BASIC ELECTRICAL ENGINEERING

DIGITAL NOTES

MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY
(Autonomous Institution – UGC, Govt. of India)
Recognized under 2(f) and 12 (B) of UGC ACT 1956
(Affiliated to JNTUH, Hyderabad, Approved by AICTE-Accredited by NBA & NACC-'A' Grade – ISO 9001:2015 Certified)
Maisammaguda, Dhulapally (Post Via. Hakimpet), Secunderabad -500100, Telangana State, India.

MALLA REDDY COLLEGE OF ENGINEERING AND TECHNOLOGY

I Year B. Tech I Sem – CSE/AIML/IOT/CS/DS/IT

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(R20A0201) BASIC ELECTRICAL ENGINEERING

Objectives:

1. To understand the basic concepts of electrical circuits & networks and their analysis which is the foundation for all the subjects in the electrical engineering discipline.
2. To emphasize on the basic elements in electrical circuits and analyze Circuits using Network Theorems.
3. To analyze Single-Phase AC Circuits.
4. To illustrate Single-Phase Transformers and DC Machines.
5. To get overview of basic electrical installations and calculations for energy consumption.

UNIT –I:

Introduction to Electrical Circuits: Concept of Circuit and Network, Types of elements, R-L-C Parameters, Independent and Dependent sources, Source transformation and Kirchhoff's Laws

UNIT –II:

Network Analysis: Network Reduction Techniques- Series and parallel connections of resistive networks, Star–to-Delta and Delta-to-Star Transformations for Resistive Networks, Mesh Analysis, and Nodal Analysis,

Network Theorems**:** Thevenin's theorem, Norton's theorem and Superposition theorem and Illustrative Problems.

UNIT-III:

Single Phase A.C. Circuits: Average value, R.M.S. value, form factor and peak factor for sinusoidal wave form, Complex and Polar forms of representation. Steady State Analysis of series R-L-C circuits. Concept of Reactance, Impedance, Susceptance, Admittance, Concept of Power Factor, Real, Reactive and Complex power, Illustrative Problems.

UNIT –IV:

Electrical Machines (elementary treatment only):

Single phase transformers: principle of operation, constructional features and emf equation.

DC. Generator: principle of operation, constructional features, emf equation. DC Motor: principle of operation, Back emf, torque equation.

UNIT –V:

Electrical Installations:

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

TEXT BOOKS:

1. Engineering Circuit Analysis - William Hayt, Jack E. Kemmerly, S M Durbin, Mc Graw Hill Companies.
2. Electric Circuits - A. Chakraborty, Dhanipat Rai & Sons.
3. Electrical Machines – P.S. Bimbra, Khanna Publishers.

REFERENCE BOOKS:

1. Network analysis by M.E Van Valkenburg, PHI learning publications.
2. Network analysis - N.C Jagan and C. Lakhminarayana, BS publications.
3. Electrical Circuits by A. Sudhakar, Shyammohan and S Palli, Mc Graw Hill Companies.
4. Electrical Machines by I.J. Nagrath & D. P. Kothari, Tata Mc Graw-Hill Publishers.

Outcomes:

At the end of the course students, would be able to

1. Apply the basic RLC circuit elements and its concepts to networks and circuits.
2. Analyze the circuits by applying network theorems to solve them to find various electrical parameters.
3. Illustrate the single-phase AC circuits along with the concept of impedance parameters and power.
4. Understand the Constructional Details and Principle of Operation of DC Machines and Transformers
5. Understand the basic LT Switch gear and calculations for energy consumption.

PREFACE

Engineering institutions have been modernizing and updating their curriculum to keep pace with the continuously developing technological trends so as to meet the correspondingly changing educational demands of the industry. As the years passed by, multi-disciplinary education system also has become more and more relevant in the present global industrial development. Thus, just as Computer Systems & Applications, *Basic Electrical Engineering* also has become an integral part of all the industrial and engineering sectors be it infrastructure, power generation, minor & major Industries, Industrial Safety or process industries where automation has become an inherent part. Accordingly, several universities have been bringing in a significant change in their graduate programs of engineering starting from the first year to meet the needs of these important industrial sectors to enhance the employability of their graduates. Thus, at college entry level itself *Basic Electrical Engineering* has become the first Multidisciplinary core engineering subject for almost all the other core engineering branches like Civil, Mechanical, Production engineering, Industrial Engineering, Aeronautical, Instrumentation, Control Systems and Computer Engineering. As a further impetus, since for understanding of this subject a practical knowledge is equally important, a laboratory course is also added in the curriculum. The chapters are so chosen that the student comprehends all the important theoretical concepts with good practical insight.

This handbook of Digital notes for *Basic Electrical Engineering* is brought out in a simple and lucid manner highlighting the important underlying concepts & objectives along with sequential steps to understand the subject.

INDEX

UNIT-I

INTRODUCTION TO ELECTRICAL CIRCUITS

- Concept of Circuit and Network
- Types of elements
- R-L-C Parameters
- Independent and Dependent sources
- Source transformation Technique
- Kirchhoff's Laws
- Simple Problems

INTRODUCTION TO ELECTRICAL 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.

Current

The current **"I"** flowing through a conductor is nothing but the time rate of flow of charge. Mathematically, it can be written as

$$I = \frac{dQ}{dt}$$

Where,

- Q is the charge and its unit is Coloumb.
- t is the time and its unit is second.

As an analogy, electric current can be thought of as the flow of water through a pipe. Current is measured in terms of Ampere. In general, Electron current flows from negative terminal of source to positive terminal, whereas, Conventional current flows from positive terminal of source to negative terminal.

Electron current is obtained due to the movement of free electrons, whereas, Conventional current is obtained due to the movement of free positive charges. Both of these are called as electric current.

Voltage

The voltage "V" is nothing but an electromotive force that causes the charge (electrons) to flow. Mathematically, it can be written as

$$V = \frac{dW}{dQ}$$

Where,

- W is the potential energy and its unit is Joule.
- Q is the charge and its unit is Coloumb.

As an analogy, Voltage can be thought of as the pressure of water that causes the water to flow through a pipe. It is measured in terms of Volt.

Power

The power "P" is nothing but the time rate of flow of electrical energy. Mathematically, it can be written as

$$P = \frac{dW}{dt}$$

Where,

- W is the electrical energy and it is measured in terms of Joule.
- t is the time and it is measured in seconds.

We can re-write the above equation a

$$P = \frac{dW}{dt} = \frac{dW}{dQ} \times \frac{dQ}{dt} = VI$$

Therefore, power is nothing but the product of voltage V and current I. Its unit is Watt.

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.

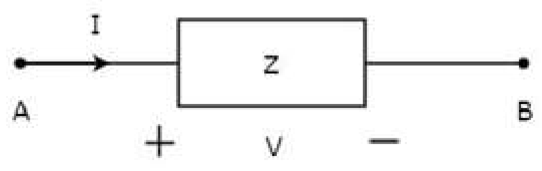
- Linear Elements are the elements that show a linear relationship between voltage and current. Examples: Resistors, Inductors, and capacitors.
- Non-Linear Elements are those that do not show a linear relation between voltage and current. Examples: Voltage sources and current sources.

Bilateral Elements and Unilateral Elements

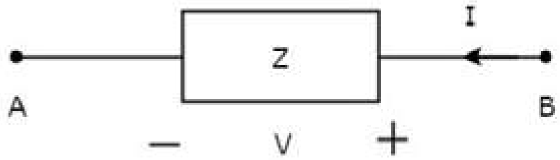
Network elements can also be classified as either bilateral or unilateral based on the direction of current flows through the network elements.

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.

The concept of Bilateral elements is illustrated in the following figures.



In the above figure, the current (I) is flowing from terminals A to B through a passive element having impedance of Z Ω. It is the ratio of voltage (V) across that element between terminals A & B and current (I).



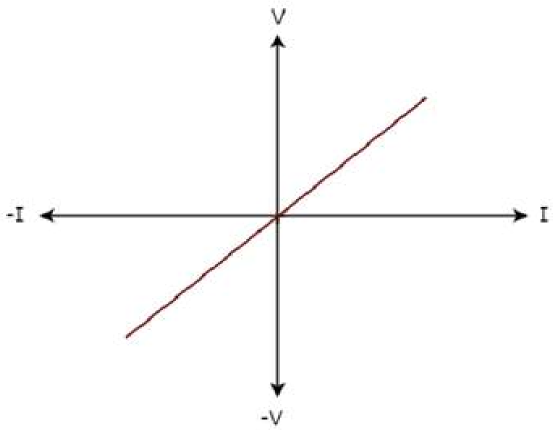
In the above figure, the current (I) is flowing from terminals B to A through a passive element having impedance of $Z\ \Omega$. That means the current (–I) is flowing from terminals A to B. In this case too, we will get the same impedance value, since both the current and voltage having negative signs with respect to terminals A & B.

Unilateral Elements are those that allow the current in only one direction. Hence, they offer different impedances in both directions.

We discussed the types of network elements in the previous chapter. Now, let us identify the nature of network elements from the V-I characteristics given in the following examples.

Example 1

The V-I characteristics of a network element is shown below.



Step 1 − Verifying the network element as linear or non-linear.

From the above figure, the V-I characteristics of a network element is a straight line passing through the origin. Hence, it is linear element.

Step 2 − Verifying the network element as active or passive.

The given V-I characteristics of a network element lies in the first and third quadrants.

- In the first quadrant, the values of both voltage (V) and current (I) are positive. So, the ratios of voltage (V) and current (I) gives positive impedance values.

- Similarly, in the third quadrant, the values of both voltage (V) and current (I) have negative values. So, the ratios of voltage (V) and current (I) produce positive impedance values.

Since, the given V-I characteristics offer positive impedance values, the network element is a Passive element.

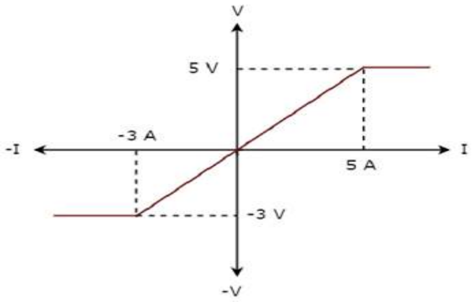
Step 3 − Verifying the network element as bilateral or unilateral.

For every point (I, V) on the characteristics, there exists a corresponding point (-I, -V) on the given characteristics. Hence, the network element is a Bilateral element.

Therefore, the given V-I characteristics show that the network element is a Linear, Passive, and Bilateral element.

Example 2

The V-I characteristics of a network element is shown below.



Step 1 − Verifying the network element as linear or non-linear.

From the above figure, the V-I characteristics of a network element is a straight line only between the points (-3A, -3V) and (5A, 5V). Beyond these points, the V-I characteristics are not following the linear relation. Hence, it is a Non-linear element.

Step 2 − Verifying the network element as active or passive.

The given V-I characteristics of a network element lies in the first and third quadrants. In these two quadrants, the ratios of voltage (V) and current (I) produce positive impedance values. Hence, the network element is a Passive element.

Step 3 − Verifying the network element as bilateral or unilateral.

Consider the point (5A, 5V) on the characteristics. The corresponding point (-5A, -3V) exists on the given characteristics instead of (-5A, -5V). Hence, the network element is a Unilateral element.

Therefore, the given V-I characteristics show that the network element is a Non-linear, Passive, and Unilateral element. The circuits containing them are called unilateral circuits.

Lumped and Distributed Elements

Lumped elements are those elements which are very small in size & in which simultaneous actions takes place. Typical lumped elements are capacitors, resistors, inductors.

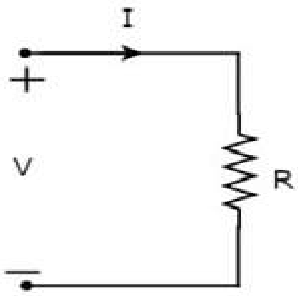
Distributed elements are those which are not electrically separable for analytical purposes.

For example a transmission line has distributed parameters along its length and may extend for hundreds of miles.

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. The symbol of resistor along with current, I and voltage, V are shown in the following figure.



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

$$V = IR \qquad \text{Equation 1}$$

$$\Rightarrow I = \frac{V}{R} \qquad \text{Equation 2}$$

Where, **R** is the resistance of a resistor.

From Equation 2, we can conclude that the current flowing through the resistor is directly proportional to the applied voltage across resistor and inversely proportional to the resistance of resistor.

Power in an electric circuit element can be represented as

$$P = VI \qquad \text{Equation 3}$$

Substitute, Equation 1 in Equation 3.

$$P = (IR)I$$

$$\Rightarrow P = I^2R \qquad \text{Equation 4}$$

Substitute, Equation 2 in Equation 3.

$$P = V\left(\frac{V}{R}\right)$$

$$\Rightarrow P = \frac{V^2}{R} \qquad \text{Equation 5}$$

So, we can calculate the amount of power dissipated in the resistor by using one of the formulae mentioned in Equations 3 to 5.

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.

Mathematically, it can be written as

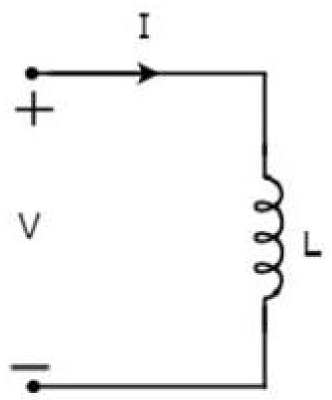
$$\Psi \, \alpha \, I$$

$$\Rightarrow \Psi = LI$$

Where,

- $\boldsymbol{\Psi}$ is the total magnetic flux
- $\boldsymbol{L}$ is the inductance of an inductor

Let the current flowing through the inductor is I amperes and the voltage across it is V volts. The symbol of inductor along with current I and voltage V are shown in the following figure.



According to Faraday's law, the voltage across the inductor can be written as

$$V = \frac{d\Psi}{dt}$$

Substitute $\Psi = LI$ in the above equation.

$$V = \frac{d(LI)}{dt}$$

$$\Rightarrow V = L\frac{dI}{dt}$$

$$\Rightarrow I = \frac{1}{L}\int V dt$$

From the above equations, we can conclude that there exists a linear relationship between voltage across inductor and current flowing through it.

We know that power in an electric circuit element can be represented as

$$P = VI$$

Substitute $V = L\frac{dI}{dt}$ in the above equation.

$$P = (L\frac{dI}{dt})I$$

$$\Rightarrow P = LI\frac{dI}{dt}$$

By integrating the above equation, we will get the energy stored in an inductor as

$$W = \frac{1}{2}LI^2$$

So, the inductor stores the energy in the form of magnetic field.

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.

So, the amount of charge stored in the capacitor depends on the applied voltage **V** across it and they have linear relationship. Mathematically, it can be written as

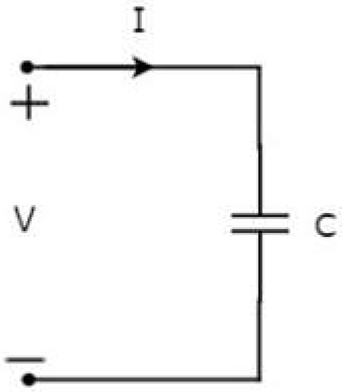
$$Q \, \alpha \, V$$

$$\Rightarrow Q = CV$$

Where,

- ***Q*** is the charge stored in the capacitor.
- ***C*** is the capacitance of a capacitor.

Let the current flowing through the capacitor is *I* amperes and the voltage across it is *V* volts. The symbol of capacitor along with current *I* and voltage *V* are shown in the following figure.



We know that the **current** is nothing but the **time rate of flow of charge**. Mathematically, it can be represented as

$$I = \frac{dQ}{dt}$$

Substitute $Q = CV$ in the above equation.

$$I = \frac{d(CV)}{dt}$$

$$\Rightarrow I = C\frac{dV}{dt}$$

$$\Rightarrow V = \frac{1}{C}\int I dt$$

From the above equations, we can conclude that there exists a linear relationship between voltage across capacitor and current flowing through it.

We know that power in an electric circuit element can be represented as

$$P = VI$$

Substitute $I = C\frac{dV}{dt}$ in the above equation.

$$P = V(C\frac{dV}{dt})$$

$$\Rightarrow P = CV\frac{dV}{dt}$$

By integrating the above equation, we will get the **energy** stored in the capacitor as

$$W = \frac{1}{2}CV^2$$

So, the capacitor stores the energy in the form of electric field.

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

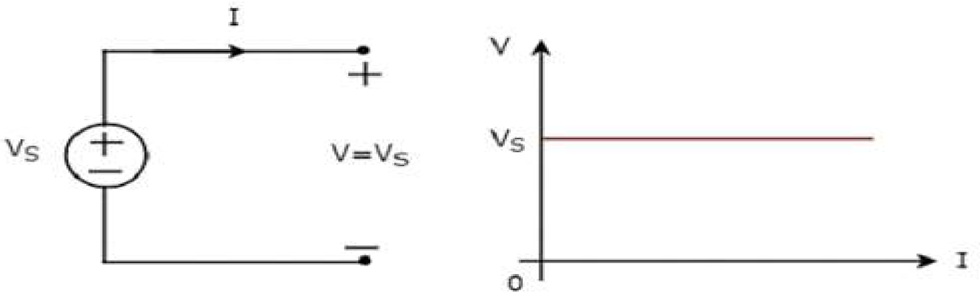
Independent Sources

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

Independent Voltage Sources

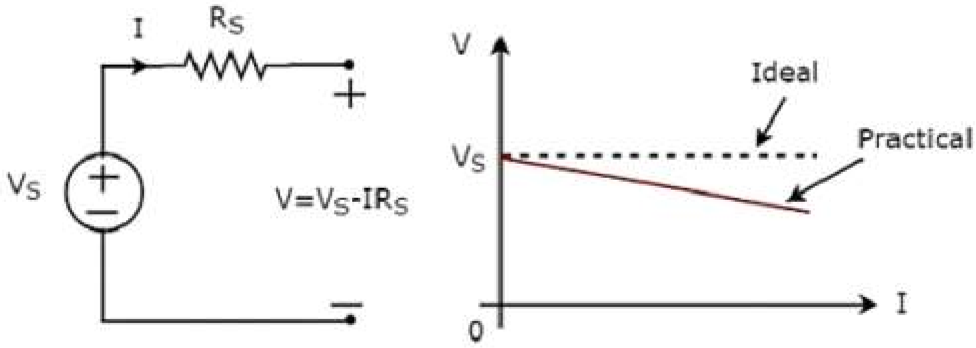
An independent voltage source produces a constant voltage across its two terminals. This voltage is independent of the amount of current that is flowing through the two terminals of voltage source. Independent ideal voltage source and its V-I characteristics are shown in the following figure.



The V-I characteristics of an independent ideal voltage source is a constant line, which is always equal to the source voltage (VS) irrespective of the current value (I). So, the internal resistance of an independent ideal voltage source is zero Ohms.

Hence, the independent ideal voltage sources do not exist practically, because there will be some internal resistance.

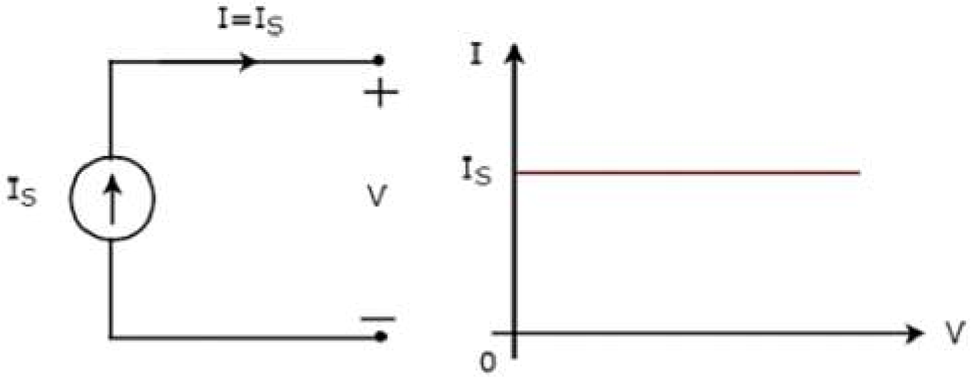
Independent practical voltage source and its V-I characteristics are shown in the following figure.



There is a deviation in the V-I characteristics of an independent practical voltage source from the V-I characteristics of an independent ideal voltage source. This is due to the voltage drop across the internal resistance (R_S) of an independent practical voltage source.

Independent Current Sources

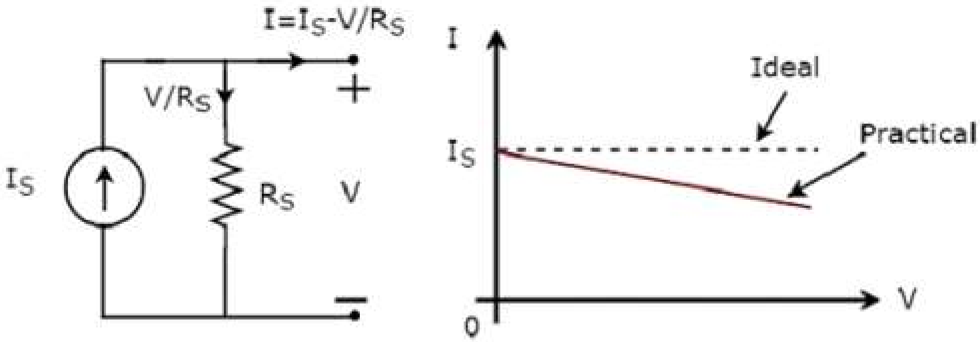
An independent current source produces a constant current. This current is independent of the voltage across its two terminals. Independent ideal current source and its V-I characteristics are shown in the following figure.



The V-I characteristics of an independent ideal current source is a constant line, which is always equal to the source current (I_S) irrespective of the voltage value (V). So, the internal resistance of an independent ideal current source is infinite ohms.

Hence, the independent ideal current sources do not exist practically, because there will be some internal resistance.

Independent practical current source and its V-I characteristics are shown in the following figure.



There is a deviation in the V-I characteristics of an independent practical current source from the V-I characteristics of an independent ideal current source. This is due to the amount of current flows through the internal shunt resistance (R_S) of an independent practical current source.

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

Dependent Voltage Sources

A dependent voltage source produces a voltage across its two terminals. The amount of this voltage is dependent on some other voltage or current. Hence, dependent voltage sources can be further classified into the following two categories −

- Voltage Dependent Voltage Source (VDVS)
- Current Dependent Voltage Source (CDVS)

Dependent voltage sources are represented with the signs '+' and '-' inside a diamond shape. The magnitude of the voltage source can be represented outside the diamond shape.

Dependent Current Sources

A dependent current source produces a current. The amount of this current is dependent on some other voltage or current. Hence, dependent current sources can be further classified into the following two categories −

- Voltage Dependent Current Source (VDCS)
- Current Dependent Current Source (CDCS)

Dependent current sources are represented with an arrow inside a diamond shape. The magnitude of the current source can be represented outside the diamond shape. We can observe these dependent or controlled sources in equivalent models of transistors.

Source Transformation Technique

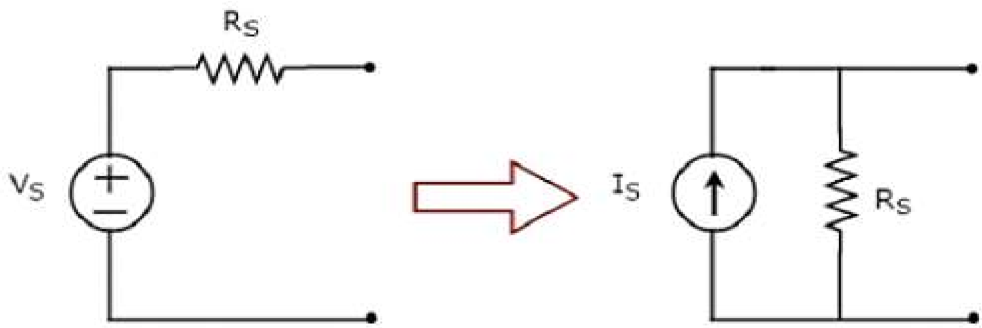
We know that there are two practical sources, namely, voltage source and current source. We can transform (convert) one source into the other based on the requirement, while solving network problems.

The technique of transforming one source into the other is called as source transformation technique. Following are the two possible source transformations −

- Practical voltage source into a practical current source
- Practical current source into a practical voltage source

Practical voltage source into a practical current source

The transformation of practical voltage source into a practical current source is shown in the following figure



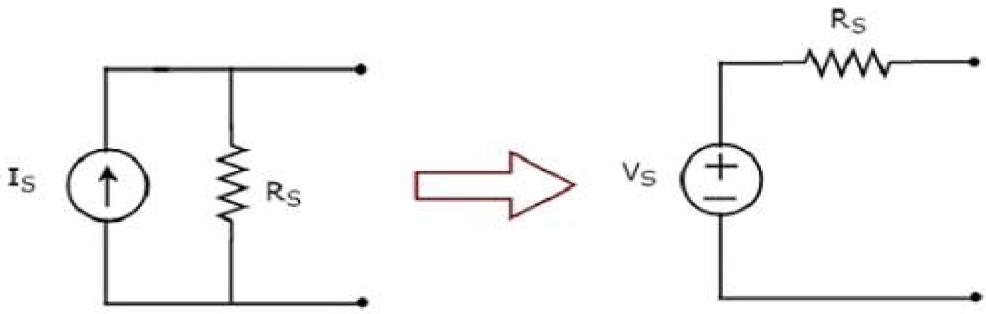
Practical voltage source consists of a voltage source (V_S) in series with a resistor (R_S). This can be converted into a practical current source as shown in the figure. It consists of a current source (I_S) in parallel with a resistor (R_S).

The value of IS will be equal to the ratio of V_S and R_S. Mathematically, it can be represented as

$$I_S = \frac{V_S}{R_S}$$

Practical current source into a practical voltage source

The transformation of practical current source into a practical voltage source is shown in the following figure.



Practical current source consists of a current source (I_S) in parallel with a resistor (R_S). This can be converted into a practical voltage source as shown in the figure. It consists of a voltage source (V_S) in series with a resistor (R_S).

The value of V_S will be equal to the product of I_S and R_S. Mathematically, it can be represented as

$$V_S = I_S R_S$$

In this chapter, we will discuss in detail about the passive elements such as Resistor, Inductor, and Capacitor. Let us start with Resistors.

