage V_2 appears across the load. Current I_2 is in phase with voltage V_2 if load is resistive, it lags behind it if load is inductive and it leads if load capacitive.

Resistive load (unity power factor) in shown in below fig. 3.5 (a)

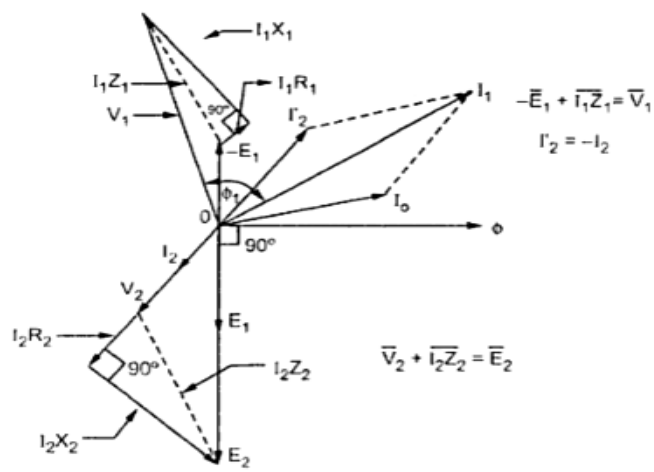


Fig. 3.5 (a)

Inductive load (lagging power factor) in shown in below fig. 3.5 (b)

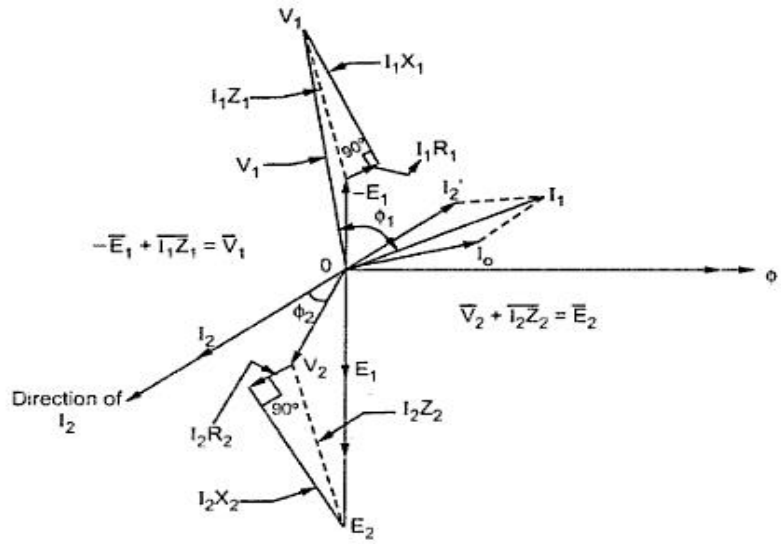


Fig. 3.5 (b)

Capacitive load (leading power factor) in shown in below fig. 3.5 (c)

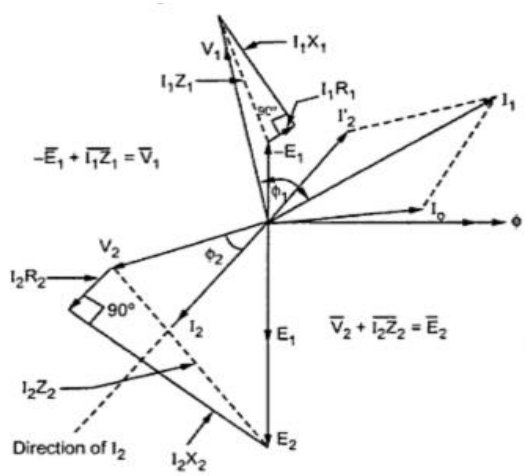


Fig. 3.5 (c)

Impedance Transfer:

To model a transformer, it is important to understand how impedance are transferred from one side to another, that is primary to secondary or secondary to primary.

$$\frac{Z_1}{Z_2} = \frac{V_1}{i_1} \div \frac{V_2}{i_2} = \frac{V_1}{V_2} \times \frac{i_2}{i_1} = a^2$$

$$Z_1 = a^2 * Z_2$$

Hence, in general, any impedance transferred from secondary side to primary side must be multiplied by the square of the turns-ratio (K^2).

Power in an ideal transformer:

The power supplied to the transformer by the primary circuit is:

$$P_{in} = V_p I_p \cos\theta_p$$

The power supplied to the output circuits is:

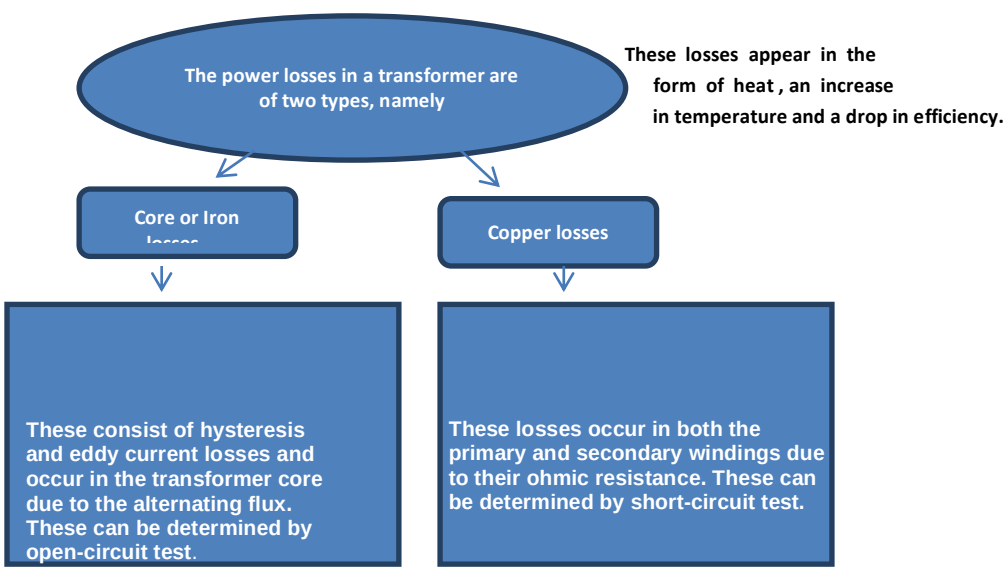
$$P_{out} = V_s I_s \cos\theta_s$$

Since ideal transformers do not affect angles between voltages and currents:

$$\theta = \theta_p = \theta_s$$

Both windings of an ideal transformer have the same power factor.

3.5. Losses of Transformer:



3.6. Voltage Regulation

Change in magnitude of voltage from no load to full load either in primary or secondary (at any particular power factor). This gives an idea voltage drop in the transformer impedances. The value should be as low as possible.

Voltage Regulation Percentage:

$$VR = \left(\frac{no \quad load \quad voltage - \quad full \quad load \quad voltage}{full \quad load \quad voltage} \right) \cdot 100\%$$

- ✓ Small numbers are often considered good (1 % to 10%)

3.7. Efficiency

What percentage of the power in to the transformer is available at the output?

$$\eta = \frac{output \quad power}{input \quad power} = \frac{Pout}{Pin} = \frac{output \quad power}{output \quad power + \quad iron \quad losses + \quad copper \quad losses}$$

Max efficiency is obtained when

$$Is^2 Rs = Pi$$

$Is^2 Rs$ = Copper losses in windings
Pi = Iron or core losses in windings

Total copper losses = Total iron losses

3.8. Open & Short Circuit Test:

The nameplate for a transformer doesn't always include the values for parameters in the equivalent circuit. They can be determined through 2 tests as shown in below fig. 6.6.

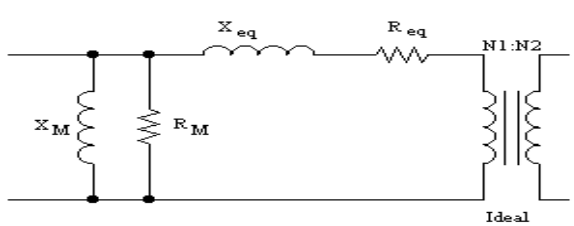


Fig. 3.6

Open Circuit Test:

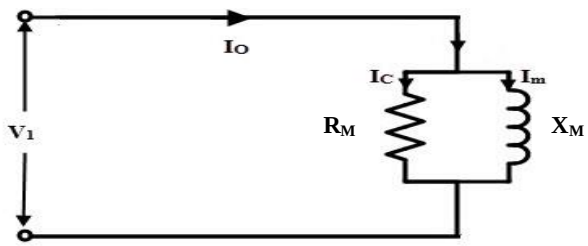


Fig. 3.6 (a)

Referring to simplified equivalent circuit above in fig.6.6 (a)

Open circuit test allows us to determine:

- Equivalent core resistance (R_M)
- Equivalent core reactance (X_M)
- Turns Ratio (K)
- Open circuit the secondary.
- Apply rated voltage to the primary (nameplate voltage). It is important for this to be the nameplate voltage, since Xm is voltage dependent.
- Measure: Voc (rated voltage), Ioc, and Poc (No load power through wattmeter)
- The large impedance of the shunt branch (Xm and Rm) compared to Xp and Rp means that the voltage across Rm and Xm is essentially the same as Voc.

Measure magnetizing current I_0, core losses (Pi) and secondary voltage (Vs)

Calculate apparent power: $S_{oc} = V_{oc} i_0$

Calculate reactive power: $Q_{oc}^{\ 2} = S_{oc}^{\ 2} - P_{oc}^{\ 2}$

Now calculate

Equivalent core resistance (RM): $R_M = \dfrac{V_{oc}^{\ 2}}{P_{oc}}$

Equivalent core reactance (XM): $X_M = \dfrac{V_{oc}2}{Q_{oc}}$

Turns Ratio (a): $K = \dfrac{Vp}{Vs}$

Short Circuit Test:

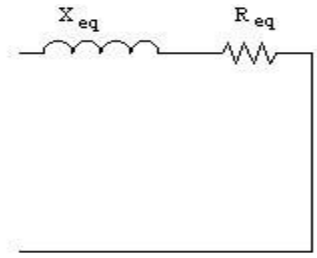


Fig. 3.6 (b)

Referring to simplified equivalent circuit above in fig.6.6 (b)

- Short the secondary terminals.
- Apply a small voltage to the primary (it is easy to produce large currents)
- Measure: Vsc, Isc (should be limited to rated current of transformer), and Psc (short circuit power)
- The large impedance of the shunt branch (Xm and Rm) compared to Xeq' and Req' means that I_m is negligble, and this test determines the series branch parameters.

