BEE

Basic of Electrical Engineering

B.Tech 1st Year

NOTES

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LEARN & GROW

UNIT-1

D.C CIRCUITS

Network theory is the study of solving the problems of electric circuits or electric networks. In this introductory chapter, let us first discuss the basic terminology of electric circuits and the types of network elements.

Basic Terminology

In Network Theory, we will frequently come across the following terms −

- Electric Circuit
- Electric Network
- Current
- Voltage
- Power

So, it is imperative that we gather some basic knowledge on these terms before proceeding further. Let's start with Electric Circuit.

Electric Circuit

An electric circuit contains a closed path for providing a flow of electrons from a voltage source or current source. The elements present in an electric circuit will be in series connection, parallel connection, or in any combination of series and parallel connections.

Electric Network

An electric network need not contain a closed path for providing a flow of electrons from a voltage source or current source. Hence, we can conclude that "all electric circuits are electric networks" but the converse need not be true

Types of Network Elements

We can classify the Network elements into various types based on some parameters. Following are the types of Network elements −

Active Elements and Passive Elements

Linear Elements and Non-linear Elements

Bilateral Elements and Unilateral Elements

Lumped Elements and Distributed Elements

Active Elements and Passive Elements

We can classify the Network elements into either active or passive based on the ability of delivering power.

Active Elements deliver power to other elements, which are present in an electric circuit. Sometimes, they may absorb the power like passive elements. That means active elements have the capability of both delivering and absorbing power. Examples: Voltage sources and current sources.

Passive Elements can't deliver power (energy) to other elements; however they can absorb power. That means these elements either dissipate power in the form of heat or store energy in the form of either magnetic field or electric field. Examples: Resistors, Inductors, and capacitors.

Linear Elements and Non-Linear Elements

We can classify the network elements as linear or non-linear based on their characteristic to obey the property of linearity.

Linear Elements are the elements that show a linear relationship between voltage and current. Examples: Resistors, Inductors, and capacitors.

Non-Linear Elements are those that do not show a linear relation between voltage and current. Examples: Voltage sources and current sources.

Bilateral Elements and Unilateral Elements Network elements can also be classified as either bilateral or unilateral based on the direction of current flows through the network elements. Bilateral Elements are the elements that allow the current in both directions and offer the same impedance in either direction of current flow. Examples: Resistors, Inductors and capacitors.

R-L-C Parameters

Resistor

The main functionality of Resistor is either opposes or restricts the flow of electric current. Hence, the resistors are used in order to limit the amount of current flow and / or dividing (sharing) voltage. Let the current flowing through the resistor is I amperes and the voltage across it is V volts

According to Ohm's law, the voltage across resistor is the product of current flowing through it and the resistance of that resistor. Mathematically, it can be represented as

$$V=IR$$

Inductor

In general, inductors will have number of turns. Hence, they produce magnetic flux when current flows through it. So, the amount of total magnetic flux produced by an inductor depends on the current, I flowing through it and they have linear relationship.

Capacitor

In general, a capacitor has two conducting plates, separated by a dielectric medium. If positive voltage is applied across the capacitor, then it stores positive charge. Similarly, if negative voltage is applied across the capacitor, then it stores negative charge

Types of Sources

Active Elements are the network elements that deliver power to other elements present in an electric circuit. So, active elements are also called as sources of voltage or current type. We can classify these sources into the following two categories −

Independent Sources

Dependent Sources

Independent Sources

As the name suggests, independent sources produce fixed values of voltage or current and these are not dependent on any other parameter. Independent sources can be further divided into the following two categories −

Independent Voltage Sources

Independent Current Sources

Dependent Sources

As the name suggests, dependent sources produce the amount of voltage or current that is dependent on some other voltage or current. Dependent sources are also called as controlled sources. Dependent sources can be further divided into the following two categories −

Dependent Voltage Sources

Dependent Current Sources

Kirchhoff's Laws

Network elements can be either of active or passive type. Any electrical circuit or network contains one of these two types of network elements or a combination of both. Now, let us discuss about the following two laws, which are popularly known as Kirchhoff's laws.

Kirchhoff's Current Law

Kirchhoff's Voltage Law

Kirchhoff's Current Law

Kirchhoff's Current Law (KCL) states that the algebraic sum of currents leaving (or entering) a node is equal to zero. A Node is a point where two or more circuit elements are connected to it. If only two circuit elements are connected to a node, then it is said to be simple node. If three or more circuit elements are connected to a node, then it is said to be Principal Node. Mathematically, KCL can be represented as

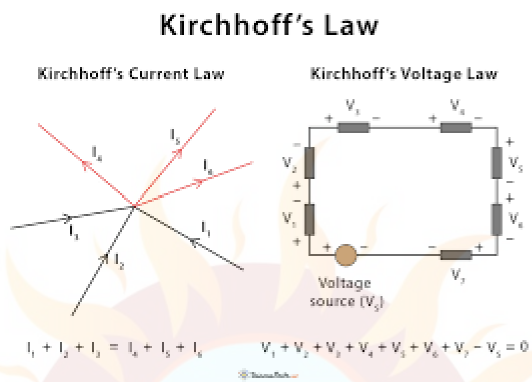
KCL is independent of the nature of network elements that are connected to a node.

Kirchhoff’s Voltage Law

Kirchhoff’s Voltage Law (KVL) states that the algebraic sum of voltages around a loop or mesh is equal to zero.

A Loop is a path that terminates at the same node where it started from. In contrast, a Mesh is a loop that doesn’t contain any other loops inside it.

The above statement of KVL can also be expressed as "the algebraic sum of voltage sources is equal to the algebraic sum of voltage drops that are present in a loop."



Star–to-Delta and Delta-to-Star Transformations for Resistive Networks:

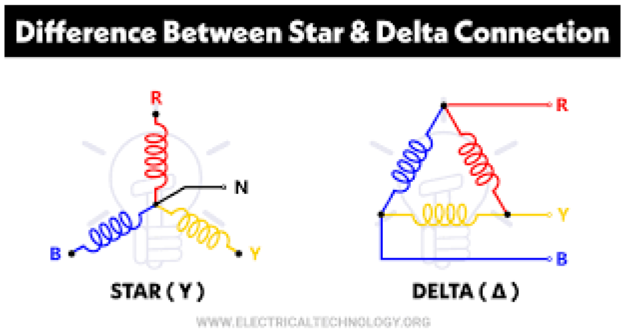
Delta to Star Transformation In the previous chapter, we discussed an example problem related equivalent resistance. There, we calculated the equivalent resistance between the terminals A & B of the given electrical network easily. Because, in every step, we got the combination of resistors that are connected in either series form or parallel form. However, in some situations, it is difficult to simplify the network by following the previous approach. For example, the resistors connected in either delta (δ) form or star form. In such situations, we have to convert the network of one form to the other in order to simplify it further by using series combination or parallel combination. In this chapter, let us discuss about the Delta to Star Conversion.

Delta Network

Consider the following delta network as shown in the following figure.

Star Network

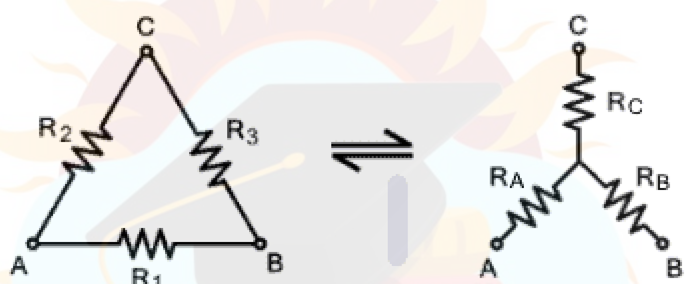
The following figure shows the equivalent star network corresponding to the above delta network.



There are two types of transformation

Star to delta Transformation

Delta to star Transformation



Delta	Star
$R_1 = \frac{R_A R_B + R_B R_C + R_A R_C}{R_C}$	$R_A = \frac{R_1 R_2}{R_1 + R_2 + R_3}$
$R_2 = \frac{R_A R_B + R_B R_C + R_A R_C}{R_B}$	$R_B = \frac{R_1 R_3}{R_1 + R_2 + R_3}$
$R_3 = \frac{R_A R_B + R_B R_C + R_A R_C}{R_A}$	$R_C = \frac{R_2 R_3}{R_1 + R_2 + R_3}$
If, $R_A = R_B = R_C = R_{star}$ $R_{delta} = 3R_{star}$	If, $R_1 = R_2 = R_3 = R_{delta}$ $R_{star} = \frac{R_{delta}}{3}$

Mesh Analysis

Mesh analysis provides general procedure for analyzing circuits using mesh currents as the circuit variables. Mesh Analysis is applicable only for planar networks. It is preferably useful for the circuits that have many loops .This analysis is done by using KVL and Ohm's law.

In Mesh analysis, we will consider the currents flowing through each mesh. Hence, Mesh analysis is also called as Mesh-current method. A branch is a path that joins two nodes and it contains a circuit element.

If a branch belongs to only one mesh, then the branch current will be equal to mesh current. If a branch is common to two meshes, then the branch current will be equal to the sum (or difference) of two mesh currents, when they are in same (or opposite) direction.

Procedure of Mesh Analysis

Follow these steps while solving any electrical network or circuit using Mesh analysis.

Step 1 − Identify the meshes and label the mesh currents in either clockwise or anti-clockwise direction.

Step 2 − Observe the amount of current that flows through each element in terms of mesh currents.

Step 3 − Write mesh equations to all meshes. Mesh equation is obtained by applying KVL first and then Ohm’s law.

Step 4 − Solve the mesh equations obtained in Step 3 in order to get the mesh currents.

Nodal Analysis

We use nodal analysis on circuits to obtain multiple KCL equations which are used to solve for voltage and current in a circuit. The number of KCL equations required is one less than the number of nodes that a circuit has.

The extra node may be referred to as a reference node. Usually, if a circuit contains a ground, whichever node the ground is connected to is selected as the reference node.

This is used to find the voltage differences at each other node in the circuit with respect to the reference.

Procedure of Nodal Analysis

Step 1. Express the current through an element in terms of the node voltages.

Step 2. With the exception of the reference node, apply KCL to each other node in the circuit.

Step 3. solve all the equations

NETWORK THEOREMS

Introduction:

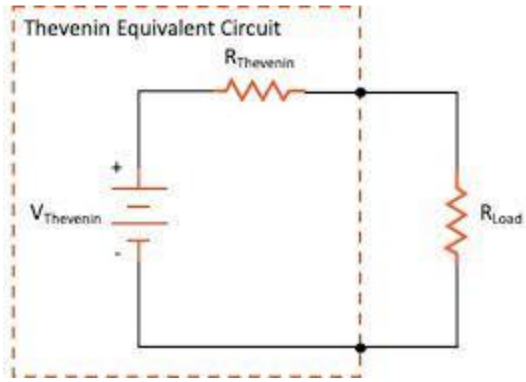
Any complicated network i.e. several sources, multiple resistors are present if the single element response is desired then use the network theorems. Network theorems are also can be termed as network reduction techniques. Each and every theorem got its importance of solving network. Let us see some important theorems with DC and AC excitation with detailed procedures.

Thevenin’s Theorem and Norton’s theorem (Introduction)

Thevenin’s Theorem and Norton’s theorem are two important theorems in solving Network problems having many active and passive elements. Using these theorems, the networks can be reduced to simple equivalent circuits with one active source and one element. In circuit analysis many a times the current through a branch is required to be found when its value is changed with all other element values remaining same. In such cases finding out every time the branch current using the conventional mesh and node analysis methods is quite awkward and time consuming. But with the simple equivalent circuits (with one active source and one element) obtained using these two theorems the calculations become very simple. Thevenin’s and Norton’s theorems are dual theorems.

Thevenin’s Theorem Statement:

Any linear, bilateral two terminal network consisting of sources and resistors (Impedance), can be replaced by an equivalent circuit consisting of a voltage source in series with a resistance (Impedance).The equivalent voltage source VTh is the open circuit voltage looking into the terminals (with concerned branch element removed) and the equivalent resistance RTh while all sources are replaced by their internal resistors at ideal condition i.e., voltage source is short circuit and current source is open circuit.



Step 1: For the analysis of the above circuit using Thevenin's theorem, firstly remove the load resistance

Step 2: Remove the voltage sources' internal resistance by shorting all the voltage sources connected to the circuit, If current sources are present in the circuit, then remove the internal resistance by open circuiting the sources. This step is done to have an ideal voltage source or an ideal current source for the analysis.

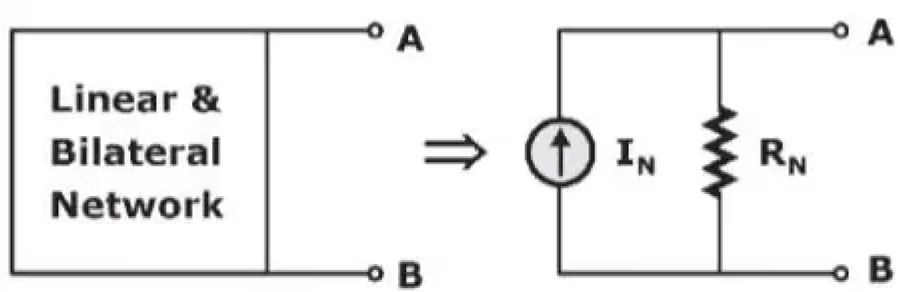
Step 3: Find the equivalent resistance

Step 4: Find the equivalent voltage.

Step 5: Draw the Thevenin's equivalent circuit.

Norton's Theorem Statement:

Any linear, bilateral two terminal network consisting of sources and resistors(Impedance),can be replaced by an equivalent circuit consisting of a current source in parallel with a resistance (Impedance),the current source being the short circuited current across the load terminals and the resistance being the internal resistance of the source network looking through the open circuited load terminals.



Step 1: Remove the element, where we are supposed to find the response from the given circuit. After the removal of the element, the terminals will be open.

Step 2: Find the current flowing through the terminals of the circuit obtained in Step 1 after shorting them. This current is known as short circuit current or Norton's equivalent current or Norton's current, I_N in short.

Step 3: Replace all the independent sources with their internal resistances in the circuit obtained in Step 1.

Step 4: Find the equivalent resistance across the open-circuited terminals of the circuit obtained in Step 3 indirect methods if there are no dependent sources. This equivalent resistance is known as Norton's equivalent resistance or Norton's resistance, R_N in short.

Step 5: If dependent sources are present, then we can find the equivalent resistance across the open-circuited terminals of the circuit obtained in Step 3 by using the Test source method. In the test source method, we will connect a 1V source (or 1A source) across the open terminals and will calculate another parameter current (or voltage). We will get the value of Norton's resistance, R_N by taking the ratio of voltage and current across the 2 terminals.

Step 6: Draw Norton's equivalent circuit by connecting Norton's current, $I_N$in parallel with Norton's resistance, R_N.

Superposition Theorem

"In any linear and bilateral network or circuit having multiple independent sources, the response of an element will be equal to the algebraic sum of the responses of that element by considering one source at a time."

Step 1: First step is to select one among the multiple sources present in the bilateral network. Among the various sources in the circuit, any one of the sources can be considered first.

Step 2: Except for the selected source, all the sources must be replaced by their internal impedance.

Step 3: Using a network simplification approach, evaluate the current flowing through or the voltage drop across a particular element in the network.

Step 4: The same considering a single source is repeated for all the other sources in the circuit.

Step 5: Upon obtaining the respective response for individual source, perform the summation of all responses to get the overall voltage drop or current through the circuit element.