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

$$\sum_{m=1}^{M} I_m = 0$$

Where,

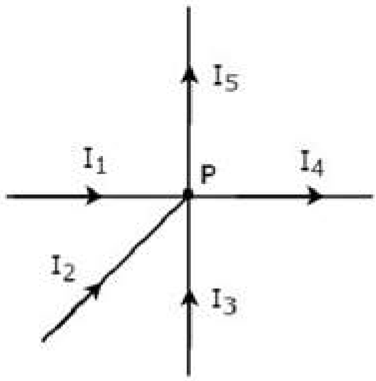
- I_m is the mth branch current leaving the node.

- ***M*** is the number of branches that are connected to a node.

The above statement of KCL can also be expressed as "the algebraic sum of currents entering a node is equal to the algebraic sum of currents leaving a node". Let us verify this statement through the following example.

Example

Write KCL equation at node P of the following figure.



- In the above figure, the branch currents I_1, I_2 and I_3 areentering at node P. So, consider negative signs for these three currents.
- In the above figure, the branch currents I_4 and I_5 areleaving from node P. So, consider positive signs for these two currents.

The KCL equation at node P will be

$$-I_1 - I_2 - I_3 + I_4 + I_5 = 0$$

$$\Rightarrow I_1 + I_2 + I_3 = I_4 + I_5$$

In the above equation, the left-hand side represents the sum of entering currents, whereas the right-hand side represents the sum of leaving currents.

In this tutorial, we will consider positive sign when the current leaves a node and negative sign when it enters a node. Similarly, you can consider negative sign when the current leaves a node and positive sign when it enters a node. In both cases, the result will be same.

Note − 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.

Mathematically, KVL can be represented as

$$\sum_{n=1}^{N} V_n = 0$$

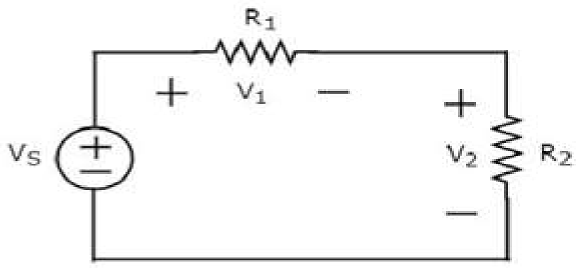
Where,

- $\mathbf{V_n}$ is the n[th] element's voltage in a loop (mesh).
- **N** is the number of network elements in the loop (mesh).

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." Let us verify this statement with the help of the following example.

Example

Write KVL equation around the loop of the following circuit.



The above circuit diagram consists of a voltage source, V_S in series with two resistors R_1 and R_2. The voltage drops across the resistors R_1 and R_2 are V_1 and V_2 respectively.

Apply KVL around the loop.

$$V_S - V_1 - V_2 = 0$$

$$\Rightarrow V_S = V_1 + V_2$$

In the above equation, the left-hand side term represents single voltage source VS. Whereas, the right-hand side represents the sum of voltage drops. In this example, we considered only one voltage source. That's why the left-hand side contains only one term. If we consider multiple voltage sources, then the left side contains sum of voltage sources.

In this tutorial, we consider the sign of each element's voltage as the polarity of the second terminal that is present while travelling around the loop. Similarly, you can consider the sign of each voltage as the polarity of the first terminal that is present while travelling around the loop. In both cases, the result will be same.

Note − KVL is independent of the nature of network elements that are present in a loop.

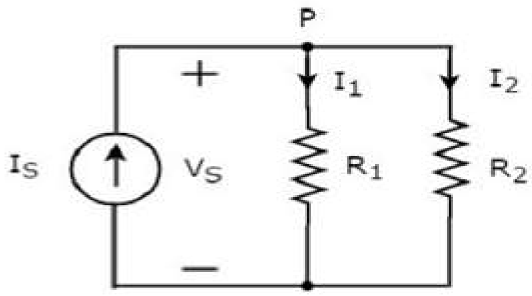
In this chapter, let us discuss about the following two division principles of electrical quantities.

- Current Division Principle
- Voltage Division Principle

Current Division Principle

When two or more passive elements are connected in parallel, the amount of current that flows through each element gets divided(shared) among themselves from the current that is entering the node.

Consider the following circuit diagram.



The above circuit diagram consists of an input current source **I_S** in parallel with two resistors **R_1** and **R_2**. The voltage across each element is **V_S**. The currents flowing through the resistors **R_1** and**R_2** are **I_1** and **I_2** respectively.

The KCL equation at node P will be

$$I_S = I_1 + I_2$$

- Substitute $I_1 = \frac{V_S}{R_1}$ and $I_2 = \frac{V_S}{R_2}$ in the above equation.

$$I_S = \frac{V_S}{R_1} + \frac{V_S}{R_2} = V_S\left(\frac{R_2 + R_1}{R_1 R_2}\right)$$

$$\Rightarrow V_S = I_S\left(\frac{R_1 R_2}{R_1 + R_2}\right)$$

- Substitute the value of V_S in $I_1 = \frac{V_S}{R_1}$.

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

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

- Substitute the value of V_S in $I_2 = \frac{V_S}{R_2}$.

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

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

From equations of I_1 and I_2, we can generalize that the current flowing through any passive element can be found by using the following formula.

$$I_N = I_S \left(\frac{Z_1 || Z_2 || \ldots || Z_{N-1}}{Z_1 + Z_2 + \ldots + Z_N} \right)$$

This is known as current division principle and it is applicable, when two or more passive elements are connected in parallel and only one current enters the node.

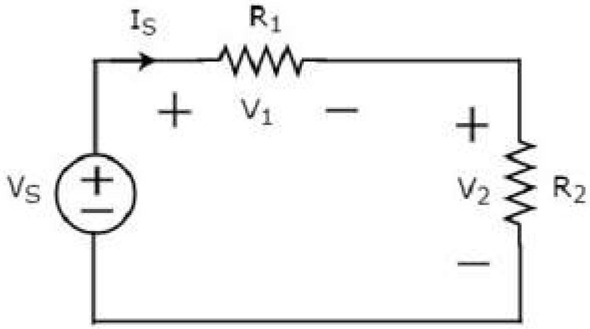
Where,

- I_N is the current flowing through the passive element of N^th branch.
- I_S is the input current, which enters the node.
  - Z_1, Z_2, …,Z_N are the impedances of 1^st branch, 2^nd branch, …, N^th branch respectively.

Voltage Division Principle

When two or more passive elements are connected in series, the amount of voltage present across each element gets divided (shared) among themselves from the voltage that is available across that entire combination.

Consider the following circuit diagram.



The above circuit diagram consists of a voltage source, V_S in series with two resistors R_1 and R_2. The current flowing through these elements is I_S. The voltage drops across the resistors R_1 and R_2 are V_1 and V_2 respectively.

The KVL equation around the loop will be

$$V_S = V_1 + V_2$$

- Substitute $V_1 = I_S R_1$ and $V_2 = I_S R_2$ in the above equation

$$V_S = I_S R_1 + I_S R_2 = I_S (R_1 + R_2)$$

$$I_S = \frac{V_S}{R_1 + R_2}$$

- Substitute the value of I_S in $V_1 = I_S R_1$.

$$V_1 = (\frac{V_S}{R_1 + R_2})R_1$$

$$\Rightarrow V_1 = V_S(\frac{R_1}{R_1 + R_2})$$

- Substitute the value of I_S in $V_2 = I_S R_2$.

$$V_2 = (\frac{V_S}{R_1 + R_2})R_2$$

$$\Rightarrow V_2 = V_S(\frac{R_2}{R_1 + R_2})$$

From equations of V_1 and V_2, we can generalize that the voltage across any passive element can be found by using the following formula.

$$V_N = V_S(\frac{Z_N}{Z_1 + Z_2 + ... + Z_N})$$

This is known as voltage division principle and it is applicable, when two or more passive elements are connected in series and only one voltage available across the entire combination.

Where,

- V_N is the voltage across Nth passive element.
- V_S is the input voltage, which is present across the entire combination of series passive elements.
- Z_1,Z_2, …,Z_3 are the impedances of 1st passive element, 2nd passive element, …, Nth passive element respectively.

UNIT-II
NETWORK ANALYSIS

- Network Reduction Techniques
- Series and Parallel connection of Resistive Networks
- Star–to-Delta and Delta-to-Star Transformations for Resistive Networks
- Mesh Analysis
- Network Theorems: Thevenin’s Theorem
- Norton’s Theorem
- Superposition Theorem
- Problems

Network Reduction Techniques:

There are two basic methods that are used for solving any electrical network: Nodal analysis and Mesh analysis. In this chapter, let us discuss about the Mesh analysis method.

Series and parallel connections of resistive networks:

If a circuit consists of two or more similar passive elements and are connected in exclusively of series type or parallel type, then we can replace them with a single equivalent passive element. Hence, this circuit is called as an equivalent circuit.

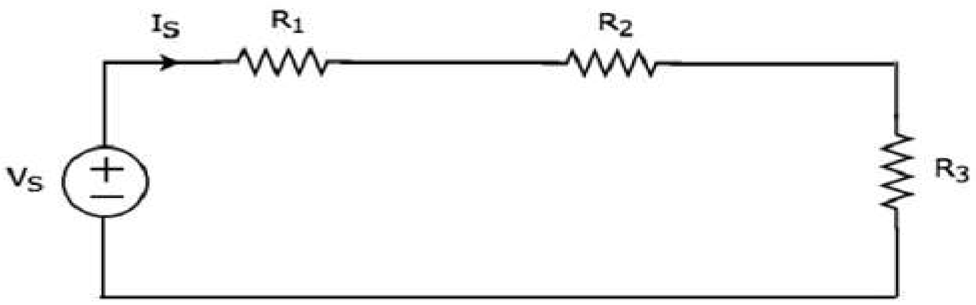
In this chapter, let us discuss about the following two equivalent circuits.

- Series Equivalent Circuit
- Parallel Equivalent Circuit

Series Equivalent Circuit

If similar passive elements are connected in series, then the same current will flow through all these elements. But, the voltage gets divided across each element.

Consider the following circuit diagram.



It has a single voltage source (V_S) and three resistors having resistances of R_1, R_2 and R_3. All these elements are connected in series. The current IS flows through all these elements.

The above circuit has only one mesh. The KVL equation around this mesh is

$$V_S = V_1 + V_2 + V_3$$

Substitute $V_1 = I_S R_1$, $V_2 = I_S R_2$ and $V_3 = I_S R_3$ in the above equation.

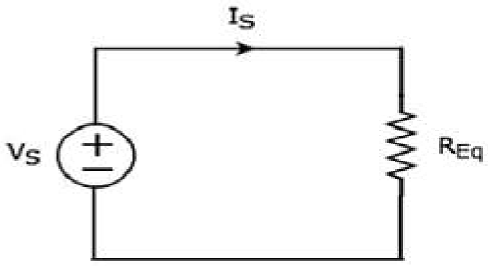
$$V_S = I_S R_1 + I_S R_2 + I_S R_3$$

$$\Rightarrow V_S = I_S (R_1 + R_2 + R_3)$$

The above equation is in the form of $V_S = I_S R_{Eq}$ where,

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

The equivalent circuit diagram of the given circuit is shown in the following figure.



That means, if multiple resistors are connected in series, then we can replace them with an equivalent resistor. The resistance of this equivalent resistor is equal to sum of the resistances of all those multiple resistors.

Note 1 − If 'N' inductors having inductances of L_1, L_2, ..., L_N are connected in series, then the equivalent inductance will be

$$L_{Eq} = L_1 + L_2 + \ldots + L_N$$

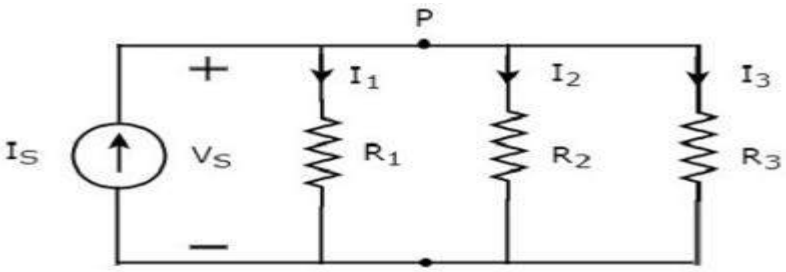
Note 2 − If 'N' capacitors having capacitances of C_1, C_2, ..., $C_N$are connected in series, then the equivalent capacitance will be

$$\frac{1}{C_{Eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_N}$$

Parallel Equivalent Circuit

If similar passive elements are connected in parallel, then the same voltage will be maintained across each element. But, the current flowing through each element gets divided.

Consider the following circuit diagram.



It has a single current source (I_S) and three resistors having resistances of R_1, R_2, and R_3. All these elements are connected in parallel. The voltage (V_S) is available across all these elements.

The above circuit has only one principal node (P) except the Ground node. The KCL equation at this principal node (P) is

$$I_S = I_1 + I_2 + I_3$$

Substitute $I_1 = \frac{V_S}{R_1}$, $I_2 = \frac{V_S}{R_2}$ and $I_3 = \frac{V_S}{R_3}$ in the above equation.

$$I_S = \frac{V_S}{R_1} + \frac{V_S}{R_2} + \frac{V_S}{R_3}$$

$$\Rightarrow I_S = V_S\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

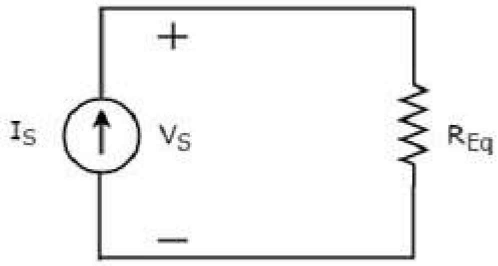
$$\Rightarrow V_S = I_S\left[\frac{1}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)}\right]$$

The above equation is in the form of $V_S = I_S R_{Eq}$ where,

$$R_{Eq} = \frac{1}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)}$$

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

The equivalent circuit diagram of the given circuit is shown in the following figure.



That means, if multiple resistors are connected in parallel, then we can replace them with an equivalent resistor. The resistance of this equivalent resistor is equal to the reciprocal of sum of reciprocal of each resistance of all those multiple resistors.

Note 1 − If ‘N’ inductors having inductances of L_1, L_2, ..., L_N are connected in parallel, then the equivalent inductance will be

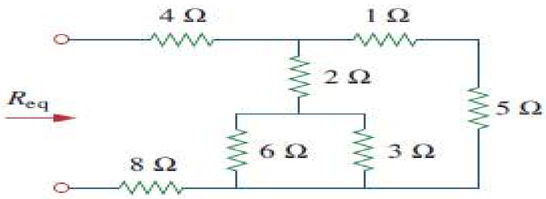
$$\frac{1}{L_{Eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \ldots + \frac{1}{L_N}$$

Note 2 − If ‘N’ capacitors having capacitances of C_1, C_2, ..., $C_N$are connected in parallel, then the equivalent capacitance will be

$$C_{Eq} = C_1 + C_2 + \ldots + C_N$$

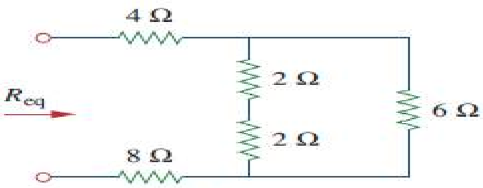
Example Problems:

1) Find the Req for the circuit shown in below figure.

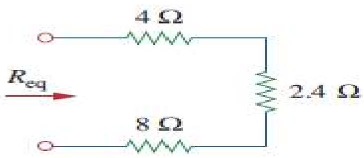


fig(a)

Solution:



fig(b)



fig(c)

To get Req we combine resistors in series and in parallel. The 6 ohms and 3 ohms resistors are in parallel, so their equivalent resistance is

$$6\ \Omega \parallel 3\Omega = \frac{6 \times 3}{6 + 3} = 2\ \Omega$$

Also, the 1 ohm and 5ohms resistors are in series; hence their equivalent resistance is

$$1\ \Omega + 5\ \Omega = 6\ \Omega$$

Thus the circuit in Fig.(b) is reduced to that in Fig. (c). In Fig. (b), we notice that the two 2 ohms resistors are in series, so the equivalent resistance is

$$2\ \Omega + 2\ \Omega = 4\ \Omega$$

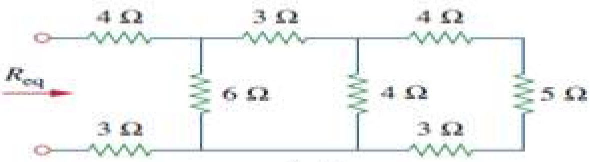
This 4 ohms resistor is now in parallel with the 6 ohms resistor in Fig.(b); their equivalent resistance is

$$4\ \Omega \parallel 6\ \Omega = \frac{4 \times 6}{4 + 6} = 2.4\ \Omega$$

The circuit in Fig.(b) is now replaced with that in Fig.(c). In Fig.(c), the three resistors are in series. Hence, the equivalent resistance for the circuit is

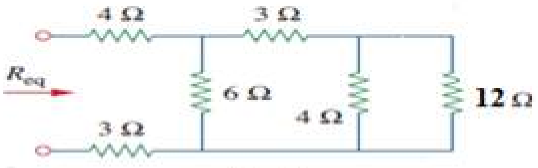
$$R_{eq} = 4\ \Omega + 2.4\ \Omega + 8\ \Omega = 14.4\ \Omega$$

2) Find the Req for the circuit shown in below figure.



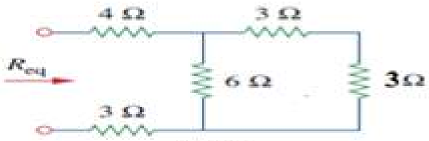
fig(a)

Solution:
In the given network 4 ohms, 5 ohms and 3 ohms comes in series then equivalent resistance is 4+5 + 3 = 12 ohms



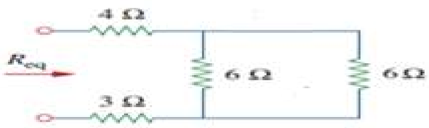
fig(b)

From fig(b), 4 ohms and 12 ohms are in parallel, equivalent is 3 ohms



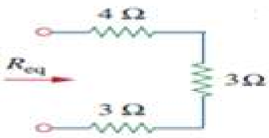
fig(c)

From fig(c), 3 ohms and 3 ohms are in series, equivalent resistance is 6 ohms



fig(d)

From fig(d), 6 ohms and 6 ohms are in parallel, equivalent resistance is 3 ohms



fig(e)

From fig(e), 4 ohms, 3 ohms and 3 ohms are in series .Hence Req = 4+ 3+ 3 =10 ohms

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

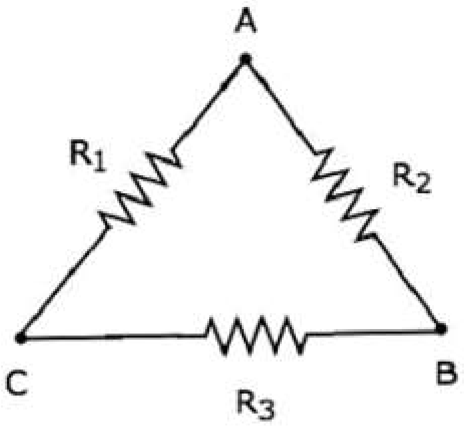
Delta to Star Transformation

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.



The following equations represent the equivalent resistance between two terminals of delta network, when the third terminal is kept open.

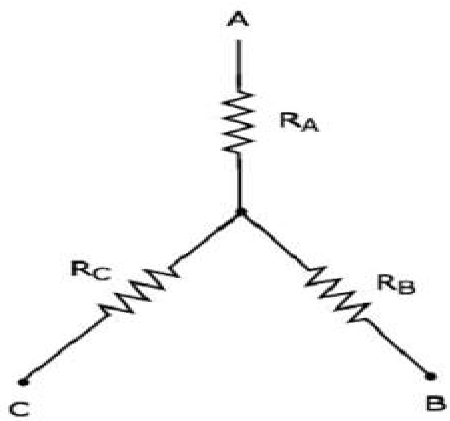
$$R_{AB} = \frac{(R_1 + R_3)R_2}{R_1 + R_2 + R_3}$$

$$R_{BC} = \frac{(R_1 + R_2)R_3}{R_1 + R_2 + R_3}$$

$$R_{CA} = \frac{(R_2 + R_3)R_1}{R_1 + R_2 + R_3}$$

Star Network

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



The following equations represent the equivalent resistance between two terminals of star network, when the third terminal is kept open.

$$R_{AB} = R_A + R_B$$

$$R_{BC} = R_B + R_C$$

$$R_{CA} = R_C + R_A$$

Star Network Resistances in terms of Delta Network Resistances

We will get the following equations by equating the right-hand side terms of the above equations for which the left-hand side terms are same.

$$R_A + R_B = \frac{(R_1+R_3)R_2}{R_1+R_2+R_3} \qquad \text{Equation 1}$$

$$R_B + R_C = \frac{(R_1+R_2)R_3}{R_1+R_2+R_3} \qquad \text{Equation 2}$$

$$R_C + R_A = \frac{(R_2+R_3)R_1}{R_1+R_2+R_3} \qquad \text{Equation 3}$$

By adding the above three equations, we will get

$$2(R_A + R_B + R_C) = \frac{2(R_1R_2 + R_2R_3 + R_3R_1)}{R_1 + R_2 + R_3}$$

$$\Rightarrow R_A + R_B + R_C = \frac{R_1R_2+R_2R_3+R_3R_1}{R_1+R_2+R_3} \qquad \text{Equation 4}$$

Subtract Equation 2 from Equation 4.

$$R_A + R_B + R_C - (R_B + R_C) = \frac{R_1R_2+R_2R_3+R_3R_1}{R_1+R_2+R_3} - \frac{(R_1+R_2)R_3}{R_1+R_2+R_3}$$

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

By subtracting Equation 3 from Equation 4, we will get

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

By subtracting Equation 1 from Equation 4, we will get

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

By using the above relations, we can find the resistances of star network from the resistances of delta network. In this way, we can convert a delta network into a star network.

Star to Delta Transformation

In the previous chapter, we discussed about the conversion of delta network into an equivalent star network. Now, let us discuss about the conversion of star network into an equivalent delta network. This conversion is called as Star to Delta Conversion.

In the previous chapter, we got the resistances of star network from delta network as

$$R_A = \frac{R_1 R_2}{R_1+R_2+R_3} \qquad \text{Equation 1}$$

$$R_B = \frac{R_2 R_3}{R_1+R_2+R_3} \qquad \text{Equation 2}$$

$$R_C = \frac{R_3 R_1}{R_1+R_2+R_3} \qquad \text{Equation 3}$$

Delta Network Resistances in terms of Star Network Resistances

Let us manipulate the above equations in order to get the resistances of delta network in terms of resistances of star network.

- Multiply each set of two equations and then add.

$$R_A R_B + R_B R_C + R_C R_A = \frac{R_1 R_2^2 R_3 + R_2 R_3^2 R_1 + R_3 R_1^2 R_2}{(R_1 + R_2 + R_3)^2}$$

$$\Rightarrow R_A R_B + R_B R_C + R_C R_A = \frac{R_1 R_2 R_3 (R_1 + R_2 + R_3)}{(R_1 + R_2 + R_3)^2}$$

$$\Rightarrow R_A R_B + R_B R_C + R_C R_A = \frac{R_1 R_2 R_3}{R_1 + R_2 + R_3}$$

Equation 4

- By dividing Equation 4 with Equation 2, we will get

$$\frac{R_A R_B + R_B R_C + R_C R_A}{R_B} = R_1$$

$$\Rightarrow R_1 = R_C + R_A + \frac{R_C R_A}{R_B}$$

- By dividing Equation 4 with Equation 3, we will get

$$R_2 = R_A + R_B + \frac{R_A R_B}{R_C}$$

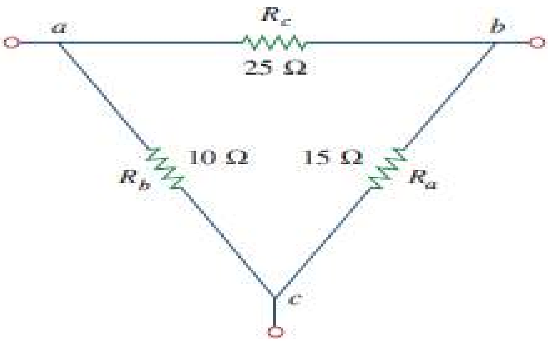
- By dividing Equation 4 with Equation 1, we will get

$$R_3 = R_B + R_C + \frac{R_B R_C}{R_A}$$

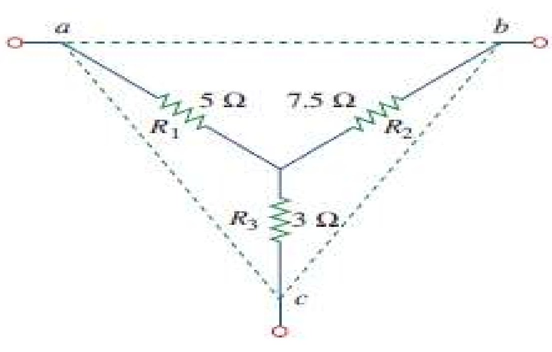
By using the above relations, we can find the resistances of delta network from the resistances of star network. In this way, we can convert star network into delta network.

