UNIT-I

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.

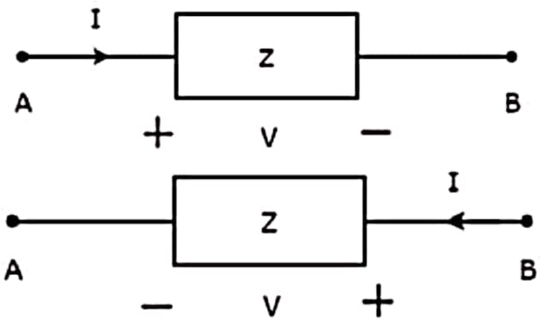
- Linear Elements are the elements that show a linear relationship between voltage and current. Examples: Resistors, Inductors, and capacitors.
- Non-Linear Elements are those that do not show a linear relation between voltage and current. Examples: Voltage sources and current sources.

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 $Z\,\Omega$. It is the ratio of voltage (V) across that element between terminals A & B and current (I).

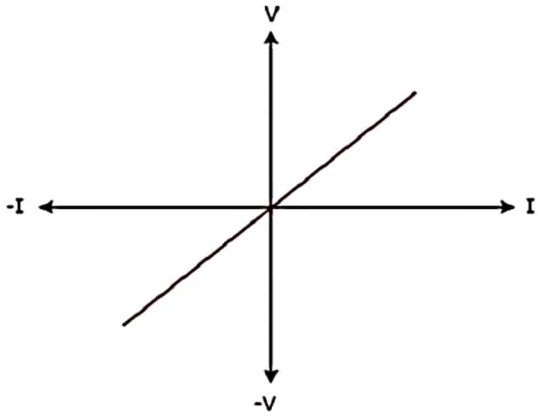
In the above figure, the current (I) is flowing from terminals B to A through a passive element having impedance of $Z\,\Omega$. That means the current (–I) is flowing from terminals A to B. In this case too, we will get the same impedance value, since both the current and voltage having negative signs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

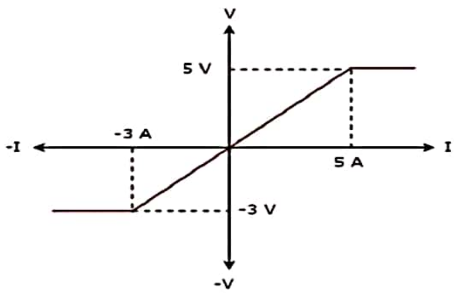
Step 3 − Verifying the network element as bilateral or unilateral.

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.

Example2

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.

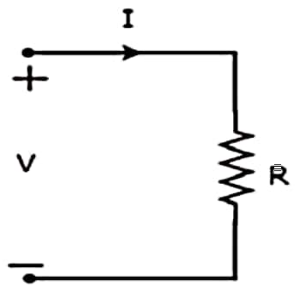
Distributed elements are those which are not electrically separable for analytical purposes.

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.

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

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

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

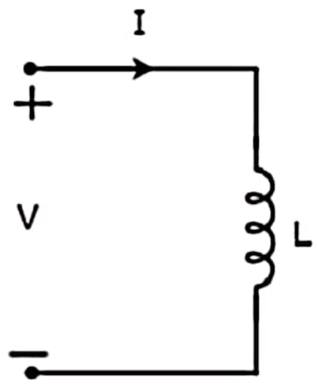
$$\Psi \alpha I$$

$$\Rightarrow \Psi = LI$$

Where,

- Ψ is the total magnetic flux
- 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.

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

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

$$\Rightarrow I = \frac{1}{L}\int Vdt$$

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

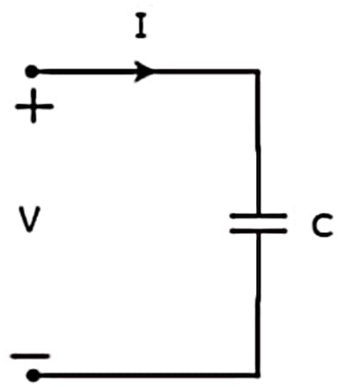
$$Q \alpha V$$

$$\Rightarrow Q = CV$$

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.

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

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

$$\Rightarrow V = \frac{1}{C}\int Idt$$

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

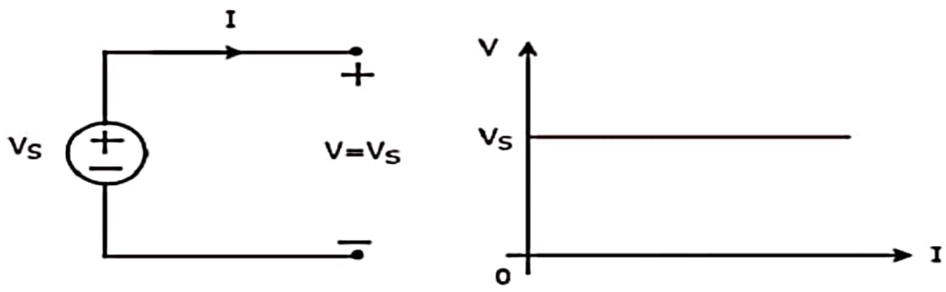
As the name suggests, independent sources produce fixed values of voltage or current and these are not dependent on any other parameter. Independent sources can be further divided into the following two categories −

- 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.

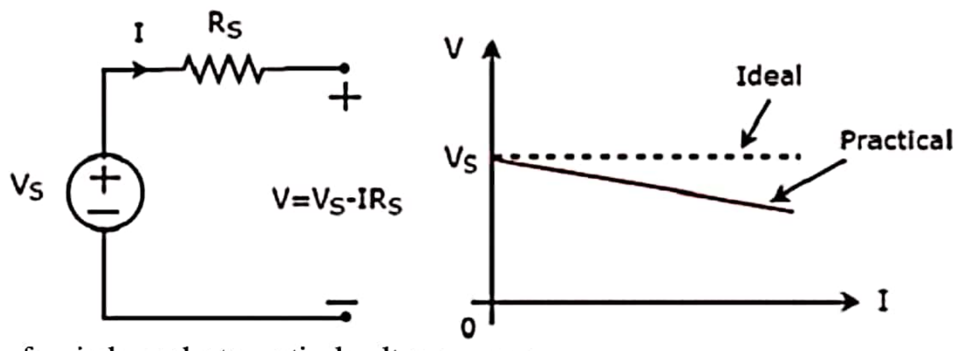


The V-I characteristics of an independent ideal voltage source is a constant line, which is always equal to the source voltage (VS) irrespective of the current value (I). So, the internal resistance of an independent ideal voltage source is zero Ohms.

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.

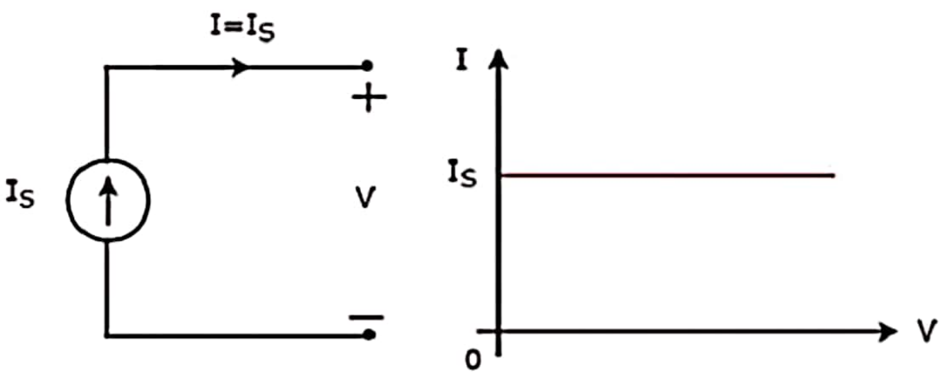
There is a deviation in the V-I characteristics of an independent practical voltage source from the V-I characteristics of an independent ideal voltage source. This is due to the voltage drop across the internal



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.

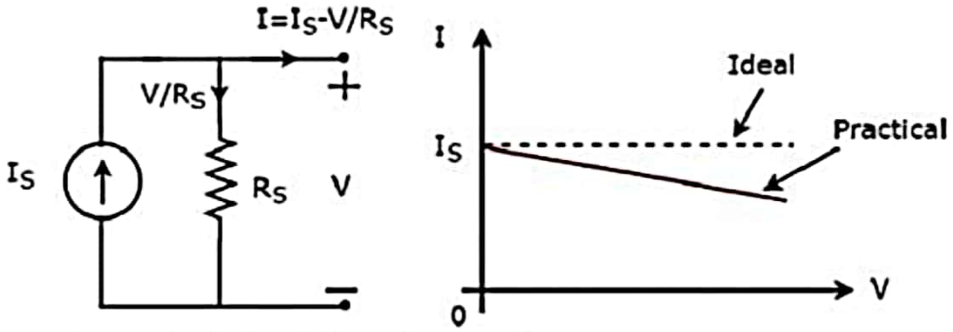


The V-I characteristics of an independent ideal current source is a constant line, which is always equal to the source current (I_S) irrespective of the voltage value (V). So, the internal resistance of an independent ideal current source is infinite ohms.

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

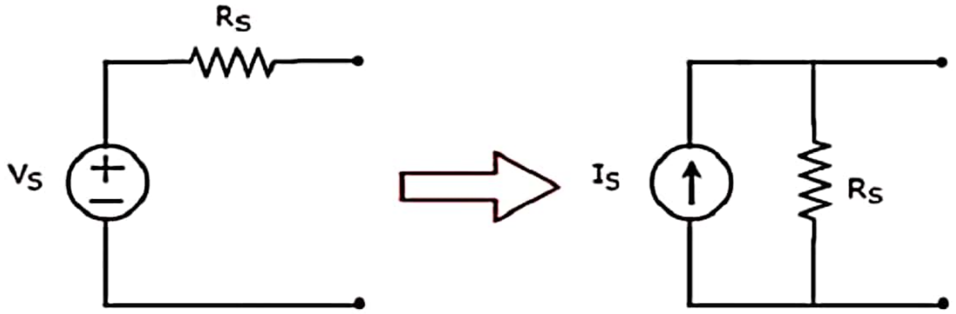
We know that there are two practical sources, namely, voltage source and current source. We can transform (convert) one source into the other based on the requirement, while solving network problems.

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



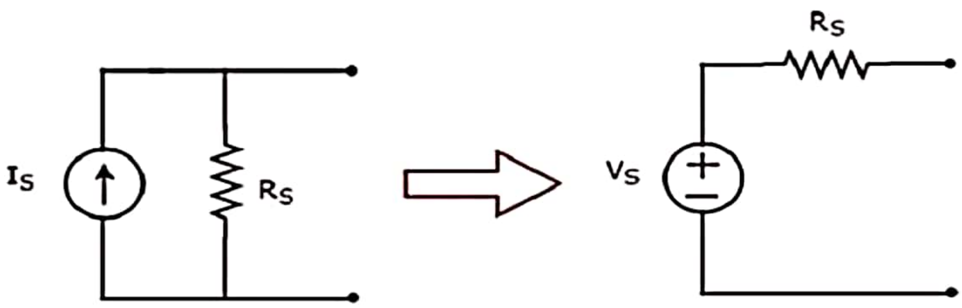
Practical voltage source consists of a voltage source (V_S) in series with a resistor (R_S). This can be converted into a practical current source as shown in the figure. It consists of a current source (I_S) in parallel with a resistor (R_S).

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

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

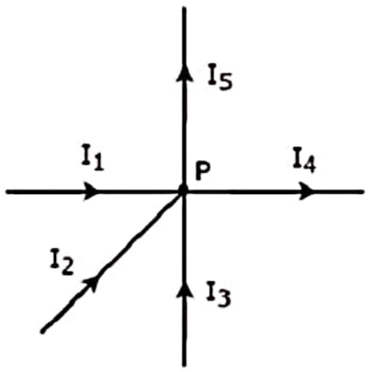
Where,

- I_m is the m[th] 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 are entering at node P. So, consider negativesigns for these three currents.

- In the above figure, the branch currents I_4 and I_5 are leaving from node P. So, consider positive signsfor 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

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

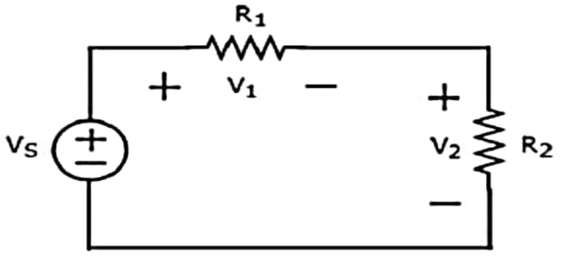
Where,

- 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.

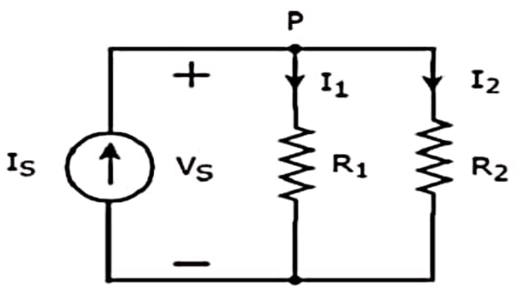
In this chapter, let us discuss about the following two division principles of electrical quantities.

- 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 $I_2 = \frac{V_S}{R_2}$.

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

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

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

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.

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.

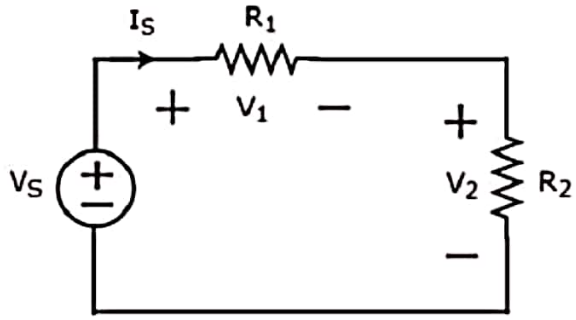
Where,

- I_N is the current flowing through the passive element of N[th] branch.
- I_S is the input current, which enters the node.
    - $Z_1, Z_2, \ldots, Z_N$ 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

$$V_S = V_1 + V_2$$

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

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

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

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

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

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

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

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

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.

$$V_N = V_S\left(\frac{Z_N}{Z_1 + Z_2 + \dots + Z_N}\right)$$

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 N^{th} passive element.
- V_S is the input voltage, which is present across the entire combination of series passive elements.
- $Z_1, Z_2, \dots, Z_3$ are the impedances of 1st passive element, 2nd passive element, …, Nth passive element respectively.

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.

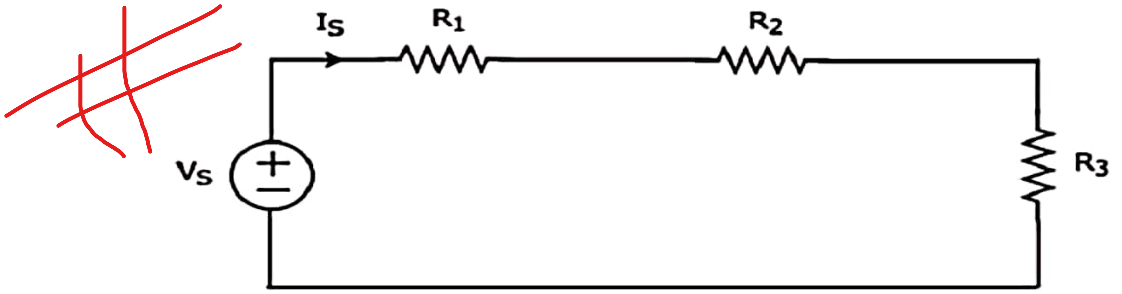
In this chapter, let us discuss about the following two equivalent circuits.

- 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.

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

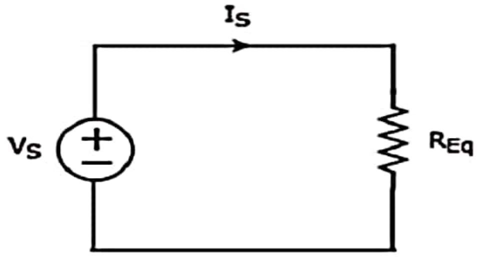
$$\Rightarrow V_S = I_S (R_1 + R_2 + R_3)$$

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 acro

$$I_S = I_1 + I_2 + I_3$$

Consider the fol

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.

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

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

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

It has a single ci ... ll these elements

are connected ir

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

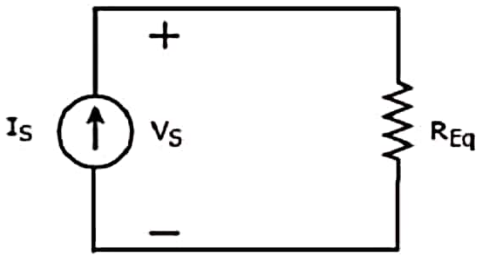
The above circ ... equation at this

principal node (

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

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

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

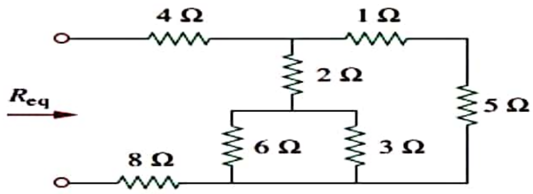
$$\frac{1}{L_{Eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \ldots + \frac{1}{L_N}$$

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

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

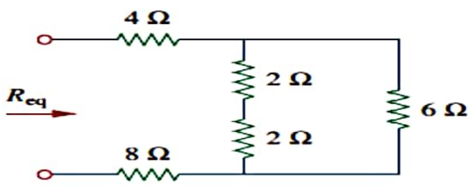
Example Problems:

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

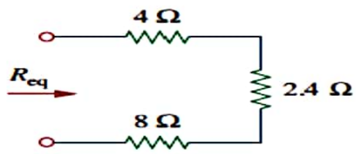


fig(a)

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 equivalentresistance 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

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

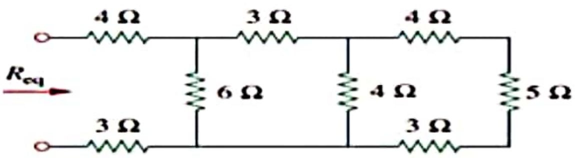
This 4 ohms resistor is now in parallel with the 6 ohms resistor in Fig.(b); their equivalent resistance is

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

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

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

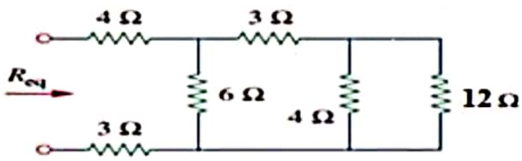
2) Find the Req for the circuit shown in below figure.



fig(a)

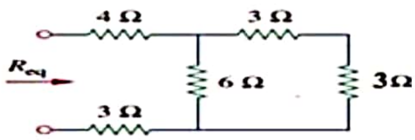
Solution:

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



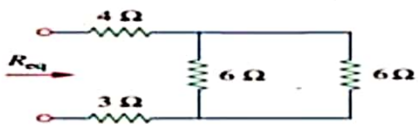
fig(b)

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



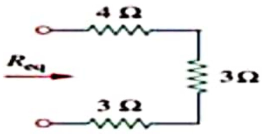
fig(c)

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

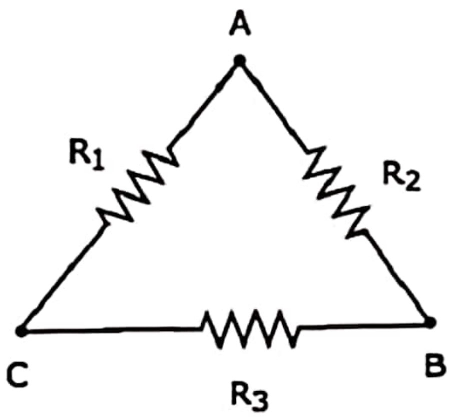
Star–to-Delta and Delta-to-Star Transformations for Resistive Networks:

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.

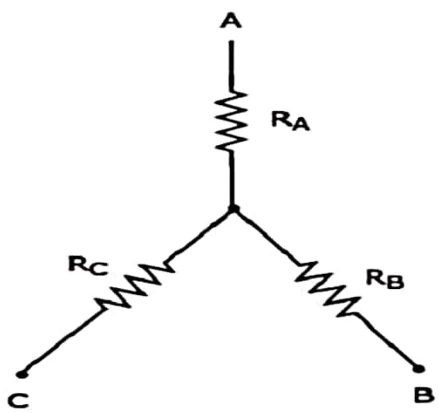
$$R_{AB} = \frac{(R_1 + R_3)R_2}{R_1 + R_2 + R_3}$$

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

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

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.

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

$$R_A = \frac{R_1R_2}{R_1 + R_2 + R_3}$$

By subtracting Equation 3 from Equation 4, we will get

$$R_B = \frac{R_2R_3}{R_1 + R_2 + R_3}$$

By subtracting Equation 1 from Equation 4, we will get

$$R_C = \frac{R_3R_1}{R_1 + R_2 + R_3}$$

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

$$R_A = \frac{R_1R_2}{R_1+R_2+R_3} \qquad \text{Equation 1}$$

$$R_B = \frac{R_2R_3}{R_1+R_2+R_3} \qquad \text{Equation 2}$$

$$R_C = \frac{R_3R_1}{R_1+R_2+R_3} \qquad \text{Equation 3}$$

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.

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.

$$R_AR_B + R_BR_C + R_CR_A = \frac{R_1R_2^2R_3 + R_2R_3^2R_1 + R_3R_1^2R_2}{(R_1 + R_2 + R_3)^2}$$

$$\Rightarrow R_AR_B + R_BR_C + R_CR_A = \frac{R_1R_2R_3(R_1 + R_2 + R_3)}{(R_1 + R_2 + R_3)^2}$$

$$\Rightarrow R_AR_B + R_BR_C + R_CR_A = \frac{R_1R_2R_3}{R_1+R_2+R_3}$$

Equation 4

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

$$\frac{R_AR_B + R_BR_C + R_CR_A}{R_B} = R_1$$

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

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

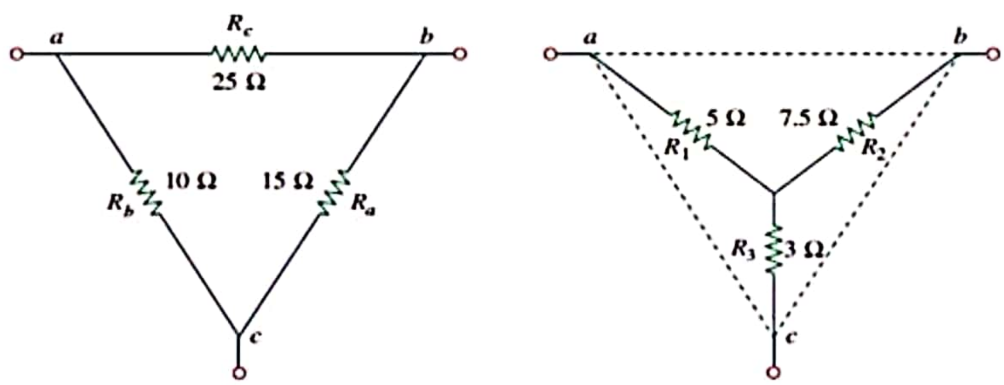
$$R_2 = R_A + R_B + \frac{R_AR_B}{R_C}$$

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

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

Example problems:

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



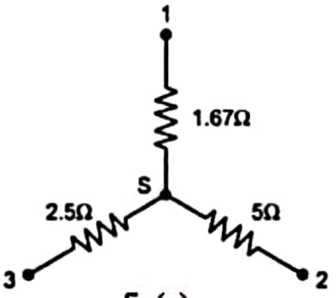
(a) (b)

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

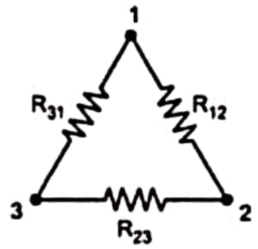
$$R_2 = \frac{R_c R_a}{R_a + R_b + R_c} = \frac{25 \times 15}{50} = 7.5\ \Omega$$

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

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

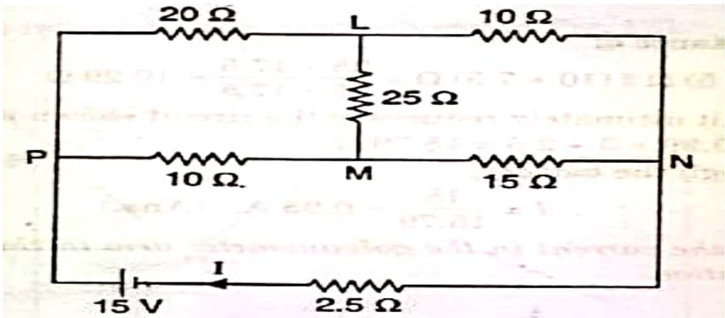
$$R_{12} = 1.67 + 5 + \frac{1.67 \times 5}{2.5} = 1.67 + 5 + 3.33 = 10\ \Omega$$

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

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

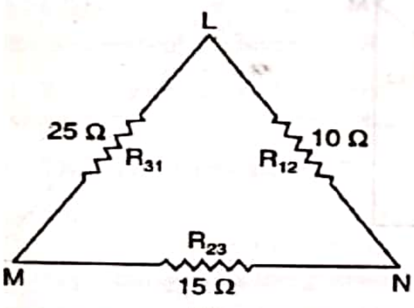
$$= 5\ \Omega$$

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

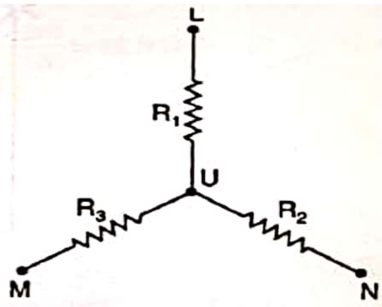


Solution: Delta connected resistors 25 ohms, 10 ohms and 15 ohms are converted in to star as shown in given figure.

$R_1 = R_{12} R_{31} / R_{12} + R_{23} + R_{31} = 10 \times 25 / 10 + 15 + 25 = 5$ ohms

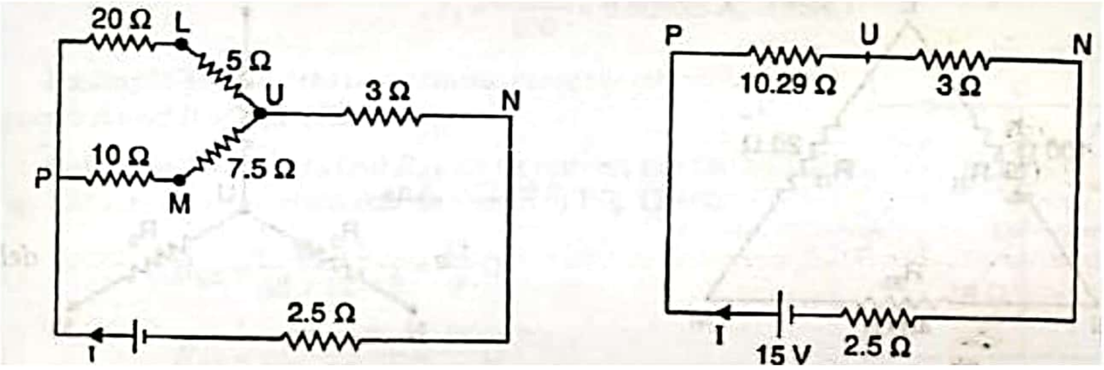


(i)



(ii)

$R_2 = R_{23} R_{12} / R_{12} + R_{23} + R_{31} = 15 \times 10 / 10 + 15 + 25 = 3$ ohms
$R_3 = R_{31} R_{23} / R_{12} + R_{23} + R_{31} = 25 \times 15 / 10 + 15 + 25 = 7.5$ 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 ohmsHence the total current through the battery, I = 15 / 15.79 = 0.95 A

Mesh Analysis:

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

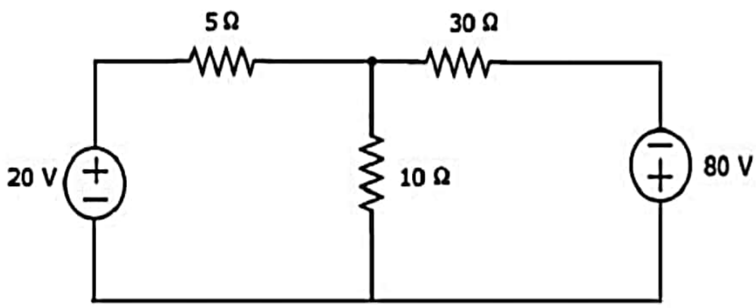
Follow these steps while solving any electrical network or circuit using Mesh analysis.

- **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

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.

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

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

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

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.

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

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

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

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

$$\Rightarrow 5I_1 = 16$$

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

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.

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:

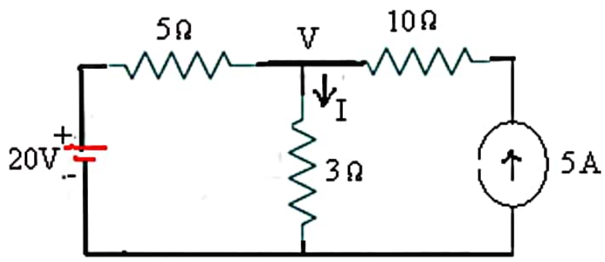
1. Replace all independent sources with their internal resistances except one source. Find the output

(voltage or current) due to that active source using nodal or mesh analysis.

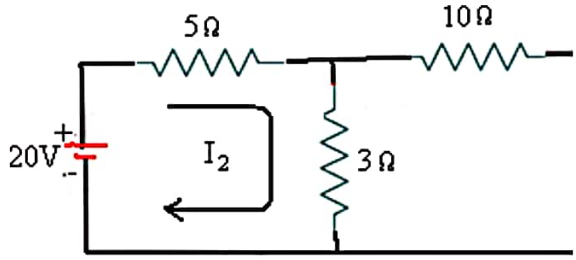
2. Repeat step 1 for each of the other independent sources.

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?

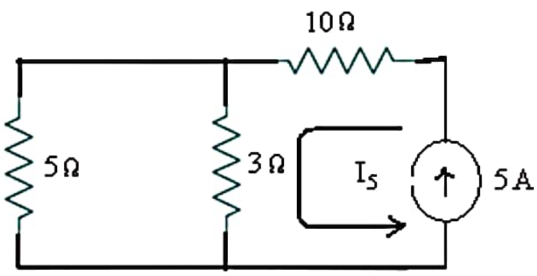


Solution: Applying the superposition theorem, the current I_2 in the resistance of 3 Ω due to the voltage source of 20V alone, with current source of 5A open circuited [as shown in the figure.1 below] is given by :



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

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 :



$I_5 = 5 \times 5/(3+5) = 3.125$ 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.**

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.

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

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) =

$$\mathbf{I_m \operatorname{Sin} \omega\, \theta = I_m \operatorname{Sin} \theta}$$

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

The Square root of this value is:

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

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

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

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

Now,

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

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

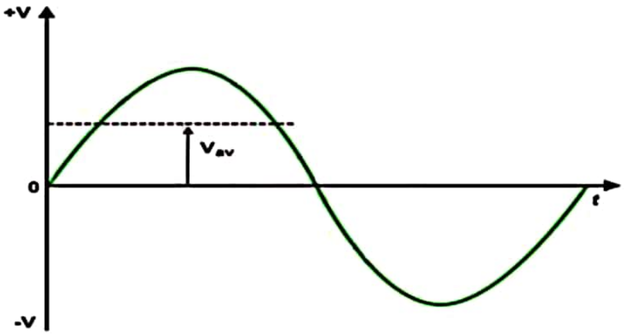
$$= \sqrt{\frac{I_m^2}{4}\ 2} \qquad \sqrt{\frac{I_m^2}{2}} \qquad \therefore \boxed{I = \frac{I_m}{\sqrt{2}} = 707\ I_m}$$

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.



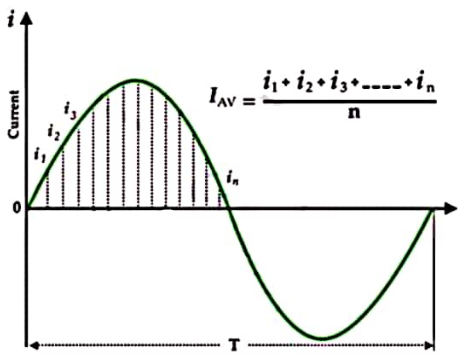
If the maximum value of alternating current is "I_{MAX}", then the value of converted DC current through rectifier would be "0.637 I_M" which is known as average value of the AC Sine wave (I_{AV}).

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.



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

$$\mathbf{i = Sin\ \omega\ \theta = I_m Sin\ \theta}$$

- 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) verage value of complete cycle:

Let $i = Sin\ \omega\ \theta = I_m Sin\ \theta$

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

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

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

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

(b) Average value of current over a half cycle

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

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

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

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

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

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 $\mathbf{I_M}$.

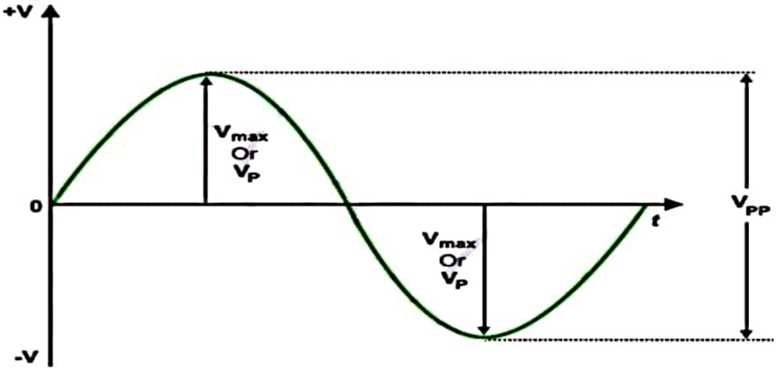
Equations of Peak Voltage Value is:

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

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

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

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.



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:

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

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

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

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.

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

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.

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

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

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;

$$T = 1/f$$

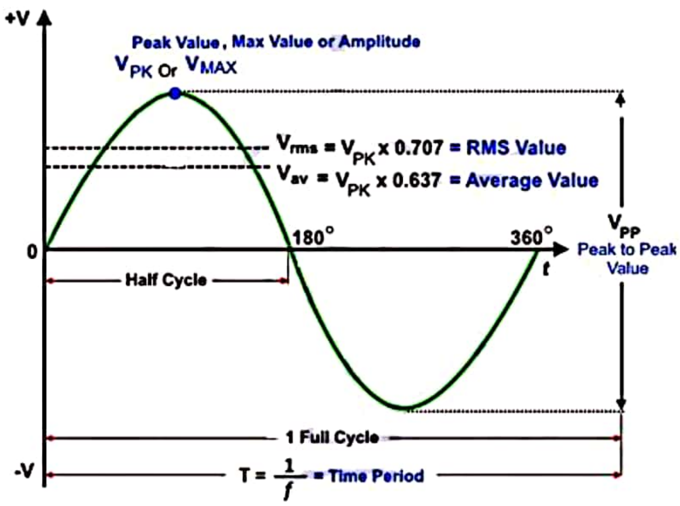
Frequency

- 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.



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

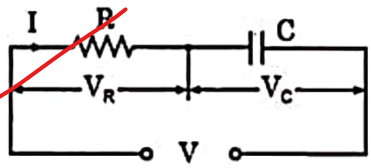
electrostatic effects are usually negligible. On the other hand with high-voltage circuits electrostatic effects may be of appreciable magnitude, and magnetic effects are also present.

- 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.

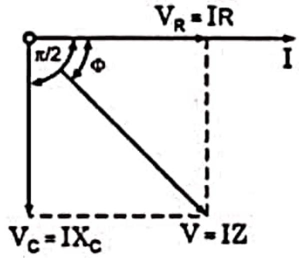
Resistance — Capacitance (R-C) Series Circuit:

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 $\pi/2$ 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 $\tan \Phi = \dfrac{V_C}{V_R} = \dfrac{I X_C}{I R} = \dfrac{X_C}{R} = \dfrac{1}{\omega RC}$ or $\Phi = \text{Tan}^{-1} \dfrac{1}{R\omega C}$

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

If instantaneous voltage is represented by:

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

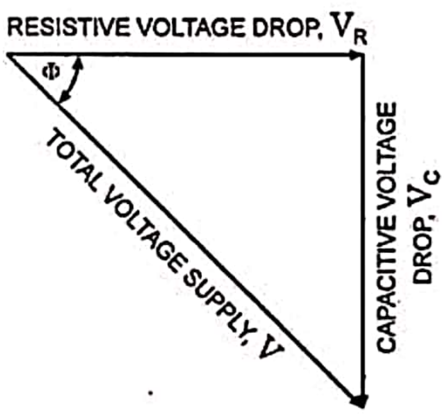
Then instantaneous current will be expressed as:

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

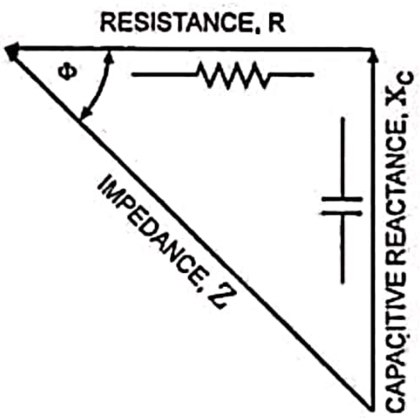
And power consumed by the circuit is given by:

$$P = VI \cos \phi$$

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



(a) Voltage Triangle



(b) Impedance Triangle

Fig. 4.19

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).

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

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

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

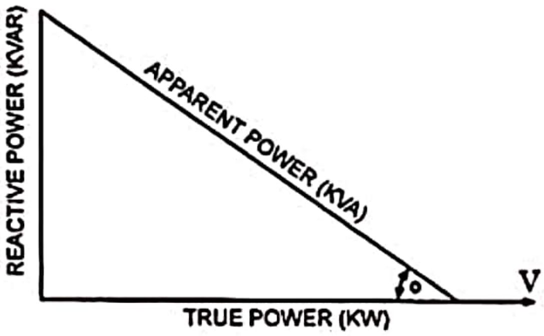
$$\text{and kVA} = \sqrt{(kW)^2 + (kVAR)^2}$$

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

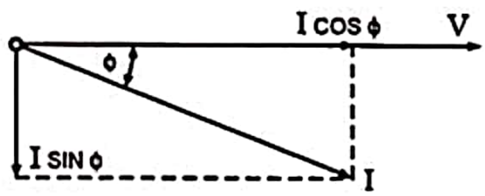
Power factor may be defined as:

(i) Cosine of the phase angle between voltage and current,

(ii) The ratio of the resistance to impedance, or



(a) Power Triangle



(b)

Fig. 4.7

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

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

$$Y = G + jB$$

$$Y \rightarrow Admittance\ in\ Siemens$$

$$G \rightarrow Conductance\ in\ Siemens = \frac{R}{R^2 + X^2}$$

$$j^2 = -1 \qquad B = -\frac{X}{R^2 + X^2}$$

$$|Y| = \sqrt{G^2 + B^2} = \frac{1}{\sqrt{R^2 + X^2}}$$

$$\angle Y = arctan\left(\frac{B}{G}\right) = arctan\left(-\frac{X}{R}\right)$$

UNIT-II
ELECTRICAL MACHINES

DC GENERATOR

Principle of DC Generator

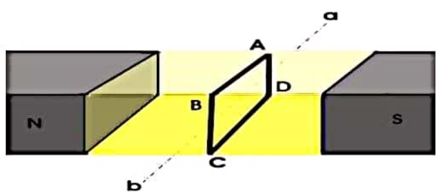
There are two types of generators, one is ac generator and other is DC generator. Whatever may be the types of generators, it always converts mechanical power to electrical power. An AC generator produces alternating power. A DC generator produces direct power. Both of these generators produce electrical 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 two essential parts of a generator are

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

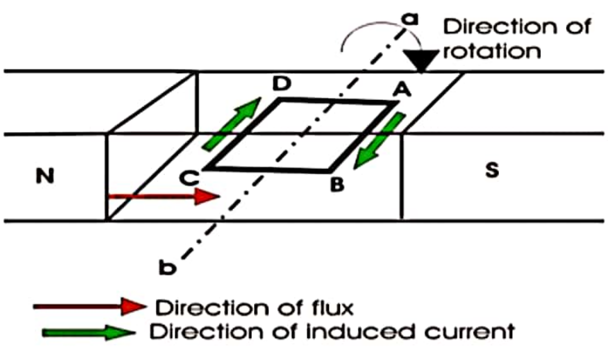
Now we will go through working principle of DC generator. As, the working principle of ac generator is not in scope of our discussion in this section.

Single Loop DC Generator

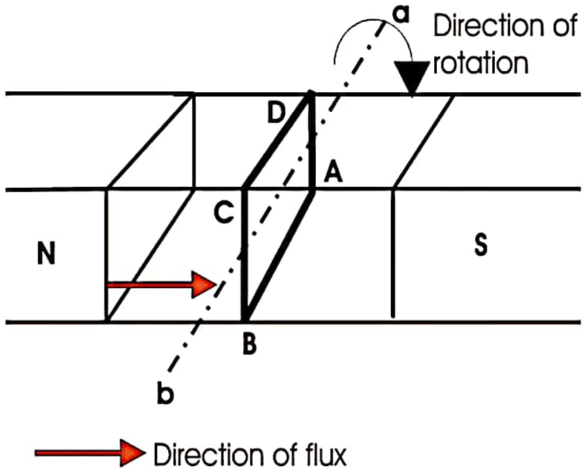


In the figure above, a single loop of conductor of rectangular shape is placed between two opposite poles of magnet.

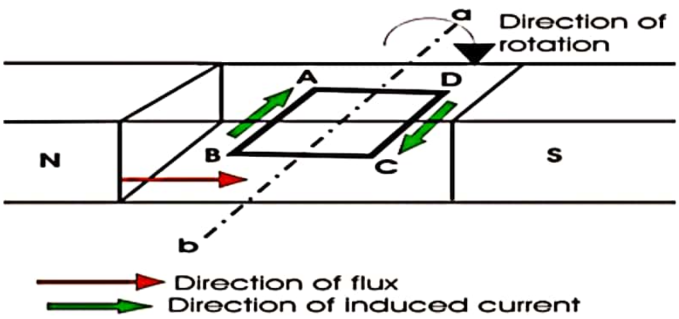
Let's us consider, the rectangular loop of conductor is ABCD which rotates inside the magnetic field about its own axis ab. When the loop rotates from its vertical position to its horizontal position, it cuts the flux lines of the field. As during this movement two sides, i.e. AB and CD of the loop cut 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.



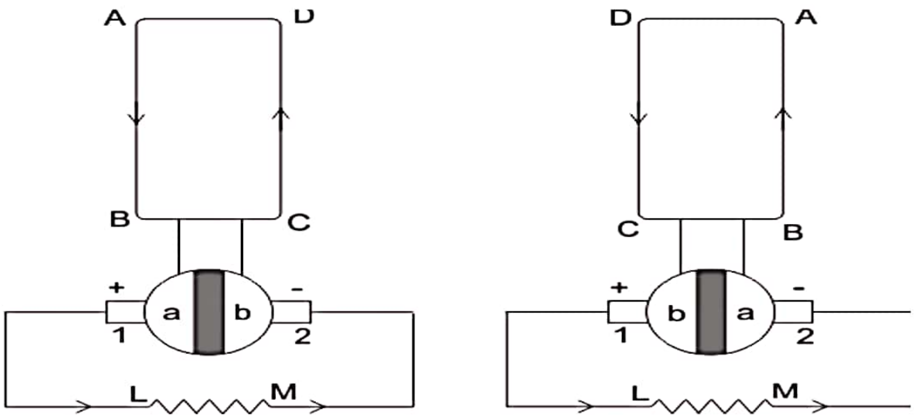
Here the tangential motion of the side of the loop is perpendicular to the flux lines, hence rate of flux cutting is maximum here and according to Fleming's right hand rule, at this position current flows from B to A and on other side from D to C.Now if the loop is continued to rotate about its axis, 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.

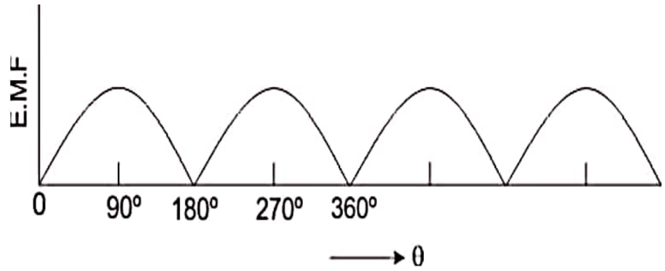
upwards from reference plane. From this, we will come to the topic of principle of DC generator.

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

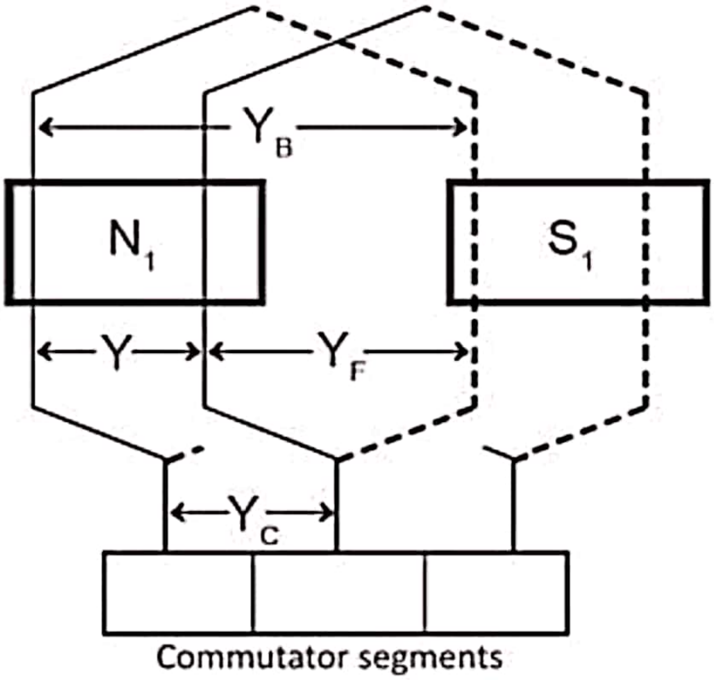
Basically armature winding of a DC machine is wound by one of the two methods, lap winding or wave winding. The difference between these two is merely due to the end connections and commutator connections of the conductor. To know how armature winding is done, it is essential to know the following terminologies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

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.

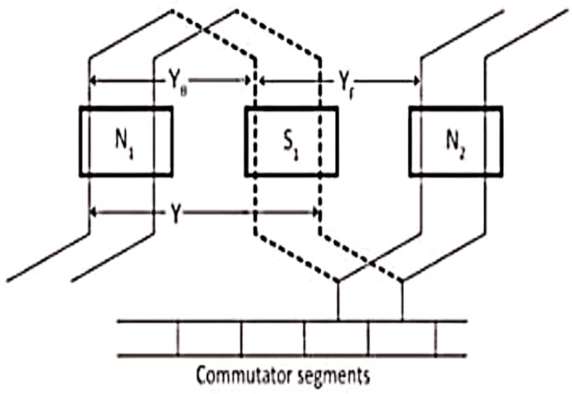
Lap Winding and Wave Winding

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, $Eg = P\Phi NZ / 60A$

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, $Eg = P\Phi NZ / 60P$

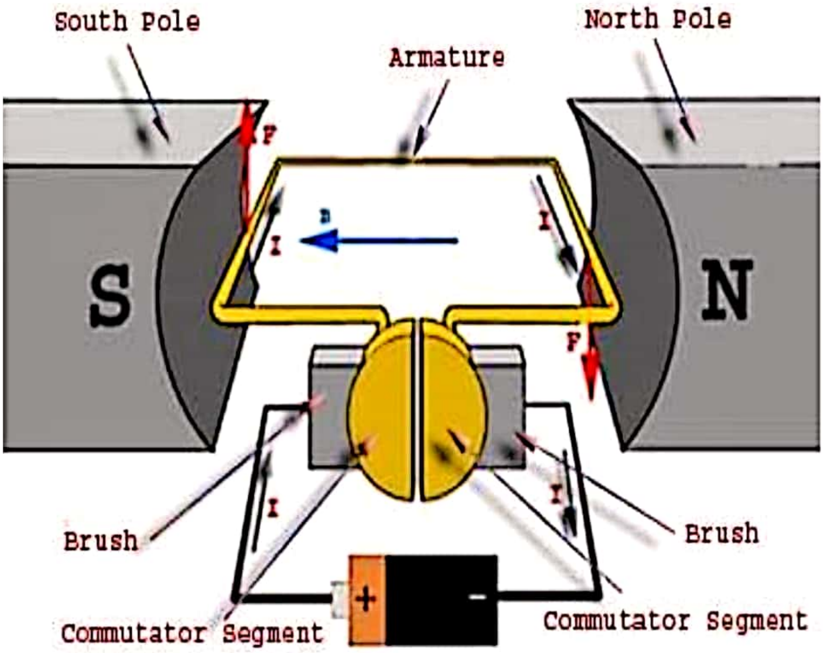
For simplex wave winding, number of parallel paths is equal to 2 (i.e

P=2),Therefore, for simplex wave wound dc generator, $Eg = P\Phi NZ / 120$

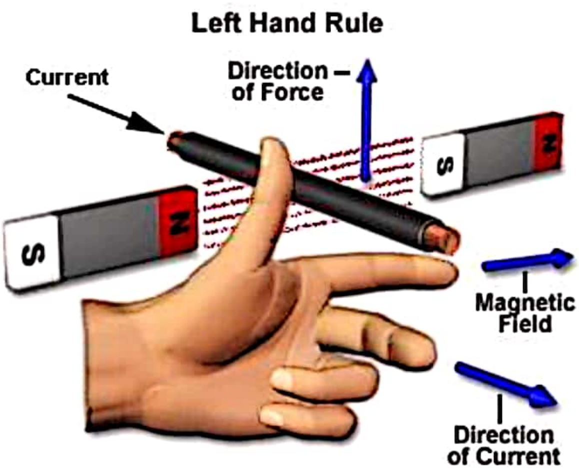
DC MOTOR

Working or Operating Principle of DC Motor

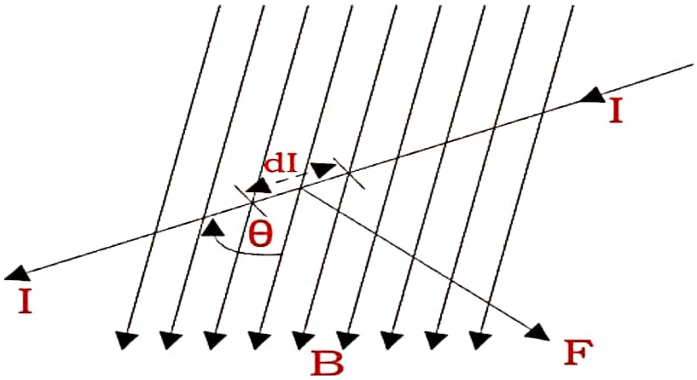
A DC motor in simple words is a device that converts electrical energy (direct current system) into mechanical energy. It is of vital importance for the industry today, and is equally important forengineers to look into the working principle of DC motor in details that has been discussed in this article. Inorder 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 thesupply end through commutator segments and brushes. The armature is placed in between north south polesof 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.

$$i.e.\ \theta = 90°$$

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,

$$F_i = BIL\sin 90° = BIL$$

Similarly force on the right hand side conductor

$$F_r = B(-I)L\sin 90° = -BIL$$

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 initialposition.

The torque produced is given by,

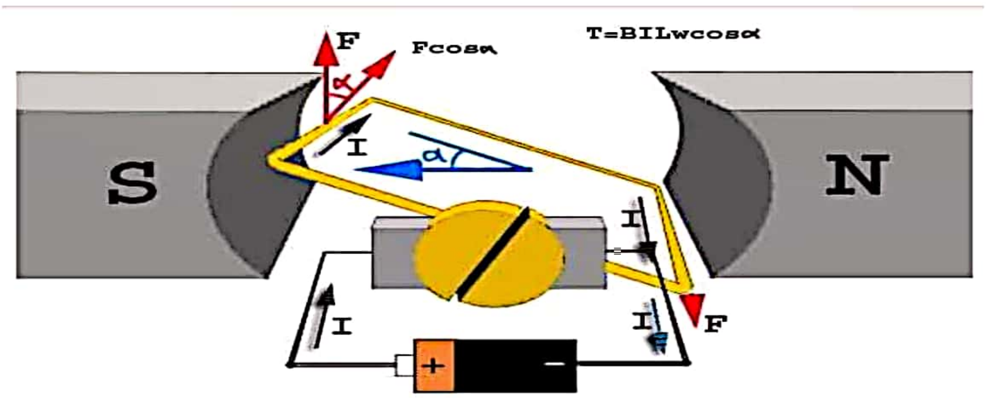
$$Torque = (force,\ tangential\ to\ the\ direction\ of\ armature\ rotation) \times (distance)$$

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

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

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 oftorque and the principle behind rotation of the motor let us do a step wise analysis.



Step 1:

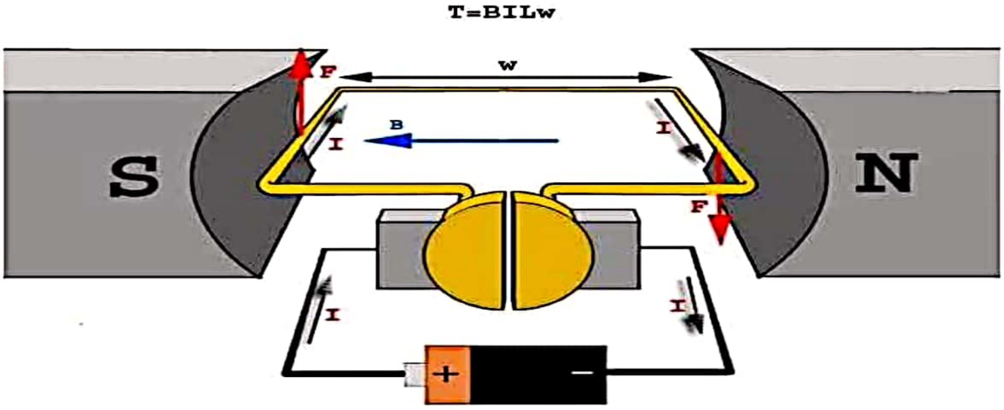
Initially considering the armature is in its starting point or reference position where the angle α = 0.

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

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

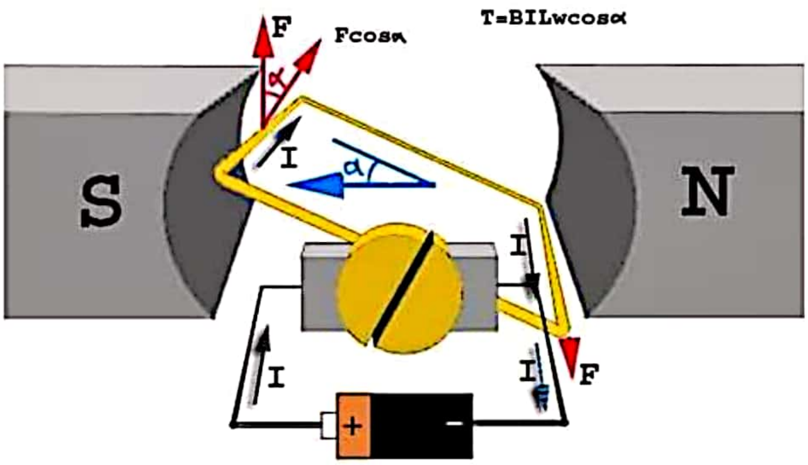
Step 2:

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 $\tau = BILw\cos\alpha$ which is less than BIL w when α is greater than 0°.



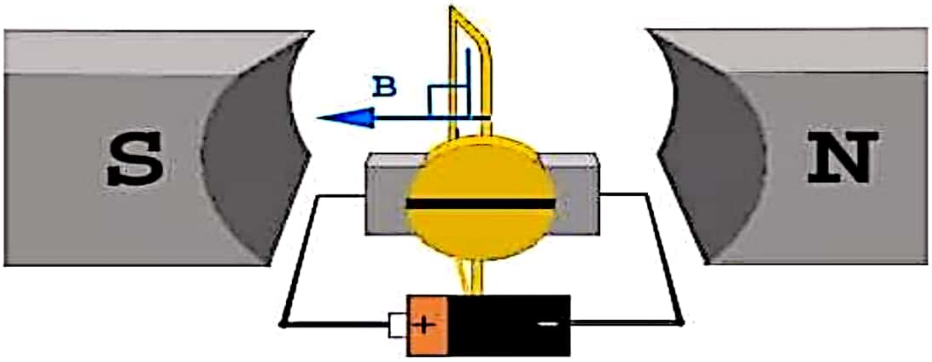
Step 3:

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. $\alpha = 90°$, and as a result the term $\cos\alpha = 0$.

The torque acting on the conductor at this position is given by, i.e. virtually no rotating torque acts on the armature at this instance. But still the armature does not come to a

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

T=BILwcos90=0



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.

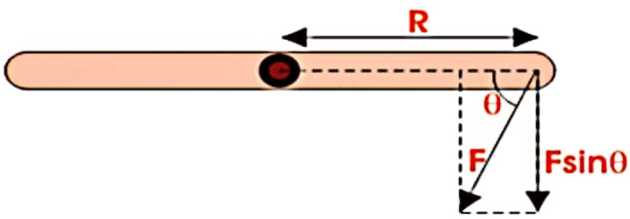
Torque Equation of DC Motor

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.

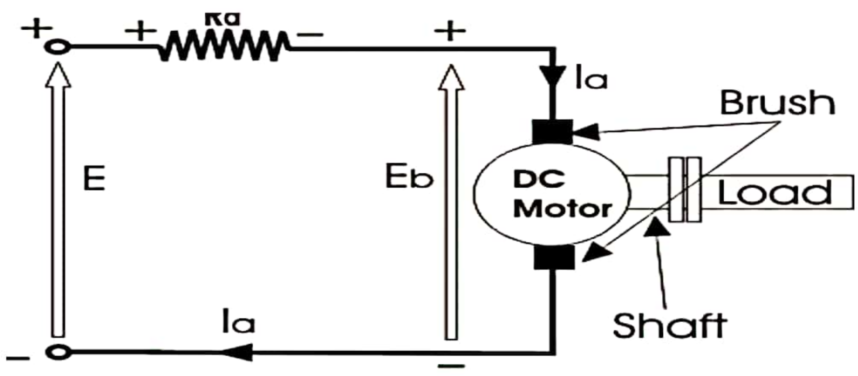
The equation of torque is given by,

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

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,

$$E = E_b + I_a R_a \text{ .... (2)}$$

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.

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

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

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

$$P_m = T_g \omega \text{ .... (5)}$$

$$P_m = E_b I_a \text{ .... (4)}$$

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.

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

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,

$$T_m = T_g - mechanical\ losses$$

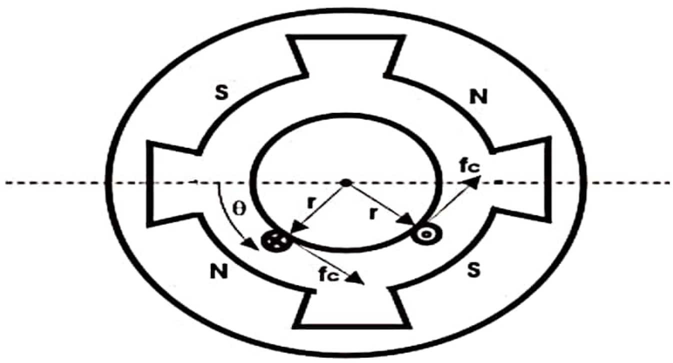
\This is the torque equation of DC motor. It can be further simplified as:

$$T_g = k_a \phi I_A$$

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

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.



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

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

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

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

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

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:

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

$$T_g = k_a\phi I_a$$

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

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

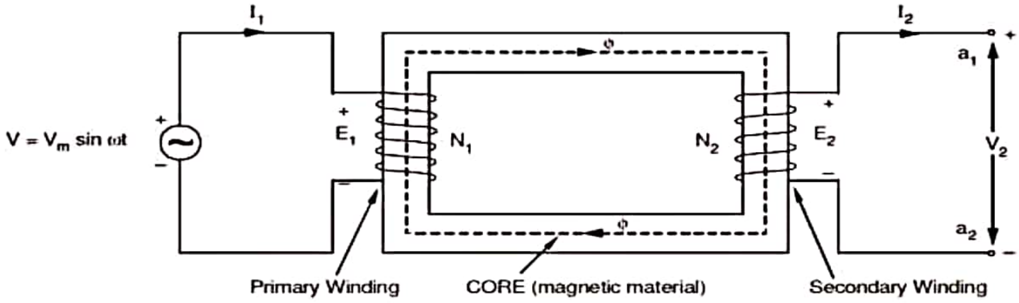
A transformer is a static device of equipment used either for raising or lowering the voltageof an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig 1.

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

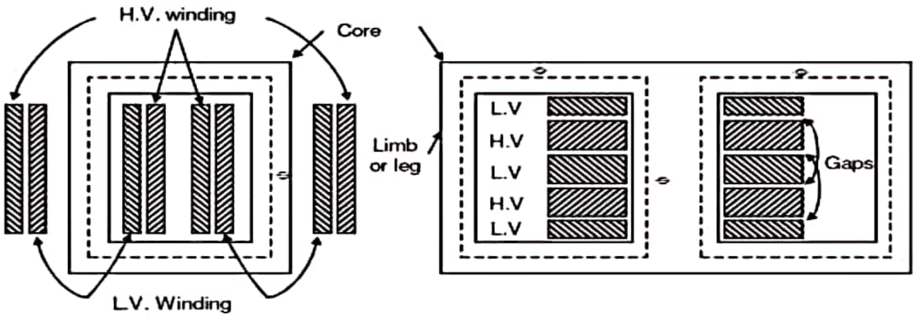
Depending upon the manner in which the primary and secondary windings are placed on the core, and the shape of the core, there are two types of transformers, called

(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 areinterleaved 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. Thematerial 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.

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

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

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

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

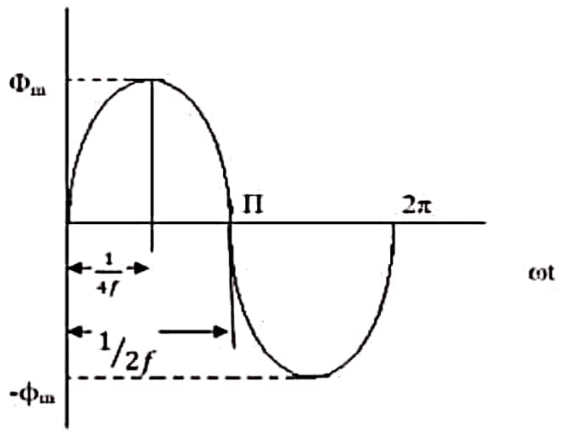
ϕm - maximum value of flux ,

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.fThe 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

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

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 = $4.44\phi_m f N1$Volts.

R.M.S Value of e.m.f induced in secondary winding = $4.44\phi_m f N2$Volts.

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.

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.

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

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

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)

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

$$V_1 I_1 = V_2 I_2$$

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

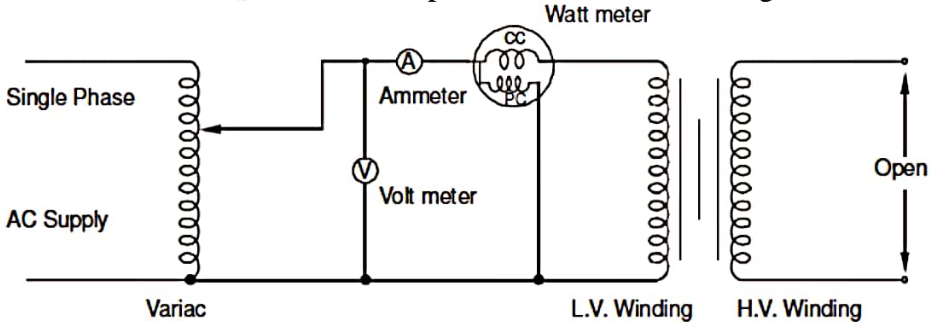
V_1 and V_2 are the V_t of primary and secondary by using KVA rating we can calculate I_1 and I_2 Full load current and it is safe maximum current.

