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Circuit Theory & Electronic Devices & Circuits

Electronics Paper-1
I B.Sc. I - Semester

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UNIT-I: SINUSOIDAL ALTERNATING WAVEFORMS

Definition of current and voltage, the sine wave - general format of sine wave for voltage or current, phase relations, average value, effective (R.M.S) values, Differences between A.C and D.C, Phase relation of R, L and C

1.1 INTRODUCTION

1.1.1 Atoms and Their Structure

A basic understanding of the fundamental concepts of current and voltage requires a degree of familiarity with the atom and its structure. The simplest of all atoms is the hydrogen atom, made up of two basic particles, the proton and the electron, in the relative positions shown in Fig. 1.1(a). The nucleus of the hydrogen atom is the proton, a positively charged particle. The orbiting electron carries a negative charge equal in magnitude to the positive charge of the proton.

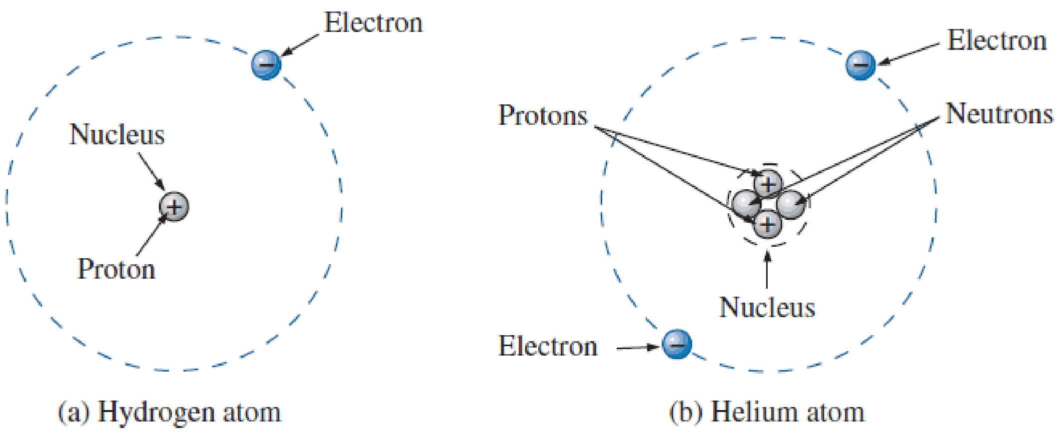


Fig. 1.1: Hydrogen and helium atoms.

In all other elements, the nucleus also contains neutrons, which are slightly heavier than protons and have no electrical charge. The helium atom, for example, has two neutrons in addition to two electrons and two protons, as shown in Fig. 1.1(b). In general, the atomic structure of any stable atom has an equal number of electrons and protons.

Different atoms have various numbers of electrons in concentric orbits called shells around the nucleus. The first shell, which is closest to the nucleus, can contain only two electrons. If an atom has three electrons, the extra electron must be placed in the next shell. The number of electrons in each succeeding shell is determined by $2n^2$, where n is the shell number. Each shell is then broken down into subshells where the number of electrons is limited to 2, 6, 10, and 14 in that order as you move away from the nucleus.

Copper is the most commonly used metal in the electrical/electronics industry. An examination of its atomic structure will reveal why it has such widespread application. As shown in Fig. 1.2, it has 29 electrons in orbits around the nucleus, with the 29th electron appearing all by itself in the 4th shell.

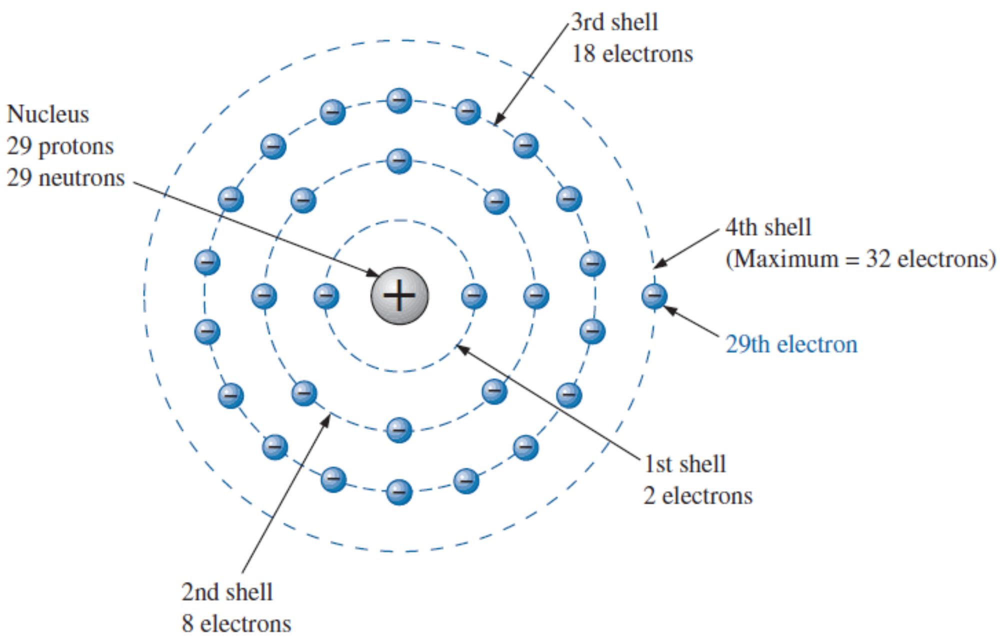


Fig. 1.2: The atomic structure of copper.

Note that the number of electrons in each shell and subshell is as defined above. There are two important things to note in Fig. 1.2. First, the 4th shell, which can have a total of $2n^2 = 2(4)^2 =$ 32 electrons, has only one electron. The outermost shell is incomplete and, in fact, is far from complete because it has only one electron. Atoms with complete shells (that is, a number of electrons equal to $2n^2$) are usually quite stable. Those atoms with a small percentage of the defined number for the outermost shell are normally considered somewhat unstable and volatile. Second, the 29th electron is the farthest electron from the nucleus. Opposite charges are attracted to each other, but the farther apart they are, the less the attraction. In fact, the force of attraction between the nucleus and the 29th electron of copper can be determined by Coulomb's law developed by ***Charles Augustin Coulomb*** in the late 18th century:

$$\boxed{F = k\frac{Q_1Q_2}{r^2}} \qquad \text{(newtons, N)}$$

where F is in newtons (N), k = a constant = 9.0×10^9 N. m^2/C^2, Q1 and Q2 are the charges in coulombs (a unit of measure discussed in the next section), and r is the distance between the two charges in meters.

1.1(b) ELECTRIC CHARGE

Electric charge is that property of matter` which causes the matter to experience a certain force when placed in an electric field. Static charges produce Electric Field and when these charges start to move and become dynamic, they produce a magnetic field as well, moving charge is responsible for the production of electricity as well, to be precise and it is the movement of electrons that produces electricity.

Unit of Charge

The SI unit of Electric Charge is Coulomb, and it is represented as 'C'. The value present on a single charge (whether positive or negative) is 1.6×10^{-19}C.

Formula

If the charge flowing inside a circuit producing electric current is needed to be calculated, the formula used for the same will be,

$$q = I \times T$$

Where, I = current flowing inside the circuit. T = Time for which the current is flowing.

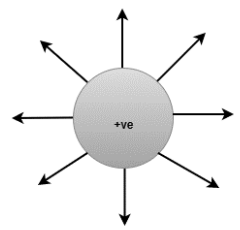
Defining 1 Coulomb charge

1 Coulomb of charge can be defined as the amount of charge transferred in one second.

Types of Electric Charge

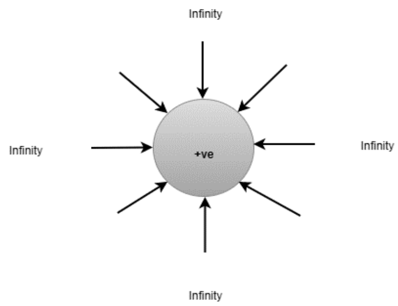
There are only two types of electric charges present, positive charge, and negative charge. They both have the same amount of charge present on them, but with opposite signs.

Positive Charge



Positive charges are also known as Protons and the electric field lines come out of the positive charge. The charge present on a proton is $+1.6 \times10^{-19}$C. If an object is positively charged, it can be concluded that the object has more protons than electrons.

Negative Charge



Negative charges are also known as electrons. The electric field lines come from infinity inside a negative charge. The amount of charge present on an electron is -1.6×10^{-19}C.

If an object is known to be negatively charged, that means that the object has more electrons than protons.

Properties of Electric Charge

1. **Additive of Electric Charges:** In an Isolated system, the total charge present inside the system is the algebraic sum of all the charges present (keep in mind that the sign of the charge is to be taken into account while adding).

   $$Q = q1+ q2+ q3+\ldots\ldots qn$$

2. **Conservation of Charges:** It is said that the charges are always conserved. This means that the charges can neither be created nor destroyed. The charges can be transferred from one body to another, and they can flow in a closed circuit.
3. **Quantization of Charge:** Electric charges cannot be defined in decimals. They are always present as the integral multiple of them. Therefore, in any system, charges are defined as,

   $$q = ne$$

   Where, n = Integer numbers, e = value of the charge (1.6× 10-19 C)

One of the important properties of electric charge states that like charges (Positive and positive charge, or negative and negative charge) repel each other while unlike charge (a positive and a negative charge) attract each other.

1.2 VOLTAGE AND CURRENT

(a) Electric Current

The directed flow of charge (free electrons) is called electric current. In other words, the electric current is defined as the rate of flow of charge (free electrons). It is represented by I or i and measured in Amperes (A). i.e.

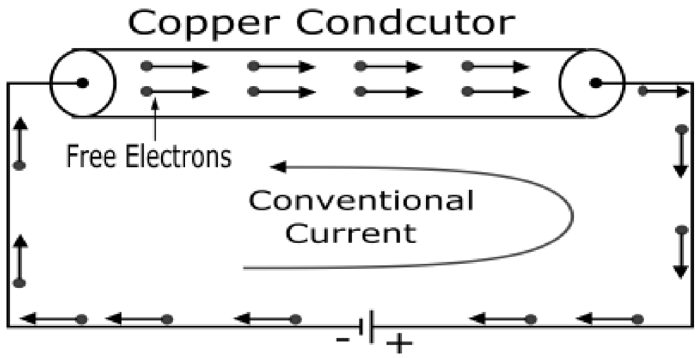
$$I = \frac{Q}{t} = \frac{ne}{t} \ \ Ampere(A)$$

Where, Q = ne, and e = 1.6 X 10^{-19} C.

In differential form,

$$i = \frac{dq}{dt}$$

How electric current flows?



In the figure, the copper conductor has a large number of free electrons. When a potential difference (voltage) is applied across it, the free electrons (negatively charged) starts moving towards the positive terminal of the source. This directed flow free electrons are called as electric current.

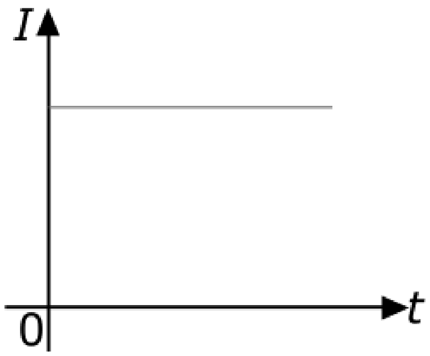
The direction of actual current (or electron current) is from negative terminal to the positive terminal through the external circuit. But prior to the electron theory of matter, it was believed that the electric current was the flow of positive charge from positive terminal to the negative terminal via the external circuit. Therefore, this assumed direction of electric current is known as Conventional Current.

<u>Types of Electric Current</u>

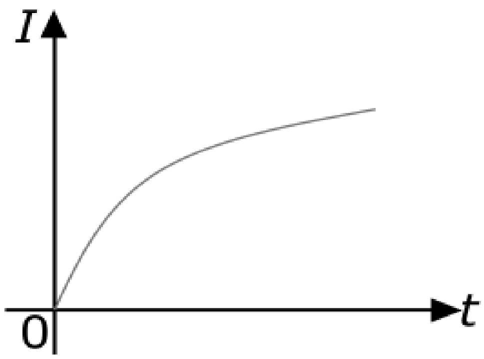
The electric current can be classified in three types –

1) Steady Current
2) Varying Current
3) Alternating Current

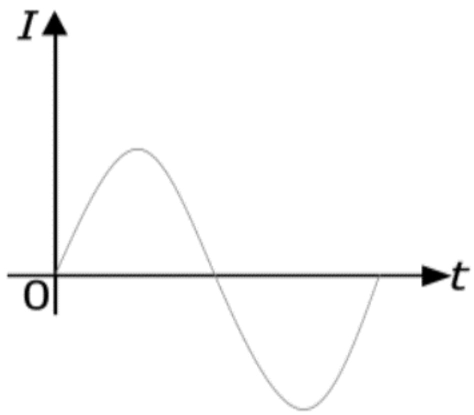
<u>Steady Current:</u> An electric current whose magnitude does not change with time, it is called a steady current (Direct Current). The current provided by a cell or a battery is an example of steady current.



Varying Current: An electric current whose magnitude changes continuously with time, it is known as a Varying Current. The exponentially changing current (as in inductor) is an example of varying current.



Alternating Current: An electric current whose magnitude changes continuously with time and direction changes periodically, it is called as an Alternating Current. As this current flows in alternate directions in the circuit i.e. during half of time period in one direction and during the other half of time period in the opposite direction, for this reason it is called as alternating current.



(b) Electric Potential

When a body is charged, work is done in charging it. This work done is stored in the body in the form of potential energy. Now, this charged body is able to move other charges by attraction or repulsion. Hence, it has ability to do work which is termed as electric potential of the body. i.e., the ability of a charged body to do work is known as electric potential of the body. The measure of electric potential is given as the ratio of work done (W) to the charge (Q) i.e.

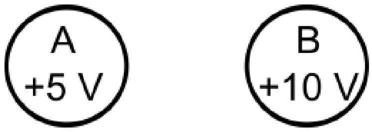
$$Electric\,Potential(V) = \frac{Work\,Done(W)}{Charge(Q}$$

Potential Difference or Voltage:

The difference in the potentials of the two charged bodies is known as potential difference.

The potential difference is also called Voltage. Hence, there is no such thing as a voltage at one point i.e. some reference must be used as the other point.

If two bodies have different electric potentials, a potential difference exists between them. Consider two bodies as shown in the above figure, the body A has potential of 5 V that means each coulomb of charge of body A has an energy of 5 joules while the body B has a potential of 10 V that means each coulomb of charge on the body B has an energy of 10 joules.