Example problems:

1) Convert the Delta network in Fig.(a) to an equivalent star network
Solution:



(a)



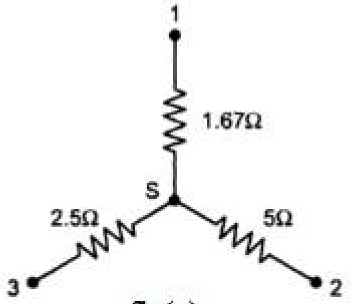
(b)

$$R_1 = \frac{R_b R_c}{R_a + R_b + R_c} = \frac{10 \times 25}{15 + 10 + 25} = \frac{250}{50} = 5\ \Omega$$

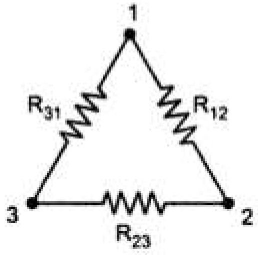
$$R_2 = \frac{R_c R_a}{R_a + R_b + R_c} = \frac{25 \times 15}{50} = 7.5\ \Omega$$

$$R_3 = \frac{R_a R_b}{R_a + R_b + R_c} = \frac{15 \times 10}{50} = 3\ \Omega$$

2) **Convert the star network in fig(a) to delta network**



fig(a)



fig(b)

Solution: The equivalent delta for the given star is shown in fig(b), where

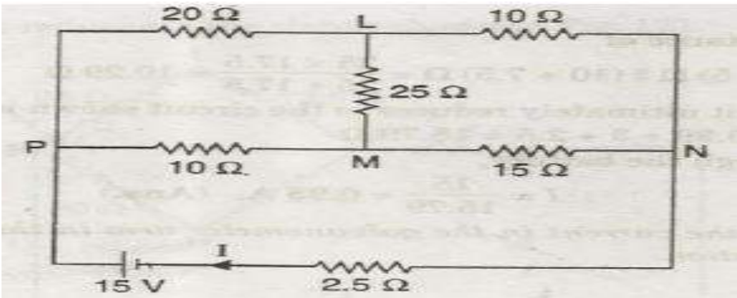
$$R_{12} = 1.67 + 5 + \frac{1.67 \times 5}{2.5} = 1.67 + 5 + 3.33 = 10\ \Omega$$

$$R_{23} = 5 + 2.5 + \frac{5 \times 2.5}{1.67} = 5 + 2.5 + 7.5 = 15\ \Omega$$

$$R_{31} = 2.5 + 1.67 + \frac{2.5 \times 1.67}{5} = 2.5 + 1.67 + 0.833$$

$$= 5\ \Omega$$

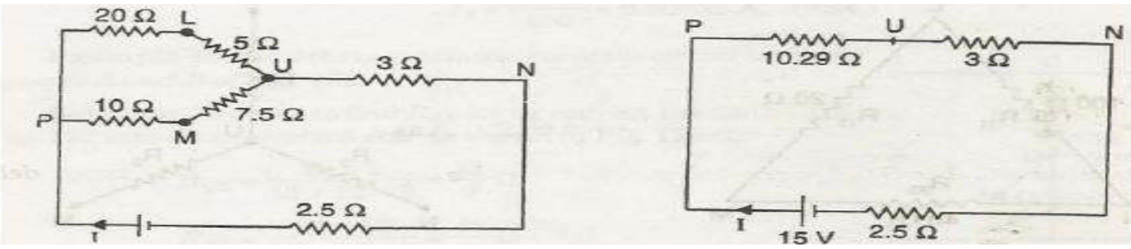
3) Determine the total current I in the given circuit.



Solution: Delta connected resistors 25 ohms, 10 ohms and 15 ohms are converted in to star as shown in given figure**.**

$R_1 = R_{12}\, R_{31} / R_{12} + R_{23} + R_{31} = 10 \text{ x } 25 / 10 + 15 + 25 = 5$ ohms
$R_2 = R_{23}\, R_{12} / R_{12} + R_{23} + R_{31} = 15 \text{ x } 10 / 10 + 15 + 25 = 3$ ohms
$R_3 = R_{31}\, R_{23} / R_{12} + R_{23} + R_{31} = 25 \text{ x } 15 / 10 + 15 + 25 = 7.5$ ohms

The given circuit thus reduces to the circuit shown in below fig.



The equivalent resistance of
(20 + 5) ohms || (10 + 7.5) ohms = 25 x 17.5 / 25 + 17.5 = 10.29 ohms
Total resistance = 10.29 + 3 + 2.5 = 15.79 ohms
Hence the total current through the battery,
I = 15 / 15.79 = 0.95 A

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

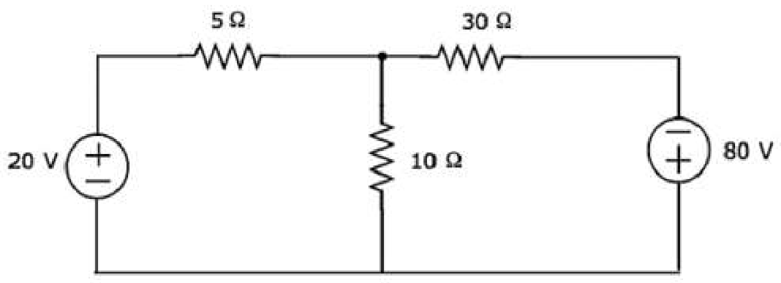
Follow these steps while solving any electrical network or circuit using Mesh analysis.

- **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.

Now, we can find the current flowing through any element and the voltage across any element that is present in the given network by using mesh currents.

Example

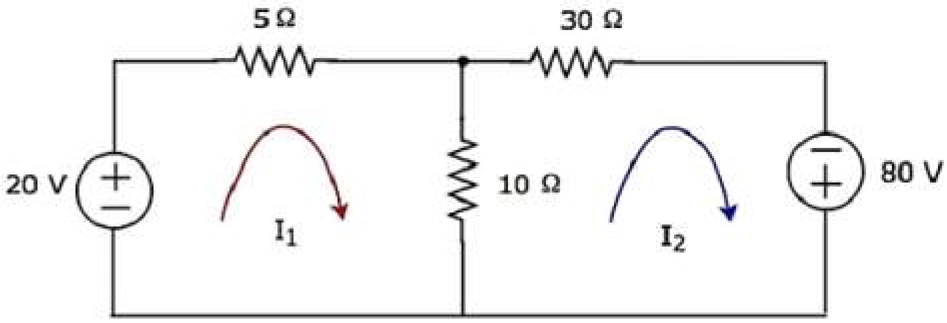
Find the voltage across 30 Ω resistor using Mesh analysis.



Step 1 − There are two meshes in the above circuit. The mesh currents I_1 and I_2 are considered in clockwise direction. These mesh currents are shown in the following figure.

Step 2 − The mesh current I_1 flows through 20 V voltage source and 5 Ω resistor. Similarly, the mesh current I_2 flows through 30 Ω resistor and -80 V voltage source. But, the difference of two mesh currents, I_1 and I_2, flows through 10 Ω resistor, since it is the common branch of two meshes.

Step 3 − In this case, we will get two mesh equations since there are two meshes in the given circuit. When we write the mesh equations, assume the mesh current of that particular mesh as greater than all other mesh currents of the circuit. The mesh equation of first mesh is



$$20 - 5I_1 - 10(I_1 - I_2) = 0$$

$$\Rightarrow 20 - 15I_1 + 10I_2 = 0$$

$$\Rightarrow 10I_2 = 15I_1 - 20$$

Divide the above equation with 5.

$$2I_2 = 3I_1 - 4$$

Multiply the above equation with 2.

$$4I_2 = 6I_1 - 8 \quad \text{Equation } 1$$

The **mesh equation** of second mesh is

$$-10(I_2 - I_1) - 30I_2 + 80 = 0$$

Divide the above equation with 10.

$$-(I_2 - I_1) - 3I_2 + 8 = 0$$

$$\Rightarrow -4I_2 + I_1 + 8 = 0$$

$$4I_2 = I_1 + 8 \quad \text{Equation } 2$$

Step 4 − Finding mesh currents I_1 and I_2 by solving Equation 1 and Equation 2.

The left-hand side terms of Equation 1 and Equation 2 are the same. Hence, equate the right-hand side terms of Equation 1 and Equation 2 in order find the value of I_1.

$$6I_1 - 8 = I_1 + 8$$

$$\Rightarrow 5I_1 = 16$$

$$\Rightarrow I_1 = \frac{16}{5}A$$

Substitute I_1 value in Equation 2.

$$4I_2 = \frac{16}{5} + 8$$

$$\Rightarrow 4I_2 = \frac{56}{5}$$

$$\Rightarrow I_2 = \frac{14}{5}A$$

So, we got the mesh currents I_1 and I_2 as $\frac{16}{5}$ **A** and $\frac{14}{5}$ **A** respectively.

Step 5 – The current flowing through 30 Ω resistor is nothing but the mesh current I_2 and it is equal to $\frac{14}{5}$ A. Now, we can find the voltage across 30 Ω resistor by using Ohm's law.

$$V_{30\Omega} = I_2 R$$

Substitute the values of I_2 and R in the above equation.

$$V_{30\Omega} = \left(\frac{14}{5}\right)30$$

$$\Rightarrow V_{30\Omega} = 84V$$

Therefore, the voltage across 30 Ω resistor of the given circuit is84 V.

Note 1 − From the above example, we can conclude that we have to solve 'm' mesh equations, if the electric circuit is having 'm' meshes. That's why we can choose Mesh analysis when the number of meshes is less than the number of principal nodes (except the reference node) of any electrical circuit.

Note 2 − We can choose either Nodal analysis or Mesh analysis, when the number of meshes is equal to the number of principal nodes (except the reference node) in any electric circuit.

Network Theorems:

Introduction:

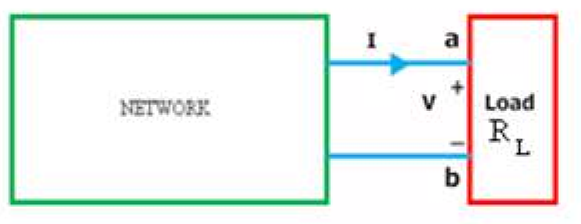
Any complicated network i.e. several sources, multiple resistors are present if the single element response is desired then use the network theorems. Network theorems are also can be termed as network reduction techniques. Each and every theorem got its importance of solving network. Let us see some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

Thevenin's Theorem and Norton's theorem (Introduction) :

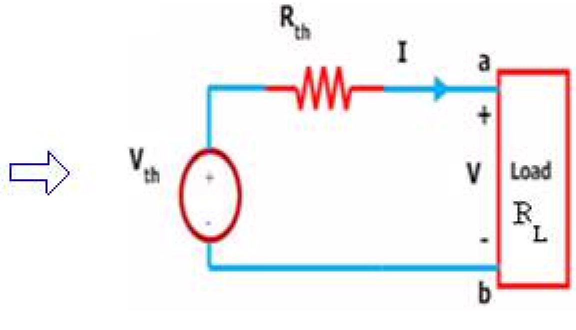
Thevenin's Theorem and Norton's theorem are two important theorems in solving Network problems having many active and passive elements. Using these theorems the networks can be reduced to simple equivalent circuits with one active source and one element. In circuit analysis many a times the current through a branch is required to be found when it's 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 V_{Th} is the open circuit voltage looking into the terminals(with concerned branch element removed) and the equivalent resistance R_{Th} 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.



(a)



(b)

Figure (a) shows a simple block representation of a network with several active / passive elements with the load resistance R_L connected across the terminals 'a & b' and figure (b) shows the Thevenin's equivalent circuit with V_{Th} connected across R_{Th} & R_L .

Main steps to find out V_{Th} and R_{Th} :

1. The terminals of the branch/element through which the current is to be found out are marked as say a & b after removing the concerned branch/element

2. Open circuit voltage V_{OC} across these two terminals is found out using the conventional network mesh/node analysis methods and this would be V_{Th} .

3. Thevenin's resistance R_{Th} is found out by the method depending upon whether the network contains dependent sources or not.

   a. With dependent sources: $R_{Th} = V_{oc} / I_{sc}$

   b. Without dependent sources : R_{Th} = Equivalent resistance looking into the concerned terminals with all voltage & current sources replaced by their internal impedances (i.e. ideal voltage sources short circuited and ideal current sources open circuited)

4. Replace the network with V_{Th} in series with R_{Th} and the concerned branch resistance (or) load resistance across the load terminals (A&B) as shown in below fig.

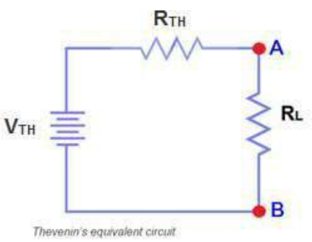
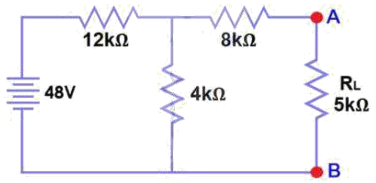


Fig.(a)

Example: Find V_{TH}, R_{TH} and the load current and load voltage flowing through R_L resistor as shown in fig. by using Thevenin's Theorem?



Solution:

The resistance R_L is removed and the terminals of the resistance R_L are marked as A & B as shown in the fig. (1)

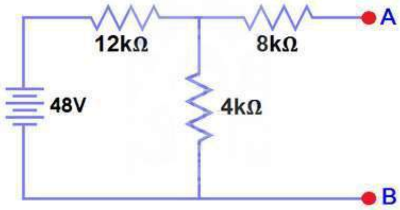


Fig.(1)

Calculate / measure the Open Circuit Voltage. This is the Thevenin Voltage (V_{TH}). We have already removed the load resistor from fig.(a), so the circuit became an open circuit as shown in fig (1). Now we have to calculate the Thevenin's Voltage. Since 3mA Current flows in both 12kΩ and 4kΩ resistors as this is a series circuit because current will not flow in the 8kΩ resistor as it is open. So 12V (3mA x 4kΩ) will appear across the 4kΩ resistor. We also know that current is not flowing through the 8kΩ resistor as it is open circuit, but the 8kΩ resistor is in parallel with 4k resistor. So the same voltage (i.e. 12V) will appear across the 8kΩ resistor as 4kΩ resistor. Therefore 12V will appear across the AB terminals.

So, V_{TH} = 12V

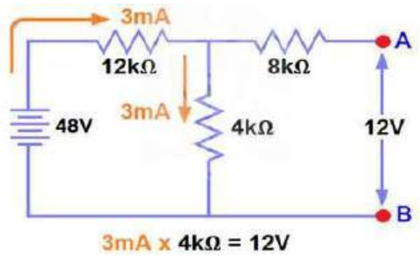
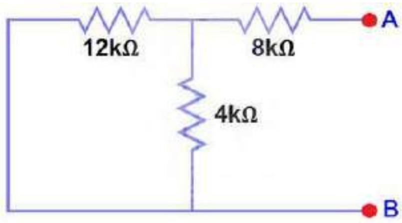


Fig (2)

All voltage & current sources replaced by their internal impedances (i.e. ideal voltage sources short circuited and ideal current sources open circuited) as shown in fig.(3)



Fig(3)

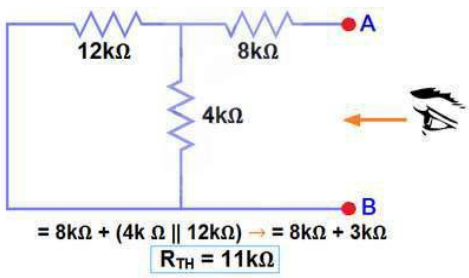
Calculate /measure the Open Circuit Resistance. This is the Thevenin's Resistance (R_{TH})We have Reduced the 48V DC source to zero is equivalent to replace it with a short circuit as shown in figure (3) We can see that 8kΩ resistor is in series with a parallel connection of 4kΩ resistor and 12k Ω resistor. i.e.:

8kΩ + (4k Ω || 12kΩ) ….. (|| = in parallel with)

R_{TH} = 8kΩ + [(4kΩ x 12kΩ) / (4kΩ + 12kΩ)]

R_{TH} = 8kΩ + 3kΩ

R_{TH} = 11kΩ



Fig(4)

Connect the R_{TH} in series with Voltage Source V_{TH} and re-connect the load resistor across the load terminals(A&B) as shown in fig (5) i.e. Thevenin's circuit with load resistor. This is the Thevenin's equivalent circuit.

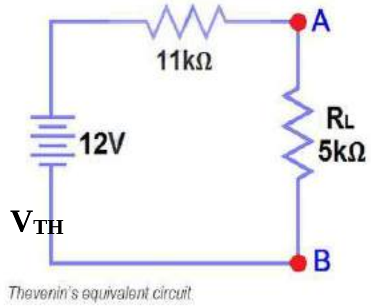


Fig (5)

Now apply Ohm's law and calculate the load current from fig 5.

$I_L = V_{TH}/ (R_{TH} + R_L)= 12V / (11k\Omega + 5k\Omega) = 12/16k\Omega$

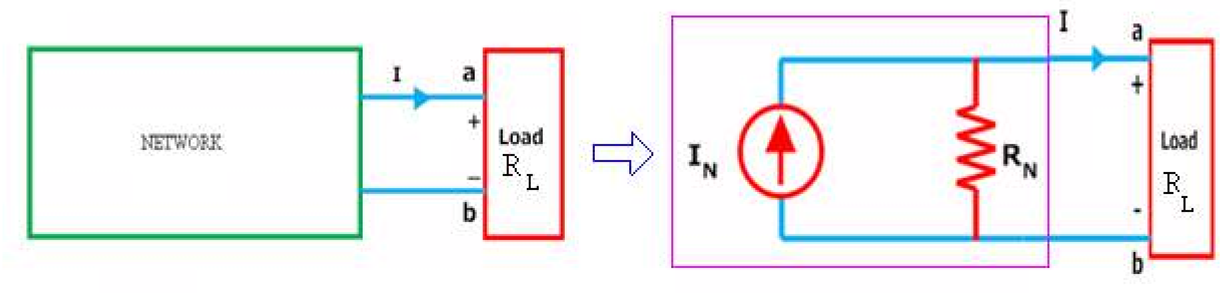
$I_L= 0.75mA$

And $V_L = I_L x\ R_L= 0.75mA \times 5k\Omega$

$V_L= 3.75V$

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.



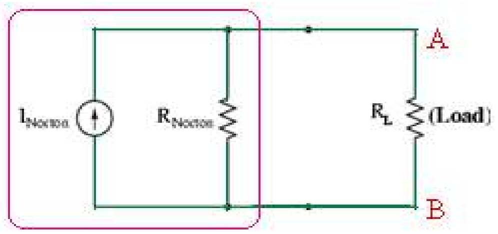
(a) (b)

Figure (a) shows a simple block representation of a network with several active / passive elements with the load resistance $\mathbf{R_L}$ connected across the terminals **'a & b'** and figure (b) shows the **Norton equivalent circuit** with $\mathbf{I_N}$ connected across $\mathbf{R_N}$ & $\mathbf{R_L}$ **.**

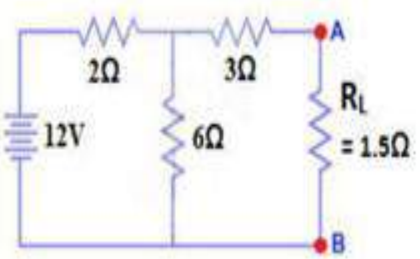
Main steps to find out $\mathbf{I_N}$ and $\mathbf{R_N}$:

- The terminals of the branch/element through which the current is to be found out are marked as say **a & b** after removing the concerned branch/element.

- Open circuit voltage V_{OC} across these two terminals and I_{SC} through these two terminals are found out using the conventional network mesh/node analysis methods and they are same as what we obtained in Thevenin's equivalent circuit**.**
- Next **Norton resistance** R_N is found out depending upon whether the network contains dependent sources or not.
  a) With dependent sources: $R_N = V_{oc} / I_{sc}$
  b) Without dependent sources : R_N = Equivalent resistance looking into the concerned terminals with all voltage & current sources replaced by their internal impedances (i.e. ideal voltage sources short circuited and ideal current sources open circuited)
- Replace the network with I_N in parallel with R_N and the concerned branch resistance across the load terminals(A&B) as shown in below fig

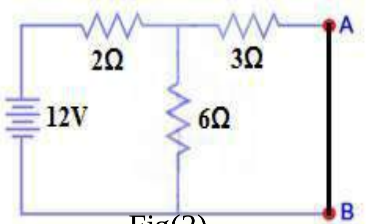


Example: Find the current through the resistance R_L (1.5 Ω) of the circuit shown in the figure (a) below using Norton's equivalent circuit.



Fig(a)

Solution: To find out the Norton's equivalent ckt we have to find out $I_N = I_{sc}$,$R_N = V_{oc} / I_{sc}$. Short the 1.5Ω load resistor as shown in (Fig 2), and Calculate / measure the Short Circuit Current. This is the Norton Current (I_N).



Fig(2)

We have shorted the AB terminals to determine the Norton current, I_N. The 6Ω and 3Ω are then in parallel and this parallel combination of 6Ω and 3Ω are then in series with 2Ω.So the Total Resistance of the circuit to the Source is:-

2Ω + (6Ω || 3Ω) ….. (|| = in parallel with)

R_T = 2Ω + [(3Ω x 6Ω) / (3Ω + 6Ω)]

R_T = 2Ω + 2Ω

R_T = 4Ω

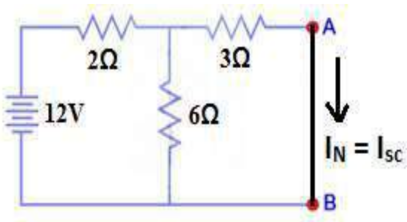
$I_T = V / R_T$

I_T = 12V / 4Ω= 3A..

Now we have to find $I_{SC} = I_N$… Apply CDR… (Current Divider Rule)…

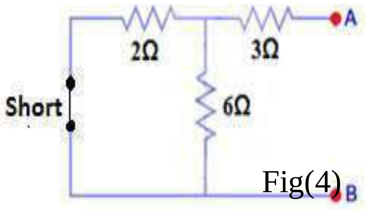
$I_{SC} = I_N$ = 3A x [(6Ω / (3Ω + 6Ω)] = 2A.

$I_{SC} = I_N$ = 2A.



Fig(3)

All voltage & current sources replaced by their internal impedances (i.e. ideal voltage sources short circuited and ideal current sources open circuited) and Open Load Resistor. as shown in fig.(4)



Fig(4)

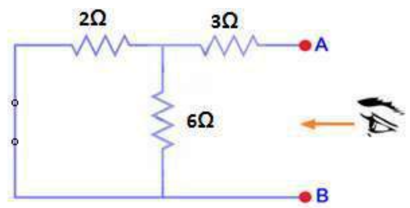
Calculate /measure the Open Circuit Resistance. This is the Norton Resistance (R_N) We have Reduced the 12V DC source to zero is equivalent to replace it with a short circuit as shown in fig(4), We can see that 3Ω resistor is in series with a parallel combination of 6Ω resistor and 2Ω resistor. i.e.:

3Ω + (6Ω || 2Ω) ….. (|| = in parallel with)

R_N = 3Ω + [(6Ω x 2Ω) / (6Ω + 2Ω)]

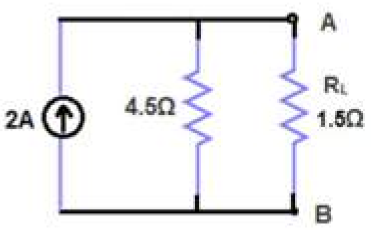
R_N = 3Ω + 1.5Ω

R_N = 4.5Ω



Fig(5)

Connect the R_N in Parallel with Current Source I_N and re-connect the load resistor. This is shown in fig (6) i.e. Norton Equivalent circuit with load resistor.



Fig(6)

Now apply the Ohm's Law and calculate the load current through Load resistance across the terminals A&B. Load Current through Load Resistor is

$I_L = I_N$ x $[R_N / (R_N + R_L)]$

$I_{L=}$ 2A x (4.5Ω /4.5Ω +1.5kΩ)

I_L = 1.5A **I_L = 1. 5A**

Superposition Theorem:

The principle of superposition helps us to analyze a linear circuit with more than one current or voltage sources sometimes it is easier to find out the voltage across or current in a branch of the circuit by considering the effect of one source at a time by replacing the other sources with their ideal internal resistances.

Superposition Theorem Statement:

Any linear, bilateral two terminal network consisting of more than one sources, The total current or voltage in any part of a network is equal to the algebraic sum of the currents or voltages in the required branch with each source acting individually while other sources are replaced by their ideal internal resistances. (i.e. Voltage sources by a short circuit and current sources by open circuit)

Steps to Apply Super position Principle:

1. Replace all independent sources with their internal resistances except one source. Find the output (voltage or current) due to that active source using nodal or mesh analysis.

2. Repeat step 1 for each of the other independent sources.
3. Find the total contribution by adding algebraically all the contributions due to the independent sources.

Example: By Using the superposition theorem find I in the circuit shown in figure?

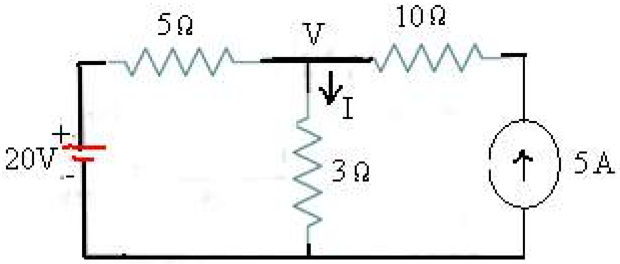


Fig.(a)

Solution: Applying the superposition theorem, the current I_2 in the resistance of 3 Ω due to the voltage source of 20V alone, with current source of 5A open circuited [as shown in the figure.1 below] is given by :

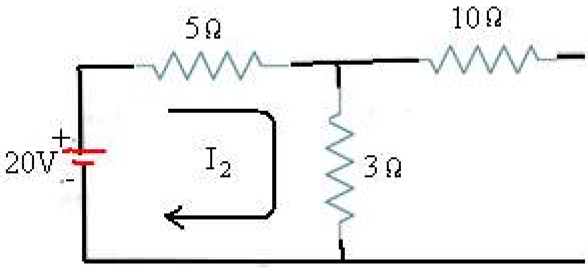


Fig.1

$$I_2 = 20/(5+3) = 2.5A$$

Similarly the current I_5 in the resistance of 3 Ω due to the current source of 5A alone with voltage source of 20V short circuited [as shown in the figure.2 below] is given by :

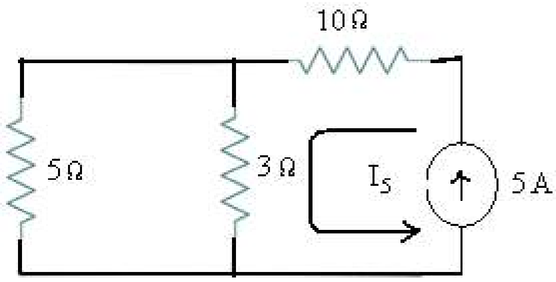


Fig.2

$$I_5 = 5 \times 5/(3+5) = 3.125 \text{ A}$$

The total current passing through the resistance of 3Ω is then = $I_2 + I_5$= 2.5 + 3.125 = **5.625 A**

Let us verify the solution using the basic nodal analysis referring to the node marked with V in fig.(a).Then we get :

$$\frac{V-20}{5}+\frac{V}{3}=5$$

3V-60+5V=15× 5

8V-60=75

8V=135

V=16.875

The current I passing through the resistance of 3Ω =V/3 = 16.875/3 = **5.625 A.**

UNIT-III
SINGLE PHASE A.C. CIRCUITS

- Average value, R.M.S. value, form factor and peak factor for sinusoidal wave form.
- Steady State Analysis of series R-L-C circuits.
- Concept of Reactance, Impedance, Susceptance, Admittance.
- Concept of Power Factor, Real, Reactive and Complex power.
- Illustrative Problems.