Maximum Power Transfer Theorem

The maximum power transfer theorem states that, to obtain *maximum* external power from a power source with internal resistance, the resistance of the load must equal the resistance of the source as viewed from its output terminals.

$$I = \frac{V_S}{R_S + R_L}.$$

$$P_L = I^2 R_L = \left(\frac{V_S}{R_S + R_L} \right)^2 R_L = \frac{V_S^2}{R_S^2 / R_L + 2R_S + R_L}.$$

$$R_S^2 / R_L + 2R_S + R_L$$

$$\frac{d}{dR_{\mathrm{L}}}\left(R_{\mathrm{S}}^2/R_{\mathrm{L}} + 2R_{\mathrm{S}} + R_{\mathrm{L}}\right) = -R_{\mathrm{S}}^2/R_{\mathrm{L}}^2 + 1.$$

$$\frac{d^2}{dR_{\mathrm{L}}^2}\left(R_{\mathrm{S}}^2/R_{\mathrm{L}} + 2R_{\mathrm{S}} + R_{\mathrm{L}}\right) = 2R_{\mathrm{S}}^2/R_{\mathrm{L}}^3.$$

$$R_{\mathrm{S}} = R_{\mathrm{L}}.$$

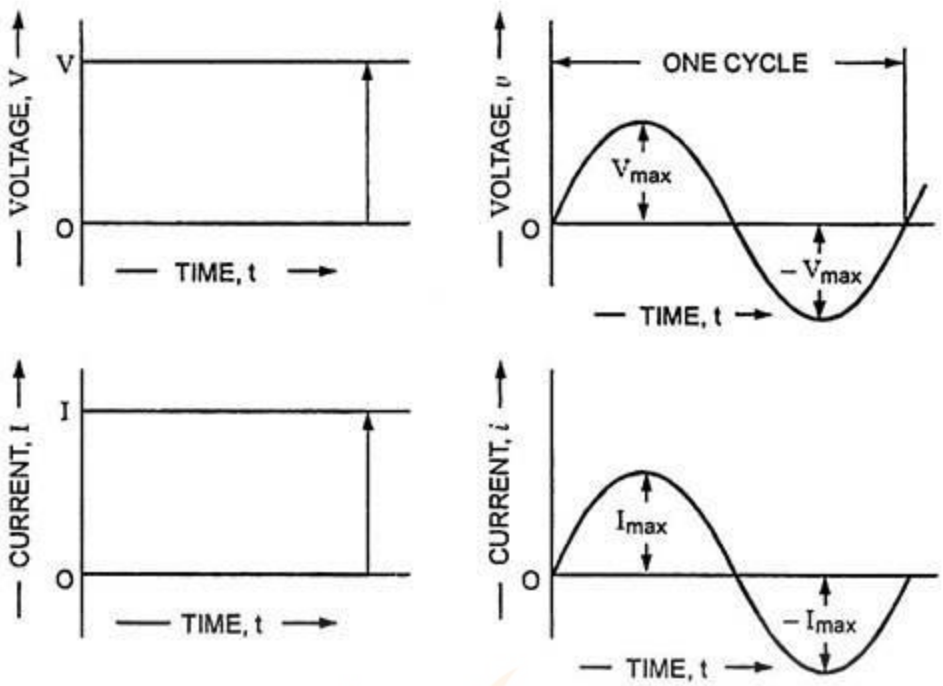
UNIT-2

AC Fundamentals

Alternating Current

A current (or voltage) is called alternating if it reverses periodically in direction, and its magnitude undergoes a definite cycle of changes in definite intervals of time. Each cycle of alternating current (or voltage) consists of two half cycles, during one of which the current (or voltage) acts in one direction; while during the other in opposite direction. In more restricted sense, alternating current is a periodically varying current, the average value of which, over a period, is zero.

The direct current always flows in one direction, and its magnitude remains unaltered. In order to produce an alternating current through an electric circuit, a source capable of reversing the emf periodically (ac generator) is required while for generating dc in an electric circuit, a source capable of developing a constant emf is required such as a battery or dc generator. The graphical representations of alternating current and direct current are given in Figs. 3.1(a) and (b) respectively.



(a) DC Voltage and Current *(b) AC Voltage and Current*

Fig. 3.1

Generation of Alternating Emf:

We know that an alternating emf can be generated either by rotating a coil within a stationary magnetic field, as illustrated in Fig. 3.2 (a) or by rotating a magnetic field within a stationary coil, as illustrated in Fig. 3.2 (b). The emf generated, in either case, will be of sinusoidal waveform.

The magnitude of emf generated in the coil depends upon the number of turns on the coil, the strength of magnetic field and the speed at which the coil or magnetic field rotates. The former method is employed in case of small ac generators while the later one is employed for large sized ac generators.

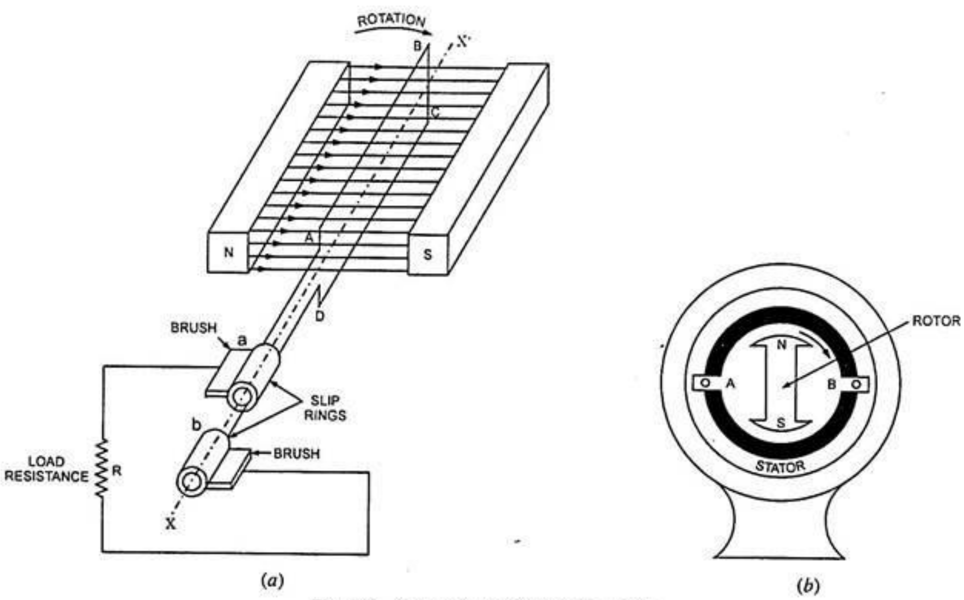


Fig. 3.2 *Generation of Alternating EMF*

Sinusoidal Quantities (Emf, Voltage or Current):

It is not an accident that the bulk of electric power generated in electric power stations throughout the world and distributed to the consumers appears in the form of sinusoidal variations of voltage and current.

There are many technical and economic advantages associated with the use of sinusoidal voltages and currents. For example, it will be learned that the use of sinusoidal voltages applied to appropriately designed coils results in a revolving magnetic field which has the capacity to do work.

As a matter of fact, it is this principle which underlies the operation of almost all the electric motors found in home appliances and about 90% of all electric motors found in commercial and industrial applications. Although other waveforms can be used in such devices, none leads to an operation which is as efficient and economical as that achieved through the use of sinusoidal quantities.

Average and Effective (RMS) Values of Alternating Voltage and Current:

In a dc system, the voltage and current are constant and, therefore, there is no problem in specifying their magnitude. But in case of ac system, an alternating voltage or current varies from instant to instant and so poses a problem how to specify the magnitude of an alternating voltage or current. An alternating voltage or current may possibly be expressed in terms of peak (maximum) value, average (mean) value or effective (rms) value.

Average Value of Alternating Current

The average (or mean) value of an alternating current is equal to the value of direct current which transfers across any circuit the same charge as is transferred by that alternating current during a given time

The average value is determined by measuring the lengths of a number of equidistant ordinates and then taking their mean i.e. of i_1, i_2, i_3 … i_n etc. which are mid-ordinates.

$$\because \text{ Average value of alternating current, } I_{av} = \frac{i_1 + i_2 + i_3 + i_4 \ldots. + i_n}{n}$$

$$= \frac{\text{Area of one alternation (or half cycle)}}{\text{Length of base over one alternation (or half cycle)}}$$

RMS Value or Effective Value of Alternating Current

The rms or effective value of an alternating current or voltage is given by that steady current or voltage which when flows or applied to a given resistance for a given time produces the same amount of heat as when the alternating current or voltage is flowing or applied to the same-resistance for the same time.

Consider an alternating current of waveform shown in Fig. 3.10 flowing through a resistor of R ohms. Divide the base of one alternation into n equal parts and let the mid-ordinates be i_1, i_2, i_3 …i_n. Etc.

Average Value for Sinusoidal Current or Voltage

Instantaneous value of sinusoidal current is given by

$$i = I_{max} \sin \omega t$$

Considering first half cycle i.e when ωt varies from 0 to π we get,

$$I_{av} = \frac{\text{Area of first half cycle}}{\pi}$$

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

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

$$\text{or } I_{av} = \frac{I_{max}}{\pi} \left[-\cos \omega t \right]_0^{\pi} = \frac{2}{\pi} I_{max} = 0.637 I_{max} \quad \text{...(3.14)}$$

Similarly $E_{av} = 0.637 E_{max}$

RMS Value for Sinusoidal Current or Voltage

$$i = I_{max} \sin \omega t$$

$$I_{rms}^2 = \frac{\text{Area of first half cycle of } i^2}{\pi}$$

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

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

$$= \frac{I_{max}^2}{2\pi} \int_0^{\pi} (1 - \cos 2\omega t) \, d(\omega t)$$

$$= \frac{I_{max}^2}{2\pi} \left[\omega t - \frac{1}{2} \sin 2\omega t \right]_0^{\pi}$$

$$= \frac{I_{max}^2}{2\pi} \times \pi = \frac{I_{max}^2}{2}$$

$$\text{or } I_{rms} = \sqrt{\frac{I_{max}^2}{2}} = \frac{I_{max}}{\sqrt{2}} \quad \text{...(3.15)}$$

$$\text{Similarly, } E_{rms} = \frac{E_{max}}{\sqrt{2}}$$

Form Factor and Peak Factor of Sinusoidal Wave

Form Factor

In certain cases, it is convenient to have calculations at first upon the mean value of the emf over half a period, therefore, it becomes essential to have some means of connecting this mean value with the effective or rms value. The knowledge of form factor, which is defined as the ratio of effective value to the average or mean value of periodic wave is, therefore, necessary.

$$\text{Form factor} = \frac{\text{Effective value}}{\text{Average value}}$$

$$\text{Form factor for sinusoidal wave, } K_f = \frac{E_{rms}}{E_{av}} = \frac{\frac{E_{max}}{\sqrt{2}}}{\frac{E_{max}}{\pi/2}} = 1.11$$

Peak Factor

Knowledge of peak factor of an alternating voltage is very essential in connection with determining the dielectric strength since the dielectric stress developed in any insulating material is proportional to the maximum value of the voltage applied to it.

$$\textit{i.e.}\ \text{Peak factor, } K_p = \frac{\text{Maximum value}}{\text{Effective value}}$$

$$\text{Peak factor for sinusoidal wave, } K_p = \frac{E_{max}}{E_{rms}} = \frac{E_{max}}{E_{max}/\sqrt{2}} = 1.414$$

RMS Value, Average Value of Half Wave Rectified Alternating Current

∴ RMS value of current,

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} i^2 \, d\theta}$$

$$= \sqrt{\frac{1}{2\pi}\int_0^{\pi} I^2 \max \sin^2\theta \, d\theta}$$

$$= \frac{I_{max}}{\sqrt{2\pi}}\sqrt{\int_0^{\pi} \sin^2\theta \, d\theta}$$

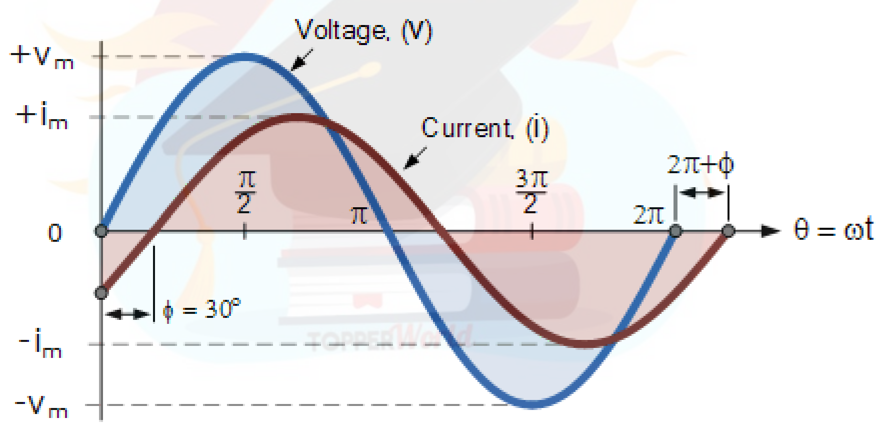
$$= \frac{I_{max}}{\sqrt{4\pi}}\sqrt{\int_0^{\pi}(1-\cos 2\theta)\, d\theta} = \frac{I_{max}}{\sqrt{4\pi}}\sqrt{\left[\theta - \frac{1}{2}\sin 2\theta\right]_0^{\pi}} = \frac{I_{max}}{\sqrt{4\pi}} \times \sqrt{\pi} = \frac{I_{max}}{2}$$

Average value of current, $I_{av} = \frac{1}{2\pi}\int_0^{\pi} i \, d\theta = \frac{1}{2\pi}\int_0^{\pi} I_{max} \sin\theta \, d\theta = \frac{I_{max}}{2\pi}\left[-\cos\theta\right]_0^{\pi} = \frac{I_{max}}{\pi}$

$$\text{Peak Factor} = \frac{I_{max}}{I_{rms}} = \frac{I_{max}}{I_{max}/2} = 2$$

$$\text{Form factor} = \frac{I_{rms}}{I_{av}} = \frac{I_{max}/2}{I_{max}/\pi} = \frac{\pi}{2} = 1.57$$

Phase Difference of a Sinusoidal Waveform

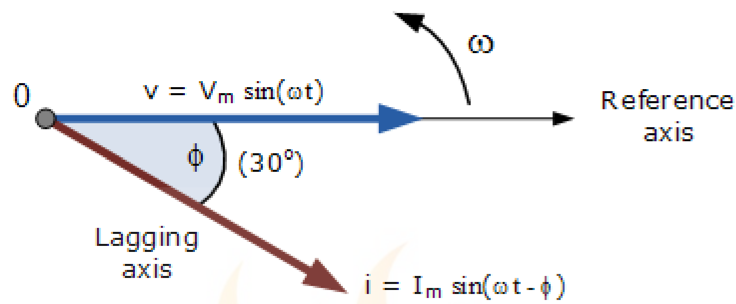


The generalized mathematical expression to define these two sinusoidal quantities will be written as

$$v_{(t)} = V_m \sin(\omega t)$$

$$i_{(t)} = I_m \sin(\omega t - \phi)$$

Phasor Diagram of a Sinusoidal Waveform



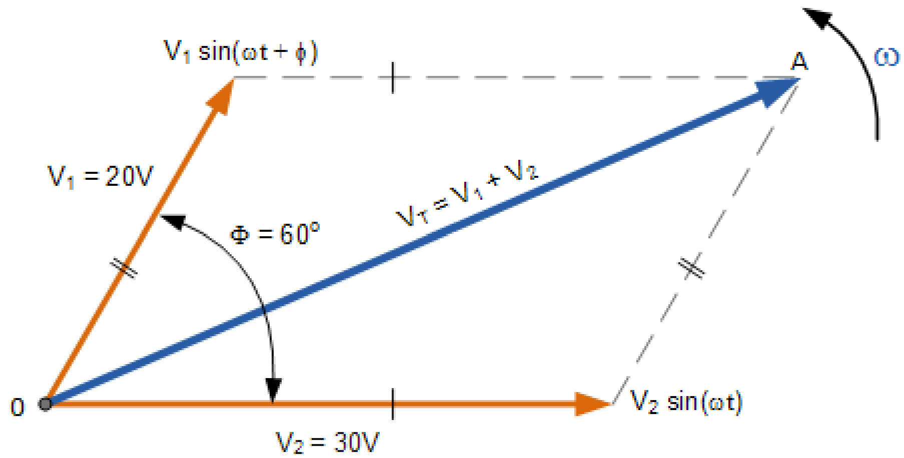
The phasor diagram is drawn corresponding to time zero (t = 0) on the horizontal axis. The lengths of the phasors are proportional to the values of the voltage, (V) and the current, (I) at the instant in time that the phasor diagram is drawn.