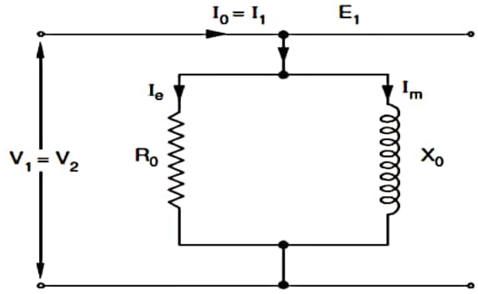
$$I_1 \text{ Full load current} = \frac{KVA\ Rating\ X\ 1000}{V1}$$

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

OPEN CIRCUIT TEST

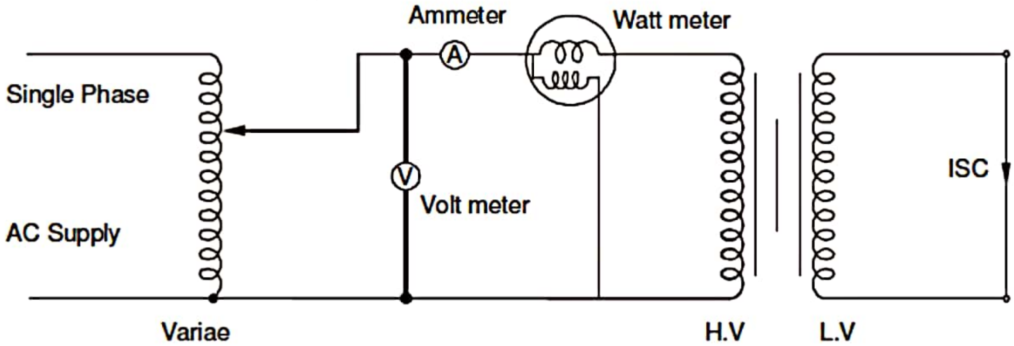
Practically we can determine the iron losses by performing the open circuit test and also the core loss components of equivalent circuit. We perform open circuit test in low voltage winding in transformer keeping the high voltage winding open. The circuit is connected as shown in Figure. The instruments are connected on the LV side. The advantage of performing the test from LV side is that the test can be performed at rated voltage. When we apply rated voltage then watt meter shows iron losses [There is some copper loss but this is negligible when compared to iron loss]. The ammeter shows no load current $I0$ which is very small [2-5 % of rated current]. Thus, the drops in $R1$ and $Xl1$ can be neglected.

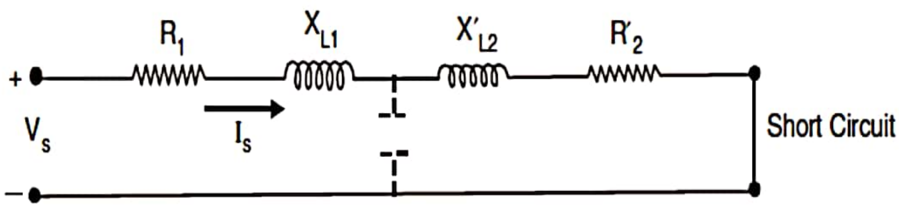




SHORT CIRCUIT TEST

From short circuit test we can determine copper losses and also the winding components of equivalent circuit. It‟s an indirect method to find out the copper losses. To perform this test, we apply a reduced voltage to the primary winding through instruments keeping LV winding short circuited. The connections are shown in Figure. We need to apply only 5-10% of rated voltage to primary to circulated rated current in the primary and secondary winding. The applied voltage is adjusted so that the ammeter shows rated current of the winding. Under this condition, the watt-meter reading shows the copper losses of the transformer. Because of low value of applied voltage, iron losses, are very small and can be neglected.





So we calculate equivalent reactance. These Req and Xeq are equivalent resistance and reactance of both windings referred in HV side. These are known as equivalent circuit resistance and reactance.

<u>Three Phase Induction Motor</u>

Three-phase induction motors are the most common machines used in industry.

- Simple design, rugged, low-price, easy maintenance.
- wide range of power ratings: fractional horsepower to 10 MW

- Run essentially as constant speed from zero to full load.
- not easy to have variable speed control
- An induction motor has two main parts

1. **STATOR:** a stationary part of the motor is known as stator.
   - It consists of a steel frame that supports a hollow, cylindrical core.
   - The core, constructed from stacked laminations, having a number of slots, providing the space for the stator winding.

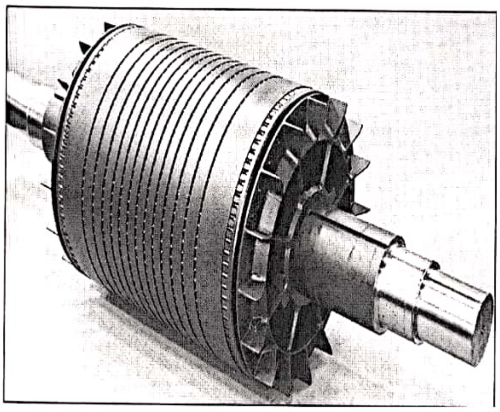
2. **ROTOR:** a revolving part of the motor is termed as rotor. It is composed of punched laminations, stacked to create a series of rotor slots, providing space for the rotor winding. There are two types of rotor windings used:

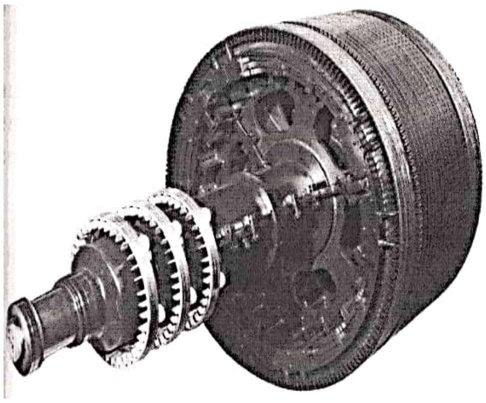
   a. Wound rotor: conventional 3-phase windings made of insulated wire, similar to the winding on the stator

   b. Squirrel cage rotor: Aluminum bus bars shorted together at the ends by two aluminum rings, forming a squirrel-cage shaped circuit.

Two basic design types depending on the rotor design

- squirrel-cage
- wound-rotor





Principle of operation:-

When three phase ac supply is connected to 3 phase stator winding. A rotating magnetic field is produced in the air gap, rotating with a speed Ns= 120f/P. Where *f* is the supply frequency and *P* is the no. of poles and *Ns* is called the synchronous speed in *rpm*. This rotating magnetic field cuts the stationary rotor conductor and produces an induced voltage in the rotor windings. Due to the fact that the rotor windings are short circuited, so induced current flows in the rotor winding. According to Lenz's law this current tries to oppose the cause due to which it is produced, since the cause is relative motion between rotating magnetic field and stationary rotor conductor. So rotor starts rotating in same direction in which magnetic field rotate. The torque is produced as a result of the interaction of those two magnetic fields

$T_{ind} = kB_R * B_S$

Can the Induction motor runs at the synchronous speed, why?

No. Induction motor does not run at synchronous speed. If rotor runs at the synchronous speed, which is the same speed of the rotating magnetic field, then the rotor will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed. When the speed falls, the rotating magnetic field will cut the rotor windings and a torque is produced.

Slip:-

- The Induction motor will always run at a speed lower than the synchronous speed
- The difference between the motor speed and the synchronous speed is called the *Slip*. It is always expressed in percentage.

$$S = Ns - Nr$$

$$S = (Ns - Nr)/ Ns \text{ ; Where } Ns = 120f/P$$

Where S = slip

Ns = Synchronous speed or speed of the magnetic field

Nr = speed of the motor.

The rotor current frequency or rotor frequency (fr) is given by

fr = s.f Hz

Notice that: if the rotor runs at synchronous speed $s = 0$ if the rotor is stationary $s = 1$

Note: the slip is a ratio and doesn't have units

Torque-slip characterstics:-

The torque slip curve for an induction motor gives us the information about the variation of torque with the slip.

$$T = \frac{k\, s\, R_2 E_{20}^2}{R_2^2 + (sX_{20})^2} \quad \dots\dots\dots\dots (1)$$

Nr = Ns(1- s)

At starting, Nr =0 & s=1. the starting torque will act on motor.

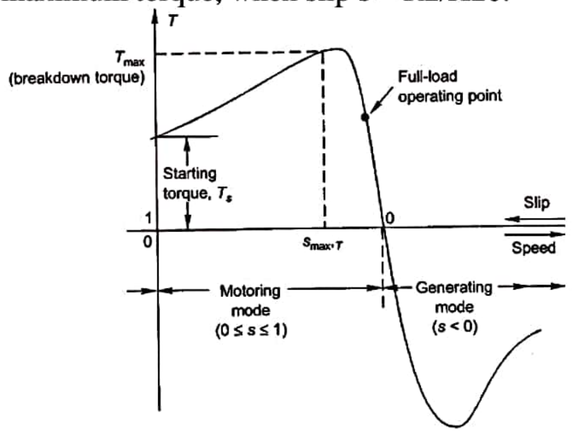
When Nr = Ns & s=0, Torque act on motor will be zero.

Torque-slip characteristic curve can be divided into three regions

- Low slip region (T α s)
- Medium slip region
- High slip region (T α 1/s)

The maximum torque is independent of the rotor resistance.

- The motor will produce maximum torque, when slip s = R2/X20.



Motoring Mode

In this mode of operation, the motor always rotates below the synchronous speed. The slip varies from zero to one. It is zero at no load and one at standstill. From the curve it is seen that the torque is directly proportional to the slip i.e. more is the slip, more will be the torque produced and vice-versa.

Generating Mode

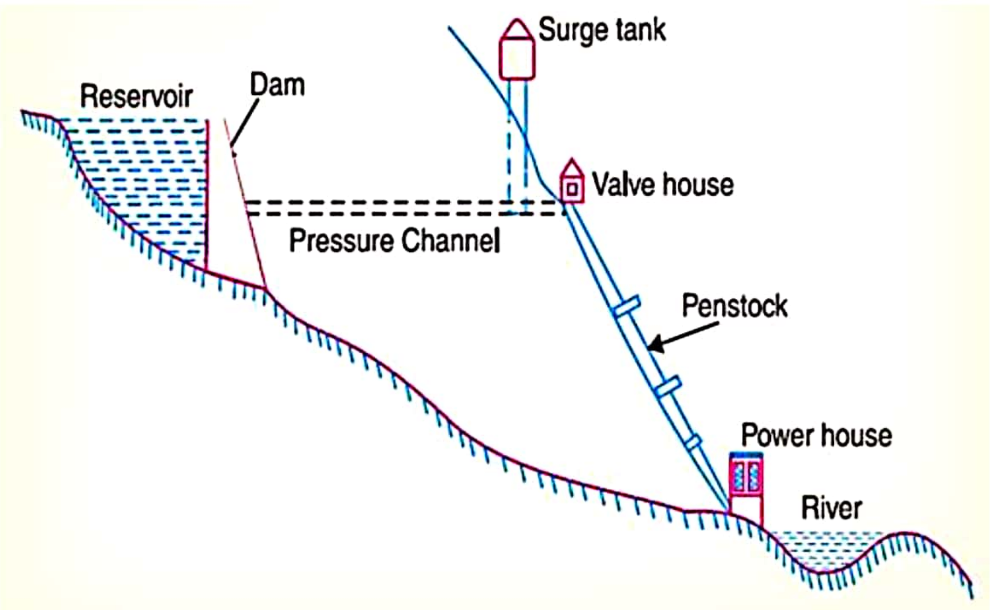
In this mode of operation induction motor runs above the synchronous speed. The torque and slip both are negative so the motor receives mechanical energy and delivers electrical energy.

UNIT – III
(BASICS OF POWER SYSTEMS)
HYDRO-ELECTRIC POWER STATION

- Generating station which utilizes the potential energy of water at a high level for the generation of electrical energy is known as a hydro-electric power station.
- Hydro-electric power stations are generally located in hilly areas where dams can be built conveniently and large water reservoirs can be obtained.
- In a hydro-electric power station, water head is created by constructing a dam across a river or lake.
- From the dam, water is led to a water turbine.
- The water turbine captures the energy in the falling water and changes the hydraulic energy (i.e., product of head and flow of water) into mechanical energy at the turbine shaft.
- The turbine drives the alternator which converts mechanical energy into electrical energy.

OPERATION OF HYDRO-ELECTRIC POWER PLANT

- Although a hydro-electric power station simply involves the conversion of hydraulic energy into electrical energy, yet it embraces many arrangementsfor proper working and efficiency.
- The schematic arrangement of a modern hydro-electric plant is shown in Fig.
- The dam is constructed across a river or lake and water from the catchmentarea collects at the back of the dam to form a reservoir.
- A pressure tunnel is taken off from the reservoir and water brought to the valve house at the start of the penstock.
- The valve house contains main sluice valves and automatic isolating valves.
- The former controls the water flow to the power house and the latter cutsoff supply of water when the penstock bursts.
- From the valve house, water is taken to water turbine through a huge steelpipe known as *penstock.*
- The water turbine converts hydraulic energy into mechanical energy.
- The turbine drives the alternator which converts mechanical energy into electrical energy.
- A surge tank (open from top) is built just before the valve house andprotects the penstock from bursting in case the turbine gates suddenly close* due to electrical load being thrown off.
- When the gates close, there is a sudden stopping of water at the lower end of the penstock and consequently the penstock can burst like a paper log. The surge tank absorbs this pressure swing by increase in its level of water



ADVANTAGES

1) It requires no fuel as water is used for the generation of electricalenergy.
2) It is quite neat and clean as no smoke or ash is produced.
3) It requires very small running charges because water is the source ofenergy which is available free of cost.
4) It is comparatively simple in construction and requires less maintenance.
5) It does not require a long starting time like a steam power station. Infact, such plants can be put into service instantly.
6) It is robust and has a longer life.
7) Such plants serve many purposes. In addition to the generation of electrical energy, they also help in irrigation and controlling floods.
8) Although such plants require the attention of highly skilled persons at the time of construction, yet for operation, a few experienced persons may do the job well.

DISADVANTAGES

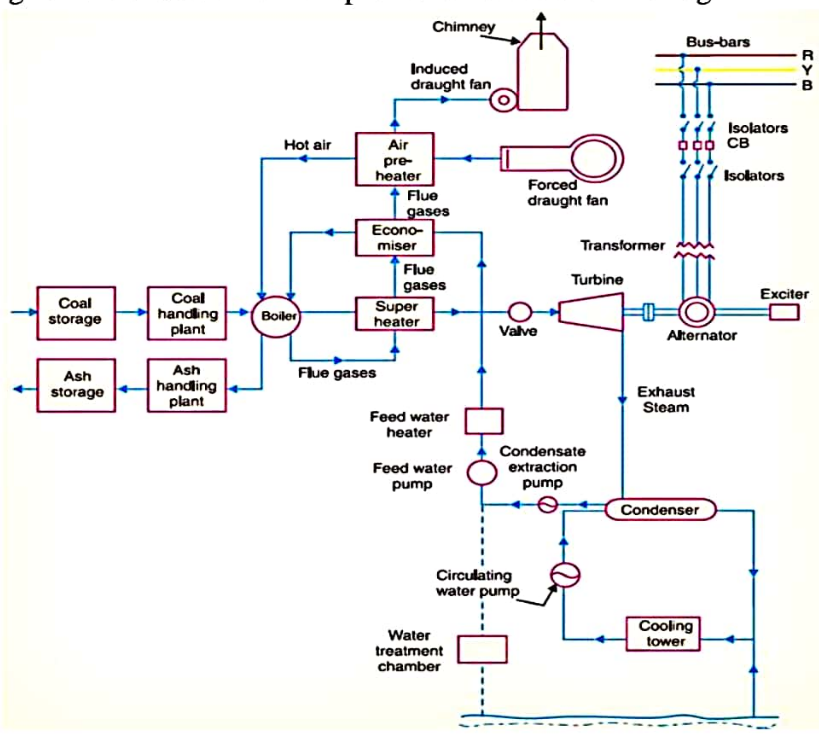
1) It involves high capital cost due to construction of dam.
2) There is uncertainty about the availability of huge amount of water due to dependence on weather conditions.
3) Skilled and experienced hands are required to build the plant.
4) It requires high cost of transmission lines as the plant is located in hilly areas which are quite away from the consumers.

THERMAL POWER PLANT

- A generating station which converts heat energy of coal combustion into electrical energy is known as a steam power station.
- A steam power station basically works on the Rankine cycle.
- The Rankine cycle is the fundamental operating cycle of all power plants where an operating fluid is continuously evaporated and condensed
- Steam is produced in the boiler by utilizing the heat of coal combustion.

WORKING OF THERMAL POWER PLANT

- The schematic arrangement of a modern steam power station is shown in Fig.



❖ The whole arrangement can be divided into the following stages for the sake of simplicity :

1. Coal and ash handling arrangement
2. Steam generating plant
3. Steam turbine
4. Alternator
5. Feed water
6. Cooling arrangement

COAL AND ASH HANDLING PLANT:

- The coal is transported to the power station by road or rail and is stored in the coal storage plant.
- Storage of coal is primarily a matter of protection against coal strikes, failure of transportation system and general coal shortages.
- From the coal storage plant, coal is delivered to the coal handling plant where it is pulverized.
- The pulverized coal is fed to the boiler by belt conveyors
- The coal is burnt in the boiler and the ash produced after the complete combustion ofcoal is removed to the ash handling plant and then delivered to the ash storage plant for disposal.

STEAM GENERATING PLANT

- The steam generating plant consists of a boiler for the production of steam and other auxiliary equipment for the utilization of flue gases.

(i) BOILER.

- The heat of combustion of coal in the boiler is utilized to convert water into steam at high temperature and pressure.
- The flue gases from the boiler make their journey through superheater, economizer, air-pre-heater and are finally exhausted to atmosphere through the chimney.

(ii) SUPERHEATER

- The steam produced in the boiler is wet and is passed through a superheater
- Where it is dried and superheated (i.e., steam temperature increased above that ofboiling point of water) by the flue gases on their way to chimney.
- Superheating provides two principal benefits.

1. The overall efficiency is increased.
2. Too much condensation in the last stages of turbine (which would cause bladecorrosion) is avoided.

- The superheated steam from the superheater is fed to steam turbine through themain valve.

(iii) ECONOMISER

- An economizer is essentially a feed water heater and derives heat from the flue gasesfor this purpose.
- The feed water is fed to the economizer before supplying to the boiler.
- The economizer extracts a part of heat of flue gases to increase the feed watertemperature.

(iv) AIR PREHEATER.

- An air preheated increases the temperature of the air supplied for coal burning byderiving heat from flue gases.
- Air is drawn from the atmosphere by a forced draught fan and is passed through air-preheater before supplying to the boiler furnace.
- The air preheated extracts heat from flue gases and increases the temperature of air used for coal combustion.

The principal benefits of preheating the air are:

1. Increased thermal efficiency
2. Increased steam capacity per square meter of boiler surface.

STEAM TURBINE

- The dry and superheated steam from the superheater is fed to the steam turbinethrough main valve.

- The heat energy of steam when passing over the blades of turbine is converted into mechanical energy.
- After giving heat energy to the turbine, the steam is exhausted to the condenser which condenses the exhausted steam by means of cold water circulation.

ALTERNATOR

- The steam turbine is coupled to an alternator.
- The alternator converts mechanical energy of turbine into electrical energy.
- The electrical output from the alternator is delivered to the bus bars through transformer, circuit breakers and isolators.

FEED WATER

- The condensate from the condenser is used as feed water to the boiler.
- Some water may be lost in the cycle which is suitably made up from external source.
- The feed water on its way to the boiler is heated by water heaters and economiser.
- This helps in raising the overall efficiency of the plant.

COOLING ARRANGEMENT

- In order to improve the efficiency of the plant, the steam exhausted from the turbine is condensed* by means of a condenser.
- Water is drawn from a natural source of supply such as a river, canal or lake and is circulated through the condenser.
- The circulating water takes up the heat of the exhausted steam and itself becomes hot. This hot water coming out from the condenser is discharged at a suitable location down the river.
- In case the availability of water from the source of supply is not assured throughout the year, cooling towers are used.
- During the scarcity of water in the river, hot water from the condenser is passed onto the cooling towers where it is cooled.
- The cold water from the cooling tower is reused in the condenser

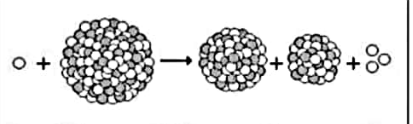
NUCLEAR POWER STATION

- A generating station in which nuclear energy is converted into electrical energy isknown as a **nuclear power station.**
- In nuclear power station, heavy elements such as Uranium (U235) or Thorium(Th232) are subjected to nuclear fission in a special apparatus known as a *reactor*.
- The heat energy thus released is utilised in raising steam at high temperature andpressure.
- The steam runs the steam turbine which converts steam energy into mechanicalenergy.
- The turbine drives the alternator which converts mechanical energy into electricalenergy.

What is Fission reaction?

- The breaking up of nuclei of heavy atoms into two nearly equal parts with release ofhuge amount of energy is known as nuclear fission.

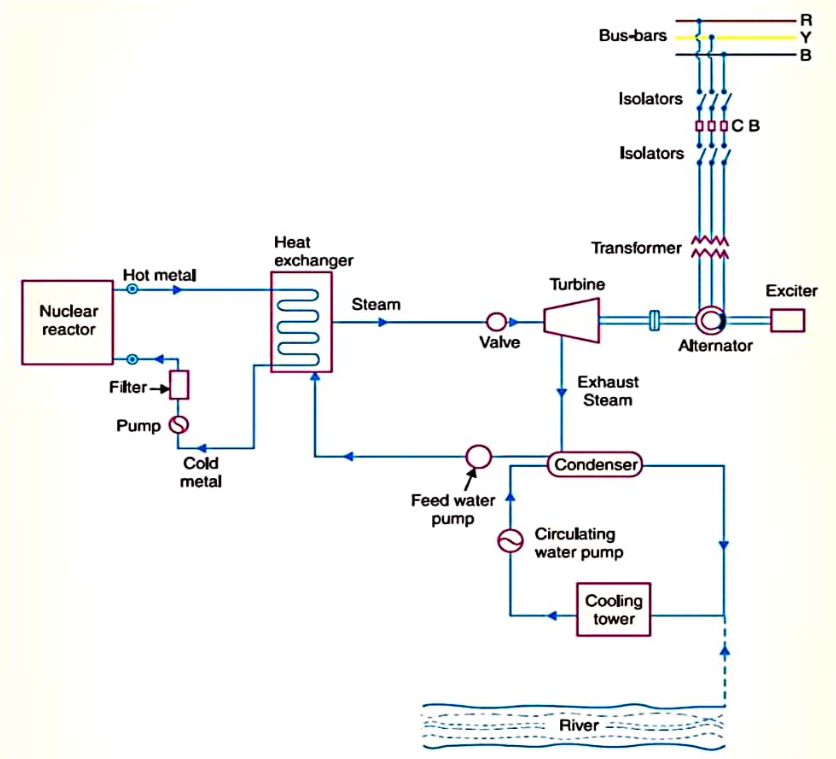
Nuclear Fission



$${}_0^1n + {}_{92}^{235}U \rightarrow {}_{56}^{141}Ba + {}_{36}^{92}Kr + 3\,{}_0^1n + \text{Energy}$$

- The release of huge amount of energy during fission is due to *mass defect i.e.* themass of the final product comes out to be less than the initial product.
- This mass defect is converted into heat energy according to Einstein's relation, $E = mc2$.

- The most important feature of a nuclear power station is that huge amount of electrical energy can be produced from a relatively small amount of nuclear fuel as compared to other conventional types of power stations.
- It has been found that complete fission of 1 kg of Uranium (U235) can produce as much energy as can be produced by the burning of 4,500 tons of high grade coal.
- Although the recovery of principal nuclear fuels (*i.e.*, Uranium and Thorium) is difficult and expensive, yet the total energy content of the estimated world reserves of these fuels are considerably higher than those of conventional fuels, *viz*., coal, oil and gas.



Schematic arrangement of Nuclear Power Station

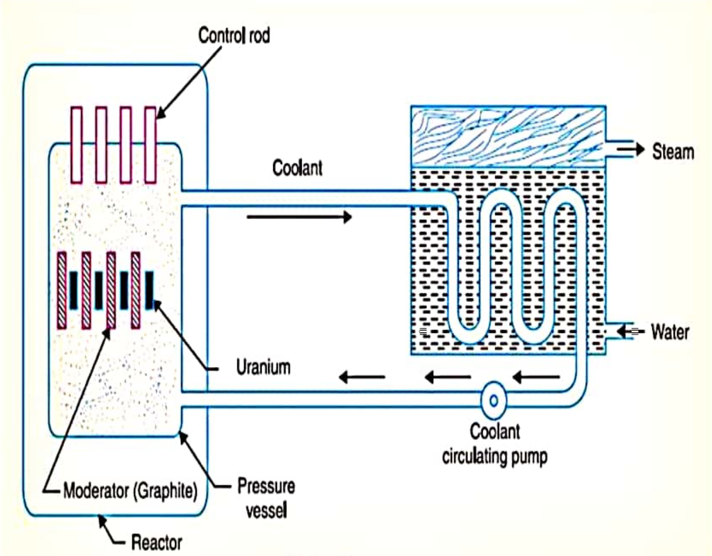
- At present, energy crisis is gripping us and, therefore, nuclear energy can be successfully employed for producing low cost electrical energy on a large scale to meet the growing commercial and industrial demands.

WORKING OF NUCLEAR POWER PLANT

- The whole arrangement can be divided into the following main stages :
  1) Nuclear reactor
  2) Heat exchanger
  3) Steam turbine
  4) Alternator.

NUCLEAR REACTOR

- It is an apparatus in which nuclear fuel (U235) is subjected to nuclear fission.
- It controls the *chain reaction* that starts once the fission is done.
- If the chain reaction is not controlled, the result will be an explosion due to the fastincrease in the energy released.
- A nuclear reactor is a cylindrical stout pressure vessel and houses fuel rods ofUranium, Moderator and control rods.



Nuclear Reactor

- The fuel rods constitute the fission material and release huge amount of energy when bombarded with slow moving neutrons.
- The moderator consists of graphite rods which enclose the fuel rods.
- The moderator slows down the neutrons before they bombard the fuel rods.
- The control rods are of cadmium and are inserted into the reactor.
- Cadmium is strong neutron absorber and thus regulates the supply of neutrons for fission. When the control rods are pushed in deep enough, they absorb most of fission neutrons and hence few are available for chain reaction which, therefore, stops.
- However, as they are being withdrawn, more and more of these fission neutrons cause fission and hence the *intensity* of chain reaction (or heat produced) is increased.
- Therefore, by pulling out the control rods, power of the nuclear reactor is increased, whereas by pushing them in, it is reduced.
- In actual practice, the lowering or raising of control rods is accomplished automatically according to the requirement of load.
- The heat produced in the reactor is removed by the coolant, generally a sodium metal.
- The coolant carries the heat to the heat exchanger.

What is chain reaction ?

- Nuclear fission is done by bombarding Uranium nuclei with slow moving neutrons.
- This splits the Uranium nuclei with the release of huge amount of energy and emission of neutrons (called fission neutrons).
- These fission neutrons cause further fission.
- If this process continues, then in a very short time huge amount of energy will be released which may cause explosion.
- This is known as *explosive chain reaction*. But in a reactor, controlled chain reaction is allowed.
- This is done by systematically removing the fission neutrons from the reactor.
- The greater the number of fission neutrons removed, the lesser is the intensity (*i.e.*, fission rate) of energy released.

HEAT EXCHANGER

- The coolant gives up heat to the heat exchanger which is utilized in raising the steam.
- After giving up heat, the coolant is again fed to the reactor.

STEAM TURBINE

- The steam produced in the heat exchanger is led to the steam turbine through avalve.
- After doing a useful work in the turbine, the steam is exhausted to condenser.
- The condenser condenses the steam which is fed to the heat exchanger through feedwater pump.

ALTERNATOR

- The steam turbine drives the alternator which converts mechanical energy intoelectrical energy.
- The output from the alternator is delivered to the bus-bars through transformer,circuit breakers and isolators.

ADVANTAGES

- The amount of fuel required is quite small. Therefore, there is a considerable savingin the cost of fuel transportation.
- A nuclear power plant requires less space as compared to any other type of the samesize.
- It has low running charges as a small amount of fuel is used for producing bulk electrical energy.
- This type of plant is very economical for producing bulk electric power.
- It can be located near the load centers because it does not require large quantities of water and need not be near coal mines. Therefore, the cost of primary distribution is reduced.
- There are large deposits of nuclear fuels available all over the world. Therefore, such plants can ensure continued supply of electrical energy for thousands of years.
- It ensures reliability of operation.

DISADVANTAGES

- The fuel used is expensive and is difficult to recover.
- The capital cost on a nuclear plant is very high as compared to other types of plants.
- The erection and commissioning of the plant requires greater technical know-how.
- The fission by-products are generally radioactive and may cause a dangerous amount of radioactive pollution.
- Maintenance charges are high due to lack of standardization. Moreover, high salaries of specially trained personnel employed to handle the plant further raise the cost.
- Nuclear power plants are not well suited for varying loads as the reactor does notrespond to the load fluctuations efficiently.
- The disposal of the by-products, which are radioactive, is a big problem. They have either to be disposed off in a deep trench or in a sea away from sea-shore.

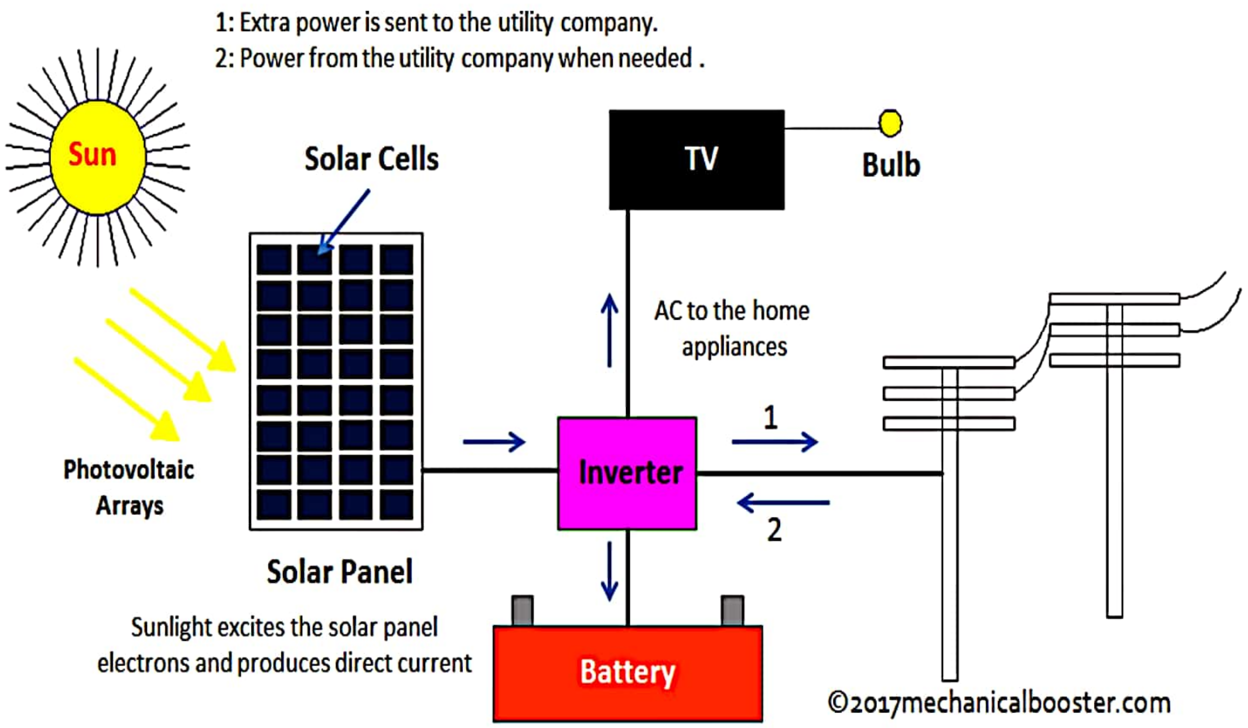
SOLAR POWER PLANT

Electrical energy can be harvested from solar power by means of either photovoltaic or concentrated solar power systems. Photovoltaic directly convert **solar energy into electricity**. They work on the principle of the **photovoltaic effect.** When certain materials are exposed to light, they absorb photons and release free electrons. Thisphenomenon is called as the photoelectric effect. Photovoltaic effect is a method of producing direct current electricity based on the principle of the photoelectric effect.

Main Components

Solar Panels

It is the heart of the solar power plant. Solar panels consists a number of solar cells. We have got around 35 solar cells in one panel. The energy produced by each solar cell is very small, but combining the energy of 35 of them we have got enough energy to charge a 12 volt battery.



Working of Solar Power Plant

Solar Cells

It is the energy generating unit, made up of p-type and n-type siliconsemiconductor. It's the heart of solar power plant.

Battery

Batteries are used to produce the power back or store the excess energyproduced during day, to be supplied during night.

D.C. to A.C. Converter (Inverter)

Solar panels produce direct current which is required to be converted intoalternating current to be supplied to homes or power grid.

Working of Solar Power Plant

As sunlight falls over solar cells, a large number of photons strike the p- type region of silicon. Electron and hole pair will get separated after absorbing the energy of photon. The electron travels from p-type region to n-type region due to the action of electric field at p-n junction. Further the diode is reversed biased to increase this electric field. So this current starts flowing in the circuit for individual solar cell. We combine the current of all the solar cells of a solar panel, to get a significant output. Solar power plant have a large number of solar panels connected to each other to get a large voltage output. The electrical energy coming from the combined effort of solar panels is stored in the Lithium ion batteries to be supplied at night time, when there is no sunlight. Storage of the energy generated by the solar panels is a important issue. Sometimes the unused energy generated during daytime is used to pump water to some height, so that it could be used to generate electricity usingits potential energy when required or mainly at night time.

For current being Tesla is providing its industrial energy pack to store energyand currently it is lighting up an entire island. Tesla has also made an offer to Australia that it could provide its battery pack for emergency blackouts. The cost of manufacturing of solar panels has decreased rapidly in last few years, same is said to be true with the industrial energy pack (Lithium ion batteries), as the production and demand increases their cost is going to decrease in coming few years.

Advantages of Solar Energy

- Most clean and renewable source of energy.
- It is available in abundance and endless.
- It provides electricity at low cost, as fuel is free.
- With new research in this sector we now have a good power storagesolution.
- Keeping in mind the pollution and cost of fossil fuel, it's becoming the most reliable source of clean energy.

Disadvantages of Solar Power Plant

- It requires a lot of land to be captured forever.
- Initial cost of installation is too high.
- The energy storage options are not efficient and moreover costly if efficient.

WIND POWER PLANT

- Wind energy is an indirect form of solar energy since wind is produced due touneven heating of the earth's crust by the sun.
- The kinetic energy of the wind can be utilized to produce with the help of wind turbine.

WIND POWER PLANT WORKING PRINCIPLE

- As the free wind stream interacts with turbine rotor, it transfers a part of the kineticenergy to the rotor due to which its speed decreases.
- This difference in kinetic energy is converted into mechanical power.
- This is the basic **wind power plant working principle**.
- The total wind power is equal to the incoming kinetic energy of the wind stream.It can be expressed as:

$$\textit{Total wind power, } P_t = (\rho A C_i^3)/2$$

Where, ρ = density of air (in kg/m^3)

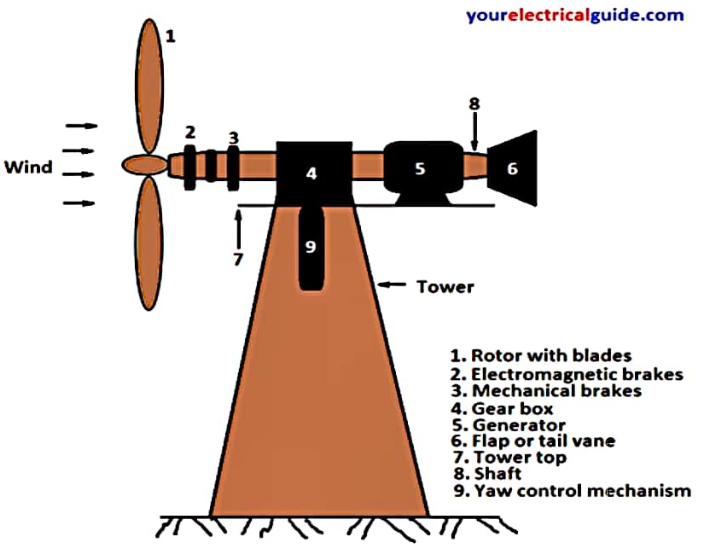
A = rotor swept area = πr^2 (r = radius of blades in meters)

C_i = incoming wind velocity (in m/s).

- From the above equation, it is clear that **total power of a wind stream is proportional to** the cube of incoming wind velocity, the density of air and the rotor swept area.
- **Hence, any small increase in wind speed can produce a significant rise in developed wind power.**

Horizontal Axis Wind Turbine Generator

- Horizontal axis wind turbine generators are being used all over the world successfully.
- The main components of a propeller type wind generator are shown in Figure.
- Usually, it has two of three blades made of high-density glass fiber reinforced plastic.
- The diameter of rotor ranges from 2 to 25 m.
- Modern rotors may be up to 100 m in diameter. Rotor blades are assembled on ahub.
- The hub, brakes, gearbox, generator with electrical controls is accommodated in a box called **nacelle**.
- Electromagnetic brakes are provided for automatic application of brakes if wind speed exceeds the designed speed.



Wind generator

- The whole system is mounted on a tower top. It is designed to bear up the wind loads during storms.
- A **yaw control mechanism** is also provided to adjust the nacelle around a vertical axis to keep it wind facing.
- A servomechanism operated by a wind direction sensor controls the nacelle so that the turbine blades are always oriented in the direction perpendicular to wind to have the maximum wind stream area.
- The pitch of the blade (0^o to 30^o) is controlled automatically so as to provide the feathering action.
- Thereby the power and speed of wind turbine shaft are adjusted to match with generator speed and its electrical output.

The pitch control mechanism adjusts the pitch to obtain the optimum performance.

- The wind energy is converted into mechanical energy by an aero turbine.
- This mechanical power is transferred through gears to the generator to increase itsspeed.
- Since rotor speeds are low, a gear system is necessary to match the synchronous speed of the generator.
- Due to fluctuations in wind speed, it not possible to obtain a power supply of a fixed frequency from windmills.
- To overcome this problem, the output of 3 phase generator is rectified and convertedinto AC with the help of a PWM inverter operating at 50 or 60 Hz.

ADVANTAGES

- It is a free and un-exhaustible source of energy.
- It is a clean and non-polluting source of energy.
- It has a low maintenance cost.
- It has a low cost of power generation (about Rs. 2.25/kWH).

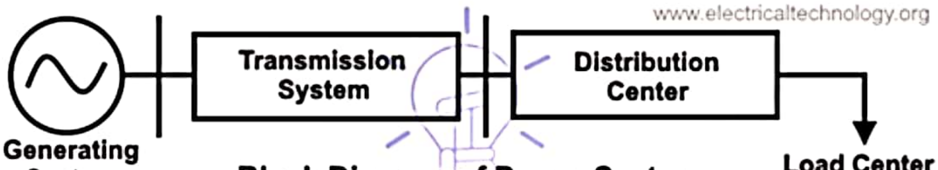
DISADVANTAGES

- At present capital cost of wind power plants is high. It is about Rs. 3.5 crores/MW.
- Wind energy is very fluctuating in nature. It is very difficult to design a wind energy system due to these fluctuations. This problem also requires the provision of a suitablestorage device to ensure continuous power supply.
- Large variations in wind speed during storms may cause damage to windmills.
- The efficiency of the system is in the range of 35 to 44%.
- **Windmill causes sound pollution.** A large unit can be heard few kilometers away.

TYPICAL AC ELECTRIC POWER SUPPLY SYSTEMS SCHEME

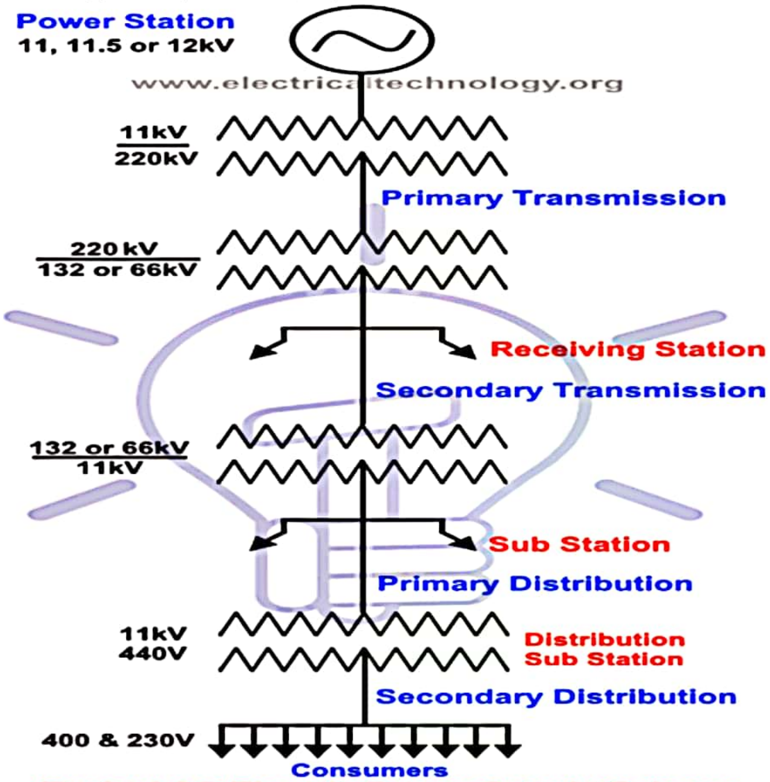
What is an Electric Power System?

- An **electric power system** or electric grid is known as a **large network of power generating plants which connected to the consumer loads**.
- The **lines network between Generating Station (Power Station) and consumer** of electric power can be divided into two parts.
- *Transmission System*
- **Distribution System**



Block Diagram of Power System

- We can explore these systems in more categories such as **primary transmission** and **secondary transmission** as well as **primary distribution** and **secondary distribution**.
- This is shown in the fig 1 below (**one line or single line diagram of typical AC power systems scheme**).
- The main objective of an electric power system is to obtain electrical energy and make it reachable safely to the load point where it is being used in usable form.
- This is done in five stages namely
    1. Generating Station
    2. Primary Transmission
    3. Secondary Transmission
    4. Primary Distribution
    5. Secondary Distribution
- The following parts of a typical power supply scheme are shown in figure 1.



Typical AC Electric Power Supply Scheme

Typical AC Electric Power Supply Systems Scheme (Generation, Transmission & Distribution)

- After these five levels, the energy must be available as the stated form in terms of voltage magnitudes, frequency and consistency.
- Generation means the conversion of a form of energy into electrical energy.
- Transmission implies the transport of this energy to very long distance with very high amount of voltage magnitude.
- Moreover, distribution is fulfilling the demand of the consumers at certified voltage level and it is done in terms of feeders.
- Feeders are the small-small chunks of load distributed at different places, physically.

GENERATION OR GENERATING STATION

- The place where **electric power produced by the parallel connected three phase alternators/generators is called Generating Station** (i.e. power plant).
- The ordinary power plant capacity and generating voltage may be **11kV, 11.5 kV 12kV** or **13kV**. But economically, it is good to step up the produced voltage from (11kV, 11.5kV Or 12 kV) to **132kV**, **220kV** or **500kV** or more (in some countries, up to **1500kV**) by Step up transformer (power Transformer).
- Generation is the part of power system where we convert some form of energy into electrical energy.
- This is the source of energy in the power system. It keeps running all the time.
- It generates power at different voltage and power levels depending upon the type of station and the generators used.
- The maximum number of generators generate the power at voltage level around **11kV- 20kV**. The increased voltage level leads to greater size of generator required and hence the cost involved.

PRIMARY TRANSMISSION

- The electric supply (in **132kV**, **220 kV**, **500kV** or greater) is transmitted to load center by three phase three wire (**3 Phase – 3 Wires** also known as **Delta connection**) overhead transmission system.
- As the voltage level which is generated is around **(11-20) kV** and the demand is at various levels of voltage and at very faraway places from the generating station.
- For example, the generating station can be generating voltage at 11kv, but the load center is **1000km** apart and at the level of **440V**.

SECONDARY TRANSMISSION

- *Area far from the city (outskirts) which have connected with receiving stations by lines is called secondary transmission.*
- At receiving station, the **level of voltage reduced by step-down transformers** upto **132kV, 66 or 33 kV**, and electric power is transferred by three phase three wire **(3 Phase – 3 Wires)** overhead system to different **sub stations**.

PRIMARY DISTRIBUTION

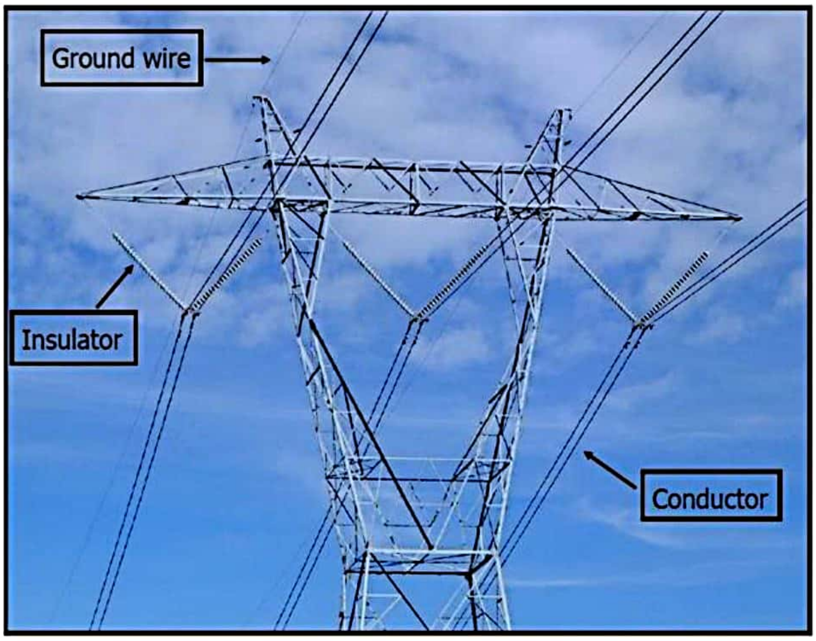
- At a substation, the level of **secondary transmission voltage (132kV, 66 or 33 kV)** reduced to **11kV** by **step down transforms**.

SECONDARY DISTRIBUTION

- Electric power is transferred by (from primary distribution line i.e.11kV) to distribution substation is known as secondary distribution.
- *This substation is located nearby domestic & consumers areas where the level of* ***voltage reduced to 440V by step down transformers****.*

ELEMENTS OF TRANSMISSION LINES

- A variety of components are required to successfully deliver electricity from generatingstations to local residential and commercial areas.
- The primary components include the transmission structures, conductors, insulators,and ground wires.



TRANSMISSION STRUCTURES

- **Transmission structures** are the most visible component of transmission lines.
- Transmission structures come in many different designs, but two common types are:

1) **Lattice Steel Towers (LST)** consists of a steel framework of individual structuralcomponents that are bolted or welded together.
2) **Tubular Steel Poles (TSP)** are hollow steel poles fabricated either as one piece or asseveral pieces fitted together.

CONDUCTORS

- **Conductors** ("wires") are comprised of materials that readily conduct electric current.
- Conductors used in transmission lines are usually aluminum placed over a steel core forreinforcement.
- Transmission line conductors are not insulated; insulation is provided by the air.

INSULATORS

- Conductors are connected to towers via **insulators** that support the conductors on thetower.
- They must withstand normal operating voltage and surges due to switching and lightning.
- Insulators have commonly been comprised of porcelain or toughened glass, which need routine cleaning to eliminate dust build-up that can lead to insulator flashover and noise.
- Newer insulators are composed of polymer or silicon, which are lightweight and shatter-resistant.

There are two common types of insulators:

1) **Horizontal post-type**, which supports the conductor to the side of the structure.
2) **Suspension-type**, which suspends the conductor below the structure

GROUND WIRES

- **Ground wires** (also called shield or earth wires) are strung along the tops of the towersto protect the system from lightning strikes.

AC DISTRIBUTION SYSTEM

- Now-a-days electrical energy is generated, transmitted and distributed in the form of alternating current.
- One important reason for the widespread use of alternating current inpreference to direct current is the fact that alternating voltage can beconveniently changed in magnitude by means of a transformer.

- Transformer has made it possible to transmit AC power at high voltage and utilize it at a safe potential.
- High transmission and AC Distribution System voltages have greatly reduced the current in the conductors and the resulting line losses.

The AC Distribution System is classified into

1) Primary distribution system and
2) Secondary distribution system.

PRIMARY DISTRIBUTION SYSTEM:

- It is that part of AC Distribution System which operates at voltages somewhat higher than general utilization and handles large blocks of electrical energy than the average low-voltage consumer uses.
- The voltage used for primary distribution depends upon the amount of power to be conveyed and the distance of the substation required to be fed.
- The most commonly used primary distribution voltages are 11 kV, 6.6 kV and 3.3 kV.
- Due to economic considerations, primary distribution is carried out by 3-phase, 3-wire system.

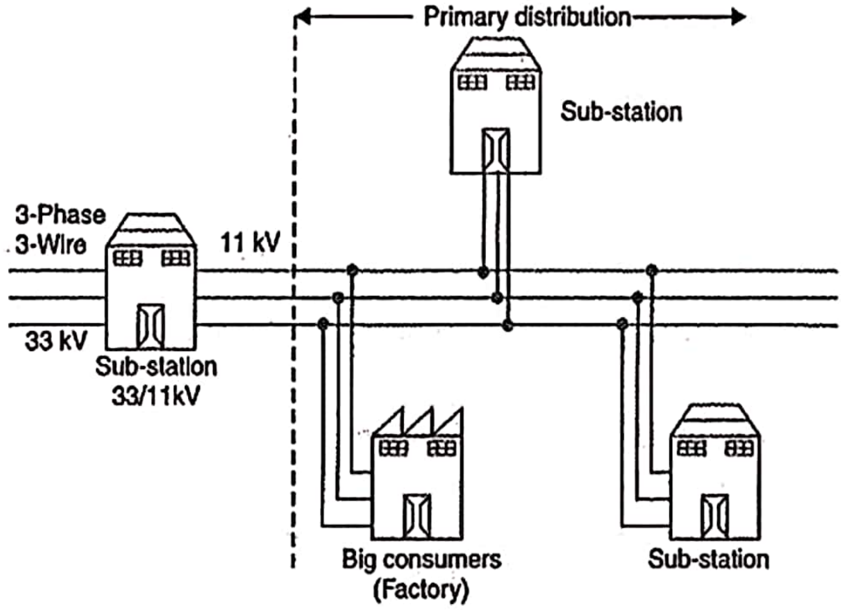


Fig. 12.2

- Electric power from the generating station is transmitted at high voltage tothe substation located in or near the city.
- At this substation, voltage is stepped down to 11 kV with the help of step-down transformer.
- Power is supplied to various substations for distribution or to bigconsumers at this voltage.
- This forms the high voltage distribution or primary distribution.

SECONDARY DISTRIBUTION SYSTEM:

- It is that part of AC Distribution System which includes the range of voltages at which the ultimate consumer utilizes the electrical energy delivered to him.
- The secondary distribution employs 400/230 V, 3-phase, 4-wire system.

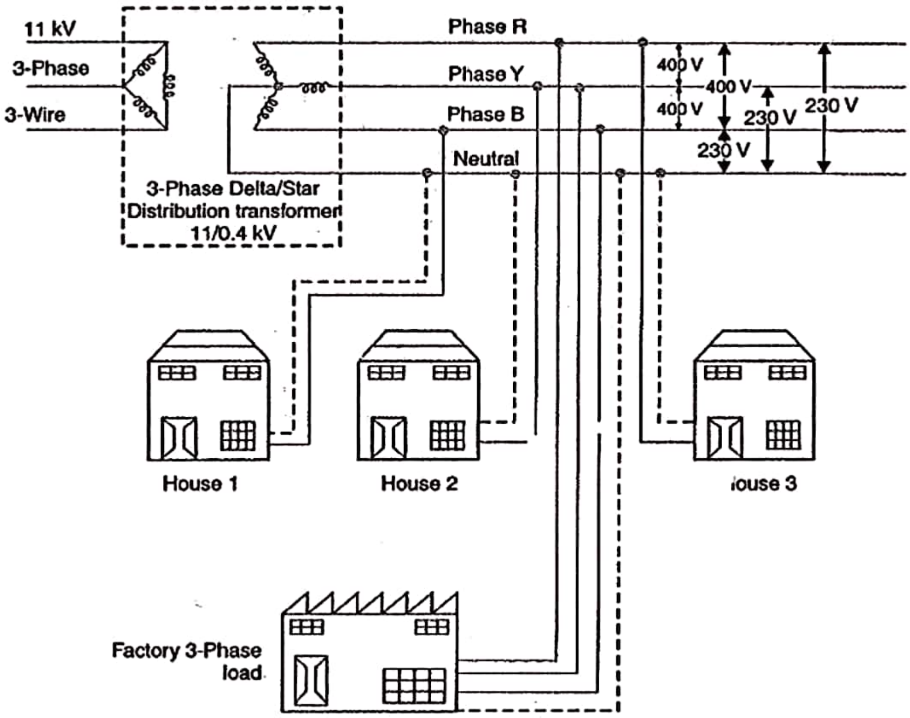


Fig. 12.3

- The primary distribution circuit delivers power to various substations, called **distribution substations**.
- The substations are situated near the consumer's localities and contain step-down transformers.
- At each distribution substation, the voltage is stepped down to 400 V and power is delivered by 3-phase,4-wire a.c. system.
- The voltage between any two phases is 400 V and between any phase and neutral is 230 V.
- The single phase domestic loads are connected between any one phase and the neutral, whereas 3-phase 400 V motor loads are connected across 3- phase lines directly.

N. praneeth Reddy

UNIT-1 Semiconductor Diode (or) P-N Junction Diode

" In a piece of semiconductor material, if one half is doped by p-type impurity and other half is doped by N-Type impurity, a PN Junction is formed." ①

(or)

" If donar Impurities are introduced into one side and acceptors are introduced into other side of single crystal of the semiconductor" i.e Germanium (or) silicon, PN junction is formed.

→ It is represented as

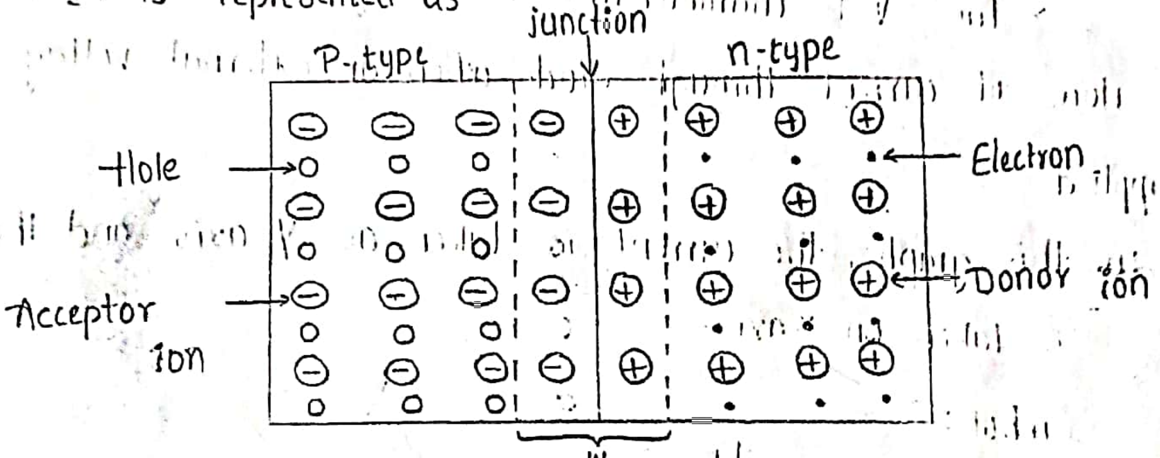


fig:- A schematic diagram of p-N junction.

→ The donar ions are indicated by plus (+) sign because it donates an electron and becomes positively charged.

→ The acceptor ion is indicated by minus (-) sign because it accepts an electron and becomes negetively charged.

→ As shown in figure, the N-type material has high concentration of free electrons, while p-type material has high concentration of holes.

N. Praneeth Reddy

→ As a result the electrons diffuse over p-side and holes diffuse over N-side.

→ This process is called as diffusion. (7)

→ Since the junction is depleted by the mobile charges or space-charge region (or) transition region.

→ The thickness of this region is in the order of

$$10^{-4}\text{ cm} = 10^{-6}\text{ m} = 1\text{ micron}$$

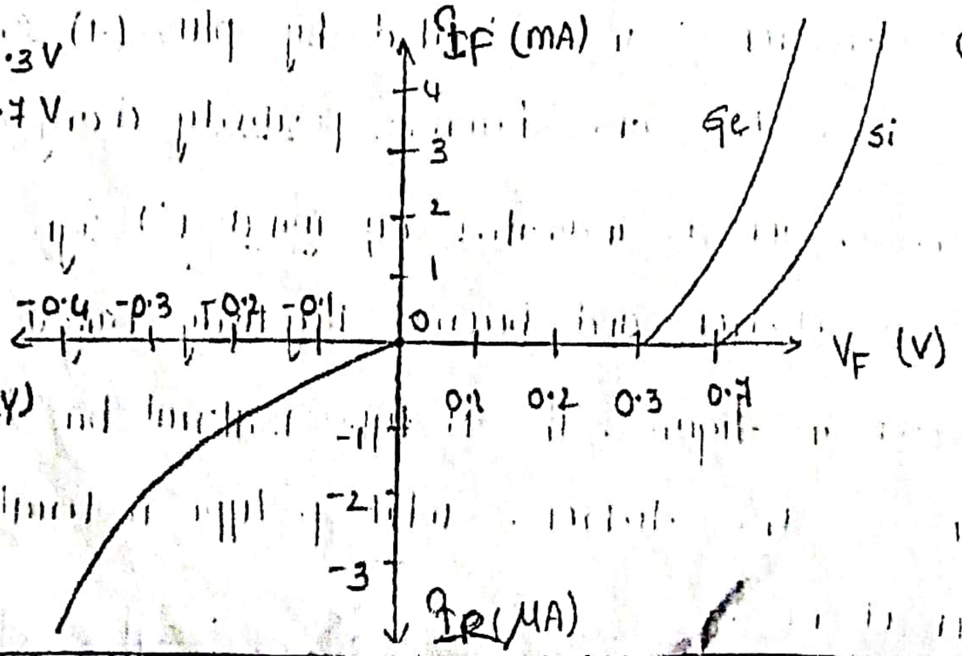
:- VI characterstics of P-N Junction Diode :-

→ The V-I characterstics is the graph which gives the flow of current through diode when an external voltage is applied.

→ In this graph, the current is taken as Y-axis and the voltage is taken on X-axis.

Symbol :-

→ Ge = 0.3 V
Si = 0.7 V

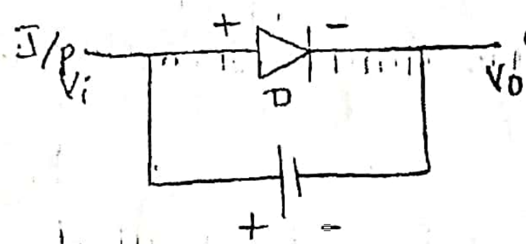


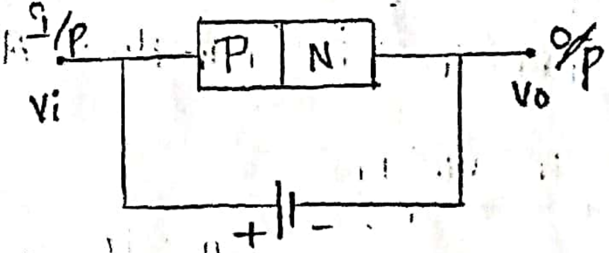
Forward Bias :-

→ Under forward bias, positive terminal of the battery is connected to the p-type and negative terminal of the battery is connected to N-type.

→ When the forward voltage Vf is applied, then the majority charge carriers are moved towards the junction.

→ The voltage at which diode starts conducting is called as cut-in voltage (or) knee voltage (or) Threshhold voltage (or) Break point voltage (or) off set voltage.





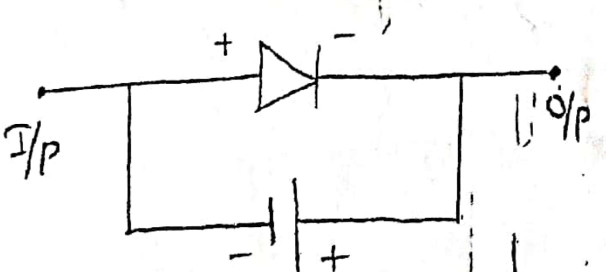
Vo = Vi

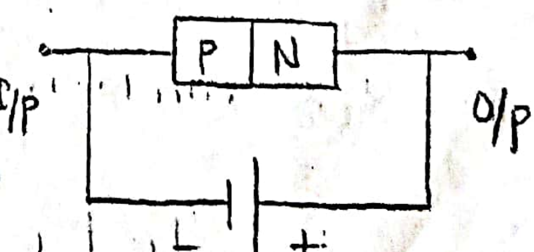
Reverse Bias :-

→ Under reverse bias, the negative terminal of the battery is connected to p type and the positive terminal of the battery is connected to N-type.

→ As a result the majority charge carriers are attracted and moved towards the battery. As a result the width of depletion region increases.

→ Theoritically no current should flow in the external circuit





→ But in practice a very small current of order of few micro Amperes flows under reverse bias. (41)

→ This current is due to minority charge carriers of both p type and n type. It is known as reverse Saturation Current

→ The magnitude of reverse Saturation current mainly depends upon the junction temperature because the major Source of minority carriers in thermally broken covalent bonds.

→ When the reverse voltage further increases at particular point the junction will break down.

→ Due to this break down the reverse current increases rapidly

Cut-In Voltage :–

→ It is the forward biased voltage at which the current through the PN-junction diode starts increasing exponentially.

The cut In voltage is 0.3 V for Germanium
0.7 for Silicon

→ In forward bias the current flowing through the diode is in the order of milli Amps (mA). i.e; 10^{-3}

→ When the forward bias voltage is keep on increasing then forward current (I_f) increases linearly.

The diode current is given by

$$I = I_0 \left[e^{V/\eta V_T} - 1 \right]$$

Where,

I_0 = Reverse Saturation Current

I = Current through the diode

V = Voltage Applied

η = Constant

$\eta = 2$ (Silicon) ; $\eta = 1$ (Germanium)

V_T = Thermal Voltage

$V_T = \frac{KT}{Q} \Rightarrow V_T = \frac{T}{11,600}$ Here, $K = 1.38 \times 10^{-23}$ J/k
$Q = 1.602 \times 10^{-19}$ C

At room temp. $T = 300k$, $V_T = 0.026\,V = 26\,mV$

Applications of PN junction diode :—

→ Rectifiers in DC power supply

→ Switch

→ clamping circuits

→ clipping circuits

→ Zener diode in voltage Regulators.

→ light emitting diodes in digital diodes.

—: ZENER DIODE :—

Radhe

Forever

VI characterstics of Zener Diode :—

→ When the reverse voltage reaches the break down voltage in a normal PN junction diode, the current through the junction will be high.

→ Such as an operation is destructive and the diode gets damaged.

→ Where as diodes can be designed with adequate power dissipation capabilities to operate in the break down region.

⑥

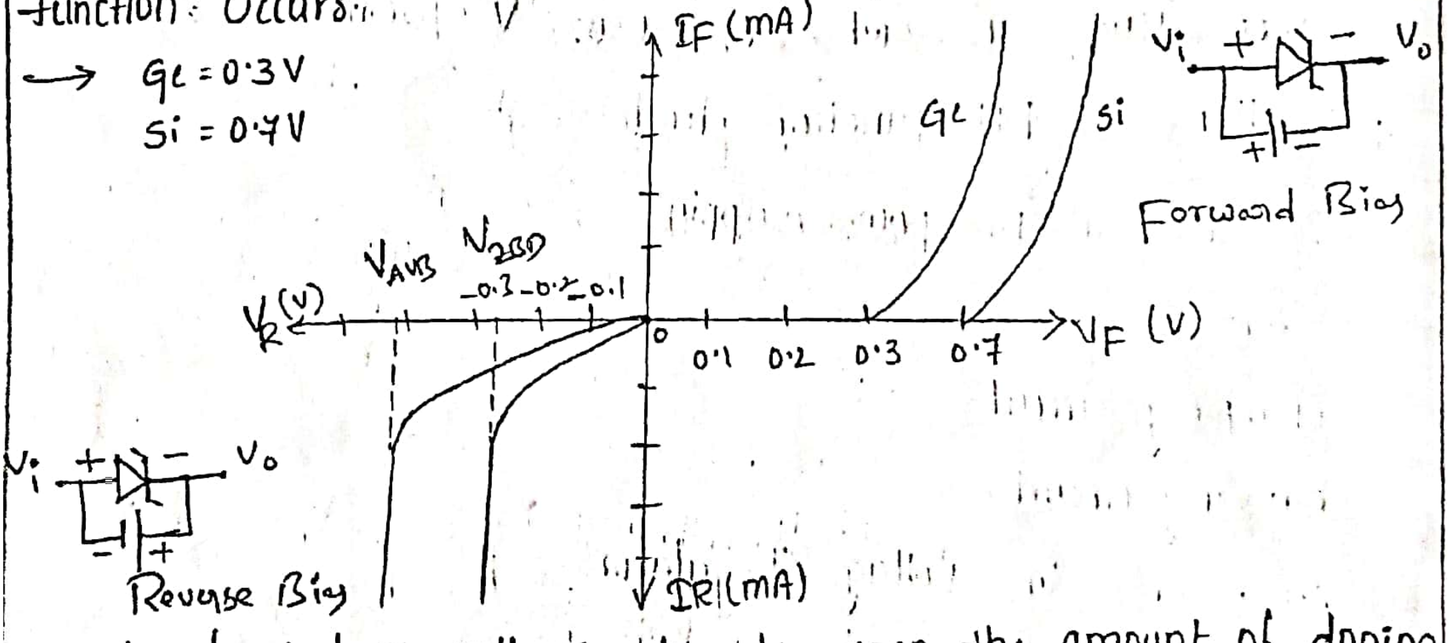
→ One Such diode is known as "zener Diode".