RMS VALUE:

- The **RMS** (**Root Mean Square**) value (also known as **effective** or **virtual** value) of of an alternating current (AC) is the value of direct current (DC) when flowing through a circuit or resistor for the specific time period and produces same amount of heat which produced by the alternating current (AC) when flowing through the same circuit or resistor for a specific time.
- The value of an AC which will produce the same amount of heat while passing through in a heating element (such as resistor) as DC produces through the element is called R.M.S Value.
- In short,
- The RMS Value of an Alternating Current is that when it compares to the Direct Current, then both AC and DC current produce the same amount of heat when flowing through the same circuit for a specific time period.

$$I_{RMS} = \frac{I_M}{\sqrt{2}}, \quad V_{RMS} = \frac{V_M}{\sqrt{2}}$$

For a sinusoidal wave

$$I = 0.707 \times I_M, \; V = 0.707 \times V_M$$

,

or

$$\mathbf{I_{RMS} = 0.707 \times I_M, \; E_{RMS} = 0.707\, E_M}$$

- Actually, the RMS value of a sine wave is the measurement of heating effect of sine wave. For example, when a resistor is connected to across an AC voltage source, it produces specific amount of heat (Fig 2 – a). When the same resistor is connected across the DC voltage source as shown in (fig 2 – b). By adjusting the value of DC voltage to get the same amount of heat generated before in AC voltage source in fig a. It means the RMS value of a sine wave is equal to the DC Voltage source producing the same amount of heat generated by AC Voltage source.
  - In more clear words, the domestic voltage level in US is 110V, while 220V AC in UK. This voltage level shows the effective value of (110V or 220V R.M.S) and it shows that the home wall socket is capable to provide the same amount of average positive power as 110V or 220V DC Voltage.
  - **Keep in mind that the ampere meters and volt meters connected in AC circuits always showing the RMS values (of current and voltage).**
  - For AC sine wave, RMS values of current and voltage are:

$$\mathbf{I_{RMS} = 0.707 \times I_M, \; V_{RMS} = 0.707\, V_M}$$

- Let's see how to find the R.M.S values of a sine wave.
- We know that the value of sinusoidal alternating current (AC) =

$$\mathbf{I_m \sin \omega\, \theta = I_m \sin \theta}$$

- While the mean of square of instantaneous values of current in in half or complete cycle is:

$$= \int_0^{2\pi} \frac{i^2 \, d\theta}{(2\pi - 0)}$$

The Square root of this value is:

$$= \sqrt{\left(\int_0^{2\pi} \frac{i^2 \, d\theta}{2\pi} \right)}$$

Hence, the RMS value of the current is (while putting $I = I_m \text{Sin } \theta$):

$$I = \sqrt{\left(\int_0^{2\pi} \frac{i^2 d\theta}{2\pi} \right)} = \sqrt{\left(\frac{I_m^2}{2\pi} \int_0^{2\pi} \sin^2 \theta \, d\theta \right)}$$

Now,

$$\cos 2\theta = 1 - 2 \sin^2 \theta \quad \therefore \sin^2 \theta = \frac{1 - \cos 2\theta}{2}$$

$$I = \sqrt{\left(\frac{I_m^2}{4\pi} \int_0^{2\pi} (1 - \cos 2\theta) \, d\theta \right)} = \sqrt{\left(\frac{I_m^2}{4\pi} \left| \theta - \frac{\sin 2\theta}{2} \right|_0^{2\pi} \right)}$$

$$= \sqrt{\frac{I_m^2}{4} \quad 2} \qquad \sqrt{\frac{I_m^2}{2}} \qquad \therefore I = \frac{I_m}{\sqrt{2}} = 707 \, I_m$$

Therefore, We may find that for a symmetrical sinusoidal current:

I_{RMS} = Max Value of Current x 0.707

Average Value:

If we convert the alternating current (AC) sine wave into direct current (DC) sine wave through rectifiers, then the converted value to the DC is known as the average value of that alternating current sine wave.

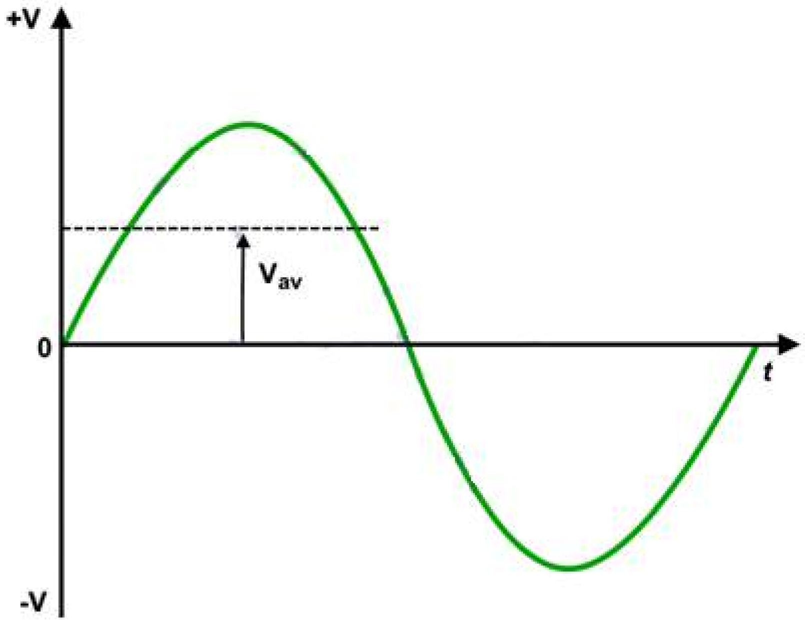


Fig 4 – Average Value of Voltage

If the maximum value of alternating current is “I_{MAX}“, then the value of converted DC current through rectifier would be “0.637 I_M” which is known as average value of the AC Sine wave (I_{AV}).

Average Value of Current = I_{AV} = 0.637 I_M

Average Value of Voltage = E_{AV} = 0.637 E_M

The Average Value (also known as Mean Value) of an Alternating Current (AC) is expressed by that Direct Current (DC) which transfers across any circuit the same amount of charge as is transferred by that Alternating Current (AC) during the same time.

Keep in mind that the average or mean value of a full sinusoidal wave is “Zero” the value of current in first half (Positive) is equal to the the next half cycle (Negative) in the opposite direction. In other words, There are same amount of current in the positive and negative half cycles which flows in the opposite direction, so the average value for a complete sine wave would be “0”. That’s the reason that’s why we don’t use average value for plating and battery charging. If an AC wave is converted into DC through a rectifier, It can be used for electrochemical works.

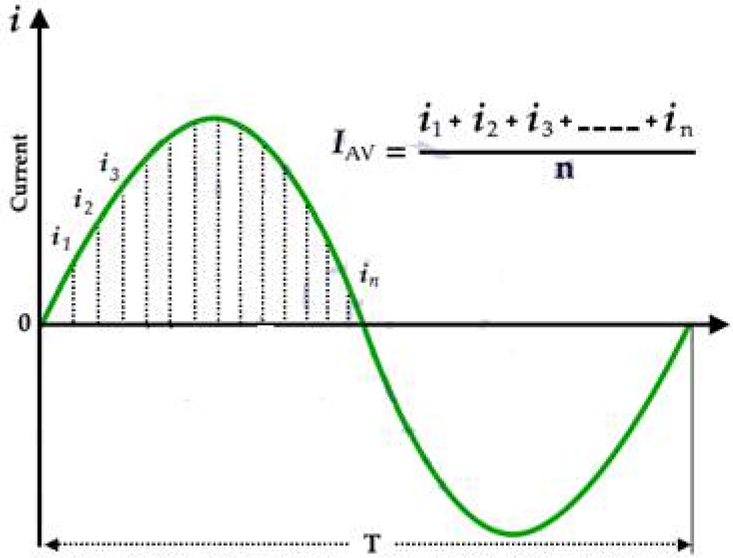


Fig 5- Average Value of Current

In short, the average value of a sine wave taken over a complete cycle is always zero, because the positive values (above the zero crossing) offset or neutralize the negative values (below the zero crossing.)

We know that the standard equation of alternating current is

$$i = \sin \omega \theta = I_m \sin \theta$$

- Maximum value of current on sine wave = I_m
- Average value of current on sine wave = I_{AV}
- Instantaneous value of current on sine wave = i
- The angle specified fir “i” after zero position of current = θ
- Angle of half cycle = π radians
- Angle of full cycle = 2π radians

(a) Average value of complete cycle:

Let i = Sin ω θ = I_m Sin θ

$$I_{AV} = \frac{1}{2\pi}\int_0^{2\pi} i\,d\theta = \frac{1}{2\pi}\int_0^{2\pi} i_m \,\text{Sin}\theta\, d\theta$$

$$= \frac{I_m}{2\pi}\left[-\text{Cos}\,\theta\right]_0^{2\pi} = \frac{I_m}{2\pi}(\text{Cos}\,2\pi - \text{Cos}\,0)$$

$$= \frac{I_m}{2\pi}(1-1) = 0\,; \quad I_{AV} = 0$$

Thus, the average value of a sinusoidal wave over a complete cycle is zero.

(b) Average value of current over a half cycle

$$I_{AV} = \frac{1}{\pi}\int_0^{\pi} i\, d\theta$$

$$= \frac{1}{\pi}\int_0^{\pi} I_m \,\text{Sin}\,\theta.d\theta \quad [\because i = I_m \,\text{Sin}\,\theta]$$

$$= \frac{I_m}{\pi}\left[-\text{Cos}\,\theta\right]_0^{\pi} = \frac{I_m}{\pi}\left[-\text{Cos}\,\pi - (-\text{Cos}\,0)\right]$$

$$= \frac{I_m}{\pi}[(+1) - (-1)] = \frac{I_m}{\pi}(+2)$$

$$I_{AV} = \frac{2}{\pi} I_m = 0.637 \text{ A}$$

Average Value of Current (Half Cycle)

$$\mathbf{I_{AV} = 0.637\ V_M}$$

Similarly, the average value of voltage over a half cycle

$$\mathbf{V_{AV} = 0.637\ V_M}$$

★ **Average Voltage Value**

$$V_{AV} = \frac{2V_P}{\pi} = 0.637 \times V_P$$

$$V_{AV} = \frac{2V_M}{\pi} = 0.637 \times V_M$$

★ **Average Current Value**

$$I_{AV} = \frac{2I_M}{\pi} = 0.637 \times I_M$$

What is Peak Voltage or Maximum Voltage Value ?

Peak value is also known as **Maximum Value**, **Crest Value** or **Amplitude**. It is the maximum value of alternating current or voltage from the "0" position no matter positive or negative half cycle in a sinusoidal wave as shown in fig 8. Its expressed as $\mathbf{I_M}$ and $\mathbf{E_M}$ or $\mathbf{V_P}$ and $\mathbf{I_M}$.

Equations of Peak Voltage Value is:

$$\mathbf{V_P = \sqrt{2} \times V_{RMS} = 1.414\ V_{RMS}}$$

$$V_P = V_{P-P}/2 = 0.5\ V_{P-P}$$

$$V_P = \pi/2 \times V_{AV} = 1.571 \times V_{AV}$$

In other words, It is the value of voltage or current at the positive or the negative maximum (peaks) with respect to zero. In simple words, it is the instantaneous value with maximum intensity.

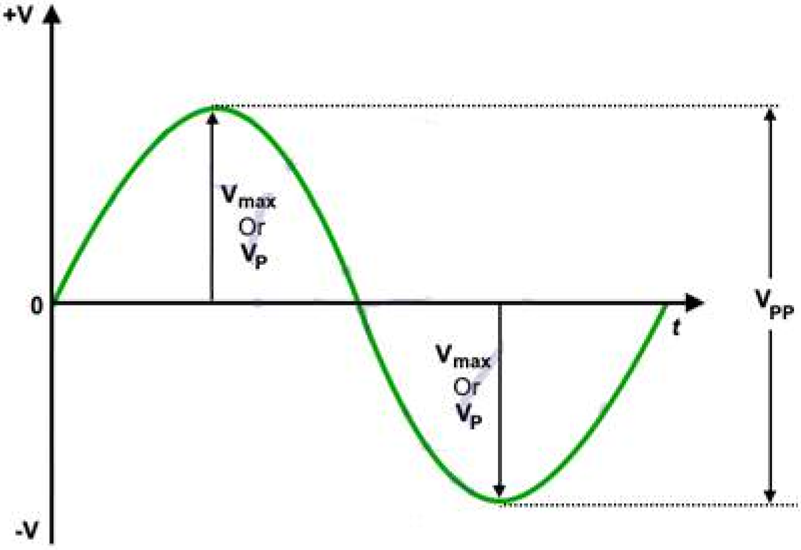


Fig 8 – Peak or Maximum Values of Voltages

Peak to Peak Value:

The sum of positive and negative peak values is known as peak to peak value. Its expressed as I_{PP} or V_{PP}.

Equations and formulas for Peak to Peak Voltage are as follow:

$$V_{P-P} = 2\sqrt{2} \times V_{RMS} = 2.828 \times V_{RMS}$$

$$V_{P-P} = 2 \times V_P$$

$$V_{P-P} = \pi \times V_{AV} = 3.141 \times V_{AV}$$

In other words, the peak to peak value of a sine wave, is the voltage or current from positive peak to the negative peak and its value is double as compared to peak value or maximum value as shown in fig 8 above.

Peak Factor:

Peak Factor is also known as Crest Factor or Amplitude Factor.

It is the ratio between maximum value and RMS value of an alternating wave.

$$\text{Peak Factor} = \frac{\text{Maximum Value}}{\text{R.M.S Value}}$$

For a sinusoidal alternating voltage:

$$\frac{E_M}{0.707\ E_M} = 1.414$$

For a sinusoidal alternating current:

$$\frac{I_M}{0.707\, I_M} = 1.414$$

Form Factor:

The ratio between RMS value and Average value of an alternating quantity (Current or Voltage) is known as Form Factor.

$$\text{Form Factor} = \frac{\text{RMS Value}}{\text{Average Value}}$$

$$= \frac{0.707\, E_M}{0.637\, E_M} \text{ Or } \frac{0.707\, I_M}{0.637\, I_M} = 1.11$$

Other Terms Related To AC Circuits

Waveform

- The path traced by a quantity (such as voltage or current) plotted as a function of some variable (such as time, degree, radians, temperature etc.) is called waveform.

Cycle

1. One complete set of positive and negative values of alternating quality (such as voltage and current) is known as cycle.
2. The portion of a waveform contained in one period of time is called cycle.
3. A distance between two same points related to value and direction is known as cycle.
4. A cycle is a complete alternation.

Period

- The time taken by a alternating quantity (such as current or voltage) to complete one cycle is called its time period "T".
- It is inversely proportional to the Frequency "*f*" and denoted by "T" where the unit of time period is second.
- Mathematically;

$$T = 1/f$$

Frequency

- Frequency is the number if cycles passed through per second. It is denoted by "f" and has the unit cycle per second i.e. Hz (Herts).
- The number of completed cycles in 1 second is called frequency.
- It is the number of cycles of alternating quantity per second in hertz.
- Frequency is the number of cycles that a sine wave completed in one second or the number of cycles that occurs in one second.

$$f = 1/T$$

Amplitude

- The maximum value, positive or negative, of an alternating quantity such as voltage or current is known as its amplitude. Its denoted by V_P, I_P or E_{MAX} and I_{MAX}.
- Alternation
- One half cycle of a sine wave (Negative or Positive) is known as alternation which span is 180° degree.

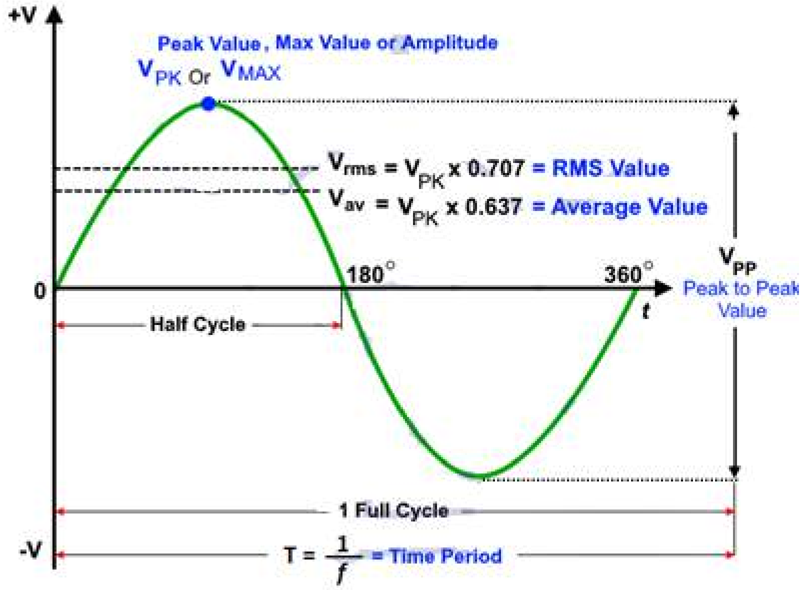


Fig 9 – Different Terms used in AC Circuits and Sine Wave

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.

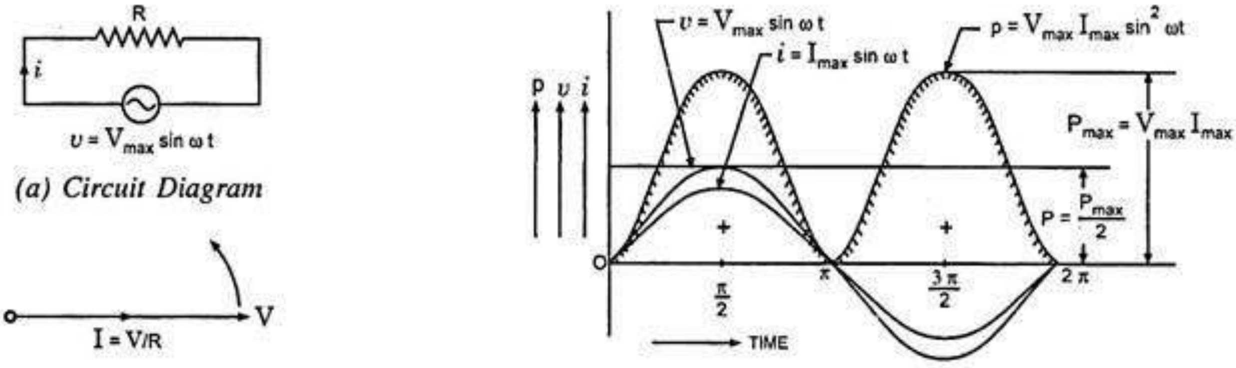


Fig. 4.1 *Purely Resistive Circuit*

As already said, when the current flowing through a pure resistance changes, no back emf is set up, therefore, applied voltage has to overcome the ohmic drop of i R only:

$$i.e. \quad iR = v$$

$$\text{or} \quad i = \frac{v}{R} = \frac{V_{max}}{R} \sin \omega t$$

Current will be maximum when $\omega t = \frac{\pi}{2}$ or $\sin \omega t = 1$

$$\therefore \quad I_{max} = \frac{V_{max}}{R}$$

And instantaneous current may be expressed as:

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

From the expressions of instantaneous applied voltage and instantaneous current, it is evident that in a pure resistive circuit, the applied voltage and current are in phase with each other, as shown by wave and phasor diagrams in Figs. 4.1 (b) and (c) respectively.

Power in Purely Resistive Circuit:

The instantaneous power delivered to the circuit in question is the product of the instantaneous values of applied voltage and current.

$$i.e. \quad p = vi = V_{max} \sin \omega t \, I_{max} \sin \omega t = V_{max} \, I_{max} \sin^2 \omega t$$

$$\text{or} \quad p = \frac{V_{max} \, I_{max}}{2}(1 - \cos 2\,\omega t) \qquad \text{Since } \sin^2 \omega t = \frac{1 - \cos 2\,\omega t}{2}$$

$$= \frac{V_{max} \, I_{max}}{2} - \frac{V_{max} \, I_{max}}{2} \cos 2\,\omega t$$

$$\text{Average power, } P = \text{Average of } \frac{V_{max} \, I_{max}}{2} - \textit{average of } \frac{V_{max} \, I_{max}}{2} \cos 2\,\omega t$$

Since average of $\frac{V_{max} \, I_{max}}{2} \cos 2\,\omega t$ over a complete cycle is zero,

$$P = \frac{V_{max} \, I_{max}}{2} = \frac{V_{max}}{\sqrt{2}} \cdot \frac{I_{max}}{\sqrt{2}} = V\,I \text{ watts}$$

Where V and I are the rms values of applied voltage and current respectively.
Thus for purely resistive circuits, the expression for power is the same as for dc circuits. From the power curve for a purely resistive circuit shown in Fig. 4.1 (b) it is evident that power consumed in a pure resistive circuit is not constant, it is fluctuating.
However, it is always positive. This is so because the instantaneous values of voltage and current are always either positive or negative and, therefore, the product is always positive. This means that the voltage source constantly delivers power to the circuit and the circuit consumes it.

Purely Inductive Circuit:

An inductive circuit is a coil with or without an iron core having negligible resistance. Practically pure inductance can never be had as the inductive coil has always small resistance. However, a coil of thick copper wire wound on a laminated iron core has negligible resistance arid is known as a choke coil.
When an alternating voltage is applied to a purely inductive coil, an emf, known as self-induced emf, is induced in the coil which opposes the applied voltage. Since coil has no resistance, at every instant applied voltage has to overcome this self-induced emf only.

Let the applied voltage $v = V_{max} \sin \omega t$
and self inductance of coil = L henry

Self induced emf in the coil, $e_L = -L \frac{di}{dt}$

Since applied voltage at every instant is equal and opposite to the self induced emf *i.e.* $v = -e_L$

$$\therefore \quad V_{max} \sin \omega t = -\left(-L\frac{di}{dt}\right)$$

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

Integrating both sides we get

$$i = \frac{V_{max}}{L} \int \sin \omega t \, dt = \frac{V_{max}}{\omega L}(-\cos \omega t) + A$$

where A is a constant of integration, which is found to be zero from initial conditions

$$i.e. \quad i = \frac{-V_{max}}{\omega L} \cos \omega t = \frac{V_{max}}{\omega L} \sin\left(\omega t - \frac{\pi}{2}\right)$$

Current will be maximum when $\sin\left(\omega t - \frac{\pi}{2}\right) = 1$, hence, maximum value of current,

$$I_{max} = \frac{V_{max}}{\omega L}$$

and instantaneous current may be expressed as $i = I_{max} \sin\left(\omega t - \frac{\pi}{2}\right)$

From the expressions of instantaneous applied voltage and instantaneous current flowing through a purely inductive coil it is observed that the current lags behind the applied voltage by π/2 as shown in Fig. 4.2 (b) by wave diagram and in Fig 4.2 (c) by phasor diagram.

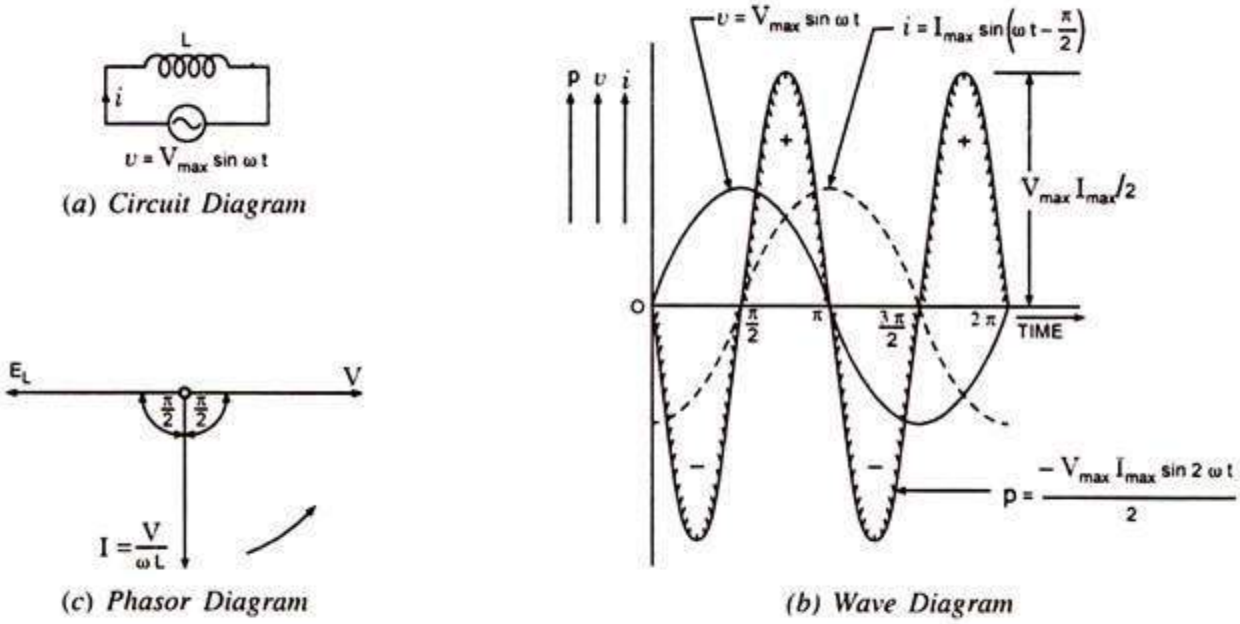


Fig. 4.2 *Purely Inductive Circuit*

Inductive Reactance:
ωL in the expression Imax = V_{max}/ωL is known as inductive reactance and is denoted by X_L i.e., $X_L = \omega L$
If L is in henry and co is in radians per second then X_L will be in ohms.