The current phasor lags the voltage phasor by the angle, Φ, as the two phasors rotate in an *anticlockwise* direction as stated earlier, therefore the angle, Φ is also measured in the same anticlockwise direction

Phasor Addition of Phasor Diagrams

One good use of phasors is for the summing of sinusoids of the same frequency. Sometimes it is necessary when studying sinusoids to add together two alternating waveforms, for example in an AC series circuit, that are not in-phase with each other.

If however, they are not in-phase that is, they do not have identical directions or starting point then the phase angle between them needs to be taken into account so they are added together using phasor diagrams to determine their **Resultant Phasor** or **Vector Sum** by using the *parallelogram law*.



By drawing out the two phasors to scale onto graph paper, their phasor sum $V_1 + V_2$ can be easily found by measuring the length of the diagonal line, known as the "resultant r-vector", from the zero point to the intersection of the construction lines 0-A. The downside of this graphical method is that it is time consuming when drawing the phasors to scale.

Mathematically we can add the two voltages together by firstly finding their "vertical" and "horizontal" directions, and from this we can then calculate both the "vertical" and "horizontal" components for the resultant "r vector", V_T. This analytical method which uses the cosine and sine rule to find this resultant value is commonly called the **Rectangular Form**.

In the rectangular form, the phasor is divided up into a real part, x and an imaginary part, y forming the generalised expression $Z = x \pm jy$. (we will discuss this in more detail in the next tutorial). This then gives us a mathematical expression that represents both the magnitude and the phase of the sinusoidal voltage as

$$v = V_m \cos(\phi) + jV_m(\sin\phi)$$

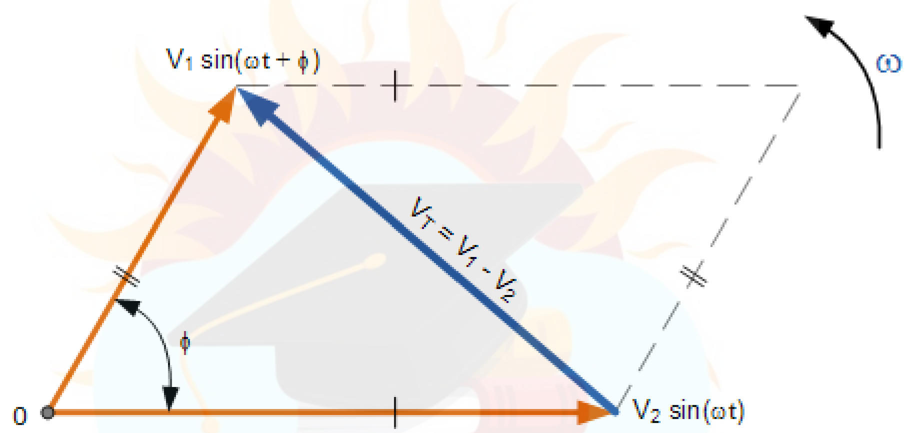
So the addition of two vectors, A and B using the previous generalised expression is as follows:

$$A = x + jy \qquad B = w + jz$$

$$A + B = (x + w) + j(y + z)$$

Phasor Subtraction of Phasor Diagrams

Phasor subtraction is very similar to the above rectangular method of addition, except this time the vector difference is the other diagonal of the parallelogram between the two voltages of V_1 and V_2 as shown.



This time instead of "adding" together both the horizontal and vertical components we take them away, subtraction.

$$A = x + jy \qquad B = w + jz$$

$$A - B = (x - w) + j(y - z)$$

AC Circuits

Introduction to Single Phase AC Circuit

In a dc circuit the relationship between the applied voltage V and current flowing through the circuit I is a simple one and is given by the expression I = V/R but in an a c circuit this simple relationship does not hold good. Variations in current and applied voltage set up magnetic and electrostatic effects respectively and these must be taken into account with the resistance of the circuit while determining the quantitative relations between current and applied voltage.

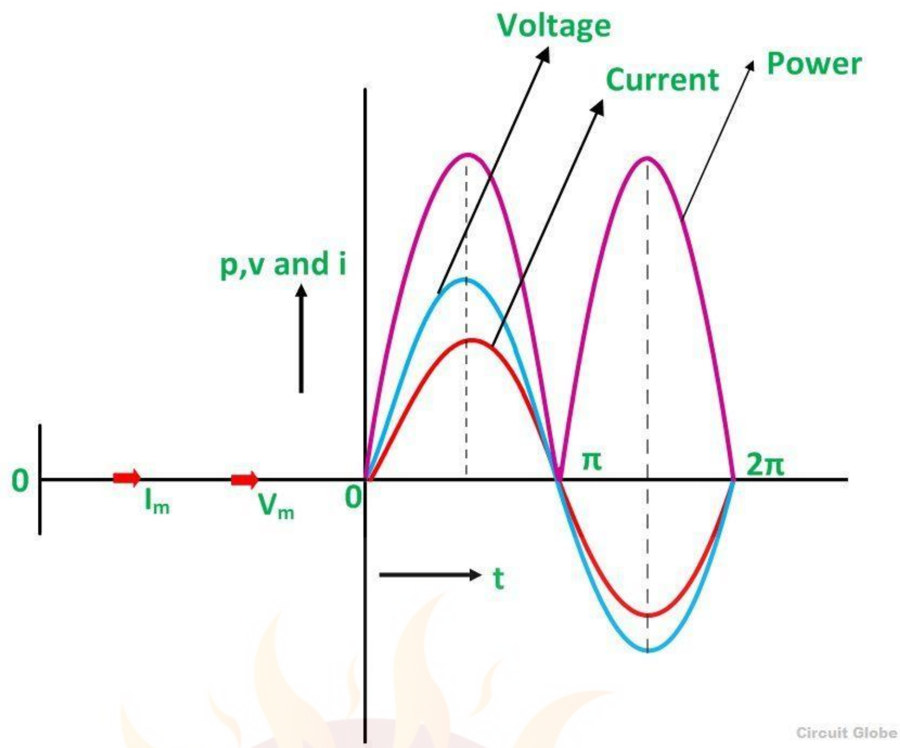
With comparatively low-voltage, heavy- current circuits magnetic effects may be very large, but electrostatic effects are usually negligible. On the other hand with high-voltage circuits electrostatic effects may be of appreciable magnitude, and magnetic effects are also present.

Here it has been discussed how the magnetic effects due to variations in current do and electrostatic effects due to variations in the applied voltage affect the relationship between the applied voltage and current.

Purely Resistive Circuit

A purely resistive or a non-inductive circuit is a circuit which has inductance so small that at normal frequency its reactance is negligible as compared to its resistance. Ordinary filament lamps, water resistances etc., are the examples of non-inductive resistances. If the circuit is purely non-inductive, no reactance emf (i.e., self- induced or back emf) is set up and whole of the applied voltage is utilized in overcoming the ohmic resistance of the circuit.

Consider an ac circuit containing a non-inductive resistance of R ohms connected across a sinusoidal voltage represented by v = V sin wt, as shown in Fig



$$v = V_m \text{Sin}\omega t \ldots\ldots\ldots\ldots\ldots(1)$$

$$i = \frac{v}{R} = \frac{V_m}{R}\sin\omega t \ldots\ldots\ldots(2)$$

$$i = I_m \sin\omega t \ldots\ldots\ldots.(3)$$

Therefore, the instantaneous power in a purely resistive circuit is given by the equation shown below:

Instantaneous power, p=vi

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

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

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

The average power consumed in the circuit over a complete cycle is given by

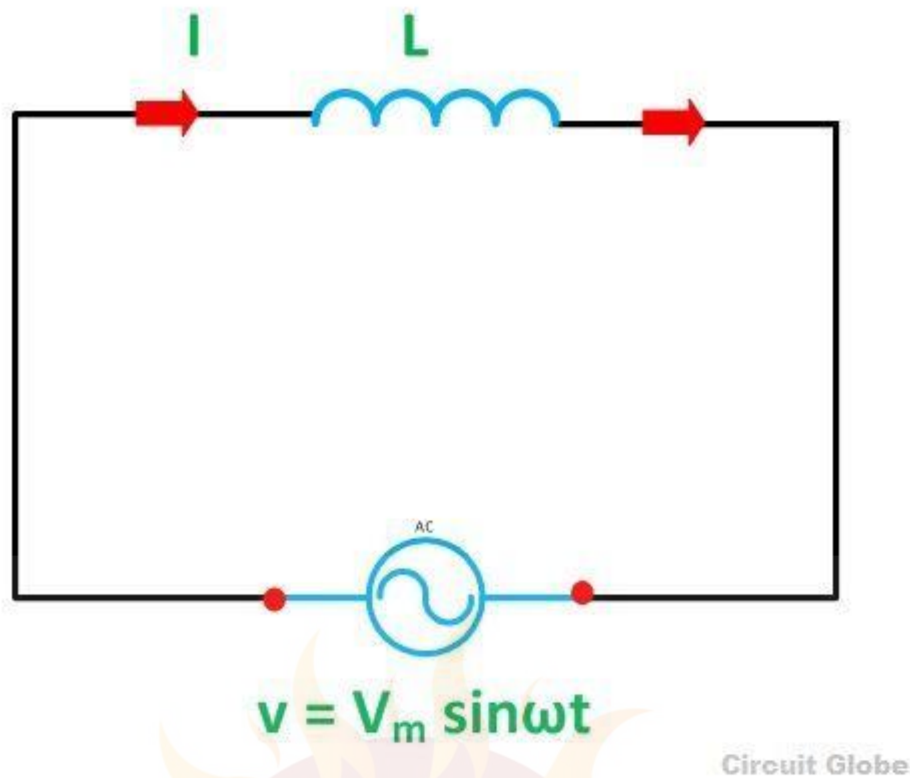
$$P = \text{average of } \frac{V_m}{\sqrt{2}} \frac{I_m}{\sqrt{2}} - \text{ average of } \frac{V_m}{\sqrt{2}} \frac{I_m}{\sqrt{2}} \cos\omega t \ldots \ldots (4)$$

As the valve of cosωt is zero.

$$P = V_{r.m.s} I_{r.m.s} - 0$$

Pure inductive Circuit

The circuit which contains only inductance (L) and not any other quantities like resistance and capacitance in the circuit is called a **Pure inductive circuit.** In this type of circuit, the current lags behind the voltage by an angle of 90 degrees.



Let the alternating voltage applied to the circuit is given by the equation:

$$v = V_m \mathrm{Sin}\omega t \ldots\ldots\ldots\ldots\ldots(1)$$

As a result, an alternating current i flows through the inductance which induces an emf in it. The equation is shown below:

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

The emf which is induced in the circuit is equal and opposite to the applied voltage. Hence, the equation becomes,

$$v = -e \ \ldots\ldots\ldots..(2)$$

Putting the value of e in equation (2) we will get the equation as

$$v = -\left(-L\frac{di}{dt}\right) \quad \text{or}$$

$$V_m \text{Sin}\omega t = L\frac{di}{dt} \quad \text{or}$$

$$di = \frac{V_m}{L}\sin\omega t \, dt \quad \dots\dots\dots\dots (3)$$

Integrating both sides of the equation (3), we will get

$$\int di = \int \frac{V_m}{L}\sin\omega t \, dt \quad \text{or}$$

$$i = \frac{V_m}{\omega L}(-\cos\omega t) \quad \text{or}$$

$$i = \frac{V_m}{\omega L}\sin\left(\omega t - {}^{\pi}/_{2}\right) = \frac{V_m}{X_L}\sin\left(\omega t - {}^{\pi}/_{2}\right) \dots\dots\dots..(4)$$

where, $X_L = \omega L$ is the opposition offered to the flow of alternating current by a pure inductance and is called inductive reactance.

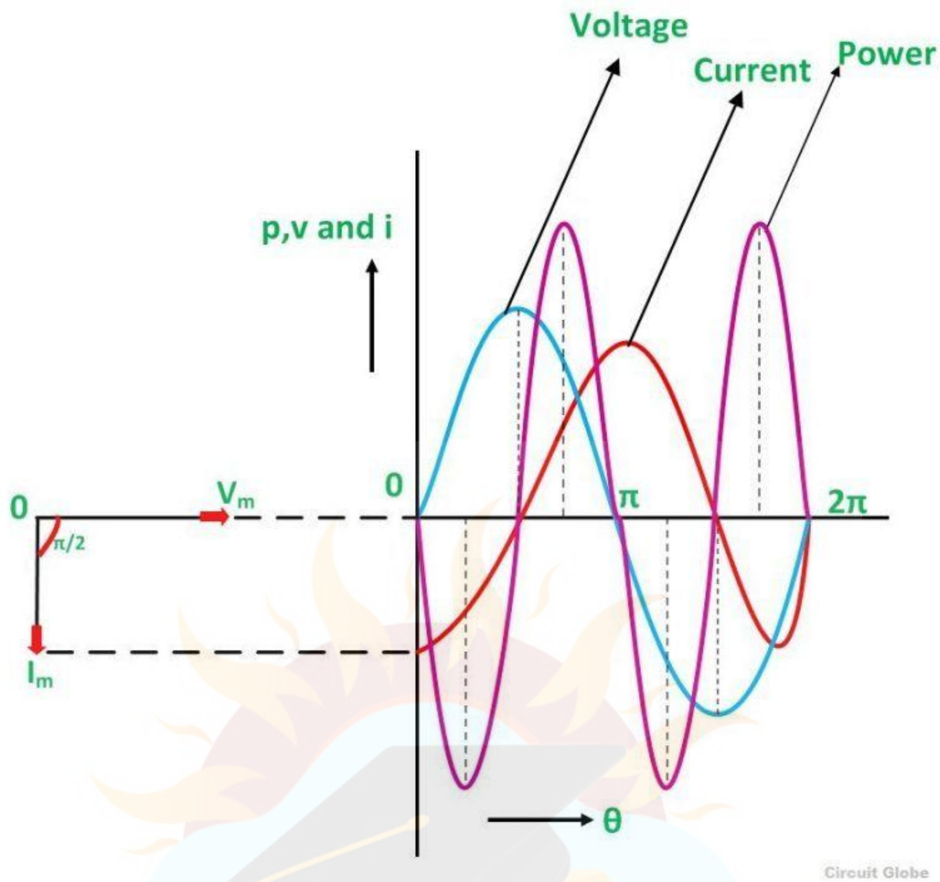
The value of current will be maximum when sin (ωt – π/2) = 1