→ The zener diode is heavily doped than the ordinary diode.

→ From the VI characterstics of zener diode shown in the figure it is found that the operation of zener diode is same as that of an ordinary PN junction diode under forward biased condition

→ Where as under reverse biased condition, break down of the junction Occurs.

→ Ge = 0·3 V
Si = 0·7 V



→ The break down voltage depends upon the amount of doping

→ If the diode is heavily doped, the depletion layer will be thin and Consequently breakdown occurs at lower reverse voltage and further the breakdown voltage is sharp.

→ Whereas a lightly doped diode has the higher breakdown voltage.

→ Thus breakdown voltage can be selected with the amount of doping.

→ The sharp increasing currents under breakdown conditions are due to the following two mechanisms (7)

1) Avalanche breakdown
2) Zener breakdown.

1) Avalanche Breakdown :—

→ As the applied reverse bias increases the field across the junction increases correspondingly.

→ Thermally generated carriers, while transversing the junction, acquire a large amount of kinetic energy from this field.

→ As a result, the velocity of these carriers increases

→ These electrons disrupt covalent bond by colliding with immobile ions and create new electron - hole pairs.

→ These new carriers again acquire sufficient energy from the field and collide with other immobile ions there by generating further electron hole pairs

→ This process is cummulative in nature and results in the generation is known as avalanche multiplication.

→ This process results in flow of large amount of current at the same value of reverse bias.

2) Zener Breakdown :—

→ When the p and N regions are heavily doped direct rupture of covalent bonds taken place, because of the strong electronic field, at the junction of the PN diode.

→ The new electron hole pairs so created increase the reverse current in a reverse biased PN diode.

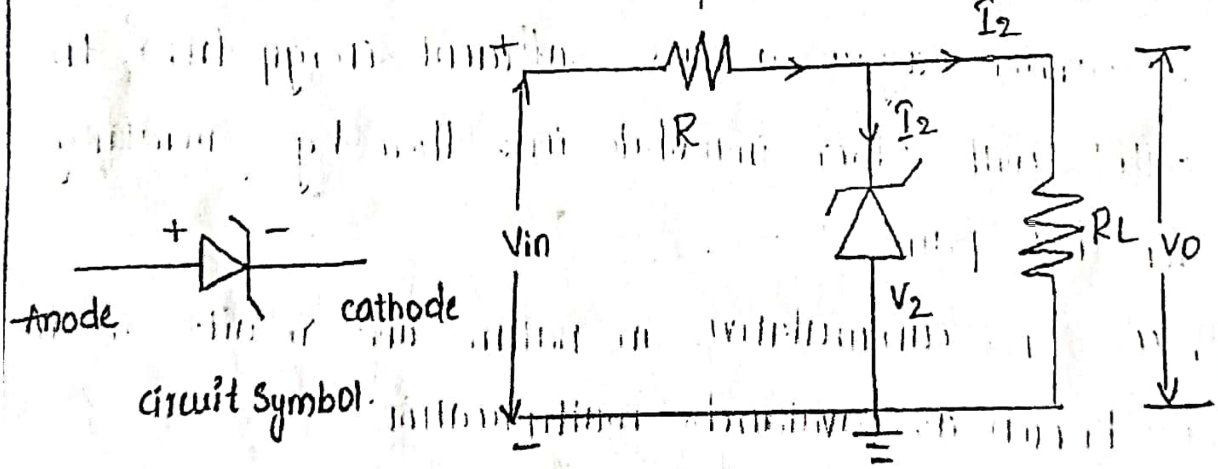
→ The increase in current taken place at a constant values of the reverse bias typically below 6V. for heavily doped diodes. 8

Applications of zener diode as voltage Regulator :-

→ From the zener characterstics, under the reverse bias condition the voltage ~~occurs~~ across the diode remains almost constant although the current through the diode increase.

→ Thus the voltage across the zener diode Senes a referance Voltage.

→ Hence the diode can be used as voltage regulator.



fig(b) :- As a Voltage regulation.

→ In figure it is required to provide constant voltage across load resistance R_L. where as the input voltage across load may be varying over a range

→ As shown, zener diode is reverse biased and as long as the input voltage does not fall

→ Below V_Z (Zener breakdown voltage) the voltage across the diode will be constant and hence the load voltage will be constant.

9

—: RECTIFIER :—

→ A Rectifier is a device which converts ac voltage (bi-directional) to pulsating dc voltage (uni-directional).

→ Any device that offers low resistance to the current in one direction but high resistance to current in the opposite direction is called Rectifier.

→ Such device is capble of converting a Sinusoidal input wave form whose average value is zero, into a unidirectional wave form with non zero average component.

→ A rectifier utilizes unidirectional conduction device like a vaccum diode (or) PN-Junction diode.

Based on period of conduction, rectifiers are classified into two types.

1) Half wave Rectifier.

2) full wave Rectifier — center-tapped FWR, Bridge FWR

1) Half Wave Rectifier :—

→ It converts an Ac voltage into a pulsating dc voltage by using only one half of the applied Ac voltage (or) one half cycle

Half Wave Rectifier without filter:-

(10)

→ It converts Ac voltage into a pulsating DC voltage using half of the applied Ac voltage.

→ In half wave rectifier the diode conducts during one half of the Ac cycle only.

→ let vi be the input voltage applied to the primary windings of the transformer. $V_i = V_m \sin\theta$, $0 \le \theta \le 2\pi$

→ It is represented as $V_i = V_m \sin\omega t$; $V_m >> V_r$

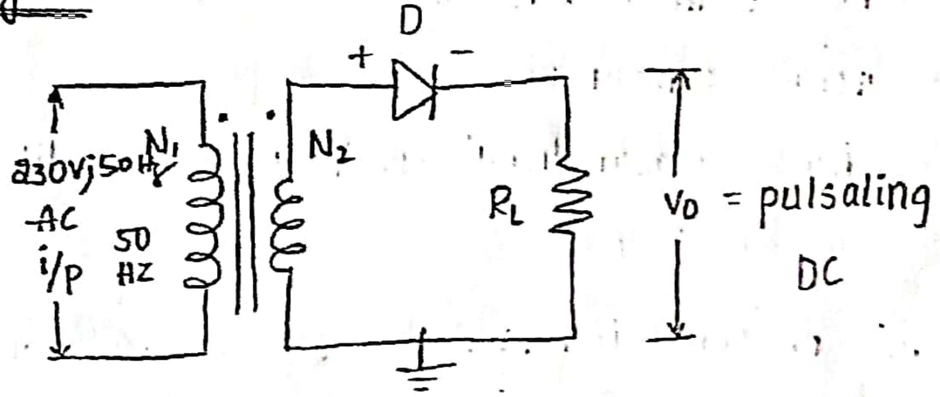
$V_i = V_m \sin 2\pi f t$

Where,

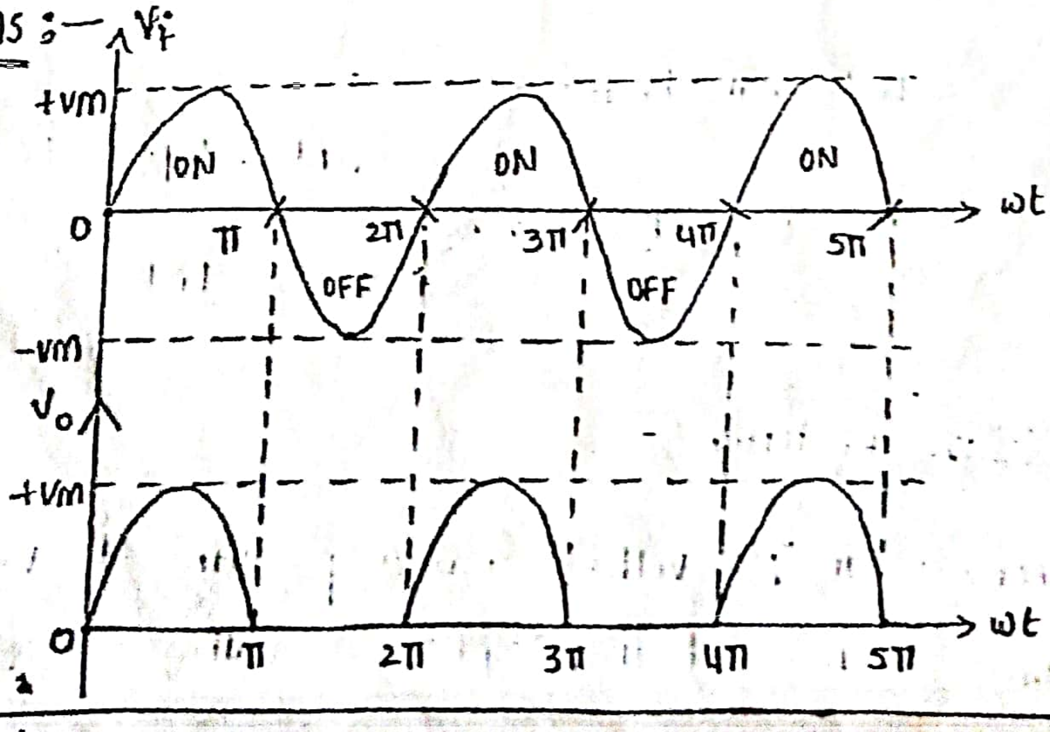
V_m = max. Value of Secondary voltage

V_r = cut in voltage of the diode.

circuit diagram :-



Wave forms :-



Ripple factor :- It is defined as the ratio of RMS value of AC component to DC component.

$$\gamma = \frac{V_{r,rms}}{V_{dc}} \qquad [\gamma = 1.21]$$

Efficiency (η) :- It is defined as the ratio of dc output power to Ac input power.

$$\eta = \frac{\text{dc. output power}}{P_{rms}\,(ac)} = \frac{P_{dc}}{P_{rms}}$$

→ The maximum efficiency of half wave rectifier is 40.6 %.

Half Wave rectifier with filter :-

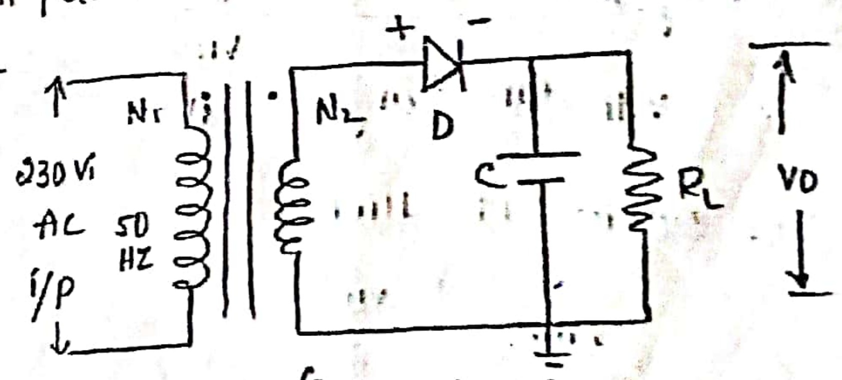
→ During positive - half cycle of the input signal, the anode of the diode is more +ve with respect to cathode hence the diode conducts i.e; "ON - State".

→ During the negetive half cycle of the input signal, the anode anode becomes -ve with respect to cathode, hence the diode does not conduct. i.e; "OFF - State"

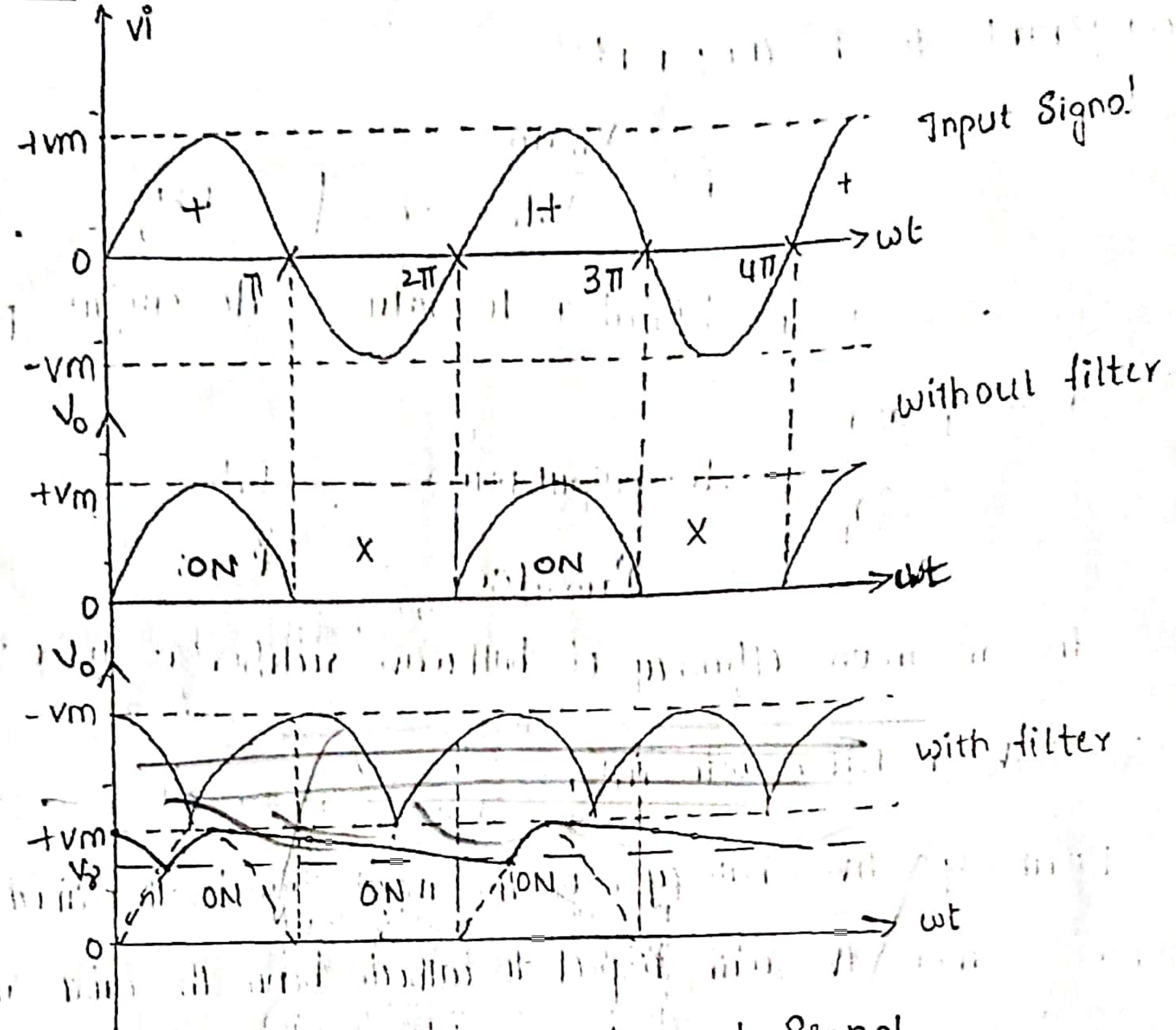
→ For an ideal diode, the impedance in this case is zero

→ Hence the out put is zero.

Circuit diagram :-



The capacitor acts as filter, i.e the capacitor (C) filter allows only Ac signal and attenuates DC signal wave forms :-



→ Average voltage (or) DC voltage of Input Signal

$$V_{dc} \text{ (or) } V_{avg} = 0$$

→ Root mean square value of Input Signal

$$V_{rms} = \frac{V_m}{\sqrt{2}} \text{ for HWR}$$

→ vdc (or) Vavg for output of HWR

$$V_{dc} \text{ (or) } V_{avg} = \frac{V_m}{\pi} \Rightarrow \frac{V_m}{\pi}$$

→ Vrms for output of HWR

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

Advantages :-

1) The circuit is Simple

2) low cost

Disadvantages :-

1) Ripple factor is large

2) Efficiency is Small

3) low TUF i.e; transformer is not utilized.

⇒ 2) Full Wave Rectifier :-

→ It converts an AC voltage into a pulsating DC voltage by using both the half cycles of the applied ac voltage.

→ It employs two diodes in which one conducts during the other half cycles.

→ full wave rectifiers are of two types :-

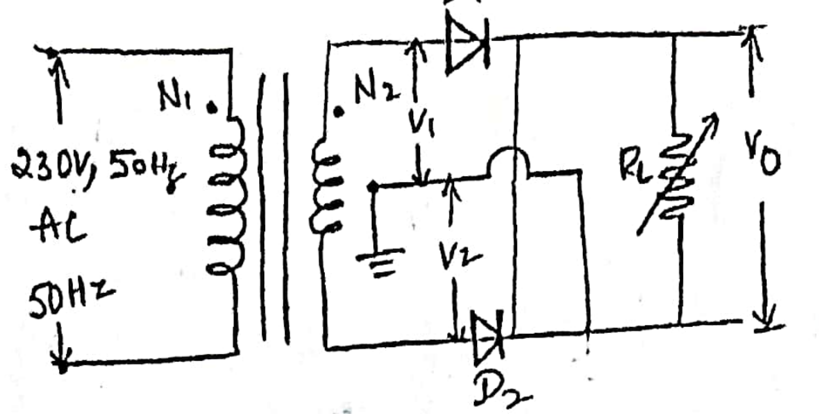
i) center tapped transformer (FWR)

ii) Bridge (FWR)

i) center-tapped Transformer :- In these rectifier the diodes are connected to a common load resistor (R_L)

→ A centre-tap transformer is one which produces two sinusodical wave forms of the same magnitude and frequency but out of phase with respect to ground in the secondary winding of the transformer.

→ The circuit for center tapped full wave rectifier is as shown in the figure



center Tapped transformer

operation :-

i) During positive half cycle :

→ During positive half cycle of input signal, the anode of diode D_1 becomes positive and at same time cathode of the diode D_2 will become negative. Hence D_1 conducts (ON) and D_2 does not conduct (OFF). so the input is appeared across the output through diode 'D_1'.

ii) During the negative half cycle :

→ During the negative half cycle of the input, the anode of diode D_1 becomes negative and at the same time the cathode of diode D_2 becomes +ve.

→ Hence diode D_2 conducts (ON) and D_1 does not conduct (OFF). So the input at diode D_2 is appeared across of output through D_2.

Analysis of FWR :-

→ The input signal equation for FWR is

$$V_i = V_m \sin\omega t \quad (\omega t = \theta)$$

$$V_i = V_m \sin\theta \; ; \quad 0 \le \theta \le 2\pi$$

→ out put equation of full wave rectifier is

$$V_0 = V_m \sin\theta \; ; \; 0 \le \theta \le \pi$$

$$V_0 = V_m \sin\theta \; ; \; \pi \le \theta \le 2\pi$$

→ Vdc (or) Vavg for input signal of FWR

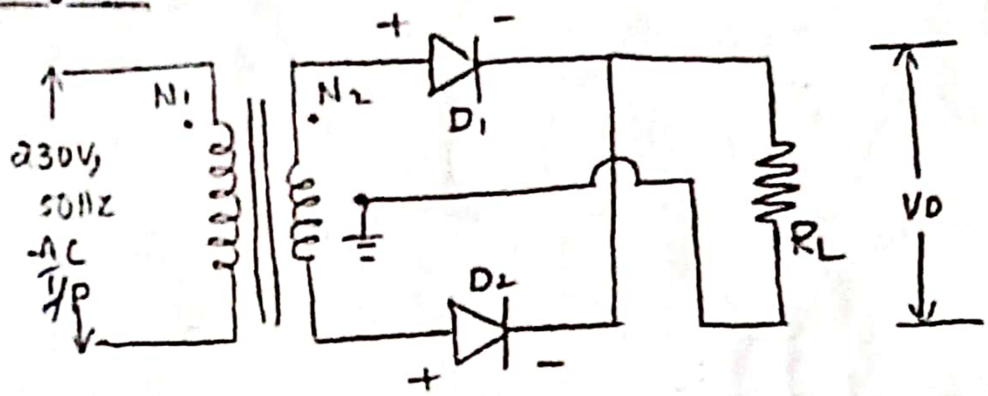
$$V_{dc} \text{ (or) } V_{avg} = 0$$

Full wave Rectifier without filter :-

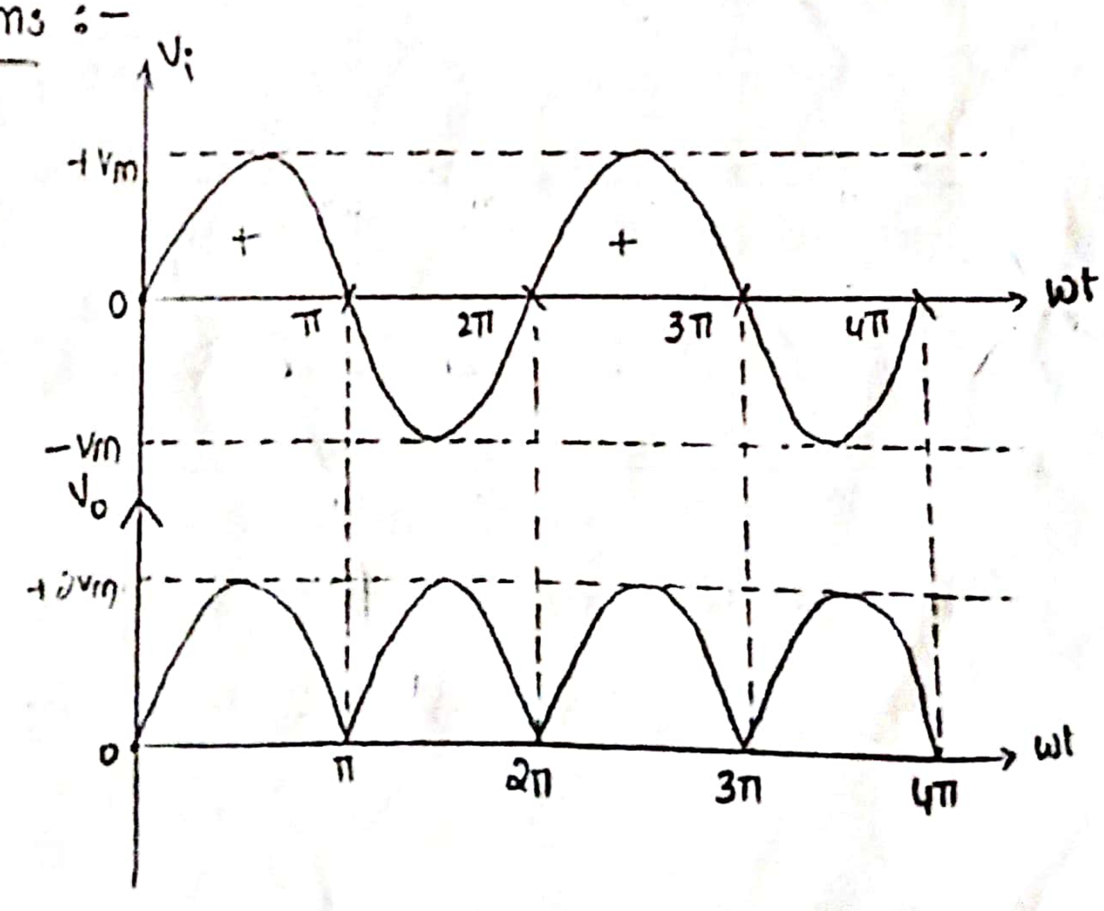
→ for the +ve half cycle, the diode "D1" gets forward biased, closed loop, ON switch and diode "D2" gets reverse biased open loop, "OFF" switch.

→ for the -ve half cycle the diode "D1" gets reverse biased, open loop, "OFF" switch and diode "D2" gets forward biased, closed loop, "ON" switch.

Circuit diagram :-

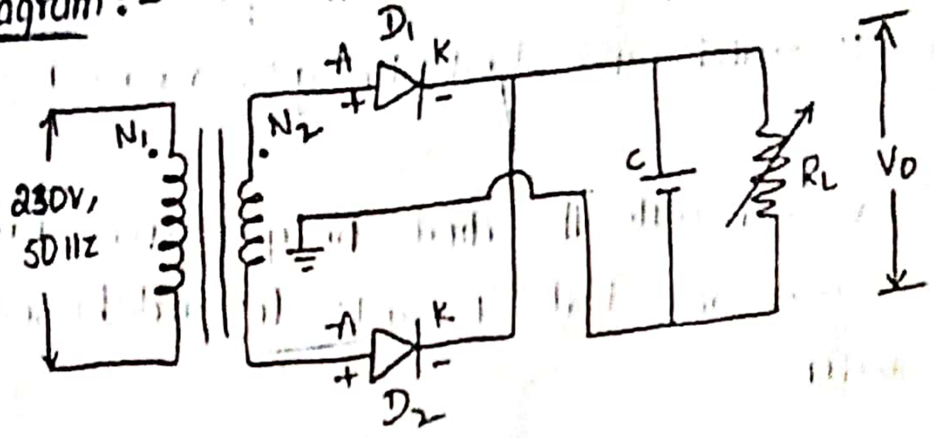


Wave forms :-

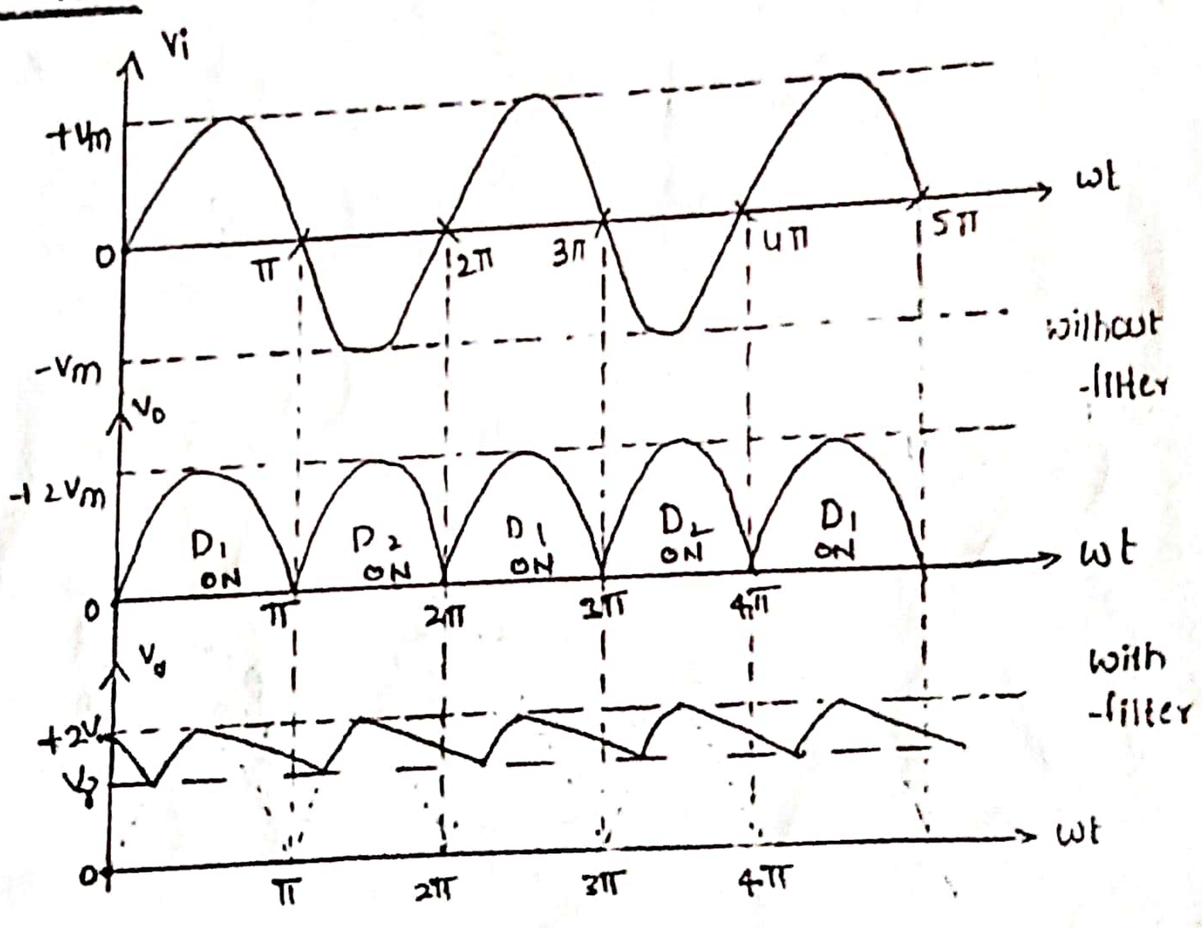


Full wave Rectifier with filter :-

circuit diagram :-



Wave forms :-



The capacitor acts as filter, i.e the capacitor (c) filter allows only AC signal and attenuates DC sign

Transistor

- BJT (bipolar)
  - NPN
  - PNP
- FET (unipolar)
  - JFET
    Depletion mode
    - N-channel
    - P-channel
  - MOSFET
    - Depletion mode
      - N-channel
      - P-channel
    - Enhancement mode
      - N-channel
      - P-channel

Bipolar junction transistor :—

→ A bipolar junction transistor is a three terminal semiconductor device in which the current ~~could~~ conduction is due to both type of charge carriers (majority & minority)

→ BJT is small in size

→ It is used as amplifier and it is also used in oscillator circuits.

→ It is used as switch in digital circuits.

→ BJT has wide range of applications in computers, satellites and other modern communication systems.

Transistor :—

→ Transistor is a three terminal device. i.e;
Emitter, Base, collector

→ Emitter is heavily doped so that it can inject a large number of charge carriers into the base.

→ Base region is lightly doped and very thin. It passes most of the injected charge carriers from emitter into collector.

→ Collector is moderately doped.

Advantages of Transistors :—

→ Small size
→ Less weight
→ Low cost
→ High efficiency
→ Rugged construction
→ low operating voltage
→ less power consumption.

Types of transistor amplifier configuration :—

When a transistor is to be ~~conducted~~ connected in a circuit, one terminal is used as a input terminal, the other other terminal is used as an output terminal, and the third terminal is common for both input and output.

Common Base configuration :—

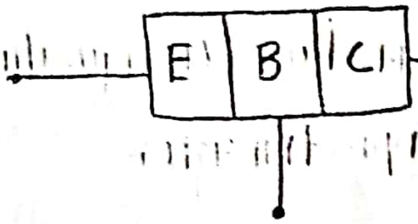
This is also called as grounded base configuration. In this configuration, Emitter is the input terminal, the collector is output terminal and base is common terminal.

Common Emitter Configuration :—

This is also known as the grounded Emitter configuration, In this the base is input terminal and collector is output terminal and emitter is common terminal.

Common collector configuration:—

In this common collector configuration, the base is input terminal and emitter is output terminal and the collector is common termial.



Emitter:—

→ Emitter emits charge carriers either p (or) n

→ Emitter is heavily doped when compared to base and collector

→ The emitter region is moderate.

→ It emits holes in pnp and electrons in npn.

Base:—

→ It lies between emitter and collector

→ It is n type in pnp and p type in npn transistor.

→ Base region is lightly doped.

→ Base region is very thin when compared to emitter and collector

→ The charge carriers emitted by the emitter must travel through the base to reach collector.

Collector:—

→ The charge carriers emitted by the emitter are collected by the collector.

→ collector and emitter are of same type materials

→ It collects holes in pnp, electrons in pnp transistors

→ collector is moderatly dopped

→ Collector region is large when compared to B and E

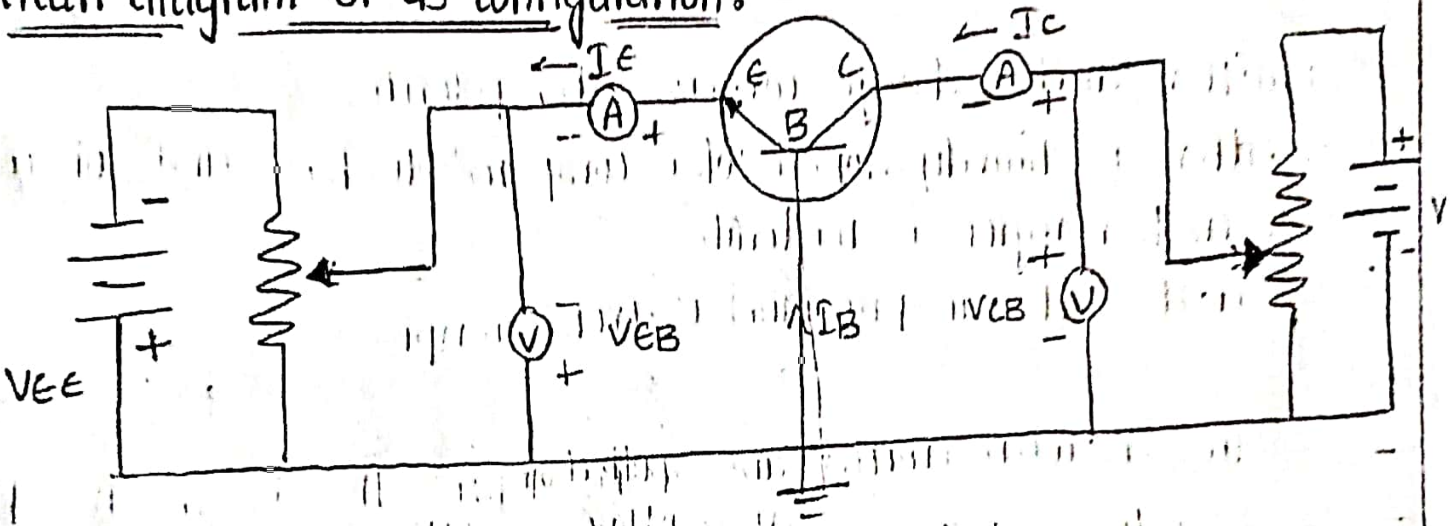
→ Due to collision of charge carriers in collector region the heat will be generated to dissipate this heat to the Surrounding the collector region is made large

Transistor Configuration's :—

Common Base configuration :—

→ The circuit diagram for common base configuration is shown below consider the transistor as npn transistors.

Circuit diagram of CB configuration:—



Input characterstics :—

→ To determine the input characterstics the collector-base voltage VCB is kept constant at zero volts and there by the emitter current IE is increased

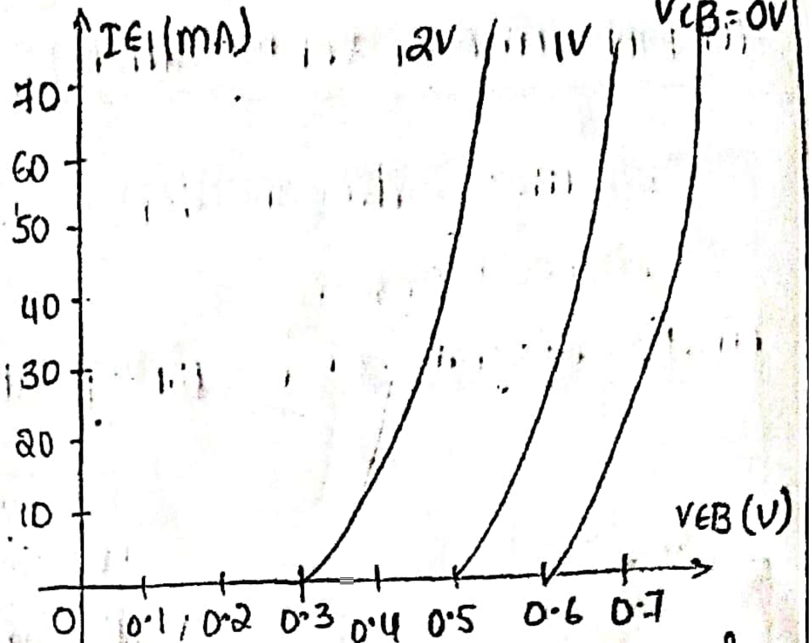
→ IE is increased by increasing VEB

→ This is repeated for higher fixed values of VCB (0V, 2V, 4V...)

→ Input characterstics is a curve down between emitter current IE and Emitter to base voltage VEB at constant collector voltage

→ when $V_{CB} = 0$ and the emitter to base junction is in forward bias. so the emitter current increases rapidly by small increasing in VBE.

→ Due to this the junction behaves as forward biased diode and the characteristics are same as diode.



→ When the VCB is increased in steps i.e (V_{CB} > 1V) the width of base junction decreases therefore current I_E Increases Therefore, the shifts towards left as VCB increased.

output characterstics :-

→ To determine the out put characterstics, the emitter current I_E is kept constant at suitable value by adjusting VEB

→ The out put characterstics is drawn between collector current I_C and collector to base voltage (VCB) at constant I_E.

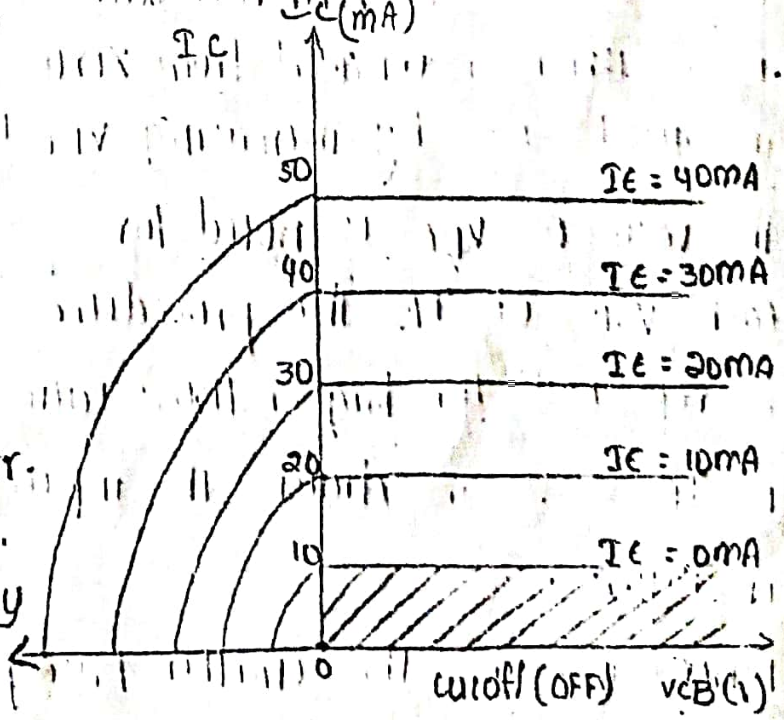
→ From the output characteristics it is clear that at constant values of I_E, I_C is independent of VCB

→ The current I_E, I_C is input of VCB

→ The current I_C flows even when VCB is equal to zero.

→ As VBE is in forward bias the majority charge carriers are injected into base.

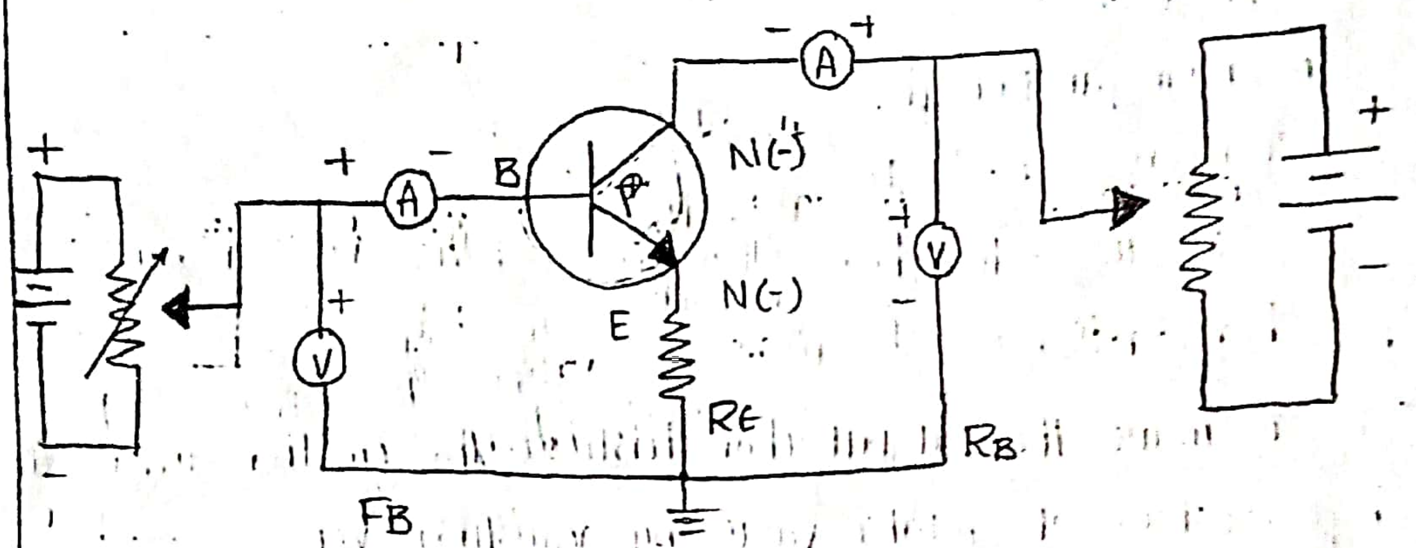
→ Due to this the majority charge carriers the collector current I_C is induced even when VCB = 0



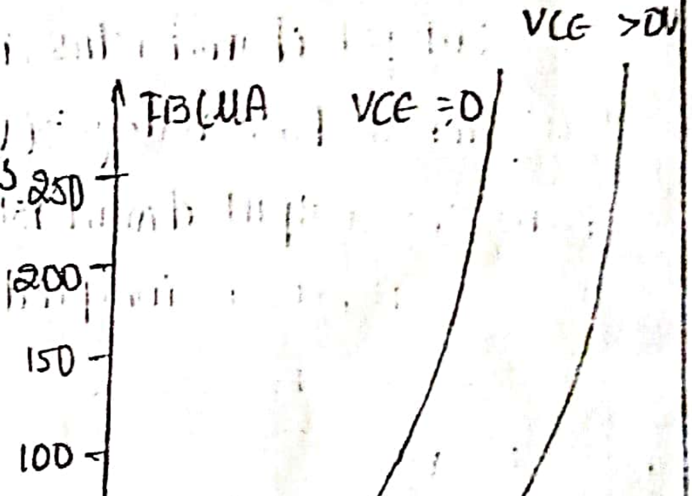
common emitter configuration :—

→ The circuit diagram for common emitter configuration is shown below.

Circuit diagram of CE configuration :—



INPUT CHARACTERSTICS :—



To determine the input characters the collector to emitter voltage is kept constant at zero volt add base current is increased from zero in equal steps by increasing VBE The value of VBE is noted for each value of IB. The procedure is repeated for higher fixed values of VCE and the curves of IB vs V are drawn. The input characterstics are shown in figure.

When VCE = 0 the emitter base junction is forward biased and the junction behaves as a forward biased diod.

Hence the input characteristics for VCE = 0 is similar to that of forward biased diode.

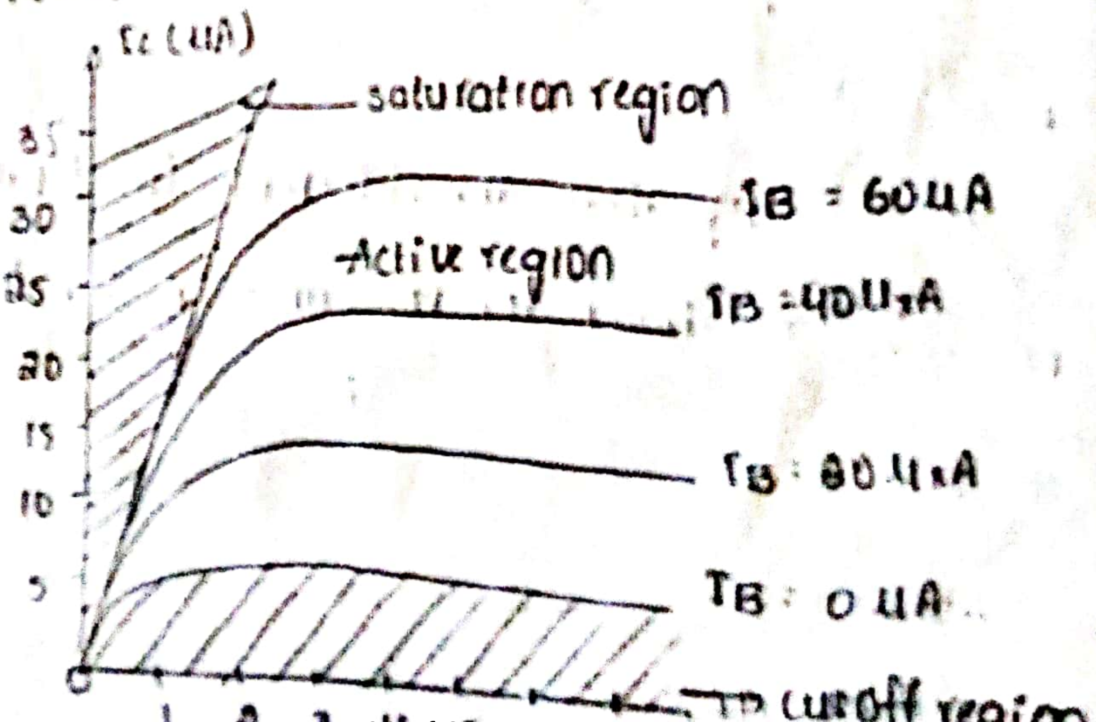
→ When VCE is increased, the width of depletion region at the reverse biased collector base junction will increase. Hence effective width of base will decrease. This causes a decrease in base current IB.

→ Hence to get the same value of IB as that for VCE = 0 VBE should be increased therefore the curve shifts to the right as VCE increases.

Output characteristics:

→ To determine the output characteristics the base current is kept constant at a suitable value by adjusting base emitter voltage VBE.

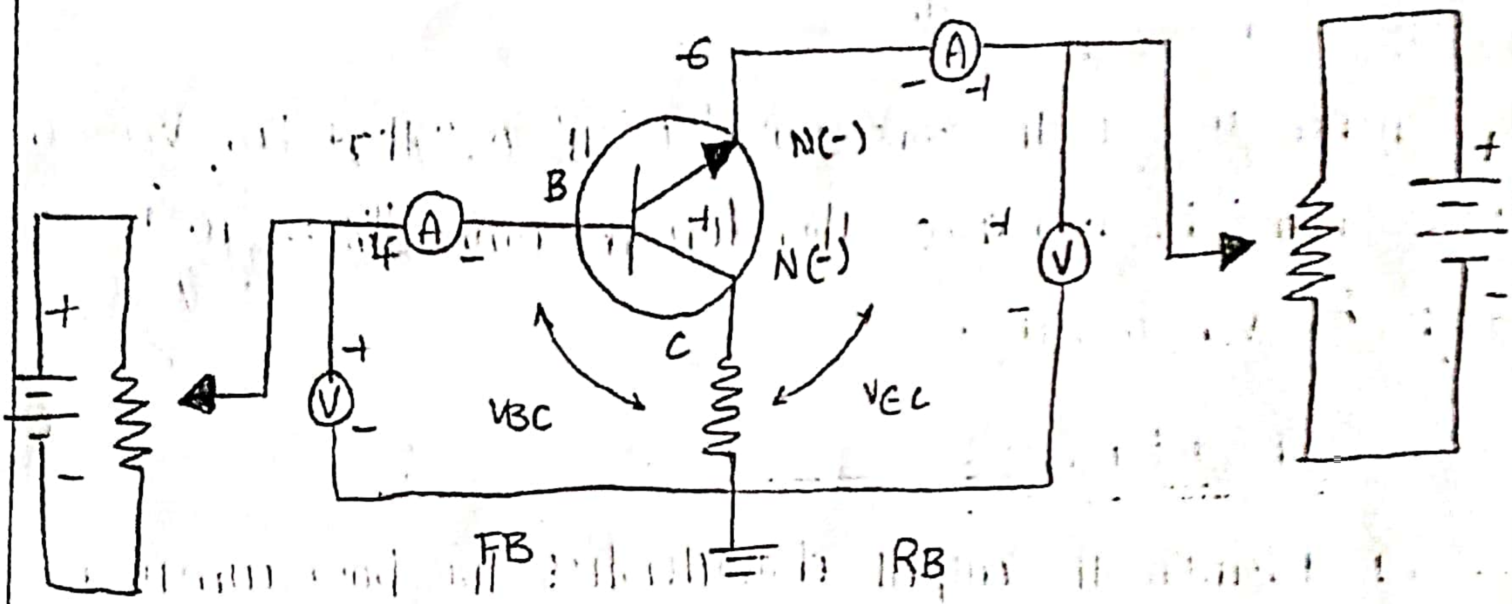
→ The magnitude of collector - emitter voltage VCE is increased in suitable steps for zero and the corresponding collector current is noted.



common collector configuration:-

→ The circuit diagram for common collector configuration is shown below.

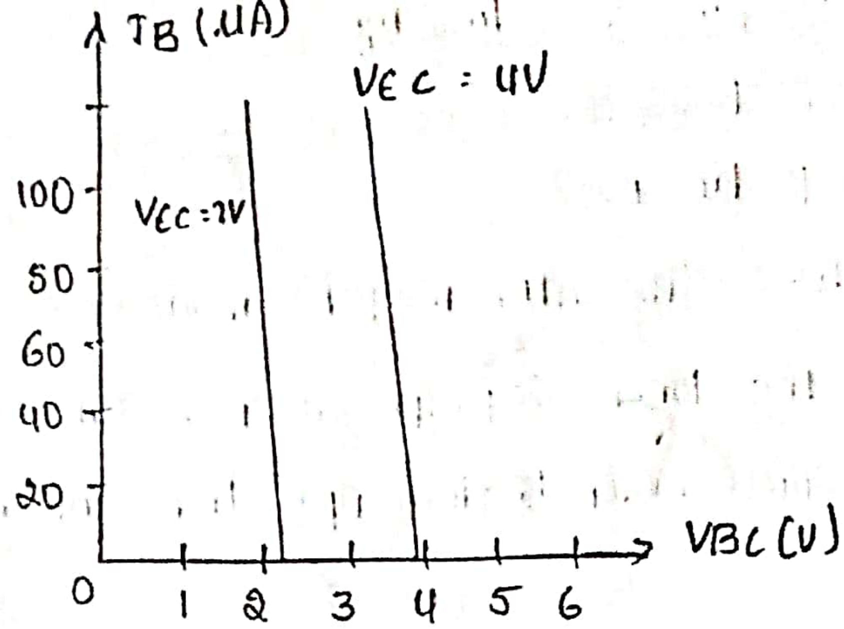
circuit diagram of CC configuration:-



Input charaiterstics:-

→ To determine the input characterstics VEC is kept at a suitable fixed value. The base collector voltage VBC is increased in equal steps and the corresponding increase in I_B is noted.

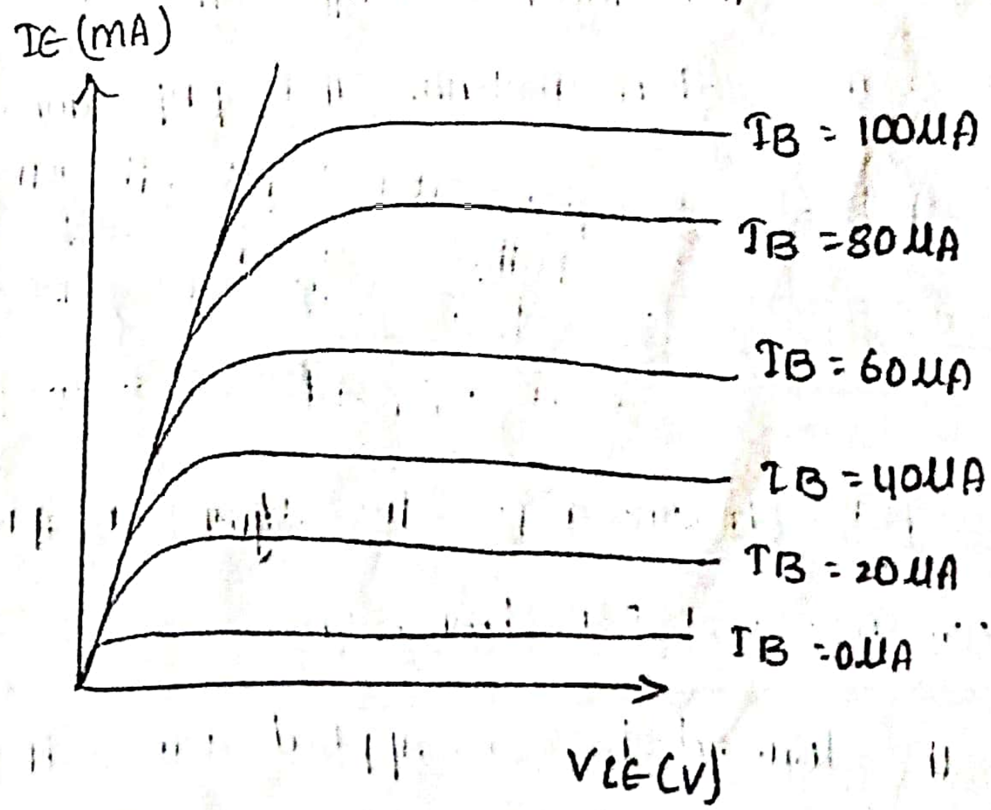
→ This is repeated for different fixed values of VEC ~~of~~ and curve is drawn for VBC and I_B for different values of VCE.



Output characteristics:

→ To determine the output characteristics the base current is kept constant at a suitable value by adjusting base-emitter voltage VBE.

→ The magnitude of collector emitter voltage VCE is increased in suitable steps for zero and corresponding collector current is noted.

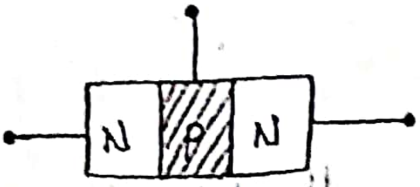


→ BJT is classified into two types.

1) n-p-n transistor
2) p-n-p transistor.

n-pn transistor:- Transistor may be made up of Ge or Si.

→ When a thin layer of p type silicon is sandwiched between two n type silicon materials then npn transistor is formed.



(or)

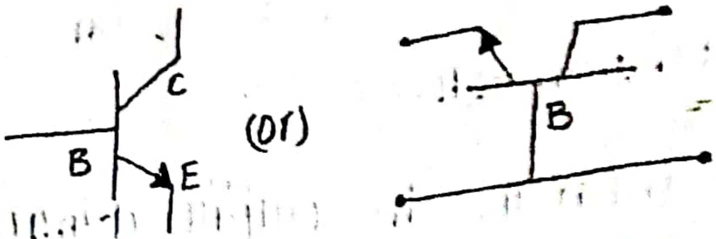
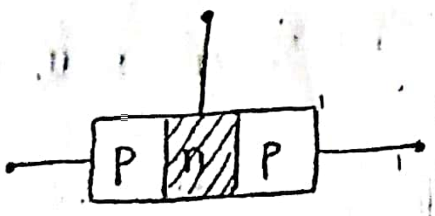


fig:- n-p-n transistor fig:- symbol of npn transistor

→ The arrow on the emitter specifies the direction of current flow then the emitter to Base junction BE is forward bias.

p-n-p - transistor :-

→ When a thin layer of n type silicon is sandwiched between two p type silicon materials then pnp transistor is formed.



(or)

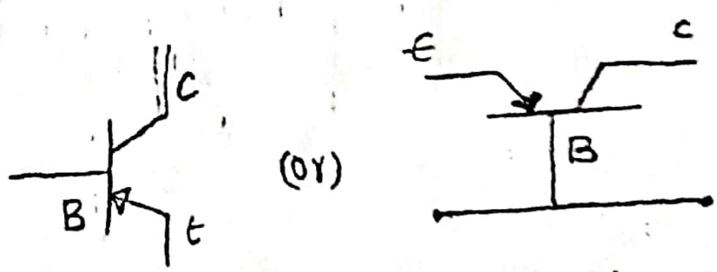
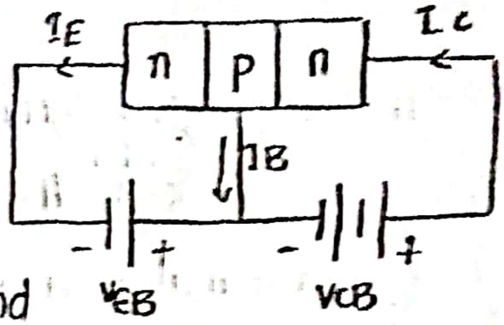


fig:- p-n-p transistor fig:- symbol of pnp transistor.

i) Working of n-p-n transistor :—

→ The forward bias is applied across the emitter base junction, and the reverse biased is applied across the collector base junction. The forward biase voltage V_{EB} is smaller than the reverse bias voltage V_{CB}.

→ As the base is p-type there is chance of recombination of electrons emitted by the emitter with the holes in ptype.



→ But base region is the thin and lightly doped only few electron's (5%) will combine with the holes in p type base.

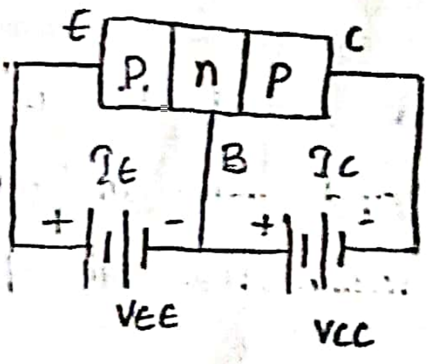
→ Remaining 95% electron's emitted by the n type emitter enters into the collector region and constitude the collector current.

∴ The emitter current $\boxed{I_E = I_B + I_C}$

ii) Working of P-n-P transistor:—

→ The p-n-p transistor with emittor junction is forward bias & collector to base junction in reverse bias.

→ As the base to emitter junction is forward biased, the majority carriers emitted by the p-type emitter is holes moves forward bias, which constitude an emitter current (I_E)



→ As the base region is ntype and is lightly doped only small holes emitted by the emitter will combine with electrons in base region.

→ Remainging 95% of charge carriers cross the base region & enters into collector region and constitute collector current

Construction of N-channel JFET :-

It consists of N-type bar which is made of silicon ohmic contacts (terminals), made at the two ends of the bar are called as Source and Drain.

Source :- This terminal is connected to positive pole of battery. The majority carriers ~~leave~~ Enter the bar through this terminal.

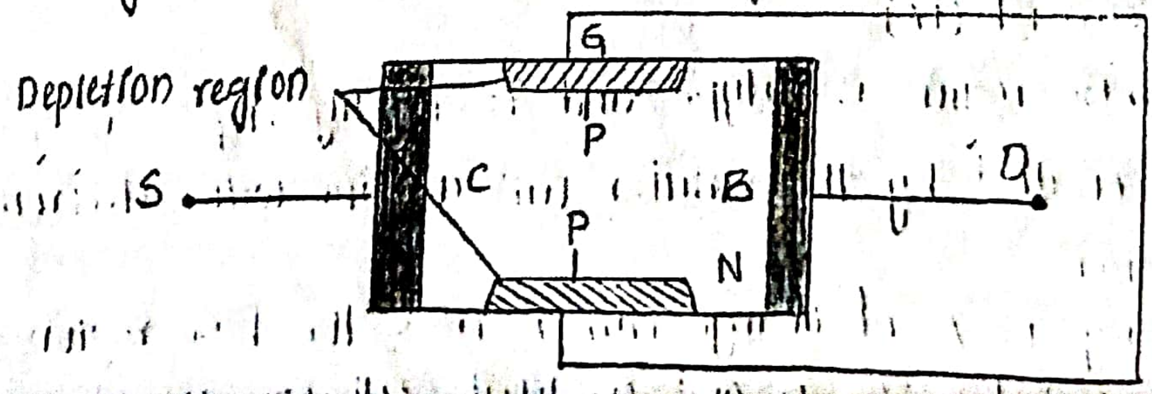
Drain :- This terminal is connected to positive pole of the battery. The majority carriers leave the bar through this terminal.

Gate :- Heavily doped p type silicon is diffused on both sides of the N type silicon bar by which PN junctions are formed. These layers are joined together called Gate (G).

Channel :- The region BC of the N type bar between the depletion region is called the channel. Majority carriers move from the source to drain when a potential difference V_{DS} is applied between the source and drain.

Operation of N channel JFET :-

When $V_{GS} = 0$ and $V_{DS} = 0$ - When no voltage is applied between the drain and Source, and gate and source, the thickness of the depletion region round the PN junction is uniform.



JFET construction

When $V_{DS} = 0$ and V_{GS} is decreased from zero:- In this case, the PN junction are reverse biased and hence the thickness of the depletion region increases. As V_{GS} is decreased from zero, the reverse bias voltage across the PN Junction is increased and hence the thickness of the depletion region in the channel increases until the two depletion regions make contact with each other. In this condition, the channel is said to be cutoff. The value of V_{GS} which is required to cutoff the channel is called the cutoff voltage V_C.

When $V_{GS} = 0$ and V_{DS} is increased from zero:- Drain is positive with respect to the Source with $V_{GS} = 0$. Now the majority carriers flow through the N channel from Source to drain. Therefore the conventional current I_D flows from drain to Source. The magnitude of the current will depend upon the following factors.

→ The number of majority carriers available in the channel.

→ The length L of the channel.

→ The cross sectional area A of the channel at B.