Now calculate

Equivalent transformer impedance $$Z_p = \frac{V_{SC}}{i_{SC}}$$

Equivalent winding resistance $$R_{eq} = \frac{P_{SC}}{i_{SC}^{\ 2}}$$

Equivalent leakage reactance $$X_{eq}^{\ 2} = Z_p^{\ 2} - R_P^{\ 2}$$

Multiple Choice Type Questions and Answers:

1. The open circuit test of the transformer can estimate its …… losses whereas the short circuit test can estimate the ……. losses.
   a) iron, copper b) copper, iron c) hysteresis, eddy d) eddy, hysteresis

2. The capacity rating of the transformer is given by
   a) kVAb) kWc) H.Pd) none of the above

Solved Numerical Problem:

1. A 220/440 V, 50 Hz transformer gave following test result:
   No load test: 220 V, 0.7 A, 66 W
   Short circuit test: 9 V, 6 A, 21.6 W
   Calculate the efficiency at full load 0.8 p.f (lag). Express the full load copper loss as a percent of kVA of the transformer.

   Sol. We know the expression of efficiency at any load

$$\eta = \frac{x \bullet output \quad power}{x \bullet output \quad power + \quad iron \quad losses + \quad copper \quad losses}$$

At full load x= 1

Output power = 440 x 6 = 2.64 kVAOutput power = $V_S \bullet I_S \bullet \cos\phi$

$$\eta = \frac{1x \quad 2640 \quad x \quad 0.8}{1 \quad x \quad 26400 \quad x \quad .8 + \quad 66 \quad + \quad 21.6}$$

$$= 0.96 = 96\%$$

Full load at 0.8 p.f

Output power = $V_S \bullet I_S \bullet \cos\phi$

= 2640 x 0.8 = 2112 W

Then

$$\frac{full \quad load \quad copperloss}{full \quad load \quad capacity} = \frac{21.66}{2112} \bullet 100$$

$$= 1.02\%$$

Exercise:

1. Derive emf equation of a transformer.

2. At no-load (open ckt) a transformer has loss of 250 W, and draws current of 5A and an applied voltage of 230V. Determine the following (**2.5 points**)
   i) No-load power factor (**pf**)
   ii) No-load current (**I_0**)
   iii) Magnetizing current (**I_m**)
   iv) Iron loss current (**I_w**) and
   v) No-load circuit parameter (**R_0, X_0**) of the transformer.

3. A 120 kVA, 50 Hz, 1 phase transformer has full load Cu loss as 1.5 kW and an iron loss as 1 kW. Find the efficiency at a load of 90 kVA and 0.85 P.F.

4. What happens if dc supply is given to a transformer?

5. What is all day efficiency of a transformer?

6. At maximum efficiency of the transformer
   a) iron loss > full load copper lossb) iron loss < full load copper lossc) iron loss = copper lossd) none of the above

ELECTRICAL ROTATING MACHINES

DC MACHINES

Objective:

The aim of this chapter is to gather knowledge about following topics of DC machines:

1. Construction, types and principle of operation of motor & generator.
2. EMF equation, characteristics(open circuit, load) DC motor
3. Torque Equation, speed and torque characteristics
4. 3 point starter, and speed control

4.1. Introduction

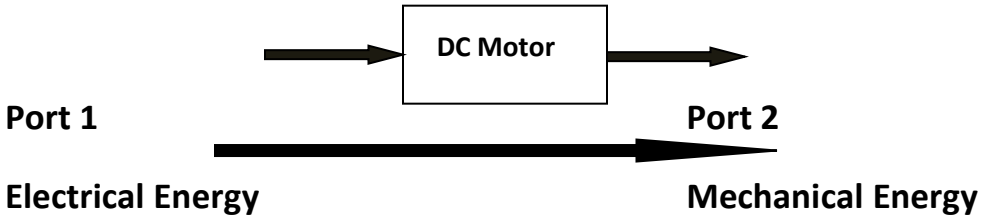


Fig. 4.1

- A DC motor is a device that converts dc electrical energy into mechanical energy. As shown in above fig. 4.1
- DC motor application is limited to mills, mines and trains. As examples, trolleys and underground subway cars may use dc motors.

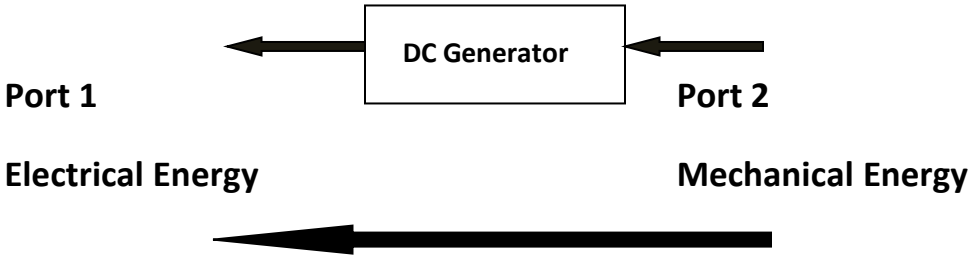


Fig. 4.2

- A DC generator is a device that converts mechanical energy into dc electrical energy. As shown in fig. 4.2
- DC generator is used for general lighting, charge battery and small power supply etc.

Any DC machine can act either as a generator or as a motor

4.2. Construction of DC Machine

A DC motor consists of two parts namely field system (stator) and armature (rotor)

1. **Stator:**Stationary part of the motor sometimes referred to as the windings. Slotted cores made of thin sections of soft iron are wound with insulated copper wire to form one or more pairs of magnetic poles.

2. **Rotor:**Rotating part of the motor, magnetic field from the stator induces an opposing magnetic field onto the rotor causing the rotor to push away from the stator field.

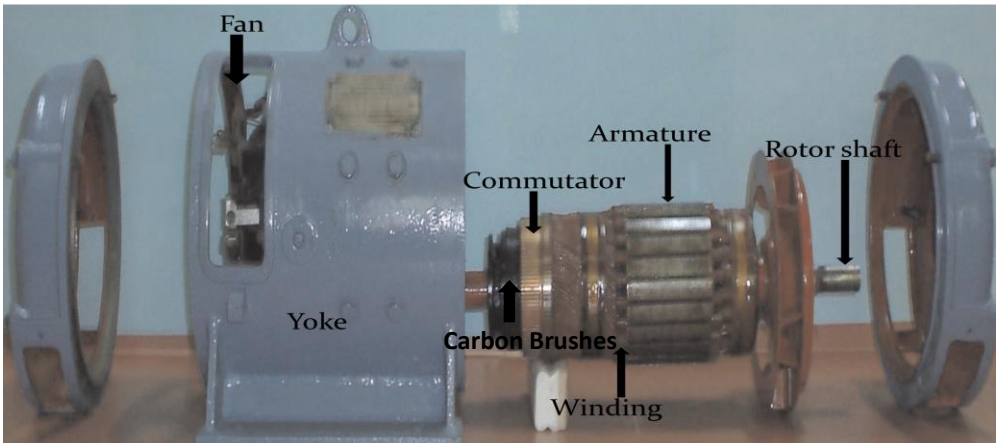


Fig. DC machine components

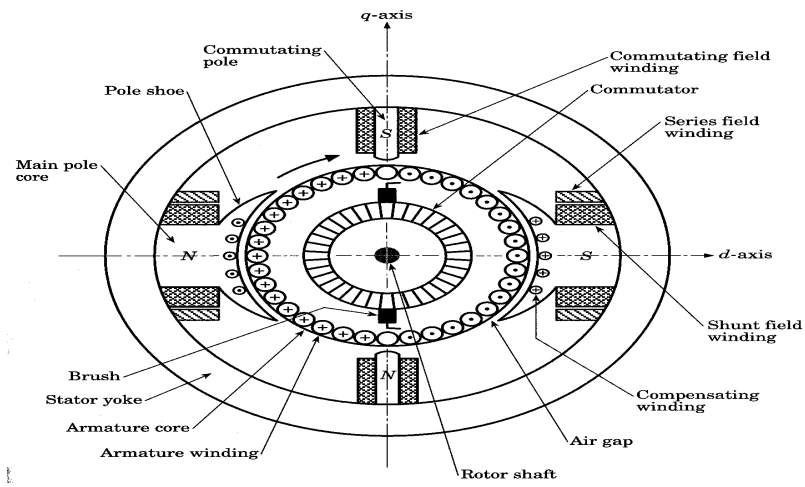


Fig. 4.4: DC machine magnetic circuit showing stator and rotor slots

A DC machine, either a generator or a motor, essentially consists of the following main parts:

i. Yoke
ii. Pole cores and pole shoes
iii. Field windings
iv. Brush gear and brushes

} **Stator**

v. Armature core and Armature windings
vi. Commutator

} **Rotor**

The DC machine: construction of individual parts will be discussed thoroughly during the lectures session

4.3 Basic concepts of winding

There are two basic types of windings- Lap & Wave**.**

Lap Winding:

This type of winding is used in dc generators designed for high-current low voltage applications. There are several parallel paths for current in the armature equal to number of poles. The connection of the lab winding follow through the end of coil is connected to the starting of the next coil under the same pole and the end of the last coil is connected to the starting of the first coil, thus closing the windings. Every end of coil is connected to a commutator segment.

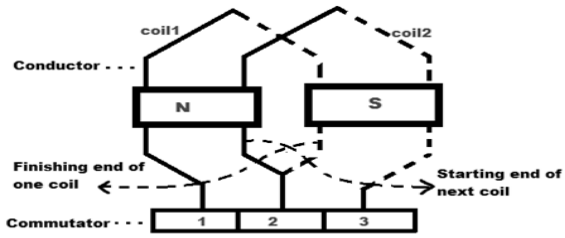


Fig. 4.5: Lap winding

Wave Winding:

Two parallel paths in wave winding, regardless of the number of poles. The wave winding is used in dc generators motors employed in high-voltage applications. Notice that the end of one coil lying under a south pole is connected to the starting of the coil lying under the next north pole.