Power in Purely Inductive Circuit:
Instantaneous power, $p = v \times i = V_{max} \sin \omega t \, I_{max} \sin (\omega t - \pi/2)$
Or $p = - V_{max} I_{max} \sin \omega t \cos \omega t = V_{max} I_{max}/2 \sin 2 \omega t$
The power measured by wattmeter is the average value of p which is zero since average of a sinusoidal quantity of double frequency over a complete cycle is zero. Hence in a purely inductive circuit power absorbed is zero.

Physically the above fact can be explained as below:
During the second quarter of a cycle the current and the magnetic flux of the coil increases and the coil draws power from the supply source to build up the magnetic field (the power drawn is positive and the energy drawn by the coil from the supply source is represented by the area between the curve p and the time axis). The energy stored in the magnetic field during build up is given as $W_{max} = 1/2 \, L \, I^2_{max}$.
In the next quarter the current decreases. The emf of self-induction will, however, tends to oppose its decrease. The coil acts as a generator of electrical energy, returning the stored energy in the magnetic field to the supply source (now the power drawn by the coil is negative and the curve p lies below the time axis). The chain of events repeats itself during the next half cycles. Thus, a proportion of power is continually exchanged between the field and the inductive circuit and the power consumed by a purely inductive coil is zero.

<u>Purely Capacitive Circuit:</u>

When a dc voltage is impressed across the plates of a perfect condenser, it will become charged to full voltage almost instantaneously. The charging current will flow only during the period of "build up" and will cease to flow as soon as the capacitor has attained the steady voltage of the source. This implies that for a direct current, a capacitor is a break in the circuit or an infinitely high resistance.
In Fig. 4.4 a sinusoidal voltage is applied to a capacitor. During the first quarter-cycle, the applied voltage increases to the peak value, and the capacitor is charged to that value. The current is maximum in the

beginning of the cycle and becomes zero at the maximum value of the applied voltage, so there is a phase difference of 90° between the applied voltage and current. During the first quarter-cycle the current flows in the normal direction through the circuit; hence the current is positive.

In the second quarter-cycle, the voltage applied across the capacitor falls, the capacitor loses its charge, and current flows through it against the applied voltage because the capacitor discharges into the circuit. Thus, the current is negative during the second quarter-cycle and attains a maximum value when the applied voltage is zero.

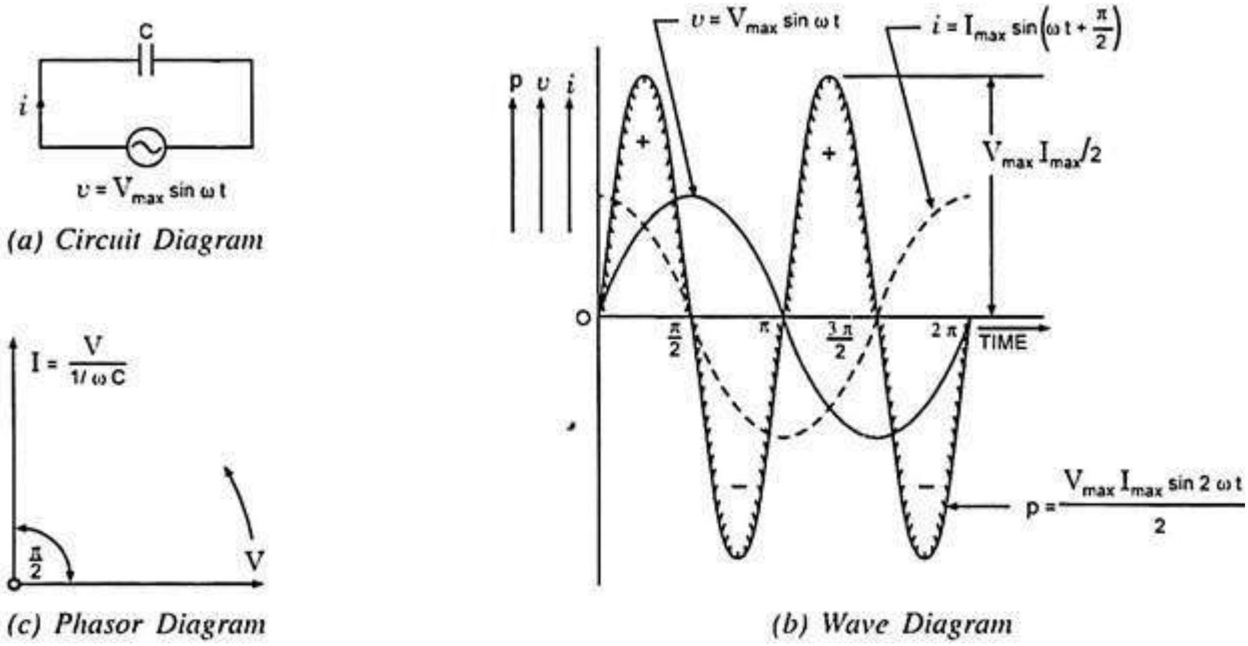


Fig. 4.4 *Purely Capacitive Circuit*

The third and fourth quarter-cycles repeat the events of the first and second, respectively, with the difference that the polarity of the applied voltage is reversed, and there are corresponding current changes.

In other words, an alternating current flow in the circuit because of the charging and discharging of the capacitor. As illustrated in Figs. 4.4 (b) and (c) the current begins its cycle 90 degrees ahead of the voltage, so the current in a capacitor leads the applied voltage by 90 degrees – the opposite of the inductance current-voltage relationship.

Let an alternating voltage represented by $v = V_{max} \sin \omega t$ be applied across a capacitor of capacitance C farads.

The expression for instantaneous charge is given as:

$$q = C V_{max} \sin \omega t$$

Since the capacitor current is equal to the rate of change of charge, the capacitor current may be obtained by differentiating the above equation:

$$i = \frac{dq}{dt} = [C\,V_{max} \sin \omega t] = \omega C V_{max} \cos \omega t = \frac{V_{max}}{1/\omega C} \sin\left(\omega t + \frac{\pi}{2}\right)$$

Current is maximum when $t = 0$

$$\therefore \quad I_{max} = \frac{V_{max}}{1/\omega C}$$

Substituting $\frac{V_{max}}{1/\omega C} = I_{max}$ in the above equation for instantaneous current, we get

$$i = I_{max} \sin\left(\omega t + \frac{\pi}{2}\right)$$

From the equations of instantaneous applied voltage and instantaneous current flowing through capacitance, it is observed that the current leads the applied voltage by $\pi/2$, as shown in Figs. 4.4 (b) and (c) by wave and phasor diagrams respectively.

Capacitive Reactance:

$1/\omega C$ in the expression $I_{max} = V_{max}/1/\omega C$ is known as capacitive reactance and is denoted by X_C i.e.,

$$X_C = 1/\omega C$$

If C is in farads and ω is in radians/s, then X_c will be in ohms.

Power in Purely Capacitive Circuit:

$$p = v\,i = V_{max} \sin \omega t.\ I_{max} \sin\left(\omega t + \frac{\pi}{2}\right) = V_{max} I_{max} \sin \omega t \cos \omega t$$

$$= \frac{V_{max} I_{max}}{2} \sin 2\omega t$$

Average power, $P = \frac{V_{max} I_{max}}{2} \times$ average of $\sin 2\,\omega t$ over a complete cycle = 0.

Hence power absorbed in a purely capacitive circuit is zero. The same is shown graphically in Fig. 4.4 (b). The energy taken from the supply circuit is stored in the capacitor during the first quarter- cycle and returned during the next.

The energy stored by a capacitor at maximum voltage across its plates is given by the expression:

$$W_C = \frac{1}{2} C V^2_{max}$$

This can be realized when it is recalled that no heat is produced and no work is done while current is flowing through a capacitor. As a matter of fact, in commercial capacitors, there is a slight energy loss in the dielectric in addition to a minute $I^2 R$ loss due to flow of current over the plates having definite ohmic resistance.

The power curve is a sine wave of double the supply frequency. Although it raises the power factor from zero to 0.002 or even a little more, but for ordinary purposes the power factor is taken to be zero. Obviously the phase angle due to dielectric and ohmic losses decreases slightly.

Resistance — Capacitance (R-C) Series Circuit:
Consider an ac circuit consisting of resistance of R ohms and capacitance of C farads connected in series, as shown in Fig. 4.18 (a).
Let the supply frequency be of *f* Hz and current flowing through the circuit be of I amperes (rms value).
Voltage drop across resistance, $V_R = I\,R$ in phase with the current.
Voltage drop across capacitance, $V_C = I\,X_C$ lagging behind I by π/2 radians or 90°, as shown in Fig. 4.18 (b).

(*a*) *Circuit Diagram* (*b*) *Phasor Diagram*

Fig. 4.18

The applied voltage, being equal to phasor sum of V_R and V_C, is given in magnitude by-

$$V = \sqrt{(V_R)^2 + (V_C)^2} = \sqrt{(IR)^2 + (IX_C)^2} = I\sqrt{R^2 + X_C^2} = IZ$$

where $Z^2 = R^2 + {X_C}^2$

The applied voltage lags behind the current by an angle ϕ:

where $\tan\Phi = \frac{V_C}{V_R} = \frac{IX_C}{IR} = \frac{X_C}{R} = \frac{1}{\omega RC}$ or $\Phi = \mathrm{Tan}^{-1}\frac{1}{R\omega C}$

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

If instantaneous voltage is represented by:

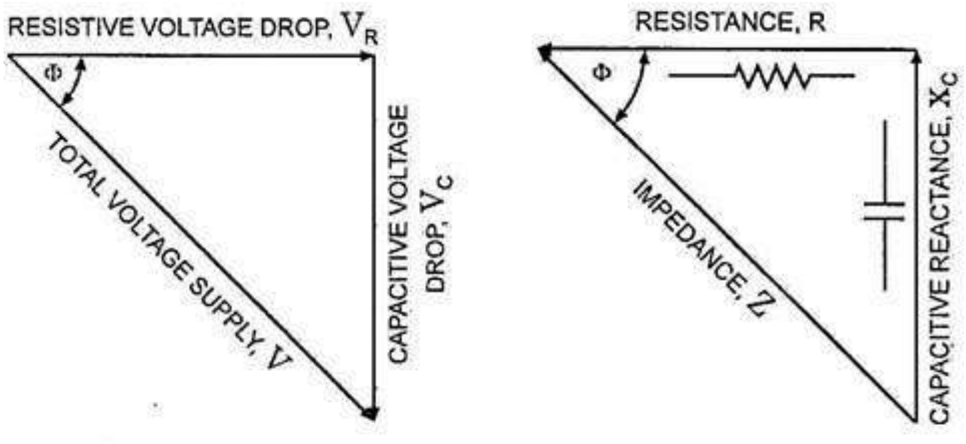
$$v = V_{max} \sin \omega t$$

Then instantaneous current will be expressed as:

$$i = I_{max} \sin(\omega t + \phi)$$

And power consumed by the circuit is given by:

$$P = VI \cos \phi$$



(a) Voltage Triangle *(b) Impedance Triangle*

Fig. 4.19

Voltage triangle and impedance triangle Fig. 4.19 are shown in Figs. 4.19 (a) and 4.19 (b) respectively.

6. Apparent Power, True Power, Reactive Power and Power Factor:

The product of rms values of current and voltage, VI is called the apparent power and is measured in volt-amperes or kilo-volt amperes (kVA).

The true power in an ac circuit is obtained by multiplying the apparent power by the power factor and is expressed in watts or kilo-watts (kW).

The product of apparent power, VI and the sine of the angle between voltage and current, sin ϕ is called the reactive power. This is also known as wattless power and is expressed in reactive volt-amperes or kilo-volt amperes reactive (kVA R).

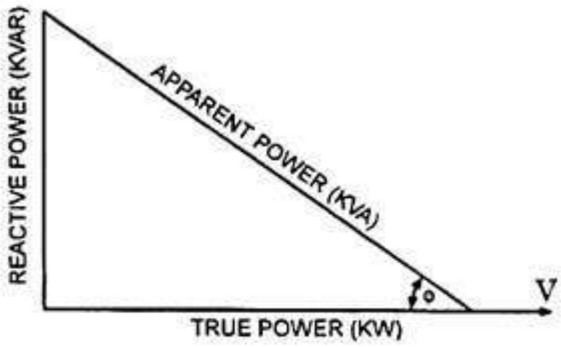
$$i.e.\ \text{Apparent power, } S = VI \text{ volt-amperes or } \frac{V\,I}{1{,}000} \text{ kVA}$$

$$\text{True power, } P = VI \cos\Phi \text{ watts or } \frac{V\,I\cos\Phi}{1{,}000} \text{ kW}$$

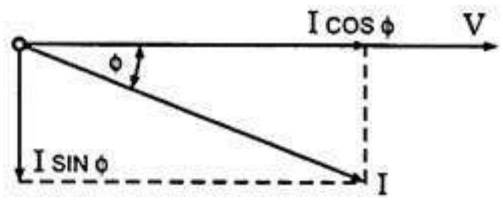
$$\text{Reactive power, } Q = VI \sin\Phi \text{ VAR or } \frac{V\,I\sin\Phi}{1{,}000} \text{ kVAR}$$

$$\text{and kVA} = \sqrt{(\text{kW})^2 + (\text{kVAR})^2}$$

The above relations can easily be followed by referring to the power diagram shown in Fig. 4.7 (a).



(a) Power Triangle



(b)

Fig. 4.7

Power factor may be defined as:
(i) Cosine of the phase angle between voltage and current,
(ii) The ratio of the resistance to impedance, or
(iii) The ratio of true power to apparent power.
The power factor can never be greater than unity. The power factor is expressed either as fraction or as a percentage. It is usual practice to attach the word ‘lagging’ or ‘leading’ with the numerical value of power factor to signify whether the current lags behind or leads the voltage.

CONCEPT OF REACTANCE, IMPEDANCE, SUSCEPTANCE AND ADMITTANCE:

Reactance is essentially inertia against the motion of electrons. It is present anywhere electric or magnetic fields are developed in proportion to applied voltage or current, respectively; but most notably in capacitors and inductors. When alternating current goes through a pure reactance, a voltage drop is produced that is 90^o out of phase with the current. Reactance is mathematically symbolized by the letter “X” and is measured in the unit of ohms (Ω).

Impedance is a comprehensive expression of any and all forms of opposition to electron flow, including both resistance and reactance. It is present in all circuits, and in all components. When alternating current goes through an impedance, a voltage drop is produced that is somewhere between 0^o and 90^o out of phase with the current. Impedance is mathematically symbolized by the letter “Z” and is measured in the unit of ohms (Ω), in complex form

Admittance is also a complex number as impedance which is having a real part, Conductance (G) and imaginary part, Susceptance (B).

$$Y = G + jB$$
$$Y \rightarrow Admittance\ in\ Siemens$$
$$G \rightarrow Conductance\ in\ Siemens = \frac{R}{R^2 + X^2}$$
$$B \rightarrow\ Susceptance\ in\ Siemens = -\frac{X}{R^2 + X^2}$$

(it is negative for capacitive susceptance and positive for inductive susceptance)

$$j^2 = -1$$
$$|Y| = \sqrt{G^2 + B^2} = \frac{1}{\sqrt{R^2 + X^2}}$$
$$\angle Y = arctan\left(\frac{B}{G}\right) = arctan\left(-\frac{X}{R}\right)$$

Susceptance (symbolized *B***)** is an expression of the ease with which alternating current (**AC**) passes through a capacitance or inductance

UNIT-IV
ELECTRICAL MACHINES

Dc Generator

- Principle of Operation
- Constructional Features
- EMF Equation

Dc Motor

- Principle of Operation
- Back EMF
- Torque Equation

Single Phase Transformer

- Principle of Operation
- Constructional Features
- EMF Equation
- Simple Problems

DC GENERATOR

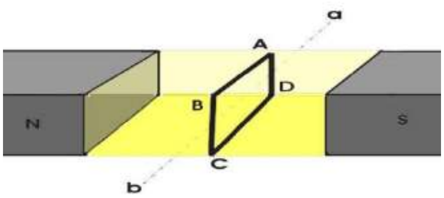
Principle of DC Generator

There are two types of generators, one is ac generator and other is DC generator. Whatever may be the types of generators, it always converts mechanical power to electrical power. An AC generator produces alternating power. A DC generator produces direct power. Both of these generators produce electrical power, based on same fundamental principle of Faraday's law of electromagnetic induction. According to this law, 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 (magnetic line force) linkage with the conductor. This emf will cause a current to flow if the conductor circuit is closed.
Hence the most basic tow essential parts of a generator are

1. a magnetic field
2. conductors which move inside that magnetic field.

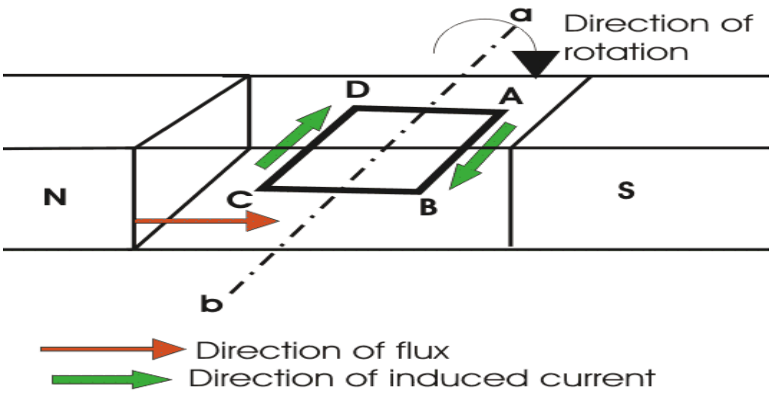
Now we will go through working principle of DC generator. As, the working principle of ac generator is not in scope of our discussion in this section.

Single Loop DC Generator

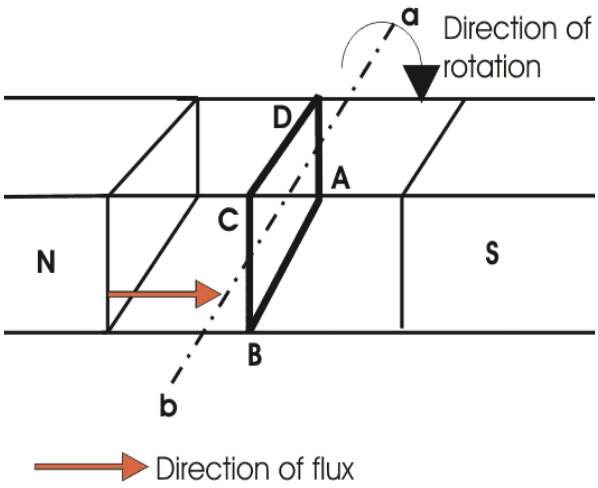


In the figure above, a single loop of conductor of rectangular shape is placed between two opposite poles of magnet.

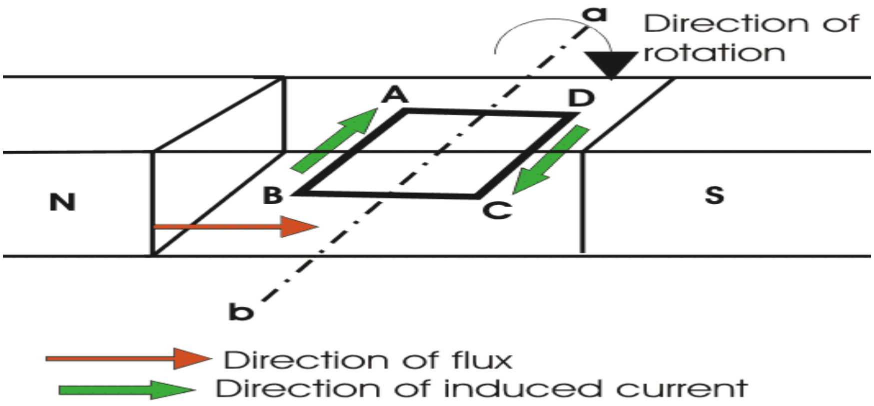
Let's us consider, the rectangular loop of conductor is ABCD which rotates inside the magnetic field about its own axis ab. When the loop rotates from its vertical position to its horizontal position, it cuts the flux lines of the field. As during this movement two sides, i.e. AB and CD of the loop cut the flux lines there will be an emf induced in these both of the sides (AB and BC) of the loop.



As the loop is closed there will be a current circulating through the loop. The direction of the current can be determined by Fleming's right hand Rule. This rule says that if you stretch thumb, index finger and middle finger of your right hand perpendicular to each other, then thumbs indicates the direction of motion of the conductor, index finger indicates the direction of magnetic field i.e. N - pole to S - pole, and middle finger indicates the direction of flow of current through the conductor. Now if we apply this right-hand rule, we will see at this horizontal position of the loop, current will flow from point A to B and on the other side of the loop current will flow from point C to D.



Now if we allow the loop to move further, it will come again to its vertical position, but now upper side of the loop will be CD and lower side will be AB (just opposite of the previous vertical position). At this position the tangential motion of the sides of the loop is parallel to the flux lines of the field. Hence there will be no question of flux cutting and consequently there will be no current in the loop. If the loop rotates further, it comes to again in horizontal position. But now, said AB side of the loop comes in front of N pole and CD comes in front of S pole, i.e. just opposite to the previous horizontal position as shown in the figure beside.

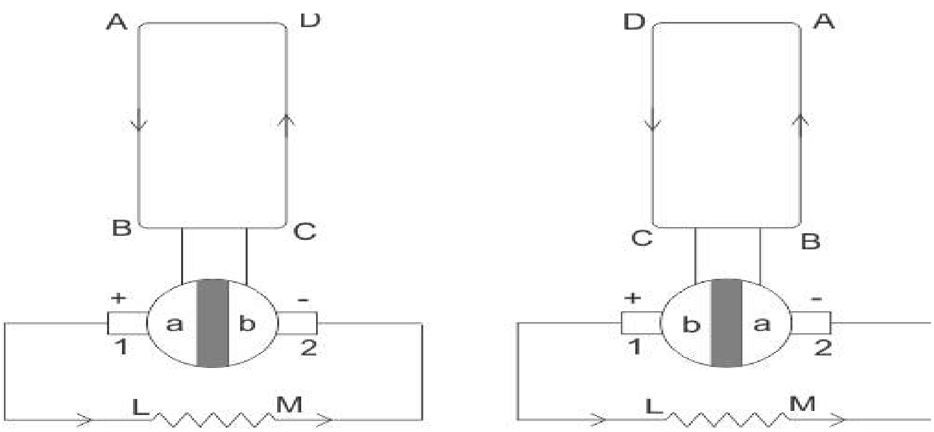


Here the tangential motion of the side of the loop is perpendicular to the flux lines, hence rate of flux cutting is maximum here and according to Fleming's right hand rule, at this position current flows from B to A and on other side from D to C.Now if the loop is continued to rotate about its axis, every time the side AB comes in front of S pole, the current flows from A to B and when it comes in front of N pole, the current flows from B to A. Similarly, every time the side CD comes in front of S pole the current flows from C to D and when it comes in front of N pole the current flows from D to C.

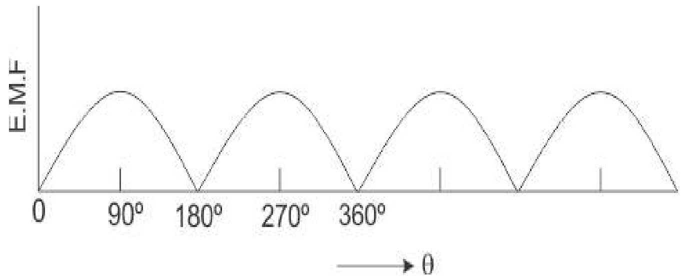
If we observe this phenomena in different way, it can be concluded, that each side of the loop comes in front of N pole, the current will flow through that side in same direction i.e. downward to the reference plane and similarly each side of the loop comes in front of S pole, current through it flows in same direction i.e. upwards from reference plane. From this, we will come to the topic of principle of DC generator.

Now the loop is opened and connected it with a split ring as shown in the figure below. Split ring are made out of a conducting cylinder which cuts into two halves or segments insulated from each other. The external load terminals are connected with two carbon brushes which are rest on these split slip ring segments.

Working Principle of DC Generator



It is seen that in the first half of the revolution current flows always along ABLMCD i.e. brush no 1 in contact with segment a. In the next half revolution, in the figure the direction of the induced current in the coil is reversed. But at the same time the position of the segments a and b are also reversed which results that brush no 1 comes in touch with the segment b. Hence, the current in the load resistance again flows from L to M. The wave from of the current through the load circuit is as shown in the figure. This current is unidirectional.



This is basic working principle of DC generator, explained by single loop generator model. The position of the brushes of DC generator is so arranged that the change over of the segments a and b from one brush to other takes place when the plane of rotating coil is at right angle to the plane of the lines of force. It is so become in that position, the induced emf in the coil is zero.

Construction of DC Generator

During explaining working principle of DC Generator, we have used a single loop DC generator. But now we will discuss about practical construction of DC Generator. A DC generator has the following parts

1. Yoke
2. Pole of generator
3. Field winding
4. Armature of DC generator
5. Brushes of generator and Commentator
6. Bearing

Yoke of DC Generator

Yoke or the outer frame of DC generator serves two purposes,

1. It holds the magnetic pole cores of the generator and acts as cover of the generator.
2. It carries the magnetic field flux.

In small generator, yoke are made of cast iron. Cast iron is cheaper in cost but heavier than steel. But for large construction of DC generator, where weight of the machine is concerned, lighter cast steel or rolled steel is preferable for constructing yoke of DC generator. Normally larger yokes are formed by rounding a rectangular steel slab and the edges are welded together at the bottom. Then feet, terminal box and hangers are welded to the outer periphery of the yoke frame.

Pole Cores and Pole Shoes

Let's first discuss about pole core of DC generator. There are mainly two types of construction available.
One: Solid pole core, where it is made of a solid single piece of cast iron or cast steel.
Two: Laminated pole core, where it made of numbers of thin, limitations of annealed steel which are riveted together. The thickness of the lamination is in the range of 0.04" to 0.01". The pole core is fixed to the inner periphery of the yoke by means of bolts through the yoke and into the pole body. Since the poles project inwards they are called salient poles. The pole shoes are so typically shaped, that, they spread out the magnetic flux in the air gap and reduce the reluctance of the magnetic path. Due to their larger cross-section they hold the pole coil at its position.
Pole Coils: The field coils or pole coils are wound around the pole core. These are a simple coil of insulated copper wire or strip, which placed on the pole which placed between yoke and pole shoes as shown.