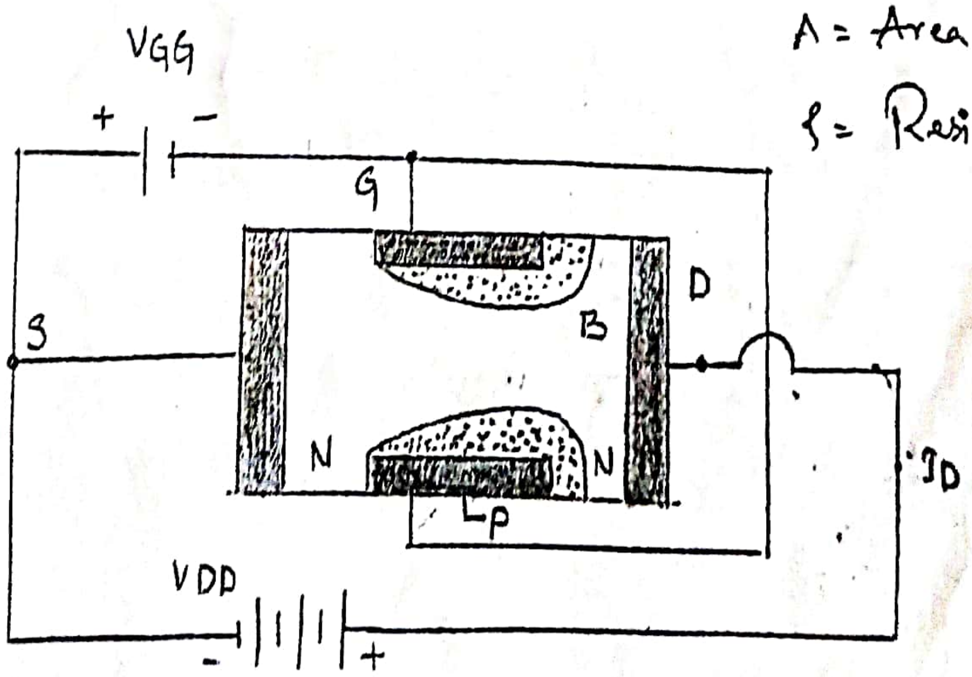
The resistor $R = \frac{\rho L}{A}$,

L = Length of channel

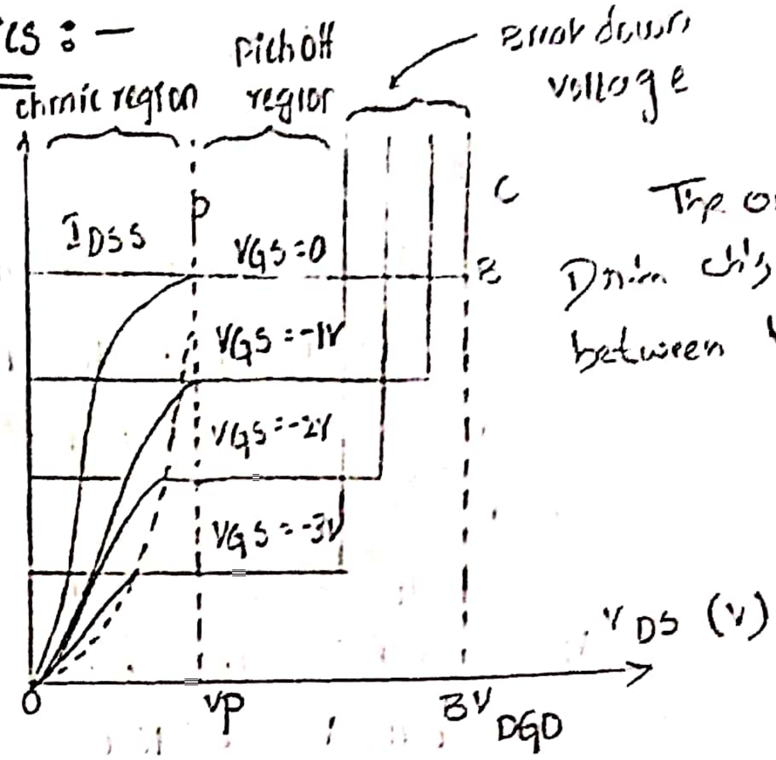
A = Area of cross section of c[hannel]

ρ = Resistivity of chan[nel]

JFET Under Applied Bias:-

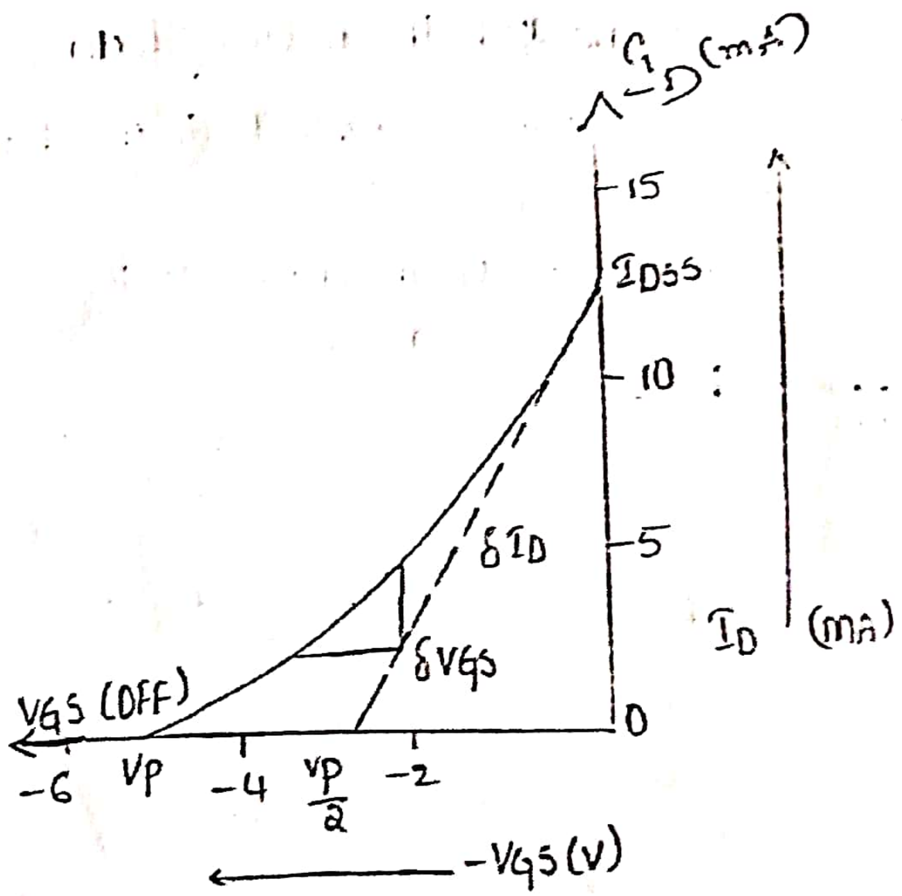


Drain characteristics :-



The output ch's (or) Drain ch's are drawn between V_{DS} and I_D at constant V_{GS}

Transfer characterstics of JFET :-



① cutoff region :-

At higher negative values of V_{GS}, both the depletion regions connects each other, channel width will be zero and $I_D = 0$

⑤ pinch off region :-

As V_{DS} is increased the cross sectional area of the channel is reduced. At a certain value of $V_{DS} = V_P$, the cross sectional area at B becomes minimum.

I_{DSS} = constant. When $V_{DS} = V_P$, I_D becomes maximum &

$I_D = I_{DSS}$ = constant even though V_{DS} increases. This region is known as "pinch-off"

③ Breakdown region :-

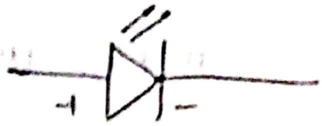
If V_{DS} increases further, I_D suddenly increases at $V_{DS} = BV_{GSO}$, the break down will occur. for negative values of V_{GS}, V_P (pinchoff voltage), I_{DSS} (drain-saturation current) and breakdown voltage increases due to redusing channel width.

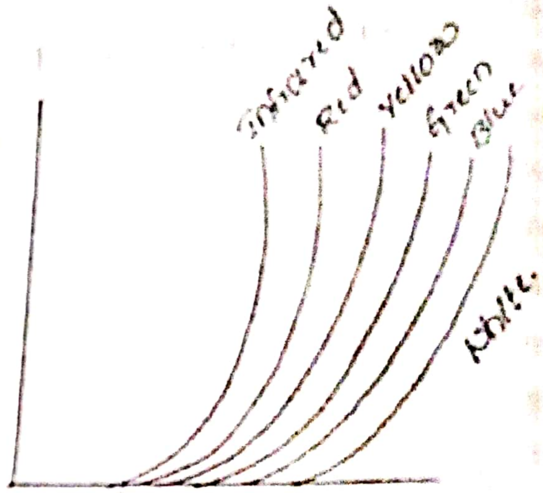
Parameter	CE	CB	CC
①. I/p resistance	Moderate	low	high
②. O/p resistance	High	High	low
③. Voltage gain	High	High	≈1
④. current gain	High	low (≈1)	High
⑤. power gain	High	Moderate	low
⑥. phase shift	180°	0°	0°

Characteristics of Rectifier :-

Property	Formula	HWR	FWR.
Ripple factor	$\frac{V_{rms}}{V_{dc}}$ $\xrightarrow{}\frac{V_{r,rms}}{V_{dc}}\rightarrow\frac{IP}{op}\rightarrow\frac{AC}{DC}$	1·21	0·482
Efficiency	$\frac{P_{dc}}{P_{ac}(rms)}$ $=\frac{op}{IP}=\frac{DC}{AC}$	40·6	81·2
percentage % Regulation	$\frac{(V_{NO}-\text{load})-(V_{full}-\text{load})}{V_{full}-\text{load}}$	-	-
TUF (Transformer utilization factor)	$\frac{P_{dc}}{P_{ac}(\text{rated})}$	0·287	0·692
PIV (peak inverse voltage)	Vm second's	Vm	2vm
form factor	$\frac{\text{RMS value}}{\text{avg value}}$	1·57	1·11
peak factor	$\frac{\text{Peak value}}{\text{RMS value}}$	2	$\sqrt{2}$.

Light emitting diode (LED):-





In this diode the electric current is given as input and we get the output as light.

photo Diode (or) photo detector:-

In this diode the light is given as input and we get the output as electric current.

UNIT-2

Operational Amplifier [op-amp] :-

The operational amplifier is a multi-terminal device which internally is a quite complex. Why the name given to IC, which performs mathematical operations like arithmetic and logical operations for the input and amplifies the output (or) result.

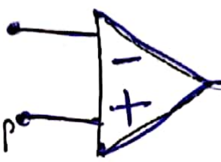


fig : Circuit symbol of op-amp

The shape of the op-amp is a triangle. It has two input terminals and one output terminal.

The terminal with a -ve sign is called inverting i/p terminal and the terminal with a +ve sign is called Non-inverting i/p terminal.

The op-amp's are designed for analog components to perform mathematical operations like integration, differentiation, Averaging, Summation, Inversion and so on.

The Linear IC's are used in no. of electronic applications like audio or video or radio communications. medical electronics and instrumentation control etc.

Definition Of Operational Amplifier :

→ An Operational amplifier is a direct coupled high gain amplifier consisting of one or more differential amplifiers, followed by a level translator and an output stage.

→ It is a versatile device that can be used to amplify ac as well as dc input signals and designed for computing mathematical functions such as addition, subtraction, multiplication, integration & differentiation.

Basic Circuit Symbol and terminals for IC's :

→ An op-amp is a triangle as shown in fig. It has 2 input terminals and one output terminal. The terminal with -ve sign is inverting i/p terminal and +ve sign is non-inverting i/p terminal.

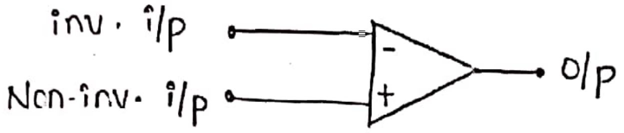
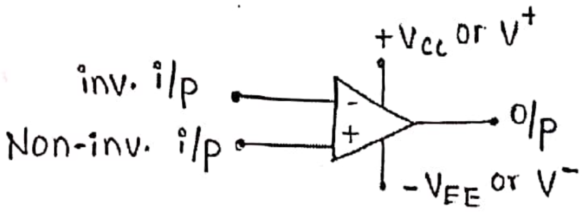


fig: Circuit Symbol

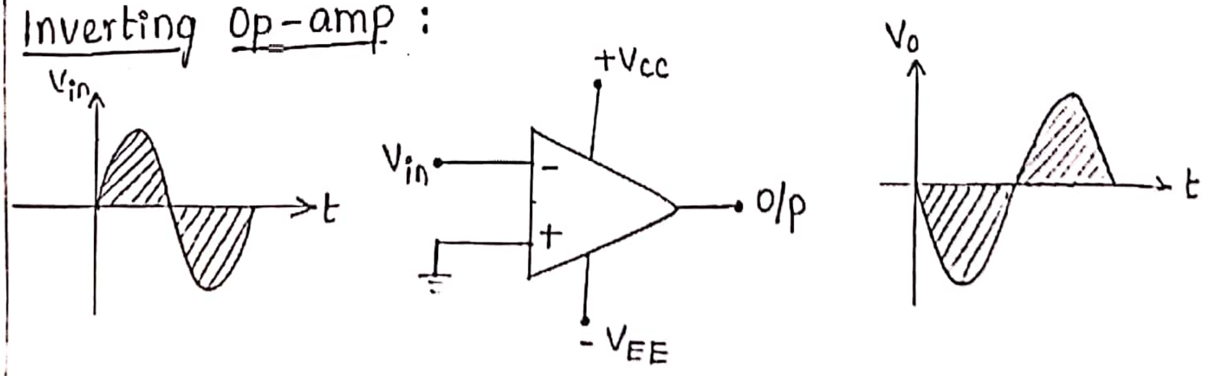
→ The symbol for an op-amp along with its various terminals is shown below.



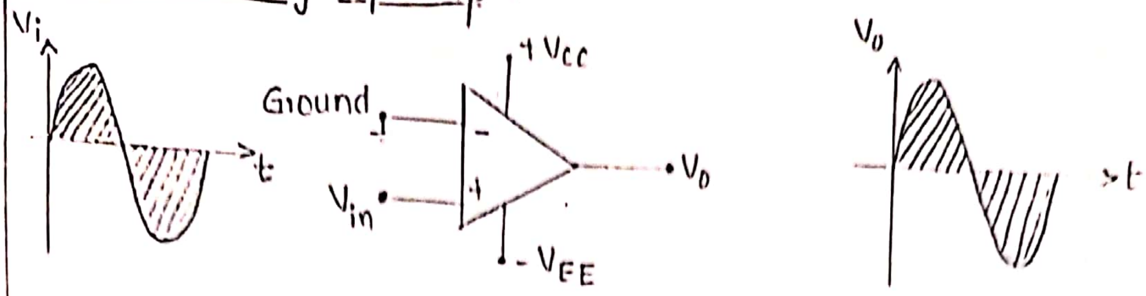
→ All the op-amp's have atleast following 5 terminals.

- +ve power supply voltage terminal (V_{cc} or V^+)
- -ve power supply voltage terminal (V_{EE} or V^-)
- o/p terminal
- inverting i/p terminal (-ve sign)
- Non-Inverting i/p terminal (+ve sign).

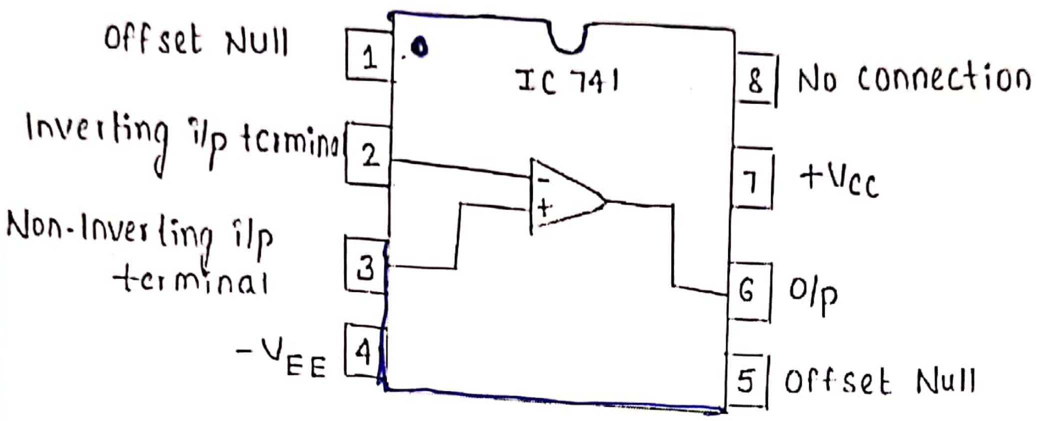
Inverting Op-amp :



Non-Inverting Op-amp :



* 741 Op-amp and its features :



→ The 741 op-amp is high performance monolithic op-amp IC. It is available in 8 pin, 10 pin, 14 pin configuration.

→ If output is produced without any i/p it is offset value. Offset value is cancelled by using offset null.

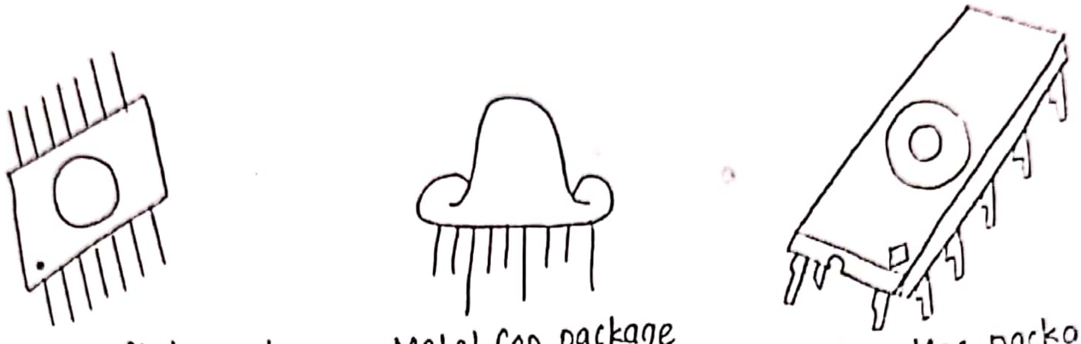
Features :

1. Short circuit protection is provided
2. No frequency compensation required
3. Offset voltage null capability
4. Large common mode & differential voltage range
5. No latch up.

Package Type :

There are three types of packages for the Integrated Circuit.

1. The flat pack
2. The metal can (or) transistor pack
3. The dual-in-line package (DIP)



Cermonic flat package   Metal Can package   Dual in line package

Flat Pack :

In this the chip is enclosed in a rectangular ceramic case with terminal loads extending through the sides and ends as shown. The flat pack comes with 8,10,14 (or) 16 leads. These lands accomodates the power supplies, inputs, outputs and several special connections required to complete the circuit.

Metal can Package :

In this the chip is encapoulates in a metal (or) plastic case. This is available with 3,5,8,10 (or) 12 pins. Power op-amp's and audio power amplifies are usually available in 15-pin packages. This package is best suited for power amplifiers because metal is good heat conductor and consequently has better dissipation capability than the flat pack (or) DIP package.

DIP :

In this the chip is mounted inside a plastic (or) ceramic case as shown. This type of package mostly used one. The 8-pin dual-in-line package are referred as mini DIP's. These are available with 12,14,16 and 20 pins. These are used in Digital IC's.

Types of Differential Amplifiers :-

(3)

The differential amplifier can be divided into four configurations based on the configuration of the differential amplifier stage.

1. Dual Input Balanced output Differential Amplifier.
2. Dual Input unbalanced output Differential Amplifier.
3. Single Input Balanced output Differential Amplifier.
4. Single Input unbalanced output Differential Amplifier.

The differential amplifier uses two transistors in common emitter configuration.

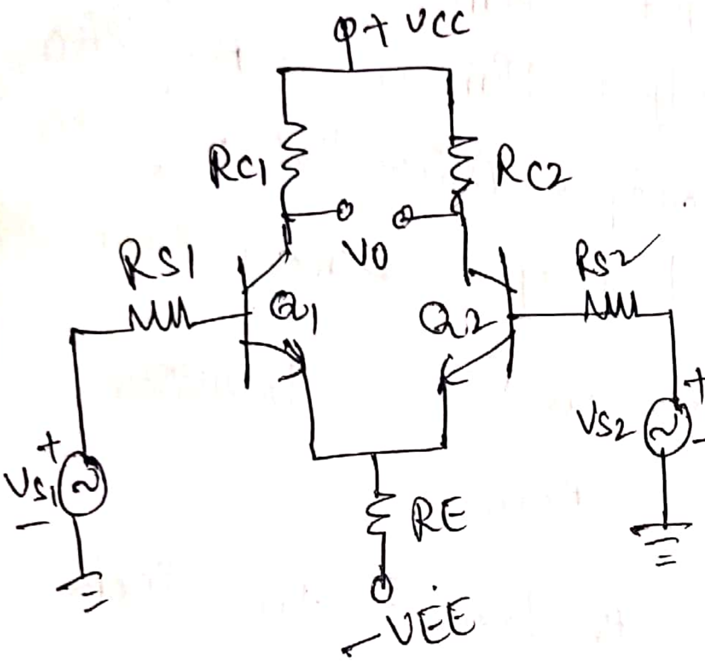
→ If the output is taken in between two collectors with none of them grounded is called Balanced output (or) double ended output

→ If the o/p is taken in between one collector with respect to ground is called unbalanced output or single ended o/p.

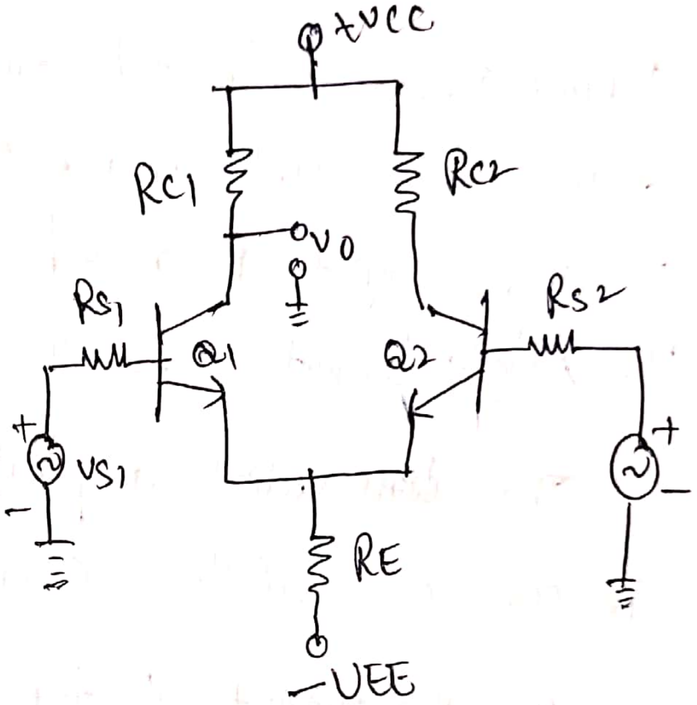
→ If the signal is given to both inputs is called dual input.

→ If the signal is given to one input & another is connected to ground is called single input.

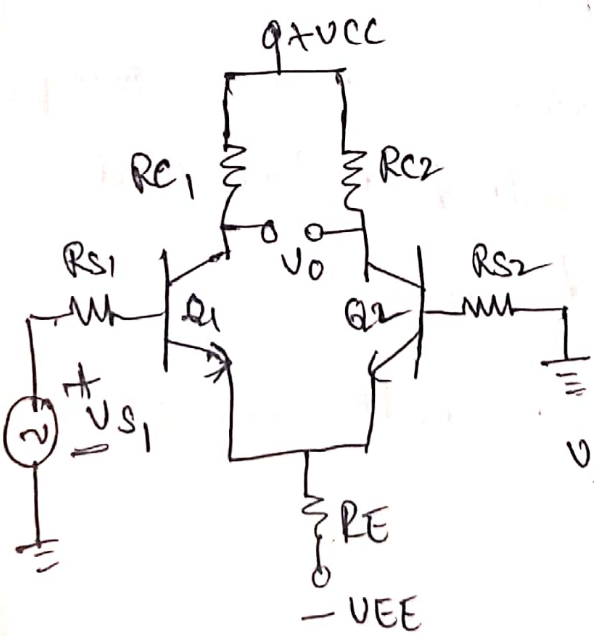
The configurations of differential amplifier is shown in figure.



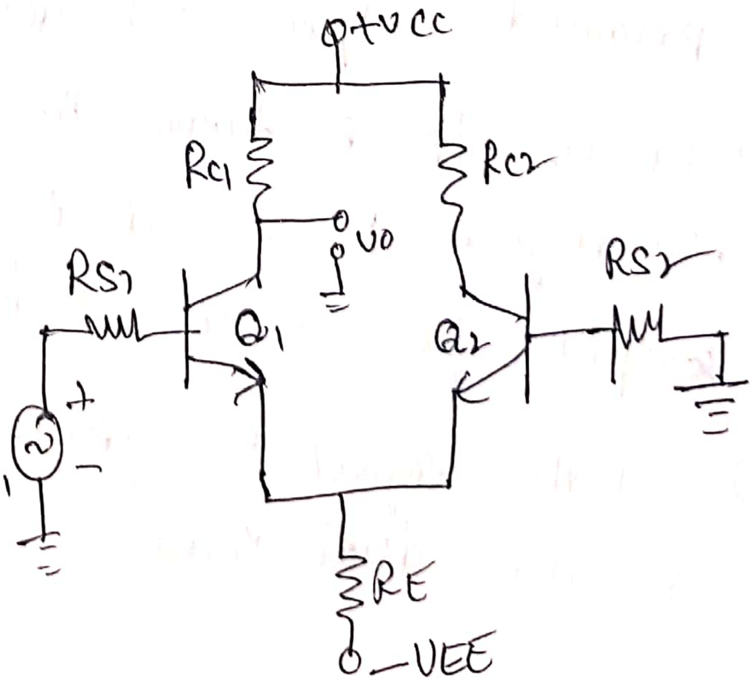
(a) DIBO



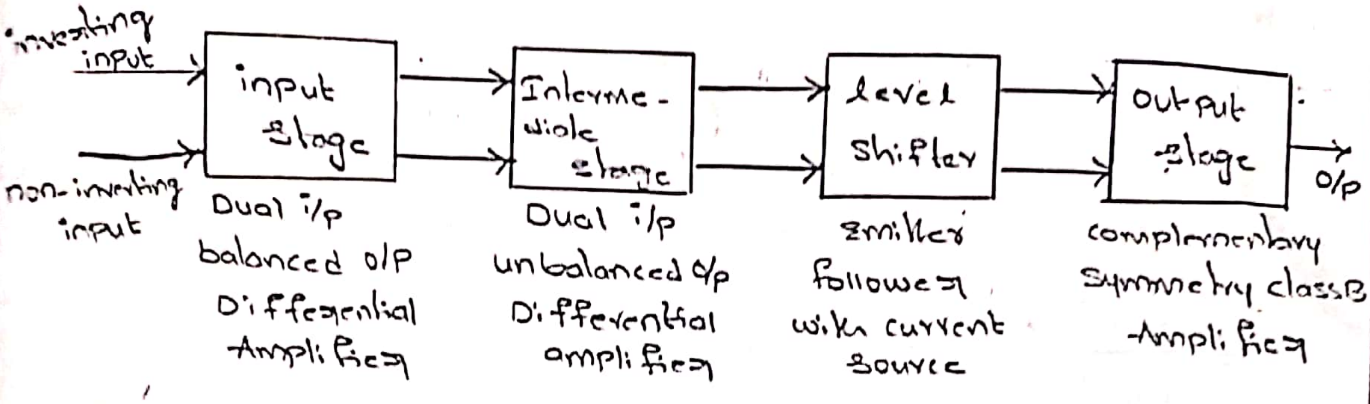
(b) DIUBO



(c) BIBO



* Block Diagram of Op-Amp :-



The fig. shows the block diagram of Op-amp. It consists of 4 cascaded blocks.

a. Input stage
b. Intermediate stage
c. Level shifter
d. Output stage

1. Input stage :-

The ~~output~~ input stage requires high i/p impedence to avoid loading on the sources. It requires 2 i/p terminals & also it requires low o/p impedence.

→ All such requirements are achieved by using dual i/p balanced o/p differential amplifier at the i/p stage.

→ This stage provides most of the voltage gain of the amplifier & also establishes the i/p resistance of the amplifier.

2. Intermediate Stage :-

The o/p of the i/p stage drives the next stage which is an intermediate stage. This is another differential amplifier with dual i/p unbalanced o/p i.e., single ended o/p.

→ The overall gain of requirement of the op-amp is very high.

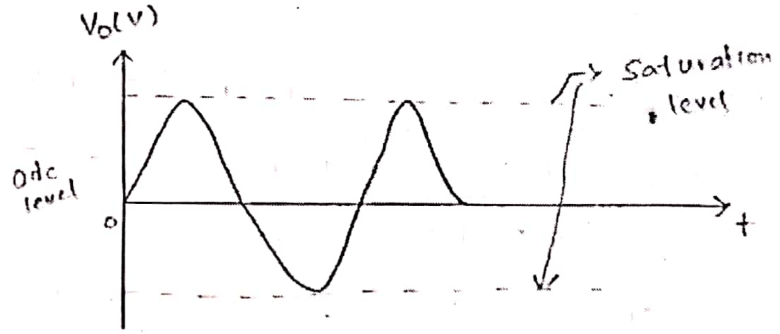
→ In most of the amplifier an intermediate stage is a dual i/p unbalanced o/p differential amplifier. This stage increases voltage gain of the amplifier.

3. Level shifting stage :-

The level shifting stage is used after the intermediate stage to shift the dc level at the o/p of the intermediate stage downward to zero volts wrt ground.

→ Here coupling capacitors are not used to couple the amplifiers in the intermediate state. Dc biasing voltage level propagates through the amplifier. Due to this a significant dc level appears at the o/p along with ac o/p.

→ Due to this effect o/p gets distorted & limits the maximum o/p voltage. This is shown in below fig.



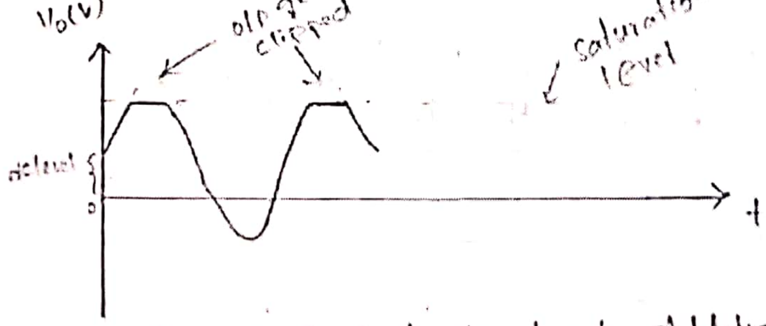


fig: Distorted o/p due to Additional level

→ So the main purpose of the level shifting stage is to shift the o/p 'Q' point dc level towards the ground with

Applying KVL to the circuit

$$V_i - V_{BE} - I(R_1 + R_2)$$

$$I(R_1 + R_2) = V_i - V_{BE}$$

$$I = \frac{V_i - V_{BE}}{R_1 + R_2}$$

$$\frac{V_o}{R_2} = \frac{V_i - V_{BE}}{R_1 + R_2}$$

$$V_o = \frac{V_i - V_{BE}}{R_1 + R_2} \times R_2$$

proof :- let us assume

$$V_o = \frac{5 - 0.7}{10 + 4} \times 4$$

$$= \frac{4.3 \times 4}{14}$$

$$= \frac{17.2}{14}$$

$$V_o = 01.22 \quad V_o \downarrow$$

4. Output Stage :-

The last stage is a complimentary Class B pushpull amplifier. The basic requirements of an o/p stage are low o/p impedence.

1. large o/p voltage
2. large o/p current
3. low o/p impedence
4. low power dissipation
5. Short circuit protection.

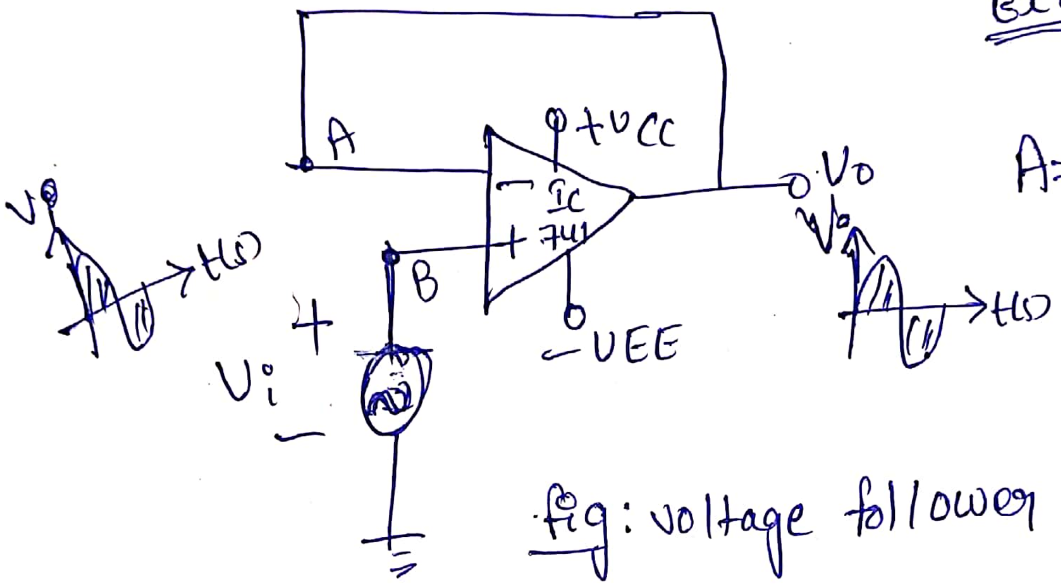
A pushpull amplifier satisfies the above requirements & hence commonly used in the o/p stage of an Op-amp.

Voltage follower :-

(or)

Unity gain amplifier

→ The voltage follower circuit is as shown below.



Ex:- $V_i = 2V$

$A = \frac{V_O}{V_i} = \frac{2}{2} = 1$

$\boxed{V_o = 2}$

fig: voltage follower

→ Here input is applied at non-inverting terminal.

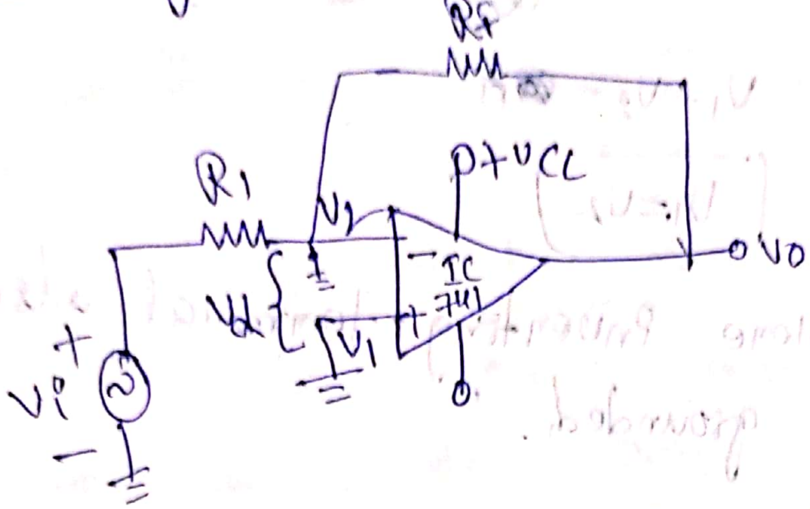
→ Due to virtual ground concept node 'A' voltage is 'V_i'.

→ ~~so~~ Because node 'B' is connected to 'V_i'.

→ so node 'A' connected to output directly. so o/p follows input.

$\boxed{V_o = V_i}$

Virtual ground concept :-



Consider an inverting amplifier to understand virtual ground concept.

It is a situation in which the inverting terminal of op-amp is connected to ground potential even though it is not connected to the ground.

Here non-inverting terminal is connected to the ground.

open loop gain $\boxed{A = \frac{V_o}{V_i}}$

Here $V_i = V_d$

$V_d = V_1 - V_2$

$$A = \frac{V_o}{V_d} = \frac{V_o}{V_1 - V_2}$$

$$V_1 - V_2 = \frac{V_o}{A}$$ (Here open loop gain is ∞)

$$V_1 - V_2 = \frac{V_0}{\infty} \quad \left[\frac{1}{\infty} = 0\right]$$

$$V_1 - V_2 = 0$$

$$\therefore \boxed{V_1 = V_2}$$

So Here inverting terminal also virtually grounded.

CMRR(Common Mode Rejection Ratio):- (7)

It is the ability of an op-amp to reject common mode signal is called "Common mode Rejection Ratio".

It is the ratio of differential mode gain to the common mode gain.

* It is denoted as 'ρ'.

* $\rho = \frac{Ad}{Ac} = \frac{\text{Differential mode gain}}{\text{Common mode gain}}$

$$\rho = \frac{Ad}{Ac} = \frac{Ad}{0} = \infty$$

$Ac \longrightarrow 0$

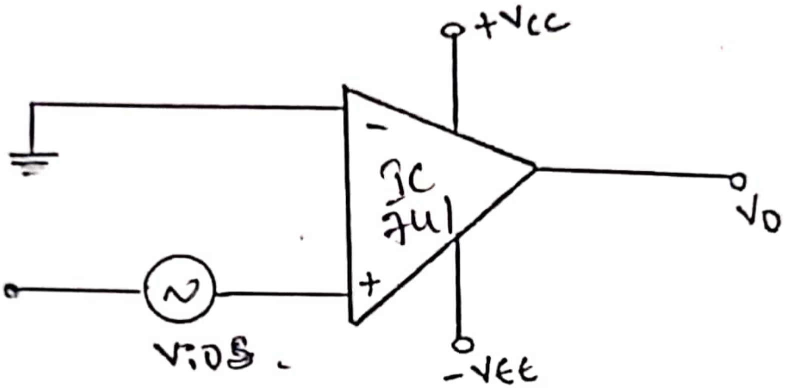
$\therefore \boxed{CMRR,\ \rho = \infty}$

Slew Rate: It is the maximum rate of change of output with respect to time is called slew rate.

$$\therefore \boxed{SR = \left.\frac{dvo}{dt}\right|_{max} \quad \text{volts/sec}}$$

PSRR (Power supply Rejection Ratio):-

It is defined as the change in i/p offset voltage due to change in any one power supply, remaining power supply must be constant is called as "Power Supply Rejection Ratio". It is also called as power supply sensitivity (PSS).



→ If V_{EE} = constant & due to certain change in V_{cc}, there is change in i/p offset voltage, then

$$\therefore \boxed{PSRR = \left.\frac{\Delta V_{iOS}}{\Delta V_{cc}}\right|_{V_{EE} = \text{constant}}}$$

→ If V_{cc} = constant & due to certain change in V_{EE}, there is change in i/p offset voltage, then

$$\therefore \boxed{PSRR = \left.\frac{\Delta V_{iOS}}{\Delta V_{EE}}\right|_{\Delta V_{cc} = \text{constant}}}$$

1. Inverting Amplifier
2. Non-inverting Amplifier
3. Differential Amplifier.

(a) Inverting Amplifier :

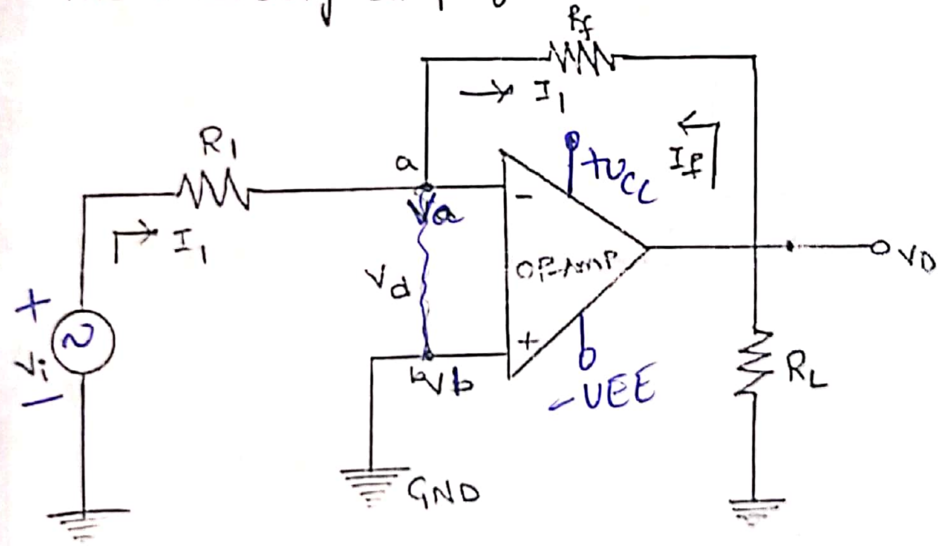
In this inverting i/p is applied at the inverting terminal and non-inverting terminal is grounded.

→ In this o/p signal is out of phase with the input signal

→ The o/p voltage Vo is fed back to the inverting input terminals through $R_f - R_1$ network.

where, R_f = feedback resistor

→ The inverting amplifier circuit shown in below figure.



Analysis :

→ Let us assume an ideal op-amp $V_d = 0$. and node A is at ground potential (virtual ground potential) then. and I_1 current flows through R_1 resistor.

$$\text{So,} \quad I_1 = \frac{V_A}{R_1} \quad \rightarrow (1)$$

→ Since op-amp draws no current, all the current flowing with R_1 must flow through R_f resistors. The o/p voltage V_o is given by

$$V_o = -I_1 R_f \rightarrow (2)$$

since on sub. eq(1) & (2), we get

$$V_o = \frac{-V_i}{R_1} \times R_f$$

$$\boxed{\frac{V_o}{V_i} = \frac{-R_f}{R_1}}$$

Hence the closed loop gain of the inverting amplifier is given by A_{CL}

$$A_{CL} = V_o/V_i$$

so, $\boxed{A_{CL} = \frac{-R_f}{R_L}}$

Method - II :

According to nodal eq" at node A,

$$I_1 = I$$

so, $$\frac{V_i - V_a}{R_1} = \frac{V_a - V_o}{R_f}$$

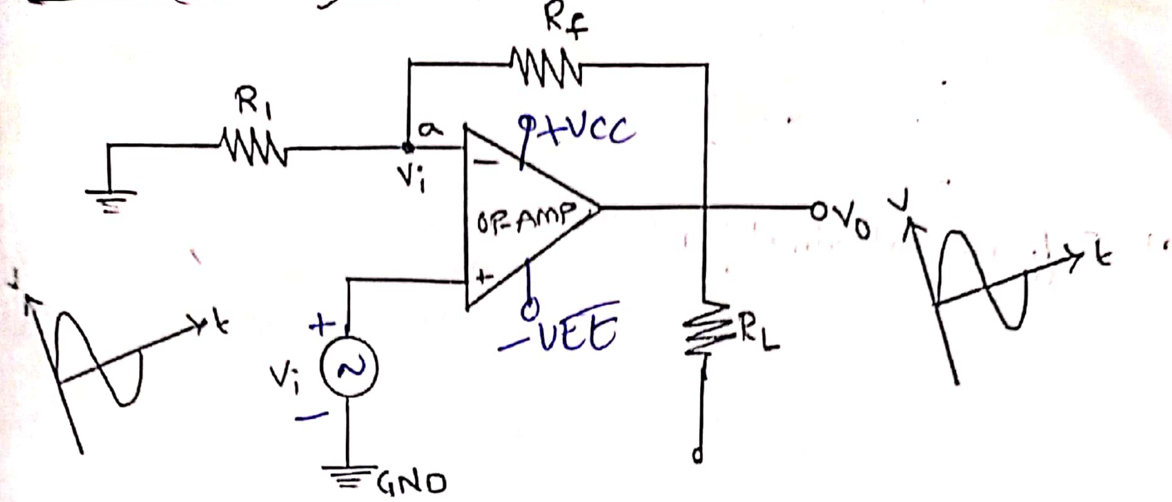
But $V_a = 0$; (because V_a is virtually grounded)

$$\frac{V_i}{R_1} = \frac{-V_o}{R_f}$$

$$\boxed{\frac{V_o}{V_i} = \frac{-R_f}{R_1}}$$

where, -ve sign indicates that the 180° phase shift provided in b/w input & output.

(b) Non-Inverting Amplifier :



→ If a signal is applied to the non-inverting input terminal then it is called as non-inverting amplifier.

→ If a signal is applied to the non-inverting terminal and feedback is connected from output to input as shown in above figure.

→ It may be noted that it is also a -ve feedback system as output is being fed back to the inverting input terminal.

→ As a differential voltage V_d at the input terminal of op-amp is zero, the voltage at node 'A' is V_i, same as the input voltage applied to non-inverting input terminal.

→ In circuit R_f and R_1 forms a potential divider. Hence, according to potential divider theorem,

$$V_i = \frac{R_1 V_o}{R_1 + R_f} \Rightarrow \frac{V_o R_1}{R_1 + R_f} = V_i$$

$$V_o = \frac{R_1 + R_f}{R_1} \times V_i$$

$$V_o = 1 + \frac{R_f}{R_1} \times V_i$$

$$\frac{V_o}{V_i} = 1 + \frac{R_f}{R_1}$$

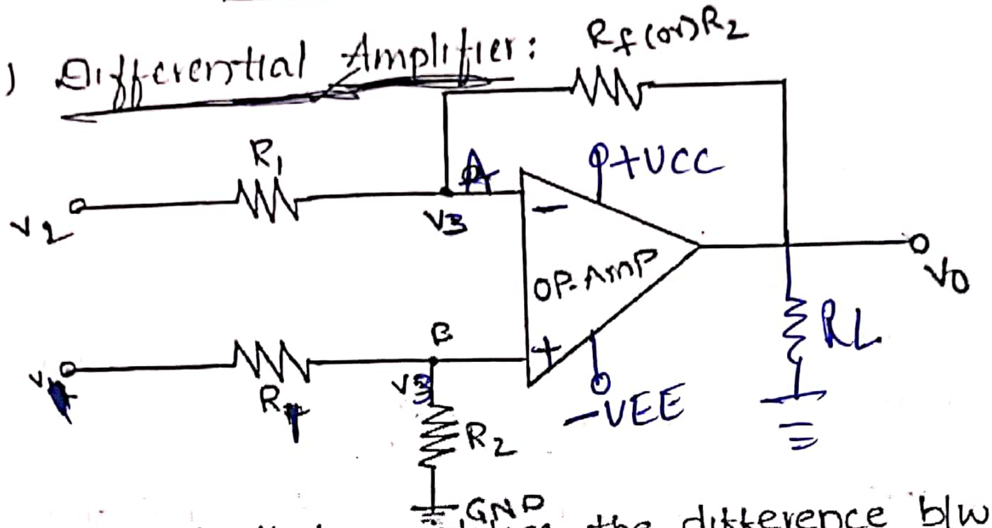
$$ACL = \frac{V_o}{V_i} = 1 + \frac{R_f}{R_1} \Rightarrow V_o = \left[1 + \frac{R_f}{R_1}\right] V_i$$

we know that,

$$A_{CL} = \frac{V_0}{V_i}$$

$$\boxed{A_{CL} = 1 + \frac{R_f}{R_1}}$$

(c) Differential Amplifier:



→ A circuit that amplifies the difference b/w two input signals is called as difference amplifier (or) Differential amplifier.

→ The differential amplifier circuit is shown in above figure

→ Since the differential voltage at the input terminal of the op-amp is zero.

→ Node A and Node B are at the same potential i.e., V_3

→ The nodal eq^n at node A is,

$$\frac{V_2 - V_3}{R_1} = \frac{V_3 - V_0}{R_2}$$

$$\frac{V_3 - V_2}{R_1} + \frac{V_3 - V_0}{R_2} = 0$$

$$V_3\left[\frac{1}{R_1} + \frac{1}{R_2}\right] - \frac{V_2}{R_1} - \frac{V_0}{R_2} = 0 \longrightarrow (1)$$

The nodal eq^n at node B is.

$$\frac{V_1 - V_3}{R_1} = \frac{V_3}{R_2}$$

$$\frac{V_3 - V_1}{R_1} + \frac{V_3}{R_2} = 0$$

$$V_3\left[\frac{1}{R_1} + \frac{1}{R_2}\right] - \frac{V_1}{R_1} = 0 \longrightarrow (2)$$

subtracting the above two equations, we get

$$\cancel{V_3\left[\frac{1}{R_1} + \frac{1}{R_2}\right]} - \frac{V_2}{R_1} - \frac{V_0}{R_2} - \cancel{V_3\left[\frac{1}{R_1} + \frac{1}{R_2}\right]} + \frac{V_1}{R_1} = 0$$

$$\frac{V_1}{R_1} - \frac{V_2}{R_1} - \frac{V_0}{R_2} = 0$$

$$1/R_1\left[V_1 - V_2\right] = V_0/R_2.$$

$$\frac{V_0}{V_1 - V_2} = \frac{R_2}{R_1}$$

$$\boxed{V_0 = \frac{R_2}{R_1}(V_1 - V_2)}$$

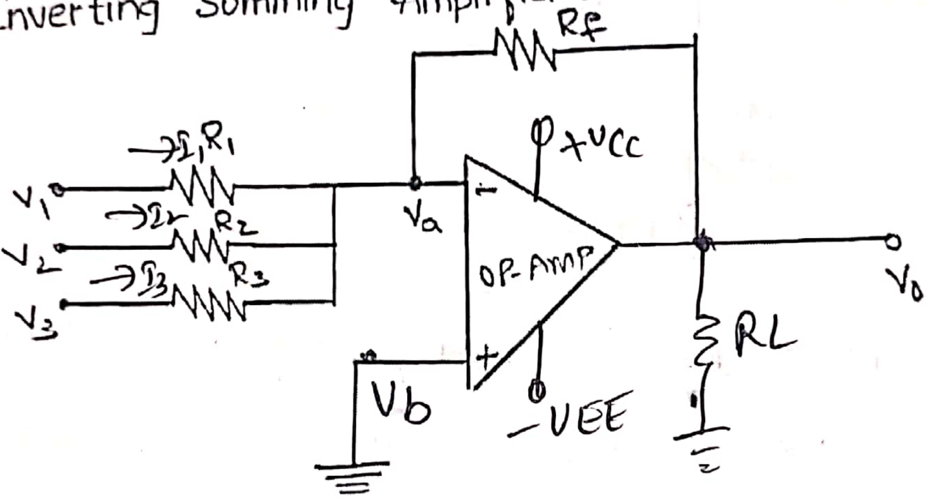
Summing Amplifier :-

Op-amp may be used to design the circuit whose o/p the sum of several i/p signals. Such a circuit is called Summing Amplifier (or) summer.

→ The summing amplifier are classified into two types.

1. Inverting summing amplifier
2. Non-inverting summing amplifier.

1. Inverting Summing Amplifier :



→ A typical summing amplifier with 3 i/p voltages V_1, V_2, V_3 & three i/p resistors R_1, R_2, R_3 & one feedback resistor R_f sho in above fig.

→ The voltage at node 'a' is zero ($V_a = 0$) because the non-inverting terminal is grounded.

The nodal eq^n at node 'a' is given by

$$\frac{V_1 - V_a}{R_1} + \frac{V_2 - V_a}{R_2} + \frac{V_3 - V_a}{R_3} = \frac{V_a - V_o}{R_f}$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = \frac{-V_o}{R_f}$$

$$\frac{V_o}{R_f} = -\left[\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right]$$

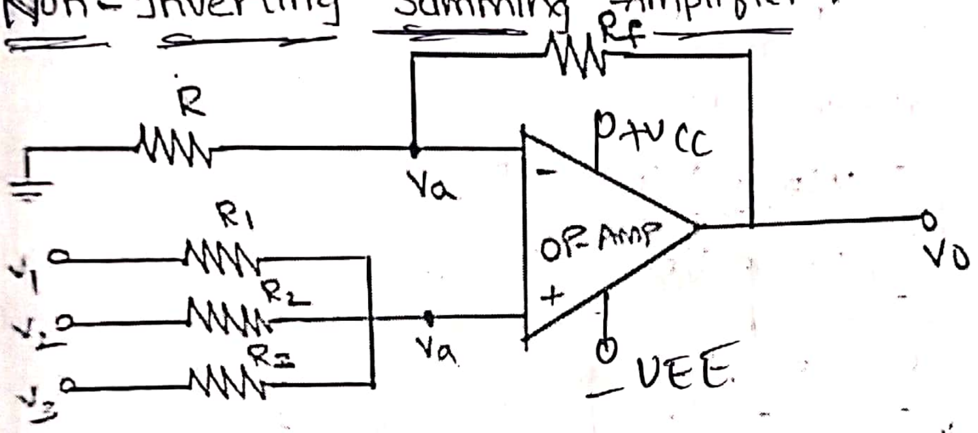
$$V_o = -\left[V_1 \frac{R_f}{R_1} + V_2 \frac{R_f}{R_2} + V_3 \frac{R_f}{R_3}\right]$$

Let $R_1 = R_2 = R_3 = R_f$

$$V_o = -\left[V_1 + V_2 + V_3\right]$$

Where "−ve" sign indicates that phase difference b/w i/p & o/p. So it is called as inverting summing amplifier.

2: Non-Inverting Summing Amplifier :-



- The non-inverting summing amplifier shown in above fig.
- The i/p voltages V_1, V_2, V_3 is fed to the non-inverting terminal. The voltage at non-inverting i/p terminal is V_a.
- The voltage at the inverting i/p terminal will also be V_a, because they are virtually grounded.

∴ the voltage across the inverting terminal is same as that the non-inverting terminal.

The nodal eqn at node 'a' is given by

$$\frac{V_1 - V_a}{R_1} + \frac{V_2 - V_a}{R_2} + \frac{V_3 - V_a}{R_3} = 0$$

$$\frac{V_1}{R_1} - \frac{V_a}{R_1} + \frac{V_2}{R_2} - \frac{V_a}{R_2} + \frac{V_3}{R_3} - \frac{V_a}{R_3} = 0$$

$$\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} = V_a\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right]$$ (13)

$$V_a = \frac{V_1/R_1 + V_2/R_2 + V_3/R_3}{1/R_1 + 1/R_2 + 1/R_3}$$

W.K.T gain of non-inverting amplifier is

$$A = \frac{V_o}{V_d} = 1 + \frac{R_f}{R_1}$$

But Here $V_d = V_a$

$$V_o = \left[1 + \frac{R_f}{R}\right] V_a$$

sub. V_a in above eqn

$$V_o = \left[1 + \frac{R_f}{R}\right]\left[\frac{V_1/R_1 + V_2/R_2 + V_3/R_3}{1/R_1 + 1/R_2 + 1/R_3}\right]$$

Let $R_1 = R_2 = R_3 = R = R_f/2$

$$V_o = \left[1 + \frac{R_f}{R_f/2}\right]\left[\frac{2V_1/R_f + 2V_2/R_f + 2V_3/R_f}{2/R_f + 2/R_f + 2/R_f}\right]$$

$$= \cancel{3} \times \frac{\cancel{2}(V_1 + V_2 + V_3)}{\cancel{6}\,\cancel{3}}$$

$$\boxed{V_o = V_1 + V_2 + V_3}$$

→ Here the o/p voltage is in phase with sum of the i/p voltages. So it is called as non-inverting summing amplifier.

Invertor :

Invertor is defined as o/p is the compliment of i/p. For example, let us consider an inverting amplifier as shown in below fig.

characteristics of op-amp :-

(14)

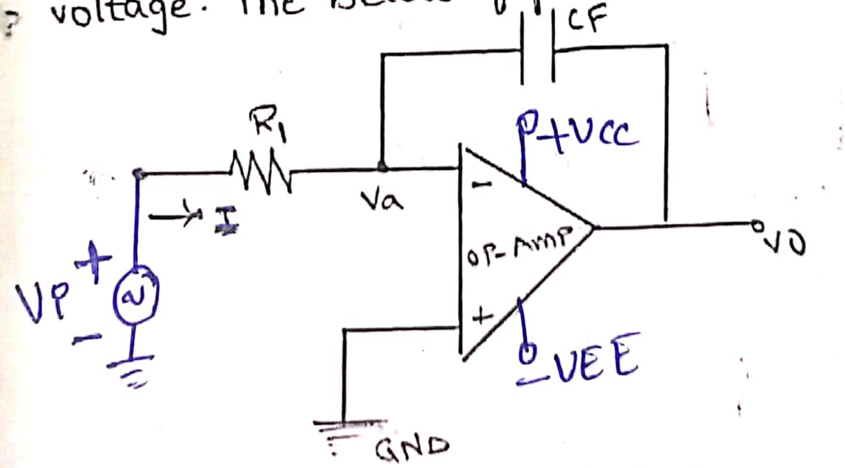
1. Input resistance $(R_i) = \infty$
2. output resistance $(R_o) = 0$
3. open loop voltage gain $(A_{CL}) = \infty$
4. Bandwidth $= \infty$
5. Offset ~~v~~ voltage $= 0$
6. common mode Rejection Ratio $(CMRR) = \infty$
7. slew rate $(SR) = \infty$

$$SR = \left.\frac{dv_o}{dt}\right|_{max} \text{ volts/sec}$$

8. PSRR (power supply Rejection Ratio) $= \infty$
9. No effect on temperature.

Integrator :-

Integrator is a circuit in which o/p voltage is integral of voltage. The below fig. shows the ideal integrator circuit.



- The i/p voltage Vi is applied to the inverting i/p terminal through

R_1 resistor.

→ The capacitor current I is given by $I = C_F \frac{dv}{dt}$.

→ Since o/p current of op-amp is zero, the entire current flowing through R_1 & C_F.

Applying KCL at node 'a'

For i/p side $I = \frac{V_i - V_a}{R_1}$

where $V_a = 0\,V$; because virtual connection.

$$\boxed{I = \frac{V_i}{R_1}} \rightarrow (1)$$

At o/p side ; $I = C_F \frac{d(V_a - V_o)}{dt}$

$$\boxed{I = -C_F \frac{dV_o}{dt}} \rightarrow (2)$$

equating eq(1) & eq(2)

$$\frac{V_i}{R_1} = -C_F \frac{dV_o}{dt}$$

$$dV_o = -\frac{V_i dt}{R_1 C_F}$$

integrating on b.s, we get

$$\int_0^t dV_o = -\frac{1}{R_1 C_F} \int_0^t V_i \, dt$$

$$V_o(t) - V_o(0) = \frac{-1}{R_1 C_F} \int_0^t V_i(t) \, dt$$

$$V_o(t) = \frac{-1}{R_1 C_F} \int_0^t V_i(t) \, dt + V_o(0)$$

Where, $R_1 C_F = \tau$ = Time constant of integrator

$V_o(0)$ is the initial o/p voltage

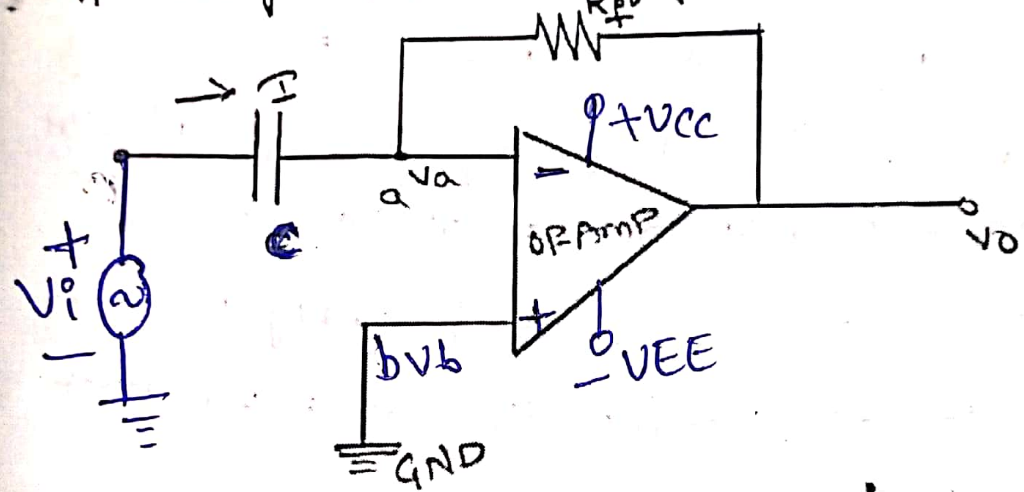
→ The above eqn shows that the o/p is $\frac{-1}{R_1 C_F}$ times the integral of i/p.

Applications :-

* It is used in Analog computers
* It is used in analog to digital convertors
* It is used in solving differential equations
* It is used in wave shapping circuits.

Differentiator :-

Differentiator is a circuit in which o/p voltage is differentiate i/p voltage. The below fig. shows the ideal differentiator.



The node 'a' is at virtual ground potential i.e., $V_a = 0$.

→ The current I flowing through the capacitor is

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

→ Apply KCL at node 'a'

$$I = C\frac{d(V_i - V_a)}{dt}$$

Due to virtual connection $V_a = 0$

$$I = C\frac{dV_i}{dt} \rightarrow (1)$$

Similarly at the o/p side

$$I = \frac{V_a - V_o}{R_f}$$

$$I = \frac{-V_o}{R_f} \rightarrow (2)$$

Equating above 2 eqns

$$C \frac{dV_i}{dt} = \frac{-V_o}{R_f}$$

$$\boxed{V_o = -R_f C \frac{dV_i}{dt}}$$

where, $R_f \cdot C$ = Time constant.

→ Thus the o/p voltage V_o is constant $(-R_f \cdot C)$ times the derivative of the i/p voltage.

Drawbacks :-

1. The gain of the differentiator increases as frequency increases. Thus at some high frequency the differentiator may become unstable & break into the oscillations.

2. The i/p impedence $X_{C1} = \frac{1}{2\pi f C}$, if frequency increases impedence decreases. This makes the circuit very much sensitive to the noise.

3. This noise may completely overwrite the o/p of the differentiator.

Hence the differentiator circuit ~~[illegible]~~ suffers from the stability & noise problem at high frequencies.

→ These problems can be overcome by adding additional components.

Practical Differentiator :

→ The differentiator circuit suffers from the stability & noise problems at high frequencies. These problems can be eliminated by practical differentiator.

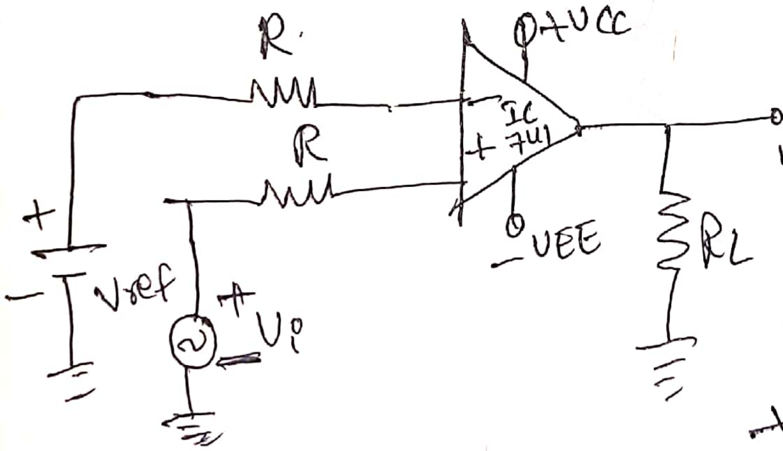
Comparator :

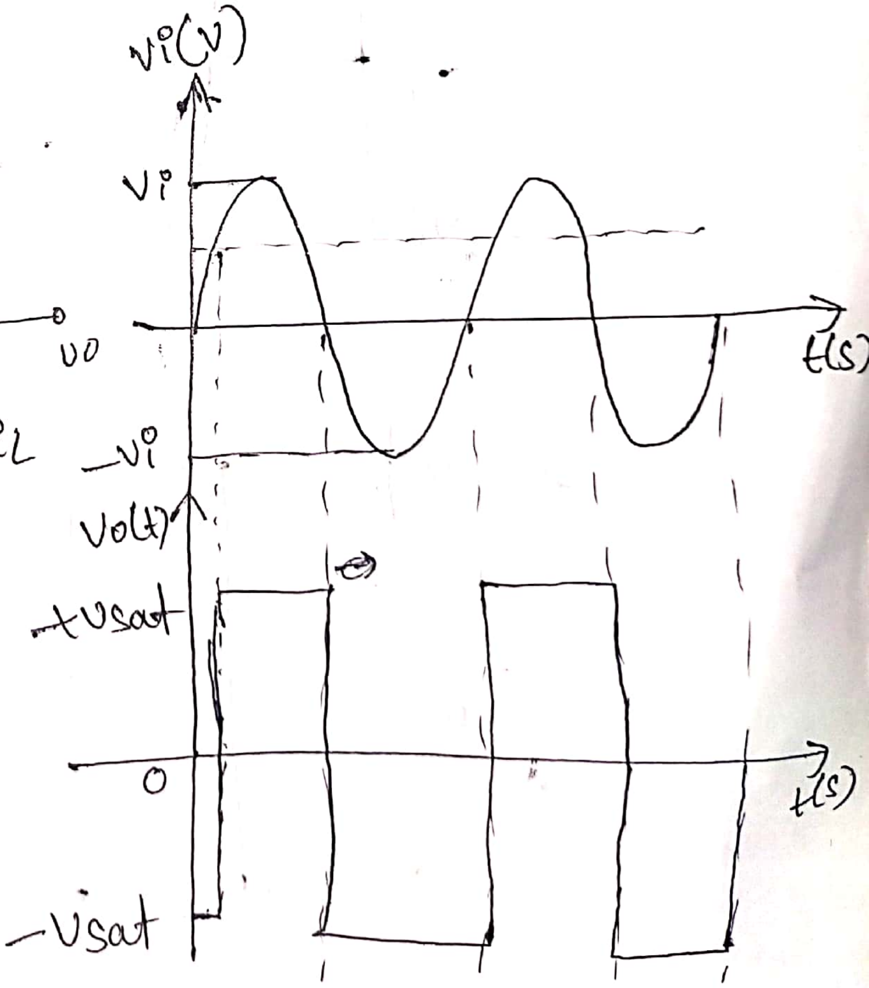
⇒ Comparator is a circuit in which compares the signal voltage in one input terminal of an op-amp with a known reference voltage at another input terminal of an op-amp.

⇒ Basically comparators are of 2 types.