Therefore,

$$I_m = \frac{V_m}{X_L} \dots\dots\dots\dots (5)$$

Substituting this value in I_m from the equation (5) and putting it in equation

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



Instantaneous power in the inductive circuit is given by

$$p = vi$$

$$P = (V_m \sin\omega t)(I_m \sin(\omega t + \pi/2)$$

$$P = V_m I_m \sin\omega t \cos\omega t$$

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

$$P = \frac{V_m}{\sqrt{2}} \frac{I_m}{\sqrt{2}} \sin 2\omega t \text{ or}$$

$$P = 0$$

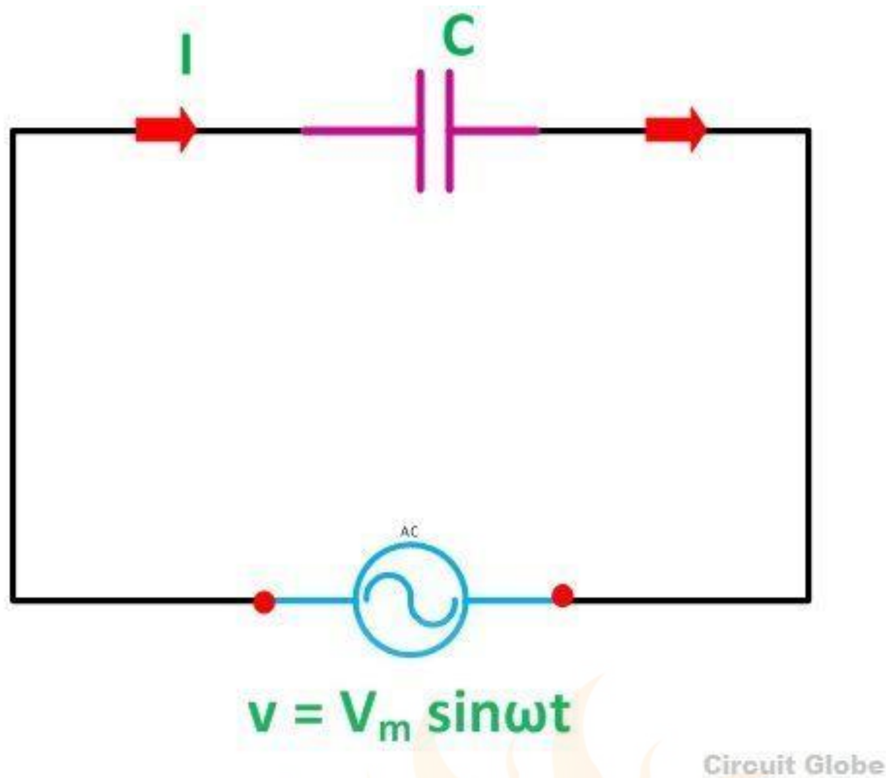
Hence, the average power consumed in a purely inductive circuit is zero.

The average power in one alteration, i.e., in a half cycle is zero, as the negative and positive loop is under power curve is the same.

Pure Capacitor Circuit

The circuit containing only a pure capacitor of capacitance C farads is known as a **Pure Capacitor Circuit**. The capacitors stores electrical power in the electric field, their effect is known as the capacitance. It is also called the **condenser**.

When the voltage is applied across the capacitor, then the electric field is developed across the plates of the capacitor and no current flow between them. If the variable voltage source is applied across the capacitor plates then the ongoing current flows through the source due to the charging and discharging of the capacitor.



Let the alternating voltage applied to the circuit is given by the equation:

$$v = V_m \text{Sin}\omega t \,\ldots\ldots\ldots\ldots\ldots(1)$$

Charge of the capacitor at any instant of time is given as:

$$q = Cv \;\ldots\ldots\ldots\ldots(2)$$

Current flowing through the circuit is given by the equation

$$i = \frac{d}{dt} q$$

Putting the value of q from the equation (2) in equation (3) we will get

$$i = \frac{d}{dt}(Cv) \ldots\ldots\ldots\ldots(3)$$

Now, putting the value of v from the equation (1) in the equation (3) we will get

$$i = \frac{d}{dt} C\, V_m \text{Sin}\omega t = C\, V_m \frac{d}{dt} \sin\omega t \quad \text{or}$$

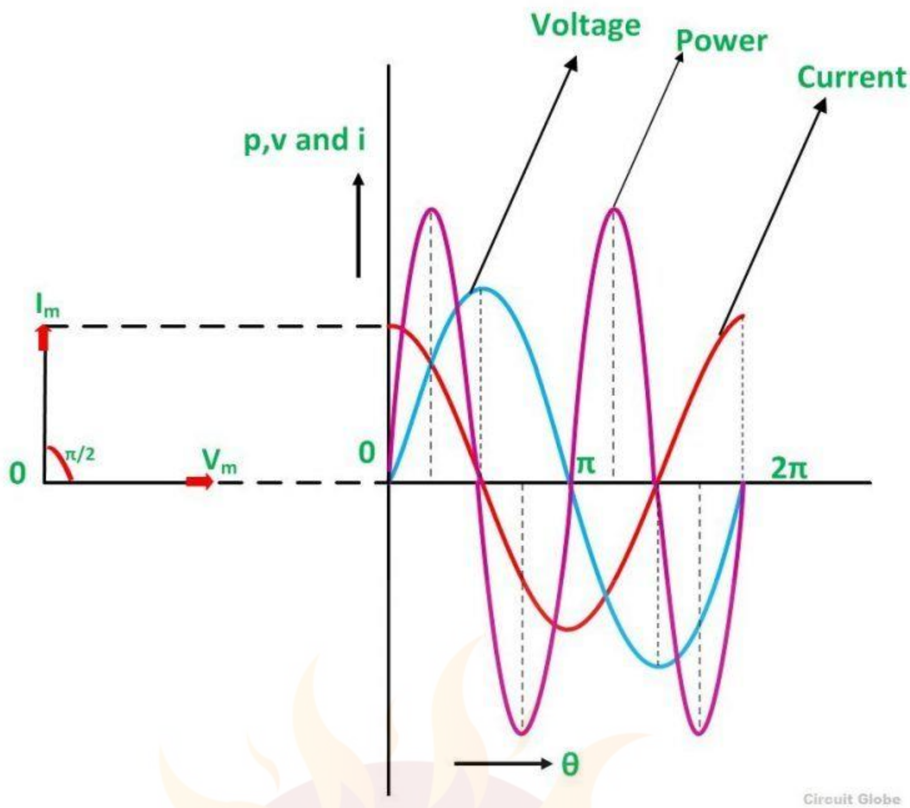
$$i = \omega C\, V_m \cos\omega t = \frac{V_m}{1/\omega C} \sin(\omega t + \pi/2) \quad \text{or}$$

$$i = \frac{V_m}{X_C} \sin(\omega t + \pi/2) \ldots\ldots\ldots\ldots(4)$$

Where Xc = 1/ωC is the opposition offered to the flow of alternating current by a pure capacitor and is called **Capacitive Reactance.**

The value of current will be maximum when sin(ωt + π/2) = 1. Therefore, the value of maximum current I_m will be given as:

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



Power

$$P = (V_m \sin\omega t)(I_m \sin(\omega t + \pi/2))$$

$$P = V_m I_m \sin\omega t \cos\omega t$$

$$P = \frac{V_m}{\sqrt{2}} \frac{I_m}{\sqrt{2}} \sin 2\,\omega t \quad \text{or}$$

$$P = 0$$

Hence, from the above equation, it is clear that the average power in the capacitive circuit is zero.

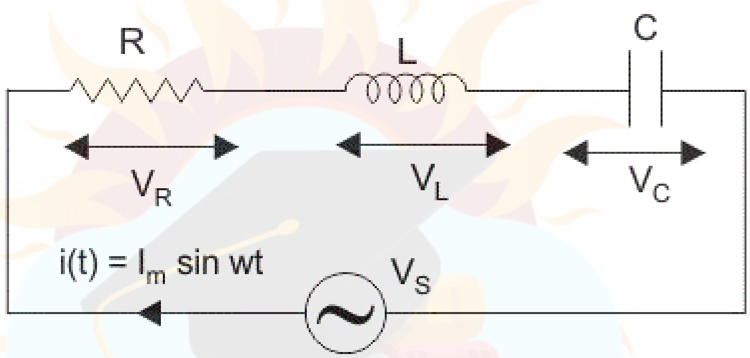
The average power in a half cycle is zero as the positive and negative loop area in the waveform shown are same.

RLC SERIES Circuit

RLC circuit consists of the passive elements Resistor (R), Inductor (L), and Capacitor (C). If we study and understand the behavior of these passive components individually, then we can design the filters, oscillators, etc., by combining these passive elements.

When a resistor, inductor and capacitor are connected in series with the voltage supply, the circuit so formed is called series RLC circuit

Let V_R be the voltage across resistor, R.
V_L be the voltage across inductor, L.
V_C be the voltage across capacitor, C.
X_L be the inductive reactance.
X_C be the capacitive reactance.



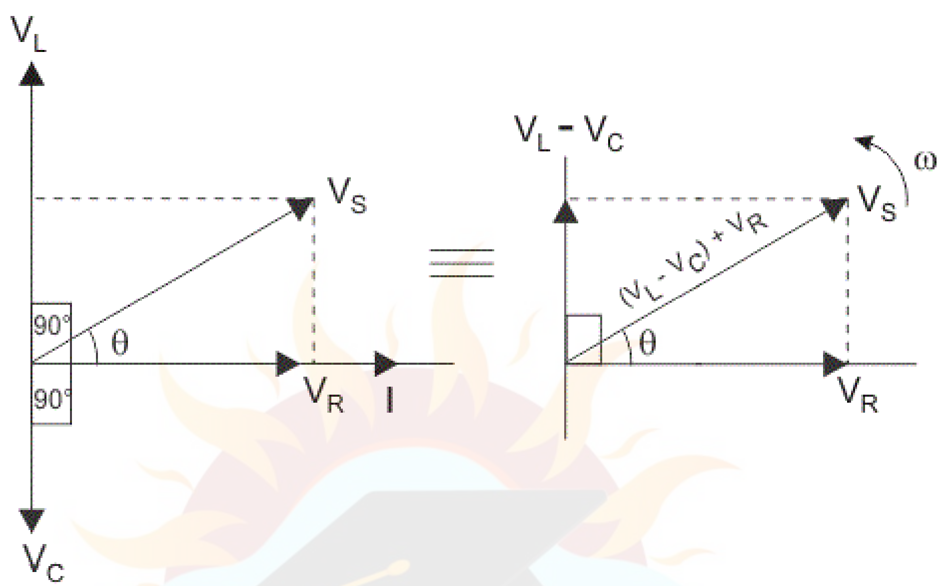
The total voltage in the RLC circuit is not equal to the algebraic sum of voltages across the resistor, the inductor, and the capacitor; but it is a vector sum because, in the case of the resistor the voltage is in-phase with the current, for inductor the voltage leads the current by 90° and for capacitor, the voltage lags behind the current by 90°

So, voltages in each component are not in phase with each other; so they cannot be added arithmetically. The figure below shows the phasor diagram of the series RLC circuit. For drawing the phasor diagram for RLC series circuit, the current is taken as reference because, in series circuit the current in each element remains the same and the corresponding voltage vectors for each component are drawn in reference to common current vector.

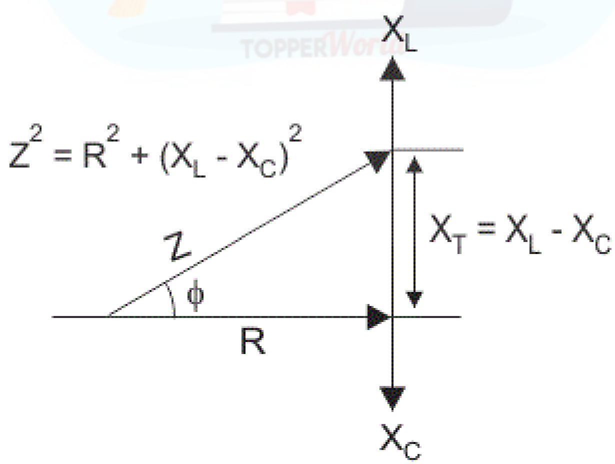
$$V_S^2 = V_R^2 + (V_L - V_C)^2 (if V_L > V_C)$$

$$V_S^2 = V_R^2 + (V_L - V_C)^2 (if V_L < V_C)$$

$$Where\ V_R = IR, V_L = IX_L, V_C = IX_C$$



The Impedance for a Series RLC Circuit



The impedance Z of a series RLC circuit is defined as opposition to the flow of current due circuit resistance R, inductive reactance, X_L and capacitive reactance, X_C.

If the inductive reactance is greater than the capacitive reactance i.e $X_L > X_C$, then the RLC circuit has lagging phase angle

If the capacitive reactance is greater than the inductive reactance i.e $X_C > X_L$ then, the RLC circuit have leading phase angle and if both inductive and capacitive are same i.e. $X_L = X_C$ then circuit will behave as purely resistive circuit.

We know that

$$V_S^2 = V_R^2 + (V_L - V_C)^2$$

Where,

$$V_R = IR, V_L = I\ X_L, V_C = I\ X_C$$

Substituting the values

$$V_S^2 = IR^2 + (I\ X_L - I\ X_C)^2$$

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

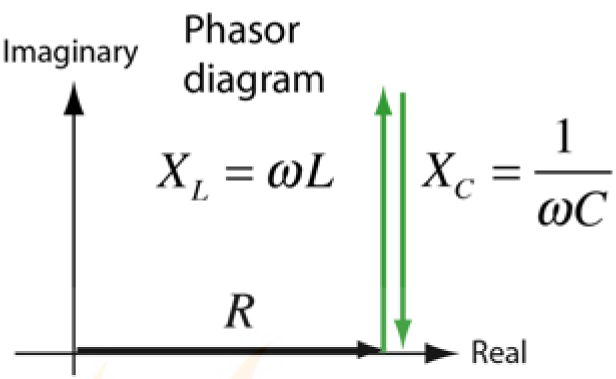
Series resonance

Series resonance is a resonance condition that usually occurs in series circuits, where the current becomes a maximum for a particular voltage.

In series resonance, the current is maximum at resonant frequency.

The series resonance current curve increases to a maximum at resonance then decreases as resonance is passed.

Series resonance is a resonance condition that usually occurs in series circuits, where the current becomes a maximum for a particular voltage.