1.3 SINUSOIDAL WAVEFORM

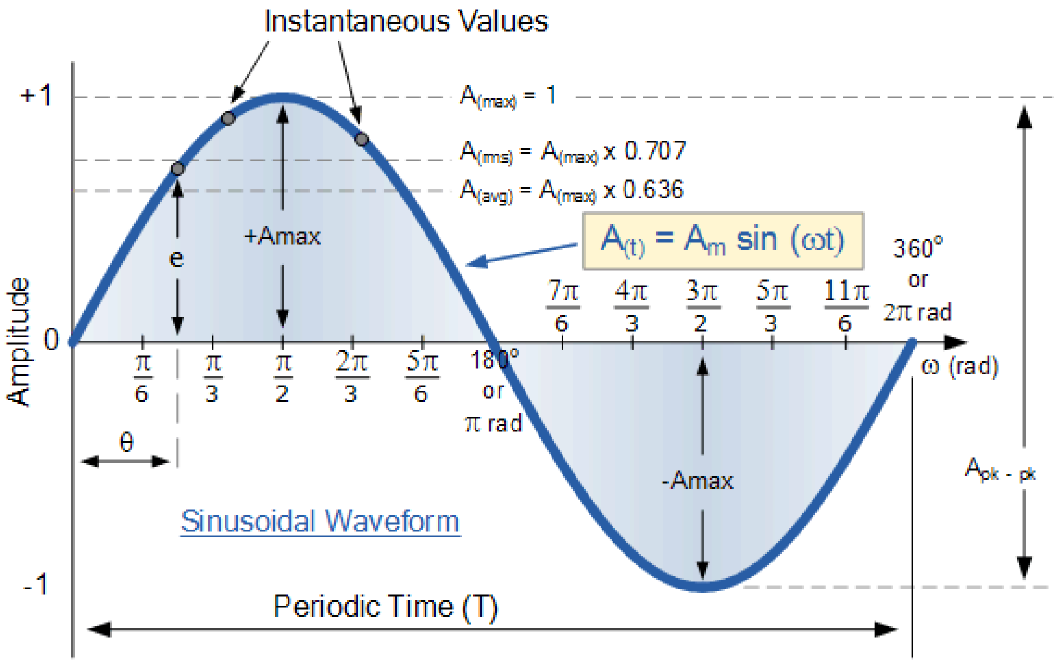


Fig. 1.3: Sinusoidal waveform.

(i) Time Period (T):

Time period is the time taken by one complete cycle and it is measured in seconds.

$$\mathbf{T = \frac{2\pi}{\omega}}$$

(ii) Frequency(f):

The frequency is the number of cycles in one second, frequency is reciprocal to time period. The units are Hertz (Hz).

$$\mathbf{f = \frac{1}{T} \text{ or } f = \frac{\omega}{2\pi}}$$

(iii) Amplitude:

The amplitude is the magnitude or peak value of the waveform. It is measured in volts.

(iv) Angular velocity (ω):

It is represented with 'ω', it defines how fast the orientation of an object changes with time.

$$\boldsymbol{\omega = 2\pi f}$$

(v) Standard equation of AC current:

The standard form of AC voltage is given by

$$\mathbf{E = E_0 \, Sin\,(\omega t)}$$

The standard form of AC current is given by

$$\mathbf{I = I_0 \, Sin\,(\omega t)}$$

Where E_0 and I_0 are amplitudes or peak values of AC; ω is the angular frequency, ωt is the phase angle.

(vi) Instantaneous value:

The value of alternating quantity at a particular time is called instantaneous value.

1.4 AVERAGE OR MEAN VALUE OF AC

The average value of AC is the average over one complete cycle. The average of a periodic wave whose half cycles are extremely similar, will be zero over one complete cycle. The average value is obtained by integrating the instantaneous value of AC over one half cycle only.

$$I_{avg} = \int_0^{\pi} \frac{I_0 \, Sin\,\omega t \, d\omega t}{\pi}$$

$$I_{avg} = \frac{I_0}{\pi} \int_0^{\pi} \sin \omega t \, d\omega t$$

$$I_{avg} = \frac{I_0}{\pi} \, [-\cos \omega t]_0^{\pi}$$

$$I_{avg} = \frac{I_0}{\pi} \, [1 + 1]$$

$$I_{avg} = \frac{I_0}{\pi} \, [2]$$

$$I_{avg} = \frac{2}{\pi} \text{ x Peak value of AC}$$

$$I_{avg} = \frac{2I_0}{\pi}$$

1.5 ROOT MEAN SQUARE (RMS) VALUE OF AC

The square root of mean square value over one complete cycle is called root mean square value of a sinusoidal signal and it is given by

$$I_{RMS} = \sqrt{\int_0^{2\pi} \frac{I^2\, d\omega t}{2\pi}}$$

The standard equation of AC is I = I_0 Sinωt

$$= \sqrt{\int_0^{2\pi} \frac{I_0^2\ \ Sin^2\omega t\, d\omega t}{2\pi}}$$

$$= \sqrt{\frac{I_0^2}{2\pi}\int_0^{2\pi} Sin^2\omega t\, d\omega t}$$

$$= \sqrt{\frac{I_0^2}{2\pi}\int_0^{2\pi} \frac{(1-\cos 2\omega t)\, d\omega t}{2}}$$

$$= \sqrt{\frac{I_0^2}{4\pi}\int_0^{2\pi}(1-\cos 2\omega t)\ \ d\omega t}$$

$$= \sqrt{\frac{I_0^2}{4\pi}\ \int_0^{2\pi}(1) d\omega t\ - \int_0^{2\pi}(\cos 2\omega t)\, d\omega t}$$

$$= \sqrt{\frac{I_0^2}{4\pi}\ [\omega t]_0^{2\pi} - \ [\frac{sin\omega t}{2}]_0^{2\pi}}$$

$$= \sqrt{\frac{I_0^2}{4\pi}\ \ 2\pi}$$

$$= \sqrt{\frac{I_0^2}{2}}$$

$$I_{RMS} = \frac{I_0}{\sqrt{2}}$$

$I_{RMS} = \frac{1}{\sqrt{2}}$ x peak value of AC

1.6 FORM FACTOR AND PEAK FACTOR OF ALTERNATING CURRENT

Form factor: The form factor of AC signal is defined as the ratio between RMS value and average value of AC signal.

$$\text{Form factor} = \frac{I_{RMS}}{I_{avg}} = \frac{I_0}{\sqrt{2}} / \frac{2I_0}{\pi} = \frac{\pi}{2\sqrt{2}} = 1.11$$

Peak factor: It is the ratio of maximum value to RMS value of an AC signal.

$$\text{Peak factor} = \frac{I_0}{I_{RMS}} = \frac{I_0}{\frac{I_0}{\sqrt{2}}} = \sqrt{2} = 1.414$$

UNIT-II: PASSIVE NETWORKS & NETWORK THEOREMS
Branch current method, nodal analysis, superposition theorem, Thevenin’s theorem, Norton’s theorem, maximum power transfer theorem, Milliman and reciprocity theorem.

2.1 BRANCH CURRENT METHOD

In the branch current method, Kirchhoff’s voltage and current laws are used to find the current in each brunch of a circuit, Once the brunch currents are known, voltages can be determined.

The following are the general steps used in applying the branch current method. These steps are demonstrated with the aid of Figure 2-1.

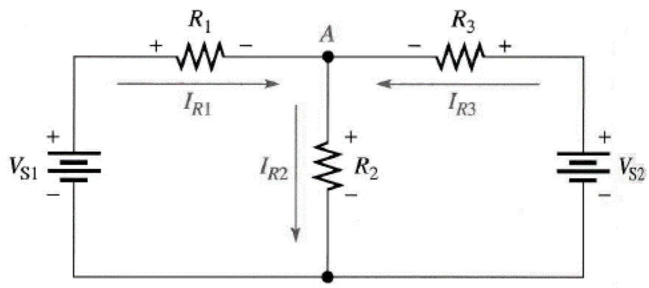


Figure 2-1: Circuit for demonstrating branch current analysis

Step 1. Assign a current in each circuit branch in an arbitrary direction.

Step 2. Show the polarities of the resistor voltages according to the assigned branch current directions.

Step 3. Apply Kirchhoff's voltage law around each closed loop (algebraic sum of voltages is equal to zero).

Step 4. Apply Kirchhoff's current law at the minimum number of nodes so that all branch currents are included (algebraic sum of currents at a node equals zero).

Step 5. Solve the equations resulting from Steps 3 and 4 for the branch current values.

First, the branch currents I_{R1}, I_{R2}, and I_{R3} are assigned in the direction shown in Figure 2-1. Don't worry about the actual current directions at this point.

Second, the polarities of the voltage drop across R_1, R_2, and R_3 are indicated in the figure according to the assigned current directions.

Third, Kirchhoff's voltage law applied to the two loops gives the following equations where the resistance values are the coefficients for the unknown currents:

Equation 1: $R_1I_{R1} + R_2I_{R2}$ - VS1 = 0 for loop 1

Equation 2: $R_2I_{R2} + R_3I_{R3} – V_{S2}$ = 0 for loop 2

Fourth, Kirchhoff's current law is applied to node A, including all branch currents as follows:

Equation 3: $I_{R1} – I_{R2} + I_{R3} = 0$

Fifth and last, the three equations must be solved for the three unknown currents, I_{R1}, I_{R2} and I_{R3}. The three equations in the above steps are called simultaneous equations and can be solved in two ways: by substitution or by determinants.

2.2 NODE VOLTAGE METHOD (Nodal Analysis)

Another method of analysis of multiple loop circuits is culled the node voltage method. It is based on finding the voltages at each node in the circuit using Kirchhoff's current law, A node is the junction of two or more components.

The general steps for the node voltage method of circuit analysis are as follows:

Step 1. Determine the number of nodes.

Step 2. Select one node as a reference. All voltages will be relative to the reference node. Assign voltage designations to each node where the voltage is unknown.

Step 3. Assign currents at each node where the voltage is unknown, except at the reference node. The directions are arbitrary.

Step 4. Apply Kirchhoff's current law to each node where currents are assigned.

Step 5. Express the current equations in terms of voltages, and solve the equations for the unknown node voltages using Ohm's law.

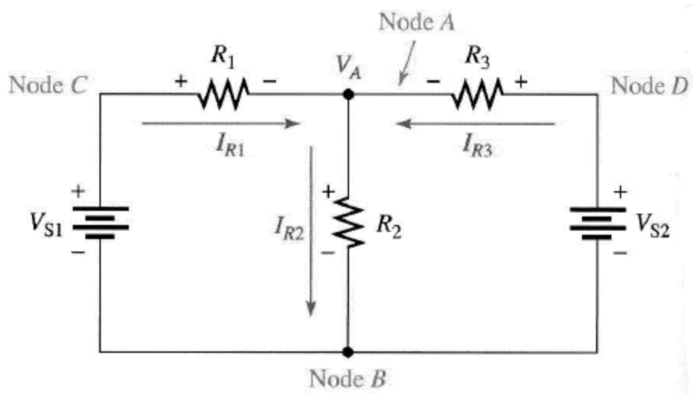


Figure 2-2: Circuit for node voltage analysis

We will use Figure 2-2 to illustrate the general approach to node voltage analysis. First, establish the nodes. In this case, there are four nodes, as indicated in the figure. Second, let's use node B as the reference. Think of it as the circuit's reference ground. Node voltages C and D are already known to be the source voltages. The voltage at node A is the only unknown; it is designated as Va. Third, arbitrarily assign the branch currents at node A as indicated in the figure. Fourth. the Kirchhoff current equation at node A is

$$I_{R1} - I_{R2} + I_{R3} = 0$$

Fifth, express the currents in terms of circuit voltages using Ohm's law.

$$I_{R1} = \frac{V_1}{R_1} = \frac{V_{S1} - V_A}{R_1}$$

$$I_{R2} = \frac{V_2}{R_2} = \frac{V_A}{R_2}$$

$$I_{R3} = \frac{V_3}{R_3} = \frac{V_{S2} - V_A}{R_3}$$

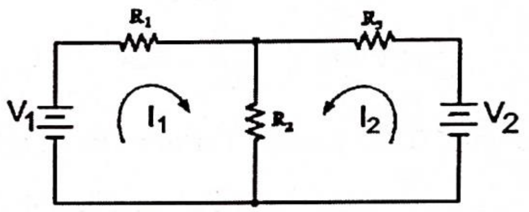
Substituting these terms into the current equation yields

$$\frac{V_{S1} - V_A}{R_1} - \frac{V_A}{R_2} + \frac{V_{S2} - V_A}{R_3} = 0$$

The only unknown is V_A so solve the single equation by combining and rearranging terms. Once the voltage is known, all branch currents can be calculated.

2.3 SUPER POSITION THEOREM

Statement: In a network containing linear impedances and energy sources, the current flowing through any element is the algebraic sum of currents which would exist if each energy source considered separately, all other sources are replaced



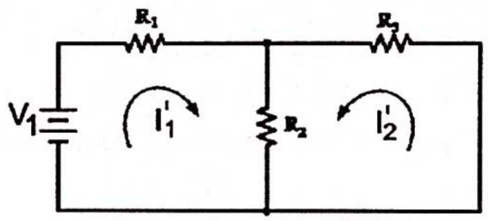
Proof: To verify the theorem, let us consider the simple network with 2 generators V_1 and V_2 as shown in fig.

The currents flowing in 1st and 2nd loops are I_1 and I_2 respectively.

Applying KVL, we have

$$I_1(R_1+R_2)+I_2R_2 = V_1 \quad ----- 1$$

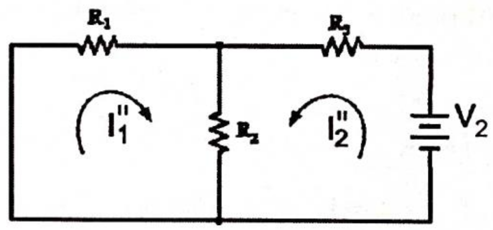
$$I_1R_2+I_2(R_2+R_3) = V_2 \quad ----- 2$$



Now, emf source V_1 considered and V_2 is removed and replaced by internal impedance.

$$I_1'(R_1+R_2)+I_2'R_2 = V_1 \quad ----- 3$$

$$I_1'R_2+I_2'(R_2+R_3) = 0 \quad ----- 4$$



Now, emf source V_2 considered and V_1 is removed and replaced by internal impedance.

$$I_1''(R_1+R_2)+I_2''R_2 = 0 \quad \text{----- 5}$$

$$I_1''R_2+I_2''(R_2+R_3) = V_2 \quad \text{----- 6}$$

Adding 3 and 5, we get

$$(I_1'+I_1'')(R_1+R_2)+(I_2'+I_2'')R_2 = V_1 \quad \text{---- 7}$$

Adding 4 and 6, we get

$$(I_2'+I_2'')(R_2+R_3)+(I_1'+I_1'')R_2 = V_2 \quad \text{---- 8}$$

Equations 7 and 8 are identical to 1 and 2 respectively,

$$I_1 = I_1'+I_1''$$

$$I_2 = I_2'+I_2''$$

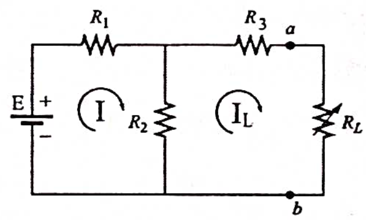
Hence, the theorem is proved.

2.4 THEVENIN'S THEOREM

Statement: Any two-terminal, linear network containing linear impedances and energy sources can be replaced by an equivalent circuit consisting of a voltage source E_{th} and series impedance (resistor) R_{th}.

The voltage E_{th} is equal to the potential difference between two terminals in open circuit position.

The series impedance is equal to the impedance between two terminals when all emf sources replaced by their internal impedances.



Proof: Here E is the emf source, I is the current supplied by the source E and I_L is the current through the load resistance R_L.