Armature Core

The purpose of armature core is to hold the armature winding and provide low reluctance path for the flux through the armature from N pole to S pole. Although a DC generator provides direct current but induced current in the armature is alternating in nature. That is why, cylindrical or drum shaped armature core is build up of circular laminated sheet. In every circular lamination, slots are either die - cut or punched on the outer periphery and the key way is located on the inner periphery as shown. Air ducts are also punched of cut on each lamination for circulation of air through the core for providing better cooling. Up to diameter of 40", the circular stampings are cut out in one piece of lamination sheet. But above 40", diameter, number of suitable sections of a circle is cut. A complete circle of lamination is formed by four or six or even eight such segment.

Armature Winding

Armature winding are generally formed wound. These are first wound in the form of flat rectangular coils and are then pulled into their proper shape in a coil puller. Various conductors of the coils are insulated from each other. The conductors are placed in the armature slots, which are lined with tough insulating material. This slot insulation is folded over above the armature conductors placed in it and secured in place by special hard wooden or fiber wedges. Two types of armature windings are used – Lap winding and Wave winding.

Commutator

The commentator plays a vital role in DC generator. It collects current from armature and sends it to the load as direct current. It actually takes alternating current from armature and converts it to direct current and then send it to external load. It is cylindrical structured and is build up of wedge-shaped segments of high conductivity, hard drawn or drop forged copper. Each segment is insulated from the shaft by means of insulated commutator segment shown below. Each commentator segment is connected with corresponding armature conductor through segment riser or lug.

Brushes

The brushes are made of carbon. These are rectangular block shaped. The only function of these carbon brushes of DC generator is to collect current from commutator segments. The brushes are housed in the rectangular box shaped brush holder or brush box. As shown in figure, the brush face is placed on the commutator segment which is attached to the brush holder.

Bearing

For small machine, ball bearing is used and for heavy duty DC generator, roller bearing is used. The bearing must always be lubricated properly for smooth operation and long life of generator.

Armature winding

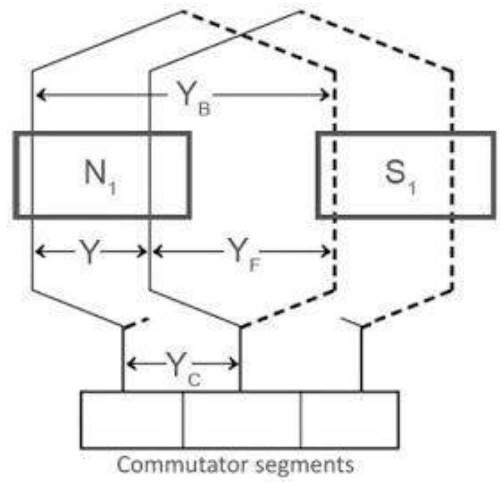
Basically armature winding of a DC machine is wound by one of the two methods, lap winding or wave winding. The difference between these two is merely due to the end connections and commutator connections of the conductor. To know how armature winding is done, it is essential to know the following terminologies -

1. Pole pitch: It is defined as number of armature slots per pole. For example, if there are 36 conductors and 4 poles, then the pole pitch is 36/4=9.
2. Coil span or coil pitch (Ys): It is the distance between the two sides of a coil measured in terms of armature slots.
3. Front pitch (Yf): It is the distance, in terms of armature conductors, between the second conductor of one coil and the first conductor of the next coil. OR it is the distance between two coil sides that are connected to the same commutator segment.
4. Back pitch (Yb): The distance by which a coil advances on the back of the armature is called as back pitch of the coil. It is measured in terms of armature conductors.
5. Resultant pitch (Yr): The distance, in terms of armature conductor, between the beginning of one coil and the beginning of the next coil is called as resultant pitch of the coil.

Armature winding can be done as single layer or double layer. It may be simplex, duplex or multiplex, and this multiplicity increases the number of parallel paths.

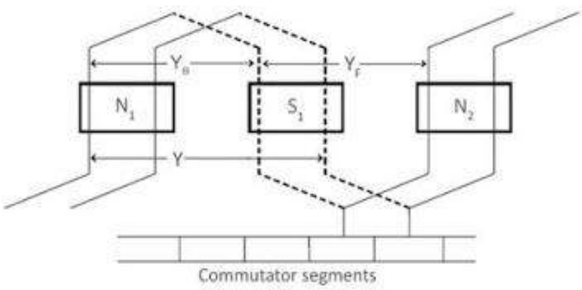
Lap Winding and Wave Winding

In lap winding, the successive coils overlap each other. In a simplex lap winding, the two ends of a coil are connected to adjacent commutator segments. The winding may be progressive or retrogressive. A progressive winding progresses in the direction in which the coil is wound. The opposite way is retrogressive. The following image shows progressive simplex lap winding.



Lap Winding

In wave winding, a conductor under one pole is connected at the back to a conductor which occupies an almost corresponding position under the next pole which is of opposite polarity. In other words, all the coils which carry e.m.f in the same direction are connected in series. The following diagram shows a part of simplex wave winding.



Wave winding

Basis For Comparison	Lap Winding	Wave Winding
Definition	The coil is lap back to the succeeding coil.	The coil of the winding form the wave shape.
Connection	The end of the armature coil is connected to an adjacent segment on the commutators.	The end of the armature coil is connected to commutator segments some distance apart.
Parallel Path	The numbers of parallel path are equal to the total of number poles.	The number of parallel paths is equal to two.
Other Name	Parallel Winding or Multiple Winding	Two-circuit or Series Winding.
EMF	Less	More
Number of Brushes	Equal to the number of parallel paths.	Two
Types	Simplex and Duplex lap winding.	Progressive and Retrogressive wave winding
Efficiency	Less	High
Additional Coil	Equalizer Ring	Dummy coil
Winding Cost	High (because more conductor is required)	Low
Uses	In low voltage, high current machines.	In high voltage, low current machines.

EMF Equation of a DC Generator

Consider a DC generator with the following parameters,

P = number of field poles

Ø = flux produced per pole in Wb (weber)

Z = total no. of armature conductors

A = no. of parallel paths in armature

N = rotational speed of armature in revolutions per min. (rpm)

Now,

- Average emf generated per conductor is given by $d\Phi/dt$ (Volts) ... eq. 1
- Flux cut by one conductor in one revolution = $d\Phi = P\Phi$ ….(Weber),
- Number of revolutions per second (speed in RPS) = $N/60$
- Therefore, time for one revolution = $dt = 60/N$ (Seconds)
- From eq. 1, emf generated per conductor = $d\Phi/dt = P\Phi N/60$ (Volts) …..(eq. 2)

Above equation-2 gives the emf generated in one conductor of the generator. The conductors are connected in series per parallel path, and the emf across the generator terminals is equal to the generated emf across any parallel path.

Therefore, $E_g = P\Phi NZ / 60A$

For simplex lap winding, number of parallel paths is equal to the number of poles (i.e. A=P),

Therefore, for simplex lap wound dc generator, $E_g = P\Phi NZ / 60P$

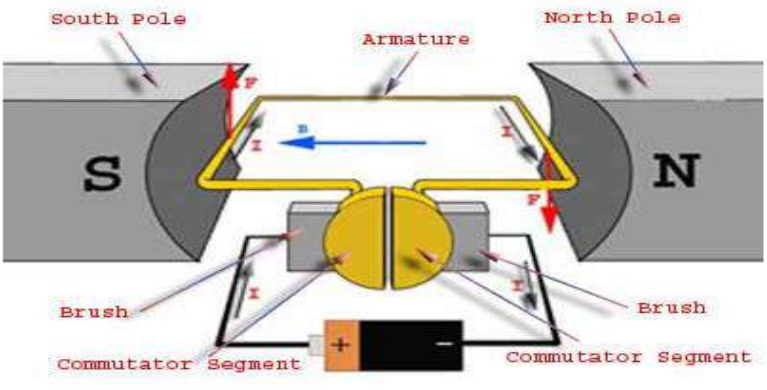
For simplex wave winding, number of parallel paths is equal to 2 (i.e P=2),

Therefore, for simplex wave wound dc generator, $E_g = P\Phi NZ / 120$

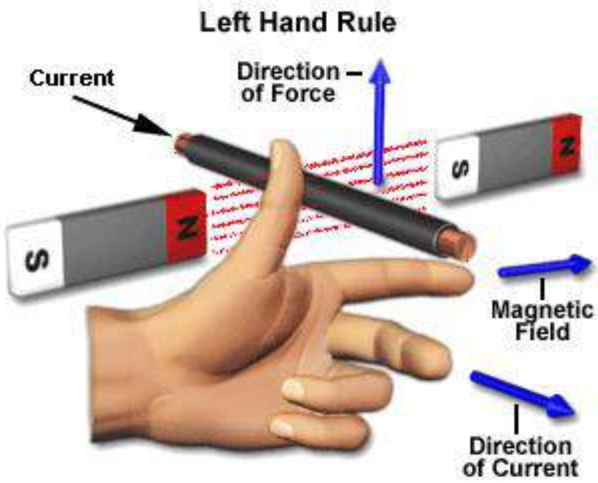
DC MOTOR

Working or Operating Principle of DC Motor

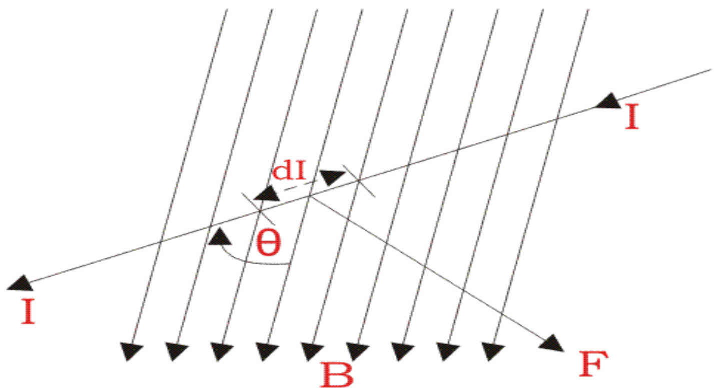
A DC motor in simple words is a device that converts electrical energy (direct current system) into mechanical energy. It is of vital importance for the industry today, and is equally important for engineers to look into the working principle of DC motor in details that has been discussed in this article. In order to understand the operating principle of DC motor we need to first look into its constructional feature. The very basic construction of a DC motor contains a current carrying armature which is connected to the supply end through commutator segments and brushes. The armature is placed in between north south poles of a permanent or an electromagnet as shown in the diagram above.



As soon as we supply direct current in the armature, a mechanical force acts on it due to electromagnetic effect of the magnet. Now to go into the details of the operating principle of DC motor its important that we have a clear understanding of Fleming's left hand rule to determine the direction of force acting on the armature conductors of DC motor.



If a current carrying conductor is placed in a magnetic field perpendicularly, then the conductor experiences a force in the direction mutually perpendicular to both the direction of field and the current carrying conductor. Fleming's left hand rule says that if we extend the index finger, middle finger and thumb of our left hand perpendicular to each other, in such a way that the middle finger is along the direction of current in the conductor, and index finger is along the direction of magnetic field i.e. north to south pole, then thumb indicates the direction of created mechanical force. For clear understanding the principle of DC motor we have to determine the magnitude of the force, by considering the diagram below.



We know that when an infinitely small charge dq is made to flow at a velocity 'v' under the influence of an electric field E, and a magnetic field B, then the Lorentz Force dF experienced by the charge is given by:-

$$dF = dq(E + vB)$$

For the **operation of DC motor**, considering E = 0

$$dF = dq \times v \times B$$

i.e. it's the cross product of dq v and magnetic field B.

$$dF = dq\frac{dL}{dt} \times B \qquad \left[V = \frac{dL}{dt}\right]$$

Where, dL is the length of the conductor carrying charge q.

$$dF = dq\frac{dL}{dt} \times B$$

$$or,\ dF = IdL \times B \qquad \left[Since,\ current\ I = \frac{dq}{dt}\right]$$

$$or,\ F = IL \times B = ILB\sin\theta$$

$$or,\ F = BIL\sin\theta$$

From the 1st diagram we can see that the construction of a DC motor is such that the direction of current through the armature conductor at all instance is perpendicular to the field. Hence the force acts on the armature conductor in the direction perpendicular to the both uniform field and current is constant.

$$i.e.\ \theta = 90^\circ$$

So if we take the current in the left hand side of the armature conductor to be I, and current at right hand side of the armature conductor to be -I, because they are flowing in the opposite direction with respect to each other.

Then the force on the left hand side armature conductor,

$$F_i = BIL\sin 90^\circ = BIL$$

Similarly force on the right hand side conductor

$$F_r = B(-I)L\sin 90^\circ = -BIL$$

Therefore, we can see that at that position the force on either side is equal in magnitude but opposite in direction. And since the two conductors are separated by some distance w = width of the armature turn, the two opposite forces produces a rotational force or a torque that results in the rotation of the armature conductor.

Now let's examine the expression of torque when the armature turn crate an angle of α (alpha) with its initial position.

The torque produced is given by,

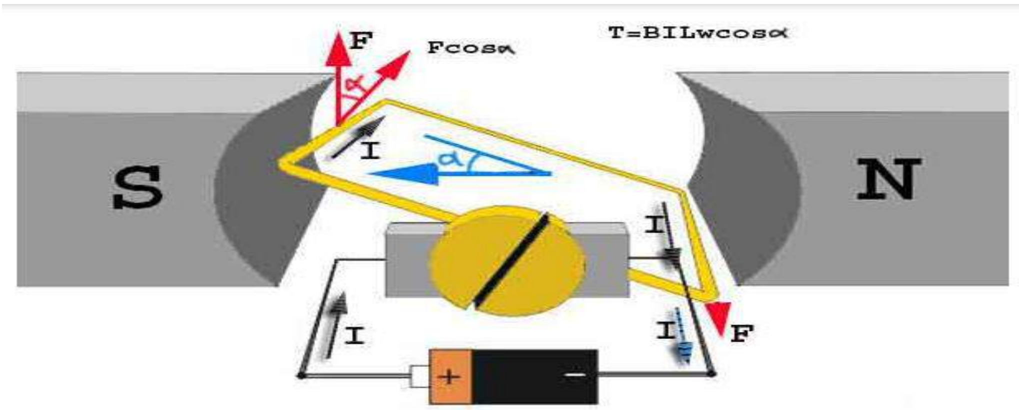
$$Torque = (force,\ tangential\ to\ the\ direction\ of\ armature\ rotation) \times (distance)$$

$$or,\ \tau = F\cos\alpha \times w$$

$$or,\ \tau = BILw\cos\alpha$$

Where, α (alpha) is the angle between the plane of the armature turn and the plane of reference or the initial position of the armature which is here along the direction of magnetic field.

The presence of the term cosα in the torque equation very well signifies that unlike force the torque at all position is not the same. It in fact varies with the variation of the angle α (alpha). To explain the variation of torque and the principle behind rotation of the motor let us do a step wise analysis.

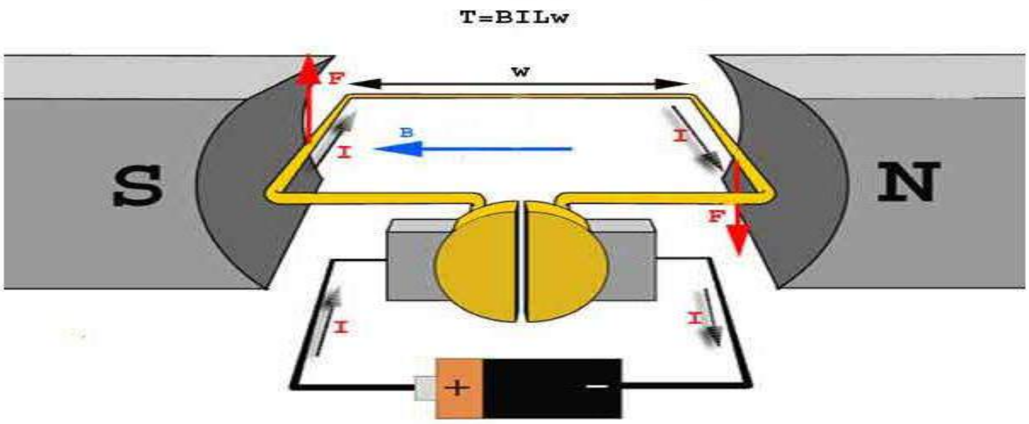


Step 1:

Initially considering the armature is in its starting point or reference position where the angle α = 0.

$$\therefore\ \tau = BILw \times \cos 0^\circ = BILw$$

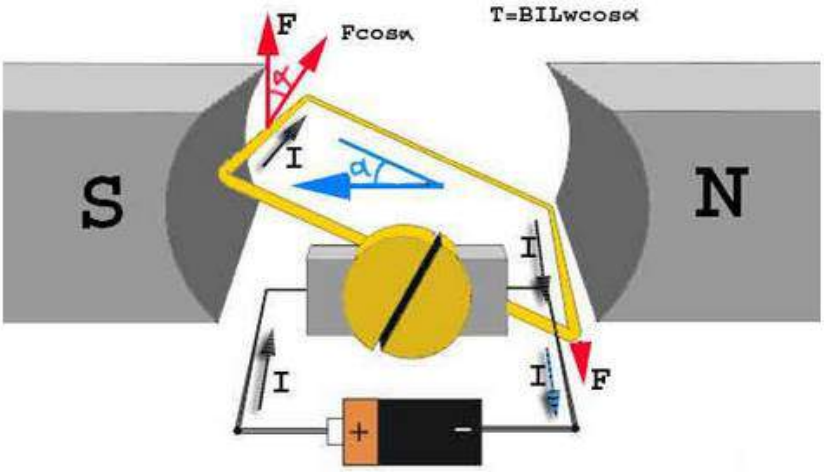
Since, α = 0, the term cos α = 1, or the maximum value, hence torque at this position is maximum given by τ = BILw. This high starting torque helps in overcoming the initial inertia of rest of the armature and sets it into rotation.



Step 2:

Once the armature is set in motion, the angle α between the actual position of the armature and its reference initial position goes on increasing in the path of its rotation until it becomes 90° from its initial position. Consequently the term cosα decreases and also the value of torque.

The torque in this case is given by τ = BILwcosα which is less than BIL w when α is greater than 0°.

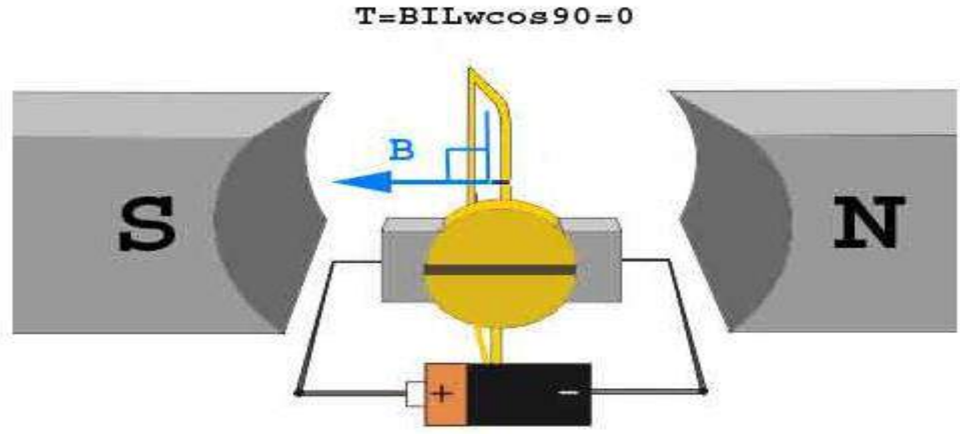


Step 3:

In the path of the rotation of the armature a point is reached where the actual position of the rotor is exactly perpendicular to its initial position, i.e. α = 90°, and as a result the term cosα = 0.

The torque acting on the conductor at this position is given by,

$$\therefore \tau = BIL\omega \times \cos 90^o = 0$$



i.e. virtually no rotating torque acts on the armature at this instance. But still the armature does not come to a standstill, this is because of the fact that the operation of DC motor has been engineered in such a way that the inertia of motion at this point is just enough to overcome this point of null torque. Once the rotor crosses over this position the angle between the actual position of the armature and the initial plane again decreases and torque starts acting on it again.

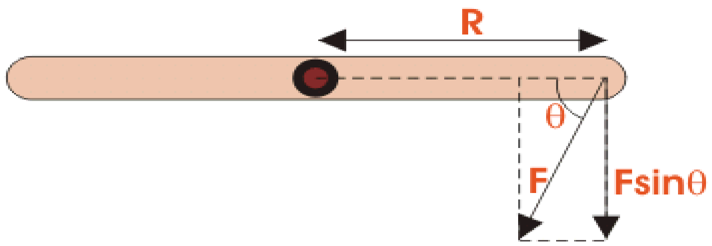
Torque Equation of DC Motor

When a DC machine is loaded either as a motor or as a generator, the rotor conductors carry current. These conductors lie in the magnetic field of the air gap. Thus each conductor experiences a force. The conductors lie near the surface of the rotor at a common radius from its center. Hence torque is produced at the circumference of the rotor and rotor starts rotating. The term torque as best explained by Dr. Huge d Young is the quantitative measure of the tendency of a force to cause a rotational motion, or to bring about a change in rotational motion. It is in fact the moment of a force that produces or changes a rotational motion.

The equation of torque is given by,

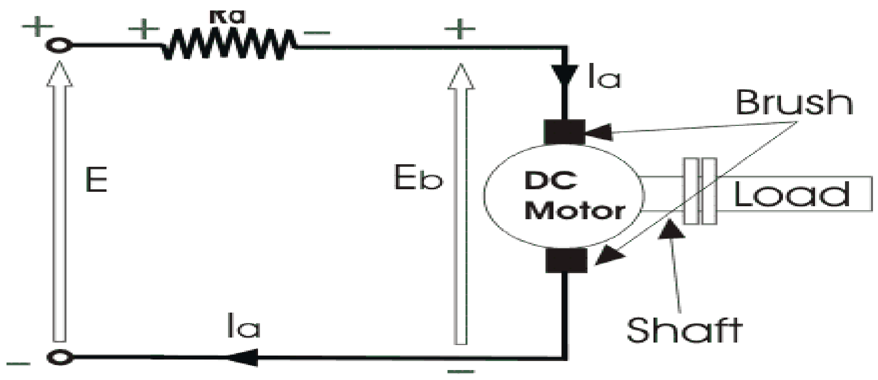
$$\tau = FR\sin\theta ....(1)$$

Where, F is force in linear direction.
R is radius of the object being rotated,
and θ is the angle, the force F is making with R vector



The DC motor as we all know is a rotational machine, and torque of DC motor is a very important parameter in this concern, and it's of utmost importance to understand the torque equation of DC motor for establishing its running characteristics.

To establish the torque equation, let us first consider the basic circuit diagram of a DC motor, and its voltage equation.



Referring to the diagram beside, we can see, that if E is the supply voltage, E_b is the back emf produced and I_a, R_a are the armature current and armature resistance respectively then the voltage equation is given by,

$$E = E_b + I_a R_a \;..................\; (2)$$

But keeping in mind that our purpose is to derive the torque equation of DC motor we multiply both sides of equation (2) by I_a.

$$Therefore,\; EI_a = E_b I_a + I_a^2 R_a \;..................\; (3)$$

Now $I_a^2.R_a$ is the power loss due to heating of the armature coil, and the true effective mechanical power that is required to produce the desired torque of DC machine is given by,

$P_m = E_b I_a$ .... (4)

The mechanical power P_m is related to the electromagnetic torque T_g as,

$P_m = T_g \omega$ .... (5)

Where ω is speed in rad/sec.

Now equating equation (4) and (5) we get,

$$E_b I_a = T_g \omega$$

Now for simplifying the torque equation of DC motor we substitute.

$$E_b = \frac{P\varphi ZN}{60A} \text{ .... } (6)$$

Where, P is no of poles,

φ is flux per pole,

Z is no. of conductors,

A is no. of parallel paths,

and N is the speed of the DC motor.

$$Hence,\ w = \frac{2\pi N}{60} \text{ .... } (7)$$

Substituting equation (6) and (7) in equation (4), we get:

$$T_g = \frac{P.Z.\varphi.I_a}{2\pi A}$$

The torque we so obtain, is known as the electromagnetic torque of DC motor, and subtracting the mechanical and rotational losses from it we get the mechanical torque. Therefore,

$$T_m = T_g - mechanical\ losses$$

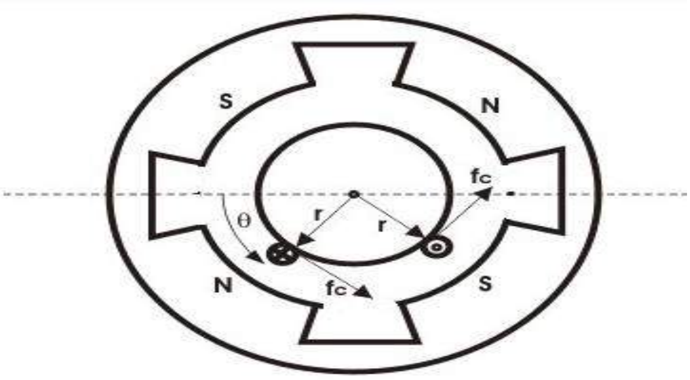
\This is the torque equation of DC motor. It can be further simplified as:

$$T_g = k_a \phi I_A$$

$$Where,\ k_a = \frac{P.Z}{2\pi A}$$

Which is constant for a particular machine and therefore the torque of DC motor varies with only flux φ and armature current I_a.

The Torque equation of a DC motor can also be explained considering the figure below.



$$Here\ we\ can\ see\ Area\ per\ pole\ A_r = \frac{2\pi.r.L}{P}$$

$$B = \frac{\varphi}{A_r}$$

$$Here\ we\ can\ see\ Area\ per\ pole\ A_r = \frac{2\pi.r.L}{P}$$

$$B = \frac{\varphi}{A_r}$$

$$B = \frac{P.\varphi}{2\pi r L}$$

Current/conductor $I_C = I_a$ A

Therefore, force per conductor = $f_C = BLI_a/A$

Now torque $T_C = f_C.\ r = BLI_a.r/A$

$$\therefore\ T_c = \frac{\varphi P.I_a}{2\pi A}$$

Hence, the total torque developed of a DC machine is,

$$T_g = \frac{P.Z.\varphi.I_a}{2\pi.A}$$

This torque equation of DC motor can be further simplified as:

$$T_g = k_a \phi I_a$$

$$Where,\ k_a = \frac{P.Z}{2\pi.A}$$

Which is constant for a particular machine and therefore the torque of DC motor varies with only flux φ and armature current I_a.