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

$$at\ \omega_0 = \frac{1}{\sqrt{LC}}$$

The average power dissipated in a series resonant circuit can be expressed in terms of the rms voltage and current as follows:

$$P_{avg} = I_{rms}^2 R = \frac{V_{rms}^2}{Z^2} R = \frac{V_{rms}^2 R}{R^2 + (X_L - X_C)^2}$$

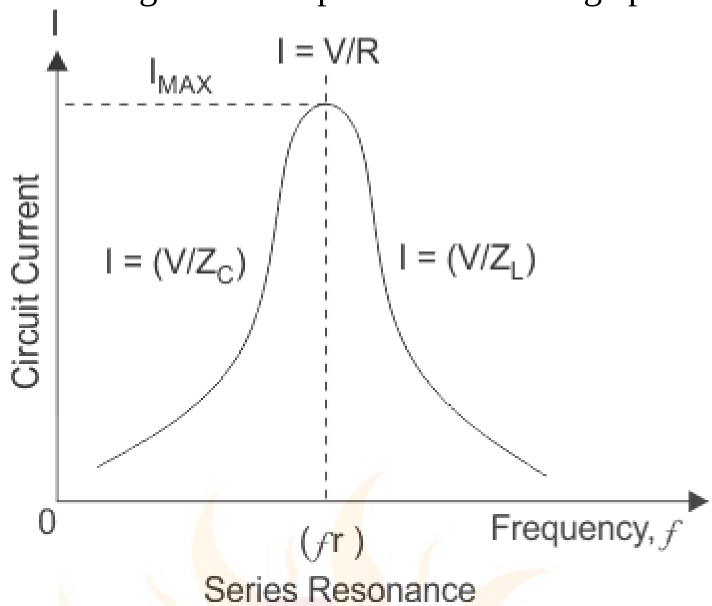
Using the forms of the inductive reactance and capacitive reactance, the term involving them can be expressed in terms of the frequency.

$$(X_L - X_C)^2 = \left(\omega L - \frac{1}{\omega C}\right)^2 = \frac{L^2}{\omega^2}(\omega^2 - \omega_0^2)^2$$

where use has been made of the resonant frequency expression

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

Substitution now gives the expression for average power as a fun



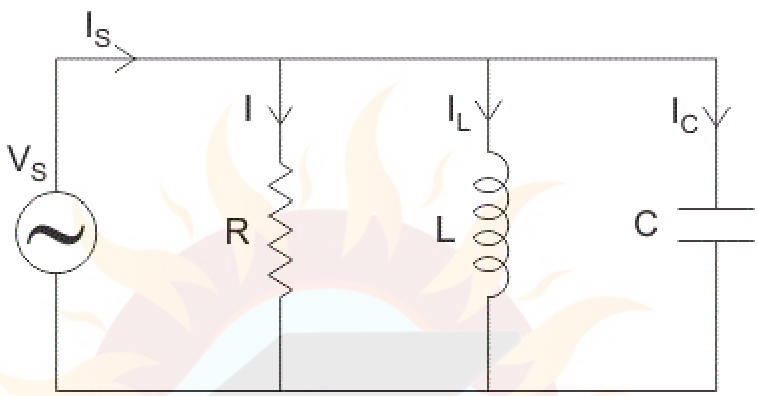
In series RLC circuit current, I = V / Z but at resonance current I = V / R, therefore the current at resonant frequency is maximum as at resonance in impedance of circuit is resistance only and is minimum.

Bandwidth of a Series Resonance Circuit If the series RLC circuit is driven by a variable frequency at a constant voltage, then the magnitude of the current, I is proportional to the impedance, Z, therefore at resonance the power absorbed by the circuit must be at its maximum value as P = I 2Z. If we now reduce or increase the frequency until the average power absorbed by the resistor in the series resonance circuit is half that of its maximum value at resonance, we produce two frequency points called the half-power points.

RLC Parallel Circuit

In parallel RLC Circuit the resistor, inductor and capacitor are connected in parallel across a voltage supply. The parallel RLC circuit is exactly opposite to the series RLC circuit. The applied voltage remains the same across all components and the supply current gets divided.

The total current drawn from the supply is not equal to mathematical sum of the current flowing in the individual component, but it is equal to its vector sum of all the currents, as the current flowing in resistor, inductor and capacitor are not in the same phase with each other; so they cannot be added arithmetically.



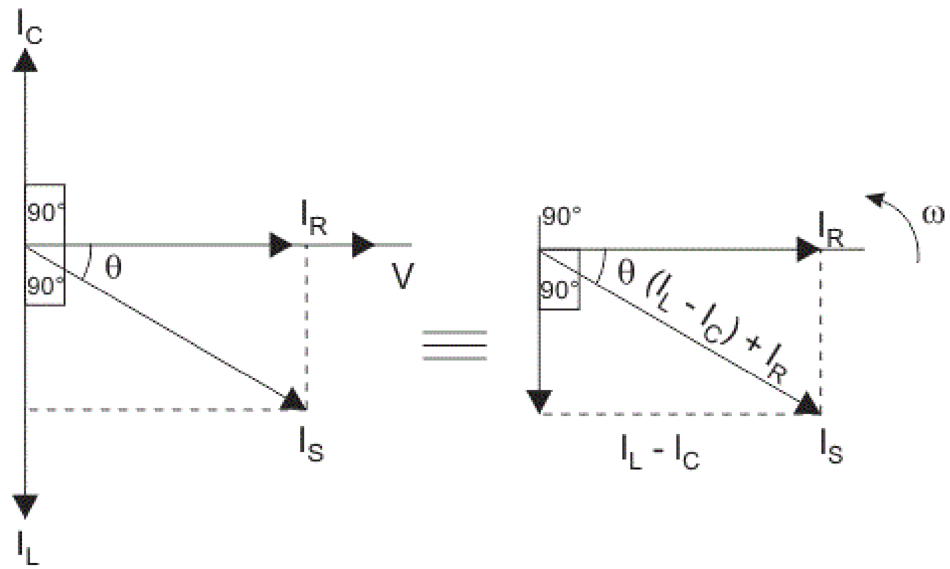
Phasor diagram of parallel RLC circuit, I_R is the current flowing in the resistor, R in amps.

I_C is the current flowing in the capacitor, C in amps.

I_L is the current flowing in the inductor, L in amps.

I_s is the supply current in amps.

In the parallel RLC circuit, all the components are connected in parallel; so the voltage across each element is same. Therefore, for drawing phasor diagram, take voltage as reference vector and all the other currents i.e I_R, I_C, I_L are drawn relative to this voltage vector. The current through each element can be found using Kirchhoff's Current Law, which states that the sum of currents entering a junction or node is equal to the sum of current leaving that node.



$$I_S^2 = I_R^2 + (I_L - I_C)^2$$

$$Now,\ I_R = \frac{V}{R}, I_C = \frac{V}{X_C}\ and\ I_L = \frac{V}{X_L}$$

$$I_S = \sqrt{\frac{V^2}{R^2} + \left(\frac{V}{X_L} - \frac{V}{X_C}\right)^2}$$

$$So,\ admitance,\ \frac{1}{Z} = \frac{I_S}{V} = Y = \sqrt{\frac{1}{R^2} + \left(\frac{1}{X_L} - \frac{1}{X_C}\right)^2}$$

As shown above in the equation of impedance, Z of a parallel RLC circuit; each element has reciprocal of impedance (1 / Z) i.e. admittance, Y. So in parallel RLC circuit, it is convenient to use admittance instead of impedance.

Resonance in RLC Circuit

During resonance, at certain frequency called resonant frequency, f_r.

$$X_L = X_C$$

$$We\ know\ that,\ X_L = 2\pi fL\ and\ X_C = \frac{1}{2\pi fC}$$

$$Therefore\ at\ resonant\ frequency,\ f_r :, 2\pi f_r L = \frac{1}{2\pi f_r C}$$

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

When resonance occurs, the inductive reactance of the circuit becomes equal to capacitive reactance, which causes the circuit impedance to be minimum in case of series RLC circuit; but when resistor, inductor and capacitor are connected in parallel, the circuit impedance becomes maximum, so the parallel RLC circuit is sometimes called as anti-resonator. Note that the lowest resonant frequency of a vibrating object is known as its fundamental frequency.

Difference between Series RLC Circuit and Parallel RLC Circuit

S.NO	RLC SERIES CIRCUIT	RLC PARALLEL CIRCUIT
1	Resistor, inductor and capacitor are connected in series	Resistor, inductor and capacitor are connected in parallel
2	Current is same in each element	Current is different in all elements and the total current is equal to vector sum of each branch of current i.e $I_s^2 = I_R^2 + (I_C – I_L)^2$

3	Voltage across all the elements is different and the total voltage is equal to the vector sum of voltages across each component i.e $V_s^2 = V_R^2 + (V_L – V_C)^2$	Voltage across each element remains the same
4	For drawing phasor diagram, current is taken as reference vector	For drawing phasor diagram, voltage is taken as reference vector
5	Voltage across each element is given by : V_R= IR, V_L = I X_L, V_C = I X_C	Current in each element is given by: I_R = V / R , I_C = V / X_C, I_L = V / X_L
6	Its more convenient to use impedance for calculations	Its more convenient to use admittance for calculations
7	At resonance , when X_L = X_C, the circuit has minimum impedance	At resonance, when X_L = X_C, the circuit has maximum impedance

UNIT-3

BALANCED THREE PHASE SYSTEM

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

Why three phase is preferred over single phase?

There are various reasons for this question because there are numbers of advantages over single phase circuit. The three phase system can be used as three single phase line so it can act as three single phase system. The three phase generation and single phase generation is same in the generator except the arrangement of coil in the generator to get 1200 phase difference. The conductor needed in three phase circuit is 75% that of conductor needed in single phase circuit.

And also the instantaneous power in single phase system falls down to zero as in single phase we can see from the sinusoidal curve but in three phase system the net power from all the phases gives a continuous power to the load. Till now we can say that there are three voltage sources connected together to form a three phase circuit and actually it is inside generator.

The generator is having three voltage sources which are acting together in 1200 phase difference. If we can arrange three single phase circuit with 1200 phase difference, then it will become a three phase circuit. So 1200 phase difference is must otherwise the circuit will not work, the three phase load will not be able to get active and it may also cause damage to the system.

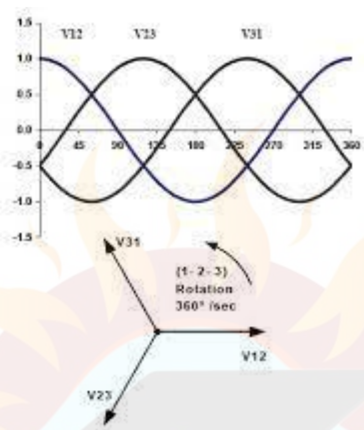


Figure 1
Three-Phase Voltage System
Sequence (1-2-3) V12 Reference

Phase sequence

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

$$\text{Red Phase:} \quad V_{RN} = V_m \sin\theta$$

$$\text{Yellow Phase:} \quad V_{YN} = V_m \sin(\theta - 120^o)$$

$$\text{Blue Phase:} \quad V_{BN} = V_m \sin(\theta - 240^o)$$

or

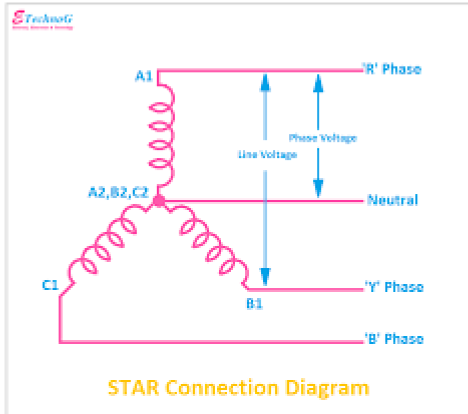
$$V_{BN} = V_m \sin(\theta + 120^o)$$

Star and Delta connection

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

Star connection

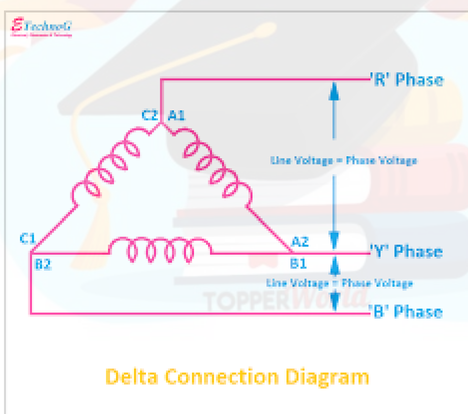
The finishing ends or starting ends of the three phase windings are connected to a common point as shown in. A', B', C' are connected to a common point called neutral point. The other ends A, B, C are called line terminals and the common terminal neutral are brought outside. Then it is called a 3 phase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



STAR Connection Diagram

Delta connection

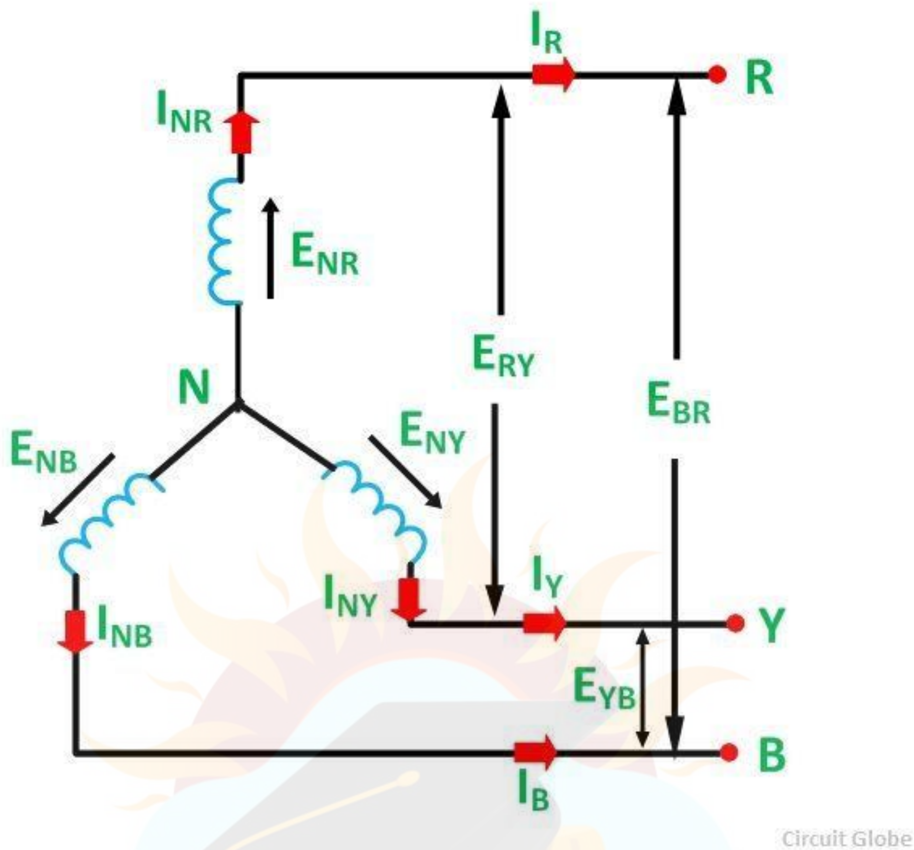
in this form of interconnection the dissimilar ends of the three coils i.e A and B', B and C', and C and A' are connected to form a closed Δ circuit (starting end of one phase is connected to finishing end of the next phase). The three junction are brought outside as line terminal A, B, C. the three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



Delta Connection Diagram

The current flowing through each phase is called **Phase current I_{ph}**, the current flowing through each line conductor is called **Line Current I_L**. Similarly, the voltage across each phase is called **Phase Voltage E_{ph}**, and the voltage across two line conductors is known as the **Line Voltage E_L.**

Relation Between Phase Voltage and Line Voltage in Star Connection



The arrowheads on the EMFs and current indicate direction and not their actual direction at any instant.

Now,

$$E_{NR} = E_{NY} = E_{NB} = E_{ph} \text{ (in magnitude)}$$

There are two-phase voltages between any two lines.

Tracing the loop NRYN

$$\overline{E_{NR}} + \overline{E_{RY}} - \overline{E_{NY}} = 0 \quad \text{or}$$

$$\overline{E_{RY}} = \overline{E_{NY}} - \overline{E_{NR}} \text{ (vector difference)}$$

To find the vector sum of ENY and –ENR, we have to reverse the vector ENR and add it with ENY as shown in the phasor diagram above.