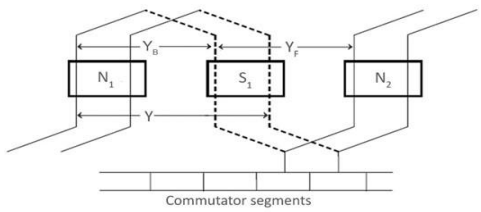


Fig. 4.6: Wave winding

4.4 Principle of Operation

The working principle of the generator is based on the Faraday's law of electromagnetic induction. The fact that when a conductor moves in a magnetic field it cuts magnetic lines of force, due to which an emf is induced in the conductor. The magnitude of this induced emf depends upon the rate of change of flux linkage with the conductor. The direction of induced emf with respect to direction of rotation of armature and direction of field flux can be obtained from Fleming's right hand rule. These alternating voltages are converted into unidirectional voltage by means of commutator & brush arrangement and are obtained as a DC voltage across the brush terminals.

4.5 DC Machines Operating Principle (E.M.F)

E.M.F Equation

Let

Φ = flux/pole in weber

Z = total number of armture conductors (Z = No.of slots x No.of conductors/slot)

P = No.of generator poles

A = No.of parallel paths in armature

N = armature rotation in revolutions per minute (r.p.m)

E = e.m.f induced in any parallel path in armature

Generated e.m.f Eg = e.m.f generated in any one of the parallel paths

Average e.m.f geneated /conductor = **dΦ/dt**

Now, flux cut/conductor in one revolution **dΦ = ΦP** Wb

No.of revolutions/second = N/60

Time for one revolution, **dt = 60/N** second

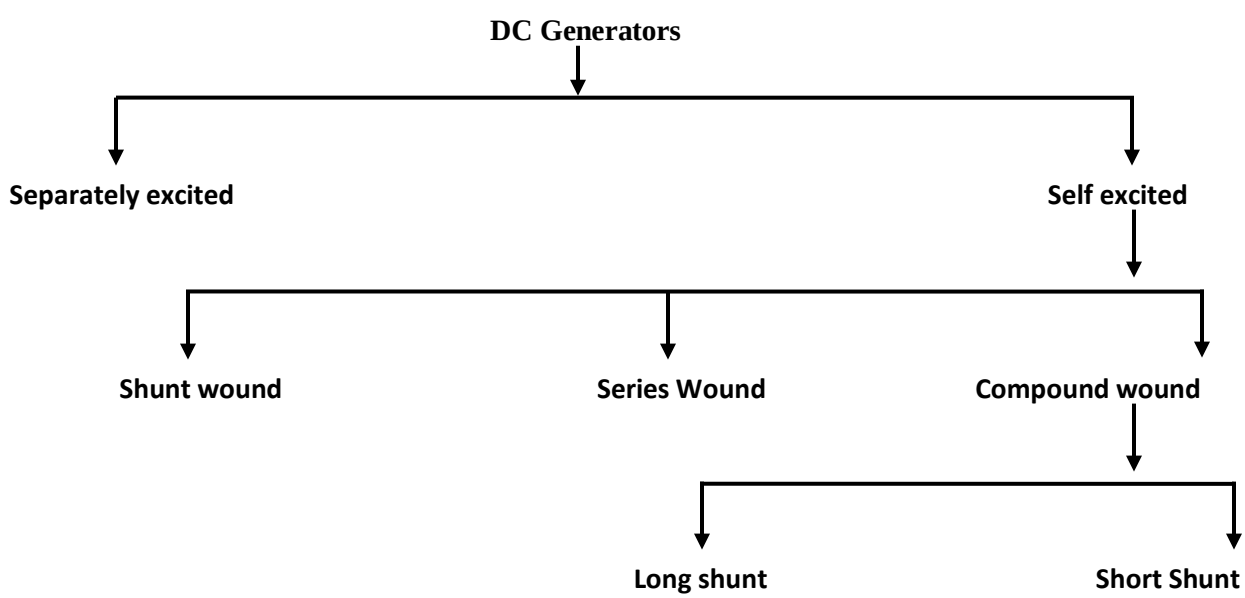
Hence, according to Faraday's Laws of Electromagnetic Induction,

emf generated/conductor = $\frac{dj}{dt} = \frac{j\,PN}{60} volt$

Since there are Z numbers of armature conductors in A parallel paths. The generated voltage Eg across the brushes:

$$Eg = \frac{ZN\phi P}{60A} \text{ Volts}$$

4.6 Type of DC generator



In general, Generators have been classified into this group depending on its mode of field supply.

1. **Separately excited generator:**This kind of generator, the field winding is excited by a separate dc source as shown in fig. 4.7.

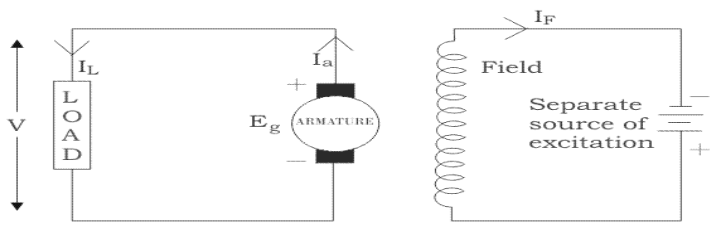


Fig. 4.7

2. **Self excited generator:**This type of generator, the field winding is excited by a part of the current produced by itself as shown in fig. 4.8

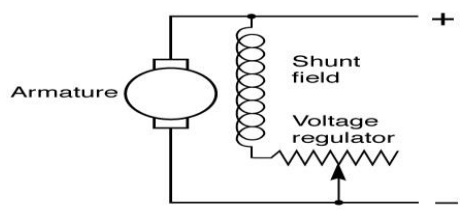


Fig. 4.8

Self excited generator further classified as:

i) **Shunt generator:**Inthis generator, shunt field winding and armature winding are connected in parallel through commutator and carbon brush as shown in fig. 4.9.

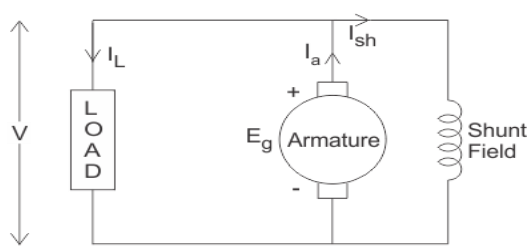


Fig. 4.9

Voltage and Current relationships:

$$I_f = \frac{V}{R_f}$$

$$I_a = I_L + I_f$$

$$E_g = V + I_a R_a$$

V_t = Terminal or output voltage

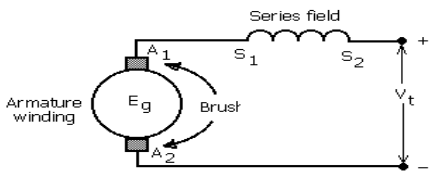
I_a = Armature current

R_a = Armature resistance

R_f = Shunt field resistance

I_f = field current

ii) Series Generator: The field winding and armature winding is connected in series. The basic circuit as illustrated in fig. 4.10 and 4.11



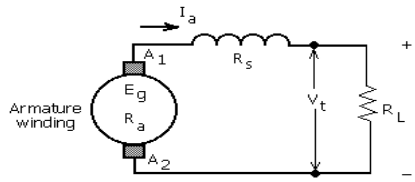


Fig. 4.10 Fig. 4.11

Voltage and Current relationships:

$$I_a = Is = I_L$$

$$E_g = V + I_a(R_a + R_s)$$

V_t = Terminal or output voltage

I_a = Armature current

R_a = Armature resistance

R_s = series resistance

I_l = load current

iii) Compound Generator: The compound generator has both a shunt and a series winding. Both these field windings are located in the collar portion of the field pole. The two winding are usually connected such that their fluxes are in the same direction. As such the generator is said to be cumulatively compound. However their electrical connections are different. The basic circuit as illustrated in fig. 4.12 and 4.13

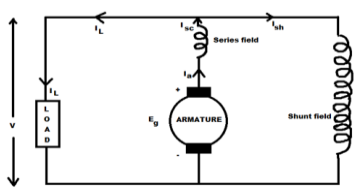


Fig. 4.12 Long Shunt

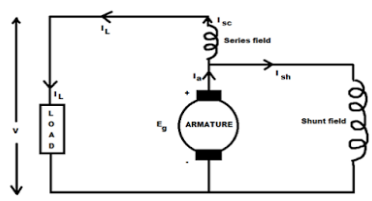


Fig. 4.13 Short Shunt

Voltage and Current relationships:

$$I_a = I_s = I_L + I_f$$

$$I_f = \frac{V}{R_f}$$

$$E_g = V + I_a(R_a + R_s)$$

Voltage and Current relationships:

$$Is = I_L$$

$$I_a = I_L + I_f$$

$$I_f = \frac{V + I_L R_s}{R_f}$$

$$E_g = V + I_a R_a + I_L R_s$$

4.7 Characteristic Curves-

The characteristics that are studied are the magnetization properties and the load voltage properties:

- Open circuit characteristic or magnetizing characteristics (OCC), the generator is operated as a separately excited generator, and Eg vs I_f curve is drawn at a particular running speed.

- Load characteristic also called external characteristic(V_t vs I_a curve at a particular speed of running). It shows the relationship between the voltage across the load and current following through the load at constant speed and with the field current the same as that under no load condition. The load characteristic is different for different types of DC machines. Sample graph of V_t vs I_f & V_t vs I_a)

4.8 DC Motor

DC motor is exactly similar to dc generator in construction; in fact the same machine can act as motor or generator. The only difference is that in a generator the EMF is greater than terminal voltage, whereas in motor the generated voltage EMF is less than terminal voltage. Thus the power flow is reversed, that is the motor converts electrical energy into mechanical energy.

- DC motors are highly versatile machines. For example, dc motors are better suited for many processes that demand a high degree of flexibility in the control of speed and torque.

Principle of Operation:

When a current carrying armature conductor is placed in a magnetic field, a force is produced by the field current, then it experience a force which cause the movement of the armature. The relationship between the direction of rotation of armature with respect to direction of field flux and direction of armature current can be obtained from Fleming's left hand rule.