Applying KVL to the circuit, we have

$$I(R_1+R_2) - I_L R_2 = E \quad \text{----- 1}$$

$$-IR_2 + I_L(R_2+R_3+R_L) = 0 \quad \text{----- 2}$$

From 2

$$I = \frac{I_L(R_2+R_3+R_L)}{R_2}$$

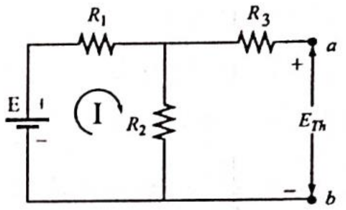
Substitute I in eqn 1

$$\frac{I_L(R_2+R_3+R_L)(R_1+R_2)}{R_2} - I_L R_2 = E$$

$$\frac{I_L(R_1R_2+R_1R_3+R_1R_L+R_2^2+R_2R_3+R_2R_L-R_2^2)}{R_2} = E$$

$$I_L = \frac{ER_2}{R_3(R_1+R_2)+R_L(R_1+R_2)+R_1R_2}$$

$$I_L = \frac{\frac{ER_2}{R_1+R_2}}{R_3 + R_L + \frac{R_1R_2}{R_1+R_2}} \quad \text{-----------} \quad 3$$



To calculate the E_{th} value, take the open circuit voltage between a and b.

Applying KVL, we have

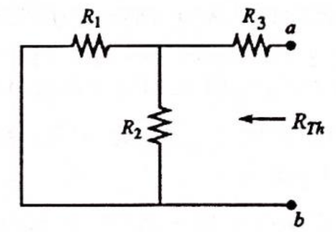
$$I(R_1 + R_2) = E$$

$$I = \frac{E}{R_1 + R_2}$$

The open circuit voltage E_{th} is voltage across R_2 and is given by

$$E_{th} = I\,R_2$$

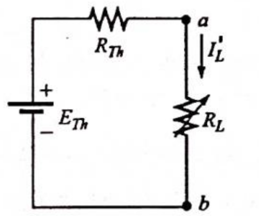
$$E_{th} = \frac{ER_2}{R_1+R_2} \quad \text{-----------} \quad 4$$



Now, to calculate R_{th} value, all energy sources replaced by their internal impedances.

$$R_{th} = (R_1 \parallel R_2) + R_3$$

$$R_{th} = \frac{R_1\,R_2}{R_1+R_2} + R_3 \quad \text{---------} \quad 5$$



Now, the thevenin's theorem equivalent circuit is shown in fig

Applying KVL, we get

$$I_L'(R_{th}+R_L) = E_{th}$$

$$I_L' = \frac{E_{th}}{R_{th}+R_L}$$

Substitute eqn 4 and 5 in above eqn.

$$I_L' = \frac{\frac{ER_2}{R_1+R_2}}{R_3 + R_L + \frac{R_1R_2}{R_1+R_2}} \quad \text{-----------} \quad 6$$

$$\therefore I_L = I_L'$$

The load currents in both circuits are equal. Hence, the theorem is proved.

2.5 NORTON'S THEOREM

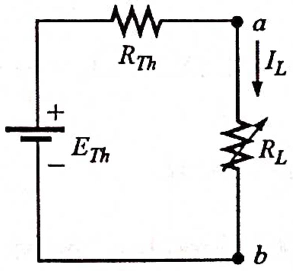
Statement: Any two-terminal, linear network containing linear impedances and energy sources can be replaced by an equivalent circuit consisting of a current source I_N or I_{SC} and a parallel impedance (resistor) R_N or R_{th}.

The current I_N is equal to the short circuit current between two terminals.

The parallel impedance is equal to the impedance between two terminals when all emf sources replaced by their internal impedances.

Proof:

To prove this theorem, the load currents in thevenin's and norton's equivalent circuits are equal. The Norton's equivalent circuit may be found by thevenin's equivalent circuit.

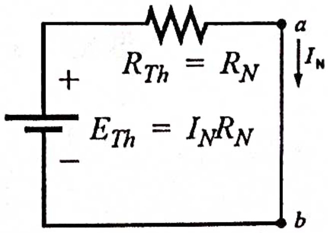


Now, current flowing through the load impedance R_L in the thevenin's equivalent cicuit.

Applying KVL, we get

$$I_L(R_{th}+R_L)=E_{th}$$

$$I_L=\frac{E_{th}}{R_{th}+R_L} \quad \text{------------ } 1$$



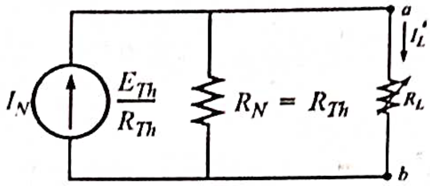
For I_N

$$E_{th}=I_N R_N$$

$$I_N=\frac{E_{th}}{R_N}=\frac{E_{th}}{R_{th}} \quad \text{--------- } 2$$

The current flowing through R_L in norton's equivalent circuit is given by

Applying KVL, we get



$$I_L'(R_{th}+R_L)-I_N R_{th}=0$$

$$I_L'(R_{th}+R_L)=I_N R_{th}$$

$$I_L'=\frac{I_N R_{th}}{R_{th}+R_L}$$

From 2

$$I_L'=\frac{\frac{E_{th}}{R_{th}}R_{th}}{R_{th}+R_L}=\frac{E_{th}}{R_{th}+R_L} \quad \text{----------- } 3$$

From eqn 1 and 3

$$I_L=I_L'$$

Hence, the theorem is proved.

2.6 MAXIMUM POWER TRANSFER THEOREM

Statement: A load will receive maximum power from a linear bilateral dc network when its load resistance is exactly equal to the total resistance of the network when all energy sources replaced by their internal impedances.

Or

This theorem states that two terminal network will absorb maximum power from the generator, if load impedance is complex conjugate of internal impedance of generator.

Proof:

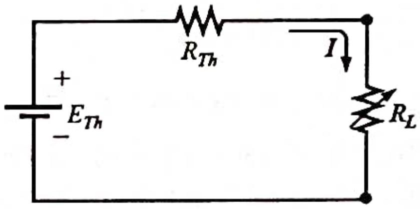


Figure shows load resistance R_L connected to a N/W consisting of generators and impedances.

For a given network load current I is given by,

$$I = \frac{E_{th}}{R_{th}+R_L}$$

Now, power delivered to load is

$$P = I^2 R_L$$

$$P = \frac{E_{th}^2 R_L}{(R_{th}+R_L)^2} \quad \text{------------} \quad 1$$

Now, let us consider variations of power P with R_L. For this, differentiate above equation with respect to load R_L and equate to 0.

$$\frac{dP}{dR_L} = \frac{d}{dR_L}\left(\frac{E_{th}^2 R_L}{(R_{th}+R_L)^2}\right) = 0$$

$$\frac{(R_{th}+R_L)^2 E_{th}^2 - E_{th}^2 R_L \; 2(R_{th}+R_L)}{(R_{th}+R_L)^4} = 0$$

$$\frac{E_{th}^2}{(R_{th}+R_L)^4}\left((R_{th}+R_L)^2 - 2(R_{th}+R_L)R_L\right) = 0$$

$$\frac{E_{th}^2}{(R_{th}+R_L)^4}\left(R_{th}^2 + R_L^2 + 2R_{th}R_L - 2R_{th}R_L - 2R_L^2\right) = 0$$

$$\frac{E_{th}^2}{(R_{th}+R_L)^4}\left(R_{th}^2 - R_L^2\right) = 0$$

$$\left(R_{th}^2 - R_L^2\right) = 0$$

$$R_{th}^2 = R_L^2$$

$$\therefore\ R_{th} = R_L$$

Hence, the theorem is proved.

For maximum power, $R_{th} = R_L$

$$P_{max} = \frac{E_{th}^2 R_L}{(R_{th}+R_L)^2}$$

$$P_{max} = \frac{E_{th}^2 R_L}{(R_L+R_L)^2} = \frac{E_{th}^2 R_L}{4R_L^2} = \frac{E_{th}^2}{4R_L}$$

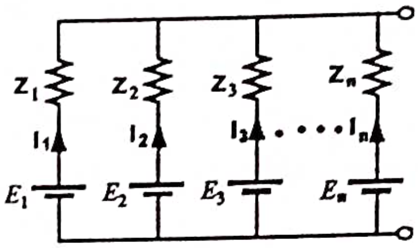
$$\text{Or } P_{max} = \frac{E_{th}^2}{4R_{th}}$$

2.7 MILLMAN'S THEOREM

Statement: If a number of voltage generators of emf E_1, E_2, E_3,….. E_n and their admittances Y_1, Y_2, Y_3,….. Y_n respectively, are connected in parallel with each other and then the resultant potential difference is as follows.

$$E = \frac{E_1Y_1 + E_2Y_2 + E_3Y_3 + \ldots\ldots + E_nY_n}{Y_1 + Y_2 + Y_3 + \ldots\ldots + Y_n}$$

$$E = \sum_1^n \frac{E_nY_n}{Y_n}$$



Proof:

If I_1, I_2, I_3, …. I_n are the currents flowing through generators E_1, E_2, E_3,….. E_n respectively, then potential difference across the terminals

$E = E_1 - I_1 Z_1 = E_2 - I_2 Z_2 = E_3 - I_3 Z_3 = \ldots\ldots = E_n - I_n Z_n$

$$E = E_1 - I_1 Z_1$$

$$\frac{E}{Z_1} = \frac{E_1}{Z_1} - I_1$$

$$EY_1 = E_1Y_1 - I_1 \qquad ----------1$$

$$E = E_2 - I_2 Z_2$$

$$\frac{E}{Z_2} = \frac{E_2}{Z_2} - I_2$$

$$EY_2 = E_2Y_2 - I_2 \qquad ----------2$$

Similarly $EY_3 = E_3Y_3 - I_3$ ----------3

/

/

Similarly $EY_n = E_nY_n - I_n$ ----------n

Adding above all equations

$$EY_1 + EY_2 + EY_3 + ... + EY_n = E_1Y_1 - I_1 + E_2Y_2 - I_2 + E_3Y_3 - I_3 + ... + E_nY_n - I_n$$

$$E(Y_1 + Y_2 + Y_3 + ... + Y_n) = E_1Y_1 + E_2Y_2 + E_3Y_3 + ... + E_nY_n - (I_1 + I_2 + I_3 + ... + I_n)$$

According to KCL $\sum I = 0$

$$E(Y_1 + Y_2 + Y_3 + ... + Y_n) = E_1Y_1 + E_2Y_2 + E_3Y_3 + ... + E_nY_n$$

$$E = \frac{E_1Y_1 + E_2Y_2 + E_3Y_3 + ... + E_nY_n}{Y_1 + Y_2 + Y_3 + ... + Y_n}$$

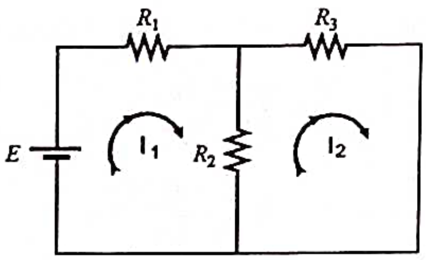
$$E = \sum_{n=1}^{n} \frac{E_nY_n}{Y_n}$$

Hence, the theorem is proved.

2.8 RECIPROCITY THEOREM

Statement: If an emf applied in 1st loop of network produces the current in the 2nd loop. When same emf acting in 2nd loop and will give identical current in the first loop.

Proof: To prove this theorem, let us consider the emf E is in 1st loop and currents in 1st and 2nd loops are I_1 and I_2 respectively.



Applying KVL, we have

$$I_1(R_1+R_2) - I_2R_2 = E \quad \text{—— 1}$$

$$-I_1R_2+I_2(R_2+R_3) = 0 \quad \text{—— 2}$$

From 2

$$I_1 = \frac{I_2(R_2 + R_3)}{R_2}$$

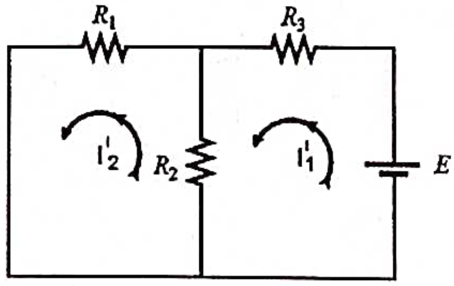
Substitute I_1 in eqn 1

$$\frac{I_2(R_2 + R_3)}{R_2}(R_1 + R_2) - I_2R_2 = E$$

$$I_2\left(\frac{(R_2+R_3)(R_1+R_2)}{R_2}-R_2\right)=E$$

$$\therefore I_2=\frac{ER_2}{(R_2+R_3)(R_1+R_2)-R_2^{\,2}} \quad ------ 3$$

Again consider the source is placed in 2nd loop and currents in 1st and 2nd loops are I_1' and I_2' respectively.



Applying KVL, we have

$$I_1'(R_2+R_3) - I_2'R_2 = E \quad ---- 4$$

$$I_2'(R_1+R_2) - I_1'R_2 = 0 \quad --- 5$$

From 5

$$I_1' = \frac{I_2'(R_1+R_2)}{R_2}$$

Substitute I_1' in eqn 4

$$\frac{I_2'(R_1+R_2)(R_2+R_3)}{R_2}-I_2'R_2=E$$

$$I_2'\left(\frac{(R_1+R_2)(R_2+R_3)-R_2^{\,2}}{R_2}\right)=E$$

$$\therefore I_2 = \frac{ER_2}{(R_2+R_3)(R_1+R_2)-R_2^{\,2}} \quad ------ 6$$

From eqn 3 and 6, we have

$$\therefore I_2 = I_2'$$

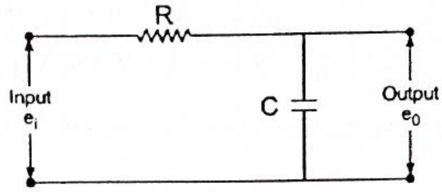
Hence, the theorem is proved.

UNIT-III: RC, RL AND RLC CIRCUITS

Frequency response of RC and RL circuits, their action as low pass and high pass filters. Passive differentiating and integrating circuits. Series resonance and parallel resonance circuits, Q–Factor.

3.1 FREQUENCY RESPONSE OF RC CIRCUITS

(1) RC Low pass circuit:



The RC circuit which acts as a low pass filter is shown fig. Here the sinusoidal voltage e_i is applied, whose frequency is varied and input voltage is constant.

When the frequency of input signal is zero, the capacitive reactance of capacitor $\left(\frac{1}{jwC}\right)$ becomes ∞ and capacitor acts as an open circuit. So, the total input voltage will appear across at the output.

If the input frequency is increasing, the capacitive reactance $\left(\frac{1}{jwC}\right)$ gradually decreases and output voltage also decreases.

At very high frequency, the capacitive reactance totally decreases and hence capacitor becomes as a short circuited. So most of the input voltage will be grounded, making the output voltage will be minimum.