Therefore,

$$E_{RY} = \sqrt{E_{NY}^2 + E_{NR}^2 + 2E_{NY}E_{NR}\cos 60^\circ} \quad \text{or}$$

$$E_L = \sqrt{E_{ph}^2 + E_{ph}^2 + 2E_{ph}E_{ph} \text{ x } 0.5} \quad \text{or}$$

$$E_L = \sqrt{3E_{ph}^2} = \sqrt{3}\,E_{ph} \text{ (in magnitude)}$$

Similarly,

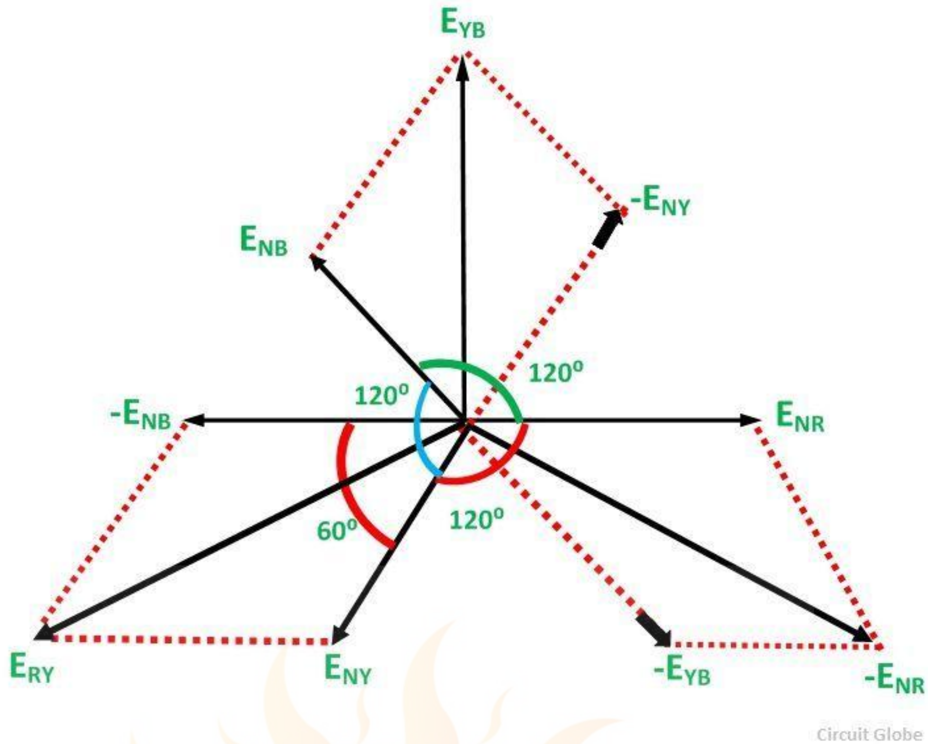
$$E_{YB} = E_{NB} - E_{NY} \quad \text{or} \quad E_L = \sqrt{3}\,E_{ph} \quad \text{and}$$

$$E_{BR} = E_{NR} - E_{NB} \quad \text{or} \quad E_L = \sqrt{3}\,E_{ph}$$

Hence, in star connection line voltage is root 3 times of phase voltage.

$$\text{Line voltage} = \sqrt{3} \text{ x Phase voltage}$$

Phasor diagram,



Relation Between Phase Current and Line Current in Star Connection

The same current flows through phase winding as well as in the line conductor as it is connected in series with the phase winding.

$$I_R = I_{NR}$$

$$I_Y = I_{NY} \quad \text{and}$$

$$I_B = I_{NB}$$

Where the phase current will be

$$I_R = I_Y = I_B = I_L$$

Hence, in a 3 Phase system of star connections, the line current is equal to phase current.

Relation Between Phase Voltage and Line Voltage in Delta Connection

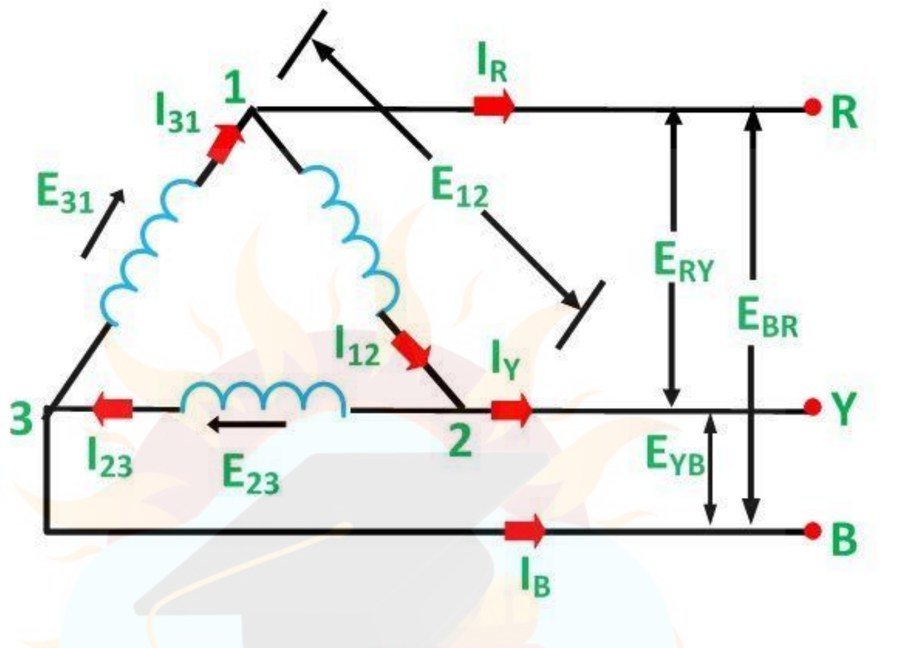


Figure A

It is clear from the figure that the voltage across terminals 1 and 2 is the same as across the terminals R and Y. Therefore,

$$E_{12} = E_{RY}$$

Similarly,

$$E_{23} = E_{YB} \quad \text{and} \quad E_{31} = E_{BR}$$

the phase voltages are

$$E_{12} = E_{23} = E_{31} = E_{ph}$$

The line voltages are:

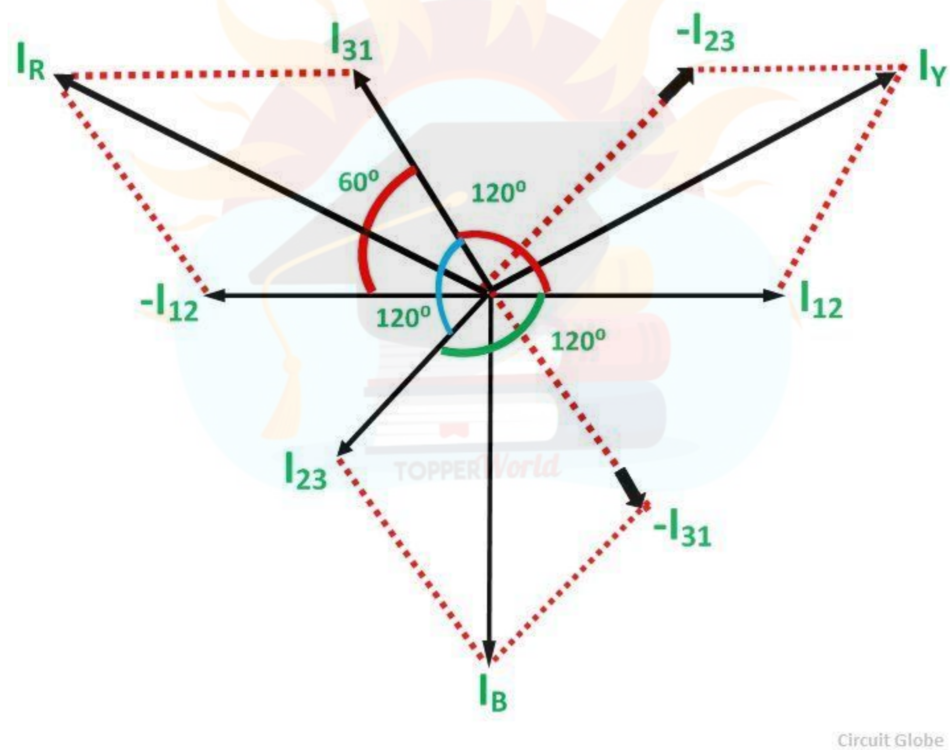
$$E_{RY} = E_{YB} = E_{BR} = E_L$$

Hence, in delta connection line voltage is equal to phase voltage.

Relation Between Phase Current and Line Current in Delta Connection

As in the balanced system the three-phase current I_{12}, I_{23} and I_{31} are equal in magnitude but are displaced from one another by 120° electrical.

The **phasor diagram** is shown below:



Hence,

$$I_{12} = I_{23} = I_{31} = I_{ph}$$

If we look at figure A, it is seen that the current is divided at every junction 1, 2 and 3.

Applying Kirchhoff's Law at junction 1,

The Incoming currents are equal to outgoing currents.

$$\overline{I_{31}} = \overline{I_R} + \overline{I_{12}}$$

The vector I_{12} is reversed and is added in the vector I_{31} to get the vector sum of I_{31} and $-I_{12}$ as shown above in the phasor diagram. Therefore,

$$I_R = \sqrt{I_{31}^2 + I_{12}^2 + 2I_{31}I_{12}\cos 60^\circ} \quad \text{or}$$

$$I_L = \sqrt{I_{ph}^2 + I_{ph}^2 + 2I_{ph}I_{ph} \text{ x } 0.5}$$

As we know, $I_R = I_L$, therefore,

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

Similarly,

$$\overline{I_Y} = \overline{I_{12}} - \overline{I_{23}} \quad \text{or} \quad I_L = \sqrt{3}I_{ph} \quad \text{and}$$

$$\overline{I_B} = \overline{I_{23}} - \overline{I_{31}} \quad \text{or} \quad I_L = \sqrt{3}I_{ph}$$

Hence, in delta connection line current is root three times of phase current.

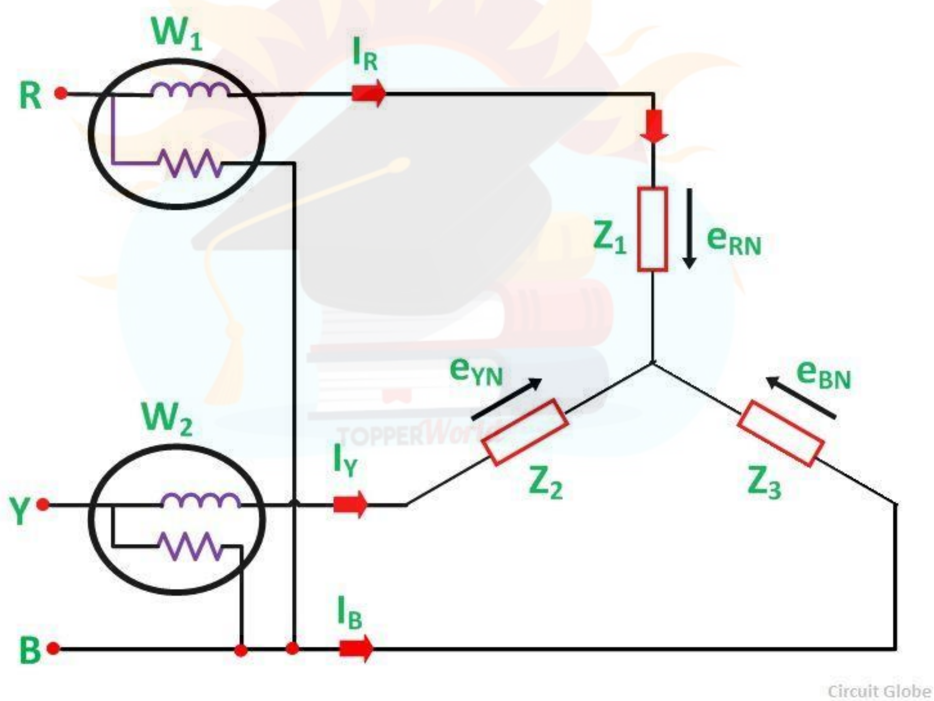
$$\text{Line Current} = \sqrt{3} \text{ x Phase Current}$$

This is all about Delta Connection In a 3 Phase System.

Two Wattmeter Method of Power Measurement

Two Wattmeter Method can be employed to measure the power in a 3 phase, three-wire star or delta connected the balanced or unbalanced load.

In two wattmeter method, the current coils of the wattmeter are connected with any two lines, say R and Y and the potential coil of each wattmeter is joined on the same line, the third line i.e. B as shown below in figure (A):



The total instantaneous power absorbed by the three loads Z_1, Z_2 and Z_3, is equal to the sum of the powers measured by the two wattmeters, W_1 and W_2.

The instantaneous potential difference across the potential coil of Wattmeter, W_1 is given as:

$$W_1 = e_{RN} - e_{BN}$$

Instantaneous power measured by the Wattmeter, W_1 is

$$W_1 = i_R (e_{RN} - e_{BN}) \;\ldots\ldots\ldots (1)$$

The instantaneous current through the current coil of Wattmeter, W_2 is given by the equation:

$$W_2 = i_Y$$

The instantaneous potential difference across the potential coil of Wattmeter, W_2 is given as:

$$W_2 = e_{YN} - e_{BN}$$

Instantaneous power measured by the Wattmeter, W_2 is:

$$W_2 = i_Y (e_{YN} - e_{BN}) \;\ldots\ldots\ldots..(2)$$

Therefore, the total power measured by the two wattmeters W_1 and W_2 will be obtained by adding the equation (1) and (2).

$$W_1 + W_2 = i_R(e_{RN} - e_{BN}) + i_Y(e_{YN} - e_{BN})$$

$$W_1 + W_2 = i_R e_{RN} + i_Y e_{YN} - e_{BN}(i_R + i_Y) \quad \text{or}$$

$$W_1 + W_2 = i_R e_{RN} + i_Y e_{YN} + i_B e_{BN} \quad (\text{i.e. } i_R + i_Y + i_B = 0)$$

$$W_1 + W_2 = P$$

SINGLE PHASE TRANSFORMER

The magnetic circuit.

Magnets possess a magneto-motive force (m.m.f.). This m.m.f. generates magnetic flux, which forms a magnetic field surrounding the magnet, between its north and south poles.

Note: We say that the magnetic flux flows from the north to the south pole of a magnet. (This is shown by the arrows on the field lines). However, it is important to point out, that in fact, there is nothing actually flowing in the flux. We refer to the flux as flowing from the north to the south pole, to emphasise the directional properties of magnetic field lines. These directional properties are most apparent in the study of electromagnetism and electromagnetic induction.

Magnetic flux can exist in a vacuum or within in a medium, e.g., the air surrounding the magnet, or any other material within the path of the flux. The complete path through which the magnetic flux passes between the north and south pole is referred to as a magnetic circuit. The amount of flux produced by a magnet will depend, among other things. on the material within the magnetic circuit. i.e. Some materials have a greater reluctance to magnetic flux than others.

- The magnet possesses a magneto motive force.
- The m.m.f generates a magnetic flux.
- The flux exists within the magnet and the air gap between the poles. The enclosed flux path is called a magnetic circuit.
- A stronger m.m.f. will produce more flux.
- The lower the reluctance of the magnetic circuit, the more flux will be produced.

Eddy Currents

When a conductor is placed in a varying magnetic field, loops of electric currents are induced in it by the magnetic field. These currents are known as eddy currents. Eddy currents are induced whenever there is a relative motion between the magnetic field and the conductor. This relative motion may be in the form of varying magnetic field or a constant magnetic field acting on a moving conductor.

Eddy currents flow in circular loops within the conductor itself, in the direction perpendicular to the magnetic field. According to Lenz's Law,the induced eddy currents generate another magnetic field so as to counter the actual magnetic field. This action resists the actual current flow in the conductor resulting in power loss in the form of heat. In AC motors, alternators, and transformers, eddy currents cause power loss in the core.

The heating property of eddy currents is used in induction heating. Other applications of eddy currents include, but not limited to electromagnetic braking, metal detection, magnetic levitation, vibration & position sensing and non-destructive sensing.

Eddy current loss

As mentioned above, the power losses in conductors and ferromagnetic cores are collectively known as Eddy current losses. Eddy current loss is essentially an I^2R loss caused within a conductor caused resistance offered by the conductor to the flow of current. This loss is further increased by the temperature rise.