When the armature of the DC motor rotates, the armature conductors cut the flux then emf is induced in them, this emf of rotation is known as back emf.

$$E_b = \frac{NP\phi Z}{60A}$$

Where Eb = Back emf
N = Speed (rpm)
ϕ = Flux / pole
Z = Total number of armature Conductors.
P = Number of poles of motor.
A = No of parallel paths 2 of the winding. (equal to the number of poles P in case of lap winding and 2(two) in case of wave winding)

Type of DC Motor:

1. Shunt Motor
2. Series Motor and
3. Compound Motor

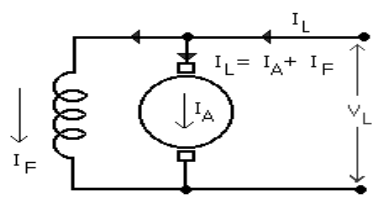
Voltage and Current relationships for different types of motors are as follows:

i) Shunt Motor:

$$I_f = \frac{V}{R_f}$$

$$I_a = I_L - I_f$$

$$E_b = V - I_a R_a$$

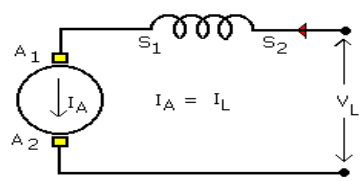


Shunt motor

ii) Series Motor:

$$I_a = I_L = I_f$$

$$E_b = V - I_a(R_a + R_s)$$



Series motor

iii) Compound Motor:

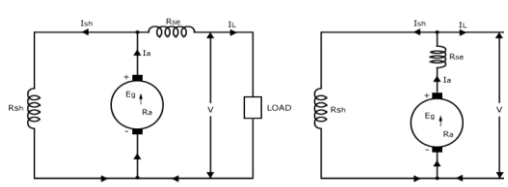
Short:

$$Is = I_L$$

$$I_a = I_L - I_f$$

$$I_f = \frac{V - I_L R_s}{R_f}$$

$$E_b = V - (I_L R_S + I_a R_a)$$



Short Shunt Compound Long Shunt Compound

Long:

$$I_a = I_s = I_L - I_f$$

$$I_f = \frac{V}{R_f}$$

$$E_b = V - I_a(R_a + R_s)$$

Torque Equation:

$$V = E + I_a R_a$$

Multiplying both the sides by I_a, so then

$$VI_a = EI_a + I_a^2 R_a$$

where

$VI_a = P$	Electrical power input to the armature
$EI_a = P_m$	Electromechanical power
$I_a^2 R_a =$	Copper loss in the armature

Let,

$\tau_{av} =$ average electromagnetic torque developed by the armature in Newton meters (Nm). Now mechanical power developed by the armature:

$$P_m = \omega \tau_{av} \qquad where \omega = 2\pi n$$

$$EI_a = \omega \tau_{av}$$

$$\frac{nP\phi Z}{A} I_a = 2\pi n \tau_{av}$$

Where

$$E = \frac{nP\phi Z}{A}$$

$$\tau_{av} = \frac{nP\phi Z}{2\pi n A} I_a$$

$$\tau_{av} = \frac{P\phi Z}{2\pi A} I_a \text{ Torque Equation of DC motor}$$

Speed Torque Characteristic:

The characteristic of dc motors can be described from the torque current and the speed current characteristics where the torque expression of shunt motor is:

$$T \propto \phi I_a$$ If the effect of armature reaction is neglected then ϕis nearly constant and we can write

$$T \propto I_a$$

The shunt motor has torque proportional to armature current. The speed torque characteristic of dc shunt motor circuit as illustrated in fig. 4.14

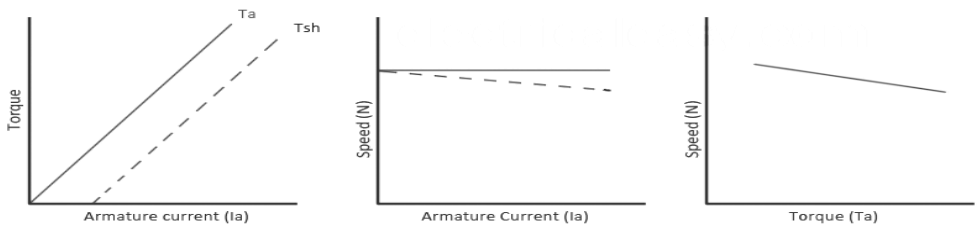


Fig. 4.14

For series motor is $\boldsymbol{\phi I_a \propto I_a^2}$ upto saturation and then $\propto \boldsymbol{I_a}$, the series motor has high torque at low speed and low torque at high speed as shown fig. 5.18, also Speed $N \propto \frac{1}{\phi} \propto \frac{1}{I_a}$. Combining these two equation speed vs torque curve will also be a rectangular hyperbola.

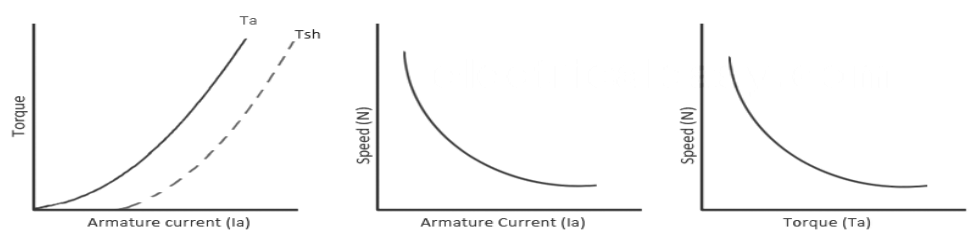
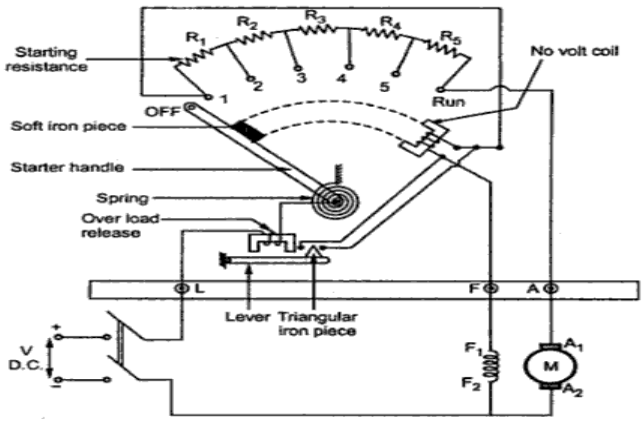


Fig. 4.15

A series motor should not be operated without load since it can assume a dangerously high speed.

5.9 Starting (By 3 point starter):



3 point Starter

A "3-point starter" is extensively used to start a D.C shunt motor. It provides additional protective features such as over load protection and no volt protection. The diagram of a 3-point starter connected to a shunt motor is shown in the above figure.

4.10 Speed Control of DC Motors:

The speed of the DC motor can be expressed by the relation

$$N = K_N \left(\frac{E_b}{\phi} \right)$$

Where $E_b = V - I_a R_a$ for shunt motor

$E_b = V - I_a (R_a + R_f)$ for series motor

The speed of the dc motor can be controlled by two methods

I. Armature Controlled Method
II. Field Controlled Method

There are three mains type of armature control method.

i. Rheostatic control
ii. Shunted armature control
iii. Series parallel control

Multiple Choice Type Questions and Answers:

1. The direction of rotation in dc motor can be determines by
   a) Lenz's law b) Fleming's left hand rule c) Fleming's right hand rule (d) All the above

2. A 220 V shunt motor develops a torque of 54 N-m at armature current of 10 A. The torque produced when the armature current is 20 A, is
   (a) 54 N-m(b) 81 N-m(c) 108 N-m(d) None of the above

Solved Numerical Problem:

1. A 220 V dc shunt motor having an armature circuit resistance of 0.5 Ω and field circuit resistance of 100 Ω, draws a line current of 30 A at full load. The brush voltage drop is 5 V and rated full load speed is 1600 rpm, Calculate (i) the speed at half load (ii) the speed at 120% of full load.

   Ans:

   Shunt field current = $\frac{220}{100} = 2A$

   Armature current at full load = 30 – 2 = 28 A

   Back emf at full load = dc supply – armature current x armature resistance – brush drop
   = 220 – 28 x 0.5 – 5
   = 201 V

   Half load line current is = $\frac{30}{2} = 15A$

   Then armature current at half load is = 15 – 2 = 13 A
   Back emf at half load = dc supply – armature current x armature resistance – brush drop
   = 220 – 13 x 0.5 – 5
   = 208.5 V

   Speed at half load/speed at full load = back emf at half load/back emf at full load

   (i) Speed at half load is = $\frac{1600x208.5}{201} = 1659.7rpm$

   At 120% of full load, line current is 1.20 x 30 = 36 A

Then armature current = 36 – 2 = 34 A
And back emf = 220 – 34 x 0.5 -5 = 198 V

(ii) The speed at 120% of full load is =

$$\frac{1600x198}{201} = 1576.11rpm$$

Exercise:

1. Describe briefly about the armature reaction of DC machine.
2. A 230V dc shunt machine has armature resistance of 0.7 Ω and field resistance of 100 Ω. If this machine is connected to 230V supply mains, find the ratio of speed as generator to the speed as a motor. The line current is each 30 A

3. A 120V dc shunt motor draws a current of 200A. The armature resistance is 0.02 Ω and shunt field resistance 30 Ω. Find the back emf. If the lap wound armature has 90 slots with 4 conductors per slot, at what speed will the motor run when the flux per pole is 0.04 Wb?

4. Deduce the emf equation of a DC generator.

5. What do you mean by back emf?

6. Explain with neat diagram, the operation of 3 point starter.

7. For lab connected dc machine
   b) A = P b) A = 2 c) A = 4 d) all the above

8. A 4 pole dc armature wave winding has 215 conductors,
   i) What flux per pole is necessary to generate 230 V when rotating at 1000 rpm?
   ii) What is the torque at this flux when the rated armature current of 50 A is flowing?
9. The commutator of a dc machine acts as
   a) Full wave rectifier b) wound rotor c) half wave rectifier d) none of these

THREE PHASE INDUCTION MOTOR

4.1.1 Introduction

Three-phase Induction Motor is the most popular type of electrical Motor. It has unique advantage compared to other type of motors, such as, DC motor orAC Synchronous motor.

In a three phase induction motor, three phase AC supply is given to the stator windings. The flux from the stator, flowing through the air gap links the rotor circuit. Voltages are induced in the short circuited rotor according to Faraday's law of Electromagnetic Induction. They are also called asynchronous motors as the operating speed of rotor is slightly less than the synchronous speed.