TRANSFORMER

Introduction

The transformer is a device that transfers electrical energy from one electrical circuit to another electrical circuit. The two circuits may be operating at different voltage levels but always work at the same frequency. Basically transformer is an electro-magnetic energy conversion device. It is commonly used in electrical power system and distribution systems. It can change the magnitude of alternating voltage or current from one value to another. This useful property of transformer is mainly responsible for the widespread use of alternating currents rather than direct currents i.e., electric power is generated, transmitted and distributed in the form of alternating current. Transformers have no moving parts, rugged and durable in construction, thus requiring very little attention. They also have a very high efficiency as high as 99%.

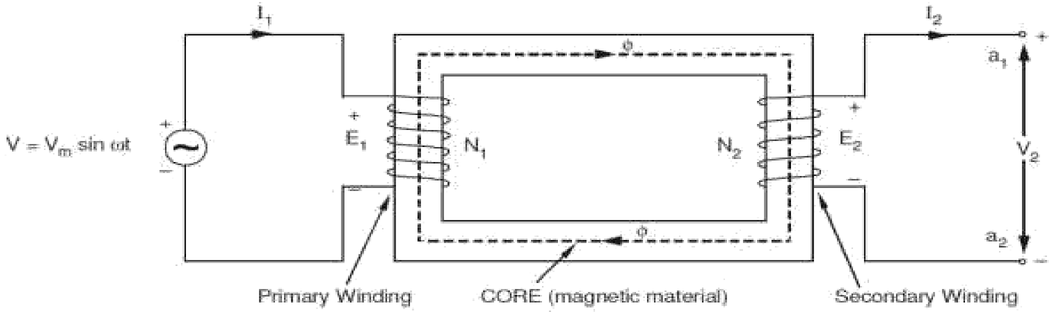
Single Phase Transformer

A transformer is a static device of equipment used either for raising or lowering the voltage of an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig 1. The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary). The alternating voltage V1 whose magnitude is to be changed is applied to the primary.

Depending upon the number of turns of the primary (N1) and secondary (N2), an alternating e.m.f. E2 is induced in the secondary. This induced e.m.f. E2 in the secondary causes a secondary current I2. Consequently, terminal voltage V2 will appear across the load.

If V2 > V1, it is called a step up-transformer.

If V2 < V1, it is called a step-down transformer.



Constructional Details

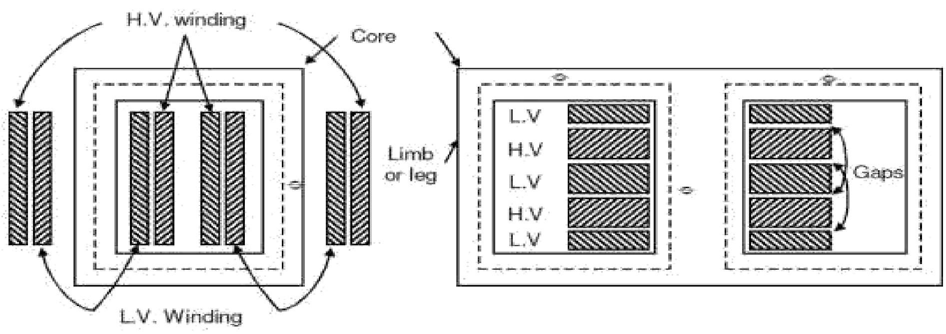
Depending upon the manner in which the primary and secondary windings are placed on the core, and the shape of the core, there are two types of transformers, called

(a) Core type

(b) Shell type.

Core-type and Shell-type Construction

In core type transformers, the windings are placed in the form of concentric cylindrical coils placed around the vertical limbs of the core. The low-voltage (LV) as well as the high- voltage (HV) winding are made in two halves, and placed on the two limbs of core. The LV winding is placed next to the core for economy in insulation cost. Figure 2.1(a) shows the cross- section of the arrangement. In the shell type transformer, the primary and secondary windings are wound over the central limb of a three-limb core as shown in Figure 2.1(b). The HV and LV windings are split into a number of sections, and the sections are interleaved or sandwiched i.e. the sections of the HV and LV windings are placed alternately.



(a) Core Type (b) Shell Type

Core

The core is built-up of thin steel laminations insulated from each other. This helps in reducing the eddy current losses in the core, and also helps in construction of the transformer. The steel used for core is of high silicon content, sometimes heat treated to produce a high permeability and low hysteresis loss. The material commonly used for core is CRGO (Cold Rolled Grain Oriented) steel. Conductor material used for windings is mostly copper. However, for small distribution transformer aluminum is also sometimes used. The conductors, core and whole windings are insulated using various insulating materials depending upon the voltage.

Insulating Oil

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

The transformer oil should possess the following qualities:

(a)High dielectric strength,

(b)Low viscosity and high purity,

(c)High flash point, and

(d)Free from sludge.

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

Tank and Conservator

The transformer tank contains core wound with windings and the insulating oil. In large transformers small expansion tank is also connected with main tank is known as conservator. Conservator provides space when insulating oil expands due to heating. The transformer tank is provided with tubes on the outside, to permits circulation of oil, which aides in cooling. Some additional devices like breather and Buchholz relay are connected with main tank. Buchholz relay is placed between main tank and conservator. It protect the transformer under extreme heating of transformer winding. Breather protects the insulating oil from moisture when the cool transformer sucks air inside. The silica gel filled breather absorbs moisture when air enters the tank. Some other necessary parts are connected with main tank like, Bushings, Cable Boxes, Temperature gauge, Oil gauge, Tapings, etc.

Principle of Operation

When an alternating voltage V1 is applied to the primary, an alternating flux ϕ is set up in the core. This alternating flux links both the windings and induces e.m.f.s E1 and E2 in them according to Faraday's laws of electromagnetic induction. The e.m.f. E1 is termed as primary e.m.f. and E2 is termed as secondary e.m.f.

Clearly, $E_1 = -N_1 \frac{d\phi}{dt}$

and $E_2 = -N_2 \frac{d\phi}{dt}$

$\therefore \frac{E_2}{E_1} = \frac{N_2}{N_1}$

Note that magnitudes of E2 and E1 depend upon the number of turns on the secondary and primary respectively.

If N2 > N1, then E2 > E1 (or V2 > V1) and we get a step-up transformer.

If N2 < N1, then E2 < E1(or V2< V1) and we get a step-down transformer.

If load is connected across the secondary winding, the secondary e.m.f. E2 will cause a current I2 to flow through the load. Thus, a transformer enables us to transfer a.c. power from one circuit to another with a change in voltage level.

The following points may be noted carefully

(a)The transformer action is based on the laws of electromagnetic induction.

(b)There is no electrical connection between the primary and secondary.

(c)The a.c. power is transferred from primary to secondary through magnetic flux.

(d)There is no change in frequency i.e., output power has the same frequency as the input power.

(e)The losses that occur in a transformer are:

(a)core losses—eddy current and hysteresis losses

(b) copper losses—in the resistance of the windings

In practice, these losses are very small so that output power is nearly equal to the input primary power. In other words, a transformer has very high efficiency

E.M.F. Equation of a Transformer

Consider that an alternating voltage V1 of frequency f is applied to the primary as shown in Fig.2.3. The sinusoidal flux ϕ produced by the primary can be represented as:

$$\phi=\phi m \sin\omega t$$

When the primary winding is excited by an alternating voltage V1, it is circulating alternating current, producing an alternating flux ϕ.

ϕ - Flux

ϕm - maximum value of flux ,

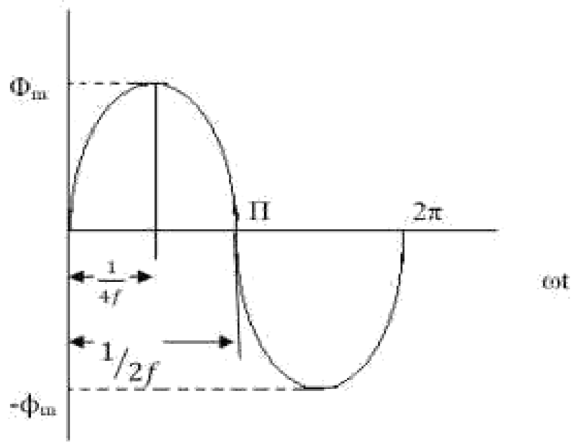
N1 - Number of primary turns ,

N2 - Number of secondary turns

f - Frequency of the supply voltage

E1 - R.M.S. value of the primary induced e.m.f ,E2 - R.M.S. value of the secondary induced e.m.f

The instantaneous e.m.f. e1 induced in the primary is –



The flux increases from zero value to maximum value ϕm in 1/4f of the time period that is in 1/4f seconds.

The change of flux that takes place in 1/4f seconds = ϕm - 0 = ϕm webers

Voltage Ratio

$$\frac{d\phi}{dt} = \frac{dt}{1/4f} = 4f\phi_m \text{ w}_b/\text{sec.}$$

Since flux ϕ varies sinusoidally, the R.m.s value of the induced e.m.f is obtained by multiplying the average value with the form factor

$$\text{Form factor of a sinwave} = \frac{\text{R.m.s value}}{\text{Average value}} = 1.11$$

R.M.S Value of e.m.f induced in one turns = $4\phi_m f \times 1.11$ Volts.

= $4.44\phi_m f$ Volts.

R.M.S Value of e.m.f induced in primary winding = $4.44\phi_m f$ N1Volts.

R.M.S Value of e.m.f induced in secondary winding = $4.44\phi_m f$ N2Volts.

The expression of E_1 and E_2 are called e.m.f equation of a transformer

$V_1 = E_1 = 4.44\phi_m f N_1$ Volts.
$V_2 = E_2 = 4.44\phi_m f N_2$ Volts.

$$\frac{E2}{E1} = \frac{4.44\phi mf\,N2}{4.44\phi mf\,N1}$$

$$\boxed{\frac{E2}{E1} = \frac{N2}{N1} = K}$$

Voltage transformation ratio is the ratio of e.m.f induced in the secondary winding to the e.m.f induced in the primary winding.

This ratio of secondary induced e.m.f to primary induced e.m.f is known as voltage transformation ratio

1. If N2>N1 i.e. K>1 we get E2>E1 then the transformer is called step up transformer.
2. If N2< N1 i.e. K<1 we get E2< E2 then the transformer is called step down transformer.
3. If N2= N1 i.e. K=1 we get E2= E2 then the transformer is called isolation transformer or 1:1 Transformer.

$$E_2 = KE_1 \qquad \text{where } K = \frac{N2}{N1}$$

Current Ratio

Current ratio is the ratio of current flow through the primary winding (I1) to the current flowing through the secondary winding (I2). In an ideal transformer -

Apparent input power = Apparent output power.

V1I1 = V2I2

$$\frac{I1}{I2} = \frac{V2}{V1} = \frac{N2}{N1} = K$$

Volt-Ampere Rating

i)The transformer rating is specified as the products of voltage and current (VA rating).

ii)On both sides, primary and secondary VA rating remains same. This rating is generally expressed in KVA (Kilo Volts Amperes rating)

$$\frac{V1}{V2} = \frac{I2}{I1} = K$$

$$V_1I_1 = V_2I_2$$

$$\text{KVA Rating of a transformer} = \frac{V1I1}{1000} = \frac{V2I2}{1000} \quad \text{(1000 is to convert KVA to VA)}$$

V_1 and V_2 are the V_t of primary and secondary by using KVA rating we can calculate I_1 and I_2 Full load current and it is safe maximum current.

$$I_1 \text{ Full load current} = \frac{KVA\ Rating\ X\ 1000}{V1}$$

$$I_1 \text{ Full load current} = \frac{KVA\ Rating\ X\ 1000}{V2}$$

UNIT –V

ELECTRICAL INSTALLATIONS

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

Wire and cable:

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

Difference Between Wire and Cable:

According to Bureau of Indian Standards (BIS), wire and cable can be defined as follows:

Bare Conductors: They have no covering. The best example is overhead transmission and distribution lines.

Wire: If bare conductors are provided with Insulation, then it is known as a wire. The insulation separates the conductor electrically from other conductors.

Cable: It consists of two or more conductors covered with suitable insulation and surrounded by a protecting cover. The necessary requirements of a cable are that it should conduct electricity efficiently, cheaply, and safely. This should neither be so small that it has a large internal voltage drop nor be too large so that it costs too much. Its insulation should be such that it prevents leakage of current in unwanted direction to minimize risk of fire and shock.

The cable essentially consists of three parts :

(i) Conductor or core- the metal wire, or strand of wires, carrying the current

(II) insulation of dielectric- a covering of insulating material to avoid leakage of current from the conductor and

(iii) protective covering for protection of insulation from mechanical damage

Basically, there is no difference between a cable and a wire. It is a relative term. The term cable is used for all heavy section insulated conductors, whereas a wire means a thin (i.e., smaller) section insulated conductor used for carrying current from one point to another point.

Classifications of Wire / Cables:

The wires/ cables used for domestic or industrial wiring are classified into different groups as follows :

(i) According to the conductor material used

(a) Copper conductor cables

(b) Aluminum conductor cable

(ii) According to number of cores

(a) Singles core cable (SCC)

(b) Double core or twin core cables (DCC)

(c) Three core cables

(d) four core cables

(e) Two core with earth continuity conductor cables

(iii) According to type of insulation

(a) Vulcanized Indian rubber (VIR) insulated wires/cables

(b) Tough rubber sheathed (TRS) or cable tyre sheathed (CTS) cables

(c) Polyvinyl chloride (PVC) cables

(b) Lead sheathed cables

(e) Weather proof cables

(f) Flexible cords and cables

(g) XLPE cables

(IV) According to the voltage at which they are manufactured

(a) Low tension (LT) cables – up to 1000V

(b) High tension (HT) cables – up to 11kV

(c) Super tension (ST) cables – from 22-33kV

(d) Extra high tension (EHT) cables – from 33-66kV

(e) Extra super voltage cables – beyond 132 kV

Specifications of Cables:

Cables are specified by providing

(i) Size of the cable in metric system (e.g., 19/2.24, 7/1.70, 7/2.24, 7/2.50 etc) giving the Number of strands used and diameter of each strand, or giving the area of cross- section of conductor used.

(ii) Type of conductor used in cables (copper or aluminium)

(iii) Number of cores that cable consists of e.g. single core, twin core, three core, four core etc.

(iv) Voltage grade (240/415V or 650/1100V grade)

(v) Type of cable with clear description regarding insulation, shielding, armouring, bedding etc.

A few specifications of a cable are given below:

(i) 7/20, VIR, aluminum conductor, twin core,650/1100 grade.

in this case, the numerator 7 indicates the number of stands in cable and denominator 20 represents the gauge number of each strand. The cable has two cores made with Aluminum, With VIR insulation and is used for 650/1100 voltage

(ii) 19/1.12, aluminium conductor,3 ½ core, 1100V, PVC cable, PVC sheathed.

in this case, the cable consists of 19 strands, each strand has a diameter of 1.12mm. The conductor is made with aluminium, insulation is made with PVC, is covered with PVC sheathing, and is used for 1100Vsupply system.

Earthing of Grounding:

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

The earth resistance is affected by the following factors :

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

(b) Temperature and moisture content of the soil

(c) Depth of the pit

(d) Quantity of the charcoal used

Necessity of Earthing:

The requirement for provision of earthing can be listed as follows :

(1) To protect the operating personnel from the danger of shock.

(2) To maintain the line voltage constant, under unbalanced load condition.

(3) To avoid risk of fire due to earth leakage current through unwanted path.

(4) Protection of the equipments.

(5) Protection of large buildings and all machines fed from overhead lines against lighting.

Methods of Earthing:

The various methods of earthing in common use are

(i) Plate earthing

(ii) Pipe earthing

(iii) Rod earthing

*(*iv) Strip or wire earthing

(i) Plate earthing:

In this method either a copper plate of 60cm × 60cm ×3.18 or GI plate of 60cm × 60cm × 6.35 is used for earthing. The plate is buried into the ground not less than 3m from the ground level. The earth plate is embedded in alternate layers of coal and salt for a thickness of 15cm as shown in figure (12.4). In addition, water is poured for keeping the earth's electrode resistance value below a maximum of 5Ω. The earth wire is securely bolted to the earth plate.

A cement masonry chamber is built with a cast iron cover for easy regular maintenance

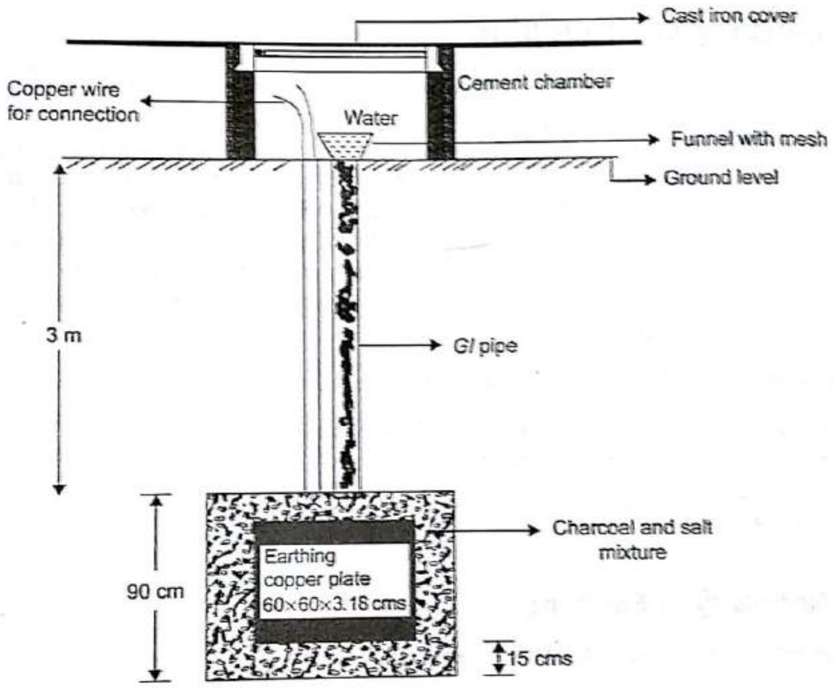


Figure (12.4): *Plate earthing*

(ii) Pipe earthing:

Earth electrode made of a GI (galvanized iron) pipe of 38mm in diameter and length of 2m (depending on the current) with 12mm holes on the surface is placed upright at a depth of 4.75cm in a permanently wet ground. To keep the value of the earth resistance at the desired level, the area (15 cm) surrounding the GI pipe is filled with a mixture of salt and coal. The efficiency of the earthing system is improved by pouring water through the funnel periodically. The GI earth wires of sufficient cross-sectional area are run through a 12.7mm diameter pipe (at 60cm below) from the 19mm diameter pipe and secured tightly at the top as shown in

figure (12.5).

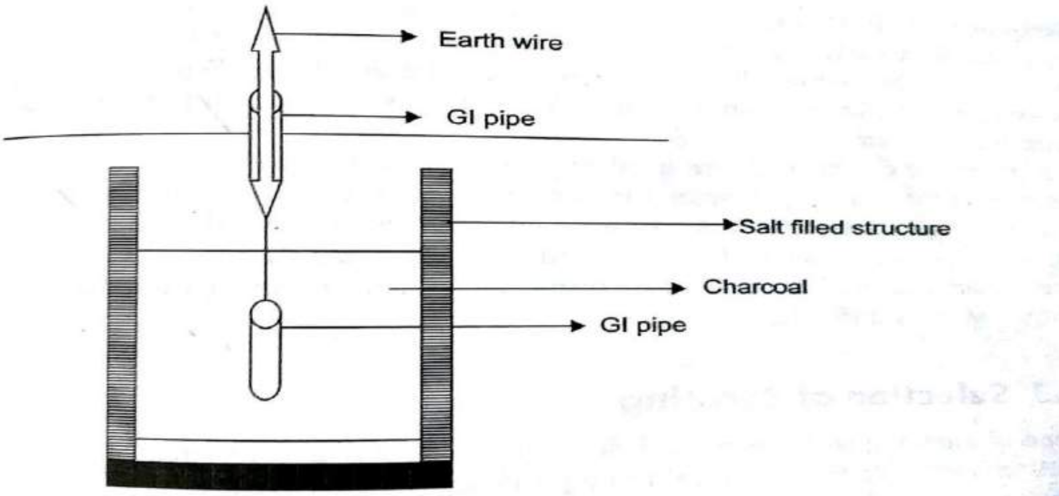


Figure (12.5): *Pipe earthing*

When compared to the plate earth system the pipe earth system can carry larger leakage currents due to larger surface area is in contact with the soil for given electrode size. This system also enables easy maintenance as the earth wire connection is housed at the ground levels.

(iii) Rod earthing:

It is the same method as pipe earthing, A copper rod of 12.5cm (1/2 inch) diameter or 16mm (0.6in) diameter of galvanized steel or hollow section 25mm (1 inch) of GI pipe of length above 2.5m (8.2 ft) are buried upright in the earth manually or with the help of a pneumatic hammer. The length of embedded electrodes in the soil reduces earth resistance to a desired value.

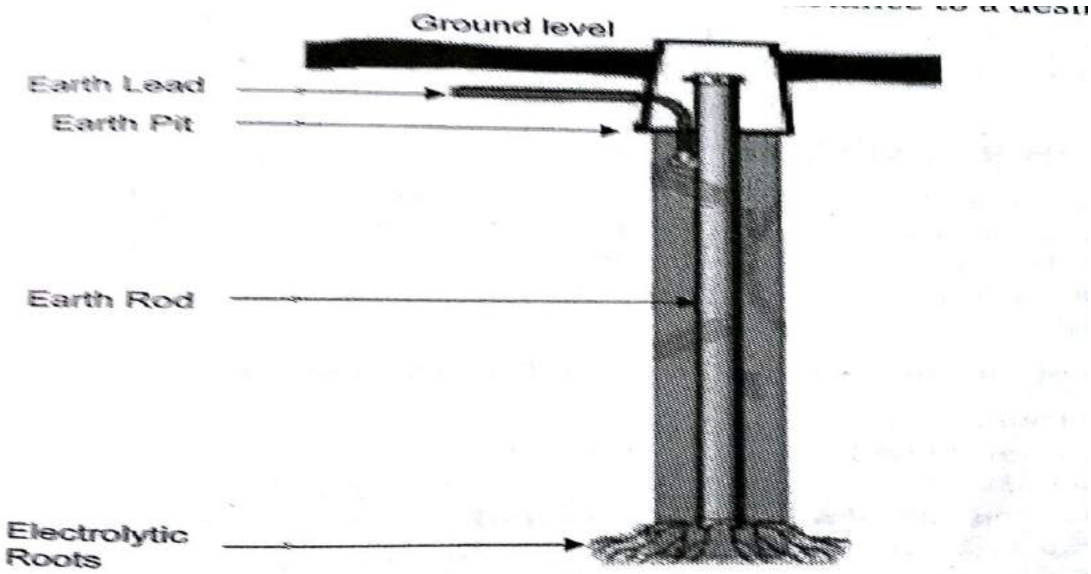


Figure (12.6): *Rod earthing*

(iv) Strip or wire earthing:

In this method of earthing strip electrodes of cross- section not less than 25mm × 1.6mm (1 in × 0.06in) is buried in a horizontal trench of a minimum depth of 0.5m. If copper with a cross-section of 25mm × 4mm (1in × 0.15in) is used and a dimension of 3.0 mm^2 if it's a galvanized iron or steel.

If at all round conductors are used, their cross-section area should not be too small, say less than 6.0 mm^2 if it's a galvanized iron or steel. The length of the conductor buried in the ground would give a sufficient earth resistance and this length should not be less than 15m. The electrodes shall be as widely distributed as possible in a single straight or circular trench radiating from a point. This type of earthing is used where the earth bed has a rocky soil and excavation work is difficult.

Selection of Earthing:

The type of earthing to be provided depends on many factors such as type of soil, type of installation, etc.. The following table helps in selecting a type of earthing for a particular application

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

Earth Resistance:

The earth resistance should be kept as low as possible so that the neutral of any electrical system, which is earthed, is maintained almost at the earth potential. The earth resistance for copper wire is 1Ω and that of GI wire less than 3Ω. The typical value of the earth resistance at large power stations is 0.5Ω , major sub-stations is 1Ω, small sub-stations is 2 Ω and in all other cases 5 Ω.

The resistance of the earth depends on the following factors

Condition of soil.

ii. Moisture content of soil.

iii. Temperature of soil.

iv. Depth of electrode at which it is embedded.

v. Size, material and spacing of earth electrode.

vi. Quality and quantity of coal and salt in the earth pit.

Difference Between Earth Wire and Neutral Wire:

Neutral Wire :

(i) In a 3-phase 4-wire system, the fourth wire is a neutral wire.

(ii) IT acts a return path for 3-phase currents when the load is not balanced.

(iii) IN domestic single phase AC circuit, the neutral wire acts as return path for the line current.

Earth Wire :

(i) Earth wire is actually connected to the general mass of the earth and metallic body of the equipment

(ii) It is provided to transfer any leakage current from the metallic body to the earth.

Fuse:

The electrical equipment are designed to carry a particular rated value of current under normal conditions. Under abnormal conditions such as short circuits, overload, or any fault; the current rises above this value, damaging the equipment and sometimes resulting in fire hazard. Fuses come into operation under fault conditions.

A fuse is short piece of metal, inserted in the circuit, which melts when excessive current flows through it and thus breaks the circuits. Under normal operating conditions it designed to carry the full load current. If the current increases beyond this designed value due to any of the reasons mentioned above, the fuse melts, isolating the power supply from the load.

(a) Desirable characteristics of a Fuse Element:

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

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

ii. High conductivity e.g., copper.

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

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

(b) Materials:

Material used are tin lead or silver having low melting points. Use of copper or iron is dangerous, though tinned copper may be used.