Formula for eddy current loss

In the above section, we have derived a formula for eddy current loss in a unit volume of steel. The total losses due to eddy currents can be derived from the following formula:

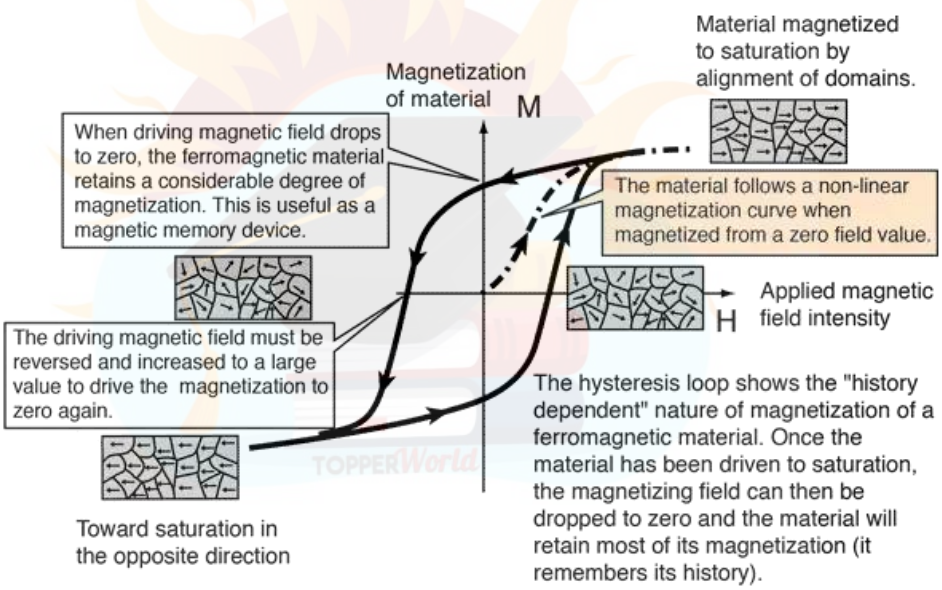
$$P_e = k_e . f^2 B_{max}{}^2 \tau^2 . V$$

Where,

- K_e is the eddy current constant.
- B_{max} is the maximum flux density.
- f is the frequency of the induced voltage.
- V is the volume of the material.

Hysteresis

Hysteresis is the inability of molecules in a ferromagnetic material to rapidly change their magnetization in accordance with the change in an applied magnetic field. For example, if a ferromagnetic material is placed in an alternating magnetic field, the magnetization in that material will follow a path as shown below:



Hysteresis can result in energy loss in the ferromagnetic cores of electric machines. This is because the alternating current changes its direction of flow constantly and therefore the direction of the magnetic field produced by them. This forces the molecules in the core to move to change their alignment in the proper direction. During this movement, these molecules collide with each other and cause friction and heat. The energy loss caused due to the friction of molecules in the core is known as hysteresis loss.

Steinmetz's empirical formula for hysteresis loss

Charles Steinmetz, a German-American Electrical Engineer, conducted several experiments on different ferromagnetic materials and coined an empirical formula for calculating hysteresis loss analytically.

$$P_h = k_h f B_{max}{}^n v$$

Where k_h is the coefficient of hysteresis of the ferromagnetic material, f is the frequency of power supply in hertz, B_{max} is the maximum flux density in weber/m^2 and volume of the ferromagnetic material in m^3. As you see the hysteresis loss increases with an increase in frequency. It highly depends on the material of the core.

Difference between hysteresis loss and eddy current loss

The major difference between hysteresis loss and eddy current loss are tabulated below:

Property	Hysteresis Loss	Eddy current loss
Phenomenon	Hysteresis loss is caused due to molecular friction in a ferromagnetic material, under alternating magnetic field.	Eddy current loss us caused due to the induction of eddy current in the core and conductors held in magnetic field.
Formula	$P_h = k_h f B_{max}{}^n v$	$P_e = k_e . f^2 B_{max}{}^2 \tau^2 . V$
Occurs in	Hysteresis loss occurs in the core of an electric machine.	Eddy current loss occurs in the core, conductor and body of an electric machine.

Single Phase AC Transformer

Transformer

It is a static device which transfers electric energy from one electric circuit to another with the desired change in voltage and current levels without any change in power and frequency. Transformer is used to increase or decrease a.c. voltage with a proportional increase or decrease in the current ratings. Sometimes transformer is used to create an isolation between primary voltage to secondary voltage which is called as one to one transformer.

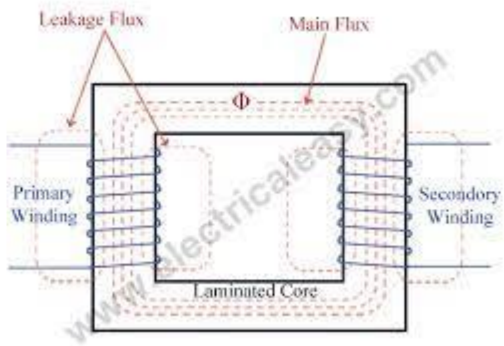
Working Principle

The main principle of operation of a transformer is mutual inductance between two electrical windings which is linked by a common magnetic flux. A basic transformer consists of two coils that are electrically separate and inductive, but are magnetically linked through a path of reluctance.

Construction Of Transformer

The transformer mainly consists of two basic components which are core and winding. Usually, the core of the transformer is rectangular or square in shape. The core is made up of high permeable and low hysteresis co-efficient silicon steel. The core is consisting of Yoke and Limb. The top and bottom horizontal portion of the transformer is called Yoke.

The copper wire is wounded on vertical portion of the core called Limb. Two windings are wounded at the left and right vertical portion of the transformer, which are called primary winding and secondary winding. The primary winding having N1 number of turns is connected to the AC supply voltage. The voltage is induced in the secondary winding. The secondary winding consists of N2 number of turns. The magnetic field is produced in around the core.



The primary winding and secondary winding are magnetically coupled with each other. When an AC is connected to the primary winding an alternating flux is produced in the core, which will produce voltage in the secondary winding. Consider an emf of E1 is applied to primary winding having N1 turns which will produce and emf of E2 in the secondary winding having N2 turns. The relation between emf E1, E2, N1 is N2.

$$E_1/E_2=N_1/N_2$$

Types Of Transformer

There are two type transformers based on its construction:

1. Core type transformer
2. Shell type transformer

Efficiency:

Efficiency is the ratio of the output power to the input power of a transformer.

It is defined as:

η = output power input power Input power Input power = output power + Iron loss + Copper loss

Theory of Transformer on No-Load

Let us consider one electrical transformer with only core losses, which means, it has only core losses but no copper loss and no leakage reactance of transformer. When an alternating source is applied in the primary, the source will supply the current for magnetizing the core of transformer.

But this current is not the actual magnetizing current; it is a little bit greater than actual magnetizing current. Total current supplied from the source has two components, one is the magnetizing current which is merely utilized for magnetizing the core, and another component of the source current is consumed for compensating the core losses in transformers.

Because of this core loss component, the source current in a **transformer on no-load** condition supplied from the source as source current is not exactly at 90° lags of the supply voltage, but it lags behind an angle θ is less than 90°. If the total current supplied from source is Io, it will have one component in phase with supply voltage V1 and this component of the current Iw is the core loss component.

This component is taken in phase with the source voltage because it is associated with active or working losses in transformers. Another component of the source current is denoted as I_{μ}.

This component produces the alternating magnetic flux in the core, so it is watt-less; means it is a reactive part of the transformer source current. Hence I_{μ} will be in quadrature with V_1 and in phase with alternating flux Φ. Hence, the total primary current in a transformer on the **no-load** condition can be represented as:

$$I_0 = I_\mu + I_w$$

$$|I_\mu| = |I_0| \cos\theta$$

$$|I_w| = |I_0| \sin\theta$$

$$|I_w| = \sqrt{|I_\mu|^2 + |I_w|^2}$$

Now you have seen how simple it is to explain the **theory of transformer** in no-load.

Theory of Transformer on Load

Now we will examine the behavior of the above-said transformer on load, which means the load is connected to the secondary terminals. Consider, a transformer having core loss but no copper loss and leakage reactance. Whenever a load is connected to the secondary winding, the load current will start to flow through the load as well as the secondary winding.

This load current solely depends upon the characteristics of the load and also upon the secondary voltage of the transformer. This current is called secondary current or load current, here it is denoted as I_2. As I_2 is flowing through the secondary, a self MMF in secondary winding will be produced. Here it is N_2I_2, where, N_2 is the number of turns of the secondary winding of the transformer

$$I_1 = I_0 + I_2'$$

This MMF or magnetomotive force in the secondary winding produces flux φ_2. This φ_2 will oppose the main magnetizing flux and momentarily weakens the main flux and tries to reduce primary self-induced emf E_1. If E_1 falls below the primary source voltage V_1, there will be an extra current flowing from source to primary winding.

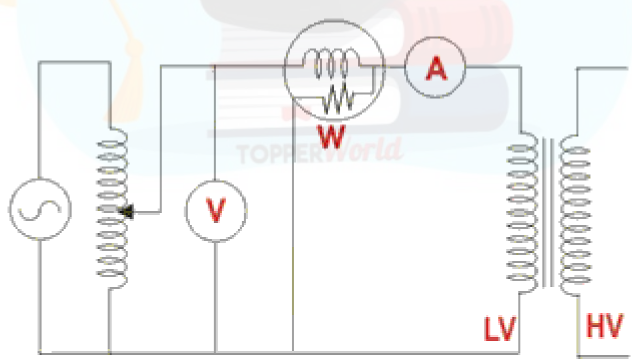
This extra primary current I2′ produces extra flux φ′ in the core which will neutralize the secondary counter flux φ2. Hence the main magnetizing flux of core, Φ remains unchanged irrespective of load. So total current, this transformer draws from the source can be divided into two components.

Where θ2 is the angle between the Secondary Voltage and Secondary Current of the transformer.
Now we will proceed one further step toward a more practical aspect of a transformer.

Open Circuit Test on Transformer

The connection diagram for **open circuit test on transformer** is shown in the figure. A voltmeter, wattmeter, and an ammeter are connected in LV side of the transformer as shown. The voltage at rated frequency is applied to that LV side with the help of a variac of variable ratio auto transformer.

The HV side of the transformer is kept open. Now with the help of variac, applied voltage gets slowly increased until the voltmeter gives reading equal to the rated voltage of the LV side. After reaching rated LV side voltage, we record all the three instruments reading (Voltmeter, Ammeter and Wattmeter readings).



Open Circuit Test on Transformer

The ammeter reading gives the no load current I_e. As no load current I_e is quite small compared to rated current of the transformer, the voltage drops due to this current that can be taken as negligible.

Since voltmeter reading V_1 can be considered equal to the secondary induced voltage of the transformer, wattmeter reading indicates the input power during the test. As the transformer is open circuited, there is no output, hence the input power here consists of core losses in transformer and copper loss in transformer during no load condition. But as said earlier, the no-load current in the transformer is quite small compared to the full load current so, we can neglect the copper loss due to the no-load current. Hence, can take the wattmeter reading as equal to the core losses in the transformer.

Let us consider wattmeter reading is P_o.

$$P_o = \frac{V_1^2}{R_m}$$

Where, R_m is shunt branch resistance of transformer.

If, Z_m is shunt branch impedance of transformer

$$Then,\ Z_m = \frac{V_1}{I_e}$$

Therefore, if shunt branch reactance of transformer is X_m,

$$Then,\ \left(\frac{1}{X_m}\right)^2 = \left(\frac{1}{Z_m}\right)^2 - \left(\frac{1}{R_m}\right)^2$$

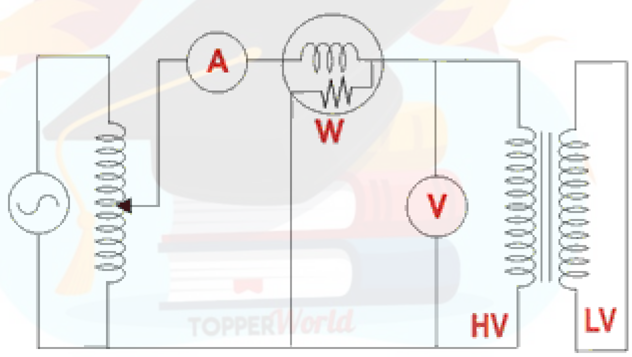
These values are referred to the LV side of the transformer due to the tests being conducted on the LV side of transformer. These values could easily be referred to HV side by multiplying these values with square of transformation ratio.

Therefore, it is seen that the **open circuit test on transformer** is used to determine core losses in transformer and parameters of the shunt branch of the equivalent circuit of the transformer.

Short Circuit Test on Transformer

The connection diagram for the short circuit test on the **transformer** is shown in the figure below. A voltmeter, wattmeter, and an ammeter are connected in HV side of the transformer as shown. A low voltage of around 5-10% is applied to that HV side with the help of a variac (i.e., a variable ratio auto transformer). We short-circuit the LV side of the transformer. Now with the help of variac applied voltage is slowly increased until the wattmeter, and an ammeter gives reading equal to the rated current of the HV side.

After reaching the rated current of the HV side, we record all the three instrument readings (Voltmeter,Ammeter and Watt-meter readings). The ammeter reading gives the primary equivalent of full load current IL. As the voltage applied for full load current in a short circuit test on the transformer is quite small compared to the rated primary voltage of the transformer, the core losses in the transformer can be taken as negligible here.



Short Circuit Test on Transformer

Let's say, voltmeter reading is V_{sc}. The watt-meter reading indicates the input power during the test. As we have short-circuited the transformer, there is no output; hence the input power here consists of copper losses in the transformer. Since the applied voltage V_{sc} is short circuit voltage in the transformer and hence it is quite small compared to the rated voltage, so, we can neglect the core loss due to the small applied voltage. Hence the wattmeter reading can be taken as equal to copper losses in the transformer. Let us consider wattmeter reading is P_{sc}.

$$P_{sc} = R_e I_L^2$$

Where, R_e is equivalent resistance of transformer.

If, Z_e is equivalent impedance of transformer.

$$Then,\ Z_e = \frac{V_{sc}}{I_L}$$

Therefore, if equivalent reactance of transformer is X_e.

$$Then,\ X_e^2 = Z_e^2 - R_e^2$$

These values are referred to the HV side of the transformer as the test is conducted on the HV side of the transformer. These values could easily be converted to the LV side by dividing these values with the square of transformation ratio.

Hence the short-circuit test of a transformer is used to determine copper losses in the transformer at full load. It is also used to obtain the parameters to approximate the equivalent circuit of a transformer.

UNIT-4

ELECTRICAL MACHINES

D.C Generator

An electrical Generator is a machine which converts mechanical energy (or power) into electrical energy (or power). The generator operates on the principle of the production of dynamically induced emf i.e., whenever flux is cut by the conductor, dynamically induced emf is produced in it according to the laws of electromagnetic induction, which will cause a flow of current in the conductor if the circuit is closed.

Hence, the basic essential parts of an electric generator are:

A magnetic field and

A conductor or conductors which can so move as to cut the flux

In dc generators the field is produced by the field magnets which are stationary. Permanent magnets are used for very small capacity machines and electromagnets are used for large machines to create magnetic flux. The conductors are situated on the periphery of the armature being rotated by the prime-mover.

DC generator construction

The actual DC generator consists of the following essential parts:

Magnetic frame or Yoke

Pole Cores and Pole Shoes

Pole Coils or Field Coils

Armature Core

Armature Windings or Conductors

Commutator

Brushes and Bearing

A) Magnetic frame or Yoke

Purpose of Yoke is

1. It act as a protecting cover for whole machine
2. It provides mechanical support for poles
3. It carries the magnetic flux produced by poles

b) Pole Cores and Pole Shoes

The field magnets consist of pole cores and pole shoes. The Pole shoes serve two purposes:

1. They spread out the flux in the air gap
2. They support the exciting coils

c) Armature

When current is passed through field coils, they electro-magnetize the poles which produce the necessary flux.