4.2.1Type Of Induction Motor

Due to the rotor construction, there are two types of Induction Motor: a) Squirrel Cage Induction Motor, b) Wound Rotor or Slip Ring Induction Motor.

4.3.1 Construction

This Motor consists of two major parts:

Stator: Stator of three phase induction motor is made up of numbers of slots to construct a 3 phase winding circuit which is connected to 3 phase AC source. The three phase winding are arranged in such a manner in the slots that they produce a rotating magnetic field after 3ph AC supply is given to them.

Stator Winding or Field Winding

The slots on the periphery of stator core of the motor carries three phase windings. This three phase winding is supplied by three phase ac supply. The three phases of the winding are connected either in star or delta depending upon which type of starting method is used.

Rotor: Rotor of three phase induction motor consists of cylindrical laminated core with parallel slots that can carry conductors. Conductors are heavy copper or aluminum bars which fits in each slots & they are short circuited by the end rings. Due to the construction, there are two types of rotor as below:

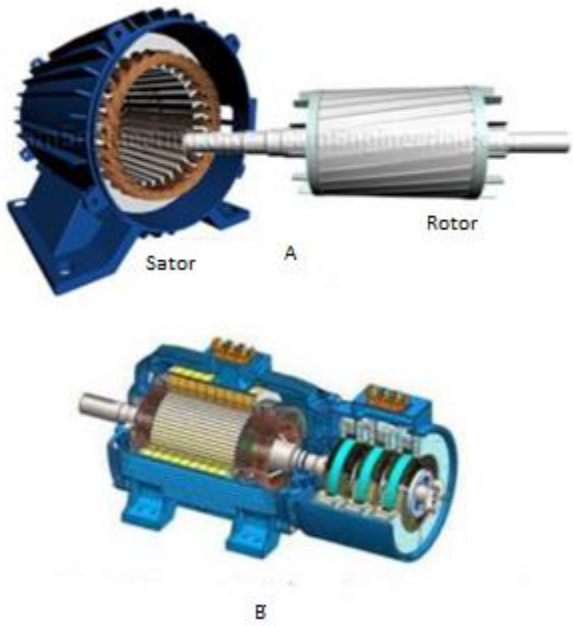


Fig.4.1.1 (A) Squirrel cage rotor and (B) Slip-ring rotor

Type of three phase induction motor :

a.Squirrel cage rotor
b. Slip-ring rotor

4.4.1 Production Of Rotating Field

The three-phase induction motor operates on the principle of a rotating magnetic field. The stator windings can be connected to a three-phase ac input and has a resultant magnetic field that rotates.
It can be shown that magnitude of this rotating field is same for all phases.
Consider a three phase winding where voltages are separated by 120° with a three phase AC supply. If the phase sequence of winding is 1-2-3 (the direction of Rotating Magnetic Field will be anti clockwise) then the mathematical equation for the instantaneous values of the fluxes Φ1, Φ2, Φ3 can be given as

$\Phi_1 = \Phi m \sin (wt)$
$\Phi_2 = \Phi m \sin (wt - 120^o)$
$\Phi_3 = \Phi m \sin (wt - 240^o)$

As windings are identical,the three fluxes are balanced in amplitude i.e. Φm.

Assumed Positive direction means that the instantaneous value of the flux is positive. Vector diagram is represented along its assumed positive direction.

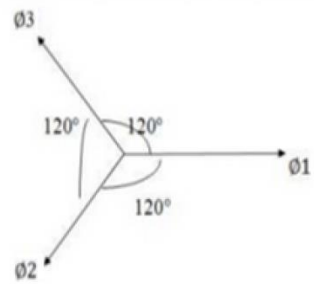


Fig.4.2.2 Assumed positive direction

4.5.1 Principle Of Operation

The balanced three-phase winding of the stator is supplied with a balanced three phase voltage. The current in the stator winding produces a rotating magnetic field, the magnitude of which remains constant. The axis of the magnetic field rotates at a synchronous speed in the stator winding. The rotating magnetic flux lines in the air gap cut both stator and rotor conductors at the same speed. The stator conductors are always stationary, with the frequency in the stator winding being same as line frequency. As the rotor winding is short-circuited at the slip-rings or end-rings, current flows in the rotor windingsdue to an induced emf which is produced by rotating magnetic field of the stator due to faraday's law of electromagnetism. This produces a rotor flux and a rotor magnetic field which attempts to catch up with the rotating magnetic field of the stator.
This interaction generates a torque and consequently a force that drives the rotor. The force is proportional with the flux density and the rotor bar current (F=BLI).
The motor speed is always less than the synchronous speed. If the rotor magnetic field catches up with the rotating magnetic field of the stator resulting in synchronous speed of motor, the induced emf in the rotor bars due to faraday's law of electromagnetism becomes zero and the rotor slips from synchronous speed. The direction of the rotation of the rotor is the same as the direction of the rotation of the revolving magnetic field in the air gap.

4.6.1 Slip & Frequency

Slip

The speed of the rotating flux is called synchronous speed (N_s). It is directly proportional to the frequency of the supply voltage and inversely proportional to the no of poles.

$N_S = \frac{120f}{P}$ in rpm. Where $N_S = \text{Synchronous speed}$, $f = \text{Frequency of the supply Voltage}$, $P = \text{No. of Poles}$.

The rotor speed of the Induction Motor = N_r , which is slightly less than synchronous speed. The difference between synchronous speed and the actual rotor speed is called, the **Slip Speed.**

i.e.: Slip speed = $N_S - N_r$ in rpm

The ratio of the slip speed and synchronous speed is called slip of induction motor and expressed as

s= $\frac{N_S - N_r}{N_S}$ and %slip = $\frac{N_S - N_r}{N_S} x\ 100.$

Frequency

The frequency of the current and voltage in the stator must be the same as supply frequency given by,

$$f = \frac{PN_S}{120}$$

The rotor frequency depends upon the slip speed. It is given by,

$$f_r = \frac{P(N_S - N_r)}{120}$$

From these above two equation we get,

$$f_r = f\ x\ s$$

4.6.2Rotor EMF, Current And Phasor Diagram.

4.6.2 a EMF Equation of Induction Motor.

Rotor induced voltage $e_r = s\ x\ stator\ voltage(E)$

Let,
suffixes 1 and 2 be used for stator and rotor quantities respectively.
V_1 = stator applied voltage per phase
T_1, T_2 = number of stator and rotor winding turns in series per phase respectively
Φ = flux per pole produced by the stator MMF.
E_1, E_2 = stator and rotor induced emf per phase respectively
E_r = rotor induced emf per phase at slip s.
R_1, R_2 = resistance of stator and rotor winding per phase respectively
L_{20} = rotor inductance per phase at stand still due to leakage flux
X_{20} = leakage reactance of the rotor winding per phase at stand still
f_1 = stator emf frequency or supply frequency
f_2 = rotor emf frequency at slip s. = sf_1
X_{2s} = leakage reactance of the rotor winding per phase at slip s
K_{w1} = winding factor of stator = $K_{d1} \times K_{c1}$,
K_{w2} = winding factor of rotor = $K_{d2} \times K_{c2}$
where, Kd = distribution factor and Kc = pitch factor
so,

$E_1 = 4.44\ K_{w1}\ f_1\ \varphi T_1$,
$E_2 = 4.44\ K_{w2}\ f_1\ \varphi T_2$
$E_r = 4.44\ K_{w2}\ sf_1\ \varphi T_2 = 4.44\ K_{w2}\ f_2\ \varphi T_2$.

4.6.2 b Rotor current of Induction Motor.

a) At stand still condition: Let,

E_{20}= EMF Induced per phase of the rotor at stand still.
R_2= Resistance per phase of the rotor.
X_{20}= Reactance per phase of the rotor at stand still. = $2\pi f_1 L_2$
Z_{20}= rotor impedance per phase at stand still
I_{20}= rotor current per phase at stand still
$Z_{20} = R_2 + jX_{20}$, $I_{20} = \frac{E_{20}}{Z_{20}}$
Power factor at standstill,
$\cos\varphi_{20} = \frac{R_2}{Z_{20}} = \frac{R_2}{\sqrt{R_2^2+X_{20}^2}}$

b) At running condition:
Induced emf per phase in the rotor winding at slip s is $E_{2s} = sE_{20}$
Where, E_{20}= EMF Induced per phase of the rotor at stand still.
R_2= Resistance per phase of the rotor.
Rotor winding Reactance per phase of the rotor at slip s is $X_{2s} = 2\pi f_2 L = sX_{20}$
Z_{2s}= rotor impedance per phase at slip s, $Z_{2s} = R_2 + jX_{2s} = R_2 + jsX_{20}$
I_{2s}= rotor current per phase at slip s , $I_{2s} = \frac{E_{2s}}{Z_{2s}}$
Power factor at standstill, $\cos\varphi 2s = \frac{R_2}{Z_{2s}}$.