1. Non-inverting comparator.
2. Inverting comparator.

(1) Non-inverting comparator :-

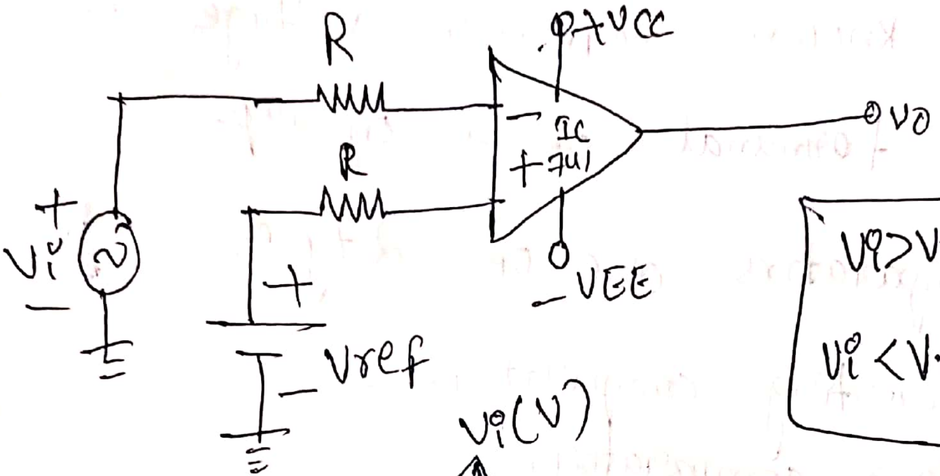




$V_i > V_{ref}$ o/p at $+V_{sat}$

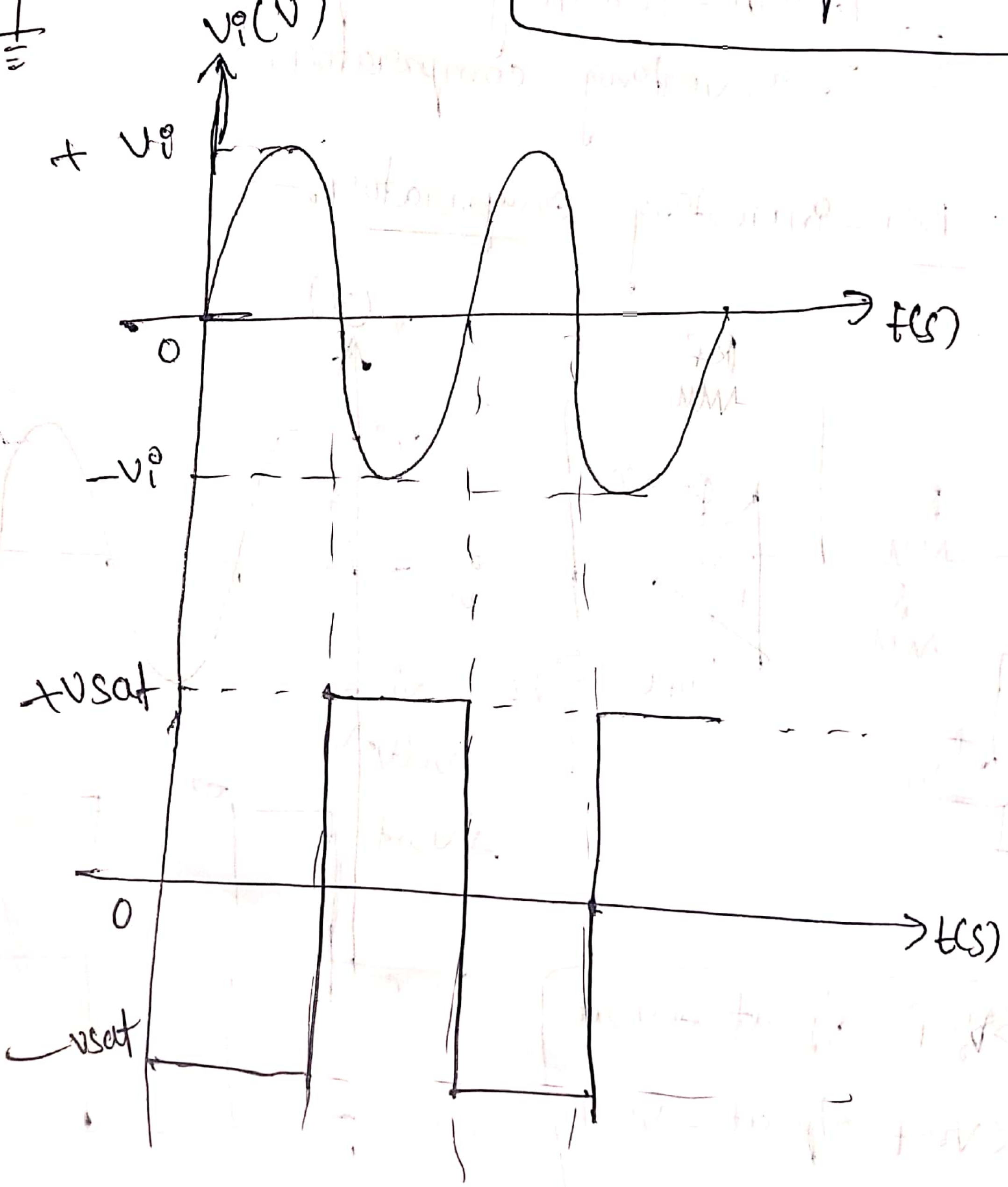
$V_i < V_{ref}$ o/p at $-V_{sat}$

② Inverting comparator :-



Vi > Vref output at -Vsat

Vi < Vref output at +Vsat

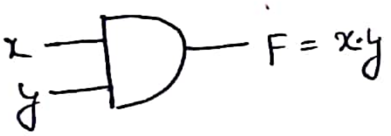


UNIT - III.

Digital Electronics.

Logic Gates :- Boolean functions can be implemented by using logic Gates. logic gates used in digital design are AND, OR, NOT, NAND, NOR, EX-OR, Exclusive-NOR logic gates.

AND Gate

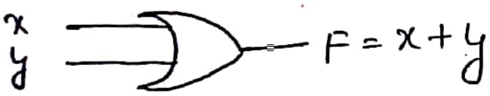


Truth table.

x	y	F = xy
0	0	0
0	1	0
1	0	0
1	1	1

when both input x and y are logic 1 then output is Logic 1, otherwise '0'

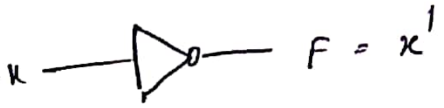
OR Gate



x	y	F = x + y
0	0	0
0	1	1
1	0	1
1	1	1

If any one input is logic '1', o/p is logic 1, otherwise logic '0'.

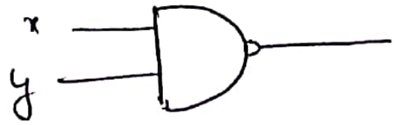
NOT Gate



x	F = x'
0	1
1	0

o/p is Complement of input

Nand Gate



$F = (xy)'$

x	y	$F = (xy)'$
0	0	1
0	1	1
1	0	1
1	1	0

If any one of the inputs is logic '0', o/p is logic 1. otherwise o/p is '0'.

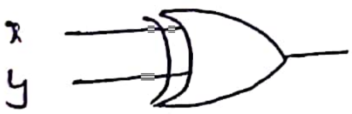
NOR Gate

$F = (x+y)'$

x	y	$F = (x+y)'$
0	0	1
0	1	0
1	0	0
1	1	0

If any one of the input is logic '1' o/p is logic '0'. otherwise o/p is '0'.

Exclusive - OR Gate



$F = xy' + x'y = (x \oplus y)$

x	y	$F = xy' + x'y$
0	0	0
0	1	1
1	0	1
1	1	0

output is logic '1', when inputs differ. o/p is logic '0' when inputs are equal.

Exclusive - NOR gate

x	y	$F = xy + x'y'$
0	0	1
0	1	0
1	0	0
1	1	1

output is logic '1', when inputs are equal.. output is logic '0' when inputs differ.

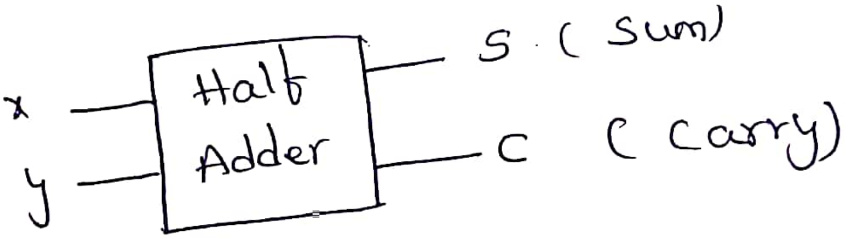
$F = (x \oplus y)'$

Half Adder

A Combinational circuit that performs the addition of two bits is called Half adder.

augend	0	1	0	1
addend	1	0	0	1
	1	1	0	10 (carry sum)

Half adder needs two binary inputs and two binary outputs



block diagram of Half adder

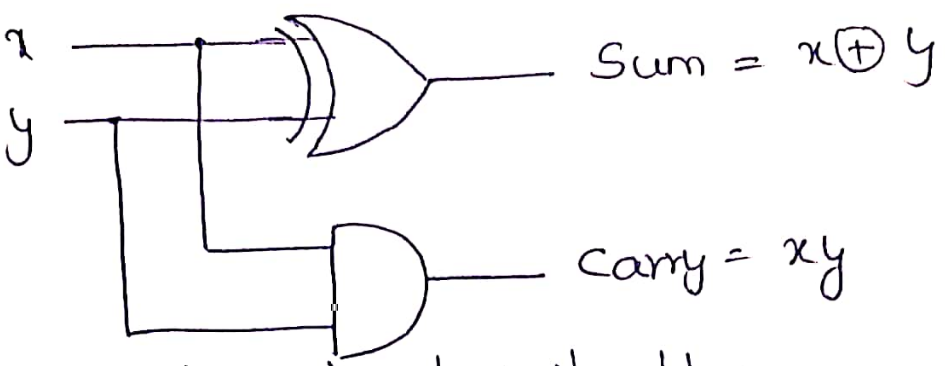
Truth Table

x	y	S	C
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

From truth table, the boolean functions for sum and carry are

$$S = xy' + x'y = x \oplus y$$

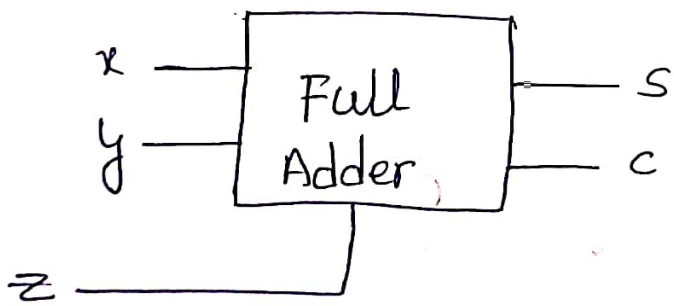
$$C = xy$$



Implemtation of Half adder.

Full Adder

It is combinational circuit that performs the addition of three bits, two significant bits, and previous carry.



block diagram of Fulladder

It has three inputs x, y and z and two o/ps Sum and carry.

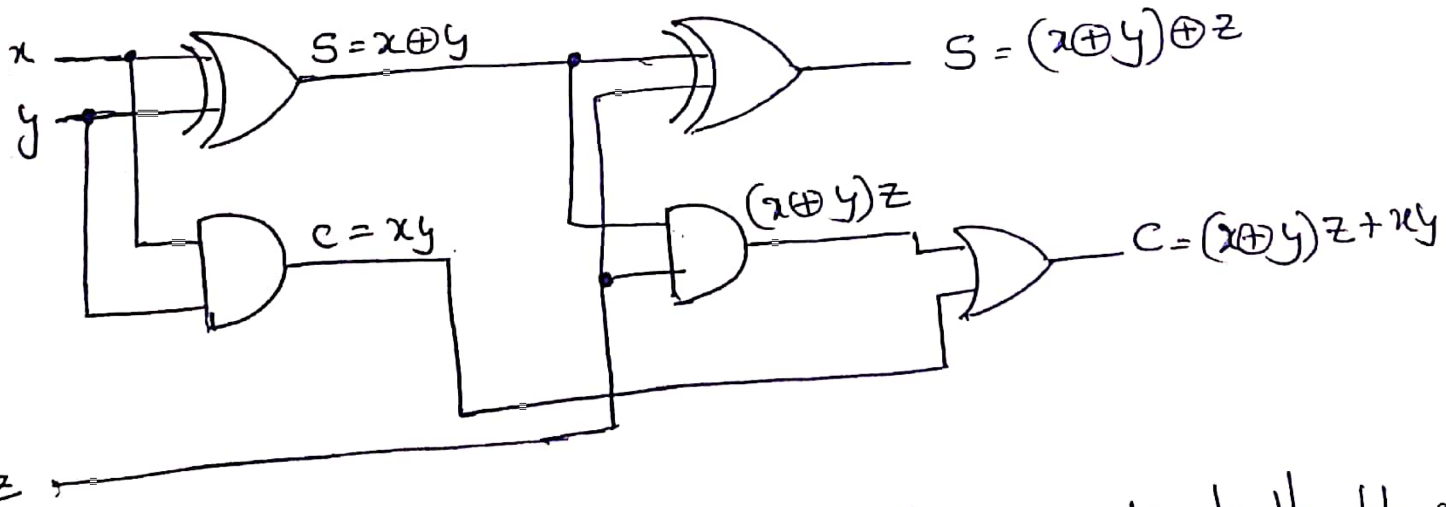
Truth Table

x	y	z	C	S
0	0	0	0	0
0	0	1	0	1
0	1	0	0	1
0	1	1	1	0
1	0	0	0	1
1	0	1	1	0
1	1	0	1	0
1	1	1	1	1

Sum and Carry can be expressed as

$$S = x'y'z + xyz + x'yz' + xy'z' = (x \oplus y) \oplus z$$

$$C = (x \oplus y)z + xy$$



Implementation of Full adder using two half adders.

BCD Adder

BCD : Binary Coded decimal.

0	1	2	3	4	5	6	7	8	9
0000	0001	0010	0011	0100	0101	0110	0111	1000	1001

<u>BCD adder</u>: It is a combinational circuit which accepts BCD inputs and produce BCD output.

BCD sum is ranging between 0 to 19 (9+9+1).

Two BCD ~~inputs~~ numbers are given to binary adder. The output of binary adder is in binary representation not in BCD representation.

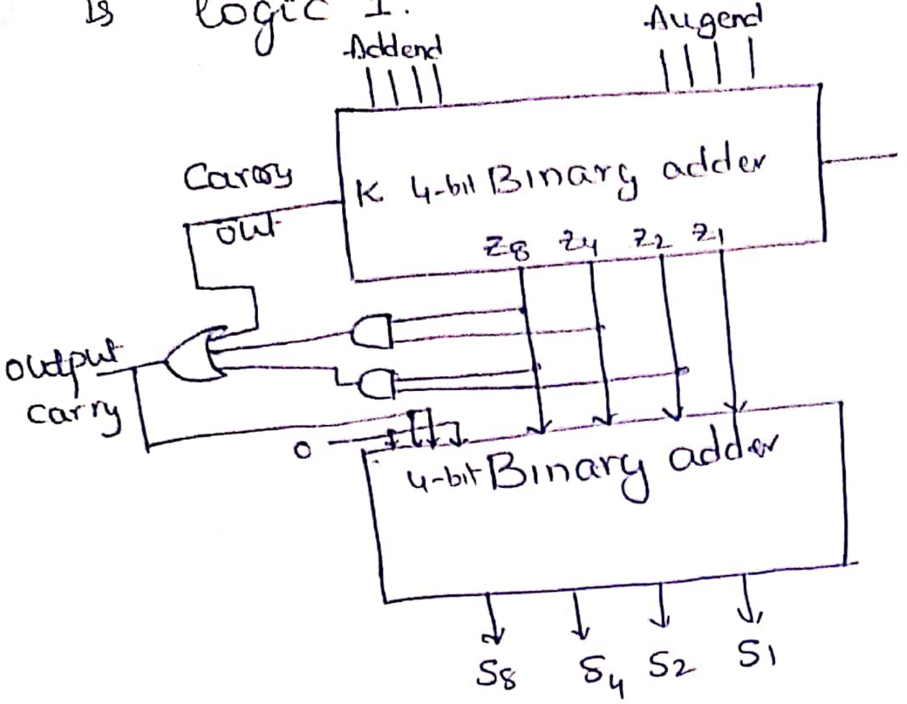
→ upto 1001, ~~sum~~ binary sum value is equal to BCD sum.

→ when the sum of binary adder exceeds 1001, The output of binary adder is given to another binary adder. Another input for second binary adder is 0110. ~~which~~ , ~~is added~~

→ this 0110 is derived from K, Z_4, Z_2 & Z_8 bits by using two <u>and</u> gates and one <u>OR</u> gates.

→ when OR Gate o/p is one (1), 0110 is added to binary sum, otherwise 0000 is added.

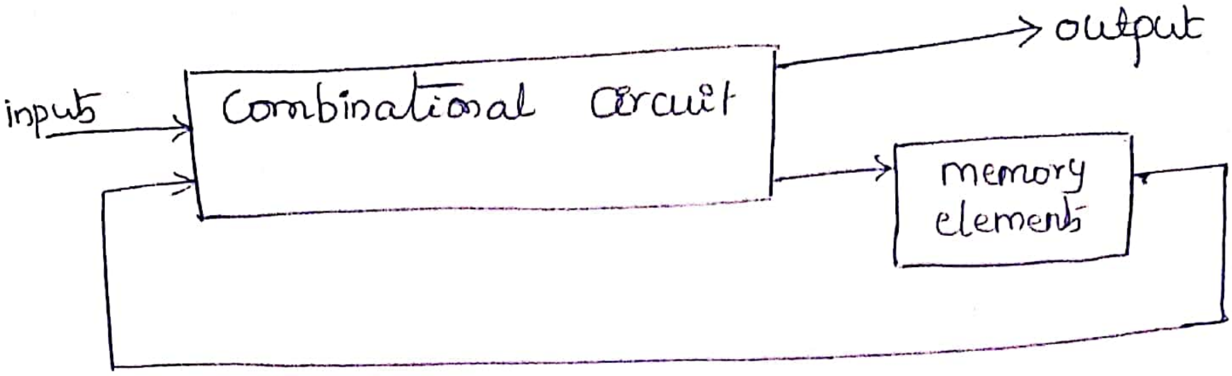
OR-Gate o/p is logic 1 when $Z_4 Z_8$ or $Z_8 Z_2$ or K is logic 1.



BCD Adder

	Binary Sum					BCD Sum				
Decimal	K	Z8	Z4	Z2	Z1	C	S8	S4	S2	S1
0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	1	0	0	0	0	1
2	0	0	0	1	0	0	0	0	1	0
3	0	0	0	1	1	0	0	0	1	1
4	0	0	1	0	0	0	0	1	0	0
5	0	0	1	0	1	0	0	1	0	1
6	0	0	1	1	0	0	0	1	1	0
7	0	0	1	1	1	0	0	1	1	1
8	0	1	0	0	0	0	1	0	0	0
9	0	1	0	0	1	0	1	0	0	1
10	0	1	0	1	0	1	0	0	0	0
11	0	1	0	1	1	1	0	0	0	1
12	0	1	1	0	0	1	0	0	1	0
13	0	1	1	0	1	1	0	0	1	1
14	0	1	1	1	0	1	0	1	0	0
15	0	1	1	1	1	1	0	1	0	1
16	1	0	0	0	0	1	0	1	1	0
17	1	0	0	0	1	1	0	1	1	1
18	1	0	0	1	0	1	1	0	0	0
19	1	0	0	1	1	1	1	0	0	1

Sequential Circuits

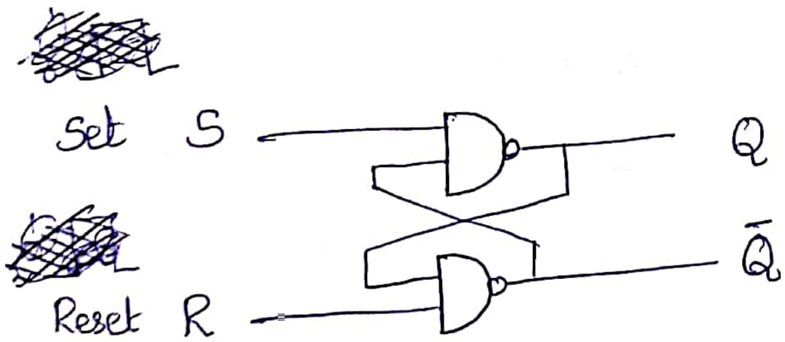


Output of sequential circuit is a function of inputs, ~~but also~~ and present state of storage elements

The next stage of storage element is a function of external inputs and present state.

Latch is a storage element, can store a bit.

SR latch



S	R	Q	Q'	
1	0	0	1	
1	1	0	1	
0	1	1	0	
1	1	1	0	
0	0	1	1	forbidden

Function table

SR latch is ~~also~~ two cross coupled nand gate

S and R are set and reset inputs. Q and $\bar{Q}$ are normal and Complement outputs. when Set input = 1 and reset input = 0 ⇒ out $Q = 0$ & $Q' = 1$

when set input = 1 and reset input = 1 ⇒ $Q = 0$ & $Q' = 1$ - no change

when $S = 0$ and $R = 1$ ⇒ the output $Q = 1$ & $Q' = 0$.

when $S = 1$ and $R = 1$ ⇒ no change in output $Q = 1$.

when $S = 0$ and $R = 0$ ⇒ $Q = Q' = 1$ - forbidden Condition

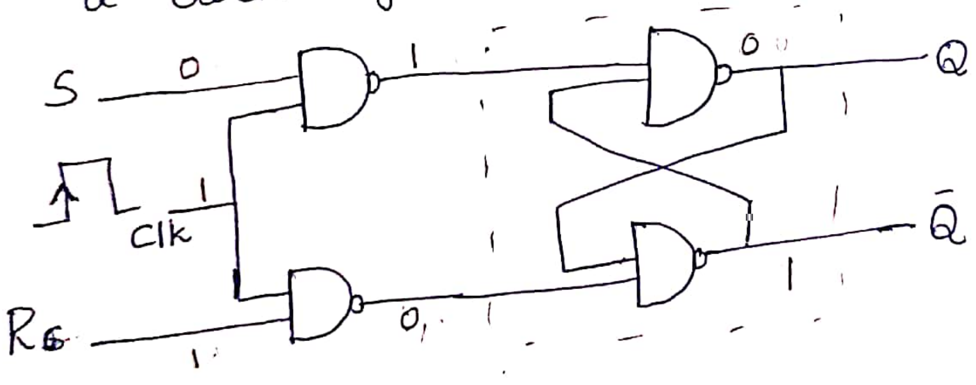
In SR latch, when $S=0, R=1 \Rightarrow$ output Q is set
when $S=1$ & $R=0 \Rightarrow$ output Q is reset.

when $R, S = 1 \Rightarrow$ no change in output.

S	R	Q	Q'	
0	1	1	0	- set
1	1	1	0	- no change
1	0	0	1	- reset
1	1	0	1	- nochange
0	0	1	1	- forbidden.

S-R flip-flop

flip-flop is a latch, which is contoolled by a clock signal.



edgetriggered S-R flip-flop

clk	S	R	Q_n	Q_{n+1}	
↑	0	0	0	0	} no change
↑	0	0	1	1	
↑	0	1	0	0	} reset
↑	0	1	1	0	
↑	1	0	0	1	} set
↑	1	0	1	1	
↑	1	1	0	—	
↑	1	1	1	—	

clk	S	R	Q_n	Q_{n+1}	
↑	1	1	0	x	invalid
↑	1	1	1	x	
0	x	x	0	0	no change
0	x	x	1	1	

The S and R input affect outputs of flip-flops only on the positive edge of the clockpulse. without clock pulse S and R inputs cannot affect the output

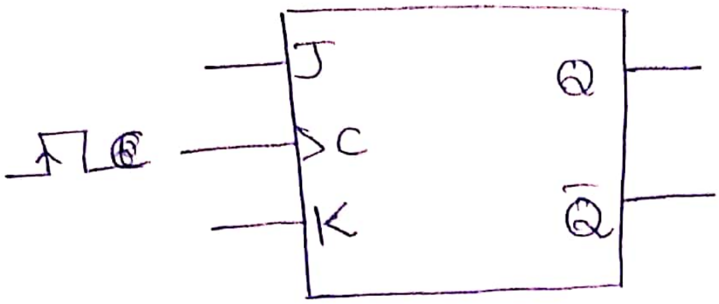
→ when S is high and R is low, the Q output goes high on positive edge of clock pulse and flip-flop is set.

→ when S is low and R is high, the Q output goes low. on the positive edge of clock pulse and flip-flop is reset

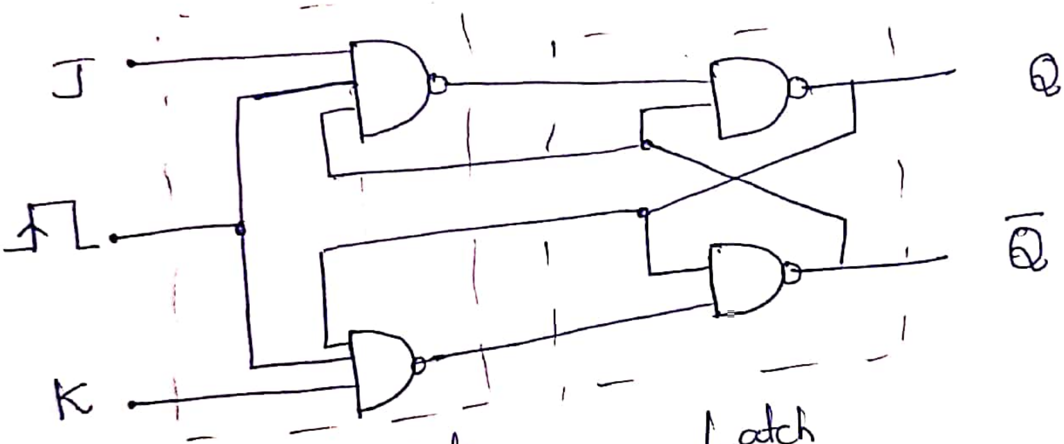
→ when both S and R are low, the output does not change from it's previous state

→ when both S and R are high, invalid condition exist

J-K flip-flop



logic Symbol.



Edge Triggered JK flip-flop

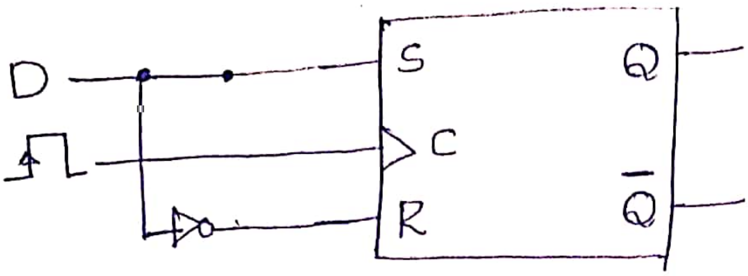
J-k flip-flop has no invalid state.

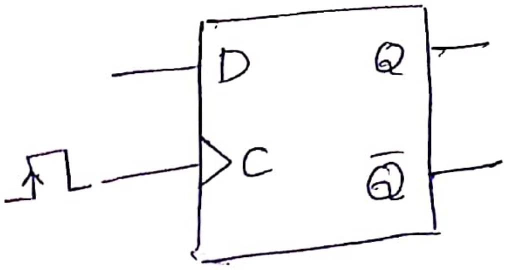
when J=0 and K=0, no change of output even a clock pulse is applied.

when J=0 and K=1, the flip-flop output is reset

~~when~~ when J=1 and K=0 the flip-flop output is set on positive edge of clock pulse.

D-flip-flop (edge triggered)





logic Symbol

D flip-flop from S-R flip-flop

D flip-flop may be obtained by just keeping one inverter between S and R terminals.

Clk	D	Q_n	Q_{n+1}	
↑	0	0	0	} reset
↑	0	1	0	
↑	1	0	1	} Set
↑	1	1	1	
0	x	0	0	} No change
0	x	1	1	

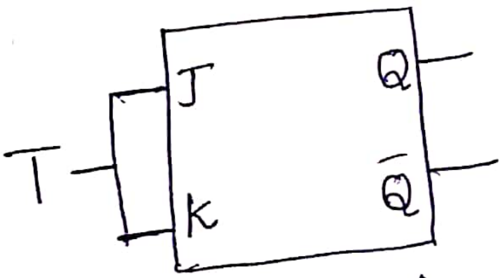
If D is logic 1 and clock is applied, Q goes to a 1. i.e

If D is logic 0 and clock is applied, Q goes to '0' when $J=1$ and $K=1$, the output toggles. i.e goes to opposite state on positive edge of clockpulse.

Clk	J	K	Q_n	Q_{n+1}	
↑	0	0	0	0	} no change
↑	0	0	1	1	
↑	0	1	0	0	} reset
↑	0	1	1	0	
↑	1	0	0	1	} set
↑	1	0	1	1	
↑	1	1	0	1	} toggle
↑	1	1	1	0	
0	x	x	0	0	} no change
0	x	x	1	1	

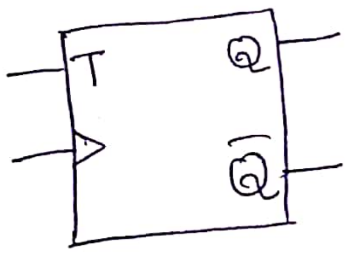
Truth Table.

→ T-flip-flop



T flip-flop from JK flipflop.

=



logic Symbol.

Clk	T	Q_n	Q_{n+1}	
↑	0	0	0	no change
↑	0	1	1	
↑	1	0	1	Toggle
↑	1	1	0	
0	x	0	0	no change
0	x	1	1	

when T is high, the flip-flop toggles on every new clock pulse. when T is low, the flip-flop o/p remains same, no change.

when T=1, J=K=1, and flip flop toggles, output is complemented. i.e $Q_{n+1} = \overline{Q_n}$

when T=0, J=K=0 and there is no change of o/p

$Q_{n+1} = Q_n$.

Shift Registers

A register is a group of flip-flops, which shares a common clock. A register is capable of shifting the binary information.

Shift Registers: a number of flip-flops connected together such that data may be shifted into and out of them is called shift register.

shift Registers are four types

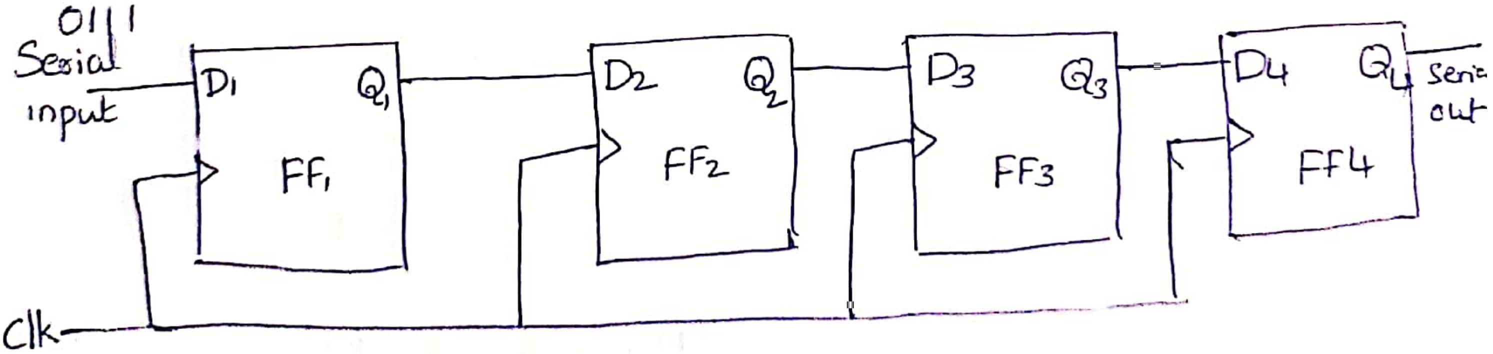
Serial in Serial out shift Registers

Serial in parallel out shift Registers

parallel in Serial out shift Registers

parallel in parallel out shift Registers.

→ Serial in Serial out shift Register (4-bit)



D-flips are used in shift Registers

common clock is connected to all D-flip-flops.

The data 0111 is loaded serially i.e bit by bit through input D1 of first flip-flop.

The output Q of D-flip-flop is connected to D-input of next flip-flop.

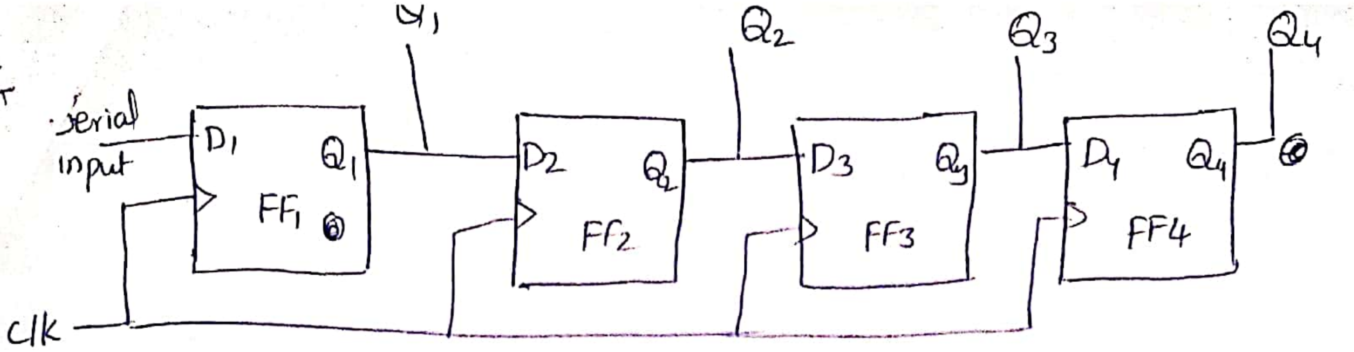
4 clock pulses are required to load 4-bit data (0111) into register

7 clock pulses are required to get output at Q_4 serially.

Clk	D input	Q_1	Q_2	Q_3	Q_4
0	0	0	0	0	0
1 ↑	1	1	0	0	0
2 ↑	1	1	1	0	0
3 ↑	1	1	1	1	0
4 ↑	0	0	1	1	1 → 1
5 ↑	0	0	0	1	1 → 1
6 ↑	0	0	0	0	1 → 1
7 ↑	0	0	0	0	0 → 0

→ Serial in parallel out shift Register

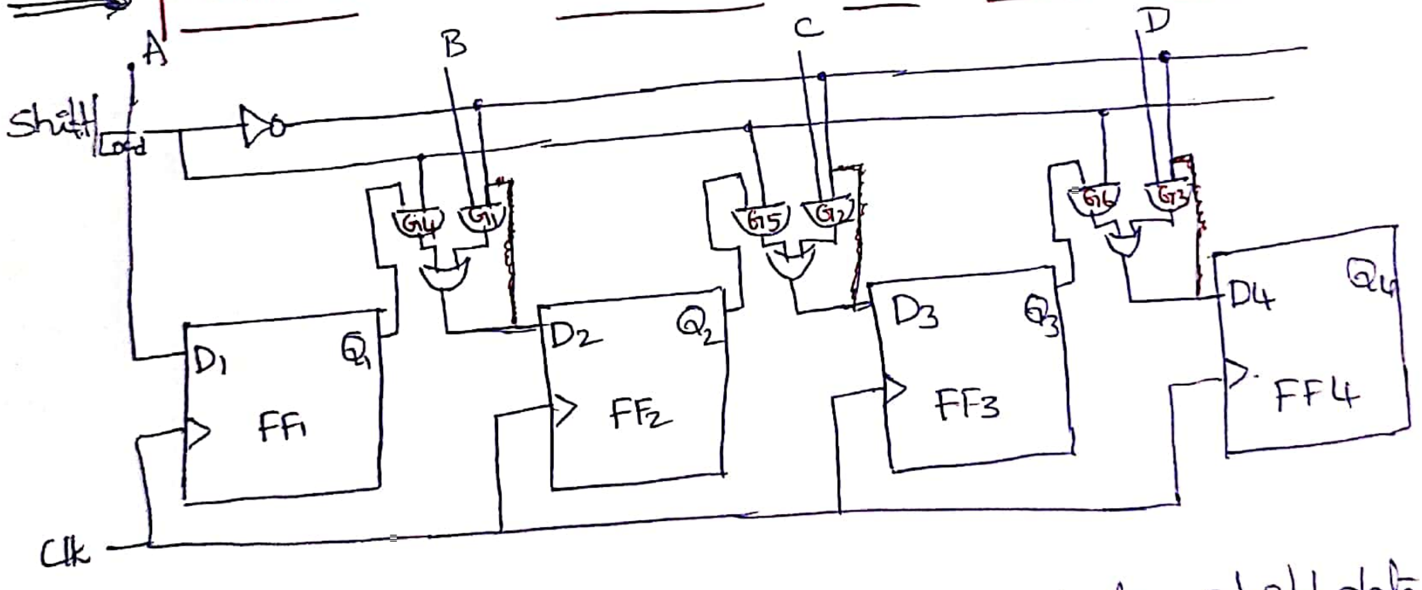
The data is loaded serially into 4-bit register through D_1 input. The output is taken parallely from Q_1, Q_2, Q_3 and Q_4.



4-bit Serial in parallel out Shift register.

4 clock pulses are required to load serially and to get output parallely.

Parallel in Serial out Shift Registers

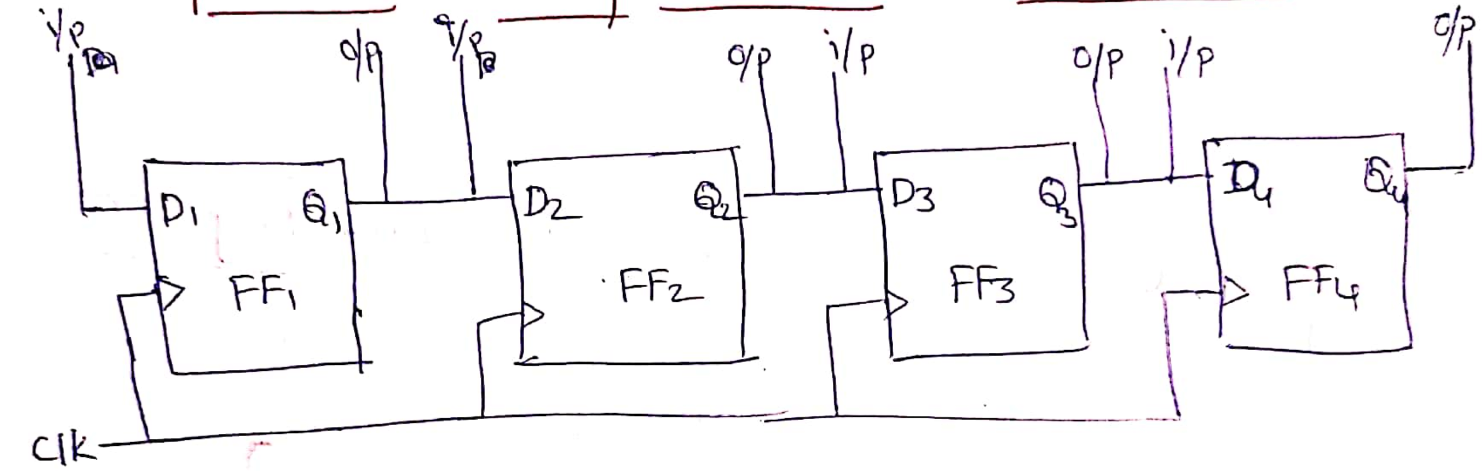


Shift/$\overline{\text{Load}}$ control signal is used to shift data serially and load data parallely

when Shift/$\overline{\text{Load}}$ is ~~high~~ low, allows G4, G5 and G6 and gates are disabled. and G1, G2 and G3 and gates are enabled. to load data parallely.

when $\overline{\text{Shift}/\text{Load}}$ is high, G_1, G_2 & G_3 are disabled, and G_4, G_5 and G_6 are enabled. allow the data bits to shift right from one stage to the next stage serially.

→ parallel in parallel out shift Register



data is loaded parallely in single clock pulse. the output is taken parallely at Q_1, Q_2, Q_3 & Q_4 parallely. in a single clock pulse.

UNIT – I

Diodes and Applications: Semiconductor Diode, Diode as a Switch& Rectifier, Half Wave and Full Wave Rectifiers with and without Filters; Operation and Applications of Zener Diode, LED, Photo Diode.

Transistor Characteristics: Bipolar Junction Transistor (BJT) – Construction, Operation, Amplifying Action, Common Base, Common Emitter and Common Collector Configurations, Operating Point, Biasing of Transistor Configuration; Field Effect Transistor (FET) – Construction, Characteristics of Junction FET, Concepts of Small Signal Amplifiers –CE & CC Amplifiers.

****

Electronic Device

The device which controls the flow of electrons is called electronic device. These devices are the main building blocks of electronic circuits. The motion of electrons through a conductor gives electric current.

Review of Semiconductors

Atomic Structure

- Atom is the basic building block of all the elements. It consists of the central nucleus of positive charge around which small negatively charged particles called electrons revolve in different paths or orbits. An Electrostatic force of attraction between electrons and the nucleus holds up electrons in different orbits.

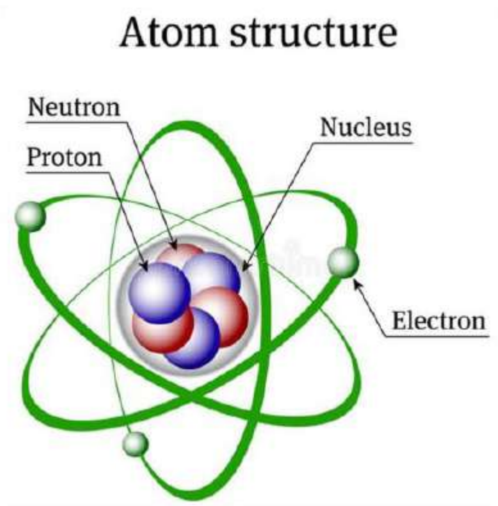


Figure 1.1 Atomic structure

- Nucleus is the central part of an atom and contains protons and neutrons. A proton is positively charged particle, while the neutron has the same mass as the proton, but has no charge. Therefore, nucleus of an atom is positively charged.
- **atomic weight = no. of protons + no. of neutrons**
- An electron is a negatively charged particle having negligible mass. The charge on an electron is equal but opposite to that on a proton. Also the number of electrons is equal to the number of protons in an atom under ordinary conditions. Therefore an atom is neutral as a whole.
- **atomic number = no. of protons or electrons in an atom**

- The number of electrons in any orbit is given by $2n^2$ where n is the number of the orbit. For example,

  I orbit contains $2x1^2 = 2$ electrons

  II orbit contains $2x2^2 = 8$ electrons

  III orbit contains $2x3^2 = 18$ electrons and so on

Positive and negative ions

- Protons and electrons are equal in number hence if an atom loses an electron it has lost negative charge therefore it becomes positively charged and is referred as **positive ion**.
- If an atom gains an electron it becomes negatively charged and is referred to as **negative ion**.

Valence electrons:

The electrons in the outermost orbit of an atom are known as valence electrons.

- The outermost orbit can have a maximum of 8 electrons.
- The valence electrons determine the physical and chemical properties of a material.
- When the number of valence electrons of an atom is less than 4, the material is usually a metal and a conductor. Examples are sodium, magnesium and aluminium, which have 1,2 and 3 valence electrons respectively.
- When the number of valence electrons of an atom is more than 4, the material is usually a non-metal and an insulator. Examples are nitrogen, sulphur and neon, which have 5,6 and 8 valence electrons respectively.
- When the number of valence electrons of an atom is 4 the material has both metal and non-metal properties and is usually a semi-conductor. Examples are carbon, silicon and germanium.

Free Electrons

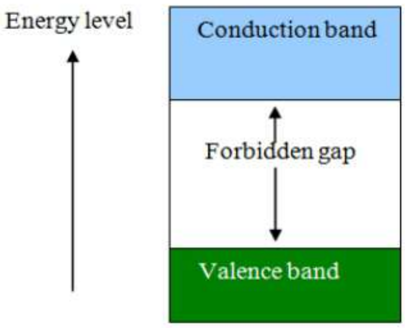
- The valence electrons of different material possess different energies. The greater the energy of a valence electron, the lesser it is bound to the nucleus.
- In certain substances, particularly metals, the valence electrons possess so much energy that they are very loosely attached to the nucleus.
- The loosely attached valence electrons move at random within the material and are called free electrons.

The valence electrons, which are loosely attached to the nucleus, are known as free electrons.

Energy bands:

- In case of a single isolated atom an electron in any orbit has definite energy.
- When atoms are brought together as in solids, an atom is influenced by the forces from other atoms. Hence an electron in any orbit can have a range of energies rather than single energy. These ranges of energy levels are known as Energy bands.
- Within any material there are two distinct energy bands in which electrons may exist viz

,Valence band and conduction band.



- The range of energies possessed by valence electrons is called valence band.
- The range of energies possessed by free electrons is called conduction band.
- Valence band and conduction band are separated by an energy gap in which no electrons normally exist this gap is called forbidden gap.

Classification of materials based on Energy band theory:

Based on the width of the forbidden gap, materials are broadly classified as

- Conductors
- Insulators
- Semiconductors.

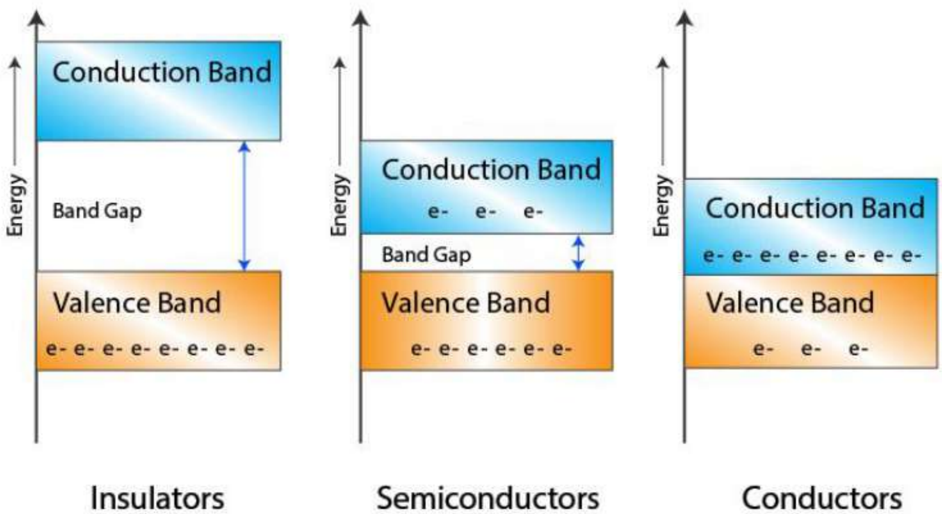


Figure 1.2: Classification of materials

Conductor

- The conduction band and the valence band partly overlap each other and there is no forbidden energy band gap in between
- The electrons from the valence band can easily move into the conduction band
- Hence, large number of electrons are available for conduction
- The resistance of such materials is low and conductivity is high

Ex: Copper, Silver, Gold etc.

The nature of bonding is metallic. It contains less than four valance electrons present.

Insulator

- In case of insulators, a large energy gap exists between the valence band and the conduction band
- The energy gap is so high that the electrons from the valence band cannot move to the conduction band by thermal excitation
- As there are no electrons in the conduction band, electrical conduction is not possible. It contains 8 valance electrons present.The nature of bonding is covalent Ionic.

Ex: Wood, Paper, diamond etc.

Semiconductor

A semiconductor is a material that has conductivity level between the insulator and conductor. The nature of bonding is covalent bonding.

Ex: Silicon and Germanium

Classification of Semiconductors

Semiconductors are classified into two types.

a) Intrinsic semiconductors.

b) Extrinsic semiconductors.

Intrinsic Semiconductors

Intrinsic Semiconductor is a pure semiconductor. The energy gap in Si is 1.1 eV and in Ge is 0.74 eV.

Si: $1s^2$, $2s^2$, $2p^6$,$3s^2$, $3p^2$. (Atomic No. is 14)

Ge: $1s^2$, $2s^2$, $2p^6$,$3s^2$, $3p^6$, $3d^{10}$, $4s^2$, $4p^2$. (Atomic No. is 32)

In intrinsic semiconductor, the number of thermally generated electrons always equals the number of holes. So, if $n_i$and p_i are the concentration of electrons and holes respectively, then

$n_i = p_i$.

The quantity $n_i$or p_i is referred to as the 'intrinsic carrier concentration'.

Each atom forms a covalent bond or electron pair bond with the electrons of neighbouring atom.

At Low temperature

At 0^0K all valance electrons are in perfect covalent bonding and therefore intrinsic semiconductor at 0^0K work as an insulator

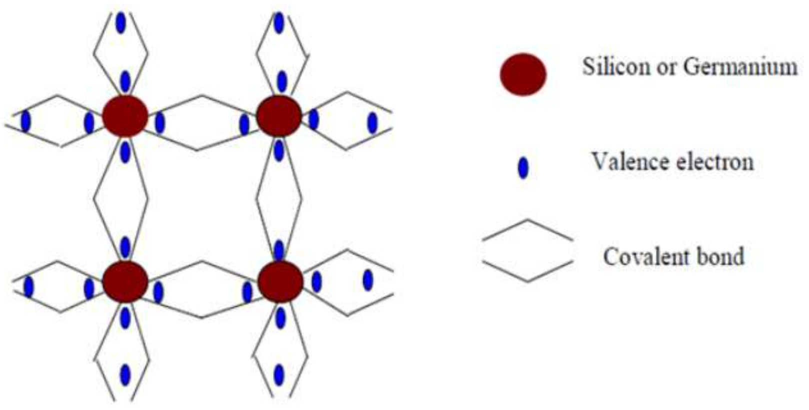


Figure 1.3: Intrinsic semiconductor at 0^0K

At room temperature

- At room temperature, some of the valence electrons gain enough thermal energy to break up the covalent bonds.
- This breaking up of covalent bonds sets the electrons free and is available for conduction.
- When an electron escapes from a covalent bond and becomes free electrons, a vacancy is created in a covalent bond. Such a vacancy is called Hole. It carries positive charge and moves under the influence of an electric field in the direction of the electric field applied.
- Numbers of holes are equal to the number of electrons since; a hole is nothing but an absence of electrons.

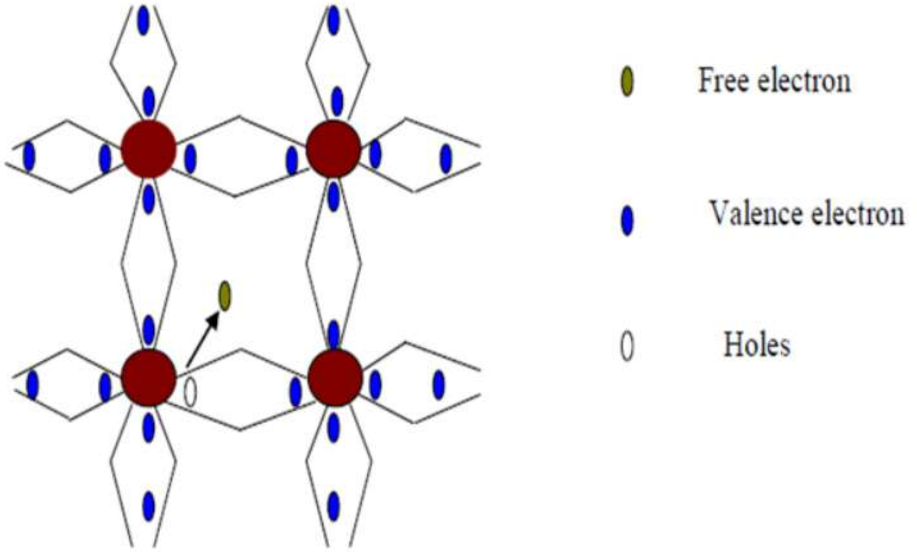


Figure 1.4: Intrinsic semiconductor at room temperature

- ❖ Because of opposite charges electrons and holes always move in opposite direction.
- ❖ Current direction is opposite to the flow of electron.
- ❖ Current direction is in the direction of hole flow.

Generation of Electron-Hole Pair

It indicates creation of charge carriers due to breaking of a number of covalent bonds.

Recombination

When a free electron, pair with a hole it is called recombination. During the recombination, the free electron and hole will disappear and a covalent bond is created.

Disadvantage of Intrinsic semiconductor

Conductivity is very small and not suitable for any practical operation.

Doping

It is the process of adding impurities to the pure semiconductor. Doping increases carrier concentration, hence therefore increases the conductivity.

Methods of doping:

i) Heating the crystal in the presence of dopant atoms.

ii) Adding impurity atoms in the molten state of semiconductor.

iii) Bombarding semiconductor by ions of impurity atoms.

Trivalent impurities: Acceptor Impurities: B, Al, Ga

Pentavalent impurities: Donar Impurities: P, As, Sb

Impurity Ratio:1:10^8

Extrinsic semiconductor

- ❖ When an impurity is added to an intrinsic semiconductor its conductivity changes.
- ❖ This process of adding impurity to a semiconductor is called Doping and the impure semiconductor is called extrinsic semiconductor.
- ❖ Depending on the type of impurity added, extrinsic semiconductors are further classified as n-type and p-type semiconductor.

Extrinsic semiconductors are of two types:

- ❖ N Type semiconductor
- ❖ P Type semiconductor

N Type semiconductor

When a semiconductor material is doped with the pentavalent atom like phosphorous or Arsenic or Antimony, n type semiconductor is formed. It contains electron as majority charge carriers. It contains large number of electrons and a few thermally generated minority holes.

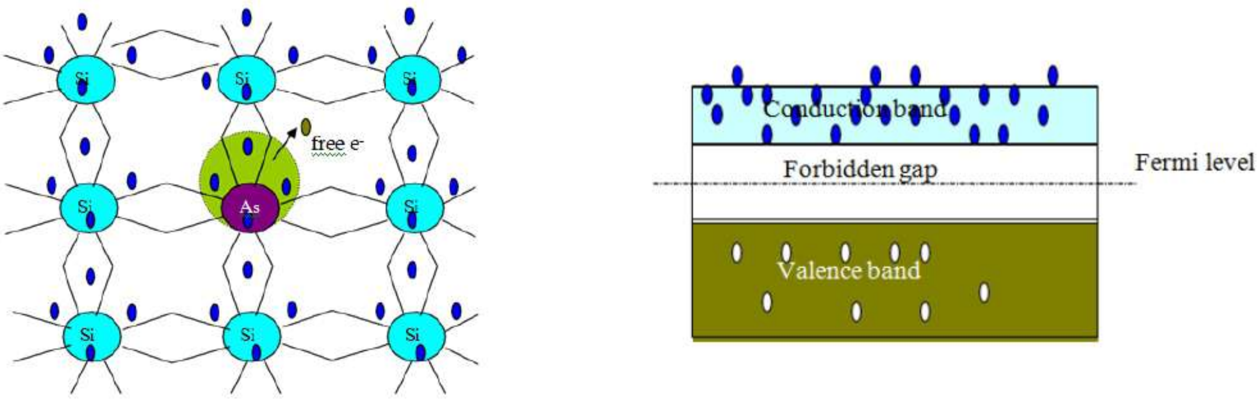


Figure 1.5: N Type semiconductor material with energy band diagram

- ❖ Such impurities which produce n-type semiconductors are known as Donor impurities because they donate or provide free electrons to the semiconductor crystal.
- ❖ Silicon atom has 4 valence electrons and Arsenic has 5 valence electrons. When Arsenic is added as impurity to silicon, the 4 valence electrons of silicon make co-valent bond with 4 valence electrons of Arsenic.
- ❖ The 5^{th} Valence electrons finds no place in the covalent bond thus, it becomes free and travels to the conduction band. Therefore, for each arsenic atom added, one free electron will beavailable in the

silicon crystal. Though each arsenic atom provides one free electron yet an extremely small amount of arsenic impurity provides enough atoms to supply millions of free electrons.

P Type Semiconductor

When semiconductor material is doped with trivalent atoms like Boron, Aluminum, Indium, P type semiconductor is formed. P type semiconductor contains holes as majority carriers. It contains large number of holes and a few thermally generated minority electrons.

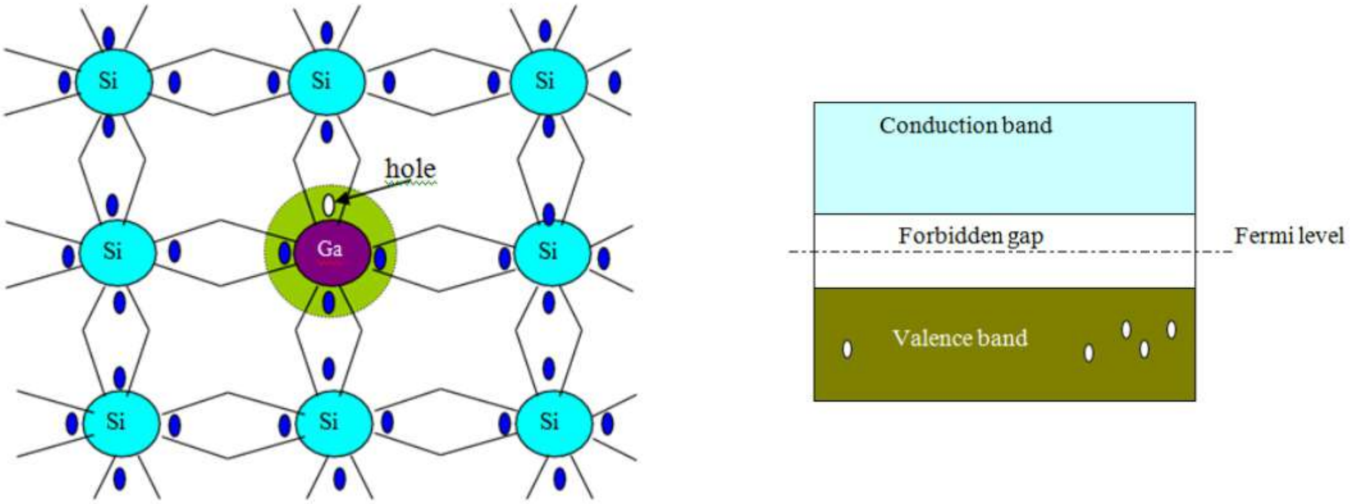


Figure 1.6: P Type semiconductor material with energy band diagram

- Silicon atom has 4 valence electrons and Gallium has 3 electrons. When Gallium is added as impurity to silicon, the 3 valence electrons of gallium make 3 covalent bonds with 3 valence electrons of silicon.
- The 4th valence electrons of silicon cannot make a covalent bond with that of Gallium because of short of one electron. This absence of electron is called a hole. Therefore for each gallium atom added one hole is created, a small amount of Gallium provides millions of holes.

SEMICONDUCTOR DIODE

When a p-type semiconductor material is suitably joined to n-type semiconductor the contact surface is called a p-n junction. The p-n junction is also called as semiconductor diode.

The terminal connected to P-type material is called Anode and the terminal connected to N-type material is called Cathode.

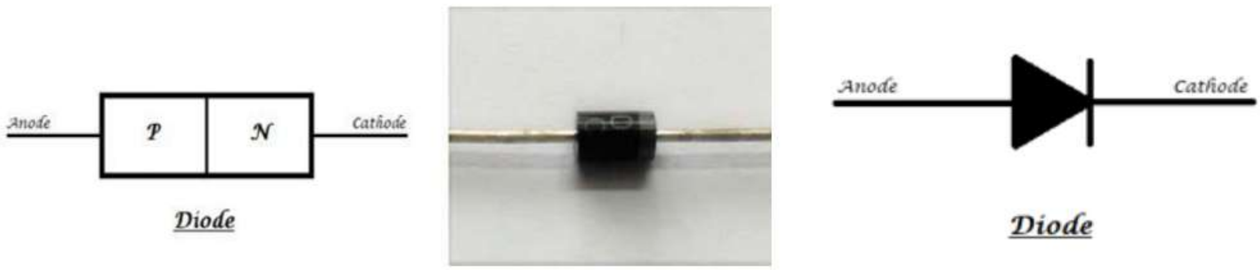


Figure 1.7: PN Junction diode symbol

The arrow indicates the flow of current through it when the diode is in forward biased mode, the dash or the block at the tip of the arrow indicates the blockage of current from the opposite direction.

P-N Junction Theory

Junction Formation:

Initially, when both the materials are joined together the excess electrons in the N-type and excess holes in the P-type will get attracted to each other and gets recombined where the formation of immobile ions (Donor ion and Acceptor ion). These immobile ions resist the flow of electrons or holes through it which now acts as a barrier in between the two materials. The barrier which is now formed is called as Depletion region. The width of the depletion region in this case depends upon the doping concentration in the materials.

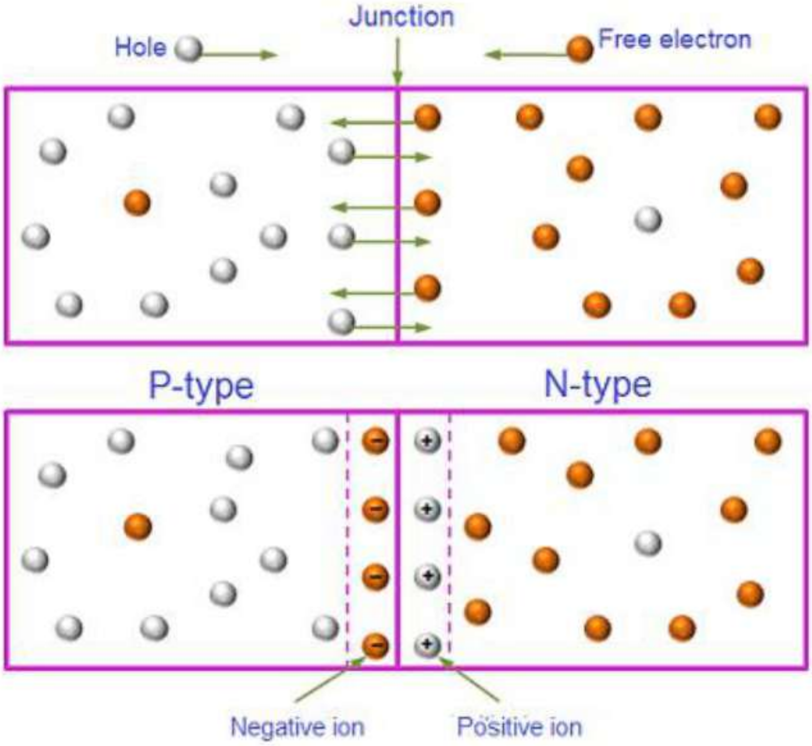


Figure 1.7: PN Junction diode formation

There are two operating regions and three possible "biasing" conditions for the standard Junction Diode and these are:

1. **Zero Bias** – No external voltage potential is applied to the PN junction diode.

2. **Reverse Bias** – The voltage potential is connected negative, (-ve) to the P-type material and positive, (+ve) to the N-type material across the diode which has the effect of Increasing the PN junction diode's width.

3. **Forward Bias** – The voltage potential is connected positive, (+ve) to the P-type material and negative, (-ve) to the N-type material across the diode which has the effect of Decreasing the PN junction diodes width.

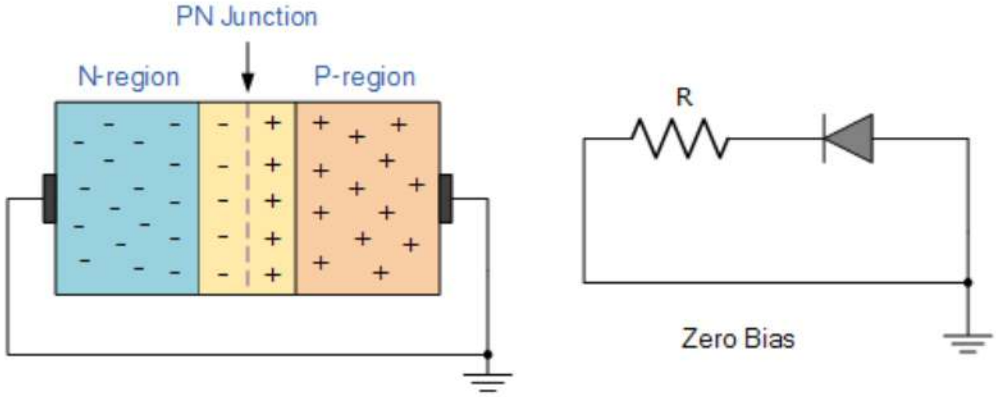
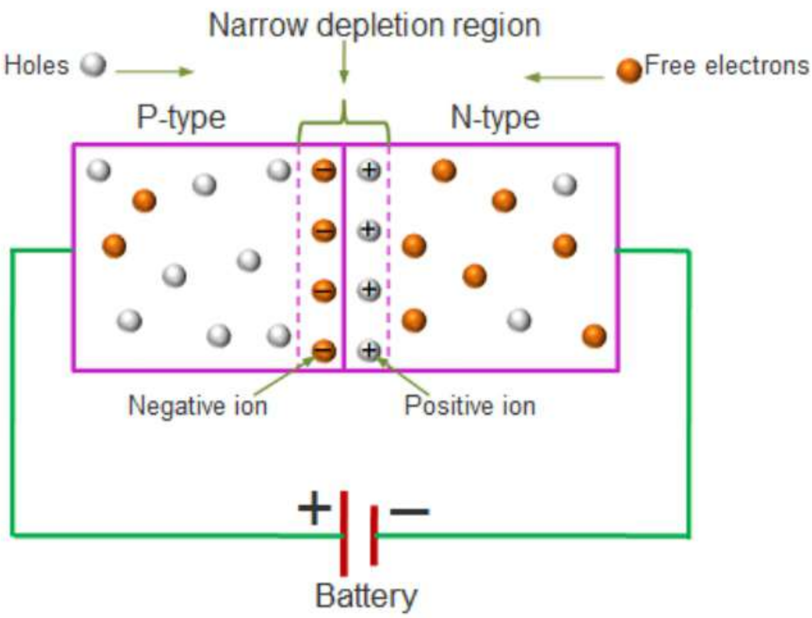


Figure 1.8: PN Junction diode with no bias

Diode in Forward Bias:

To break a barrier within a normal diode a minimum of **+0.7 Volts** (for Silicon) and **+0.3 Volts** (for Germanium) external voltage should be applied to the terminals. These voltages are called as Cut-in voltage or Offset voltage or Break-point voltage or firing voltage or **Threshold voltage**.