The input voltage is $e_i = e_{in} \sin wt$

The output voltage is given by $e_0 = i \times \frac{1}{jwC}$

$$e_0 = \frac{e_i}{R + \frac{1}{jwC}} \times \frac{1}{jwC} \qquad \because \; i = \frac{e_i}{R + \frac{1}{jwC}}$$

$$e_0 = \frac{e_{in} \sin wt}{R + \frac{1}{jwC}} \times \frac{1}{jwC}$$

The voltage gain can be defined as the ratio of output voltage to input voltage.

$$\text{Gain}(A) = \frac{e_0}{e_i}$$

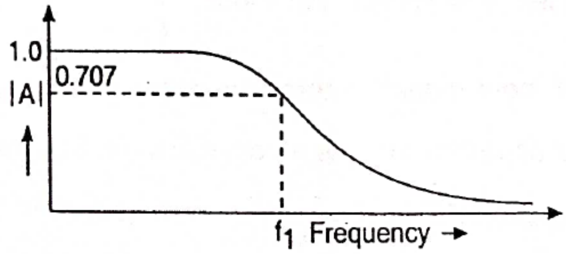
$$= \frac{\frac{e_{in} \sin wt}{R + \frac{1}{jwC}} \times \frac{1}{jwC}}{e_{in} \sin wt} = \frac{\frac{1}{jwC}}{R + \frac{1}{jwC}} = \frac{1}{jwRC + 1} = \frac{1}{1 + j2\pi f RC} = \frac{1}{1 + j\left(\frac{f}{f_1}\right)}$$

Where $f_1 = \frac{1}{2\pi RC}$

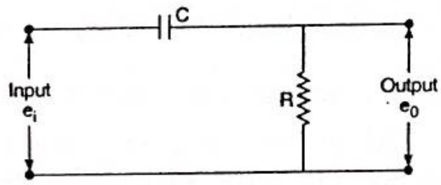
$$\text{Magnitude of gain } |A| = \frac{1}{\sqrt{1+\left(\frac{f}{f_1}\right)^2}}$$

$$\text{And angle } \theta = \tan^{-1}\left(\frac{f}{f_1}\right)$$

The frequency response of RC low pass filter.



(2) **RC high pass circuit**



The RC circuit which acts as a high pass filter shown fig. Here the sinusoidal voltage e_i is applied, whose frequency is varied and input voltage is constant.

When the frequency of input signal is zero, the capacitive reactance of capacitor $\left(\frac{1}{jwC}\right)$ becomes ∞ and capacitor acts as an open circuit. So, the output voltage is zero.

If the input frequency is increasing, the capacitive reactance $\left(\frac{1}{jwC}\right)$ gradually decreases and output voltage increases gradually.

At very high frequency, the capacitive reactance totally decreases and hence capacitor becomes as a short circuited. Hence the output voltage will follow the input voltage.

The input voltage is $e_i = e_{in} \sin wt$

The output voltage is given by $e_0 = i \times R$

$$e_0 = \frac{e_i}{R+\frac{1}{jwC}} \times R \qquad \because \; i = \frac{e_i}{R+\frac{1}{jwC}}$$

$$e_0 = \frac{e_{in}\sin wt}{R+\frac{1}{jwC}} \times R$$

The voltage gain can be defined as the ratio of output voltage to input voltage.

$$\text{Gain}(A) = \frac{e_0}{e_i}$$

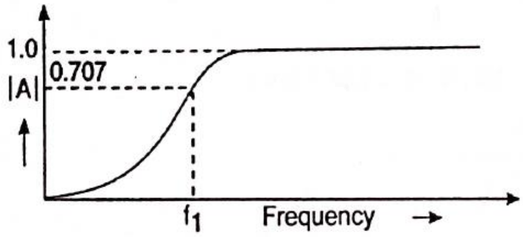
$$= \frac{\dfrac{e_{in}\sin wt}{R+\dfrac{1}{jwC}}\times R}{e_{in}\sin wt} = \frac{R}{R+\dfrac{1}{jwC}} = \frac{1}{1+\dfrac{1}{jwRC}} = \frac{1}{1+\dfrac{1}{j2\pi fRC}} = \frac{1}{1+\dfrac{1}{j}\left(\dfrac{f_1}{f}\right)}$$

Where $f_1 = \dfrac{1}{2\pi RC}$

Magnitude of gain $|A| = \dfrac{1}{\sqrt{1+\left(\dfrac{f_1}{f}\right)^2}}$

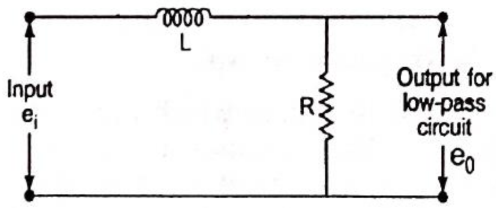
And angle $\theta = \tan^{-1}\left(\dfrac{f_1}{f}\right)$

The frequency response of RC high pass filter.



3.2 FREQUENCY RESPONSE OF RL CIRCUITS

(1) RL Low pass circuit



The RL circuit which acts as a low pass filter shown fig. Here the sinusoidal voltage e_i is applied, whose frequency is varied and input voltage is constant.

When the frequency of input signal is zero, the inductive reactance of inductor jwL becomes zero and inductor acts as a short circuit. So, the total input voltage will appears across at the output.

If the input frequency is increasing, the inductive reactance jwL gradually increases and output voltage decreases gradually.

At very high frequency, the inductive reactance increases to maximum and hence inductor acts as a open circuited and output voltage is zero.

The input voltage is $e_i = e_{in}\sin wt$

The output voltage $e_0 = i \times R$

$$e_0 = \frac{e_i}{R+jwL}\times R \qquad \because\ i = \frac{e_i}{R+jwL}$$

$$e_0 = \frac{e_{in}\sin wt}{R+jwL}\times R$$

The voltage gain can be defined as the ratio of output voltage to input voltage.

$$\text{Gain}(A) = \frac{e_0}{e_i}$$

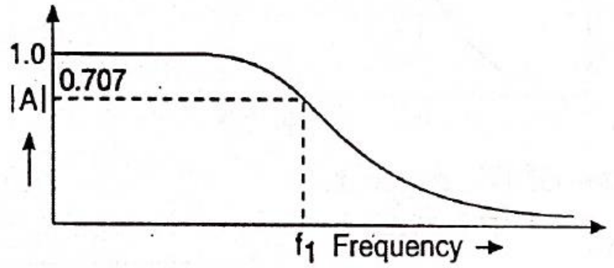
$$= \frac{\dfrac{e_{in}\sin wt}{R + jwL} \times R}{e_{in}\sin wt} = \frac{R}{R + jwL} = \frac{1}{1 + jw\dfrac{L}{R}} = \frac{1}{1 + j2\pi f\dfrac{L}{R}} = \frac{1}{1 + j\left(\dfrac{f}{f_1}\right)}$$

Where $f_1 = \dfrac{1}{2\pi\dfrac{L}{R}}$

Magnitude of gain $|A| = \dfrac{1}{\sqrt{1+\left(\dfrac{f}{f_1}\right)^2}}$

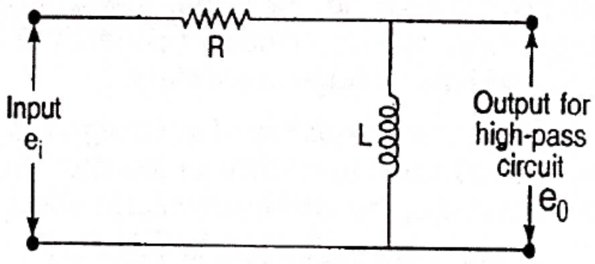
And angle $\theta = \tan^{-1}\left(\dfrac{f}{f_1}\right)$

The frequency response of RL low pass filter.



(2) RL high pass circuit

The RL circuit which acts as a high pass filter is shown in fig. Here the sinusoidal voltage e_i is applied, whose frequency is varied and input voltage is constant.



When the frequency of input signal is zero, the inductive reactance of inductor jwL becomes zero and inductor acts as a short circuit. So, the total input current flows through the inductor and no voltage appears at output.

If the input frequency is increasing, the inductive reactance jwL gradually increases and output voltage also increases gradually.

At very high frequency, the inductive reactance increases to maximum and hence inductor acts as an open circuited. Hence, output voltage follows the input voltage.

The input voltage is $e_i = e_{in}\sin wt$

The output voltage $e_0 = i \times jwL$

$$e_0 = \frac{e_i}{R + jwL} \times jwL \qquad \because \; i = \frac{e_i}{R + jwL}$$

$$e_0 = \frac{e_{in} \sin wt}{R + jwL} \times jwL$$

The voltage gain can be defined as the ratio of output voltage to input voltage.

$$\text{Gain}(A) = \frac{e_0}{e_i}$$

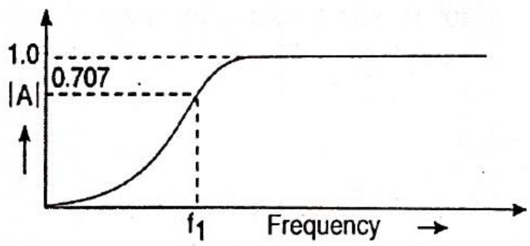
$$= \frac{\dfrac{e_{in} \sin wt}{R + jwL} \times jwL}{e_{in} \sin wt} = \frac{jwL}{R + jwL} = \frac{1}{1 + \dfrac{R}{jwL}} = \frac{1}{1 + \dfrac{1}{j}\dfrac{R}{2\pi fL}} = \frac{1}{1 + \dfrac{1}{j}\dfrac{1}{2\pi f \dfrac{L}{R}}} = \frac{1}{1 + j\left(\dfrac{f_1}{f}\right)}$$

Where $f_1 = \dfrac{1}{2\pi \dfrac{L}{R}}$

$$\text{Magnitude of gain } |A| = \frac{1}{\sqrt{1 + \left(\dfrac{f_1}{f}\right)^2}}$$

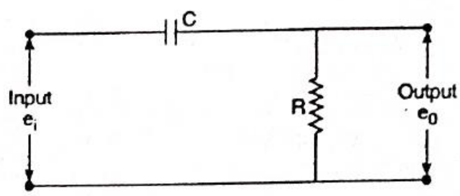
$$\text{And angle } \theta = \tan^{-1}\left(\frac{f_1}{f}\right)$$

The frequency response of RL high pass filter.



3.3 DIFFERENTIATOR CIRCUITS

(1) RC circuit as a differentiator



The circuit shows RC circuit which can be used for differentiation and input voltage e_i is applied.

Def: A differentiating circuit is one whose output voltage is directly proportional to the derivative of input voltage.

$$\therefore \text{ output} = \frac{d}{dt}\text{input}$$

The applied input voltage is equal to the sum of voltage drop across capacitor and drop across resistor.

$$\text{i.e.} \quad e_i = \frac{1}{C}\int i\,dt + iR$$

$$i = \frac{dq}{dt} \quad \Rightarrow q = \int i\,dt \quad \Rightarrow \quad Cv = \int i\,dt \quad (q = cv) \quad \Rightarrow \quad v = \frac{1}{C}\int i\,dt$$

If time constant RC is small compared to time period of applied voltage. Then, The term iR is very small as compared to the term $\frac{1}{C}\int i\,dt$

$$iR << \frac{1}{C}\int i\,dt$$

$$e_i = \frac{1}{C}\int i\,dt$$

$$\int i\,dt = Ce_i \qquad \Rightarrow \quad i = C\frac{de_i}{dt}$$

Now, the output voltage $e_0 = iR$

$$e_0 = C\frac{de_i}{dt}R$$

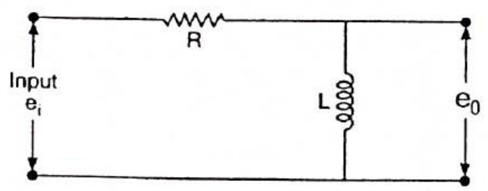
$$e_0 = RC\frac{de_i}{dt}$$

$$e_0 \ \alpha \ \frac{de_i}{dt}$$

Here RC is the time constant.

Hence, the output voltage is derivative of the input voltage.

(2) **RL circuit as a differentiator**



The circuit shows RL circuit which can be used for differentiation and input voltage e_i is applied.

Def: A differentiating circuit is one whose output voltage is directly proportional to the derivative of input voltage.

$$\therefore \text{ output} = \frac{d}{dt}\text{input}$$

The applied input voltage is equal to the sum of voltage drop across inductor and drop across resistor.

$$\text{i.e.} \quad e_i = L\frac{di}{dt} + i\,R$$

Divide both sides with R

$$\frac{e_i}{R} = \frac{L}{R}\frac{di}{dt} + i$$

$$i = \frac{e_i}{R} - \frac{L}{R}\frac{di}{dt}$$

Assuming that the time constant L/R is small compared to time period of applied voltage. Then,

i.e., $\frac{e_i}{R} >> \frac{L}{R}\frac{di}{dt}$

So the term $\frac{L}{R}\frac{di}{dt}$ is negligible

Therefore $i = \frac{e_i}{R}$

Now the output voltage is $e_0 = L\frac{di}{dt}$

$$e_0 = L\frac{d}{dt}\left(\frac{e_i}{R}\right)$$

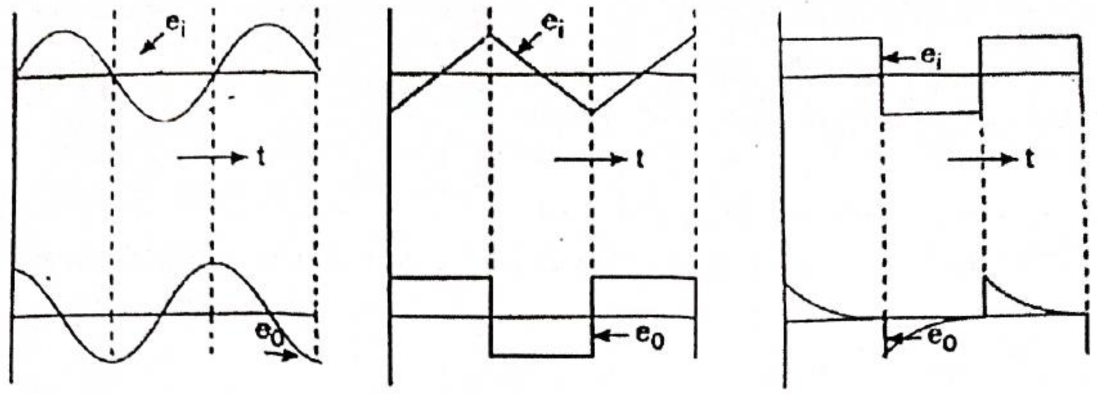
$$e_0 = \frac{L}{R}\frac{de_i}{dt}$$

$$e_0 \ \alpha \ \frac{de_i}{dt}$$

Here L/R is the time constant.

Hence, the output voltage is derivative of the input voltage.

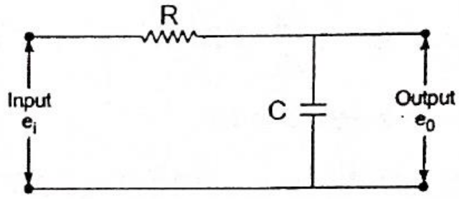
Figure shows the input and output wave forms of differentiator.



3.4 INTRGRATOR CIRCUITS

Integrator circuits

(1) **RC circuit as an integrator**



The circuit shows RC circuit which can be used for integration and input voltage e_i is applied.

Def: An integrating circuit is one whose output voltage is directly proportional to the integral of input voltage.