4.6.2 c Phasor diagram

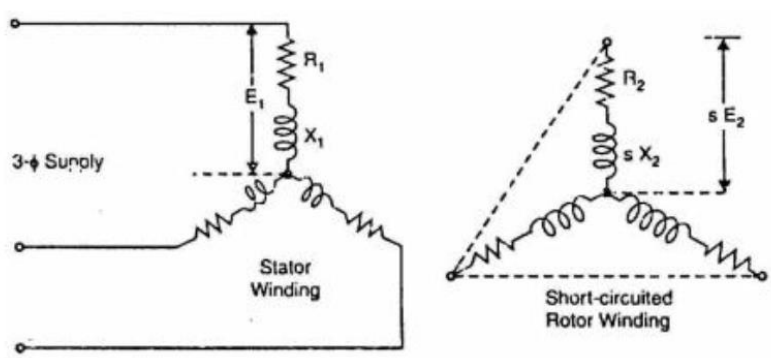


Fig.4.3.3 circuit diagram

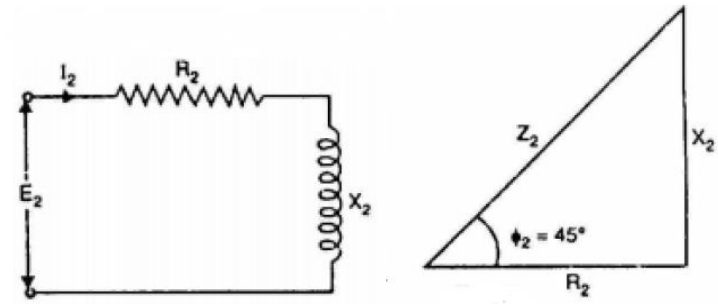


Fig.4.4.4 Phasor diagram at rotor circuit at standstill condition

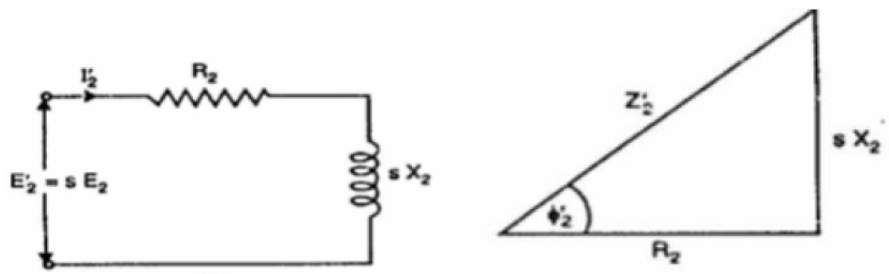


Fig.4.5.5 Phasor diagram at rotor circuit at running condition

4.7.1 Equivalent Circuit of Induction Motor:

The stator of an induction motor consists of a winding resistance r_1 and winding leakage reactance x_1. The major amount of no-load current is required for magnetization and called the magnetizing current I_m which will flow through the magnetizing reactance X_m. A few amount of no-load current is circulated as the core-loss current I_c through the resistor R_c called loss component of no-load current. Hence

$$\vec{I}_0 = \vec{I}_c + \vec{I}_m$$

The rotor of three-phase induction motor consists of resistance r_2 and leakage reactance sx_2, where s is the slip and x_2 is the rotor reactance at standstill.

The complete equivalent circuit can be derived by referring the rotor parameters to the stator at stator circuit frequency and voltage level. The equivalent rotor resistance $\frac{r_2}{s}$ derived from the rotor current can be simplified into parts, the first one r_2 associates with rotor copper loss and the second part $r_2\left(\frac{1-s}{s}\right)$ denoted the mechanical power developed. The equivalent circuit is shown in Fig.4.6.6

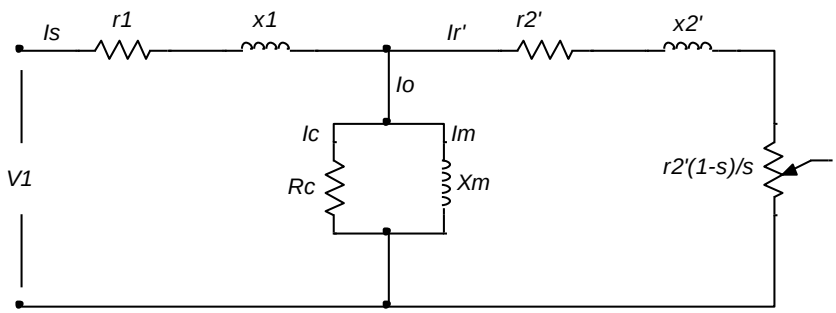


Fig.4.6.6 Per phase complete equivalent circuit referred to stator

Phasor Diagram:

Phasor diagram of three-phase induction motor derived from the equivalent circuit is shown in Fig.4.7.7

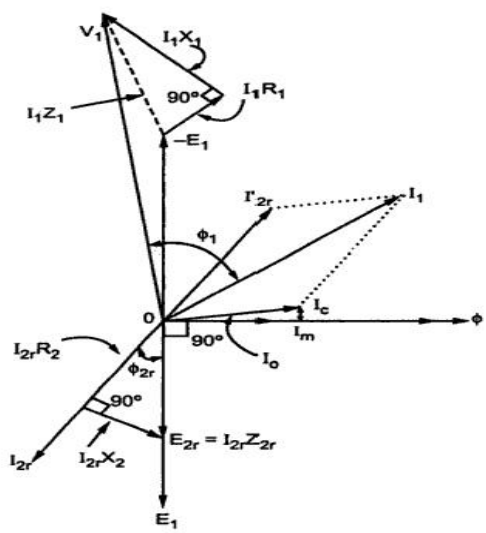


Fig4.7.7 Phasor diagram.

4.8.1 Torque developed in Three-Phase Induction Motor:

Electromagnetic developed torque in three-phase induction motor is expressed as,

$$T_e = \frac{3sE_2^2 r_2}{\omega_s\left[r_2^2 + (sx_2)^2\right]}$$

where, ω_s is the angular synchronous speed in rad/sec. The torque-speed characteristics is shown in Fig.4.8.1

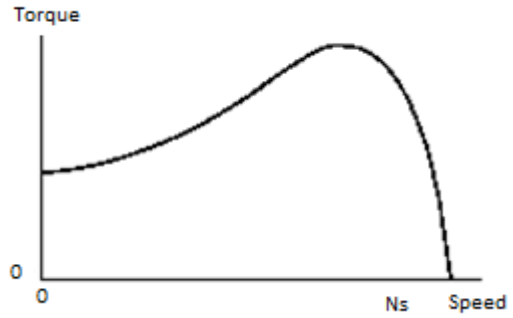


Fig.7.8.1 Torque-Speed characteristics of induction motor

Multiple Choices of Questions (MCQ)

1. Induction motor operation depends on

   a) rotating magnetic field
   b) stationary magnetic field
   c) either of these
   d) none of the above

2. Find the number of poles required, when the frequency is 50Hz and speed of the motor is 500 rpm?

   a) 5 b) 6 c) 10 d) 12

3. The sequence of induction motor is RYB, then the direction of induction motor can be changed by which of the following sequence?

   a)RYB b)YBR c)BRY d) All of the above

4. A 4 pole 50 Hz induction motor is running at 1470 rpm. What is the slip value?

   a)0.4 b) 0.2 c)0.04 d)0.02

5. At stand still condition the value of slip is

   a) 1 b) 0 c) infinite d) none of these

Example 1:

A three phase 20 HP, 208 V, 60 Hz, 6-pole Y-connected induction motor delivers 15 KW at a slip of 5%. Calculate: a) Synchronous Speed, b) Rotor Speed, c) frequency of rotor current.

Solution:

P= 6, s= 0.05, f = 60 Hz.,

a) Synchronous speed $N_s = (120 \times f) /P$ or, $N_s = (120 \times 60)/6 = 1200$ r.p.m

b) $N_r = (1 - s) N_s$; or $N_r = (1-0.05) \times 1200$; or $N_r = 1140$ rpm

c) $f_r = s \times f$; or $f_r = 0.05 \times 60 = 3$ Hz.

Short Answer type question:

1. What is an Induction Motor?
   An induction motor (IM) is a type of asynchronous AC motor where power is supplied to the rotating device by means of electromagnetic induction.

2. What is an Electric Motor?
   An Electric Motor converts electrical power to mechanical power in its rotor.

3. How to supply power to rotor?
   In a DC motor this power is supplied to the armature directly from a DC source, while in an AC motor this power is induced in the rotating device.

4. Why an Induction Motor sometimes called Rotating transformer?
   An induction motor is sometimes called a rotating transformer because the stator (stationary part) is essentially the primary side of the transformer and the rotor (rotating part) is the secondary side.
5. Why the speed of the physical rotor and the speed of the rotating magnetic field in the stator must be different?
   The speed of the physical rotor and the speed of the rotating magnetic field in the stator must be different, or else the magnetic field will not be moving relative to the rotor conductors and no currents will be induced.

6. What is the SLIP?

7. What is the relationship between the supply frequency number of poles and synchronous speed?

What is a Rotor Speed?

GENERAL STRUCTURE OF ELECTRICAL POWER SYSTEM

5.1 Introduction

Electrical power system deals with the technology of generation, transmission and distribution of electrical energy. An electric power system consisting of different subsystems are explained as follows

1. Generation
2. Transmission
3. Distribution

Generation: The generation at the power station produces three phase electrical energy using other energy sources like, fossil fuel or hydrosource,nuclear power and non-conventional power like solar power, wind power and tidal power are also used in a small scale.

Transmission: The power generated in power station has to be transported over long distances to bring power to loads centers. Normally the generated voltage is stepped up to extra high voltage and transmitted through towers. This part is known as transmission.

Distribution: The extra high voltage is stepped down to 3 phase 415 volt medium voltage and 230 volts single pahse in number of stages and supplied for industrial and domestic purposes.The single line diagram of below fig. 5.1 illustrated the whole system.

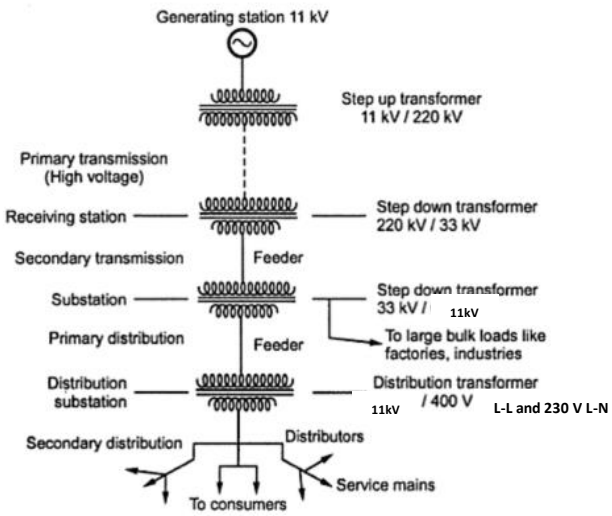


Fig. 5.1 Single line diagram of electrical power generation to distribution system

5.2 Overhead Line and Underground Cable

Electrical power can be transmitted or distributed either by overhead system or underground cables. Both types have some advantages and disadvantages. Table 5.2 presents a comparison between them.