(c) Types of Fuses:

Fuses are classified into following types

(i) Re-wireable or kit-Kat fuse and

(ii) High rupturing capacity (H.R.C) cartridge fuse

Re-wireable or Kit-Kat Fuse:

Re-wireable fuse is used where low values of fault current are to be interrupted. These fuses are simple in construction, cheap and available up to a current rating of 200A.They are erratic in operation and their performance deteriorates with time. An image of re-wireable fuse is as shown in figure (12.7)

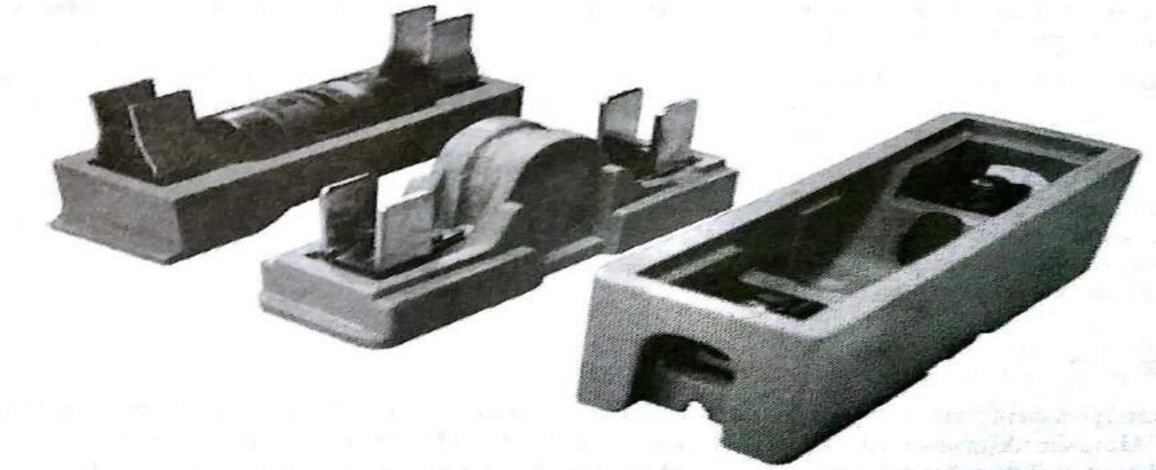


Figure (12.7): *Re-wireable or kit-kat fuse*

High Rupturing Capacity (HRC) Cartridge Fuse:

Figure (12.8) shown an image of HRC cartridge fuse and figure (12.9) shown the essential parts of a typical HRC cartridge fuse. It consists of a heat resisting ceramic body having metal end-caps to which a silver current-carrying element is welded. The space within the body surrounding the elements is completely packed with a filling powder. The filling material may be chalk, plaster of Paris, quartz or marble dust and acts as an arc quenching and cooling medium. Therefore, it carries the normal current without overheating

Under normal loading conditions, the fuse element is at a temperature below its melting point. When a fault occurs, the current increases and the fuse element melts before the fault current reaches its first peak. The heat produced in the process vaporizes the melted silver element. The chemical reaction between the silver vapors and the filling powder results in the formation of a high resistance substance which helps in quenching the arc.

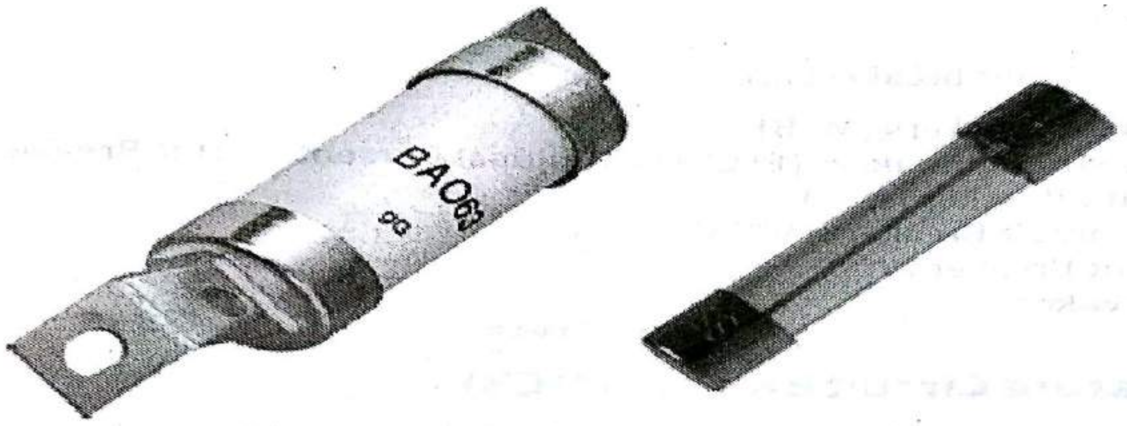


Figure (12.8): *HRC cartridge fuse*

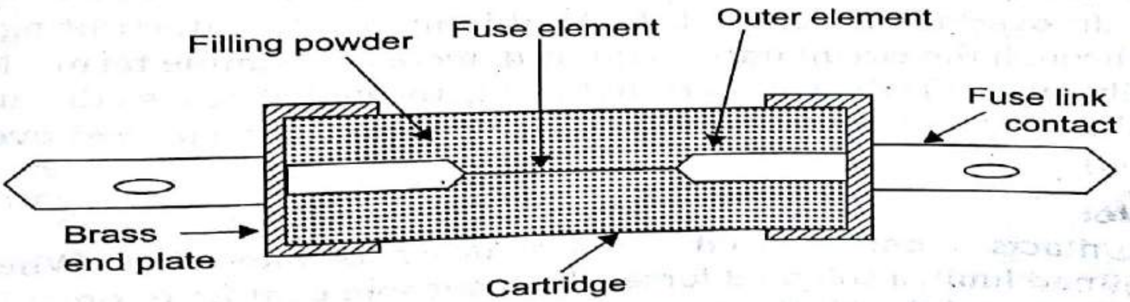


Figure (12.9): *Cross-section of HRC cartridge fuse*

Circuit Breaker:

Electrical circuits breaker is a switching device which can be operated manually and automatically for the controlling and protection of electrical power system, respectively. The modern power system deals with a huge power network and huge numbers of associated electrical equipment. During shirt circuits fault or any other type of electrical fault, this equipment, as well as the power network, suffer a high stress of fault current, which in turn damage the equipment and networks permanently. For saving this equipment and the power networks, the fault current should be cleared from the system as quickly as possible. Again, after the cleared, the system must come to its normal working condition as soon is possible for supplying reliable quality power to the receiving ends. The circuits breaker is the special device all the required switching operations during current carrying condition.

A circuits breaker essentially consists of fixed and moving contacts, called electrodes. Under normal operating conditions, these contacts remain closed and will not open automatically until and unless the system becomes faulty. The contacts can be opened manually or by remote control whenever desired. When a fault occurs in any part of the system, the trip coils of the breaker get energized and the moving contacts are pulled apart by some mechanism, thus opening the circuits.

The main types of circuits breakers are

i. Miniature circuits breakers (MCB)

ii. Earth leakage circuits breakers (ELCB) or Residual Current Breaker (RCCB)

iii. Air blast Circuits Breaker (ACB)

iv. Molded Case Circuits Breakers (MCCB)

v. Vacuum Circuits Breaker (VCB)

vi. SF_6 Circuits Breaker

Miniature Circuit Breaker (MCB):

Minimum circuits breakers are electromechanical devices which protect an electrical circuit from over currents. Over currents in an electrical circuit may results from short circuits overload, or faulty design. An MCB is better alternative than fuse, since it does not require replacement once an overload is detected. An MCB functions by interrupting the continuity of electrical flow through the circuits once a fault is detected. In simple terms, MCB is a switch which automatically turns off when the current flowing through it passes the maximum allowable limit. Generally, MCB is designed to protect against over current and over temperature faults (over heating).

Working Principle:

There are two contact - one is fixed and the other is moveable. When the current exceeds the predefined limit, a solenoid forces the moveable contact to open (i.e., disconnect from the fixed contact) and the MCB turns off, thereby stopping the current from flowing in the circuits.

Operation:

An image of MCB is shown in figure (12.10) and internal parts of an MCB are shown in figure (12.11). It mainly consists of one bi- metallic strip, one trip coil and one hand operated on-off lever. Electric current carrying path of a MCB is as follows - first left hand side power terminal-then bimetallic strip - then current coil - then moving contact - then fixed contact and - lastly

right hand side power terminal, and all are arranged in series.

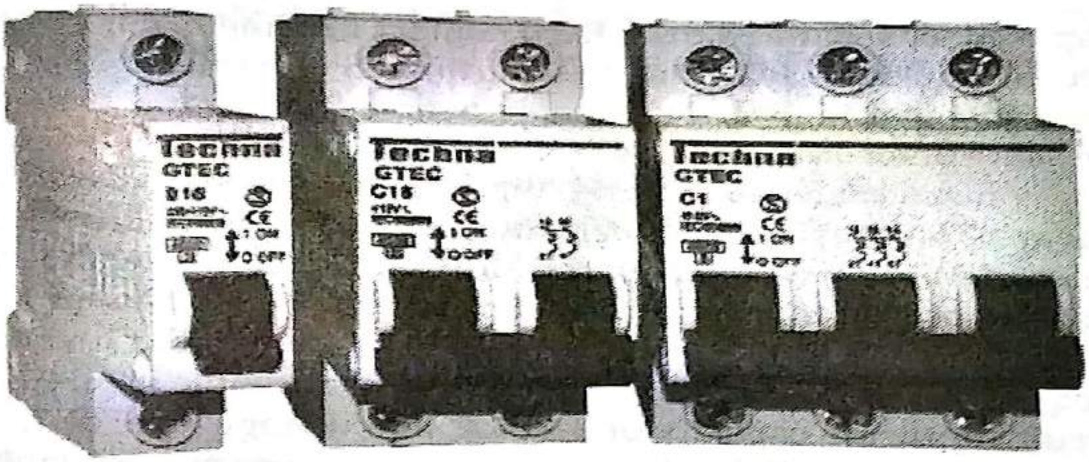


Figure (12.10): *Miniature circuit breaker*

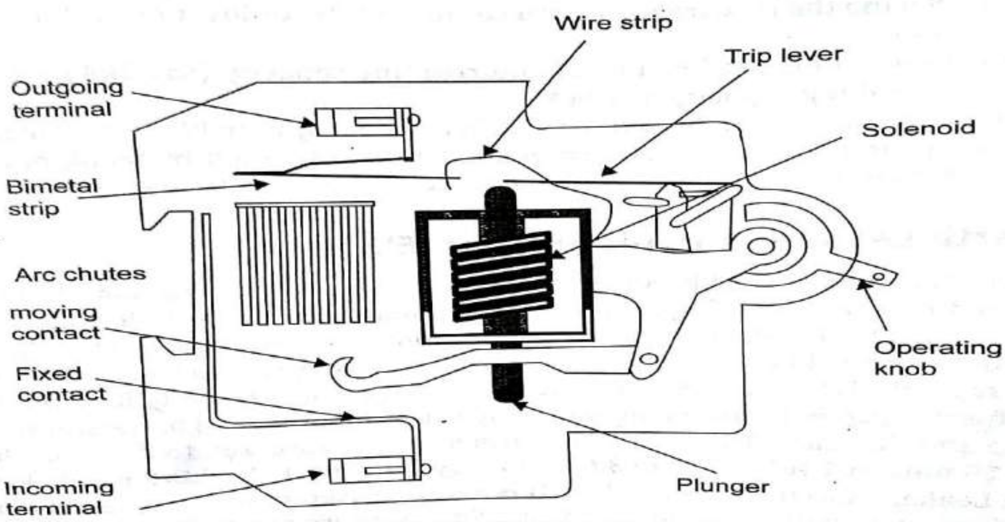


Figure (12.11): *Cross-section of MCB*

if circuits is overload for a long time, the bi -metallic strip becomes over heated and deformed. This deformation of bi-metallic strip causes displacement of latch point. The moving contact of the MCB is so arranged by means of spring, with this latch point, that a little displacement of latch causes releases of spring and makes the moving contact to move for opening the MCB. The current coil or trip coil placed in such a manner that during SC faults, the MMF of that coil causes its plunger to hit the same latch point and force the latch to be displaced. Hence, the MCB will open in the same manner. Again when operating lever of the MCB is operated by hand, that means when we make the MCB at off position manually, the same latch point is displaced as a result moving contact separated from fixed contact in same manner. So, whatever may be the operating mechanism, i.e., may be due to deformation of bi-metallic strip or may be due to increased MMF of trip coil or may be due to manual operation - actually the same latch point is displaced and the deformed spring is released, which is ultimately responsible for movement of the moving contact. When the moving contacts is separated from fixed contact, there may be a high chance of arc. This are then goes up thorough the arc runner and enters into arc splitters and is finally quenched. When we switch on the MCB, we actually reset the displaced operating latch to its previous on position and make the MCB ready for another switch off or trip operation.

These are available in single pole, double pole, triple pole, and four pole versions with neutral poles, if required. The normal current ratings are available from 0.5-63 A with a symmetrical short circuit rupturing capacity of 3-10kA, at a voltage level of 230/440v. MCBs are generally designed to trip within 2.5 millisecond when an over current fault arises. In case of temperature rise or over heating it may take 2 seconds to 2 min. For the MCB to trip.

Advantages:

i. MCBs are replacing the re-wireable switch i.e., fuse units for low power domestic and industrial applications.

ii. The disadvantages of fuses, like low SC interrupting capacity (say 3kA), Etc. Are overcome with high SC breaking capacity of 10kA.

iii. MCB is combination of all three functions in a wiring system like switching, overload and short circuits protection. Overload protection can be obtained by using bi-metallic strips whereas shorts circuits protection can be obtained by using solenoid

Earth Leakage Circuits Breaker (ELCB):

None of the protection devices like MCB, MCCB, etc. Can protect the human life against electric shocks or avoid fire due to leakage current. The human resistance noticeably drops with an increase in voltage. It also depends upon the duration of impressed voltage and drops with increase in time. As per IS code, a contact potential of 65V is within tolerable limit of human body for 10 seconds, whereas 250V can be withstood by human body for 100 milliseconds. The actual effect of current thorough human body varies from person to person with reference to magnitude and duration. The body resistance at 10V is assessed to be 19 kΩ for 1 second and 8kΩ for 15 min. At 240V, 3 to 3.6 kΩ for dry skin and 1-1.2 kΩ for wet skin.

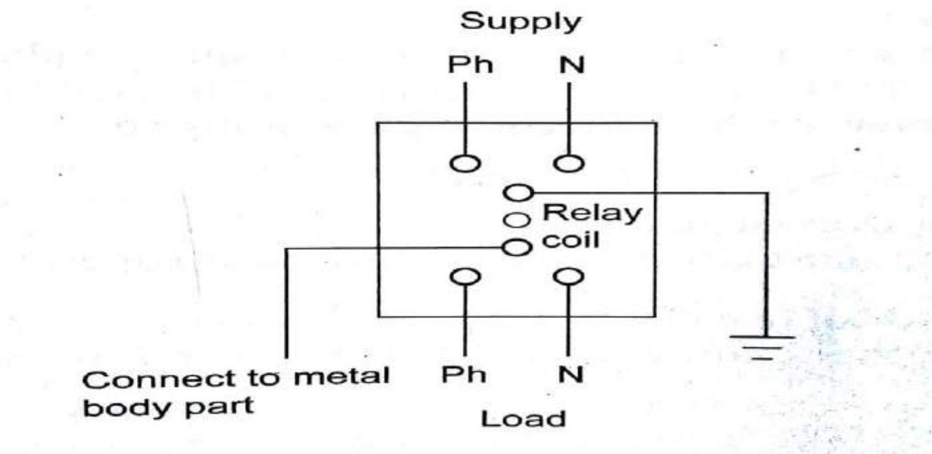
An Earth Leakage Circuits Breakers (ELCB) is a device used to directly detect currents leaking to earth from an installation and cut the power. There are two types of ELCBs:

(i) Voltage Earth Leakage Circuits Breaker (voltage -ELCB)

(ii) Current Earth Leakage Circuits Breaker (Current -ELCB)

(i) Voltage Earth Leakage Circuits Breaker (voltage -ELCB):

Voltage –ELCB is a voltage operated circuits breaker. The device will function when the current passes thorough the ELCB. Voltage-ELCB contains relay coil and one end of the coil is connected to metallic load body and the other end is connected to ground wire as shown in figure (12.12). If the voltage of the equipment body rises (by touching phase to metal part or insulation failure of equipment), which could cause the difference between earth and load body voltage and the danger of electric shock will occur. This voltage difference will produce an electric current from the load metallic body and phase through the loop to the Earth. When voltage on the equipment metallic body rises to danger level i.e., which exceed to 50V, the flowing current through relay loop could move the relay contact by disconnecting the supply current avoid from any danger electric shock. The ELCB detects fault currents from line to the earth (ground) wire within the installation it protects. If sufficient voltage appears across the ELCB's sensing coil, it will switch off the power, and remain off until manually reset. A voltage –sensing ELCB does not sense fault current from line to any other earthed body.



(ii) Current Earth Leakage Circuits Breaker (Current -ELCB):

Current –ELCB is a current operated circuits breaker which is a commonly used ELCB. Current-ELCB consists of a 3- winding transformer, which has two primary windings and 1 secondary winding as shown in figure (12.13). Neutral and line wires act as the two primary windings. A wire wound coil is the secondary winding. The current thorough the secondary winding is zero at the balanced condition. In the balanced condition, the flux due to current through the phase wire will be neutralized by the current through the neutral wire, since the current which flows from the phase will be returned back to the neutral. When a fault occurs, a small current will flow to the ground also. This makes an unbalanced between line and neutral currents and creates an unbalanced magnetic field. This induces a current through the secondary winding, which is connected to the sensing circuits. This will sense the leakage and send a signal to the tripping system and trips the contact.

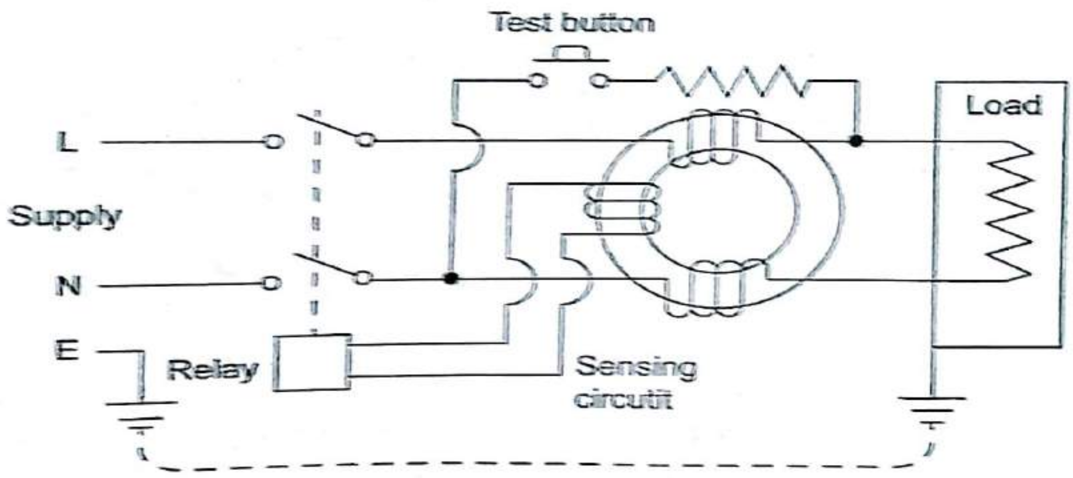


Figure (12.13): *Current earth leakage circuit breaker*

Safety precautions in Handling Electrical Appliance:

It is essentially important to take precautions when we are working with electricity and using electrical appliances. Here, some of the basic precautions are mentioned for safe usage of electrical appliance :

(i) Follow the manufacturer’s instructions :

Always read the manufacturer’s instructions carefully before using a new appliance.

(ii) Replace or repair damaged power cords :

Exposed wiring is a danger that cannot be ignored. If you see the protective coating on a wire is stripped away, be sure to replace it or cover it with electrical tape as soon as possible.

(iii) Keep electrical equipment or outlets away from water:

Avoid water at all times when working with electricity. Never touch or repairing any electrical equipment or circuits with wet hands. It increases the conductivity of electrical current. Keep all electrical appliance away from water such as sinks, bathtubs, pools or overhead vents that may drip.

(iv) use insulated tools while working:

Always use appropriate insulated rubber gloves, goggles, protective clothes and shoes with insulated soles while working on any branch circuits or any other electrical circuits. Use only tools and equipment with non-conducting handles when working on electrical devices. Never use metallic pencils or rulers or wear rings or metal watchbands when working with electrical equipment as they cause a strong electric shock.|

(v) Don't overload your outlets:

Every outlet in your home is designed to deliver a certain amount of electricity; by plugging too many devices into it at once, you could cause a small explosion or a fire. If you have a lot of things to plug in, use a power strip that can safely accommodate your needs.

(vi) Shut-off the power supply:

Always make sure that the power source should be shut-off before performing any work related to electricity. For example; inspecting, installing, maintaining or repairing.

(vii) Avoid extension cords as much as possible:

Running extension cords through the house can trip up residence; this can cause injury and damage to the wire or outlet if it causes the cord to be ripped out of the wall. If you find yourself using extension cords very often, consider having an electrician install new outlets throughout your home.

(viii) When to repair:

Everyone want to have the safe electrical environment. Equipment producing "tingle" sound should be disconnected and reported promptly for repair.

(ix) Avoid the usage of flammable liquids:

Never use highly flammable liquids near electrical equipment. Never touch another person's equipment or electrical control devices unless instructed to do so.

(x) Use electric tester:

Never try repairing energized equipment. Always check that it is de-energized first by using a tester. When an electric tester touches a live or hot wire, the bulb inside the tester lights up showing that an electrical current is flowing through the respective wire. Check all the wires, the outer metallic covering of the service panel any other hanging wires with an electrical tester before proceeding with your work.

(xi) In case of electric shock:

If an individual comes in contact with a live electrical conductor, do not touch the equipment, cord person. Disconnect the power source from the circuits breaker or pull out the plug using a leather belt. By enclosing all electric conductors and contacts can save people from getting the electric shock. Use three-pin plugs, which have earth wire connection which prevents electrical shock.

(xii) Display danger board :

Danger board should be displayed at the work place. We should not allow any unauthorized person to enter in the working place and we should not put any new equipment into the service without necessary testing by the concern authority.

(xiii) Usage of proper ladder:

Never use an aluminium or steel ladder if you are working on any receptacle at height in your home. An electrical surge will ground you and the whole electric current will pass through your body. Use a bamboo, wooden or a fiberglass ladder instead.

(xiv) Usage of circuits breaker or fuse:

Always use a circuits breaker or fuse with the appropriate current rating. Circuits breakers and fuses are protection devices that automatically disconnect the live wire a condition of short circuits or over current occurs. The selection of the appropriate fuse or circuit breaker is essential. Normally for protection against short circuits a fuse rated of 150% of the normal circuit current is selected. In the case of a circuit with 10 amperes of current, a 15 ampere fuse will against direct short circuits a 9.5 amperes fuse will blow out.

(xv) Use ceiling on live wire :

Always put a cap on the hot/live wire while working on an electric board or service panel as you could end up short circuiting the bare ends of the live wire with the neutral. The cap insulates the copper ends of the cable thus preventing any kind of shock even if touched mistakenly.

(xvi) Precaution during soldering:

Always take care while soldering your circuits boards. Wear goggles and keep yourself away from the fumes. Keep the solder iron in its stand when not in use; it can get extremely hot and can easily cause burns.

(xvii) Things to remember:

The circuits is bad, electricity appliances are not working well, and lights are fluctuating. It means you need an electrical inspection or repair. In this case, either you'll call an electrician or do it yourself. So if you are trying to repair, always remember that your hands are well dry, you have essential tools, rubber gloves & shoe are good, As all these acts as an insulator. Do not wear loose clothing or tied near electrical equipment.

(xviii) Keep heaters away from bedclothes, clothing and curtains to avoid risk fire. Be extra careful when using electrical appliances attached to power outlets near kitchen or bathroom sinks, tubs, swimming pools, and other wet areas. Don't cover an electric heater with clothing or other items.

Energy Consumption Calculation:

Energy and power are closely related. Electrical energy can be measured only when electrical power is known. So first we understand the electrical power. Electrical power it the amount of electrical current that results from a certain amount of voltage or we can say that power is the rate which energy is delivered. It is measured in watts. Mathematically it is written as

Power = Voltage × Current

The measurement of electrical energy is completely dependent on power which is measured in watt, kilowatts, megawatts, gigawatts, and time which is measured in an hour. Joule is the smallest unit of energy. But for some bigger calculation, some better unit it required. So, the unit used for electrical energy is watt-hour.

Electrical energy is the product of electrical power and time, and it measured in joules. It is defined as "1 joule of energy is equal to 1 watt of power is consumed for 1 second". I.e.,

Energy = Power × Time

1 Joule = 1 watt × 1 second

Watts are the basic unit of power in which electrical power is measured or we can say that rate at which electrical current is being used at a particular moment.

Watt-hour is the standard unit used for measurement of energy, describing the amount of watts used over a time. It shows how fast the power is consumed in the period of time.

Energy in watt hours = Power in watts × Time in hours

Kilowatt-hour is simply a bigger unit of energy when large appliance drawn power in kilowatts. It can be described as one kilowatt hour is the amount of energy drawn by the 1000 watts appliance when used for an hour.

Where, One kilowatt = 1000 watts

Energy in kilowatt hours = Power in kilowatts × Time in hours

The electrical supply companies take electric energy charges from their consumer per kilowatt hour unit basis.

This kilowatt hour is board of trade (BOT) unit.

Illustration for Energy Consumption:

A consumer uses a 10 kW geezer, a 6 kW electric furnace and five 100 W bulbs for 15 hours. How many units (kWh) of electrical energy have been used?

Explanation : Given that

Load – 1 = 10 kW geezer

Load – 2 = 6 kW electric furnace

Load – 3 = 500 watt (five 100 watt bulbs)

Total load = 10kW + 6kW + 0.5kW = 16.5kW

Time taken = 155 hours

Energy consumed = Power in kW × Time in hours

= 16.5 × 15 = 247.5 kWh

For above electrical energy consumption, the tariff can be calculated as follows :

1 unit = 1kWh

So, the total energy consumption = 247.5 units

If the cost per unit is 2.5, then the total cost of energy consumption

$= 247.5 \times 2.5 = 618.75$/-