$\therefore$ output = $\int$input

The applied input voltage is equal to the sum of voltage drop across capacitor and drop across resistor.

i.e. $e_i = \frac{1}{C}\int i dt + iR$

$$i = \frac{dq}{dt} \quad \Rightarrow q = \int i dt \quad \Rightarrow \quad Cv = \int i dt \quad (q = cv) \quad \Rightarrow \quad v = \frac{1}{C}\int i dt$$

Divide both sides with R

$$\frac{e_i}{R} = \frac{1}{RC}\int i dt + i$$

$$i = \frac{e_i}{R} - \frac{1}{RC}\int i dt$$

If time constant RC is large compared to time period of applied voltage. Then, the term $\frac{1}{C}\int i dt$ is neglected

i.e., $iR >> \frac{1}{C}\int i dt$

Therefore $i = \frac{e_i}{R}$

Now, the output voltage $e_0 = \frac{1}{C}\int i dt$

$$e_0 = \frac{1}{C}\int \frac{e_i}{R} dt$$

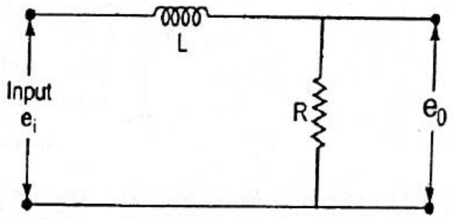
$$e_0 = \frac{1}{RC}\int e_i dt$$

$$e_0 \ \alpha \int e_i dt$$

Here RC is the time constant.

Hence, the output voltage is integral of the input voltage.

(2) RL circuit as an integrator



The circuit shows RL circuit which can be used for integration and input voltage e_i is applied.

Def: An integrating circuit is one whose output voltage is directly proportional to the integral of input voltage.

$\therefore$ output = $\int$input

The applied input voltage is equal to the sum of voltage drop across an inductor and drop across resistor.

i.e. $e_i = L\frac{di}{dt} + iR$

If time constant L/R is large compared to time period of applied voltage. Then, the term iR is neglected

i.e. $L\frac{di}{dt} >> iR$

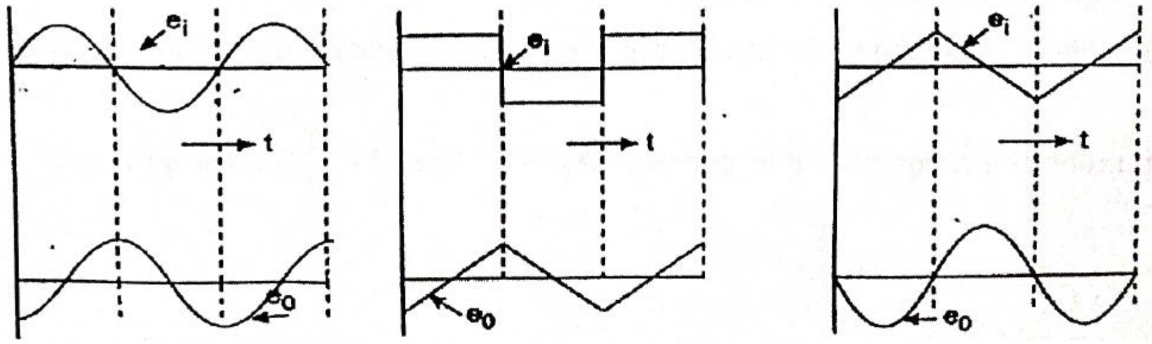
Therefore $e_i = L\frac{di}{dt} \quad \Rightarrow \frac{di}{dt} = \frac{e_i}{L} \quad \Rightarrow i = \frac{1}{L}\int e_i\,dt$

Now, the output voltage $e_0 = i\,R$

$$e_0 = \frac{R}{L}\int e_i\,dt$$

Here L/R is the time constant.

Hence, the output voltage is integral of the input voltage.



3.5 RESONANCE

A circuit said to be resonant when the applied input frequency is equal to the natural frequency of the circuit.

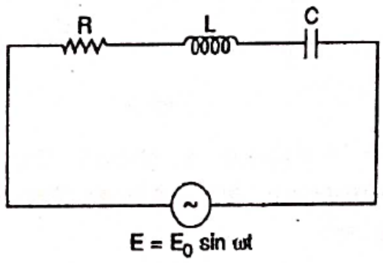
We know that in any AC circuit the voltage and currents are usually out of phase, but in some conditions the voltage and currents are in phase, that condition is called resonance.

At resonance the reactive components of impedance is zero. In other words the inductive reactance is exactly equal to capacitive reactance.

i.e., $wL = \frac{1}{wC}$

3.6 SERIES RLC CIRCUIT

Series resonance RLC circuit.



The resistance R, inductance L and capacitance C are connected in series and emf of $E=E_0 \sin wt$ is applied to the circuit as shown in figure.

The impedance of this circuit is given by

$$Z = R + jwL + \frac{1}{jwC}$$

$$i^2 = -1 \quad \Rightarrow j^2 = -1; \quad \frac{1}{jwC} = \frac{j}{j^2 wC} = \frac{-j}{wC}$$

$$Z = R + jwL - \frac{j}{wC}$$

$$Z = R + j\left(wL - \frac{1}{wC}\right)$$

At resonance the reactive component of impedance is equal to zero.

i.e., $wL - \frac{1}{wC} = 0$

$$wL = \frac{1}{wC} \quad \Rightarrow w^2 = \frac{1}{LC} \quad \Rightarrow w = \frac{1}{\sqrt{LC}} \quad \Rightarrow 2\pi f_0 = \frac{1}{\sqrt{LC}}$$

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

Hence, the resonant frequency is $f_0 = \frac{1}{2\pi\sqrt{LC}}$

At resonant frequency the reactive term varies with frequency and magnitude of impedance is $|Z| = R$

Thus at resonant frequency the impedance is equal to resistance ($|Z| = R$), while at other frequency the magnitude of impedance is

$$|Z| = \sqrt{R^2 + \left(wL - \frac{1}{wC}\right)^2}$$

In series resonance ckt the impedance minimum at resonance & current will be maximum at resonance and is given by $i = \frac{E}{R}$

Frequency response

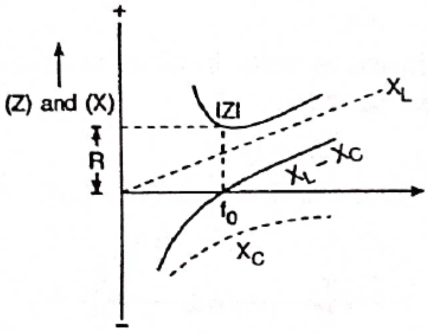


Fig a

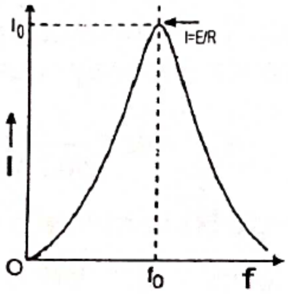


Fig b

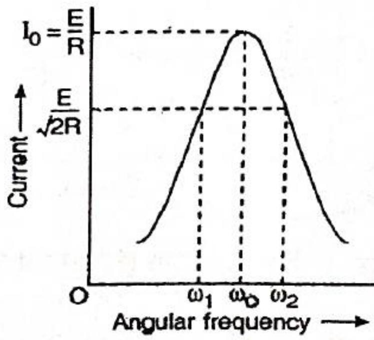
Figure a shows the variation of impedance(Z) and reactance (X) with frequency, fig b shows the variation of current with frequency in series resonant circuit.

At frequency lower than resonant frequency, the capacitive reactance of the circuit is large as compared to the inductive reactance $\left(\frac{1}{wC} >> wL\right)$ and total reactance is capacitive.

At frequency higher than resonant frequency, the inductive reactance of the circuit is large as compared to the capacitive reactance $\left(wL >> \frac{1}{wC}\right)$ and total reactance is inductive.

At the resonant frequency, inductive reactance and capacitive reactance are exactly equal to each other $\left(wL = \frac{1}{wC}\right)$ and circuit is purely resistive.

Selectivity and band width of series circuit (Q-factor)



A series RLC ckt has minimum impedance at resonance frequency. If the total circuit resistance is low, the selectivity of the circuit is high. On the other hand if the resistance is high, the selectivity is poor.

The band width can be defined as the range of frequencies represented by two points on either side of resonance frequency at which current falls $\frac{1}{\sqrt{2}}$ times of its maximum value. The selectivity of resonance is expressed in terms of symbol Q, known as Quality factor and is given by

$$Q = \frac{w_0}{w_1 - w_2} = \frac{w_0}{\wedge w} = \frac{f_0}{\wedge f}$$

Now, if w be the angular frequency corresponding to the points where, $i = \frac{E}{\sqrt{2}R}$, then these points called half power points.

From circuit $i = \dfrac{E}{\sqrt{R^2 + \left(wL - \dfrac{1}{wC}\right)^2}}$

From above $\sqrt{2}R = \sqrt{R^2 + \left(wL - \dfrac{1}{wC}\right)^2}$

By squaring both sides

$$2R^2 = R^2 + \left(wL - \frac{1}{wC}\right)^2 \qquad \Rightarrow 2R^2 - R^2 = \left(wL - \frac{1}{wC}\right)^2$$

$$R^2 = \left(wL - \frac{1}{wC}\right)^2$$

$$wL - \frac{1}{wC} = \pm R$$

Multiply both sides with $\frac{w}{L}$, we get

$$w^2 - \frac{1}{LC} = \pm \frac{wR}{L}$$

$$w^2 \mp \frac{wR}{L} - \frac{1}{LC} = 0$$

$$a = 1 \qquad b = \mp\frac{R}{L} \qquad c = -\frac{1}{LC}$$

$$w = \frac{\pm\frac{R}{L} \pm \sqrt{\left(\frac{R}{L}\right)^2 - \frac{4}{LC}}}{2}$$

$$w = \pm\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 - \frac{1}{LC}}$$

Since R is minimum when circuit is most selective, hence in a selective the term $\left(\frac{R}{2L}\right)^2$ is negligible as compared to $\frac{1}{LC}$.

$$\therefore \quad w = \pm\frac{R}{2L} \pm \sqrt{\frac{1}{LC}}$$

$$wL = \frac{1}{wC} \qquad \Rightarrow w^2 = \frac{1}{LC} \qquad \Rightarrow w_0 = \frac{1}{\sqrt{LC}}$$

$$\therefore \quad w = \pm w_0 \pm \frac{R}{2L}$$

Now, consider +ve values of w_0

$$w = w_0 \pm \frac{R}{2L}$$

We get two values of w as

$$w_1 = w_0 - \frac{R}{2L} \qquad w_2 = w_0 + \frac{R}{2L}$$

Now, the band width is given by

$$w_2 - w_1 = w_0 + \frac{R}{2L} - w_0 + \frac{R}{2L}$$

$$w_2 - w_1 = \frac{R}{L}$$

Here w_1 and w_2 are limiting frequencies at which current is equal to 70.7% of its maximum value. The frequency w_1 is called lower half power frequency and w_2 is called upper half power frequency.

Hence, the selectivity of the circuit is given by

$$Q = \frac{w_0}{\wedge w} = \frac{w_0}{w_2 - w_1} = \frac{w_0}{R/L} = \frac{w_0 L}{R}$$

Thus the Q factor of resonant circuit is defined as the ratio of the inductive reactance to the total resistance in the circuit at resonance.

Since at resonance $w_0 L = \frac{1}{w_0 C}$, therefore

$$Q = \frac{w_0 L}{R} = \frac{1}{w_0 CR} = \frac{1}{\frac{1}{\sqrt{LC}} CR} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Sharpness of resonance and Q factor.

Sharpness of the resonance is defined as the ratio of band width of the circuit to its resonance frequency.

Thus sharpness of resonance $= \frac{w_2 - w_1}{w_0}$

This is equal to $\frac{1}{Q}$. Thus the sharpness of the resonance is reciprocal of the quality factor Q.

3.7 PARALLEL RESONANCE CIRCUIT

Parallel resonance RLC circuit

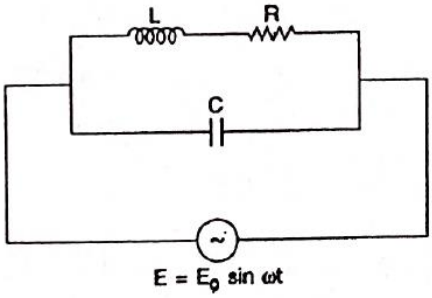


Fig shows a parallel resonance circuit, the series combination of inductor L and resistor R is connected to capacitor in parallel and emf of $E=E_0 \sin wt$ is applied to the circuit.

The impedance Z of circuit is given by

$$Z = (R + jwL) \parallel \frac{1}{jwC}$$

$$\frac{1}{Z} = \frac{1}{R + jwL} + \frac{1}{1/jwC} = \frac{1}{R + jwL} + jwC$$

$$\frac{1}{Z} = \frac{R - jwL}{(R + jwL)(R - jwL)} + jwC$$

$$\frac{1}{Z} = \frac{R - jwL}{R^2 + w^2L^2} + jwC$$

$$\frac{1}{Z} = \frac{R}{R^2 + w^2L^2} - \frac{jwL}{R^2 + w^2L^2} + jwC$$

$$\frac{1}{Z} = \frac{R}{R^2 + w^2L^2} + jw\left(C - \frac{L}{R^2 + w^2L^2}\right) \quad \text{-------1}$$

At resonance, the reactive term of impedance is zero. Hence resonance occurs when

$$jw\left(C - \frac{L}{R^2 + w^2L^2}\right) = 0$$

$$C - \frac{L}{R^2 + w^2L^2} = 0$$

$$C = \frac{L}{R^2 + w^2L^2}$$

$$R^2 + w^2L^2 = \frac{L}{C}$$

$$w^2L^2 = \frac{L}{C} - R^2$$

$$w^2 = \frac{1}{LC} - \frac{R^2}{L^2}$$

$$w = w_0 = \sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}$$

The resonant frequency is $f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}$

If R is very small, $\frac{R^2}{L^2}$ is small as compared to $\frac{1}{LC}$ and resonant frequency becomes $f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} = \frac{1}{2\pi\sqrt{LC}}$

The impedance at resonance is given by equ 1

$$\frac{1}{Z} = \frac{R}{R^2 + w^2L^2}$$

$$Z = \frac{R^2 + w^2L^2}{R} = \frac{L}{RC}$$

If R is small, the impedance may be written as

$$\frac{1}{Z} = \frac{R}{R^2 + w^2L^2}$$

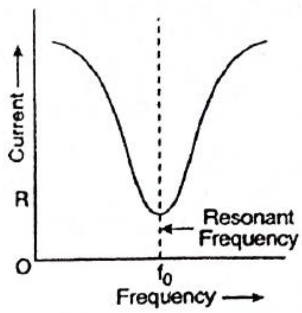
$$Z = \frac{R^2 + w^2L^2}{R} = R + \frac{w^2L^2}{R} = \frac{w^2L^2}{R}$$

$$Z = \frac{w^2L^2}{R} = \frac{w_0L_0}{R}.w_0L_0 = Q\ .\ w_0L_0$$

The impedance at resonance is dynamic impedance.

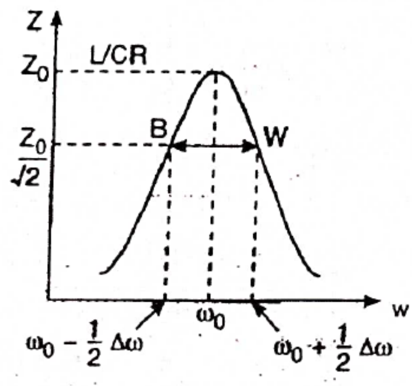
Frequency response

Figure shows variation of current with frequency in parallel resonance circuit. Here current will be minimum at resonance. It does not allow a frequency equal to natural frequency of the circuit. That means it rejects a particular frequency from several frequencies. Hence, it is called rejecter circuit or filter.



Selectivity and band width of parallel circuit (Q-factor)

The variation of parallel circuit impedance with angular frequency w is shown in figure.