Overhead Line	Underground Line
It has high maintenance cost, installation is less costly and easy to repair	Installation is more costly and repair is inconvenient and costly.
Prone to hazards like heavy rain and wind etc	Free from these problems
Reliability of service poor	Reliability of service good
Tapping at any point is convenient so as serve a new consumer	Tapping cannot be done easily

MODULE VI

ELECTRICAL INSTALLATIONS

6.1. Earthing of Electrical Equipment

6.1.1 What is Earthing?

Equipment earthing is a connection done through a metal link between the body of any electrical appliance, or neutral point, as the case may be, to the deeper ground soil. The metal link is normally of MS flat, CI flat, GI wire which should be penetrated to the ground earth grid. Equipment earthing is based on IS:3043-1987 Standards.

1. Classification of electrical equipment IS: 9409-1980
2. Important rules for safety and earthing practice is based on IE rules 1956
3. Guide on effects of current passing through human body – IS:8437-1997
4. Protection of buildings and structures from lightning – IS:2309-1969
5. **Earth:** The conductive mass of the earth, whose electric potential at any point is conventionally assumed and taken as ZERO.
6. **Earth Electrode:** A Conductor or group of conductors in intimate contact with and providing as electrical connection to earth.
7. **Earth Electrode Resistance:** The electrical resistance of an earth electrode to the general mass of earth.
8. **Earthing Conductor:** A protective conductor connecting the main earthing terminal to an earth electrode or other means of earthing.
9. **Equipotential Bonding:** Electrical connection putting various exposed conductive parts and extraneous conductive parts at a substantially equal potential. Example: Inter connect protective conductor, earth continuity conductors and risers of AC/HV systems if any.
10. **Potential gradient:** The potential difference per unit length measured in the direction in which it is max.
11. **Touch Voltage:** The P.D. between a grounded metallic structure and a point on the earth's surface separated by a horizontal reach of one Metre.

12. **Step Voltage:** The P.D. between two points on the earth's surface separated by a distance one pace (step) assumed to be one Metre.
13. **Earth Grid:** A System of grounding electrodes consisting of interconnected connectors buried in the earth to provide a common ground from electrical devices and metallic structures.
14. **Earth Mat:** A grounding system formed by a grid of horizontally buried conductors - Serves to dissipate the earth fault current to earth and also as an equipotential bonding conductor system.

6.1.2 Necessity of Equipment Earthing Protection

- Safety of personnel
- Safety of equipment Prevent or at least minimize damage to equipment as a result of flow of heavy currents.
- Improvement of the reliability of the power system.

6.1.3 Classification of Earthing

The earthing is broadly divided as

1. System earthing (Connection between part of plant in an operating system like LV neutral of a power transformer winding) and earth.
2. Equipment earthing (safety grounding) connecting bodies of equipment (like electric motor body, transformer tank, switchgear box, operating rods of air break switches, LV breaker body, HV breaker body, feeder breaker bodies etc) to earth.

6.1.4 Permissible Values of Earth Resistance

- Power stations - 0.5 ohms
- EHT stations - 1.0 ohms
- 33KV SS - 2 ohms
- DTR structures - 5 ohms
- Tower foot resistance - 10 ohms

6.1.5 What is the Basics for arriving at Permissible Earth Resistances?

As per IE rules one has to have a definite base for that as per IE rules one has to keep touch potential less than

Recommended safe value 523 volts

I_{fault} = maximum current in fault conditions, $resistance = \frac{Touch\ voltage}{I_{fault}} = \frac{V_{touch}}{I_{fault}}$

Maximum fault current is 100 KVA the current in 100 KVA is about 100 A; where percentage impedance is 4% $\frac{100X100}{4} = 2500\ A\ Say\ 2000\ A\ Max$

For a substation of 100 KVA transformer $R = \frac{V_{touch}}{I_{fault}} = \frac{523}{2000} = 0.26\ ohms$ 0.26 ohms being quite low, quality work is to be done during construction, to obtain such a value of earthing system, and the expenditure for that will be very high. Hence the electrical inspectors are insisting about 1.0 ohms. This seems justifying for the urban areas. This value may be 2 ohms in case of rural areas, which is recommended by most of the authorities.

The earth electrode resistance value also carries importance in view of full protection by lightning arrestors against lightning. The earth electrode resistance value in that case is given by the formula $R = \frac{Flash\ over\ voltage\ of\ 11\ KV}{Lightning\ Discharge\ Current}$ Flash over voltage of 11 KV = 75 KV

Lightning arrestor Displacement = 40 KA.

$$The\ earth\ electrode\ resistance\ R = \frac{75\ KV}{40\ KA} = 1.9\ \Omega$$

6.1.6 Type of Earthing

1. Plate Type Earthing

2. Pipe Type Earthing

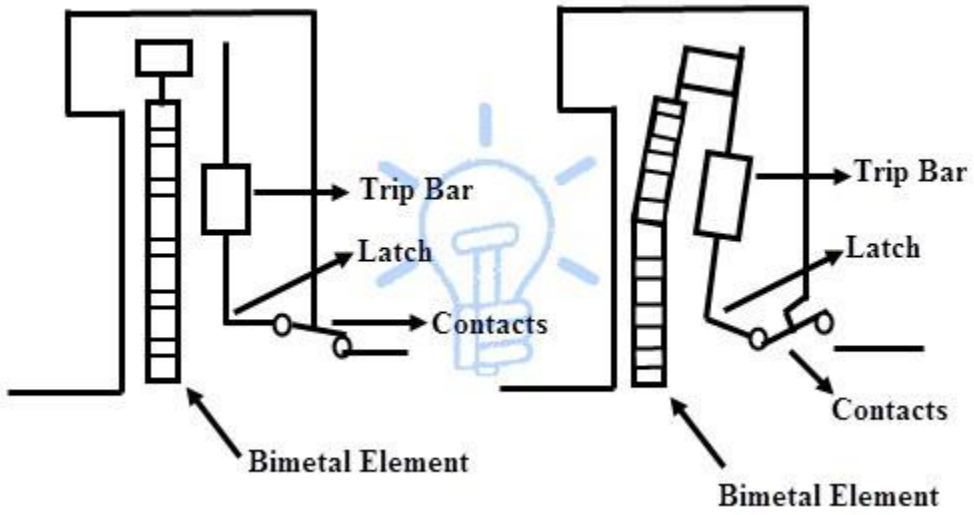
3. Other Types of Earthing: When the capabilities of certain equipment are limited, they may not with stand certain fault currents then the following types of earthing are resorted to limit the fault current.

1. Resistance earthing
2. Reactance earthing
3. Peterson coil earthing.
4. Earthing through grounding transformer.

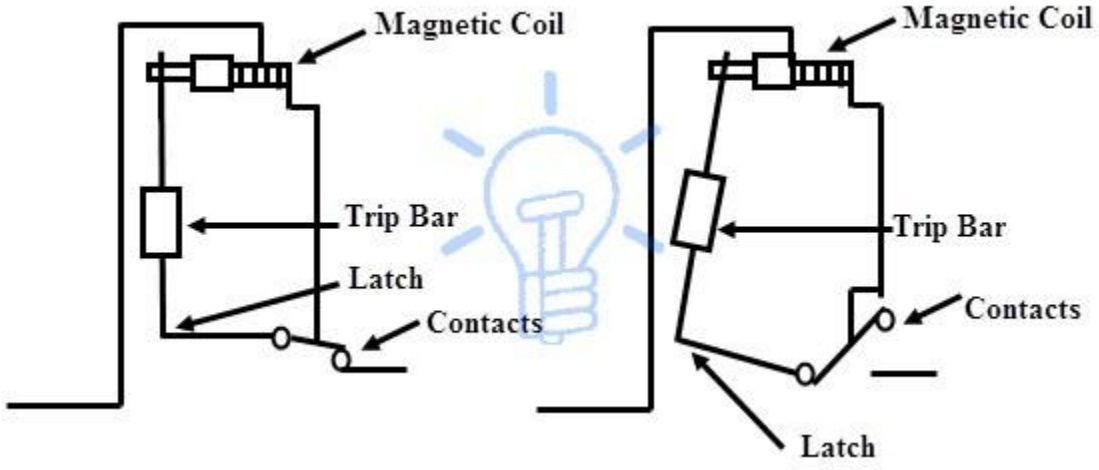
6.2 Ideas of basic components- MCB, MCCB, ELCB, SFU, Megger.

6.2.1 Working & Operation of MCB

Under normal working conditions, MCB operates as a switch (manual one) to make the circuit ON or OFF. Under overload or short circuit condition, it automatically operates or trips so that current interruption takes place in the load circuit. The visual indication of this trip can be observed by automatic movement of the operating knob to OFF position. This automatic operation MCB can be obtained in two ways as we have seen in MCB construction; those are magnetic tripping and thermal tripping.



Under overload condition, the current through the bimetal causes to raise the temperature of it. The heat generated within the bimetal itself enough to cause deflection due to thermal expansion of metals. This deflection further releases the trip latch and hence contacts get separated. In some MCBs, magnetic field generated by the coil causes develop pull on bimetal such that it deflection activates the tripping mechanism.



Under short circuit or heavy overload conditions, magnetic tripping arrangement comes into the picture. Under normal working condition, the slug is held in a position by light spring because magnetic field generated by the coil is not sufficient to attract the latch. When a fault current

flows, the magnetic field generated by the coil is sufficient to overcome the spring force holding slug in position. And hence slug moves and then actuate the tripping mechanism.
A combination of both magnetic and thermal tripping mechanisms are implemented in most of MCBs. In both magnetic and thermal tripping operations, an arc is formed when the contacts start separating. This arc is then forced into arc splitter plates via arc runner. These arc splitter plates are also called arc chutes where arc is formed into a series of arcs and at the same time energy extracted and cools it. Hence this arrangement achieves the arc extinction.

6.2.2. Molded Case Circuit Breaker Definition and Function

A *molded case circuit breaker*, abbreviated MCCB, 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 the MCCB can have current ratings of up to 2,500 amperes, and its trip settings are normally adjustable. An additional difference is that MCCBs tend to be much larger than MCBs. As with most types of circuit breakers, an MCCB has three main functions:

- Protection against overload – currents above the rated value that last longer than what is normal for the application.
- Protection against electrical faults – During a fault such as a short circuit or line fault, there are extremely high currents that must be interrupted immediately.
- 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 isn't an adequate manual switch.

6.3 Molded Case Circuit Breaker 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 overcurrent conditions that last 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.

As with all types of circuit breakers, the MCCB includes a disconnection switch which is used to trip the breaker manually. It is used whenever the electric supply must be disconnected to carry out field work such as maintenance or equipment upgrades.