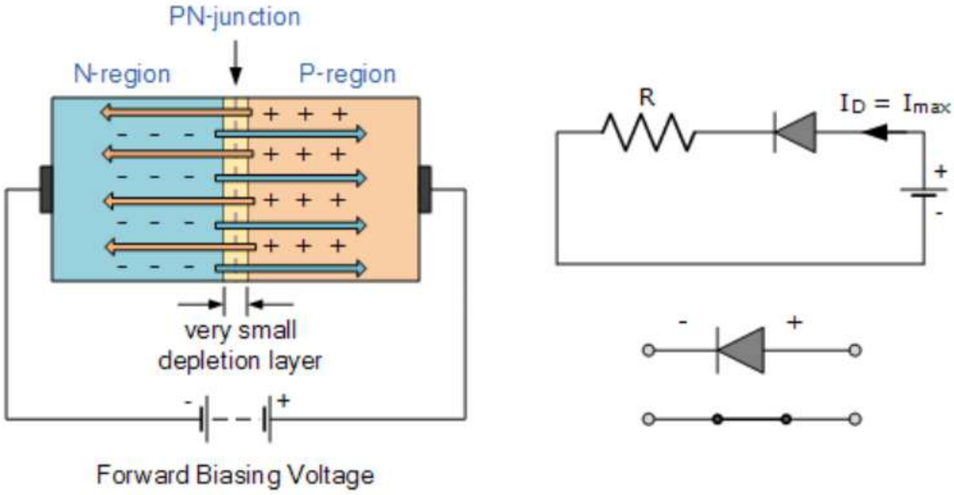
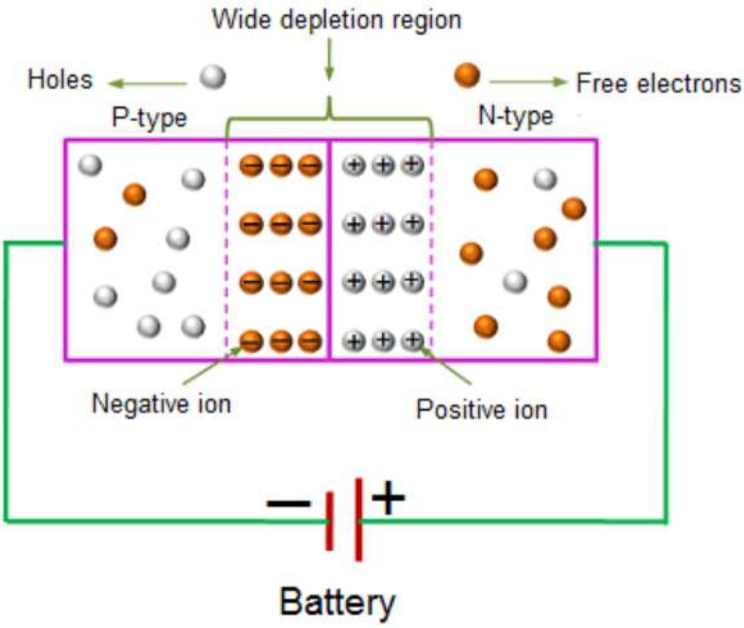


Figure 1.8: PN Junction diode with forward bias

If a positive terminal of the battery or a voltage source is applied to the anode or P region of the diode and negative terminal to the cathode or N region of the diode, it is said to be forward biased.Due to forward bias, majority charge carriers in both regions get repelled (because positive voltage is applied to P region and negative to N region) and enter into the depletion region. Hence immobile ions get back lost carriers become neutral and move to undepleted region hence width of the barrier decreases gradually, when the applied voltage is greater than or equal to cut-in voltage, entire barrier is destructed and the electrons and holes are now free to cross the junction which then forms a closed circuit and enables the flow of current.

Diode in Reverse bias:

If negative terminal of a voltage source is applied to the anode or P region of the diode and positive terminal to the cathode or N region of the diode, it is said to be Reverse biased.



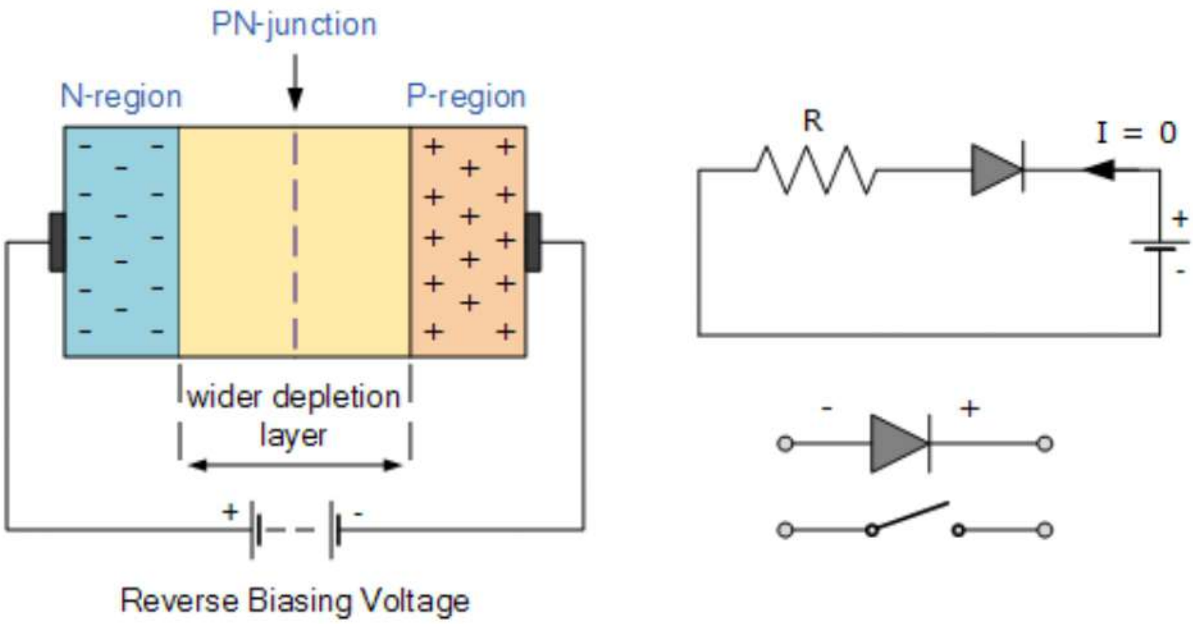


Figure 1.9: PN Junction diode with Reverse bias

When such voltage is applied, the majority charge carriers in both regions get attracted towards source such that large numbers of immobile ions are created and enter into the P and N regions. Therefore, width of the depletion region also increases gradually which is now difficult for the electrons and holes to cross the junction so open circuit forms and current flows. But if we go on increase the voltage, at a point barrier or depletion region cannot withhold the external force and the junction breaks down which may sometimes cause the normal diode damage permanently. The reverse voltage at which the diode conducts is called as Break down voltage. As the diode in reverse bias acts as an open switch, its resistance is in the order of Mega ohms. When the reverse voltage is applied to the diode small amount of current flows in the circuit due to the minority charge carriers which is generally called as **Reverse saturation current**. These currents are also called as Leakage currents because even when the diode is open circuited, current exists in circuit so it is termed as **leakage**.

Diode terminal characteristics equation for diode junction current:

$$I_D = I_0 (e^{\frac{v}{\eta V_T}} - 1)$$

Where $V_T = kT/q$;

V _ diode terminal voltage, Volts

Io _ temperature-dependent saturation current, µA

T _ absolute temperature of p-n junction, K

k _ Boltzmann's constant 1.38x 10 -23J/K)

q _ electron charge 1.6x10-19 C

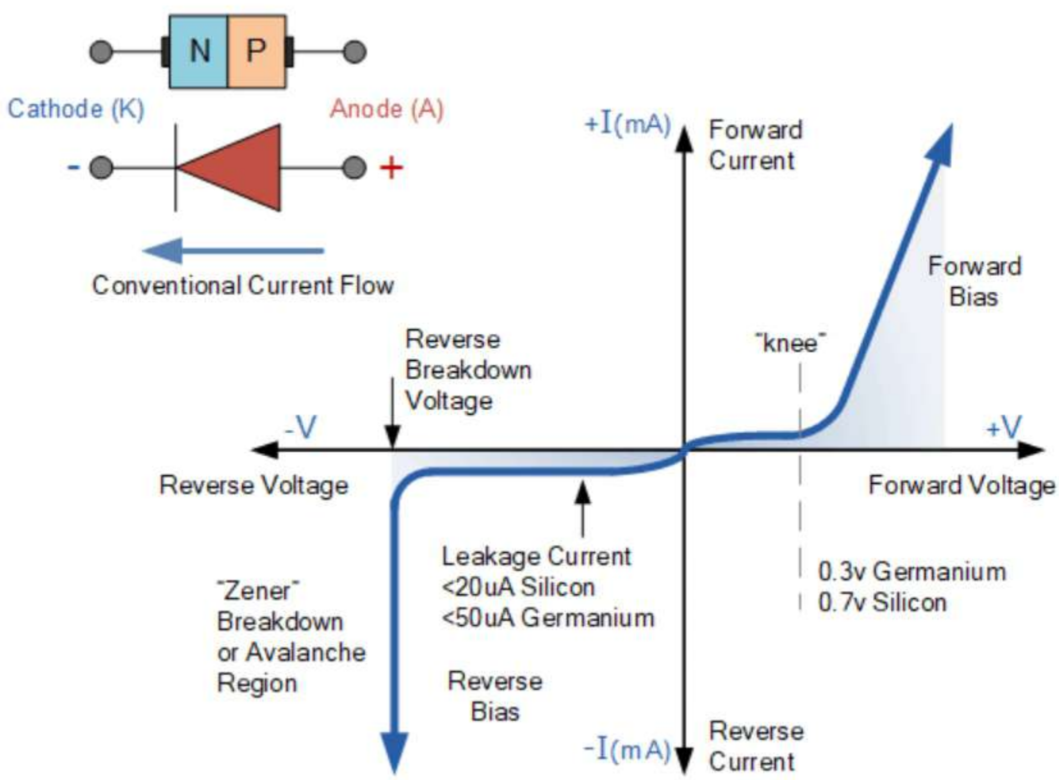


Figure 1.10: V-I Characteristics of PN Junction diode

DC or Static Resistance

When forward biased voltage is applied to a diode that is connected to a DC circuit, a DC or direct current flows through the diode. Direct current or electric current is nothing but the flow of charge carriers (free electrons or holes) through a conductor. In DC circuit, the charge carriers flow steadily in single direction or forward direction. The resistance offered by a p-n junction diode when it is connected to a DC circuit is called **static resistance**.

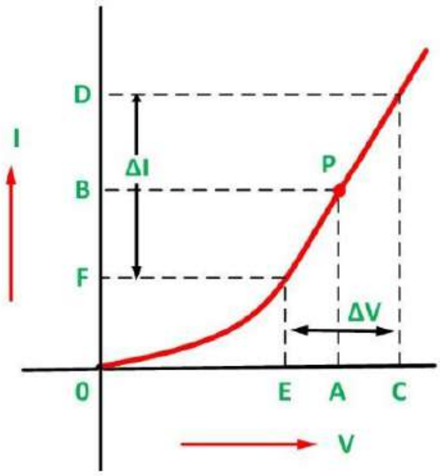


Figure 1.11:Forward Characteristics of PN Junction diode

$$R_f = \frac{\text{DC voltage}}{\text{DC current}}$$

Dynamic resistance or AC resistance

The dynamic resistance is the resistance offered by the p-n junction diode when AC voltage is applied.

When forward biased voltage is applied to a diode that is connected to AC circuit, an AC or alternating current flows though the diode. In AC circuit, charge carriers or electric current does not flow in single direction. It flows in both forward and reverse direction.

Dynamic resistance is also defined as the ratio of change in voltage to the change in current. It is denoted as r_f.

$$r_f = \frac{\text{Change in voltage}}{\text{Change in current}}$$

Diode Equivalent Circuit

Components of the piecewise-linear equivalent circuit.

• The ideal diode establishes that there is only one direction of conduction through the device and areverse bias condition will result in the open circuit state

• The average ac resistance r_{av} defines the resistance level of the device when it is in the 'on' state

• The battery V_T which opposes the conduction direction appears in the circuit to establish that the Si semiconductor does not reach the conduction state until V_D reaches 0.7V with a forward bias

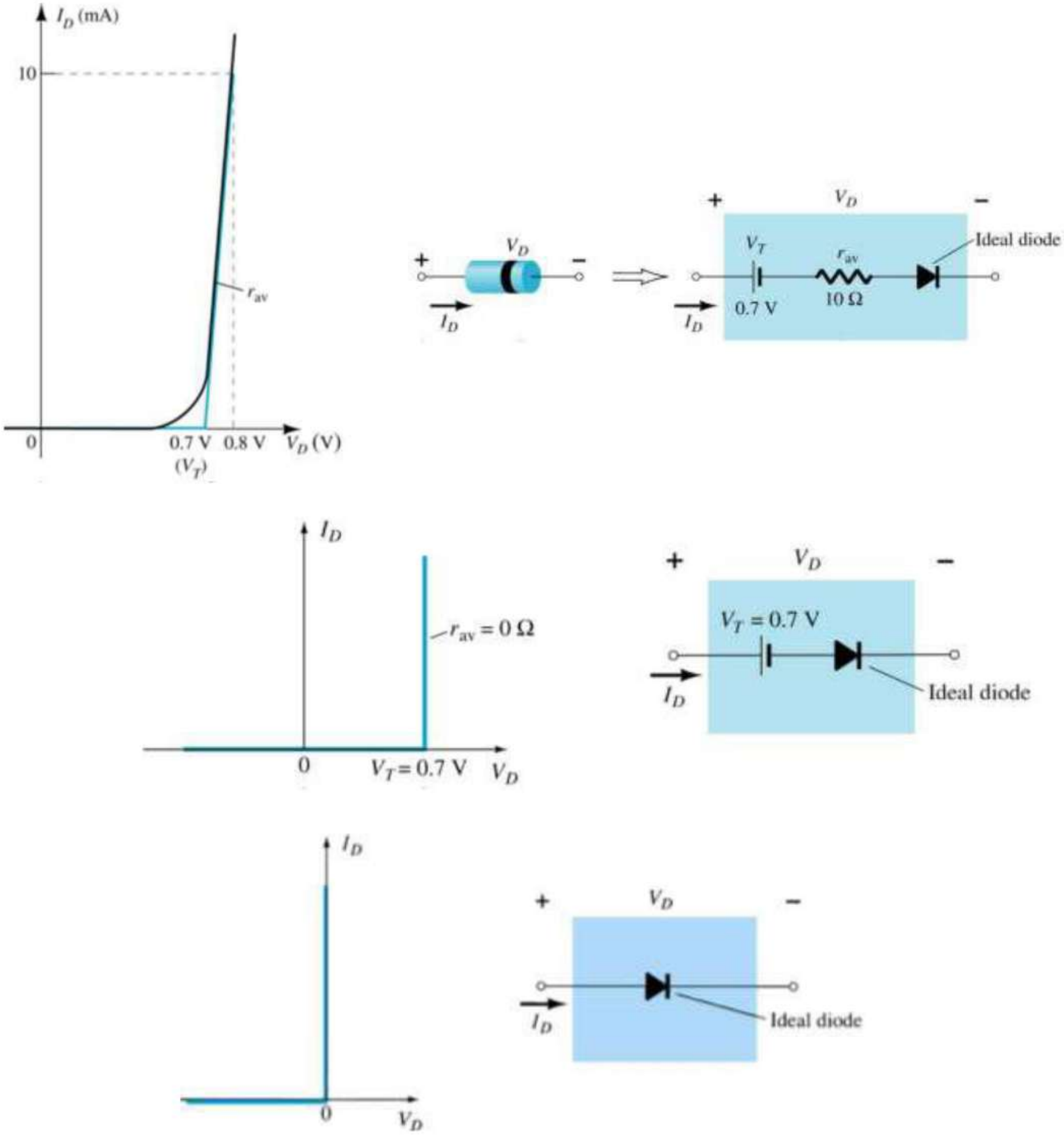


Figure 1.12: Diode equivalent circuit of PN Junction diode

DIODE AS a SWITCH

The Diode is a two terminal PN junction that can be used in various applications. One of the applications of diode is an electrical switch. The PN junction, when forward biased acts as closed circuit with finite forward resistance, said to be in ON state. The PN junction, when reverse biased acts as open circuit with high reverse resistance, said to be in OFF state.

Factors that affect diode switching times:

- **Diode Capacitance** – The PN junction capacitance changes depending upon the bias conditions.
- **Diode Resistance** – The resistance offered by the diode while change of its state.
- **Doping Concentration** − The level of doping of the diode, affects the diode switching times.
- **Depletion Width** − The narrower the width of the depletion layer, the faster the switching will be.

Regulated Power Supply

A **regulated power supply** converts unregulated AC (Alternating Current) to a constant DC (Direct Current). A regulated power supply is used to ensure that the output remains constant even if the input changes.

The regulated power supply will accept an AC input and give a constant DC output. The figure below shows the block diagram of a typical regulated DC power supply.

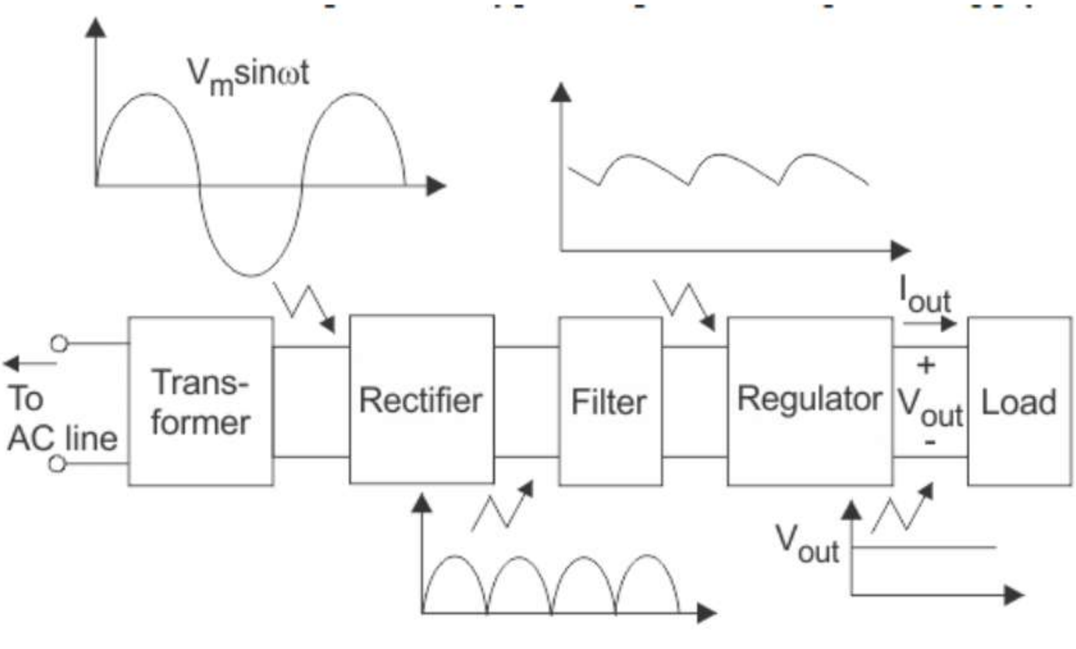


Figure 1.13: Block diagram of Regulated Power Supply

The basic building blocks of a regulated DC power supply are as follows:

1. A step-down transformer
2. A rectifier
3. A DC filter
4. A regulator

DIODE AS A RECTIFIER

A rectifier may be defined as an electronic device, such as a semiconductor diode, used for converting Alternate current voltage or current into unidirectional voltage or current.

The main application of p-n junction diode is in rectification circuits. These circuits are used to describe the conversion of a.c signals to d.c in power supplies. Diode rectifier gives an alternating voltage which pulsates in accordance with time.

Any electrical device which offers a low resistance to the current in one direction but a high resistance to the current in the opposite direction is called rectifier. Such a device is capable of converting a sinusoidal input waveform, whose average value is zero, into a unidirectional Waveform. A rectifier is a device, which converts a.c. voltage (bi-directional) to pulsating d.c. voltage (Unidirectional).

Rectifiers may be classified in to two categories depending upon the period of conduction. They are

(a) Half-wave rectifiers

(b) Full–wave rectifiers

Full wave rectifiers may further be classified in to two categories depending upon nature of the circuit connection. They are

(a) Centre tapped full-wave rectifier

(b) Bridge full-wave rectifier

Half wave rectifier

A half wave rectifier is a type of rectifier which allows only half cycle (either positive half cycle or negative half cycle) of the input AC signal while another half cycle is blocked.

A complete half-wave rectifier circuit consists of 3 main parts:

1. A transformer
2. A resistive load
3. A diode

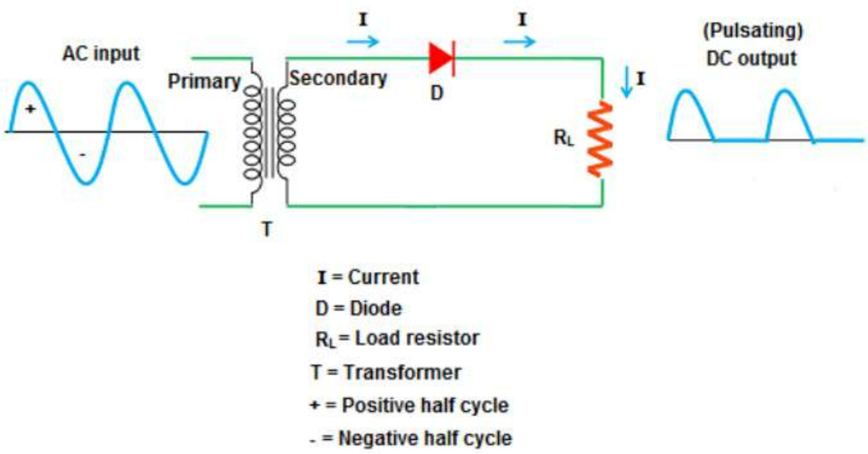


Figure 1.14: Half Wave Rectifier Circuit

The low AC voltage produced by the step-down transformer is directly applied to the diode.When low AC voltage is applied to the diode (D), during the positive half cycle of the signal, the diode is forward biased and allows electric current whereas, during the negative half cycle, the diode is reverse biased and blocks electric current. The positive half-cycle of the input AC signal applied to the diode is analogous to the forward DC voltage applied to the p-n junction diode similarly the negative half-cycle of the input AC signal applied to the diode is analogous to the reverse DC voltage applied to the p-n junction diode.

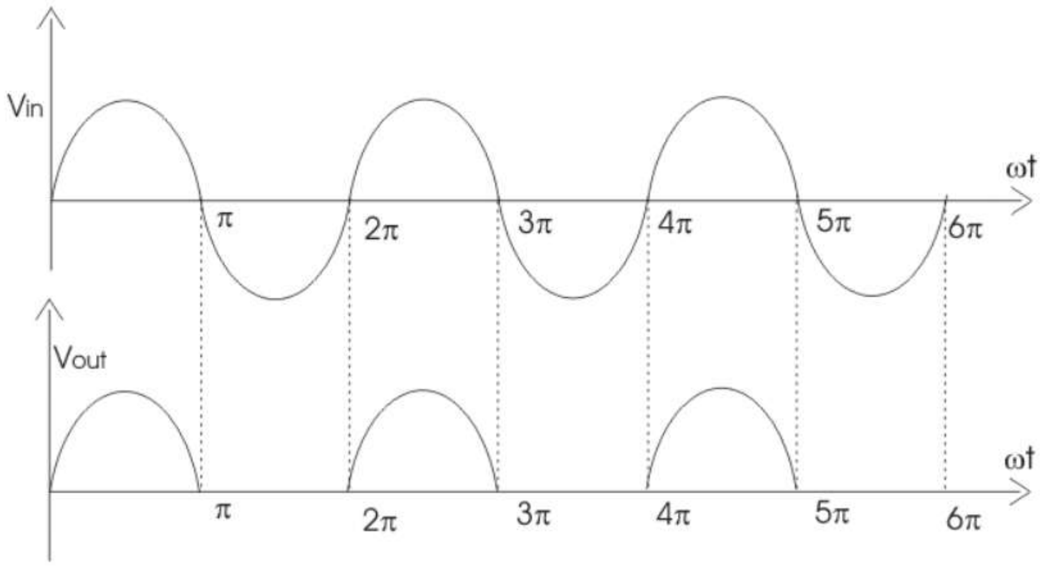


Figure 1.15: Input and output waveforms of Half Wave Rectifier

Aadvantages of half-wave rectifiers are:

- Simple (lower number of components)
- Cheaper upfront cost (as their is less equipment. Although there is a higher cost over time due to increased power losses)

Disadvantages of half-wave rectifiers are:

- They only allow a half-cycle through per sine wave, and the other half-cycle is wasted. This leads to power loss.
- The a.c. supply delivers power on half the time therefore, the output is low.
- The output current we obtain is not purely DC, and it still contains a lot of ripple (i.e. it has a high ripple factor)

INTROUCTION to FILTER

The half wave rectifier converts the Alternating Current (AC) into Direct Current (DC). But the obtained Direct Current (DC) at the output is not a pure Direct Current (DC). It is a pulsating Direct Current (DC).The pulsating Direct Current (DC) is not constant. It fluctuates with respect to time. When this fluctuating Direct Current (DC) is applied to any electronic device, the device may not work properly. Sometimes the device may also be damaged. So the fluctuating Direct Current (DC) is not useful in most of the applications.The only solution for this is smoothing the fluctuating Direct Current (DC). This can be achieved by using a device called filter.

The pulsating Direct Current (DC) contains both AC and DC components. DC components are useful but AC components are not useful. So to reduce or completely remove the AC components.The filter is an electronic device that allows dc components and blocks the ac components of the rectifier output.The filter is made up of a combination of components such as capacitors, resistors, and inductors. The capacitor allows the ac component and blocks the dc component. The inductor allows the dc component and blocks the ac component.

Half Wave Rectifier Capacitor Filter

In the half wave rectifier with capacitor with filter, the capacitor C is connected in shunt with load resistor (RL).

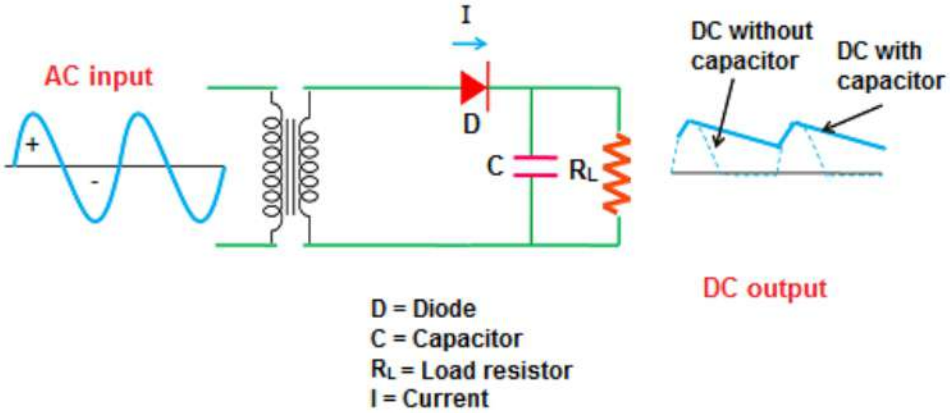
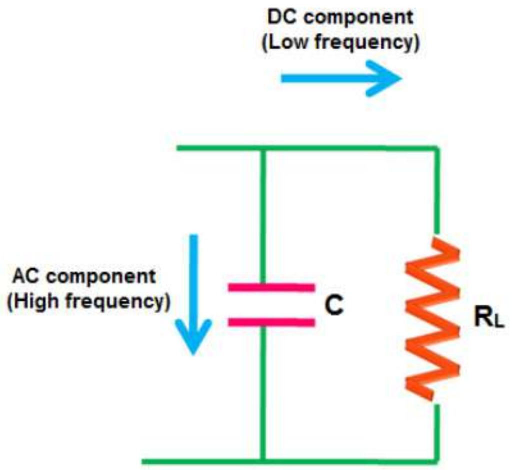


Figure 1.16: Circuit diagram of Half Wave Rectifier with filter

When AC voltage is applied, during the positive half cycle, the diode D is forward biased and allows electric current through it.The capacitor provides high resistive path to dc components (low-frequency signal) and low resistive path to ac components (high-frequency signal).The dc components does not like to flow through the capacitor (high resistance path). So they find an alternative path (low resistance path) and flows to the load resistor (R_L) through that path.



During the conduction period, the capacitor charges to the maximum value of the supply voltage. When the voltage between the plates of the capacitor is equal to the supply voltage, the capacitor is said to be fully charged. When the capacitor is fully charged, it holds the charge until the input AC supply to the rectifier reaches the negative half cycle. When the negative half cycle is reached, the diode D gets reverse biased and stops allowing electric current through it. During this non-conduction period, the input voltage is less than that of the capacitor voltage. So the capacitor discharges all the stored charges through the load resistor R_L. This prevents the output load voltage from falling to zero.

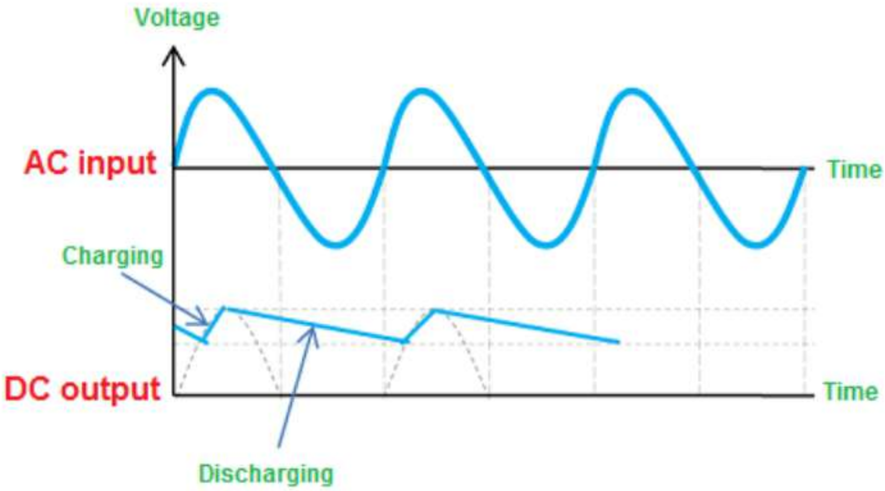


Figure 1.17: Input and outputwaveforms of Half Wave Rectifier with filter

Thus, a smooth and steady DC voltage is obtained by using the filter.

Characteristics of Half Wave Rectifier

Ripple Factor of Half Wave Rectifier

'Ripple' is the unwanted AC component remaining when converting the AC voltage waveform into a DC waveform. Even though we try out best to remove all AC components, there is still some small amount left on the output side which pulsates the DC waveform. This undesirable AC component is called 'ripple'.

To quantify how well the half-wave rectifier can convert the AC voltage into DC voltage, we use what is known as the ripple factor (represented by γ or r). The ripple factor is the ratio between the RMS value of the AC voltage (on the input side) and the DC voltage (on the output side) of the rectifier.

The formula for ripple factor is:

$$\gamma = \sqrt{\left(\frac{V_{rms}}{V_{DC}}\right)^2 - 1}$$

Which can also be rearranged to equal:

$$Ripple\ factor(r) = \frac{(I_{rms}^2 - I_{dc}^2)}{I_{dc}} = 1.21$$

The ripple factor of half wave rectifier is equal to 1.21 (i.e. $\gamma = 1.21$).

Efficiency of Half Wave Rectifier

Rectifier efficiency (η) is the ratio between the output DC power and the input AC power. The formula for the efficieny is equal to:

$$\eta = \frac{P_{dc}}{P_{ac}}$$

The efficiency of a half wave rectifier is equal to 40.6% (i.e. η_{max} = 40.6%)

RMS value of Half Wave Rectifier

To derive the RMS value of half wave rectifier, we need to calculate the current across the load. If the instantaneous load current is equal to $i_L = I_m \sin\omega t$, then the average of load current (I_{DC}) is equal to:

$$I_{dc} = \frac{1}{2\pi} \int_0^{\pi} I_m\, sin\omega t = \frac{I_m}{\pi}$$

Where I_m is equal to the peak instantaneous current across the load (I_{max}). Hence the output DC current (I_{DC}) obtained across the load is:

$$I_{DC} = \frac{I_{max}}{\pi},\ where\ I_{max} = maximum\ amplitude\ of\ dc\ current$$

For a half-wave rectifier, the RMS load current (I_{rms}) is equal to the average current (I_{DC}) multiple by π/2. Hence the RMS value of the load current (I_{rms}) for a half wave rectifier is:

$$I_{rms} = \frac{I_m}{2}$$

Where $I_m = I_{max}$ which is equal to the peak instantaneous current across the load.

Output DC Voltage

The output voltage (V_{DC}) across the load resistor is denoted by:

$$V_{DC} = \frac{V_{Smax}}{\pi},\ where\ V_{Smax} = maximum\ amplitude\ of\ secondary\ voltage$$

Full wave rectifier

In fill wave rectifier, current flows through the load in the same direction for both half cycles of input a.c. voltage. The commonly used full wave rectifier circuits are 1) centretap full wave rectifier (2) full wave bridge rectifier.

Centre tapped full wave rectifier

A center tapped full wave rectifier is a type of rectifier which uses a center tapped transformer and two diodes to convert the complete AC signal into DC signal. The center tapped full wave rectifier is made up of an AC source, a center tapped transformer, two diodes, and a load resistor.

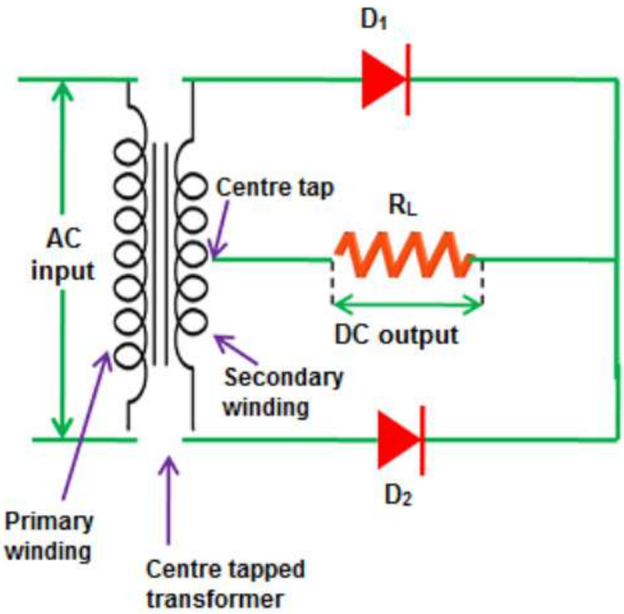


Figure 1.18: Centre Tapped Full wave rectifier

When input AC voltage is applied, the secondary winding of the center tapped transformer divides this input AC voltage into two parts: positive and negative.

During the positive half cycle of the input AC signal, terminal A become positive, terminal B become negative and center tap is grounded (zero volts). The positive terminal A is connected to the p-side of the diode D_1 and the negative terminal B is connected to the n-side of the diode D_1. So the diode D_1 is forward biased during the positive half cycle and allows electric current through it.On the other hand, the negative terminal B is connected to the p-side of the diode D_2 and the positive terminal A is connected to the n-side of the diode D_2. So the diode D_2 is reverse biased during the positive half cycle and does not allow electric current through it.

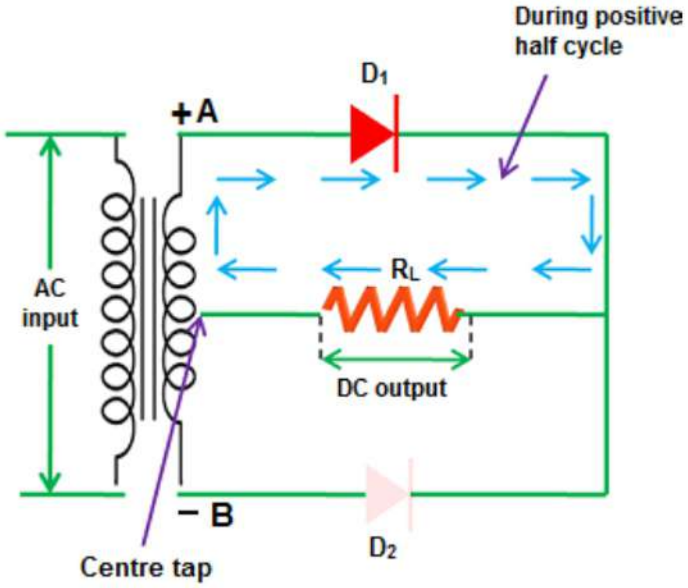
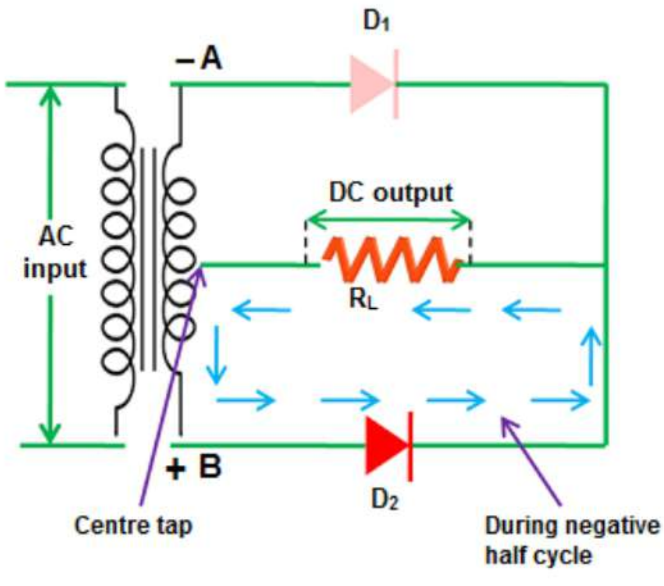


Figure 1.19:During positive cycle Centre Tapped Full wave rectifier

During the negative half cycle of the input AC signal, terminal A become negative, terminal B become positive and center tap is grounded (zero volts). The negative terminal A is connected to the p-side of the diode D_1 and the positive terminal B is connected to the n-side of the diode D_1. So the diode D_1 is reverse biased during the negative half cycle and does not allow electric current through it.On the other hand, the positive terminal B is connected to the p-side of the diode D_2 and the negative terminal A is connected to the n-side of the diode D_2. So the diode D_2 is forward biased during the negative half cycle and allows electric current through it.



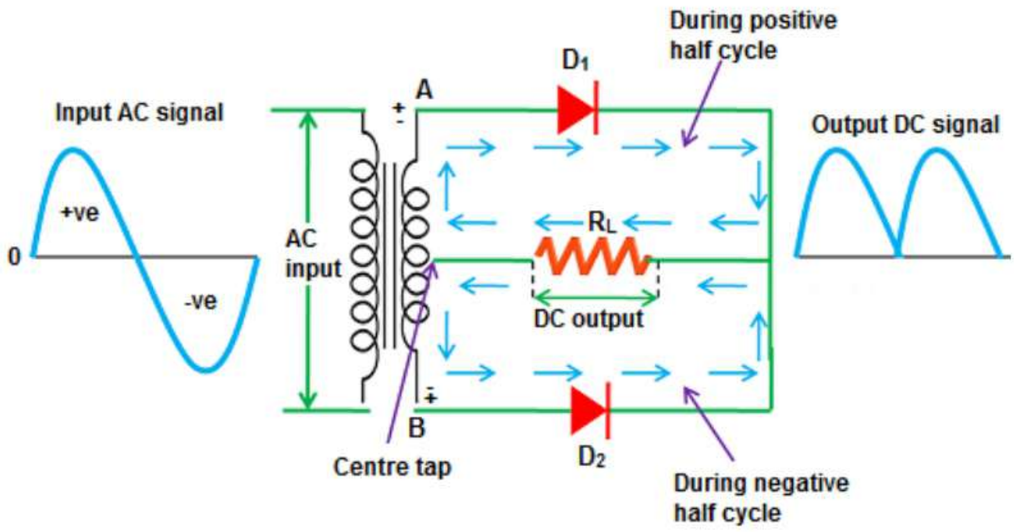


Figure 1.20:During negative cycle Centre Tapped Full wave rectifier

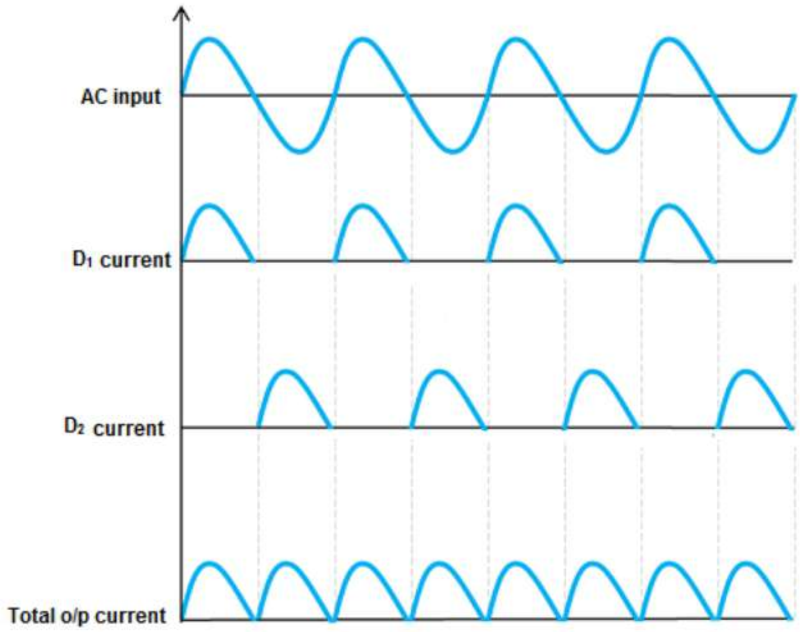


Figure 1.21:Input and output waveforms of Centre Tapped Full wave rectifier

Characteristics of full wave rectifier

Ripple factor

The ripple factor is used to measure the amount of ripples present in the output DC signal. A high ripple factor indicates a high pulsating DC signal while a low ripple factor indicates a low pulsating DC signal.

Ripple factor is defined as the ratio of ripple voltage to the pure DC voltage

The ripple factor is given by

$$\gamma = \sqrt{\left(\frac{V_{rms}}{V_{DC}}\right)^2 - 1}$$

$\gamma = 0.48$

Rectifier efficiency

Rectifier efficiency indicates how efficiently the rectifier converts AC into DC. A high percentage of rectifier efficiency indicates a good rectifier while a low percentage of rectifier efficiency indicates an inefficient rectifier.

Rectifier efficiency is defined as the ratio of DC output power to the AC input power.

It can be mathematically written as

$$\eta = \text{output } P_{DC} / \text{input } P_{AC}$$

The rectifier efficiency of a full wave rectifier is 81.2%.

The rectifier efficiency of a full wave rectifier is twice that of the half wave rectifier. So the full wave rectifier is more efficient than a half wave rectifier

DC output current

At the output load resistor R_L, both the diode D_1 and diode D_2 currents flow in the same direction. So the output current is the sum of D_1 and D_2 currents.

So the output current $I_{DC} = 2I_{max} / \pi$

Where,

I_{max} = maximum DC load current

DC output voltage

The DC output voltage appeared at the load resistor R_L is given as

$$V_{DC} = 2V_{max} / \pi$$

Where,

V_{max} = maximum secondary voltage

Root mean square (RMS) value of load current I_{RMS}

The root mean square (RMS) value of load current in a full wave rectifier is

$$I_{RMS} = \frac{I_m}{\sqrt{2}}$$

Root mean square (RMS) value of the output load voltage V_{RMS}

The root mean square (RMS) value of output load voltage in a full wave rectifier is

$$V_{RMS} = I_{RMS}\, R_L = \frac{I_m}{\sqrt{2}} R_L$$

Advantages of full wave rectifier with center tapped transformer

- High rectifier efficiency
- Low power loss
- Low ripples

Disadvantages of Centre tapped full wave rectifier

1. It is difficult to locate the Centre tap on the secondary winding.
2. The d.c output is small as each diode utilizes only one half of the transformer secondary voltage.
3. The center tapped transformers are expensive and occupy a large space.

Centre tapped full wave rectifier with filter

When input AC voltage is applied, during the positive half cycle, the diode D_1 is forward biased and allows electric current whereas the diode D_2 is reverse biased and blocks electric current. On the other hand, during the negative half cycle the diode D_2 is forward biased (allows electric current) and the diode D_1 is reverse biased (blocks electric current).

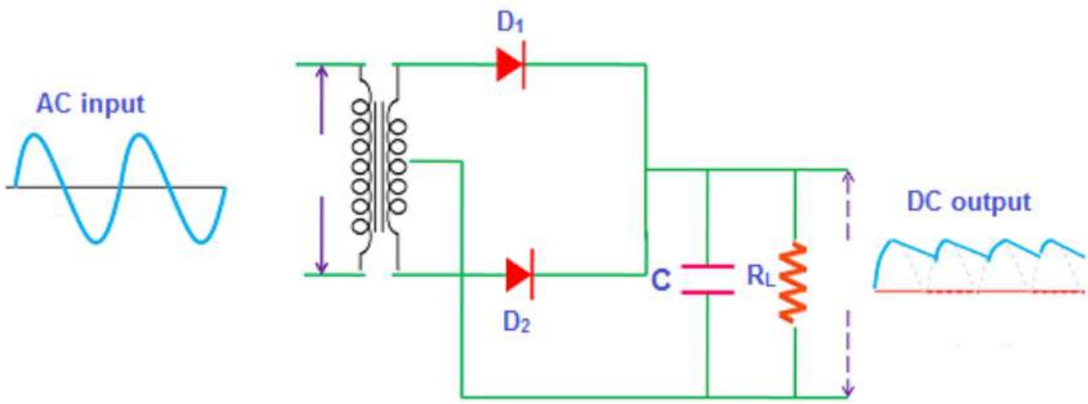


Figure 1.22: Circuit diagram of Centre Tapped rectifier with filter

During the positive half cycle, the diode (D_1) current reaches the filter and charges the capacitor. However, the charging of the capacitor happens only when the applied AC voltage is greater than the capacitor voltage.

Initially, the capacitor is uncharged. That means no voltage exists between the plates of the capacitor. So when the voltage is turned on, the charging of the capacitor happens immediately.

During this conduction period, the capacitor charges to the maximum value of the input supply voltage. The capacitor stores a maximum charge exactly at the quarter positive half cycle in the waveform. At this point, the supply voltage is equal to the capacitor voltage. When the AC voltage starts decreasing and becomes less than the capacitor voltage, then the capacitor starts slowly discharging. Before the complete discharge of the capacitor happens, the charging again takes place.

The capacitor is not completely uncharged, so the charging of the capacitor does not happens immediately. When the supply voltage becomes greater than the capacitor voltage, the capacitor again starts charging.

In both positive and negative half cycles, the current flows in the same direction across the load resistor R_L. So we get either complete positive half cycles or negative half cycles.

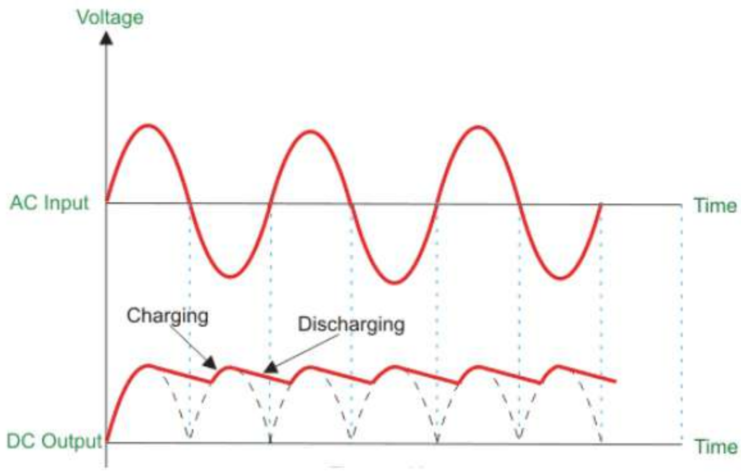


Figure 1.23:Input and output waveforms of Centre Tapped rectifier with filter

Full wave bridge rectifier

The bridge rectifier is made up of four diodes namely D_1, D_2, D_3, D_4 and load resistor R_L. The four diodes are connected in a closed loop (Bridge) configuration to efficiently convert the Alternating Current (AC) into Direct Current (DC). The main advantage of this bridge circuit configuration is that we do not require an expensive center tapped transformer, thereby reducing its cost and size.

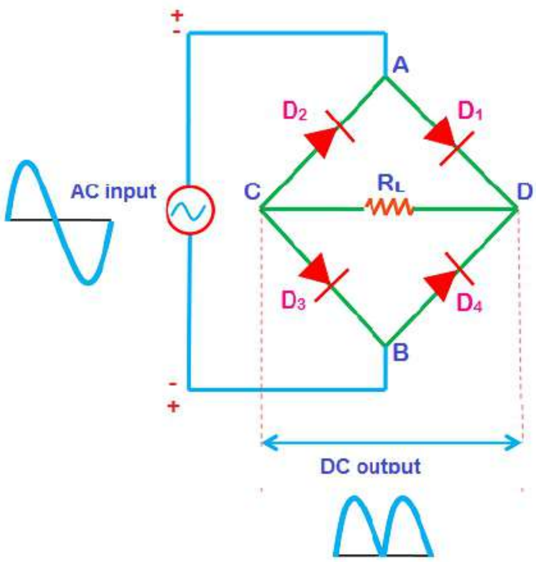


Figure 1.24:Circuit diagram of full wave bridge rectifier

The input AC signal is applied across two terminals A and B and the output DC signal is obtained across the load resistor R_L which is connected between the terminals C and D.

During the positive half cycle, the terminal A becomes positive while the terminal B becomes negative. This causes the diodes D_1 and D_3 forward biased and at the same time, it causes the diodes D_2 and D_4 reverse biased. The current flow direction during the positive half cycle is shown in the figure A (I.e. A to D to C to B).

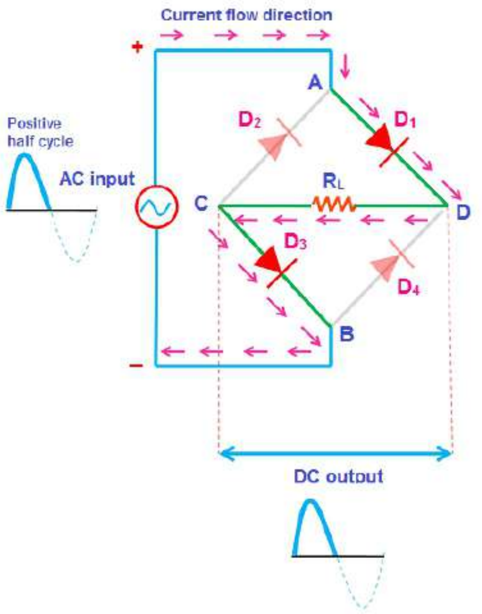


Figure 1.25:During positive half cycle- full wave bridge rectifier

During the negative half cycle, the terminal B becomes positive while the terminal A becomes negative. This causes the diodes D_2 and D_4 forward biased and at the same time, it causes the diodes D_1 and D_3 reverse biased.The current flow direction during negative half cycle is shown in the figure B (I.e. B to D to C to A).

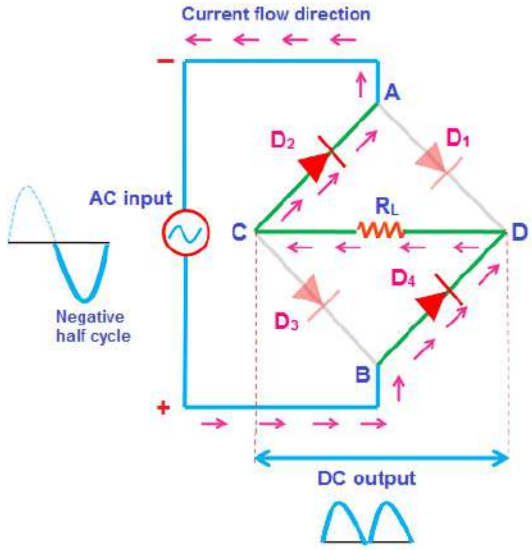


Figure 1.26:During negative half cycle- full wave bridge rectifier

The output waveforms of the bridge rectifier is shown in the below figure.

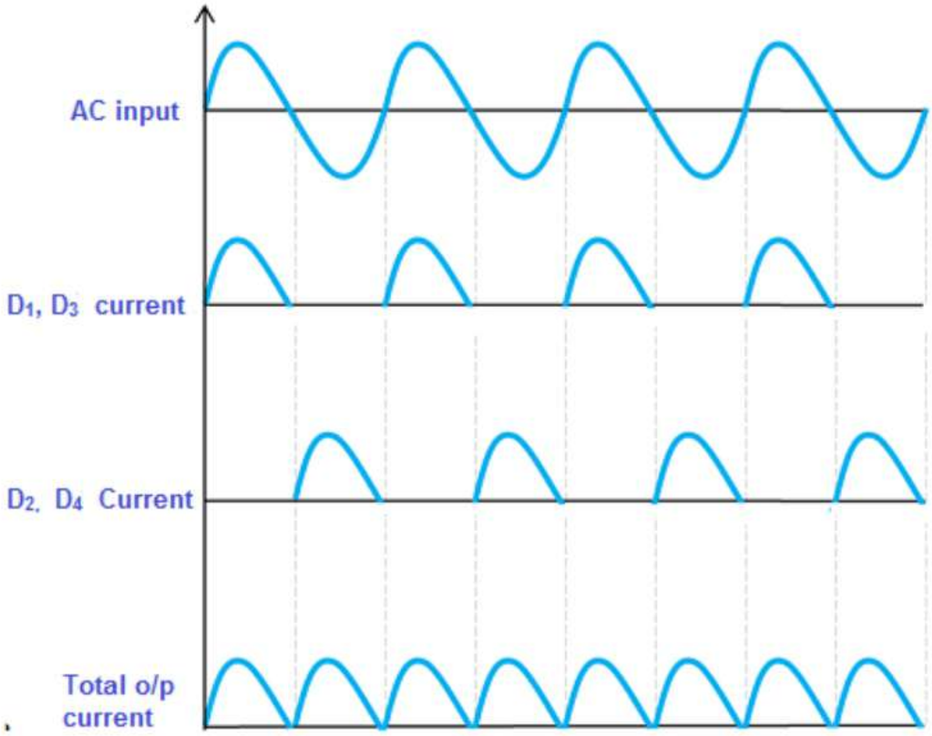


Figure 1.27:Input and Output waveforms of full wave bridge rectifier

Advantages and disadvantages of bridge rectifier

The following are advantages

1. No centre tap is needed in the transformer secondary.
2. The output is twice that of the centre tap circuit for the same secondary voltage.
3. The peak inverse voltage is one half that of the centre tap circuit.

The following are disadvantages

1. It requires four diodes.
2. As during each half cycle of a.c input two diodes that conduct are in series, therefore voltage drop in the internal resistance of the rectifying unit will be twice. This is objectionable when secondary voltage is small.

Break Down in Zener diode

There are two types of reverse breakdown regions in a zener diode: avalanche breakdown and zener breakdown.

Avalanche breakdown

The avalanche breakdown occurs in **both normal diodes** and **zener diodes** at high reverse voltage. when the diode is reverse biased a small reverse saturation current I_0 flows across the junction because of the minority carriers in the depletion region.The velocity of the minority charge carriers is directly proportional to the applied voltage. Hence when the reverse bias voltage is increased, the velocity of minority charge carriers will also increase and consequently their energy content will also increase.

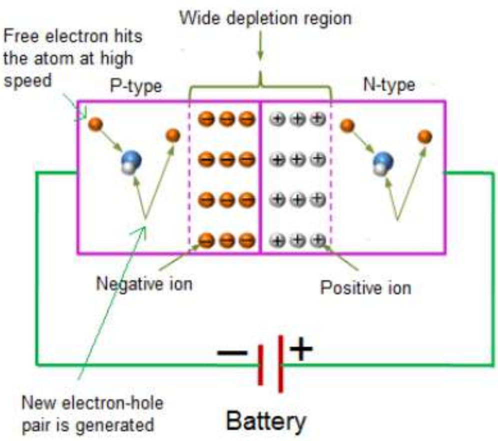


Figure 1.28:Avalanche Breakown Mechanism

The free electrons moving at high speed will collides with the atoms and knock off more electrons. These electrons are again accelerated and collide with other atoms. Because of this continuous collision with the atoms, a large number of free electrons are generated. As a result, electric current in the diode increases rapidly.This cumulative process is referred to as avalanche multiplication which results in the flow of large reverse current and this breakdown of the diode is called avalanche breakdown. Avalanche breakdown occurs in zener diodes with**zener voltage (V_z) greater than 6V.**

Zener breakdown

The zener breakdown occurs in **heavily doped** p-n junction diodes because of their **narrow depletion region**. When reverse biased voltage applied to the diode is increased, the narrow depletion region generates strong electric field.

$$Electrical\ filed\ strength = \frac{Reverse\ Voltage}{Depletion\ Region}$$

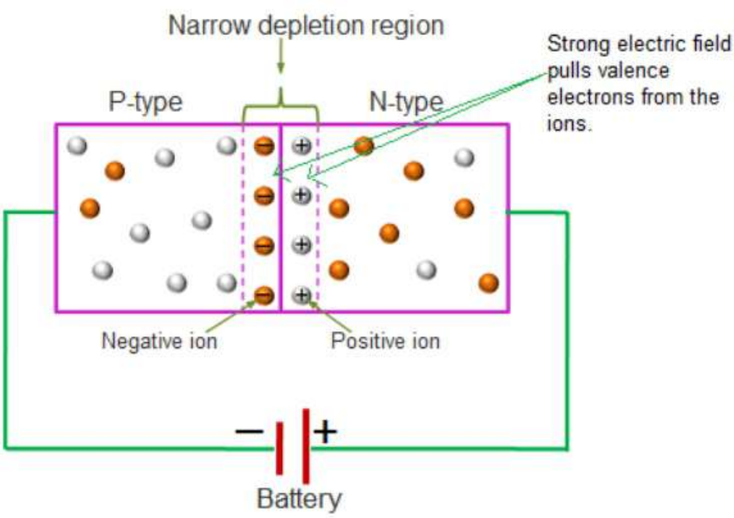


Figure 1.29:Zener Breakown Mechanism

From the above relation, the reverse voltage is directly proportional to the electric field hence, a small increase in reverse voltage produces a very high intensity electric field with in a narrow Depletion region. Therefore, when the reverse voltage to a diode is increased, under the influence of high intensity electric filed large number of electrons within the depletion region break the covalent bonds with their atoms and thus a large reverse current flow through the diode. This breakdown is referred to as Zener breakdown.

- Zener breakdown occurs at low reverse voltage whereas avalanche breakdown occurs at high reverse voltage.
- Zener breakdown occurs in zener diodes because they have very thin depletion region.
- Breakdown region is the normal operating region for a zener diode.
- Zener breakdown occurs in zener diodes with zener voltage (V_Z) less than 6V.

ZENER DIODE:

When the reverse voltage reaches breakdown voltage in normal PN junction diode, the current through the junction and the power dissipated at the junction will be high. Such an operation is destructive and the diode gets damaged. Whereas diodes can be designed with adequate power dissipation capabilities to operate in a break down region. One such a diode is known as Zener diode.

Zener diode is heavily doped than the ordinary diode. Due to this the depletion layer will be very thin and for small applied reverse voltage(V_R) there will be sharp increase in current.

From the V-I characteristics of the Zener diode, It is found that the operation of Zener diode is same as that of ordinary PN diode Under forward-biased condition. Whereas under reverse-biased condition, breakdown of the junction occurs. The breakdown voltage depends upon the amount of doping. If the diode is heavily doped, depletion layer will be thin and consequently, breakdown occurs at lower reverse voltage and further, the breakdown voltage is sharp. Whereas a lightly doped diode has a higher breakdown voltage. Thus breakdown voltage can be selected with the amount of doping.

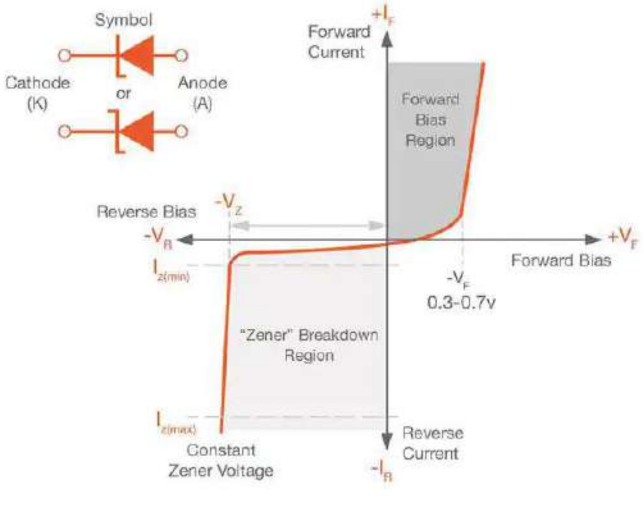


Figure 1.30:V-I Characteristics of Zener diode

Note:

A heavily doped diode has a low Zener breakdown voltage, while a lightly doped diode has ahigh Zener breakdown voltage.

Application of zener Diode are as follows:

Zener diodes have a large number of applications.

(i) Zener diode is used as a voltage regulator.

(ii) Zener diode is used as a peak clipper in wave shaping circuits.

(iii) Zener diode is used as a fixed reference voltage in transistor biasing circuits.

(iv) Zener diode is used for meter protection against damage from accidental application of excessive voltages.

Zener diode act as a Voltage Regulator

The Zener diode maintains a constant output voltage in the breakdown region, even though the current through it varies. This is an important feature of the zener diode, which can be used in voltage regulator applications. Therefore, a zener diode is sometimes called a Voltage-regulator diode.

For example, the output of half-wave, full-wave or bridge rectifiers consists of ripples superimposed on a DC voltage. By connecting a simple zener diode across the output of the rectifier, obtain a more stable DC output voltage.

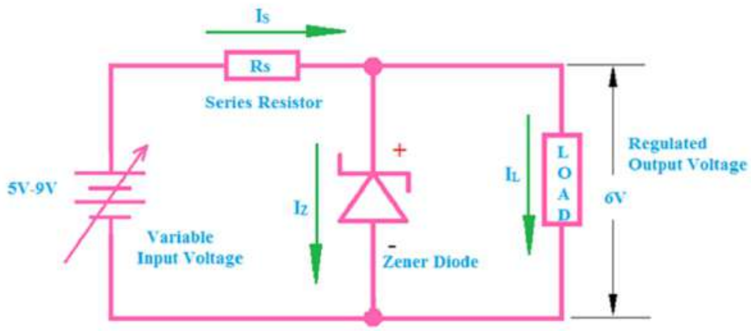
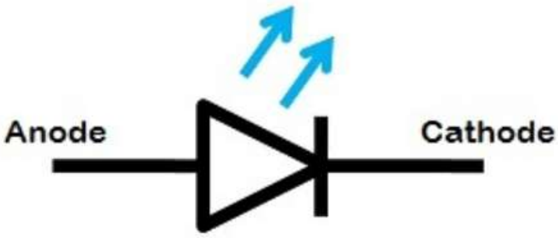


Figure 1.31:Zener Diode act as a voltage reglator

The zener diode is connected with its cathode terminal connected to the positive rail of the DC supply so it is reverse biased and will be operating in its breakdown condition. Resistor R_S is selected so to limit the maximum current flowing in the circuit. With no load connected to the circuit, the load current will be zero, ($I_L = 0$), and all the circuit current passes through the zener diode which in turn dissipates its maximum power. The load is connected in parallel with the zener diode, so the voltage across R_L is always the same as the zener voltage, ($V_R = V_Z$). The supply voltage V_S must be greater than V_Z. It is required to provide constant voltage across load resistance R_L, whereas the input voltage may be varying over a range. Zener diode is reverse biased and as long as the input voltage does not fall below Vz (zener breakdown voltage), the voltage across the diode will be constant and hence the load voltage will also be constant.

LIGHT EMITTING DIODE

The LED symbol is similar to a diode symbol except for two small arrows that specify the emission of light, thus it is called LED (light-emitting diode). The LED includes two terminals namely anode (+) and the cathode (-). The LED symbol is shown below.



When the LED is forward biased, the free electrons cross the PN junction and recombine with holes. The recombination indicates that the electrons in the conduction band jump down to the valence band. In ordinary diodes, this energy is radiated as heat while in an LED, energy is radiated as light. This effect is called Electroluminescence. Diodes constructed of GaAs emit light in the infrared zone during the recombination process at the PN junction. The light is emitted when electrons from N side cross the junction and recombine with the holes on the P side. Here the electrons on N side are in the higher conduction band whereas the holes on p-side are in the lower valence band. Recombination of excess electrons and holes takes place whenever current is passed through P-N junction diode.

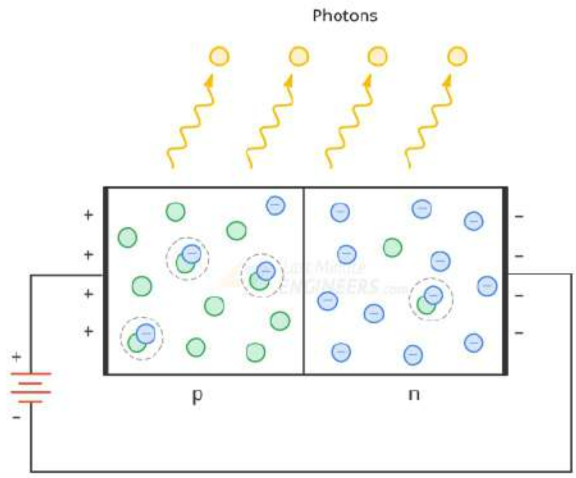
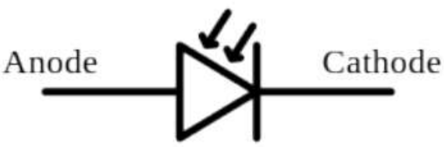


Figure 1.32:Recombination process of LED

PHOTO DIODE

PN junction photodiode is also simply referred as photodiode.