The peak value of curve is corresponds impedance at resonance.

$$Z_0 = \frac{L}{RC}$$

Band width can be defined as a range of frequency of given two points on either side of resonant frequency, which are given by $\frac{1}{\sqrt{2}}$ times of its maximum value.

The selectivity can be given as

$$Q = \frac{w_0}{w_2 - w_1} = \frac{w_0}{\wedge w}$$

The total impedance in parallel circuit is given by

$$Z = (R + jwL) \parallel \frac{1}{jwC}$$

$$Z = \frac{(R + jwL)\ \frac{1}{jwC}}{(R + jwL) + \frac{1}{jwC}}$$

$wL >> R$, R is neglected

$$Z = \frac{\frac{jwL}{jwC}}{\frac{jwCR - w^2LC + 1}{jwC}} = \frac{jwL}{jwCR - w^2LC + 1} = \frac{-jwL}{(w^2LC - 1) - jwCR}$$

$$Z = \frac{wL}{\sqrt{(w^2LC - 1)^2 + (wCR)^2}}$$

Multiply both numerator and denominator with $\frac{1}{wCR}$

$$Z = \frac{\frac{wL}{wCR}}{\frac{1}{wCR}\sqrt{(w^2LC - 1)^2 + (wCR)^2}} = \frac{\frac{L}{CR}}{\frac{1}{wCR}\sqrt{(w^2LC - 1)^2 + (wCR)^2}}$$

$$Z = \frac{Z_0}{\frac{1}{wCR}\sqrt{(w^2LC - 1)^2 + (wCR)^2}} \quad ---------1 \qquad \left(\because Z_0 = \frac{L}{RC}\right)$$

At half power points, the impedance is given by

$$Z = \frac{Z_0}{\sqrt{2}} \quad --------------- \ 2$$

From equ1 and equ2

$$\sqrt{2} = \frac{1}{wCR}\sqrt{(w^2LC - 1)^2 + (wCR)^2}$$

$$\sqrt{2}wCR = \sqrt{(w^2LC-1)^2 + (wCR)^2}$$

$$2(wCR)^2 = (w^2LC-1)^2 + (wCR)^2$$

$$2(wCR)^2 - (wCR)^2 = (w^2LC-1)^2$$

$$(wCR)^2 = (w^2LC-1)^2$$

$$w^2LC - 1 = \pm wCR$$

$$w^2LC \mp wCR - 1 = 0$$

$a = LC, \quad b = \mp CR \quad \text{and} \quad c = -1$

$$w = \frac{\pm CR \pm \sqrt{(CR)^2 + 4LC}}{2LC}$$

$$w = \pm\frac{R}{2L} \pm \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

Here $\frac{R}{2L}$ is very small as compared to $\frac{1}{LC}$

$$w = \pm\frac{R}{2L} \pm \sqrt{\frac{1}{LC}}$$

$$w = \pm w_0 \pm \sqrt{\frac{1}{LC}}$$

Now, taking +ve values of w

$$w = w_0 \pm \frac{R}{2L}$$

$$w_1 = w_0 - \frac{R}{2L}, \qquad w_2 = w_0 + \frac{R}{2L}$$

Band width $w_2 - w_1 = \frac{R}{2L}$

Selectivity or Quality factor Q is given by

$$Q = \frac{w_0}{\wedge w} = \frac{w_0}{w_2 - w_1} = \frac{w_0}{R/L} = \frac{w_0 L}{R}$$

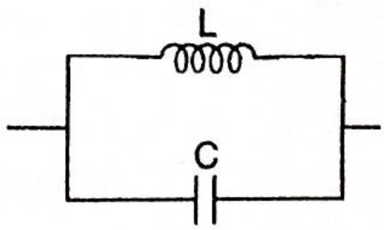
At resonance $w_0L = \frac{1}{w_0C}$

$$Q = \frac{1}{w_0CR} = \frac{1}{\sqrt{\frac{1}{LC}}CR} = \frac{\sqrt{LC}}{CR} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

3.8 Comparison of Series and Parallel Resonance

Series resonance	Parallel resonance
1. The series resonant circuit is called acceptor circuit and it offers easy path for current at resonant frequency. (current is maximum at resonance)	1. The parallel resonant circuit is called rejecter circuit and it offers difficult path for current at resonance. (current is minimum at resonance)
2. Impedance Z is minimum at resonance and is purely resistive $Z = R$	2. Impedance is maximum at resonance $Z = \frac{L}{CR}$
3. Resonant frequency f_0 is independent of resistance R $f_0 = \frac{1}{2\pi\sqrt{LC}}$	3. Resonant frequency f_0 is dependent of resistance R $f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}$
4. At resonance, exhibits a voltage magnification of $Q = \frac{w_0 L}{R}$	4. At resonance, exhibits a current magnification of Q

Tank circuit – LC oscillations



The parallel combination of a fully charged capacitor C and an inductor L produces electrical oscillations. In these oscillations the electrical energy associated with the capacitor is completely transferred to the magnetic field energy linked with the inductor. This process continues and is known as electrical oscillations. The LC circuit is known as tank circuit. The frequency of oscillations is same as the resonant frequency of the tank circuit and is given by $f = \frac{1}{2\pi\sqrt{LC}}$ Hz.

UNIT-IV: DIODES, BJT, FET AND UJT

DIODES: Construction, working of PN, Zener Diodes. BJT: Construction, working, and characteristics of CE Configurations. FET: Construction, working and characteristics of JFET, Advantages of FET. UJT: Construction, working and characteristics of UJT. Relaxation Oscillator.

4.1 CLASSIFICATION OF SEMICONDUCTORS

Semiconductors are classified as (i) intrinsic (pure) and (ii) extrinsic (impure) types. The extrinsic semiconductors are of N-type and P-type.

Intrinsic Semiconductors:

A pure semiconductor is called intrinsic semiconductor. Even at room temperature, some of the valence electrons may acquire sufficient energy to enter the conduction band to form free electrons. Under the influence of electric field, these electrons constitute electric current. A missing electron in the valence band leaves a vacant space there, which is known as a hole, as shown in Fig. 4.1. Holes also contribute to electric current.

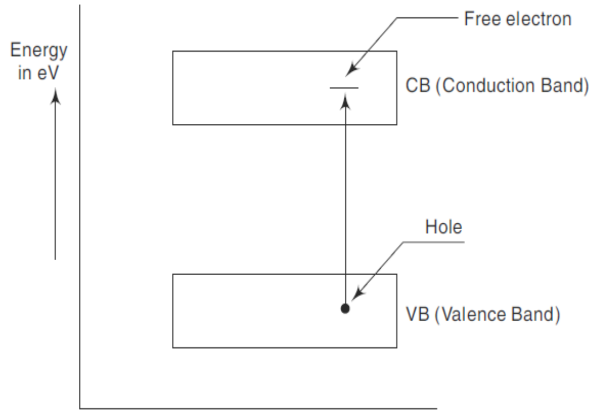


Fig. 4.1 *Creation of electorn-hole pair in a semiconductor*

In an intrinsic semiconductor, even at room temperature, electron-hole pairs are created. When electric field is applied across an intrinsic semiconductor, the current conduction takes place due to free electrons and holes. Under the influence of electric field, total current through the semiconductor is the sum of currents due to free electrons and holes.

Though the total current inside the semiconductor is due to free electrons and holes, the current in the external wire is fully by electrons. In Fig. 4.2, holes being positively charged move towards the negative terminal of the battery. As the holes reach the negative terminal of the battery, electrons enter the semiconductor near the terminal (X) and combine with the holes. At the same time, the loosely held electrons near the positive terminal (Y) are attracted towards the positive terminal. This creates new holes near the positive terminal which again drift towards the negative terminal.

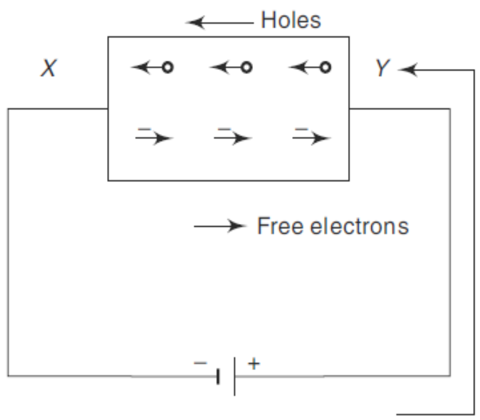


Fig. 4.2 *Current conduction in semiconductor*

Extrinsic Semiconductors:

Due to the poor conduction at room temperature, the intrinsic semiconductor as such, is not useful in the electronic devices. Hence, the current conduction capability of the intrinsic semiconductor should be increased. This can be achieved by adding a small amount of impurity to the intrinsic semiconductor, so that it becomes impure or extrinsic semiconductor. This process of adding impurity is known as doping. The amount of impurity added is extremely small, say 1 to 2 atoms of impurity for 10^6 intrinsic atoms.

(a) N-Type Semiconductor:

A small number of pentavalent impurities such as arsenic, antimony or phosphorus is added to the pure semiconductor (germanium or silicon crystal) to get N-type semiconductor.

Germanium atom has four valence electrons and antimony has five valence electrons. As shown in Fig. 4.3, each antimony atom forms a covalent bond with surrounding four germanium atoms. Thus, four valence electrons of antimony atom form covalent bond with four valence electrons of individual germanium atom and fifth valence electron is left free which is loosely bound to the antimony atom.

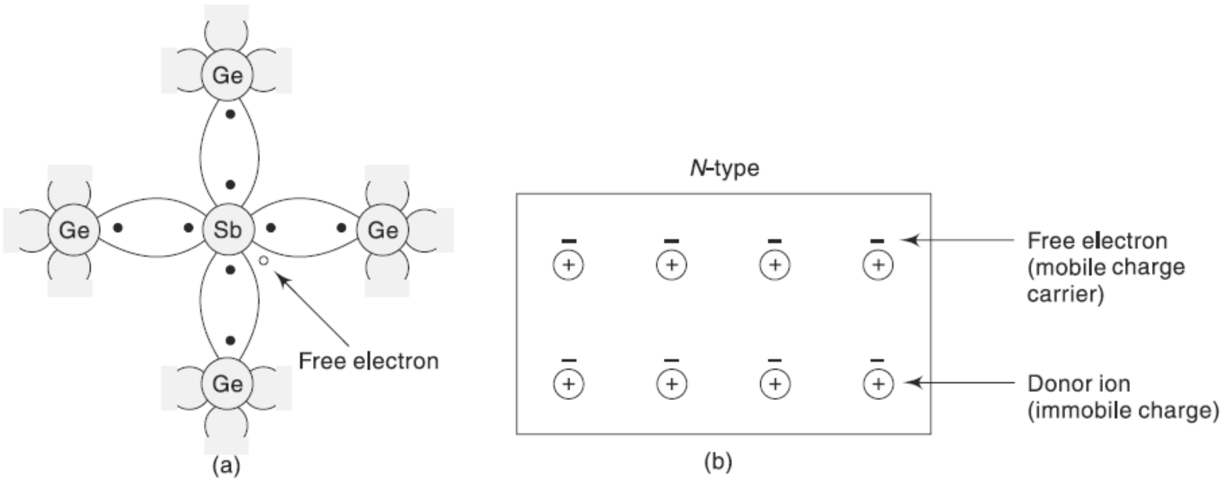


Fig. 4.3 *N-type semiconductor: (a) Formation of covalent bonds, and (b) Charged carriers*

This loosely bound electron can be easily excited from the valence band to the conduction band by the application of electric field or increasing the thermal energy. Thus, every antimony atom contributes one conduction electron without creating a hole. Such pentavalent impurities are called donor impurities because it donates one electron for conduction. On giving an electron for conduction, the donor atom becomes positively charged ion because it loses one electron. But it cannot take part in conduction because it is firmly fixed in the crystal lattice.

Thus, the addition of pentavalent impurity (antimony) increases the number of electrons in the conduction band thereby increasing the conductivity of N-type semiconductor. As a result of doping, the number of free electrons far exceeds the number of holes in an N-type semiconductor. So, electrons are called majority carriers and holes are called minority carriers.

(b) P-Type Semiconductor:

A small amount of trivalent impurity such as aluminium or boron is added to the pure semiconductor to get the p-type semiconductor. Germanium (Ge) atom has four valence electrons and boron has three valence electrons as shown in Fig. 4.4. Three valence electrons in boron form covalent bond with four surrounding atoms of Ge leaving one bond incomplete which gives rise to a hole. Thus, trivalent impurity (boron) when added to the intrinsic semiconductor (germanium) introduces a large number of holes in the valence band. These positively charged holes increase the conductivity of P-type semiconductor. Trivalent impurities such as boron is called acceptor impurity because it accepts free electrons in the place of holes. As each boron atom donates a hole for conduction, it becomes a negatively charged ion. As the number of holes is very much greater than the number of free electrons in a P-type material, holes are termed as majority carriers and electrons as minority carriers.

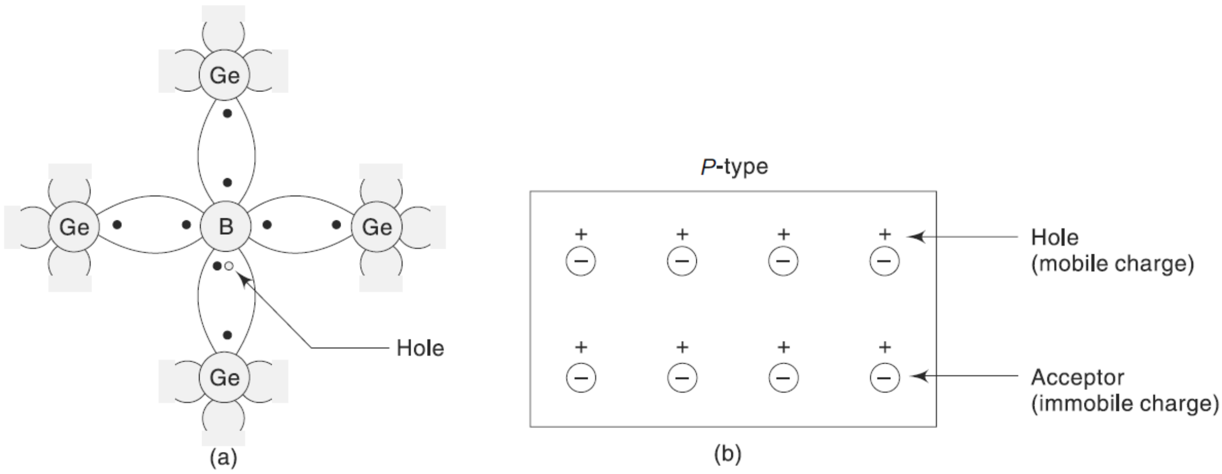


Fig. 4.4 *P-type semiconductor: (a) Formation of covalent bonds, and (b) Charged carriers*

4.2 PN – JUNCTION DIODE

After having known about various components, let us focus on another important component in the field of electronics, known as a Diode. A semiconductor diode is a two terminal electronic component with a PN junction. This is also called as a Rectifier. The anode which is the positive terminal of a diode is represented with A and the cathode, which is the negative terminal is represented with K.

To know the anode and cathode of a practical diode, a fine line is drawn on the diode which means cathode, while the other end represents anode.