6.4 Types of MCCB Circuit Breaker by Application

Molded case circuit breakers can have very high current ratings, which allows them to be used in heavy duty applications. The following are some typical uses of an MCCB:

- **Main electric feeder protection**
- **Capacitor bank protection Generator protection**
- **Welding applications**
- **Low current applications that require adjustable trip settings**
- **Motor protection**

6.5 What is an Earth Leakage Circuit Breaker (ELCB)

An ECLB is one kind of safety device used for installing an electrical device with high earth impedance to avoid shock. These devices identify small stray voltages of the electrical device on the metal enclosures and intrude the circuit if a dangerous voltage is identified. The main purpose of Earth leakage circuit breaker (ECLB) is to stop damage to humans & animals due to electric shock.

An ELCB is a specific type of latching relay that has a structure's incoming mains power associated through its switching contacts so that the circuit breaker detaches the power in an unsafe condition.The ELCB notices fault currents of human or animal to the earth wire in the connection it guards. If ample voltage seems across the ELCB's sense coil, it will turn off the power, and remain off until manually rearrange. A voltage sensing ELCB doesn't detect fault currents from human or animal to the earth.

The ELCB notices fault currents of human or animal to the earth wire in the connection it guards. If ample voltage seems across the ELCB's sense coil, it will turn off the power, and remain off until manually rearrange. A voltage sensing ELCB doesn't detect fault currents from human or animal to the earth .

6.5.1 How to Connect Earth Leakage Circuit Breaker

The earth circuit is adapted when an ELCB is used; the connection to the earth rod is accepted through the earth leakage circuit breaker by linking to its two earth terminals. One goes to the fitting earth circuit protective conductor (CPC), and the other to the earth rod or another kind of earth connection. Thus the earth circuit permits through the ELCB's sense coil.

6.5.2 Types of Earth Leakage Circuit Breaker (ELCB)

There are two types of Earth Leakage Circuit Breaker (ELCB)

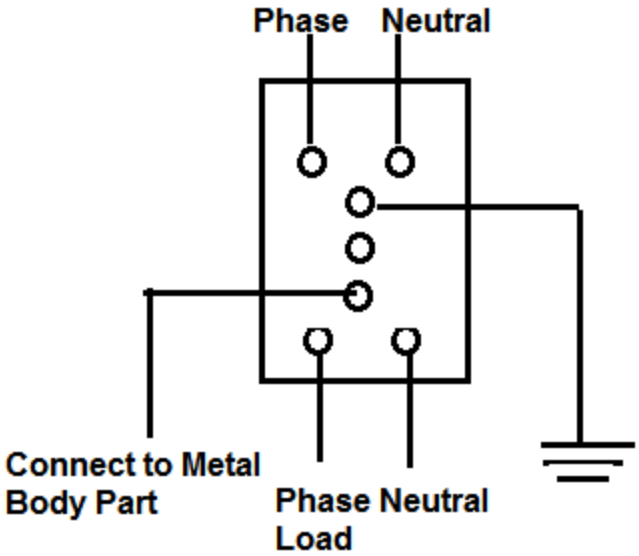
- Voltage Operated ELCB
- Current Operated ELCB

6.6 Types of Earth Leakage Circuit Breaker

6.6.1 Voltage Operated ELCB

Voltage-operated ELCB device is used to detect a voltage to choose the Earth leakage. A single-phase voltage ELCB includes 6-terminals namely line in, line out, neutral in, neutral out, Earth and fault. The metal body of the load is associated with the fault terminal of the Earth Leakage Circuit Breaker (ELCB) & Earth terminal is

associated with the ground. For usual working, the voltage across the trip coil is '0', as the Load's body is isolated from the supply line. When an Earth fault happens on the load due to the interaction of line wire to the metal body, a current will run through fault to the ground. The flow of current will set up a voltage across the trip coil, which is associated between E & F. The energized trip coil will tour the circuit to guard the load device & the user.



Voltage Operated ELCB

A voltage-operated ELCB detects a growth in potential between the threatened consistent metalwork and a distant isolated Earth reference electrode. They work as a sensed potential of around 50V to open the main breaker & separate the supply from the threatened premises.A voltage-operated ELCB includes a second terminal for linking to the remote reference Earth connection.

The Earth circuit is improved when an ELCB is utilized; the link to the Earth rod is delivered through the ELCB by linking to its two Earth terminals. One terminal energy to the installation Earth circuit protective conductor, aka Earth wire (CPC), and the other to the Earth rod or some type of earth connection.

6.6.2 Advantages of Voltage Operated ELCB

- ELCBs are less sensitive to fault conditions and have few nuisance trips.
- While current and voltage on the ground line generally fault current from a live wire, this is not continuously the case, therefore there are conditions in which an ELCB can annoyance trip.
- When an installation of the electrical instrument has two contacts to earth, a near high current lightning attack will root a voltage gradient in the earth, offering the ELCB sense coil with sufficient voltage to source it to a trip.
- If either of the soil wires become detached from the ELCB, it will no longer install will frequently no longer be correctly earthed.

- These ELCBs are the necessity for a second connection and the opportunity that any extra connection to ground on the threatened system can inactivate the detector.

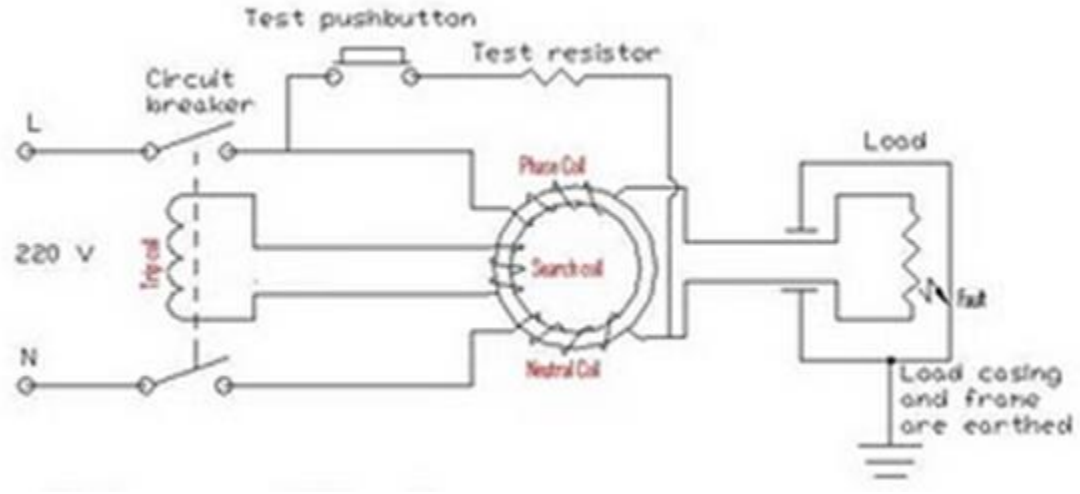
6.6.3 Disadvantages of Voltage Operated ELCB

- They do not sense errors that don't permit current through the CPC to the ground rod.
- They do not permit an only building system to be simply divided into many sections with independent error protection because earthing systems are typically used mutual earth, Rod.
- They may be skipped by outside voltages from something associated with the earthing system like as metal pipes, a TN-C-S or a TN-S earth mutual neutral and earth.
- As electrical leaky utilizations like washing machines, some water heaters and cookers might source the ELCB to trip.
- ELCBs present an extra resistance & an extra point of failure in the earthing system.

6.7 Current Operated ELCB

RCCB is the generally used ELCB and it comprises of a three winding transformer, that has two primary windings and also one secondary winding. Neutral & line wires work as the two main windings. A wire wound coil is the minor winding. The flow of current through the minor winding is "0" in the stable condition. In this condition, the flux owed to the current over the phase wire will be deactivated by the current through the neutral wire, meanwhile the current, that flows from the phase will be refunded to the neutral.

When an error occurs, a slight current will run into the ground also. This creates a confuse between line and neutral current and that makes an unstable magnetic field. This encourages a current flow through the minor winding, which is associated with the sensing circuit. This will detect the outflow and direct signal to tripping system.



Current Operated ELCB

Thus, this is all about Earth Leakage Circuit Breaker (ELCB), types of ELCB and its working.We hope that you have got a betterunderstanding of this concept.

6.8 S.F.U

It is Switched Fuse Unit. It has one switch unit and one fuse unit. When we operate the breaker, the contacts will get closed through switch and then the supply will pass through the fuse unit to the output. Whereas in a Fuse Switch Unit there is no separate switch and fuse unit. There is only the fuse unit which itself acts as a switch. When we operate it the fuse unit will close the input and output of the breaker. SFU has been used to trip the circuit, particularly for high capacity tripping.

6.9 What is Megger?

Insulation resistance IR quality of an electrical system degrades with time, environment condition i.e. temperature, humidity, moisture and dust particles. It also get impacted negatively due to the presence of electrical and mechanical stress, so it's become very necessary to check the IR (Insulation resistance) of equipment at a constant regular interval to avoid any measure fatal or electrical shock.

6.9.1 Uses of Megger

The device enable us to measure electrical leakage in wire, results are very reliable as we shall be passing electric current through device while we are testing. The equipment basically use for verifying the electrical insulation level of any device such as motor, cable, generator winding, etc. This is a very popular test being carried out since very long back. Not necessary it shows us exact area of electrical puncture but shows the amount of leakage current and level of moisture within electrical equipment/winding/system.

Exercises:

Q1. What are main elements of the overhead transmission line? Mention their functions.

Q2. What are the advantages of underground cables over the overhead transmission lines?

Q3. Explain the process of Electrical Power generation.

Q4. Describe Power distribution through overhead lines with single line diagram.

Q5. Explain the advantage and disadvantages of underground power distribution system.

REFRENCES:

1. https://en.wikipedia.org/wiki/Armature_(electrical_engineering)

2. http://www.electrical4u.com/working-or-operating-principle-of-dc-motor/
3. http://www.powerelectricalblog.com/2007/03/armature-and-its-windings.html
4. http://www.electrical4u.com/theory-of-transformer-on-load-and-no-load-operation/
5. http://kbreee.blogspot.in/2013/11/power-generation-introduction.html
6. http://www.electrotechnik.net/2011/11/comparison-of-overhead-and-underground.html