When external light energy is supplied to the p-n junction photodiode, the valence electrons in the depletion region gains energy. If the light energy applied to the photodiode is greater the band-gap of semiconductor material, the valence electrons gain enough energy and break bonding with the parent atom and it will become free electronFree electrons moves freely from one place to another place by carrying the electric current.

When the valence electron leave the valence band and creates hole. Thus, both free electrons and holes are generated as pairs. The mechanism of generating electron-hole pair by using light energy is known as the inner photoelectric effect.

For example, free electrons in the depletion region experience repulsive and attractive force from the negative and positive ions present at the edge of depletion region at p-side and n-side. As a result, free electrons move towards the n region. When the free electrons reaches n region, they are attracted towards the positive terminals of the battery. In the similar way, holes move in opposite direction.

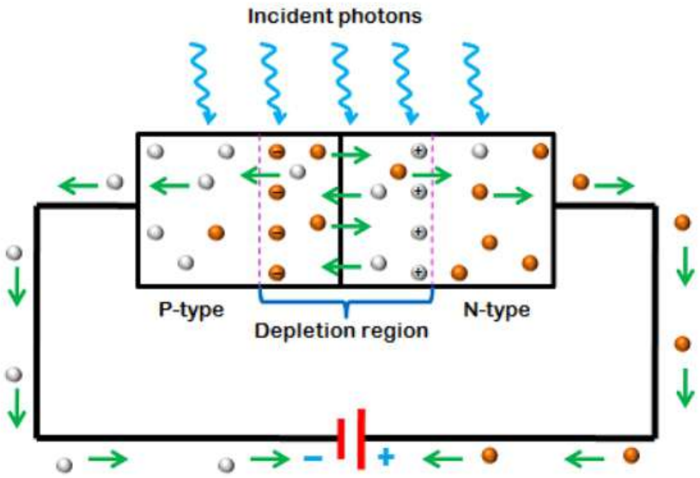
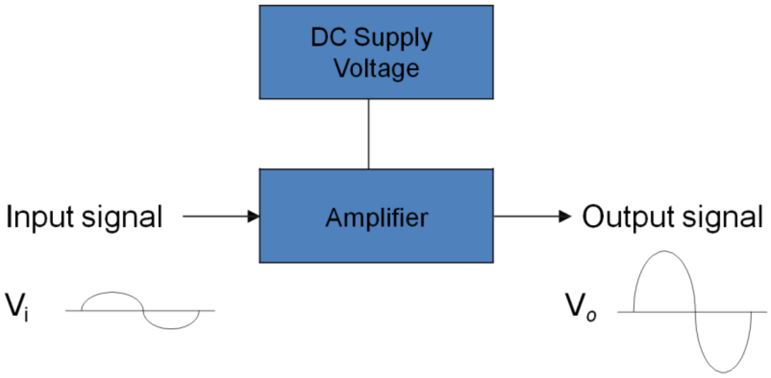


Figure 1.32: photoelectric effect of photo diode

Concepts of Small Signal Amplifiers –CE & CC Amplifiers.

- Amplifier is a system that can amplify weak electrical signal into strong one by increasing the power level of the weak input signal.
- Amplifier can amplify current, voltage, and/or power.



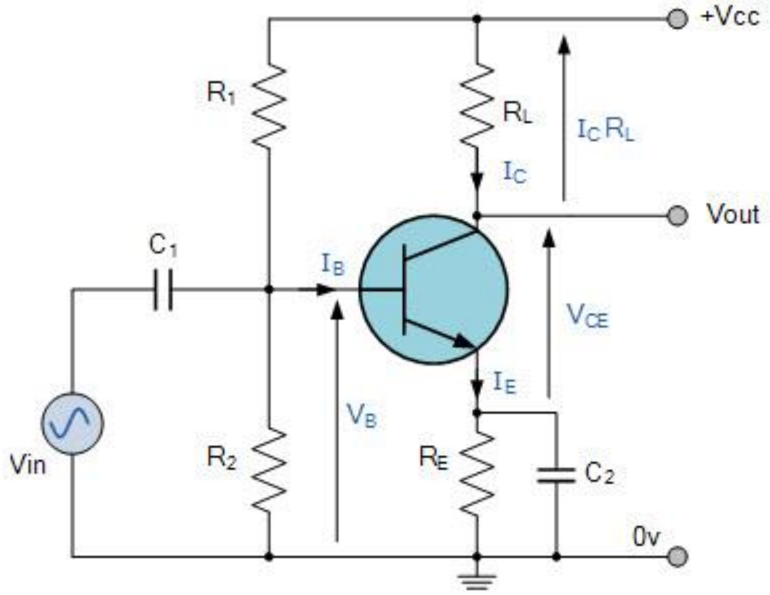
- Amplifier has 3 basic quantities (gain, A; input impedance, Z_i, & output impedance, Z_o).

<u>Gain</u>

- Voltage gain : $$A_V = \frac{V_O}{V_i}$$
- Current gain : $$A_i = \frac{I_O}{I_i}$$
- Power gain : $$A_P = \frac{P_O}{P_i} = A_V A_i$$

- Small Signal Amplifiers are also known as **Voltage Amplifiers**.
- Voltage Amplifiers have 3 main properties, **Input Resistance**, **Output Resistance** and **Gain**.
- The Gain of a small signal amplifier is the amount by which the amplifier "Amplifies" the input signal.
- Gain is a ratio of output divided by input, therefore it has no units but is given the symbol (A) with the most common types of transistor gain being, **Voltage Gain (Av), Current Gain (Ai)** and **Power Gain (Ap)**
- The power Gain of the amplifier can also be expressed in **Decibels** or simply **dB**.
- The **Common Emitter Amplifier** configuration is the most common form of all the general purpose voltage amplifier circuit using a Bipolar Junction Transistor.

Common Emitter Amplifier



common emitter amplifier circuit and it consists of voltage divider biasing, used to supply the base bias voltage as per the necessity. The voltage divider biasing has a potential divider with two resistors are connected in a way that the midpoint is used for supplying base bias voltage.

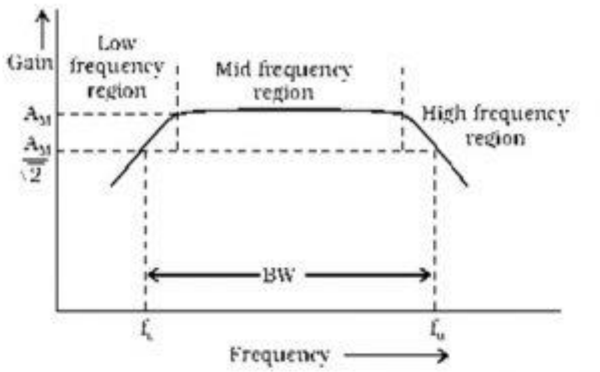
There are different types of electronic components in the common emitter amplifier which are R1 resistor is used for the forward bias, the R2 resistor is used for the development of bias, the RL resistor is used at the output it is called the load resistance. The RE resistor is used for thermal stability. The C1 capacitor is used to separate the AC signals from the DC biasing voltage and the capacitor is known as the coupling capacitor.

When a signal is applied across the emitter-base junction, the forward bias across this junction increases during the upper half cycle. This leads to an increase in the flow of electrons from the emitter to a collector through the base, hence increases the collector current. The increasing collector current makes more voltage drops across the collector load resistor RC.

The negative half cycle decreases the forward bias voltage across the emitter-base junction. The decreasing collector-base voltage decreases the collector current in the whole collector resistor Rc. Thus, the amplified load resistor appears across the collector resistor.

CE Amplifier Frequency Response

The voltage gain of a CE amplifier varies with signal frequency. It is because the reactance of the capacitors in the circuit changes with signal frequency and hence affects the output voltage. The curve drawn between voltage gain and the signal frequency of an amplifier is known as frequency response. The below figure shows the frequency response of a typical CE amplifier.



At Low Frequencies (< FL) The reactance of coupling capacitor C2 is relatively high and hence very small part of the signal will pass from the amplifier stage to the load.

Moreover, CE cannot shunt the RE effectively because of its large reactance at low frequencies. These two factors cause a drops off of voltage gain at low frequencies.

At High Frequencies (> FH) The reactance of coupling capacitor C2 is very small and it behaves as a short circuit. This increases the loading effect of the amplifier stage and serves to reduce the voltage gain.

Moreover, at high frequencies, the capacitive reactance of base-emitters junction is low which increases the base current. This frequency reduces the current amplification factor β. Due to these two reasons, the voltage gain drops off at a high frequency.

At Mid Frequencies (FL to FH) The voltage gain of the amplifier is constant. The effect of the coupling capacitor C2 in this frequency range is such as to maintain a constant voltage gain. Thus, as the frequency increases in this range, the reactance of CC decreases, which tends to increase the gain.

Frequency points like fL & fH are related to the lower corner & the upper corner of the amplifier which are the gain falls of the circuits at high as well as low frequencies. These frequency points are also known as decibel points. So the BW can be defined as

BW = fH – fL

Advantages

The advantages of a common emitter amplifier include the following.

- The common emitter amplifier has a low input impedance and it is an inverting amplifier
- The output impedance of this amplifier is high
- This amplifier has the highest power gain when combined with medium voltage and current gain
- The current gain of the common emitter amplifier is high

Disadvantages

The disadvantages of a common emitter amplifier include the following.

- In the high frequencies, the common emitter amplifier does not respond
- The voltage gain of this amplifier is unstable
- The output resistance is very high in these amplifiers

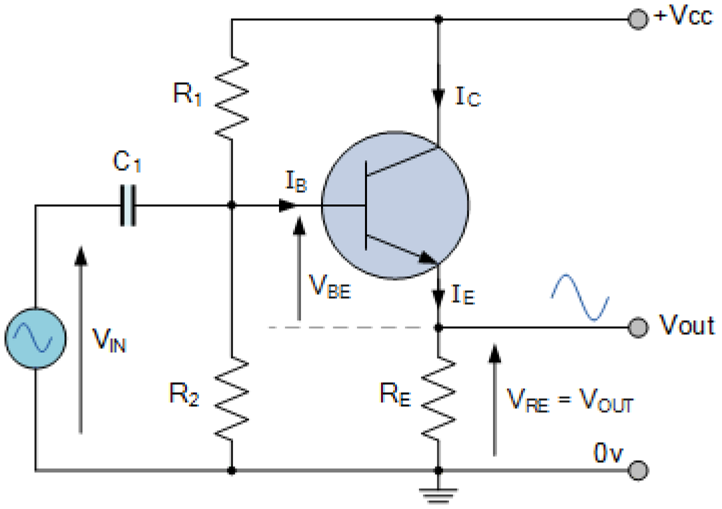
- In these amplifiers, there is a high thermal instability
- High output resistance

Common Collector/ Emitter Follower Transistor Amplifier

Common collector amplifiers have the following circuit configurations.

- The input signal enters the transistor at the base terminal
- The input signal exits the transistor at the emitter terminal
- The collector is connected to a constant voltage, i.e. ground, sometimes with an intervening resistor

The common collector or grounded collector configuration is generally used where a high impedance input source needs to be connected to a low impedance output load requiring a high current gain. Consider the common collector amplifier circuit below.



Resistors R_1 and R_2 form a simple voltage divider network used to bias the NPN transistor into conduction. Since this voltage divider lightly loads the transistor, the base voltage, V_B can be easily calculated by using the simple voltage divider formula as shown.

With the collector terminal of the transistor connected directly to V_{CC} and no collector resistance, ($R_C = 0$) any collector current will generate a voltage drop across the emitter resistor R_E.

However, in the common collector amplifier circuit, the same voltage drop, V_E also represents the output voltage, V_{OUT}.

Ideally we would want the DC voltage drop across R_E to be equal to half the supply voltage, V_{CC} to make the transistors quiescent output voltage sit somewhere in the middle of the characteristics curves allowing for a maximum unclipped output signal. Thus the choice of R_E depends greatly on I_B and the transistors current gain Beta, β.

As the base-emitter pn-junction is forward biased, base current flows through the junction to the emitter encouraging transistor action causing a much larger collector current, I_C to flow. Thus the emitter current is a combination of base current and collector current as: $I_E = I_B + I_C$. However, as the base current is extremely small compared to the collector current, the emitter current is therefore approximately equal to the collector current. Thus $I_E \approx I_C$

As the amplifiers output signal is taken from across the emitter load this type of transistor configuration is also known as an *Emitter Follower* circuit as the emitter output “follows” or tracks any voltage changes to the base input signal, except that it remains about 0.7 volts (V_{BE}) below the base voltage. Thus V_{IN} and V_{OUT} are in-phase producing zero phase difference between the input and output signals.

UNIT – II

Operational Amplifiers and Applications: Introduction to Op-Amp, Differential Amplifier Configurations, CMRR, PSRR, Slew Rate; Block Diagram, Pin Configuration of 741 Op-Amp, Characteristics of Ideal Op-Amp, Concept of Virtual Ground; Op-Amp Applications - Inverting, Non-Inverting, Summing and Difference Amplifiers, Voltage Follower, Comparator, Differentiator, Integrator.

****

2.1 BASICS OF DIFFERENTIAL AMPLIFIER

The Differential amplifier is a basic building block of the op-amp. The function of the differential amplifier is to amplify difference in between two input signals. Let us consider 2 emitter-biased circuits as shown in the figure.

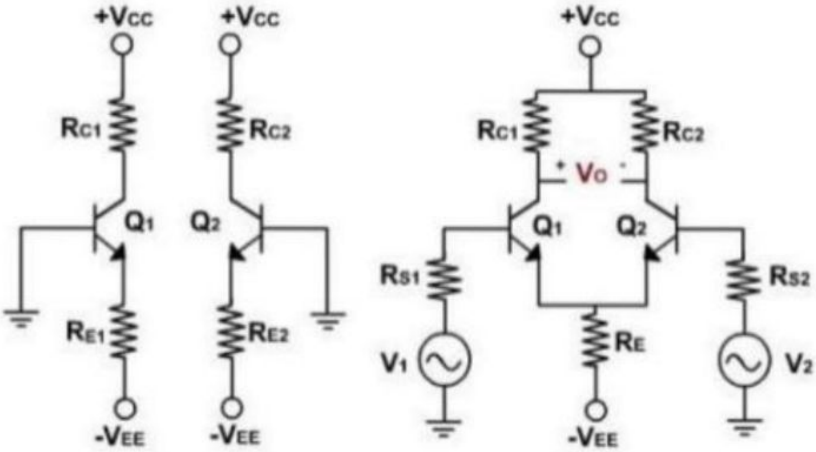


Figure 2.1: Basic Differential Amplifier

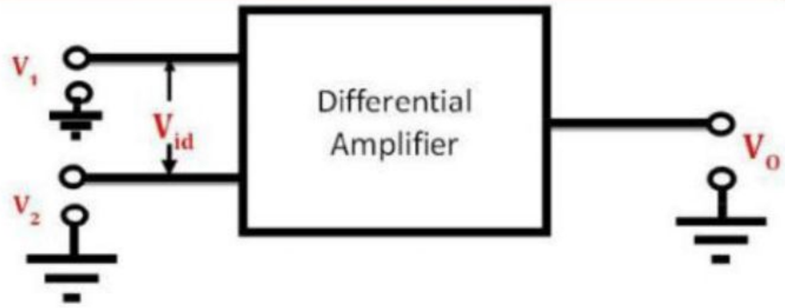
The 2 transistors Q_1 and Q_2 have the same characteristics. The resistances of circuits are equal, that is $R_{E1} = R_{E2}$, $R_{C1} = R_{C2}$ and magnitude of $+V_{CC}$ is equal to magnitude of $-V_{EE}$. These voltages are measured with respect to the ground.

To make a differential amplifier, two circuits are connected as shown in the figure. The two $+V_{CC}$ and $-V_{EE}$ supply terminals are made common as they are same. The two emitters are also connected and parallel combination of R_{E1} and R_{E2} is replaced by the resistance R_E. The two input signals V_1 & V_2 are applied at base of Q_1 and at base of Q_2. The output voltage is taken between the two collectors. The collector resistances are equal and hence denoted by $R_C = R_{C1} = R_{C2}$.

Ideally, output voltage is zero when the two inputs are equal. When V_1 is greater than V_2 output voltage with the polarity shown appears. When V_1 is less than V_2, output voltage has the opposite polarity.

Differential Amplifier

The differential amplifier amplifies the difference between two input voltage signals. Hence it is also called difference amplifier. The need for differential amplifier in many physical measurements arises where response from d.c to many megahertz is required. It is also the *basic input stage of an integrated amplifier.*



The output signal in a differential amplifier is proportional to the difference between the two input signals.

$$V_o \alpha (V_1 - V_2)$$

Where,

V_1 & V_2 – Two input signals

V_o – Single ended output

Each signal is measured with respect to the ground.

Modes of operation of Differential Amplifier

There are two modes of operations of differential amplifier

- Differential mode operation
- Common mode operation

Differential mode operation

Two input signals are of **same magnitude** but **opposite polarity** are used (180^0 out of phase)

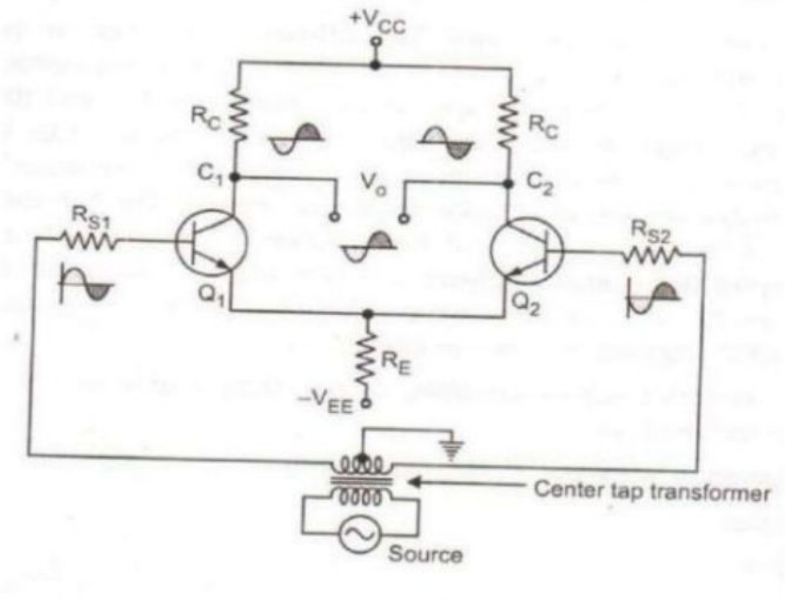


Figure 2.2: Differential Mode Operation

Assume sine wave on base of Q_1 is +Ve going signal while on the base of Q_2 –Ve going signal

- An amplified –Ve going signal will appear at collector of Q1
- An amplified +ve going signal will appear at collector of Q_2
- Due to +ve going signal of base of Q_1, current increases in R_E & hence a +ve going wave is developed across R_E

- Due to -ve going signal of base of Q2, -ve going wave is developed across R_E because of emitter follower action of Q2
- So, signal voltages across R_E, due to effect of Q1 &Q2 are equal in magnitude &180^0 out of phase-due to matched transistors. Hence the two signals cancel each other & there is no signal across R_E. No AC signal flows through it
- V_o= +10-(-10)= 20
- V_o is difference voltage in two signals

Differential Gain (A_d):

The output voltage $\mathbf{V_o \alpha (V_1 - V_2)}$

$$V_0 = A_d (V_1 - V_2)$$

Where,

A_d is the **constant of proportionality**.

A_d is the gain with which differential amplifier amplifies the difference between two input signals.

Hence it is known as '***differential gain of the differential amplifier***'.

$$Ad = \frac{V_O}{V_d}$$

V_1-V_2= Difference of two voltage

Generally, differential gain is expressed in decibel (dB) as

$$A_d = 20 \log_{10} (Ad) \text{ in dB}$$

Common Mode Operation

Two input signals are of **equal in magnitude** and **same phase** are used

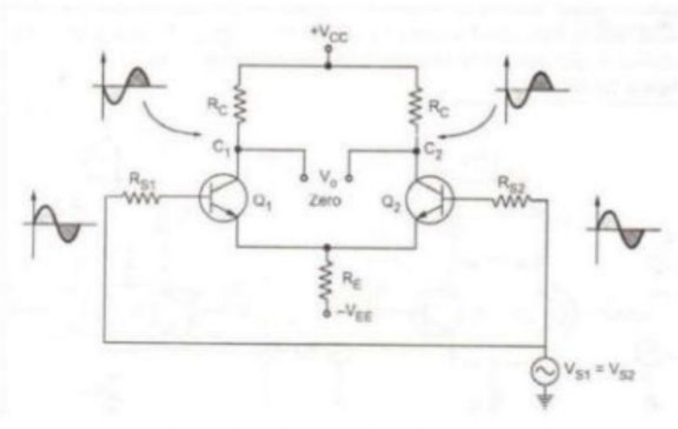


Figure 2.3: Common Mode operation

- Two input signals are of equal in magnitude and same phase are used
- In phase signal develops in phase signal voltages across R_E
- Hence R_E carries a signal current & provides **-ve feedback**
- This –ve feedback decreases AC in signal voltages of equal magnitude will appear across two collectors of Q1 &Q2
- Vo= 10-10=0 Negligibly small. Ideally it should be zero

Common Mode Gain (Ac)

If we apply two input voltages which are equal in all the respect to the differential amplifier i.e $V_1=V_2$ then ideally the output voltage $V_O= (V_1-V_2)\,A_d$, must be zero.

But the output voltage of the practical differential amplifier not only depends on the difference voltage but also depends on the average common level of the two inputs. Such an average level of the two input signals is called common mode signal denoted as V_{cm}.

$$V_{cm} = \frac{V_1 + V_2}{2}$$

Practically, the differential amplifier produces the output voltage proportional to such common mode signal. The gain with which it amplifies the common mode signal to produce the output is called common mode gain of the differential amplifier denoted as A_c.

$\mathbf{V_o = A_c V_c}$ Where A_c is the common mode gain.

Therefore, there exists some finite output for $V_1 = V_2$ due to common mode gain Ac.

Hence the total output of any differential amplifier can be given as,

$$\mathbf{V_o = A_d V_d + A_c V_c}$$

For an ideal differential amplifier, the differential gain A_d must be infinite while the common mode gain must be zero. This ensures zero output for $V_1=V_2$.

But due to mismatch in the internal circuitry, there is some output available for $V_1=V_2$ and gain Ac is not practically zero. The value of such common mode gain Ac is very small while the value of the differential gain Ad is always very large.

Common Mode Rejection Ratio (CMRR):

The ability of a differential amplifier to reject a common mode signal is defined by a ratio called '***Common Mode Rejection Ratio***' denoted as CMRR.

CMRR is defined as the ***ratio of the differential voltage gain A_d to common mode gain A_c*** and is expresses in dB.

$$CMRR = 20\,log\left|\frac{A_d}{A_c}\right| dB$$

Ideally the common mode voltage gain is zero; hence the ideal value of CMRR is infinite. For a practical differential amplifier Ad is large and Ac is small hence the value of CMRR is also very large.

2.2 DIFFERENTIAL AMPLIFIER CONFIGURATIONS

The differential amplifiers are of the various configurations. The 4 differential amplifier configurations are given as follows:

1. The Dual input, balanced output differential amplifier.
2. The Dual input, unbalanced output differential amplifier.
3. The Single input balanced output differential amplifier.
4. The Single input unbalanced output differential amplifier.

Here V_1& V_2 are input voltages and the difference between them is called **"Differential Input Voltage"**. It is very essential that the transistors Q_1& Q_2 match perfectly for proper functioning of the differential amplifier. The differential input voltage gets amplified and appears as the output voltage V_0 across the collector terminals C_1& C_2.

If the output is measured between C_1& C_2 it is termed as **Balanced Output**. If the output is measured between either of the collector terminals and ground, it is termed as **Unbalanced Output**.

On observing phase relationship between output (V_0) and inputs (V_1& V_2), V_0& V_1 are in phase and V_0& V_2 are 180° out of phase. Hence B_1 at which input signal V_1 is applied is called "Non-Inverting Input Terminal" and is at which input signal V_2 applied is called "Inverting Input Terminal".

$\therefore V_0 = A(V_1 - V_2)$

Where A - Gain of the amplifier.

If B_2 is grounded i.e., $V_2 = 0$, $V_0 = AV_1$

If B_1 is grounded i.e., $V_1 = 0$, $V_0 = -AV_2$.

Dual Input Balanced Output Differential Amplifier Configuration

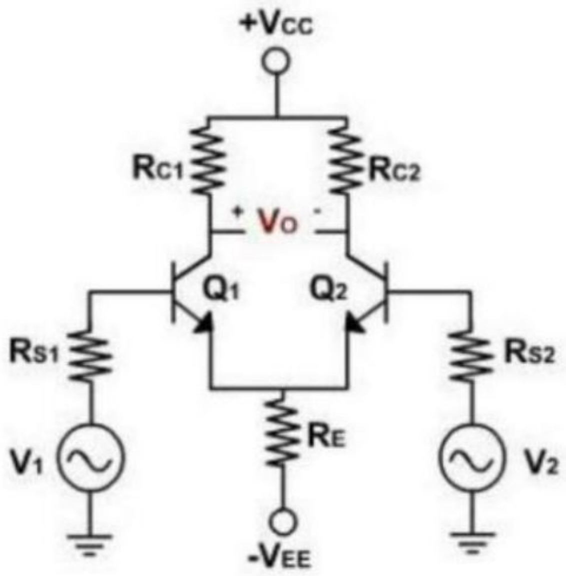


Figure 2.4: Dual Input Balanced Output Differential Amplifier

The two input signals V_1 and V_2 are applied to the bases B_1 and B_2 of transistors Q_1 and Q_2. The output V_O is measured between the two collectors C_1 and C_2, which are at the same DC potential. Because of the equal dc potential at the two collectors with respect to ground, the output is referred to as a balanced output.

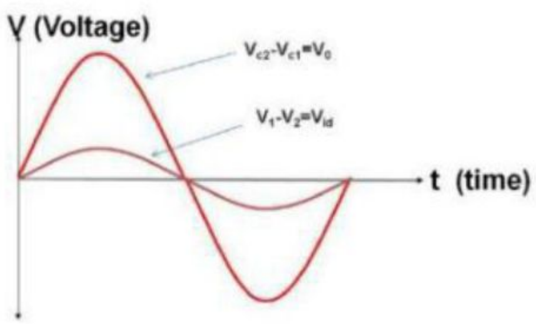


Figure 2.5: Input and Output waveforms of DIBO Differential Amplifier

Inverting and Non-Inverting inputs

In the differential amplifier circuit, the input voltage V_1 is called the "non inverting input" because a positive voltage V_1 acting alone produces a positive output voltage. Similarly, the positive voltage V_2 acting alone produces a negative output voltage; hence V_2 is called inverting input. The base terminal B_1 to which V_1 is applied as the non-inverting input terminal and the base terminal B_2 is called the inverting input terminal.

Dual - Input Unbalanced Output Differential Amplifier

Here two input signals are used; the output is measured at only one of the two collectors with respect to ground. The output is referred as an unbalanced output because the collector at which the output voltage is measured is at some finite DC potential with respect to ground.

In other words, there is some DC voltage at the output terminal without any input signal applied. The output is measured at collector of Q_2 with respect to ground.

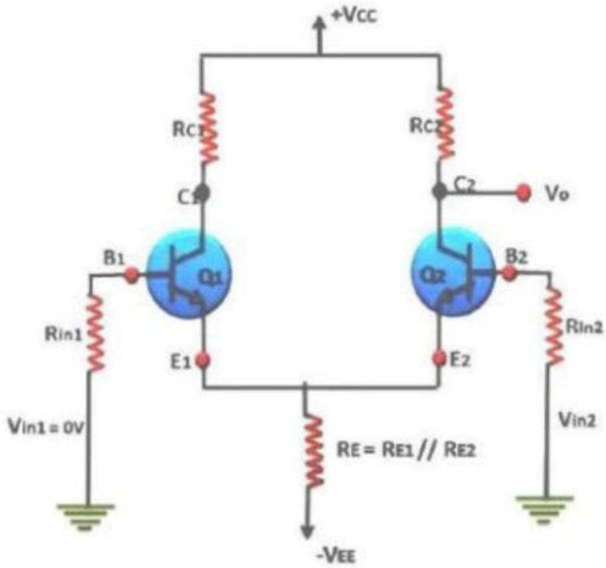


Figure 2.6: Dual Input Unbalanced Output Differential Amplifier

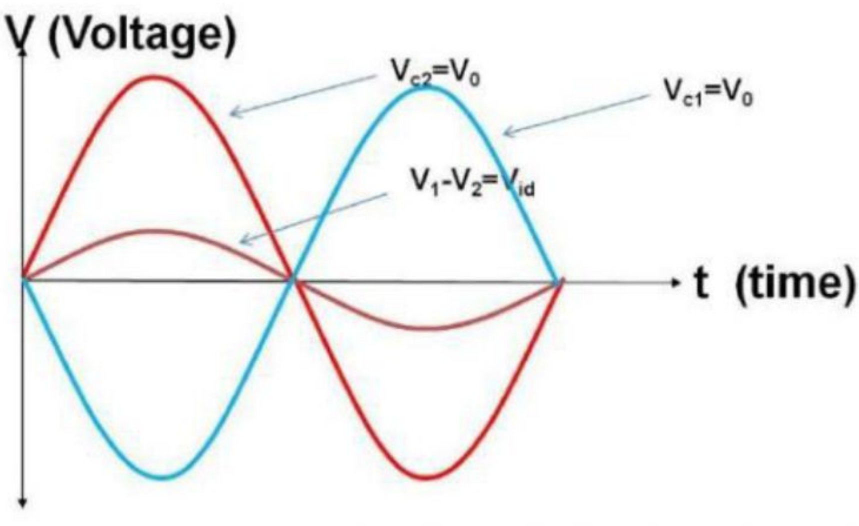


Figure 2.7: Input and output waveforms of Dual Input Unbalanced Output Differential Amplifier

Single Input Balanced Output Differential Amplifier

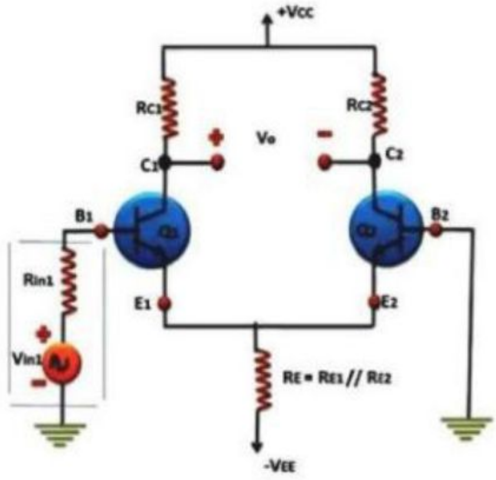


Figure 2.8: Single Input Balanced Output Differential Amplifier

Here the output is applied to the base of transistor Q_1 and the output is measured between the two collectors which are at the same DC potential. Hence the output is said to be balanced output.

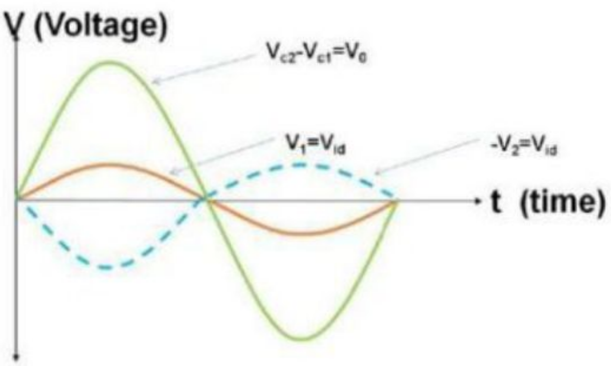


Figure 2.9: Input and output waveforms of Single Input Balanced Output Differential Amplifier

Single Input Unbalanced Output Differential Amplifier

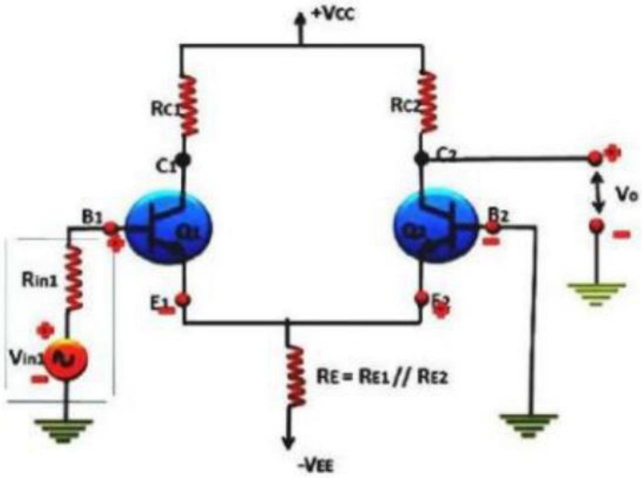


Figure 2.10: Single Input Unbalanced Output Differential Amplifier

Here the output is applied to the base of transistor Q_1 and the output is measured at collector 2 terminals which are at the same DC potential. Hence the output is said to be unbalanced output.

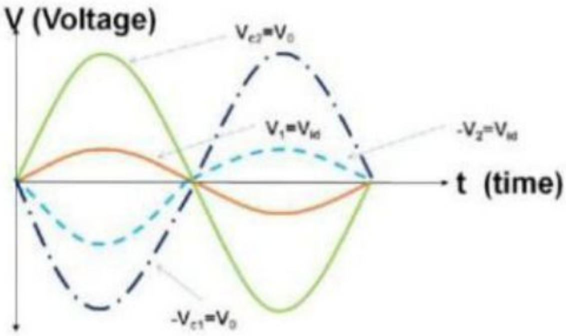


Figure 2.11: Input and output waveforms of Single Input Unbalanced Output Differential Amplifier

2.3 INTRODUCTION TO OPERATIONAL AMPLIFIERS

An Op-Amp is a direct coupled high gain amplifier usually consists of one or more differential amplifiers and usually followed by a level translator and an output stage. The output stage is generally a push pull complementary symmetric pair. An op-amp is available as a single IC package.

Op-Amp is a versatile device that can be used to amplify dc as well as ac input signals and was originally designed for performing mathematical operations such as addition, subtraction, multiplication, differentiation and integration with the addition of suitable external feedback components, the modern day op-amp can be used for a variety of applications such as ac and dc signal amplification, active filters, oscillators, comparators, regulators and others.

Packages:

There are three popular packages available:

1. The metal can (TO) Package
2. The Dual-in-line Package
3. The flat package or flat pack.

Op-Amp packages may certain single, two (dual) or four (quad) Op-Amps

Typical Packages have 8 terminals, 10 terminals and 14 terminals.

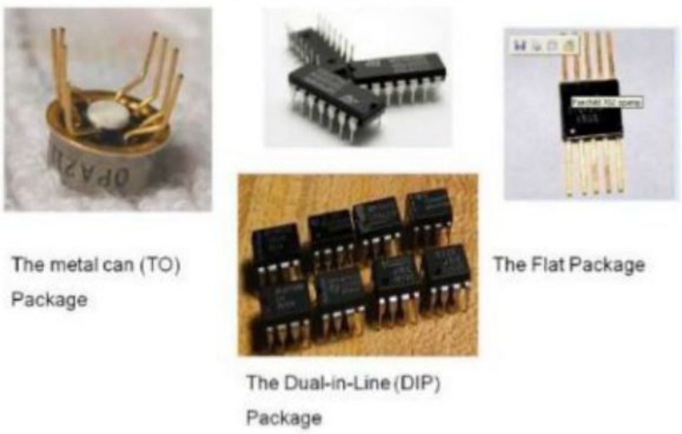


Figure 2.12: IC Packages

Circuit Symbol

The circuit symbol of an Op-Amp is a triangular as shown in figure.

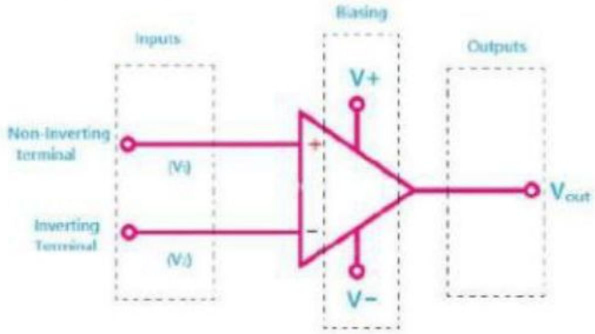


Figure 2.13: Schematic of Op-Amp

The V^+ and V^- power supply terminals are connected to two DC Voltage sources. It has two input terminals and one output terminal. The two inputs of the operational amplifier are called Non-Inverting terminal and Inverting terminal. The Non-Inverting terminal is indicated by the **'plus (+)'** sign and the Inverting terminal is indicated by **'minus (-)'** sign. When there is no feedback path from the output to the input of the Op Amp then the A is called open loop gain. So the output will be $\mathbf{V_{out} = A(V_1\text{-}V_2)}$

Suppose one input signal to the Non-Inverting terminal and the Inverting terminal is grounded. In this case, the output will be $\mathbf{V_{out} = A(V1\text{-}V_2) = A(V_1\text{-}0) = A*V_1}$

From this equation, the amplified output signal is in the same phase as the input signal.

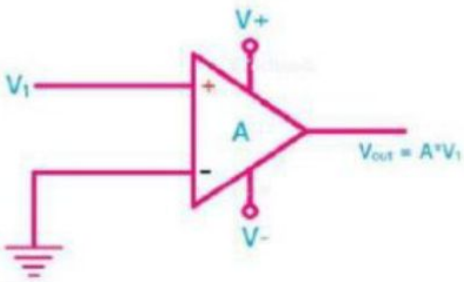


Figure 2.14: Non inverting amplifier

If he input signal to the Inverting terminal and the Non-Inverting is grounded then the output signal will be

$\mathbf{V_{out} = A(V_1\text{-}V_2) = A(0\text{-}V_2) = A*\text{-}V_2 = \text{-}AV_2}$

From this equation, the amplified output signal having a 180^{O} phase with respect to the input signal.

As when we applied the input signal that terminal the output signal is inverted that is why it is called Inverting terminal.

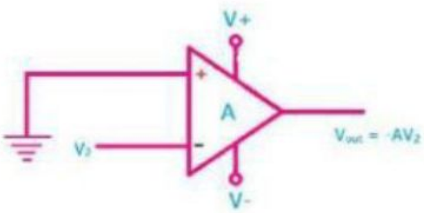


Figure 2.15: Inverting amplifier

Equivalent circuit of an Op-amp

The equivalent circuit is useful in analysing the basic operating principles of op-amps and in observing the effect of feedback arrangements.

For the circuit, the output voltage is

$V_o = AV_{id} = A(V_1 - V_2)$

Where A = large signal voltage gain

V_{id} = differential input voltage

V_1 and V_2 are the voltages at non-inverting and inverting input terminals respectively.

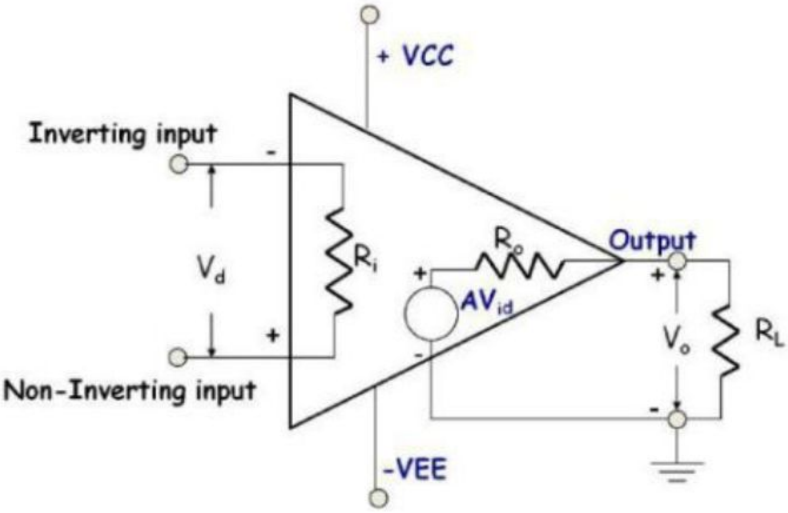


Figure 2.16: Equivalent circuit of Op-amp

The output voltage V_0 is directly proportional to the algebraic difference between the two input voltages. Hence the polarity of the output voltage depends on the polarity of the difference voltage.In the figure the output voltage V_o is plotted against differential input voltage $V_{id,}$ keeping the gain constant.However, the output voltage cannot exceed the positive and negative saturation voltages.

Voltage Transfer Curve

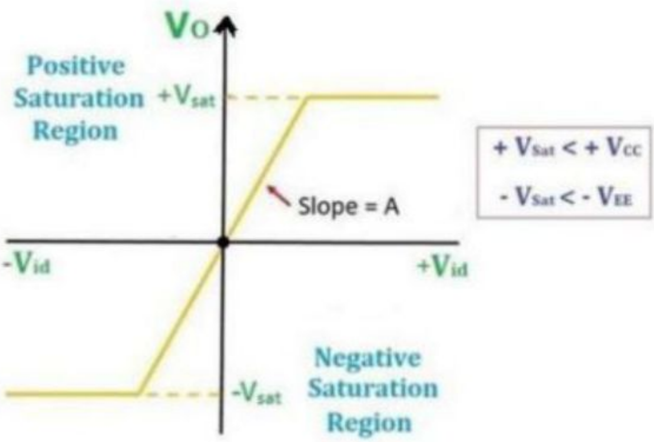


Figure 2.17: Ideal Voltage Transfer Curve

$+V_{sat}$---→Positive Saturation Voltage ($+V_{sat} < +V_{CC}$)

$-V_{sat}$----→Negative Saturation Voltage ($-V_{sat} < -V_{EE}$)

The output voltage cannot exceed the positive and negative saturation voltages. These saturation voltages are specified by an output voltage swing rating of the op-amp for given values of supply voltages. This means that the output voltage is directly proportional to the input difference voltage only until it reaches voltages and that thereafter output voltage remains constant.

2.4 BLOCK DIAGRAM OF OP-AMP

An op-amp is a multistage amplifier; it is represented as shown in figure.

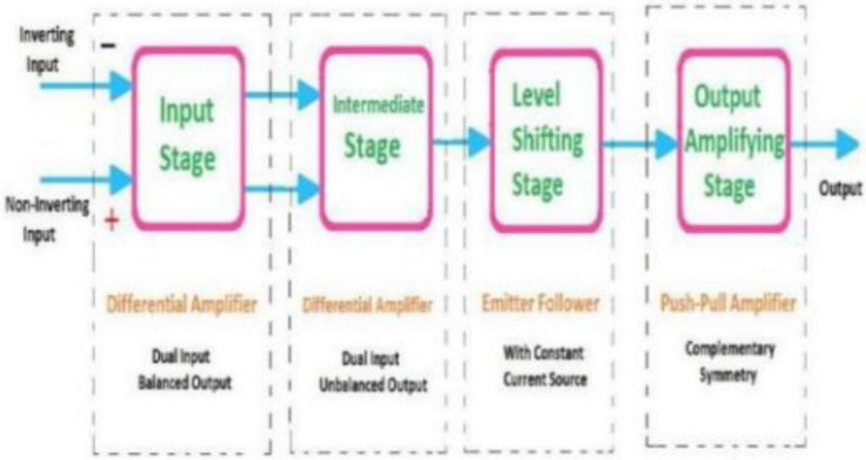


Figure 2.18: Block Diagram of a Typical Op-Amp

The input stage is a dual input balanced output differential amplifier. This stage generally provides most of the voltage gain of the amplifier and also establish the input resistance of the op-amp.

The intermediate stage is usually another differential amplifier, which driven by the output of the first stage. In most of the amplifiers the intermediate stage is dual input unbalanced output differential amplifier. Because direct coupling is used, the dc voltage at the output of the intermediate stage is well above ground potential.

So generally level translator (shifting) circuit is used after the intermediate stage to shit the dc level at the output of the intermediate stage downward to zero volts with respect to ground. The final stage is a push pull complementary output stage. The output stage increases the output voltage swing and raises the current supplying capability of the op-amp. A well-designed output stage also provides low output impedance.

Input Stage:

- Generally, for any circuit loading effect on sources is one of the major problems. To avoid this, the input impedance of input stage will be taken as high.
- Input stage consists of two input terminals (inverting & non-inverting) & also requires low output impedance.
- All such requirements are achieved by using the Dual Input Balanced Output differential amplifier.

- This Differential amplifier consists of high input impedance and it amplifies the difference of the two applied inputs.
- This stage provides most of the voltage gain of the amplifier.

Intermediate Stage:

- It is another differential amplifier with Dual Input balanced Output configuration. For an op-amp the overall gain requirement is very high.
- The main function of the intermediate stage is to provide an additional voltage gain required. Practically it is a chain of cascaded amplifiers called multistage amplifier.

Level Translating Stage:

- In Op-amp all the stages are directly coupled to each other. As the op-amp amplifies dc signals also, the coupling capacitors are not used to cascade the stages.
- Hence the Quiescent voltage level of previous stage gets applied as the input to the next stage. Hence stage by stage dc level increases well above the ground potential.
- Such high dc voltage level may drive the transistors into saturation.
- This further may cause distortion in the output due to clipping.
- This may limit the maximum output voltage swing without distortion. Hence before the output stage it is necessary to bring such a high dc level to zero.
- The level shifter stage brings the dc level down to ground potential when no signal is applied at the input terminals.
- The buffer is usually an emitter follower provides high input impedance to prevent the loading of the high gain stage.

Output Stage:

Generally, the output stage requires

- ✓ low output impedance
- ✓ Large ac output voltage swing
- ✓ High current sourcing & sinking capability

The Push-pull complimentary amplifier meets all these requirements and used as an output stage.

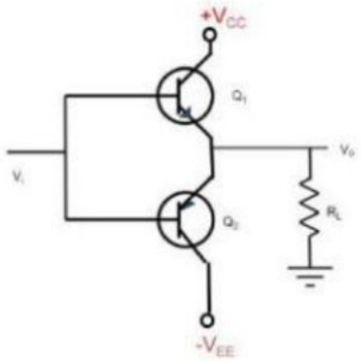


Figure 2.19: Output stage

2.5 DC CHARACTERISTICS

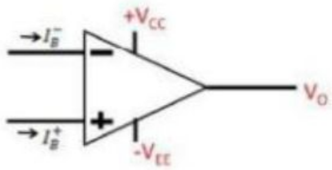
An ideal op-amp draws no current from the source and its response is also independent of temperature. However, a real op-amp does not work this way. Current is taken from the source into the op-amp inputs. These non-ideal dc characteristics that add error components to the dc output voltage are:

Input Bias current:

In an ideal op-amp, we assumed that no current is drawn from the input terminals. However, practically, input terminals do conduct a small value of dc current to bias the input transistors. The base currents entering into the inverting and non-inverting terminals are shown as I_B^- and I_B^+ respectively. Even though both the transistors are identical, I_B^- and I_B^+ are not exactly same.

The input bias current I_B is the average of the current entering the input terminals of a balanced amplifier

$$I_B = \frac{I_B^- + I_B^+}{2}$$



Input offset current:

The input transistors cannot be made identical, there will always be some small difference between I_B^+ and I_B^-. This difference is called the offset current I_{os} and can be written as

$I_{io} = | I_{B1} - I_{B2} |$

Input offset voltage:

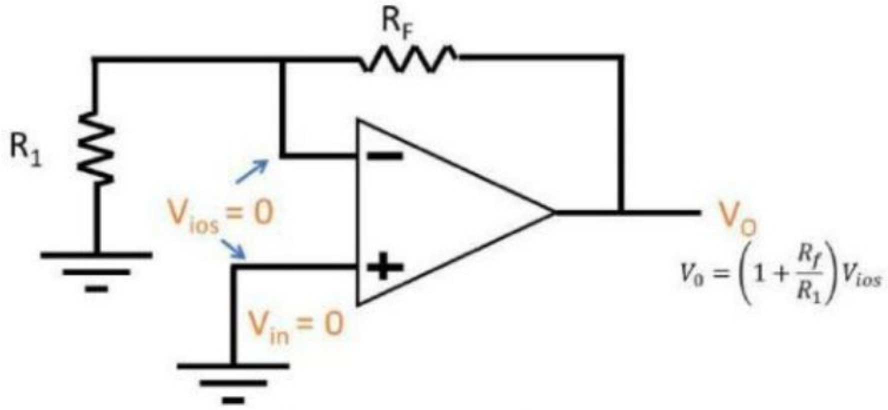


Figure 2.20: Non-Inverting amplifier

In spite of the use of the compensating techniques discussed above, the output voltage may still not be zero with zero input voltage. This is due to unavoidable imbalance inside the op-amp and one may have to apply a small amount of voltage at the input terminals to make output voltage zero. This voltage is known as input offset voltage V_{ios}.

Thermal drift

The op-amp parameters input offset voltage V_{ios}, input bias current I_b and input offset current I_{ios} are not constant but vary with the factors.

1. Temperature
2. Supply voltage changes
3. Time

Bias current, offset current and offset voltage change with temperature. A circuit capability carefully null at 25^0C may not remain so when the temperature rises to 35^0C. This is called drift. Forced air cooling may be used to stabilize the temperature.

The thermal drift is used to identify such changes and it is defined as the average rate of change of input offset voltage per unit change in temperature.

Thermal drift in Input offset voltage drift= $\frac{\Delta V_{ios}}{\Delta T}$ Units µV/°C

Thermal drift in Input bias current= $\frac{\Delta I_B}{\Delta T}$ Units nA/°C

Thermal drift in Input offset current= $\frac{\Delta I_{os}}{\Delta T}$ Units nA/°C

Power Supply Rejection Ratio (PSRR)

The Power Supply Rejection Ratio is defined as the ratio of the change in input offset voltage due to the change in supply voltage producing it, keeping other power supply voltage constant. It is also called Power Supply Sensitivity (PSS) or Supply Voltage Rejection Ratio (SVRR). Now if V_{EE} is constant due to certain in V_{CC}, there is change in input offset output voltage then PSRR is defined as

$$PSRR = \frac{\Delta V_{ios}}{\Delta V_{CC}} \because constant\ V_{EE}\ Unit - mV$$

For a fixed V_{CC}, if there is change in V_{EE} then

$$PSRR = \frac{\Delta V_{ios}}{\Delta V_{EE}} \because constant\ V_{CC}\ Unit - mV$$

Common Mode Rejection Ratio (CMRR)

It can be defined as the ratio of the differential voltage gain (A_d) to the common mode voltage gain A_{cm}.

$$CMRR = \frac{A_d}{A_{cm}}$$

The differential voltage gain A_d is the same as the large signal voltage gain A.

$$A_{cm} = \frac{V_{ocm}}{V_{cm}}$$

Where V_{ocm}= common mode output voltage

V_{cm}=common mode input voltage

A_{cm}= common mode voltage gain

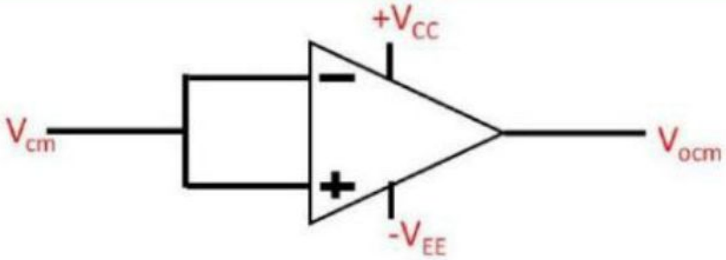


Figure 2.21: Common mode operation

Slew Rate:

The maximum rate of change of the output voltage in response to a step input voltage is the **slew rate** of an op-amp. The slew rate is dependent upon the high-frequency response of the amplifier stages within the op-amp.

For a step input, the slope on the output is inversely proportional to the upper critical frequency. Slope increases as upper critical frequency decreases.

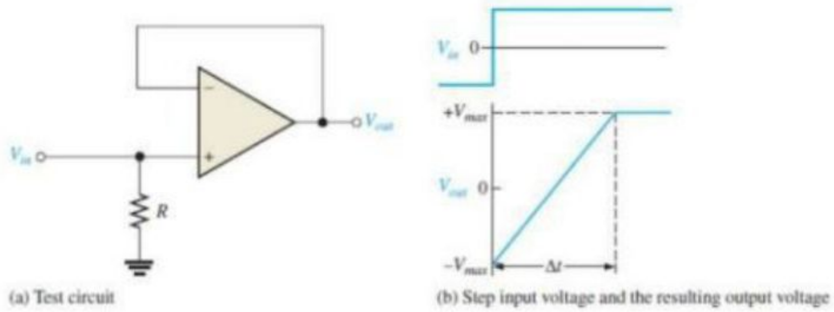


Figure 2.22: concept of slew rate

The width of the input pulse must be sufficient to allow the output to "slew" from its lower limit to its upper limit. A certain time interval, Δt, is required for the output voltage to go from its lower limit $-V_{max}$ to its upper limit $+V_{max}$, once the input step is applied. The slew rate is expressed as:

$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

where $\Delta V_{out} = +V_{max} - (-V_{max})$. The unit of slew rate is volts per microsecond (V/μs).

2.6 PIN CONSTRUCTION OF 741 OP-AMP

The operational amplifier comes in form of IC. The IC no. of Op-Amp is 741. The internal block diagram of **IC 741**

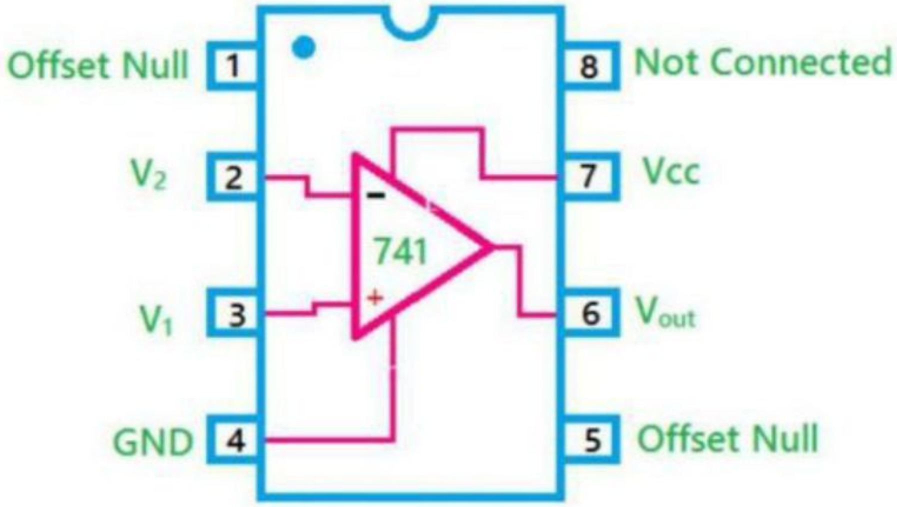


Figure 2.23: Pin diagram of Op-Amp

IC 741 is an 8-pin Op-Amp IC. The 8 pins are,

Pin 1: Offset Null

Pin 2: Inverting terminal for giving input signal.

Pin 3: Non-Inverting terminal for giving input signal.

Pin 4: Ground terminal to provide power supply or biasing to the Op-Amp

Pin 5: Offset Null

Pin 6: Output pin to connect the load and feedback path.

Pin 7: Vcc or Positive pin to provide power supply.

Pin 8: Not connected to the internal circuit.

The different Op-amp ICs has a different specification.

2.7 IDEAL CHARACTERISTICS OF OP-AMP

An ideal OP-amp would exhibit the following electrical characteristics:

- Infinite voltage gain A.
- Infinite input resistance R_i so that almost any signal source can drive it and there is no loading of the preceding stage.
- Zero output resistance R_o so that output can drive an infinite number of other devices.
- Zero output voltage when input voltage is zero.
- Infinite Bandwidth so that any frequency signal from 0 to ∞ Hz can be amplified without attenuation.
- Infinite Common Mode Rejection Ratio so that the output common mode noise voltage is zero.
- Infinite slewrate so that output voltage changes occur simultaneously with input voltage changes.

2.8 VIRTUAL GROUND

In opamps **the term virtual ground means that the voltage at that particular node is almost equal to ground voltage** (0V). It is **not** physically connected to ground. This concept is very useful in analysis of opamp circuits and it will make a lot of calculations very simple.

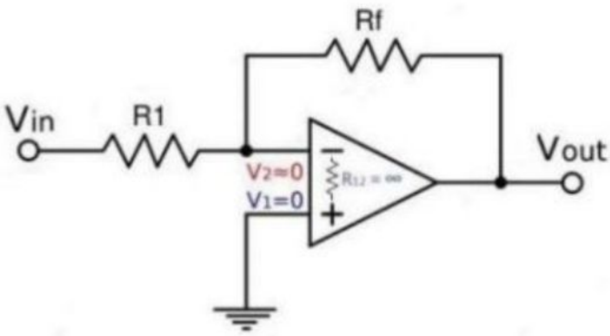


Figure 2.24: Schematic of Op-Amp

- **Gain = Vo/Vin**

As gain is infinite, **Vin = 0**

- Vin = V2 – V1

In the above circuit V1 is connected to ground, so V1 = 0. Thus V2 also will be at ground potential.

- **V2 = 0**

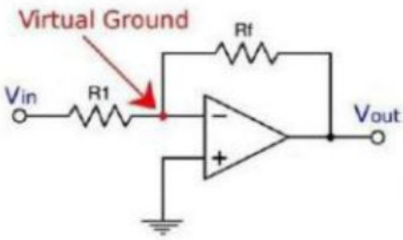


Figure 2.25: Schematic of Op-Amp

2.9 APPLICATIONS OF OP-AMP

There are many useful applications of Op-Amp. Some applications of Op-Amp are given below,

1. A very important application of the Op-Amp is amplification. The Op-Amp is used as Inverting amplifier, Non-Inverting amplifier.
2. The Op-Amp is used as Voltage Follower.
3. The Op-Amp is used as Comparator.
4. The Op-Amps sometimes used as audio preamplifier which used before the power amplifier in the audio system.
5. The Operational amplifier is also used as Active Filter.
6. The other important application of operational amplifier is Oscillator. The Op-Amp can produce the oscillating signal of any desired frequency and waveforms.

7. The operational amplifiers are used for convert waveforms that means we can convert a sine wave into square wave using an Op-Amp.

8. By using operational amplifier we can convert the analog signal into digital signal.

9. The conversion of the digital signal into analog signal also be possible by the Op-Amp.

Inverting amplifier

The output voltage V_O is fed back to the inverting input terminal through the R_f-R_1 network where Rf is the feedback resistor. Input signal V_{in} (ac or dc) is applied to the inverting input terminal through R_1 and non-inverting terminal of op-amp is grounded.

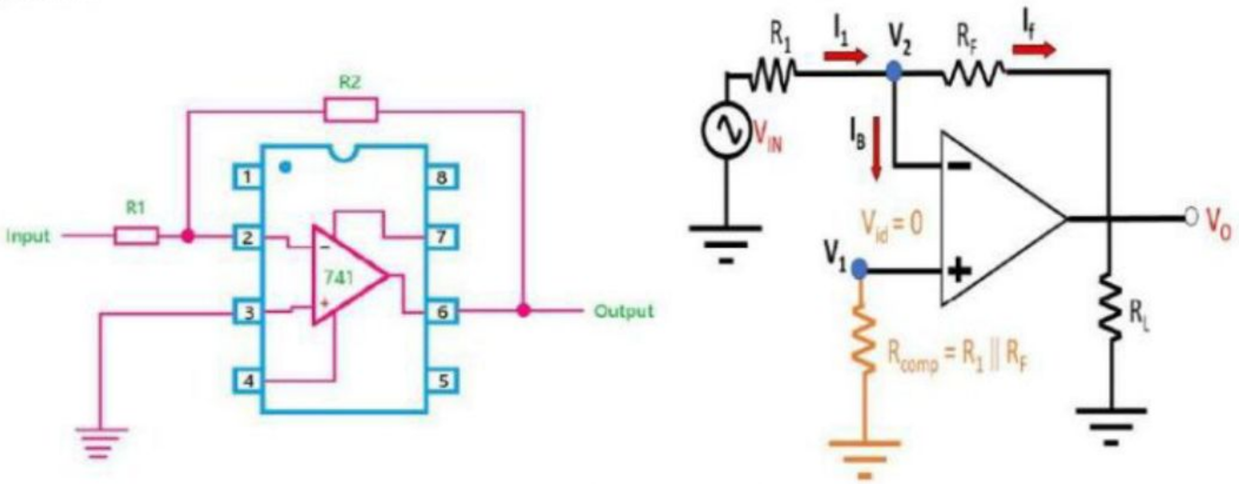


Figure 2.26: Inverting amplifier

Analysis: For simplicity assume an ideal op-amp V_{id}=0. Apply KCL at node V_2

$$I_1 = I_f + I_B$$

But I_B=0

$$I_1 = I_f$$

$$\frac{V_{in} - V_2}{R_1} = \frac{V_2 - V_O}{R_f}$$

From virtual ground concept V_{id}=0V so V_1=V_2=0

$$\frac{V_{in} - 0}{R_1} = \frac{0 - V_O}{R_f}$$

$$V_O = \frac{-R_f}{R_1} V_{in}$$

The closed loop gain of inverting amplifier

$$A_f = \frac{V_O}{V_{in}} = \frac{-R_f}{R_1}$$

The negative sign indicates a phase shift of 180^0 between V_{in} and V_O. Also, since inverting input terminal is at virtual ground, the effective input impedance is R_1.

Non-Inverting Amplifier

If a signal (ac or dc) is applied to the non-inverting input terminal and the circuit amplifies without inverting the input signal. Such a circuit is called non-inverting amplifier. It may be noted that it is also a negative feedback system as output is being fed back to the inverting input terminal.

Analysis: For simplicity assume an ideal op-amp V_{id}=0. Apply KCL at node V_2

$$I_1 = I_f + I_B$$

But I_B=0

$$I_1 = I_f$$

$\frac{0-V_2}{R_1} = \frac{V_2-V_O}{R_f}$

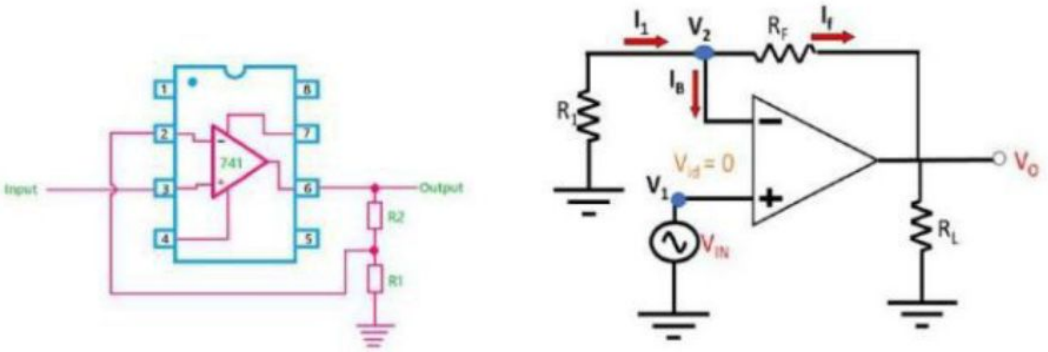


Figure 2.27: Non-Inverting Amplifier

From virtual ground concept V_{id}=0V so V_1=V_2 and V_1=V_{in}

$$\frac{0 - V_{in}}{R_1} = \frac{V_{in} - V_O}{R_f}$$

$$\frac{-V_{in}}{R_1} + \frac{-V_{in}}{R_f} = \frac{-V_O}{R_f}$$

$$-V_{in}\left(\frac{R_1 + R_f}{R_1 R_f}\right) = \frac{-V_O}{R_f}$$

$$\frac{V_O}{V_{in}} = 1 + \frac{R_f}{R_1}$$

Thus, for non-inverting amplifier the voltage gain,

$$A_f = \frac{V_O}{V_{in}} = 1 + \frac{R_f}{R_1}$$

Voltage follower

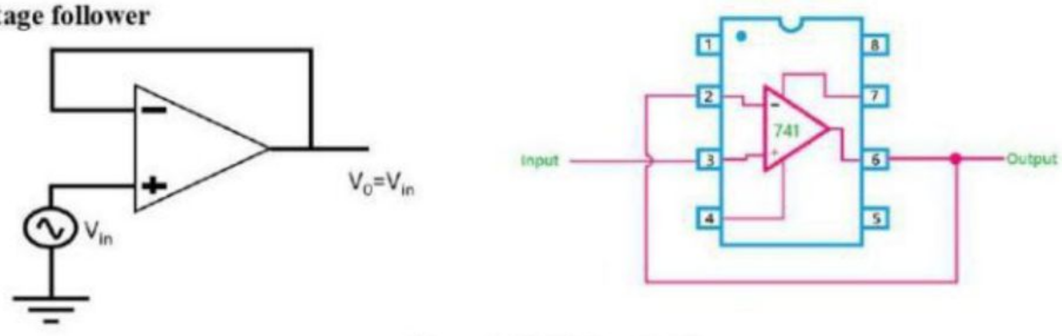


Figure 2.28: Voltage follower

When the non-inverting amplifier is configured for unity gain, it is called a voltage follower because the output voltage is equal to and in-phase with the input.

$$R_1 \rightarrow \text{open circuited} \rightarrow \infty$$
$$R_f \rightarrow \text{short circuited} \rightarrow 0$$
$$A_f = \frac{V_0}{V_{in}} = \left(1 + \frac{R_f}{R_1}\right) = \left(1 + \frac{\infty}{0}\right) = 1$$
$$V_0 = V_{in}$$

The voltage follower is also called a non-inverting buffer because, when placed between two networks, it removes the loading on the first network.