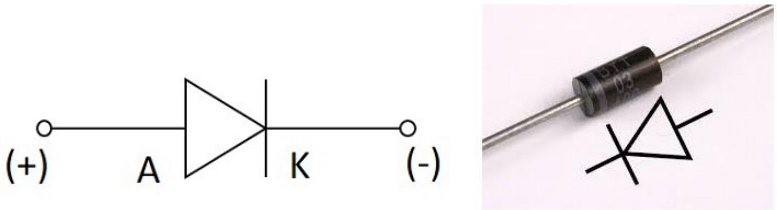


Fig. 4.5 Diode circuit symbol & Representing anode and cathode of practical diode through its symbol

Construction of a Diode:

If a P-type and an N-type material are brought close to each other, both of them join to form a junction, as shown in the figure below.

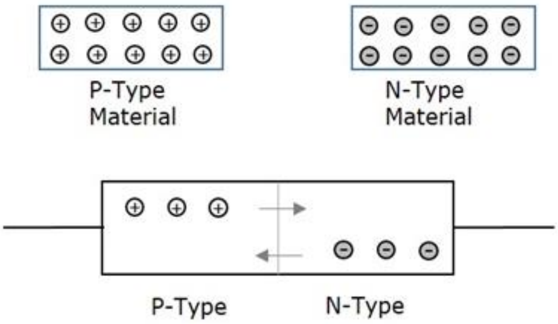


Fig. 4.6 Formation of a PN-Junction

A P-type material has holes as the majority carriers and an N-type material has electrons as the majority carriers. As opposite charges attract, few holes in P-type tend to go to n-side, whereas few electrons in N-type tend to go to P-side. As both of them travel towards the junction, holes and electrons recombine with each other to neutralize and forms ions. Now, in this junction, there exists a region where the positive and negative ions are formed, called as PN junction or junction barrier as shown in the figure.

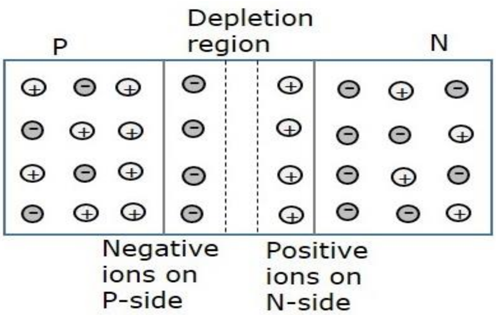


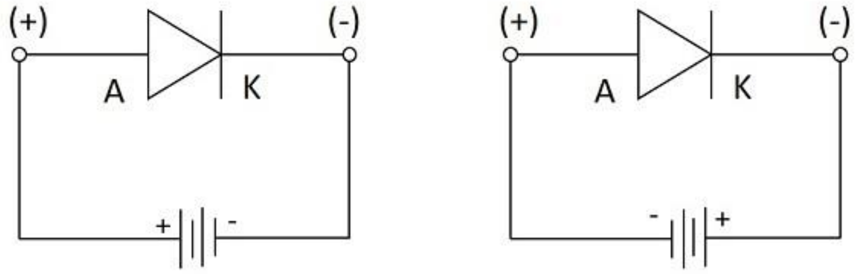
Fig. 4.7 PN junction diode with depletion region

The formation of negative ions on P-side and positive ions on N-side results in the formation of a narrow-charged region on either side of the PN junction. This region is now free from movable charge carriers. The ions present here have been stationary and maintain a region of space between them without any charge carriers.

As this region acts as a barrier between P and N type materials, this is also called as Barrier junction. This has another name called as Depletion region meaning it depletes both the regions. There occurs a potential difference V_D due to the formation of ions, across the junction called as Potential Barrier as it prevents further movement of holes and electrons through the junction.

Biasing of a Diode:

When a diode or any two-terminal component is connected in a circuit, it has two biased conditions with the given supply. They are Forward biased condition and Reverse biased condition. Let us know them in detail.

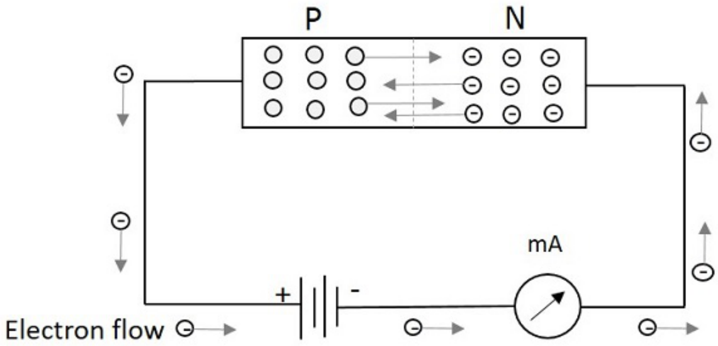


Forward biased Connection Reverse biased Connection

Forward Biased Condition

When a diode is connected in a circuit, with its anode to the positive terminal and cathode to the negative terminal of the supply, then such a connection is said to be forward biased condition. This kind of connection makes the circuit more and more forward biased and helps in more conduction. A diode conducts well in forward biased condition.

When an external voltage is applied to a diode such that it cancels the potential barrier and permits the flow of current is called as forward bias. When anode and cathode are connected to positive and negative terminals respectively, the holes in P-type and electrons in N-type tend to move across the junction, breaking the barrier. There exists a free flow of current with this, almost eliminating the barrier.



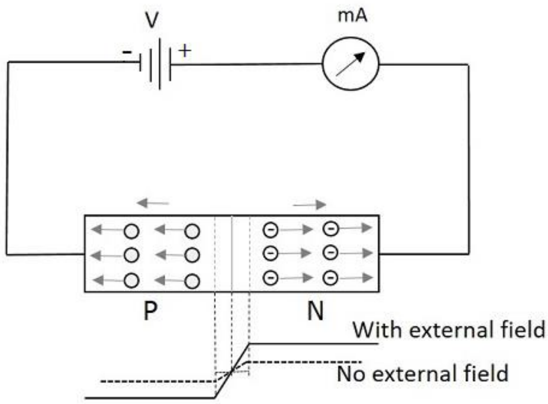
PN junction forward biased

With the repulsive force provided by positive terminal to holes and by negative terminal to electrons, the recombination takes place in the junction. The supply voltage should be such high that it forces the movement of electrons and holes through the barrier and to cross it to provide forward current.

Forward Current is the current produced by the diode when operating in forward biased condition and it is indicated by I_f.

Reverse Biased Condition

When a diode is connected in a circuit, with its anode to the negative terminal and cathode to the positive terminal of the supply, then such a connection is said to be Reverse biased condition. This kind of connection makes the circuit more and more reverse biased and helps in minimizing and preventing the conduction. A diode cannot conduct in reverse biased condition.



PN junction reverse biased

When an external voltage is applied to a diode such that it increases the potential barrier and restricts the flow of current is called as Reverse bias. When anode and cathode are connected to negative and positive terminals respectively, the electrons are attracted towards the positive terminal and holes are attracted towards the negative terminal. Hence both will be away from the potential barrier increasing the junction resistance and preventing any electron to cross the junction.

With the increasing reverse bias, the junction has few minority carriers to cross the junction. This current is normally negligible. This reverse current is almost constant when the temperature is constant. But when this reverse voltage increases further, then a point called reverse breakdown occurs, where an avalanche of current flows through the junction. This high reverse current damage the device.

Reverse current is the current produced by the diode when operating in reverse biased condition and it is indicated by Ir. Hence a diode provides high resistance path in reverse biased condition and doesn't conduct, where it provides a low resistance path in forward biased condition and conducts.

V – I Characteristics (Volt – Ampere Characteristics) of Diode:

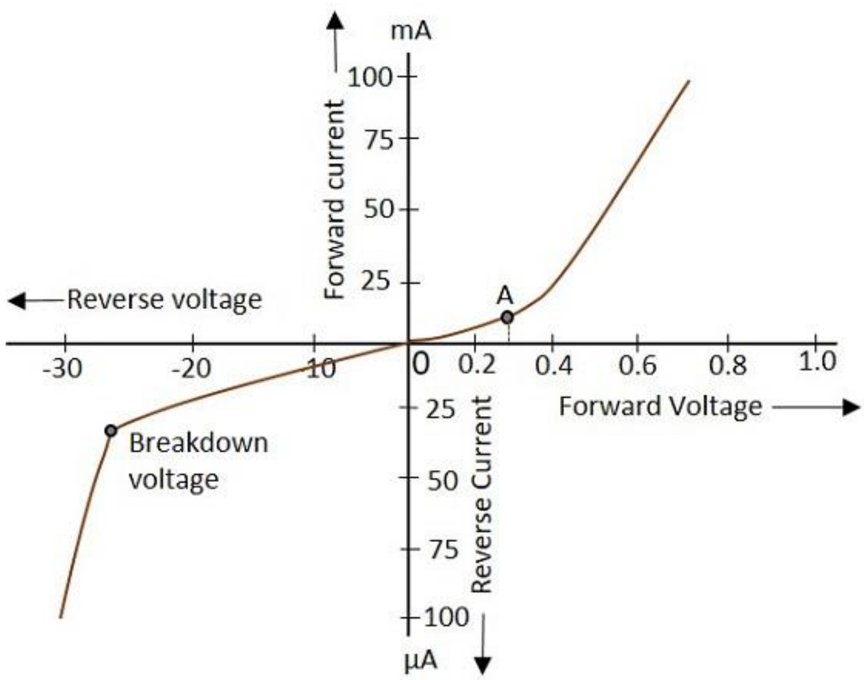


Fig. 4.8 V-I characteristics of Diode

Diode Current Equations:

The diode-current equation relating the voltage V and current I is given by

$$I = I_o[e^{(V/\eta V_T)} - 1]$$

where I = diode current

I_o = diode reverse saturation current at room temperature

V = external voltage applied to the diode

η = a constant, 1 for germanium and 2 for silicon

Now, $V_T = kT/q = T/11600$, volt-equivalent of temperature, i.e., thermal voltage,

where k = Boltzmann's constant (1.38×10^{-23} J/K)

q = charge of the electron (1.602×10^{-19} C)

T = temperature of the diode junction (K) = (°C + 273)

At room temperature (T = 300 K), V_T = 26 mV. Substituting this value in the current equation, we get

$$I = I_o[e^{(40\,V/\eta)} - 1]$$

Therefore, for a germanium diode, $I = I_o[e^{40V} - 1]$, since $\eta = 1$ for germanium. For a silicon diode, $I = I_o[e^{20V} - 1]$, since $\eta = 2$ for silicon.

4.3 ZENER DIODE

Zener diode is heavily doped than the normal p-n junction diode, which is designed to operate in the reverse breakdown region. The breakdown voltage of a zener diode is carefully set by controlling the doping level during manufacture. Zener diode is heavily doped than the normal p-n junction diode. Hence, it has very thin depletion region. Therefore, zener diodes allow more electric current than the normal p-n junction diodes.

A zener diode is a special type of device designed to operate in the zener breakdown region. Zener diodes acts like normal p-n junction diodes under forward biased condition. When forward biased voltage is applied to the zener diode it allows large amount of electric current and blocks only a small amount of electric current. The symbol of Zener diode is nearly similar to the PN junction diode. Below figure shows the symbol of Zener diode.

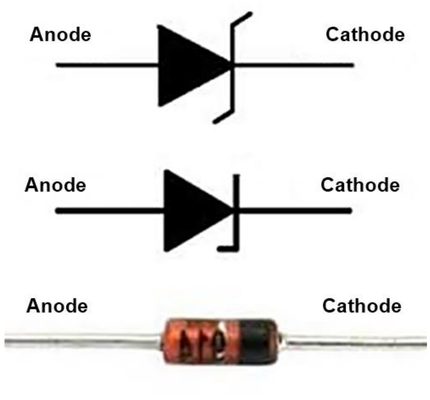
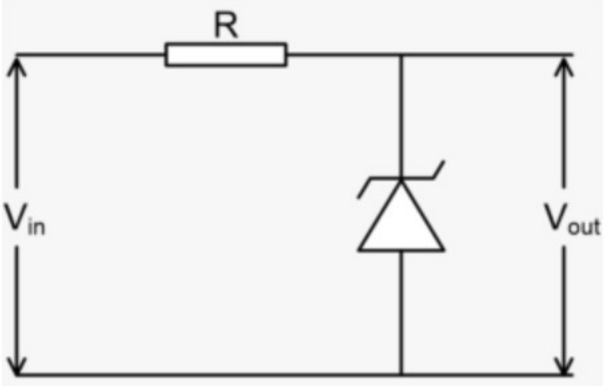


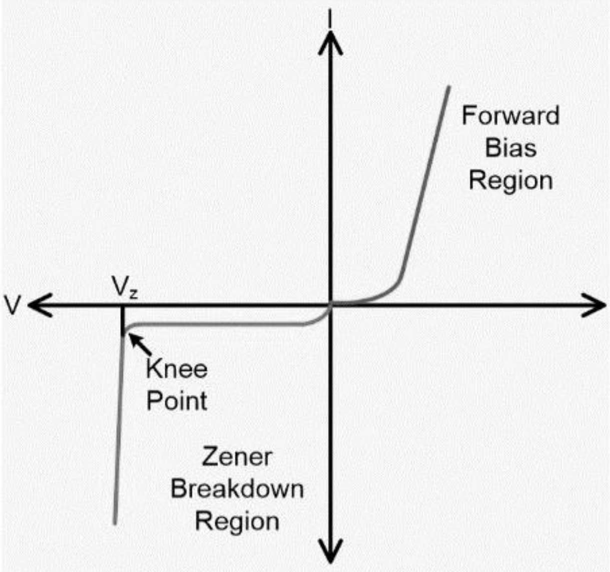
Fig. 4.9 Zener diode circuit symbol

Zener diode V-I characteristics:

The VI characteristics of a zener diode is shown in the below figure. When forward biased voltage is applied to the zener diode, it works like a normal diode. However, when reverse biased voltage is applied to the zener diode, it works in different manner.



Circuit of Zener Diode



VI characteristic of Zener Diode

When reverse biased voltage is applied to a zener diode, it allows only a small amount of leakage current until the voltage is less than zener voltage. When reverse biased voltage applied to the zener diode reaches zener voltage, it starts allowing large amount of electric current. At this point, a small increase in reverse voltage will rapidly increases the electric current. Because of this sudden rise in electric current, breakdown occurs called zener breakdown. However, zener diode exhibits a controlled breakdown that does damage the device.

The zener breakdown voltage of the zener diode is depends on the amount of doping applied. If the diode is heavily doped, zener breakdown occurs at low reverse voltages. On the other hand, if the diode is lightly doped, the zener breakdown occurs at high reverse voltages. Zener diodes are available with zener voltages in the range of 1.8V to 400V.

4.4 BREAKDOWN MECHANISM IN DIODES

There are two types of reverse breakdown mechanism in diodes: avalanche breakdown and zener breakdown.

Avalanche Breakdown:

The avalanche breakdown occurs in both normal diodes and zener diodes at high reverse voltage. When high reverse voltage is applied to the p-n junction diode, the free electrons (minority carriers) gain large amount of energy and accelerated to greater velocities.