The Armature serves two purposes:

1. Armature houses the armature conductors or coils
2. It provides low reluctance path for flux

It is drum shaped and is built up of laminations made sheet steel to reduce eddy current loss. Slots are punched on the outer periphery of the disc. The Armature windings or conductors are wound in the form of flat rectangular coils and are placed in the slots of the Armature. The Armature windings are insulated from the armature body by insulating materials.

d) Commutator and brushes

The function of Commutator is to facilitate collection of current from the armature conductors and converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit. The commutator is made up of insulated copper segments. Two brushes are pressed to the commutator to permit current flow. The Brushes are made of carbon or Graphite. Bearings are used for smooth running of the machine.

E.M.F. equation

Let,

Fi = flux per pole in weber

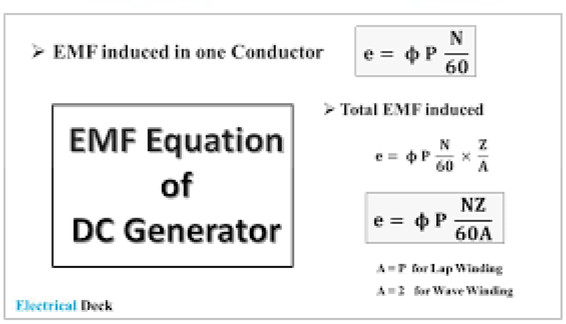
z = total number of armature conductors=no. of slots * no. of conductors/slot

P = no. of generator poles

A = no. of parallel paths in armature

N = armature rotation in revolutions per minute (rpm)

E = emf induced in any parallel path in armature



Types of generators

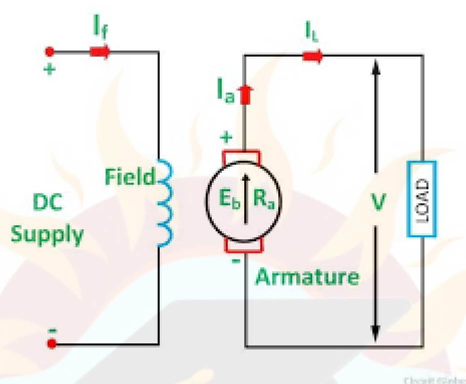
DC generators are usually classified according to the way in which their fields are excited. DC generators may be divided into,

(a) separately excited dc generators, and

(b) self-excited dc generators.

a) separately excited dc generators

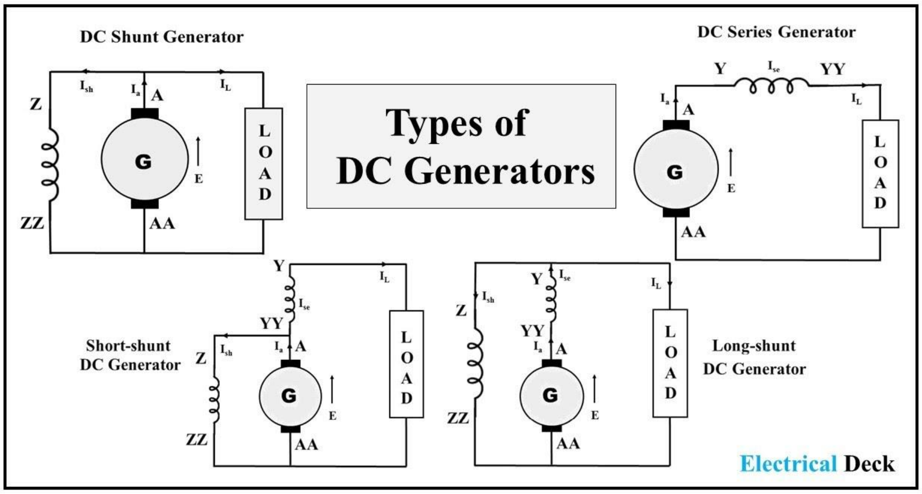
Separately excited generators are those whose field magnets are energized from an independent external source of dc current.



b) self-excited dc generators

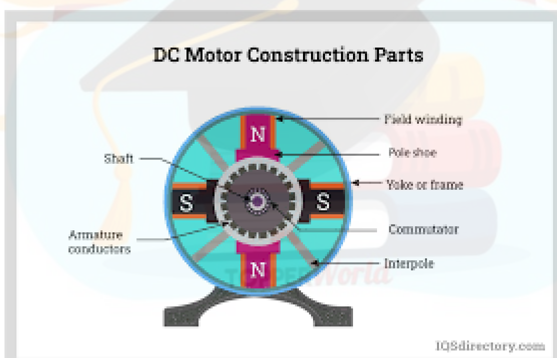
Self-excited generators are those whose field magnets are energized by the current produced by the generators themselves. Due to residual magnetism, there is always present some flux in the poles. When the armature is rotated, some emf and hence some current flows which is partly or fully passed through the field coils thereby strengthening the residual pole flux.

There are three types of self-excited dc generators named according to the manner in which their field coils (or windings) are connected to the armature. In shunt the two windings, field and armature are in parallel while in series type the two windings are in series. In compound type the part of the field winding is in parallel while other part in series with the armature winding.



DC Motor

A DC motor is an electrical machine that converts electrical energy into mechanical energy. In a DC motor, the input electrical energy is the direct current which is transformed into the mechanical rotation



Different Parts of a DC Motor

A DC motor is composed of the following main parts:

Armature or Rotor
The armature of a DC motor is a cylinder of magnetic laminations that are insulated from one another. The armature is perpendicular to the axis of the cylinder. The armature is a rotating part that rotates on its axis and is separated from the field coil by an air gap.

Field Coil or Stator
A DC motor field coil is a non-moving part on which winding is wound to produce a magnetic field. This electro-magnet has a cylindrical cavity between its poles.

Commutator and Brushes
Commutator

The commutator of a DC motor is a cylindrical structure that is made of copper segments stacked together but insulated from each other using mica. The primary function of a commutator is to supply electrical current to the armature winding.

Brushes

The brushes of a DC motor are made with graphite and carbon structure. These brushes conduct electric current from the external circuit to the rotating commutator. Hence, we come to understand that the commutator and the brush unit are concerned with transmitting the power from the static electrical circuit to the mechanically rotating region or the rotor.

DC Motor Working

In the previous section, we discussed the various components of a DC motor. Now, using this knowledge let us understand the working of DC motors.

A magnetic field arises in the air gap when the field coil of the DC motor is energized. The created magnetic field is in the direction of the radii of the armature. The magnetic field enters the armature from the North pole side of the field coil and "exits" the armature from the field coil's South pole side.

The conductors located on the other pole are subjected to a force of the same intensity but in the opposite direction. These two opposing forces create a torque that causes the motor armature to rotate.

Working principle of DC motor When kept in a magnetic field, a current-carrying conductor gains torque and develops a tendency to move. In short, when electric fields and magnetic fields interact, a mechanical force arises. This is the principle on which the DC motors work.

Types of DC motor

DC motors have a wide range of applications ranging from electric shavers to automobiles. To cater to this wide range of applications, they are classified into different types based on the field winding connections to the armature as:

- Self Excited DC Motor
- Separately Excited DC Motor

Now, let us discuss the various types of DC Motors in detail.

Self Excited DC Motor

In self-excited DC motors, the field winding is connected either in series or parallel to the armature winding. Based on this, the self-excited DC motor can further be classified as:

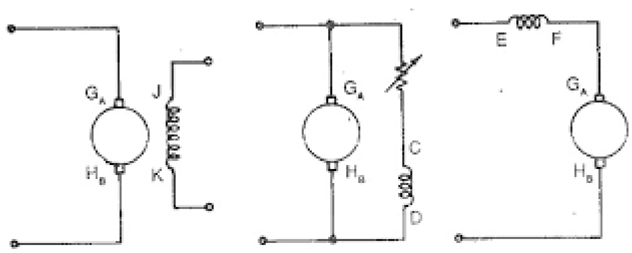
- Shunt wound DC motor
- Series wound DC motor
- Compound wound DC motor

Shunt wound DC motor

In a shunt wound motor, the field winding is connected parallel to the armature as shown in the figure.

Series wound DC motor
In a series wound DC motor, the field winding is connected in series with the armature winding as shown in the figure.

Compound wound DC motor
DC motors having both shunt and series field winding is known as Compound DC motor, as shown in the figure.



(a) Separately excited dc motor. (b) Shunt motor (c) Series motor

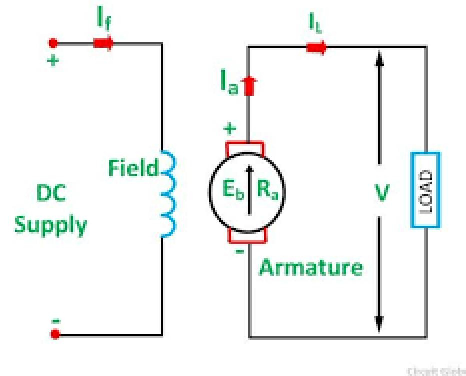
The compound motor is further divided into:

- Cumulative Compound Motor
- Differential Compound Motor

In a cumulative compound motor, the magnetic flux produced by both the windings is in the same direction. In a differential compound motor, the flux produced by the series field windings is opposite to the flux produced by the shunt field winding.

Separately Excited DC Motor

In a separately excited DC motor, the field coils are energised from an external source of DC supply as shown in the figure.



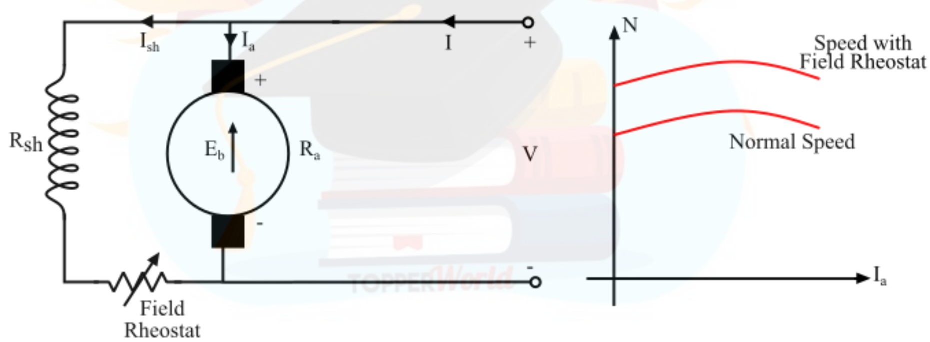
Speed Control of DC Shunt Motors

The speed of a DC shunt is given by,

- Flux Control Method
- Armature Resistance Control Method
-

Flux Control Method

The *flux control method* is based on the principle that by varying the field flux ϕ, the speed of DC shunt motor can be changed.



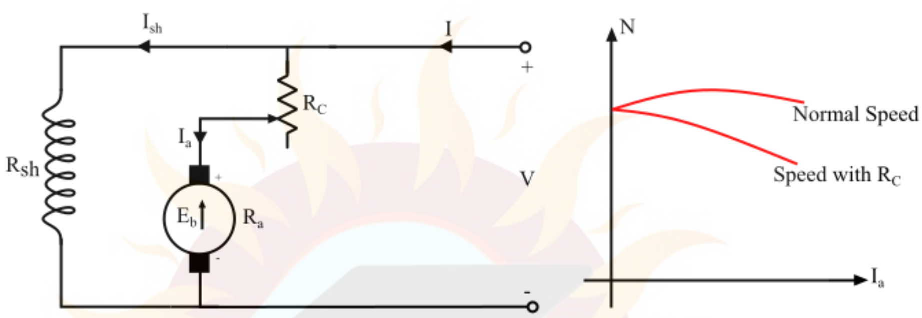
In this method, a variable resistance (called *field rheostat*) is connected in series with the shunt field winding. By increasing the resistance of the field rheostat, the shunt field current Ish can be reduced and hence the field flux. Thus, by the flux control method, the speed of a DC shunt can only be increased above the normal speed.

The flux control method is frequently used for the speed control of DC shunt motors because it is simple and inexpensive method.

Armature Resistance Control Method

The *armature resistance control method* is based on the principle that by varying the voltage available across the armature, the back EMF of the motor can be changed, which in turn changes the speed of the shunt motor.

In this method, a variable resistance RC (called *controller resistance*) is inserted in series with the armature.



Thus, due to the voltage drop in the controller resistance, the back EMF is decreased and hence the speed of the motor. The maximum speed that can be obtained using armature resistance control method is the speed corresponding to $R_C = 0$, i.e., the normal speed. Therefore, by this method only speed below the normal speed can be obtained.

ELECTRICAL INSTALLATIONS

Fuse

A fuse is a short piece of wire or thin strip which melts when excessive current flows through sufficient time. whenever the current flowing through fuse element increases beyond its rated capacity then short circuit or overload occurs. This raises the temperature and the fuse element melts, disconnecting the circuit is protected by it.

SFU

It is Switched Fuse Unit. It has one switch unit and one fuse unit. When we operate the breaker, the contacts will get close through switch and then the supply will passes through the fuse unit to the output.

MCB

MCB is an electromechanical device which guards an electrical circuit which automatically switches off electrical circuit during abnormal condition of the network means in over load condition as well as faulty condition. The normal current rating is ranges from 0.5-63 A with a symmetrical short circuit breaking capacity of 3-10 KA, at a voltage level of 230 or 440V.

Characteristics of MCB The characteristics of an MCB mainly include the following
•Rated current is not more than 100 amperes

•Normally, trip characteristics are not adjustable

•Thermal magnetic operation

ELCB

Early earth leakage circuit breakers are voltage detecting devices, which are now switched by current sensing devices (RCD/RCCB). An ECLB is one kind of safety device used for installing an electrical device with high earth impedance to avoid shock. There are two types of Earth Leakage Circuit Breaker (ELCB) Voltage Operated ELCB Current Operated ELCB

Characteristics of ELCB

This circuit breaker connects the phase, earth wire and neutral

The working of this circuit breaker depends on current leakage

MCCB

Molded case circuit breakers are a type of electrical protection device that is commonly used when load currents exceed the capabilities of miniature circuit breakers. They are also used in applications of any current rating that require adjustable trip settings, which are not available in plug-in circuit breakers and MCBs. 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.

Wires and cables

Wire is a single electrical conductor, whereas a cable is a group of wires swathed in sheathing.

Cables

The main requirements of the insulting materials used for cable are:

1. High insulation resistance.

2. High dielectric strength.

3. Good mechanical properties i.e. tenacity and elasticity.

4. It should not be affected by chemicals around it.

5. It should be non-hygroscopic because the dielectric strength of any material goes very much down with moisture connect

Electrical Earthing

The process of transferring the immediate discharge of the electrical energy directly to the earth by the help of the low resistance wire is known as the electrical earthing. Mostly galvanized iron is used for earthing.

Earthing provides simple path to the leakage current. Earthing is an important component of electrical systems because of the following reasons:

•It keeps people safe by preventing electric shocks

•It prevents damage to electrical appliances and devices by preventing excessive current from running through the circuit

•It prevents the risk of fire that could otherwise be caused by current leakage

Types of Electrical Earthing

Neutral Earthing: In neutral earthing, the neutral of the system is directly connected to earth by the help of the GI wire.

The neutral earthing is also called the system earthing. Ex. Generator, T/F, Motor etc.,

Equipment Earthing: Such type of earthing is provided to the electrical equipment. The noncurrent carrying part of the equipment like their metallic frame is connected to the earth by the help of the conducting wire.