Summing, Scaling and Averaging Amplifiers

The inverting, Non-inverting and differential amplifier configurations are used in applications as

- Summing amplifiers
- Scaling amplifiers
- Averaging amplifiers

Inverting summing amplifier

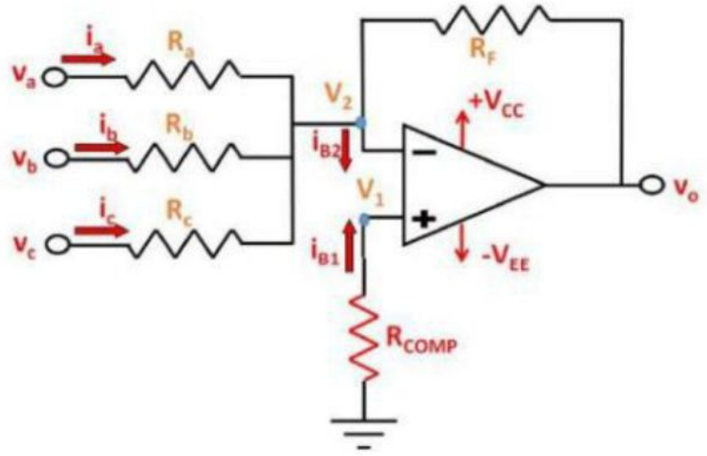


Figure 2.29: Inverting summing amplifier

Inverting configuration with three inputs V_a, V_b, V_c and R_a, R_b, R_c are the input resistances. Rf is the feedback resistance. Depending on the relation between R_a,R_b, R_c, R_f circuit can be summing, scaling or averaging amplifier.

The voltage at node 'V_2' is zero as the non-inverting input terminal is grounded. The nodal equation by KCL at node 'a' is

$$I_a + I_b + I_c = I_B + I_F$$

$$\frac{V_a - V_2}{R_a} + \frac{V_b - V_2}{R_b} + \frac{V_c - V_2}{R_c} = \frac{V_2 - V_o}{R_f}$$

Since R_i and A of op-amp are ideally infinity I_B=0, V1=V2=0

$$\frac{V_a}{R_a}+\frac{V_b}{R_b}+\frac{V_c}{R_c}+\frac{V_0}{R_f}=0$$

$$V_0=-\left(\frac{R_f}{R_a}V_a+\frac{R_f}{R_b}V_b+\frac{R_f}{R_c}V_c\right)$$

Thus, the output is an inverted, weighted sum of the input.

Summing Amplifier

If $R_a = R_b = R_c = R$ above equation becomes

$$V_0=-\frac{R_f}{R}(V_a+V_b+V_c)$$

If output voltage is equal to the negative sum of all the inputs times the gain of the circuit R_f/R then it is called summing amplifier.

In the special case, when $R_a = R_b = R_c = R_f$ we have the output voltage is equal to negative sum of all input voltages.

$$V_0=-(V_a+V_b+V_c)$$

Differential amplifier

Differential amplifier is a combination of inverting and non-inverting amplifiers. That is, when V_x is reduced to zero the circuit is a non-inverting amplifier, whereas the circuit is an inverting amplifier when input V_y is reduced to zero.

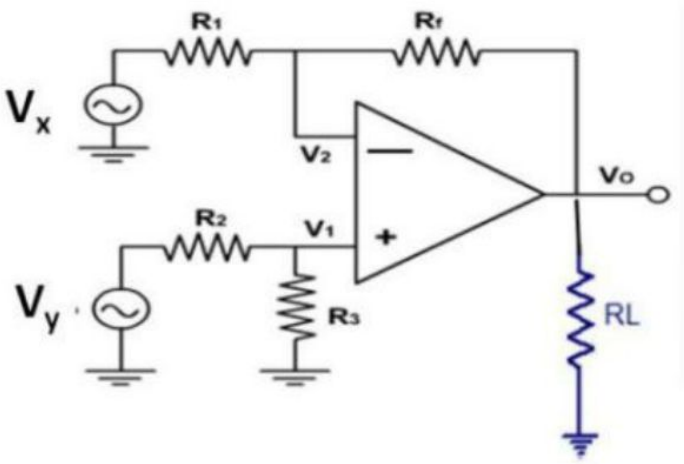


Figure 2.30: Differential amplifier with one op-amp

Voltage gain

Use the super position theorem in order to establish the relationship between inputs and outputs.

When V_y=0, the configuration comes an inverting amplifier. The output due to V_x only

$$\therefore V_{01}=\frac{-R_f}{R_1}V_x$$

When V_x=0, the configuration comes an non-inverting amplifier. The output due to V_y only

$$V_1=V_y\frac{R_3}{R_2+R_3}$$

$$\therefore V_{02} = (1 + \frac{R_f}{R_1})V_y \frac{R_3}{R_2 + R_3}$$

If R_1=R_2& R_f=R_3 then

$$\therefore V_{02} = (\frac{R_1 + R_f}{R_1})V_y \frac{R_f}{R_1 + R_f}$$

$$\therefore V_{02} = \frac{R_f}{R_1} V_y$$

The net output voltage $V_0 = V_{01} + V_{02}$

$$V_0 = \frac{-R_f}{R_1} V_x + \frac{R_f}{R_1} V_y$$

$$= \frac{-R_f}{R_1} (V_x - V_y)$$

The voltage gain$A_D = \frac{V_0}{V_x - V_y} = \frac{-R_f}{R_1}$

The gain of the differential amplifier is the same as that of the inverting amplifier.

Differentiator

Differentiator or differentiation amplifier, the circuit peroms the mathematical operation of differentiation, that is, the output waveform is the derivative of the input waveform. The differentiator may be constructed from a basic inverting amplifier if an input resistor R_1 is replaced by a capacitor C_1.

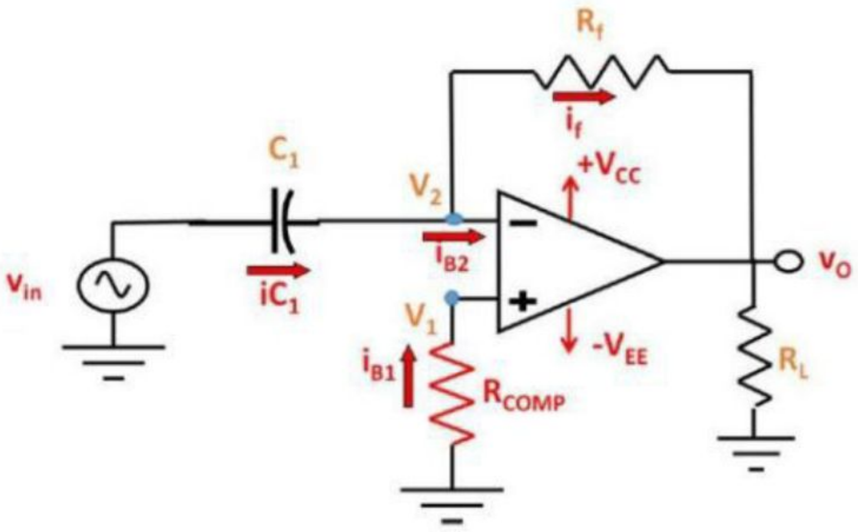


Figure 2.31: Differentiator

The expression for the output voltage can be obtained rom KCL equation written at node V_2 as follows:

$$I_c = I_f + I_B$$

Since $I_B \cong 0$ and $V_1 = V_2 \cong 0$ and A is very large. Therefore

$$I_C = I_f$$

$$C\frac{d}{dt}(V_{in} - V_2) = \frac{V_2 - V_O}{R_f}$$

$$C\frac{d}{dt}(V_{in} - 0) = \frac{0 - V_O}{R_f}$$

$$C\frac{d}{dt}V_{in} = \frac{-V_O}{R_f}$$

$$V_O = -R_f C\frac{d}{dt}V_{in}$$

Thus, the output voltage V_o is a constant $-R_fC_1$ times the derivative of the input voltage V_{in} and the circuit is a differentiator. The minus sign indicates an 180^0 phase shift of the output waveform V_O with respect to the input signal.

Integrator

A circuit in which the output voltage waveform is the integral of the input voltage waveform is the integrator or the integration amplifier. Such a circuit is obtained by using a basic inverting amplifier configuration if the feedback resistor R_f is replaced by a capacitor C_f. The expression for the output voltage V_o can be obtained by writing KCL at node V_2.

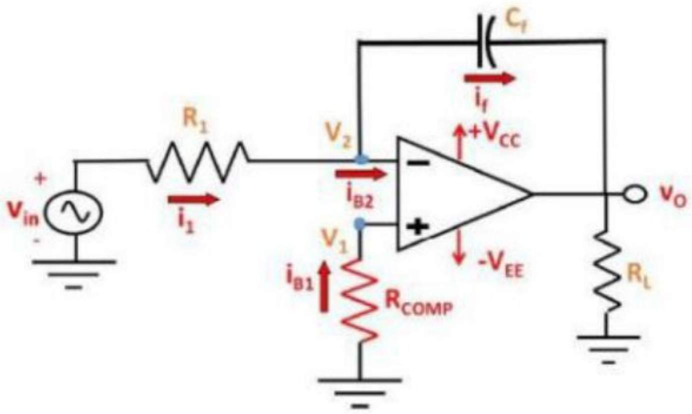


Figure 2.32: Integrator

$$I_1 = I_B + I_F$$

But I_B=0 and V_1=V_2=0, so

$$I_1 = I_F$$

The current flowing through the feedback capacitor C is given as

$$I_F = C\frac{d}{dt}(V_2 - V_O) = C\frac{d}{dt}(0 - V_O)$$

$$= -C\frac{d}{dt}V_O$$

$$I_1 = \frac{V_{in} - V_2}{R_1}; V_2 = 0$$

$$I_1 = \frac{V_{in}}{R_1}$$

The output voltage can be obtained by integrating both sides with respect to time

$$\therefore \frac{V_{in}}{R_1} = -C\frac{d}{dt}V_O$$

$$V_O = -\frac{1}{R_1C}\int V_{in}dt + C$$

Where C is the integration constant and is proportional to the values of the output voltage Vo at time t=0 seconds. Here above equation indicates that the output voltage is directly proportional to the negative integral of the input voltage and inversely propotional to the time constant R_1C_f.

Basic Comparator

A comparator compares a signal voltage on one input of an op-amp with a known voltage called the reference voltage on the other input.

Non-Inverting Comparator

A fixed reference voltage V_{ref} is applied to the (-) input, and the other time varying signal voltage Vin is applied to the (+) input, then the circuit is called the non-inverting comparator. When Vin is less than V_{ref}, the output voltage V_O is $-V_{sat}$ ($-V_{EE}$) because the voltage at the (-) input is higher than that at the (+) input. When V_{in} is greater than V_{ref}, the (+) input becomes positive with respect to the (-) input and V_O goes to $+V_{sat}$ ($+V_{CC}$).

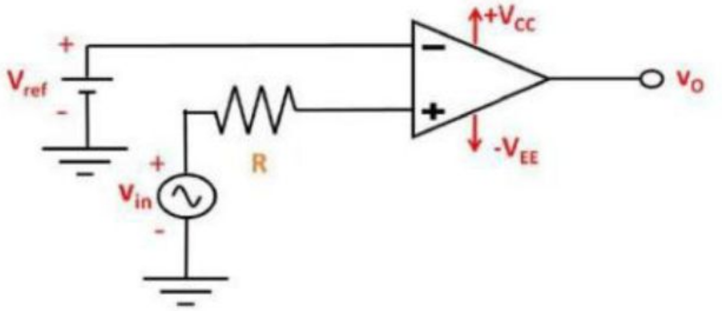


Figure 2.33: Non-Inverting comparator

Thus, V_O changes from one saturation level to another whenever Vin≈Vref. The comparator is a type of analog to digital converter. At any given time, the VO waveform shows whether Vin is greater or less than Vref. The comparator is sometimes also called a voltage level detector because, for a desired value of Vref, the voltage level of the input Vin can be detected.

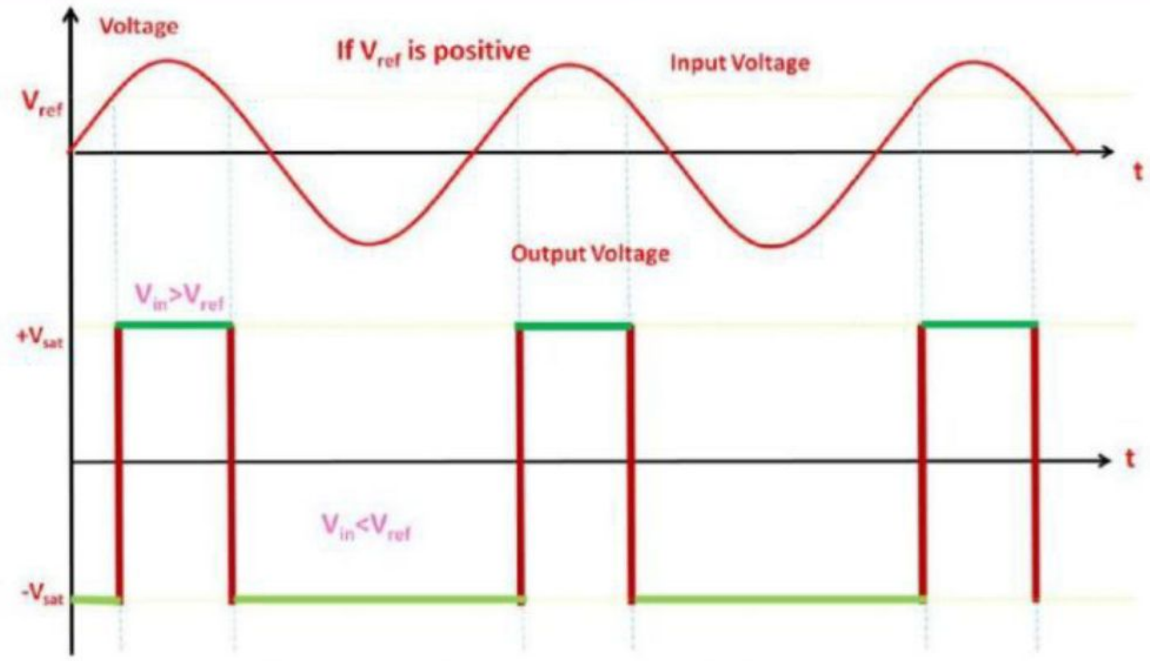


Figure 2.34: Input and output waveforms of Non-Inverting comparator

If the reference voltage Vref is negative with respect to ground, with sinusoidal signal applied to the (+) input, the output waveform shown in figure.

When $V_{in}>V_{ref}$ $\quad V_O=+V_{sat}$

$V_{in}<V_{ref}$ $\quad V_O=-V_{sat}$

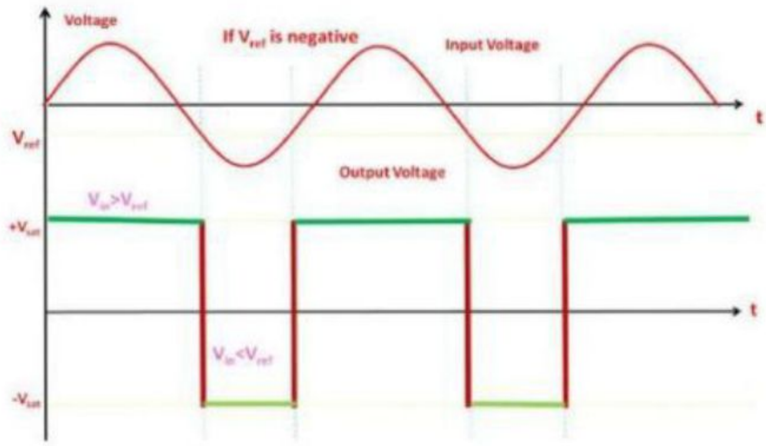


Figure 2.35: Input and output waveforms of Non-Inverting comparator

Inverting Comparator

An inverting comparator in which the reference voltage Vref is applied to the (+) input and Vin is applied to the (-) input.

When $V_{in}>V_{ref}$ $\quad V_O=-V_{sat}$

$V_{in}<V_{ref}$ $\quad V_O=+V_{sat}$

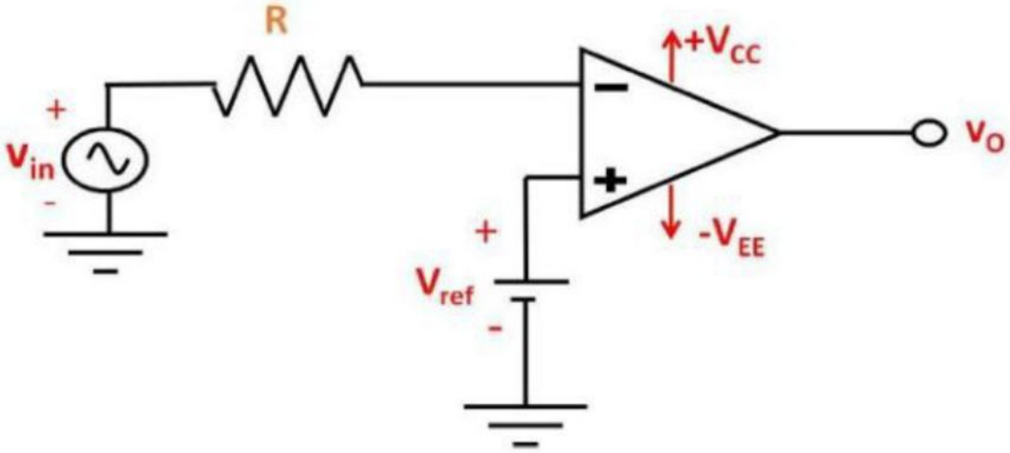


Figure 2.36: Inverting comparator

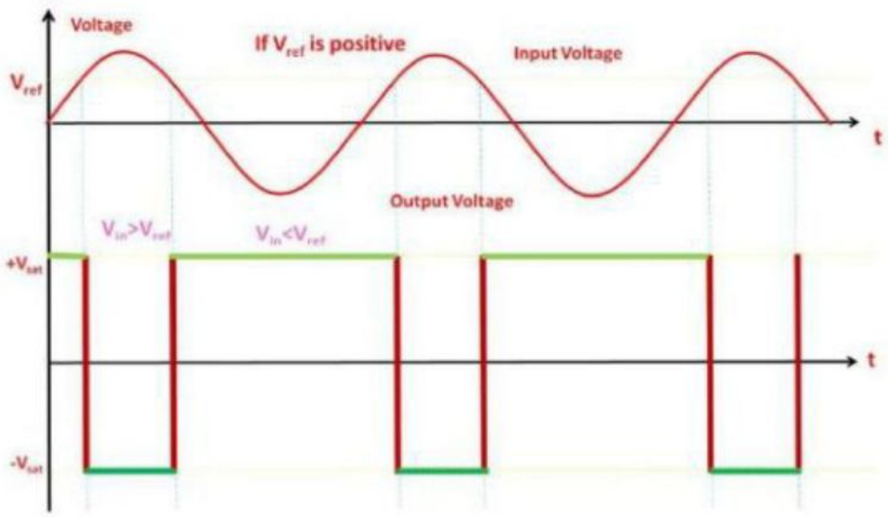


Figure 2.37: Input and output waveforms of Inverting comparator

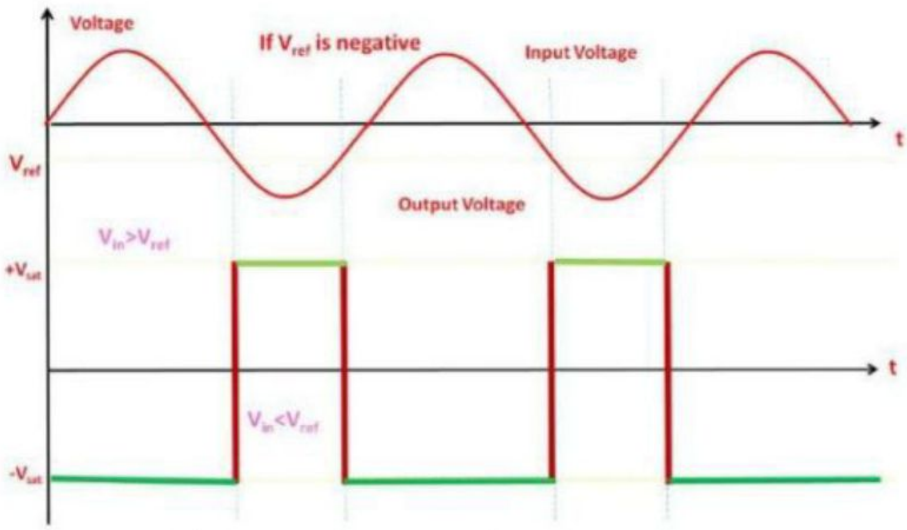


Figure 2.38: Input and output waveforms of Inverting comparator

Model Questions

1. What is a differential amplifier? Explain balanced and unbalanced output in differential amplifier.
2. Explain the operating modes of differential amplifier.
3. Define an op-amp. Explain the ideal characteristics of an op-amp.
4. Organize the op-amp with block diagram representation and explain the functionality of each block.
5. Draw the diagram of basic integrator and derive the equation for its output voltage.
6. Define the terms input offset voltage, input offset current, common mode rejection ratio, large signal voltage gains and slew rate.
7. Draw the diagram of basic differentiator and derive the equation for its output voltage.
8. Derive the expressions for output voltage of an inverting and non-inverting operational amplifier.
9. What is an op-amp? Explain the operation of non-inverting comparator
10. Derive the expression for 3 input summing amplifier with circuit diagram.
11. Derive the expression for difference amplifier with circuit diagram.
12. Design an inverting and non inverting amplifier with gain of 5.
13. Design an inverting amplifier with a gain of -5 and an input resistance of 10 KΩ.

UNIT – III

Digital Electronics: Logic Gates, Simple combinational circuits–Half and Full Adders, BCD Adder. Latches and Flip-Flops (S-R, JK and D), Shift Registers and Counters. Introduction to Microcontrollers and their applications (Block diagram approach only).

****

Logic Gates

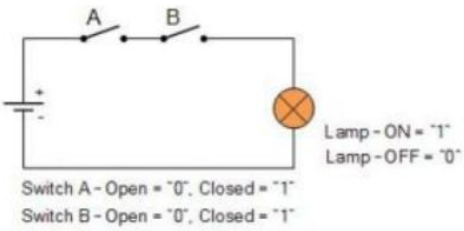
Boolean functions may be practically implemented by using electronic gates. The following points are important to understand.

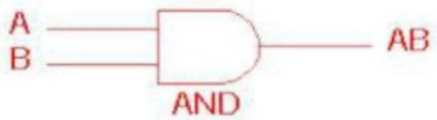
- Electronic gates require a power supply.
- Gate **INPUTS** are driven by voltages having two nominal values, e.g. 0V and 5V representing logic 0 and logic 1 respectively.
- The **OUTPUT** of a gate provides two nominal values of voltage only, e.g. 0V and 5V representing logic 0 and logic 1 respectively. In general, there is only one output to a logic gate except in some special cases.
- There is always a time delay between an input being applied and the output responding.

Logic gates

Digital systems are said to be constructed by using logic gates. These gates are the AND, OR, NOT, NAND, NOR, EXOR and EXNOR gates. The basic operations are described below with the aid of truth tables.

AND gate



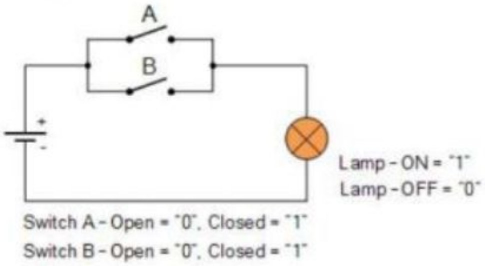


2 Input AND gate		
A	B	A.B
0	0	0
0	1	0
1	0	0
1	1	1

Figure 3.1: AND Gate operation

The AND gate is an electronic circuit that gives a **high** output (1) only if **all** its inputs are high. A dot (.) is used to show the AND operation i.e. A.B. Bear in mind that this dot is sometimes omitted i.e. AB

OR gate



2 Input OR gate		
A	B	A+B
0	0	0
0	1	1
1	0	1
1	1	1

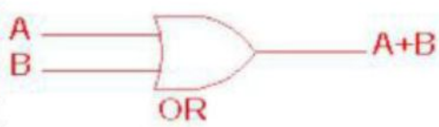
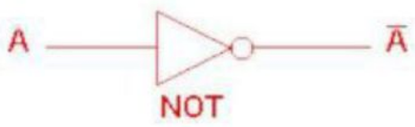


Figure 3.2: OR Gate operation

The OR gate is an electronic circuit that gives a high output (1) if **one or more** of its inputs are high. A plus (+) is used to show the OR operation.

NOT gate



NOT gate	
A	Ā
0	1
1	0

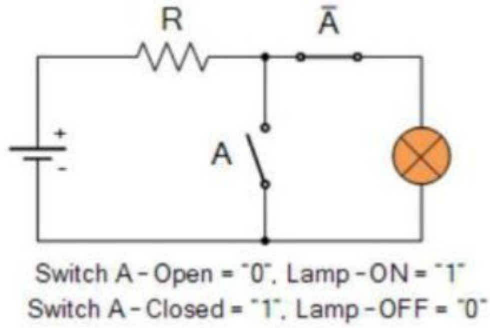
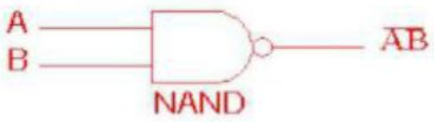


Figure 3.3: NOT Gate operation

The NOT gate is an electronic circuit that produces an inverted version of the input at its output. It is also known as an *inverter*. If the input variable is A, the inverted output is known as NOT A. This is also shown as A', or A with a bar over the top, as shown at the outputs.

NAND gate



2 Input NAND gate		
A	B	$\overline{A.B}$
0	0	1
0	1	1
1	0	1
1	1	0

Figure 3.4:NAND Gate operation

This is a NOT-AND gate which is equal to an AND gate followed by a NOT gate. The outputs of all NAND gates are high if **any** of the inputs are low. The symbol is an AND gate with a small circle on the output. The small circle represents inversion.

NOR gate

2 Input NOR gate		
A	B	$\overline{A+B}$
0	0	1
0	1	0
1	0	0
1	1	0

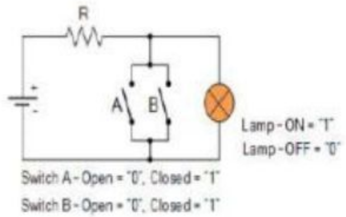


Figure 3.5:NOR Gate operation

This is a NOT-OR gate which is equal to an OR gate followed by a NOT gate. The outputs of all NOR gates are low if **any** of the inputs are high.

The symbol is an OR gate with a small circle on the output. The small circle represents inversion.

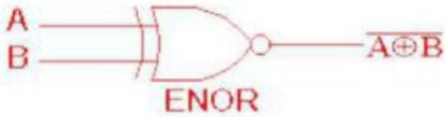
EXOR gate

2 Input EXOR gate		
A	B	A⊕B
0	0	0
0	1	1
1	0	1
1	1	0

Figure 3.6: EXOR Gate operation

The '**Exclusive-OR**' gate is a circuit which will give a high output if **either, but not both**, of its two inputs are high. An encircled plus sign (⊕) is used to show the EOR operation.

EXNOR gate

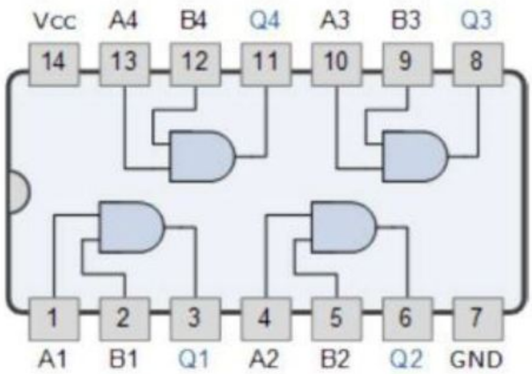


2 Input EXNOR gate		
A	B	$\overline{A \oplus B}$
0	0	1
0	1	0
1	0	0
1	1	1

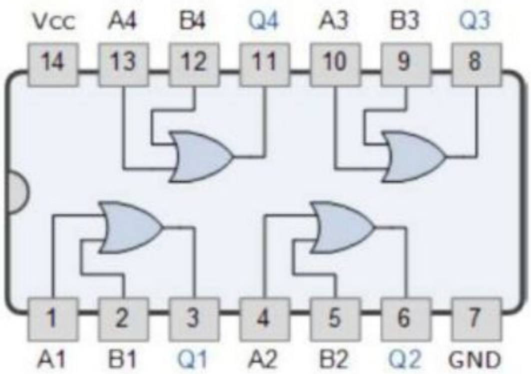
Figure 3.7: ENOR Gate operation

The '**Exclusive-NOR**' gate circuit does the opposite to the EOR gate. It will give a low output if **either, but not both**, of its two inputs are high. The symbol is an EXOR gate with a small circle on the output. The small circle represents inversion.

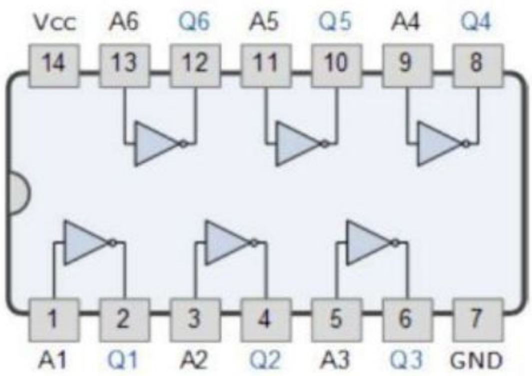
The NAND and NOR gates are called *universal functions* since with either one the AND and OR functions and NOT can be generated.



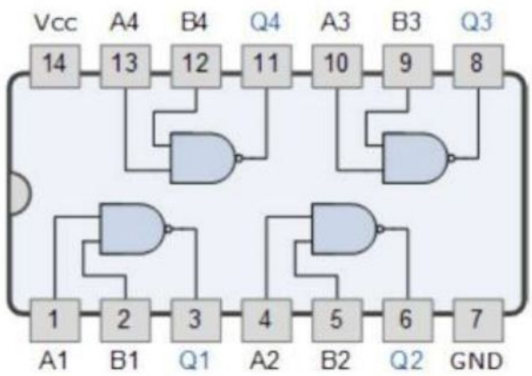
7408 Quad 2-input AND Gate



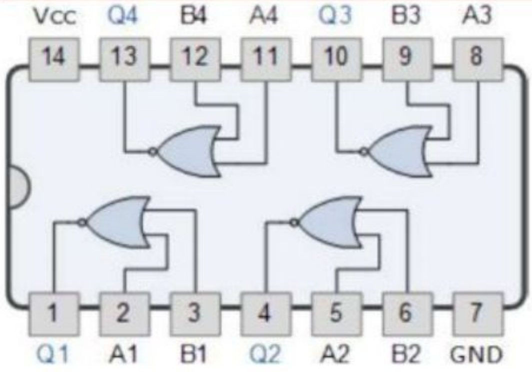
7432 Quad 2-input Logic OR Gate



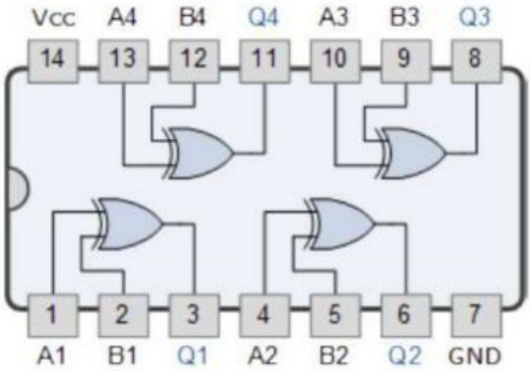
7404 NOT Gate or Inverter



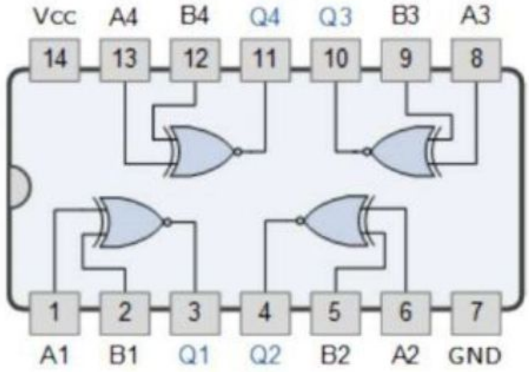
7400 Quad 2-input Logic NAND Gate



7402 Quad 2-input NOR Gate



7486 Quad 2-input Exclusive-OR Gate



74266 Quad 2-input Ex-NOR Gate

Figure 3.8:Pin diagram of Logic Gates

HALF ADDER

The simplest adder, called a *half adder*, adds two 1-bit operands A and B, producing a 2-bit sum. The sum can range from 0 to 2, which requires two bits to express. The low-order bit of the sum may be named HS (half sum), and the high-order bit may be named C_O (carry out). We can write the following equations for SUM and CARRY:

SUM<=A XOR B;

CARRY<=A AND B;

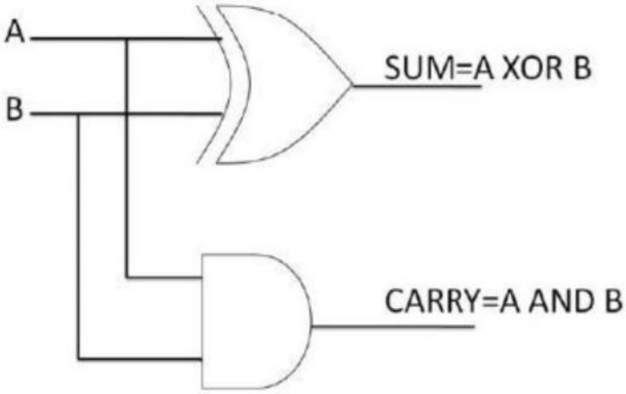
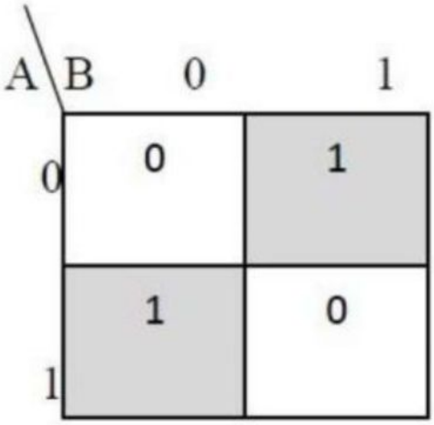
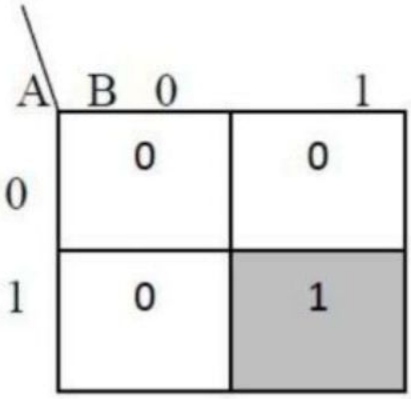


Figure 3.9:Half Adder Logic diagram





TRUTH TABLE

A	B	SUM	CARRY
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

FULL ADDER

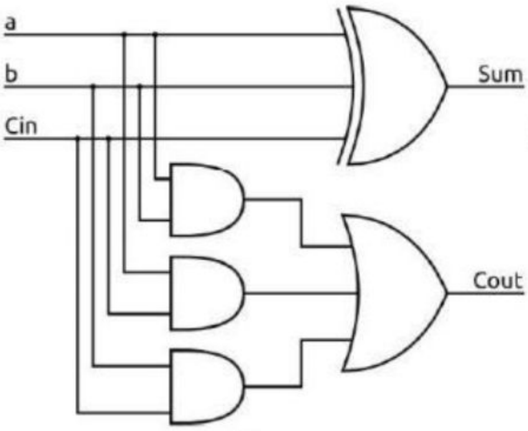
Full adder is a digital circuit used to calculate the sum of three binary bits which is the main difference between this and half adder. Full adders are complex and difficult to implement when compared to half adders. Two of the three bits are same as before which are A, the augend bit and B, the addend bit. The additional third bit is carry bit from the previous stage and is called Carry – in generally represented by CIN. It calculates the sum of three bits along with the carry. The output carry is called Carry – out and is represented by COUT.

SUM<=A XOR B XOR C;

CARRY<=AB+BC+AC;

A \ BC_{IN}	00	01	11	10
0	0	1	0	1
1	1	0	1	0

A \ BC_{IN}	00	01	11	10
0	0	0	1	0
1	0	1	1	1



$$\text{Sum} = \bar{A}\,\bar{B}\,C_{in} + \bar{A}\,B\,\bar{C}_{in} + A\,\bar{B}\,\bar{C}_{in} + A\,B\,C_{in}$$

$$= C_{in}\,(\bar{A}\,\bar{B} + AB) + \bar{C}_{in}\,(\bar{A}\,B + A\,\bar{B})$$

$$= C_{in}\,(A \odot B) + \bar{C}_{in}\,(A \oplus B)$$

$$= C_{in}\,(\overline{A \oplus B}) + \bar{C}_{in}\,(A \oplus B)$$

$$= C_{in} \oplus (A \oplus B)$$

Input			Output	
A	B	Cin	Sum	Carry
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

Figure 3.10: Full Adder Logic diagram

BCD Adder

BCD stand for binary coded decimal. Suppose, two 4-bit numbers A and B. The value of A and B can varies from 0(0000 in binary) to 9(1001 in binary) because we are considering decimal numbers.

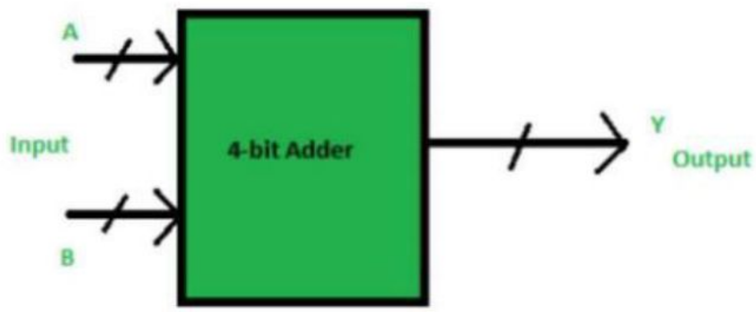


Figure 3.11: BCD Addition

The output will varies from 0 to 18, if not considering the carry from the previous sum. But if considering the carry, then the maximum value of output will be 19 (i.e. 9+9+1 = 19).

When we are simply adding A and B, then we get the binary sum. Here, to get the output in BCD form, we will use BCD Adder.

Decimal	Binary Sum					BCD Sum				
	C'	S3'	S2'	S1'	S0'	C	S3	S2	S1	S0
0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	1	0	0	0	0	1
2	0	0	0	1	0	0	0	0	1	0
3	0	0	0	1	1	0	0	0	1	1
4	0	0	1	0	0	0	0	1	0	0
5	0	0	1	0	1	0	0	1	0	1
6	0	0	1	1	0	0	0	1	1	0
7	0	0	1	1	1	0	0	1	1	1
8	0	1	0	0	0	0	1	0	0	0
9	0	1	0	0	1	0	1	0	0	1
10	0	1	0	1	0	1	0	0	0	0
11	0	1	0	1	1	1	0	0	0	1
12	0	1	1	0	0	1	0	0	1	0
13	0	1	1	0	1	1	0	0	1	1
14	0	1	1	1	0	1	0	1	0	0
15	0	1	1	1	1	1	0	1	0	1
16	1	0	0	0	0	1	0	1	1	0
17	1	0	0	0	1	1	0	1	1	1
18	1	0	0	1	0	1	1	0	0	0
19	1	0	0	1	1	1	1	0	0	1

When C'= 1, it indicates that the sum is greater than 9 or if there is a carry. When C'= 1, a binary 0110 is added to the binary sum through the second adder. A decimal parallel adder that adds n' decimal digit needs n' BCD adder stages. A BCD adder that adds two BCD digits and produces a sum digit in BCD is shown in Figure. The two decimal digits, together with the input carry, are first added in the top four-bit adder to produce the binary sum. When the output carry is equal to 0, nothing is added to the binary sum. When it is equal to 1, binary 0110 is added to the binary sum through the bottom four-bit adder. The output carry generated from the bottom adder can be ignored, since it supplies information already available at the output carry terminal.

The conditions are:

1. If C' = 1 (Satisfies 16-19)
2. If $S_3'.S_2' = 1$ (Satisfies 12-15)
3. If $S_3'.S_1' = 1$ (Satisfies 10 and 11)

So, our logic is

$$\mathbf{C' + S_3'.S_2' + S_3'.S_1' = 1}$$

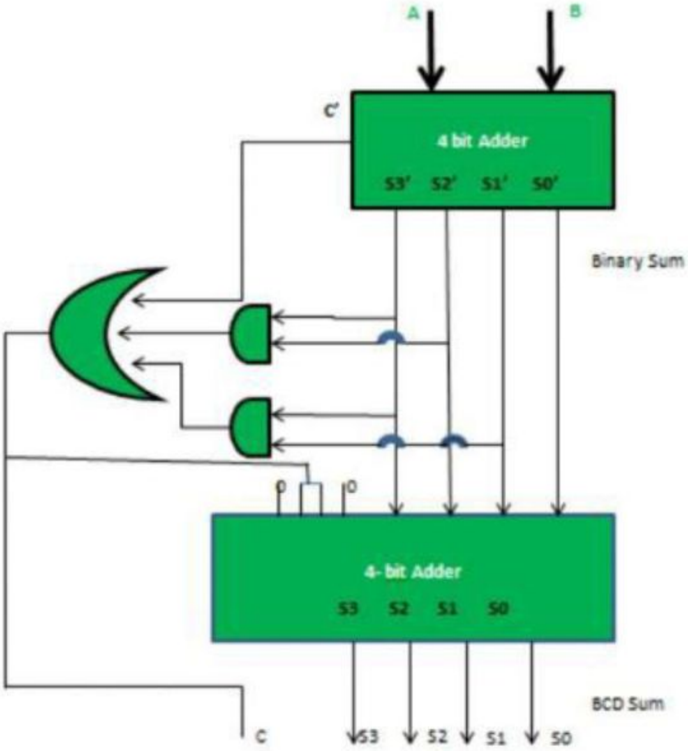


Figure 3.12: BCD Adder

Introduction to Sequential Circuits

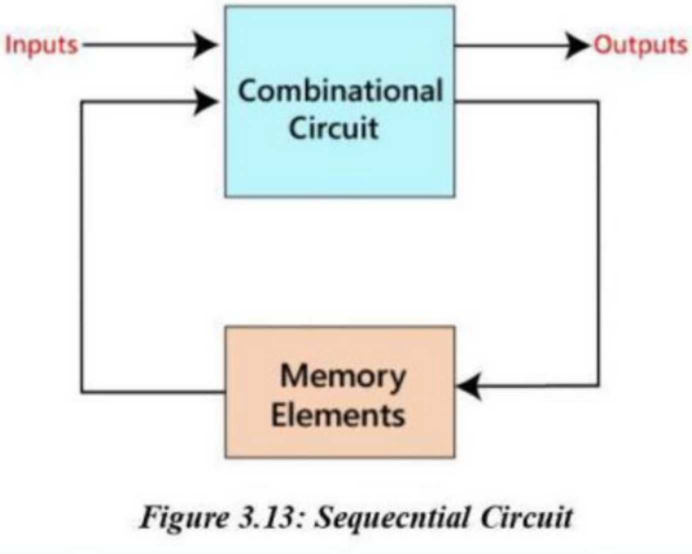


Figure 3.13: Sequecntial Circuit

The sequential circuit is a special type of circuit that has a series of inputs and outputs. The outputs of the sequential circuits depend on both the combination of present inputs and previous outputs. The previous output is treated as the present state. So, the sequential circuit contains the combinational circuit and its memory storage elements. A sequential circuit doesn't need to always contain a combinational circuit. So, the sequential circuit can contain only the memory element.

Types of Sequential Circuits

Asynchronous sequential circuits

The clock signals are not used by the **Asynchronous sequential circuits**. The internal state is changed when the input variable is changed.

Synchronous sequential circuits

In synchronous sequential circuits, synchronization of the memory element's state is done by the clock signal. The output is stored in either flip-flops or latches(memory devices). The synchronization of the outputs is done with either only negative edges of the clock signal or only positive edges.

Clock signal

A clock signal is a periodic signal in which ON time and OFF time need not be the same. When ON time and OFF time of the clock signal are the same, a square wave is used to represent the clock signal. Below is a diagram which represents the clock signal:

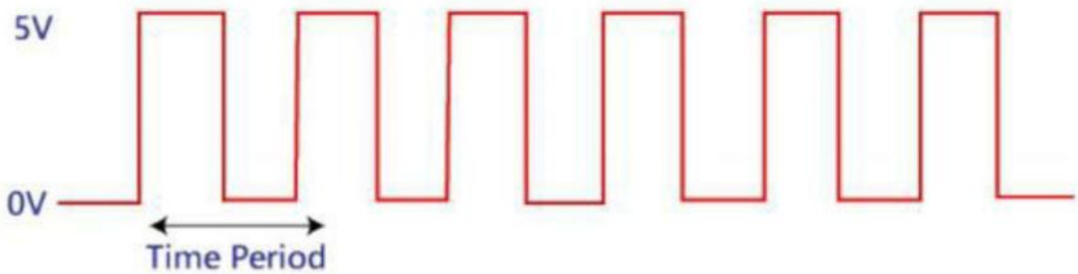


Figure 3.14: Clock Signal

Types of Triggering

These are two types of triggering in sequential circuits:

Level triggering

The logic High and logic Low are the two levels in the clock signal. In level triggering, when the clock pulse is at a particular level, only then the circuit is activated. There are the following types of level triggering:

Positive level triggering

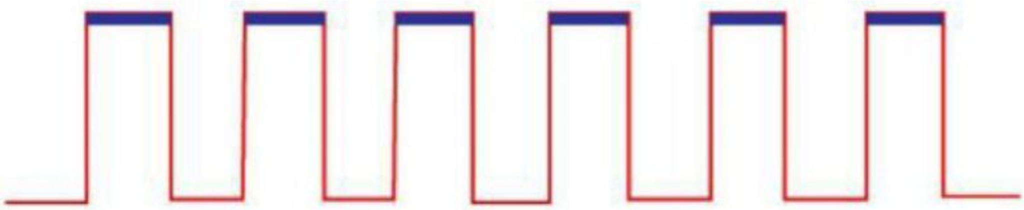


Figure 3.15: Positive Level Triggering

In a positive level triggering, the signal with Logic High occurs. So, in this triggering, the circuit is operated with such type of clock signal.

Negative level triggering

In negative level triggering, the signal with Logic Low occurs. So, in this triggering, the circuit is operated with such type of clock signal.

Figure 3.16: Negative Level Triggering

Edge triggering

In clock signal of edge triggering, two types of transitions occur, i.e., transition either from Logic Low to Logic High or Logic High to Logic Low. Based on the transitions of the clock signal, there are the following types of edge triggering.

Positive edge triggering

The transition from Logic Low to Logic High occurs in the clock signal of positive edge triggering. So, in positive edge triggering, the circuit is operated with such type of clock signal.

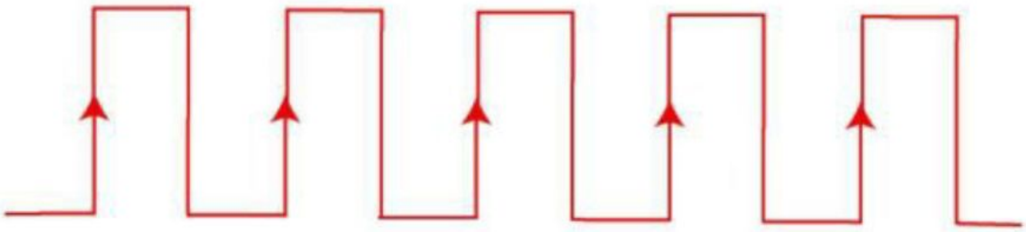


Figure 3.17: Positive Edge Triggering

Negative edge triggering

The transition from Logic High to Logic low occurs in the clock signal of negative edge triggering. So, in negative edge triggering, the circuit is operated with such type of clock signal.

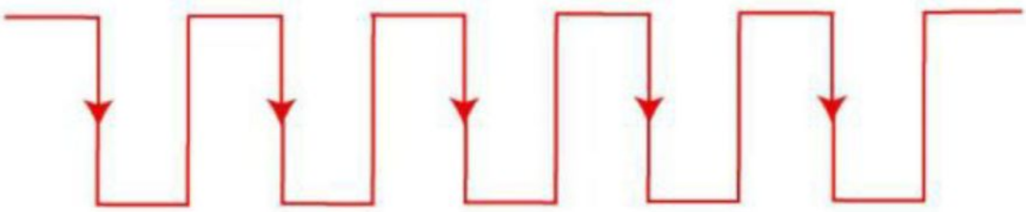


Figure 3.18: Negative Edge Triggering

LATCHES

There are two types of memory elements based on the type of triggering that is suitable to operate it.

- Latches
- Flip-flops

Latches operate with enable signal, which is level sensitive. Whereas, flip-flops are edge sensitive. A **Latch** is a special type of logical circuit. The latches have **low** and **high** two stable statesWhen the enable input is high, then both the inputs are low, and when the enable input is low, both the inputs are high.

Types of Latches

- **SR Latch**
- **D latch**
- **JK Latch**
- **T Latch.**

S-R Latch

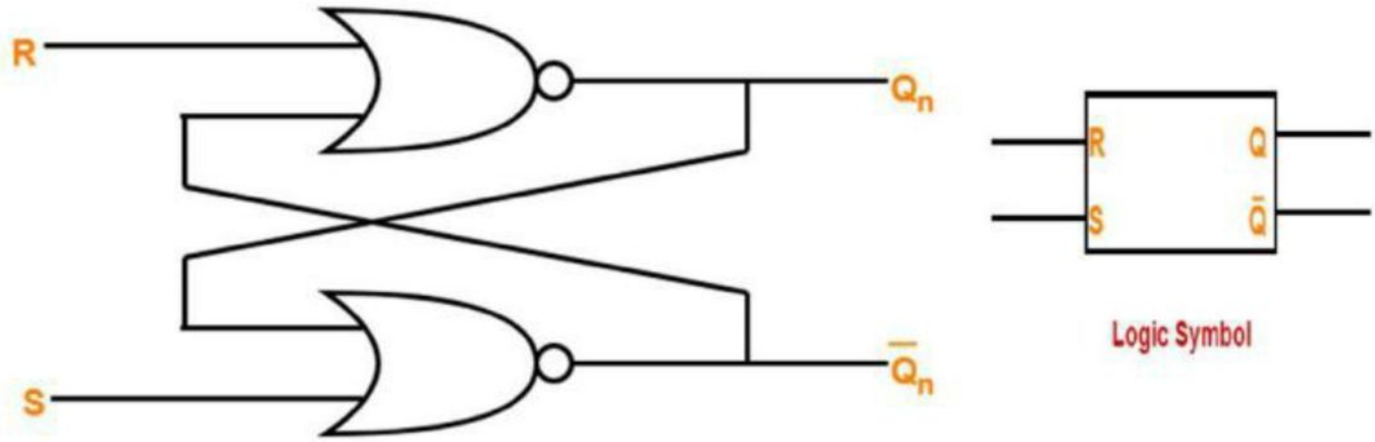


Figure 3.19: S-R Latch using NOR gate

While neither constructing a latch using NOR gates, it is compulsory to consider-

- Reset input R in normal output Q_n.
- Set input S in complemented output Q'_n.

INPUTS			OUTPUTS	REMARKS
R	S	Q_n (Present State)	Q_{n+1} (Next State)	States and Conditions
0	0	X	Q_n	Hold state condition R = S = 0
0	1	X	1	Set state condition R = 0 , S = 1
1	0	X	0	Reset state condition R = 1 , S = 0
1	1	X	Indeterminate	Indeterminate state condition R = S = 1

The circuit has two inputs, S and R, and two outputs, labeled Q_n. and Q'_n, where Q'_n is normally the complement of Q_n.

S=1, R=0—Q_n=1, Q'_n=0 This state is also called the SET state.

S=0, R=1— Q_n **=0,** Q'_n**=1** This state is known as the RESET state.

In both the states, the outputs are compliments of each other and that the value of Q follows the value of S.

S=0, R=0— Q_n **&** Q'_n **= Remember**

If both the values of S and R are switched to 0, then the circuit remembers the value of S and R in their previous state.

S=1, R=1— Q_n **=0,** Q'_n **=0 [Invalid]**

This is an invalid state because the values of both Q and Q' are 0. They are supposed to be compliments of each other. Normally, this state must be avoided.

S-R Latch using NAND Gate

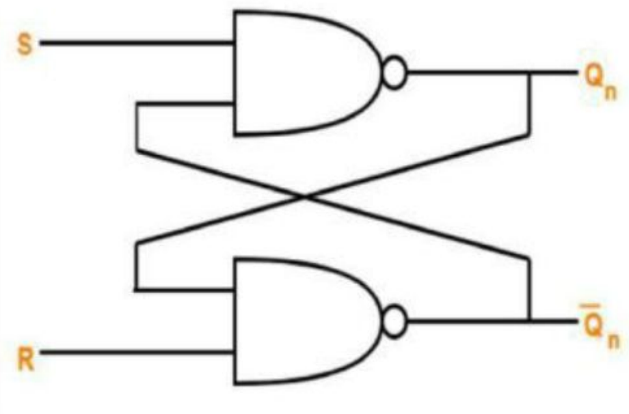
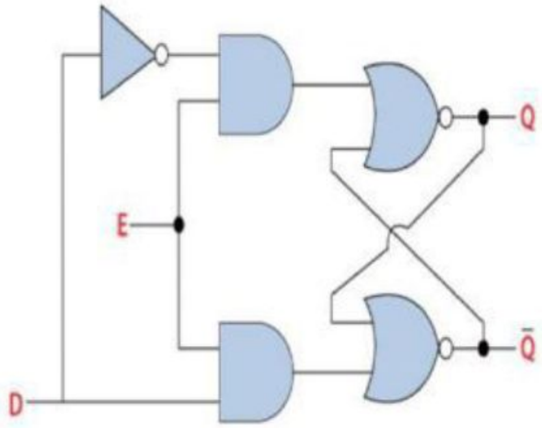


Figure 3.20: S-R Latch using NAND gate

D Latch

The **D latch** is the same as D flip flop. The only difference between these two is **the ENABLE** input. The output of the latch is the same as the input passed to the **Data** input when the **ENABLE** input set to 1. At that time, the latch is open, and the path is transparent from input to output. If the **ENABLE** input is set to 0, the D latch's output is the last value of the latch, i.e., independent from the input D, and the latch is closed. Below are the circuit diagram and the truth table of the D latch.



E	D	Q	Q'
0	0	latch	latch
0	1	latch	latch
1	0	0	1
1	1	1	0

Figure 3.21: D Latch Logic circuit & Truth Table

Basics of Flip Flop

- A Flip Flop is a memory element that is capable of storing one bit of information.
- It is also called as **Bistable Multivibrator** since it has two stable states either 0 or 1.

Flip flops are of different types depending on how their inputs and clock pulses cause transition between two states.

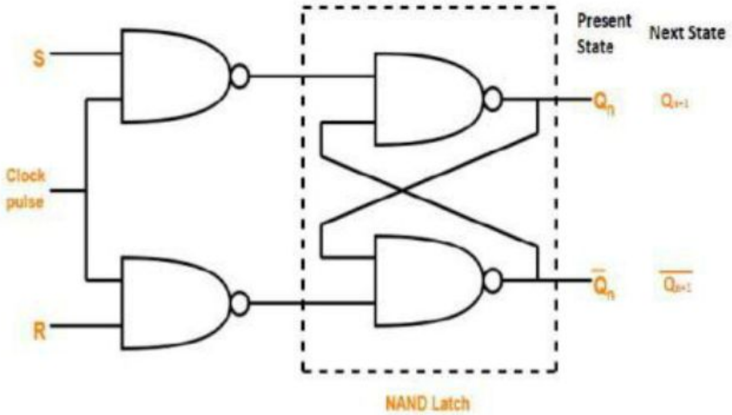
There are 4 basic types of flip flops-

1. SR Flip Flop
2. JK Flip Flop
3. D Flip Flop
4. T Flip Flop

S-R Flip Flop

- SR flip flop is the simplest type of flip flops.
- It stands for **Set Reset flip flop.**
- It is a clocked flip flop.

The name SR represents the SET and RESET function of the flip flop. This type of flip flop has two inputs named S & R for SET & RESET respectfully & and two outputs name Q_n & Q'_n, whereas Q'_n is the invert of Q_n. The SET function represents when output Q_n is high & Q'_n is low. RESET function represents clear function when output Q_n low & Q'_n High. At each trigger pulse, the output of SR flip flop sets when the input S is high and input R is low. And clears the output when the input R is HIGH & S is low. When both inputs R & S are LOW, the output status Q_n & Q'_n Remains unchanged. Both HIGH input combination is considered forbidden (invalid) as they will produce race condition (undetermined state) which causes ambiguity in the system.



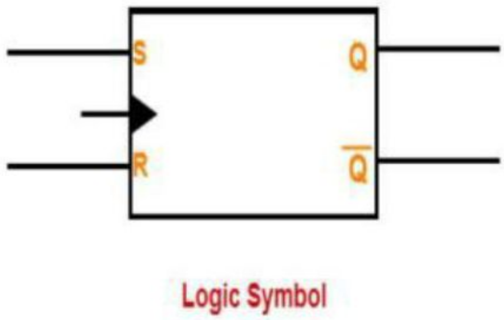
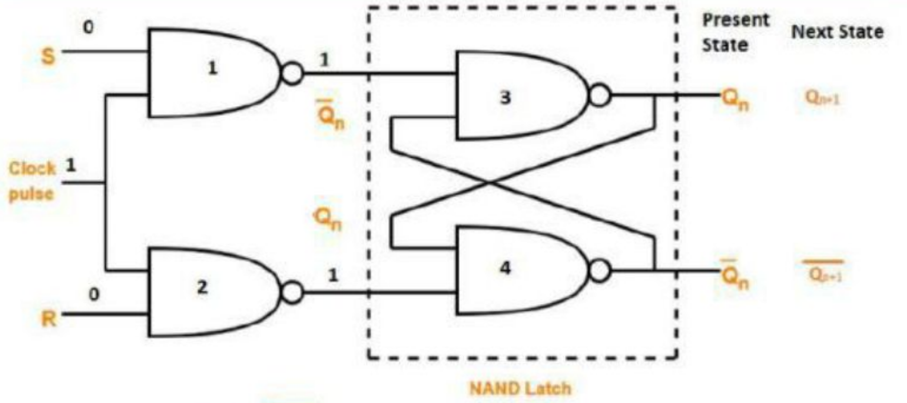


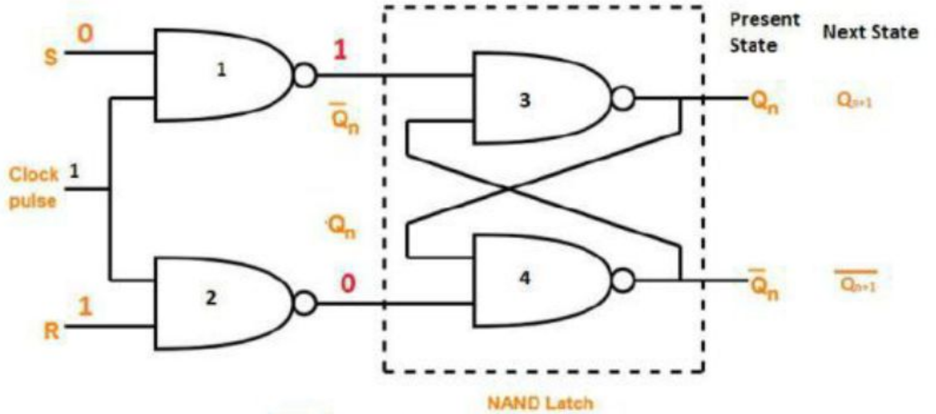
Figure 3.22: S-R Flip Flop Logic diagram



$$Q_{n+1} = \overline{1.\overline{Q_n}} = Q_n$$

$$\overline{Q_{n+1}} = \overline{1.Q_n} = \overline{Q_n}$$

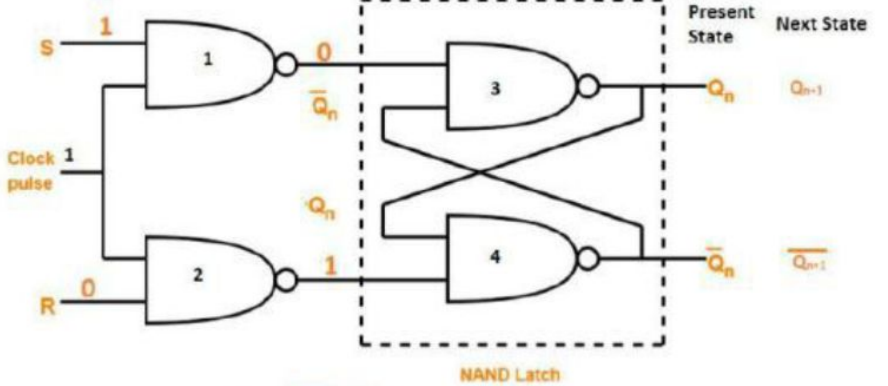
Figure 3.23: S=0, R=0



$$Q_{n+1} = \overline{1.\overline{Q_n}} = Q_n = 0$$

$$\overline{Q_{n+1}} = \overline{0.Q_n} = \overline{0} = 1$$

Figure 3.24: S=0, R=1



$$Q_{n+1} = \overline{0.\overline{Q_n}} = \overline{0} = 1$$

$$\overline{Q_{n+1}} = \overline{1.Q_n} = \overline{Q_n} = 0$$

Figure 3.25: S=1, R=0

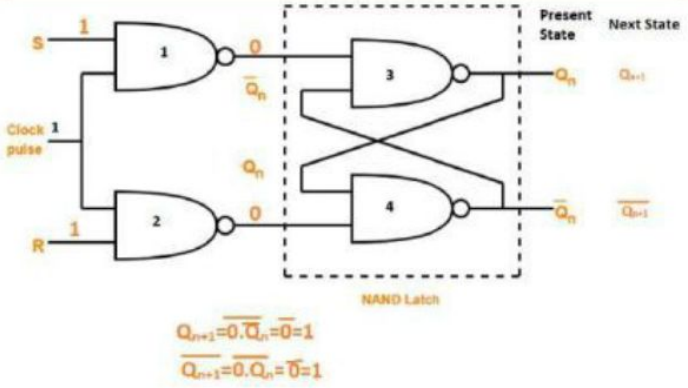


Figure 3.26: S=1, R=1

The circuit has two inputs, S and R, and two outputs, labeled Q_n. and Q'_n, where Q'_n is normally the complement of Q_n.

S=1, R=0—Q_n=1, Q'_n=0 This state is also called the SET state.

S=0, R=1— Q_n **=0, Q'_n=1** This state is known as the RESET state.

In both the states, the outputs are compliments of each other and that the value of Q follows the value of S.

S=0, R=0— Q_n **&** Q'_n **= Remember**

If both the values of S and R are switched to 0, then the circuit remembers the value of S and R in their previous state.

S=1, R=1— Q_n **=1, Q'_n =1 [Invalid]**

This is an invalid state because the values of both Q and Q' are 0. They are supposed to be compliments of each other. Normally, this state must be avoided.

INPUTS			OUTPUTS		ACTIONS
CLK	S	R	Qn+1	$\overline{Q}$n+1	
1	0	0	Qn	$\overline{Q}$n	No Change
1	0	1	0	1	Reset
1	1	0	1	0	Set
1	1	1	X	X	Indeterminate

J-K Flip Flop

JK flip flop can also be considered a better and modified version of SR flip-flop with J input corresponding to SET and K input corresponding to RESET of the JK flip flop. The invalid inputs of the SR flip-flops are used in this type of flip flop for a meaning full function. When both inputs are high the output status is toggled during each clock cycle. When the inputs are same, the JK flip-flop retains its original status even after clock pulses.

In JK flip flop,

- Input J behaves like input S of SR flip flop which was meant to set the flip flop.
- Input K behaves like input R of SR flip flop which was meant to reset the flip flop.