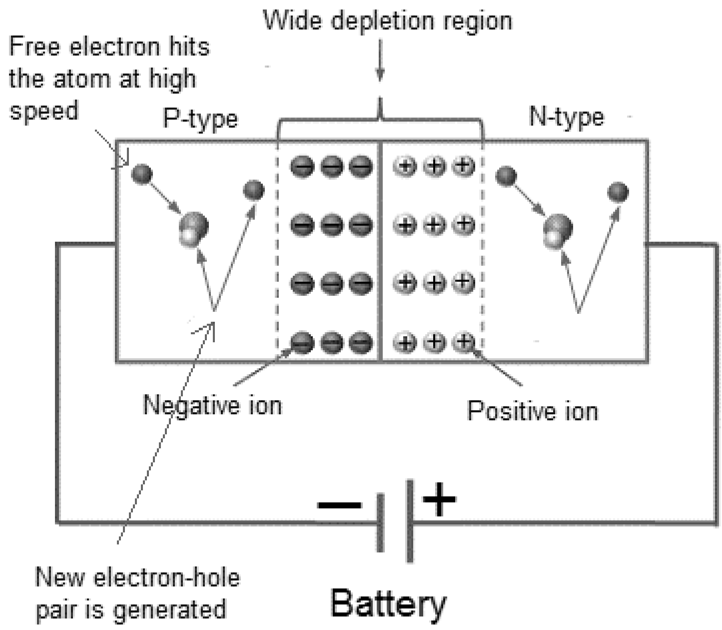


Fig. 4.10 Avalanche breakdown mechanism

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 sudden increase in electric current may permanently destroys the normal diode. However, zener diodes may not be destroyed because they are carefully designed to operate in zener breakdown region.

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.

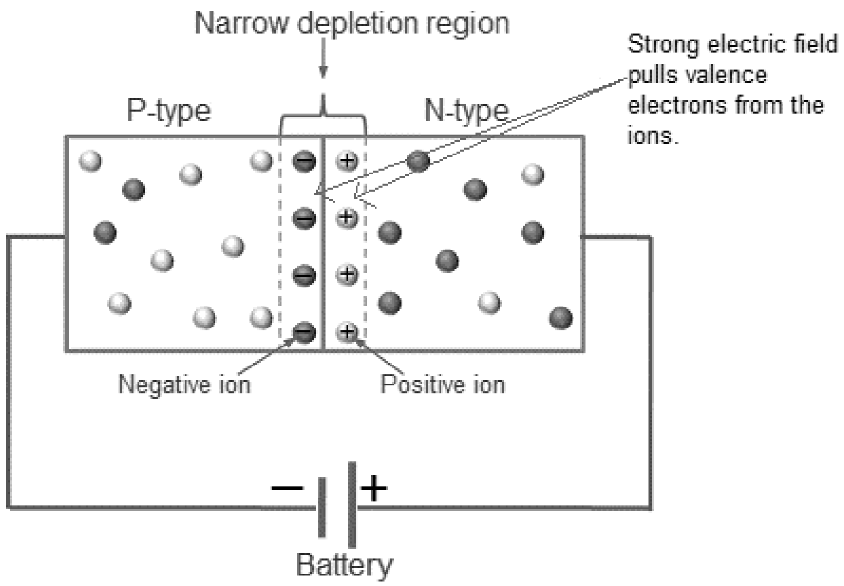


Fig. 4.11 Zener breakdown mechanism

When reverse biased voltage applied to the diode reaches close to zener voltage, the electric field in the depletion region is strong enough to pull electrons from their valence band. The valence electrons which gain sufficient energy from the strong electric field of depletion region will breaks bonding with the parent atom. The valance electrons which break bonding with parent atom will become free electrons. These free electrons carry electric current from one place to another place. At zener breakdown region, a small increase in voltage will rapidly increases the electric current.

- 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 (Vz) less than 6V.

4.5 BIPOLAR JUNCTION TRANSISTOR (BJT)

(a) Construction:

A Bipolar Junction Transistor (BJT) is a three terminal semiconductor device in which the operation depends on the interaction of both majority and minority carriers and hence the name Bipolar. The BJT consists of a silicon (or germanium) crystal in which a thin layer of N-type Silicon is sandwiched between two layers of P-type silicon. This transistor is referred to as PNP. Alternatively, in a NPN transistor, a layer of P-type material is sandwiched between two layers of N-type material. The two types of the BJT are represented in Fig. 4.12.

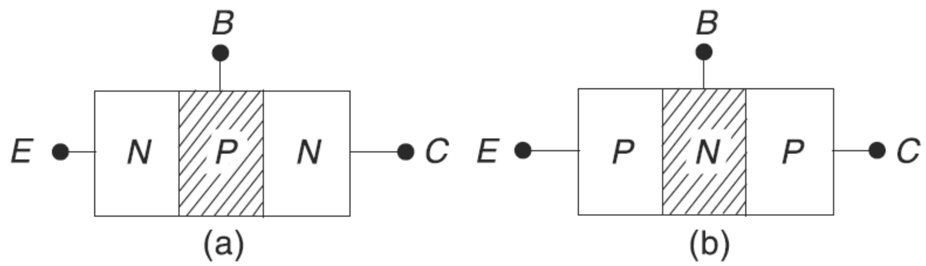


Fig. 4.12 Transistor (a) NPN and (b) PNP

The symbolic representation of the two types of the BJT is shown in Fig. 4.13. The three portions of the transistor are Emitter, Base and Collector, shown as E, B and C, respectively. The arrow on the emitter specifies the direction of current flow when the EB junction is forward biased.

Emitter is heavily doped so that it can inject a large number of charge carriers into the base. Base is lightly doped and very thin. It passes most of the injected charge carriers from the emitter into the collector. Collector is moderately doped.

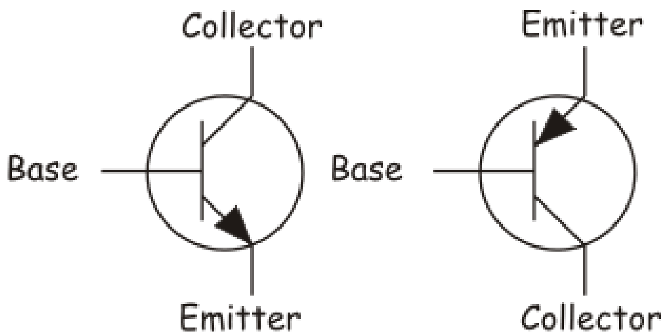


Fig. 4.13 Circuit symbols of NPN and PNP transistors

(b) Transistor Biasing:

As shown in Fig. 4.14, usually the emitter-base junction is forward biased and collector-base junction is reverse biased. Due to the forward bias on the emitter-base junction an emitter current flows through the base into the collector. Though the, collector-base junction is reverse biased, almost the entire emitter current flows through the collector circuit.

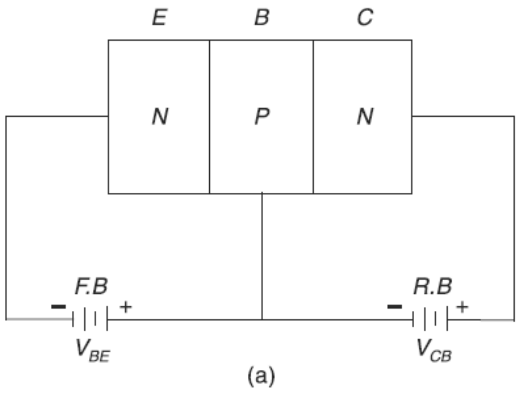


Fig. 4.14 Transistor biasing (a) NPN and (b) PNP

(C) Operation of NPN transistor:

As shown in Fig. 4.15, the forward bias applied to the emitter base junction of an NPN transistor causes a lot of electrons from the emitter region to crossover to the base region. As the base is lightly doped with P-type impurity, the number of holes in the base region is very small and hence the number of electrons that combine with holes in the P-type base region is also very small. Hence a few electrons combine with holes to constitute a base current I_B. The remaining electrons (more than 95%) crossover into the collector region to constitute a collector current I_C. Thus, the base and collector current summed up gives the emitter current, i.e., $I_E = (I_C + I_B)$.

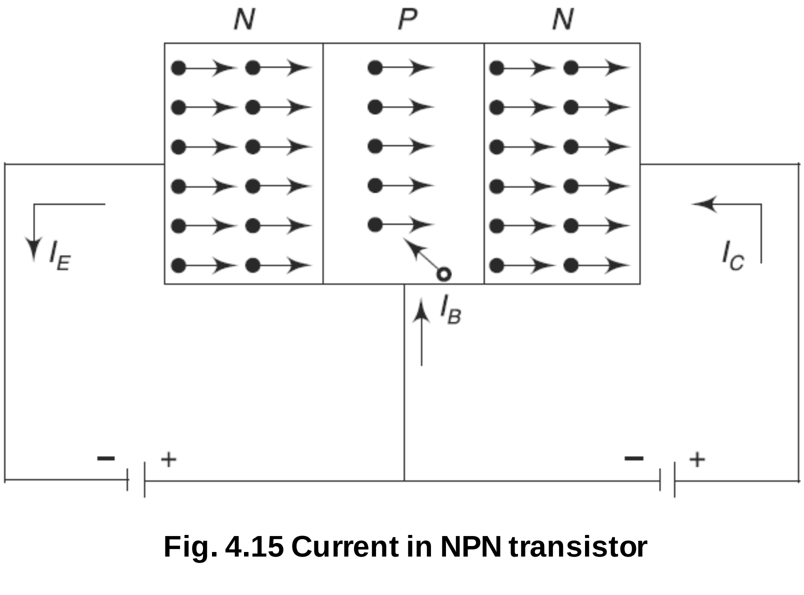


Fig. 4.15 Current in NPN transistor

In the external circuit of the NPN bipolar junction transistor, the magnitudes of the emitter current I_E, the base current I_B and the collector current I_C are related by $I_E = I_C + I_B$.

(d) Types of Configurations:

When a transistor is to be connected in a circuit, one terminal is used as an input terminal, the other terminal is used as an output terminal and the third terminal is common to the input and output. Depending upon the input, output and common terminal, a transistor can be connected in three configurations. They are: (i) Common base (CB) configuration, (ii) Common emitter (CE) configuration, and (iii) Common collector (CC) configuration.

(i) CB Configuration: This is also called grounded base configuration. In this configuration, emitter is the input terminal, collector is the output terminal and base is the common terminal.

(ii) CE Configuration: This is also called grounded emitter configuration. In this configuration, base is the input terminal, collector is the output terminal and emitter is the common terminal.

(iii) CC Configuration: This is also called grounded collector configuration. In this configuration, base is the input terminal, emitter is the output terminal and collector is the common terminal.

The supply voltage connections for normal operation of an NPN transistor in the three configurations are shown in Fig. 4.16.

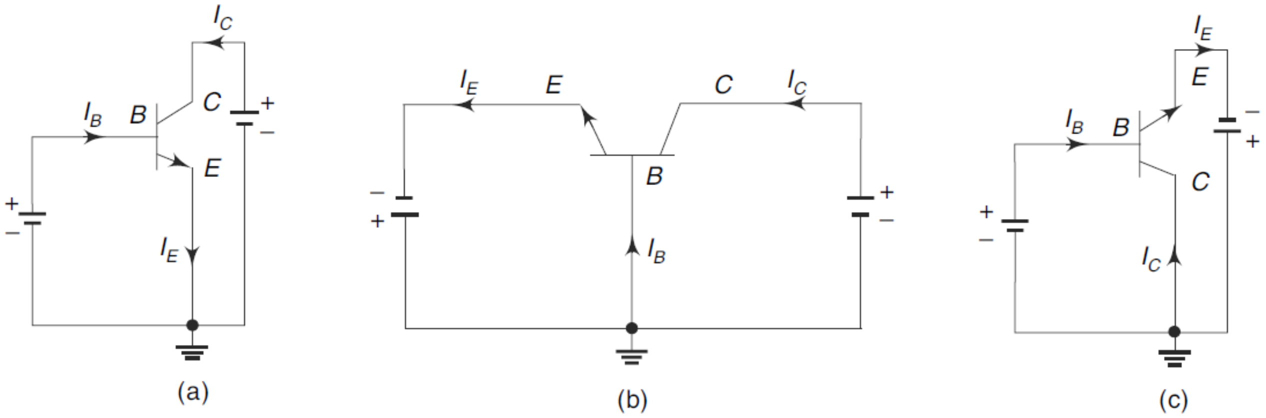
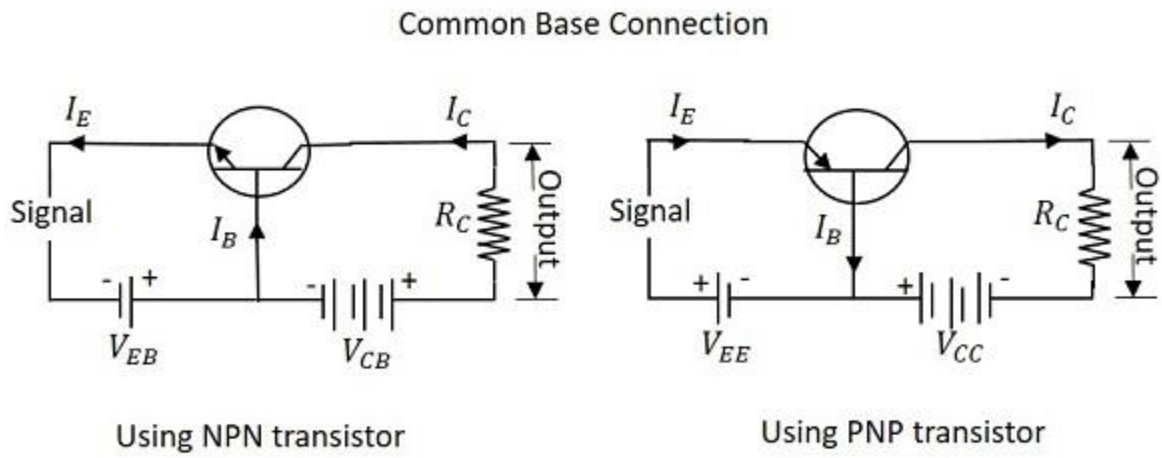


Fig. 4.16 Transistor configurations (a) Common base (b) Common emitter (c) Common Collector

4.6 TYPES OF CONFIGURATIONS

(i) COMMON BASE (CB) CONFIGURATION

The name itself implies that the Base terminal is taken as common terminal for both input and output of the transistor. The common base connection for both NPN and PNP transistors is as shown in the following figure.



For the sake of understanding, let us consider NPN transistor in CB configuration. When the emitter voltage is applied, as it is forward biased, the electrons from the negative terminal repel the emitter electrons and current flows through the emitter and base to the collector to contribute collector current. The collector voltage V_{CB} is kept constant throughout this.

In the CB configuration, the input current is the emitter current I_E and the output current is the collector current I_C.

Current Amplification Factor α:

The ratio of change in collector current ΔI_C to the change in emitter current ΔI_E when collector voltage V_{CB} is kept constant, is called as Current amplification factor. It is denoted by α.

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \; at\, constant\, V_{CB}$$

Expression for Collector current:

With the idea above, let us try to draw some expression for collector current. Along with the emitter current flowing, there is some amount of base current IB which flows through the base terminal due to electron hole recombination. As collector-base junction is reverse biased, there is another current which is flown due to minority charge carriers. This is the leakage current which can be understood as $I_{Leakage}$. This is due to minority charge carriers and hence very small.

The emitter current that reaches the collector terminal is – αI_E

Total collector current

$$I_C = \alpha I_E + I_{leakage}$$

If the emitter-base voltage $V_{EB} = 0$, even then, there flows a small leakage current, which can be termed as I_{CBO} collector−base current with output open.

The collector current therefore can be expressed as

$$I_C = \alpha I_E + I_{CBO}$$

$$I_E = I_C + I_B$$

$$I_C = \alpha(I_C + I_B) + I_{CBO}$$

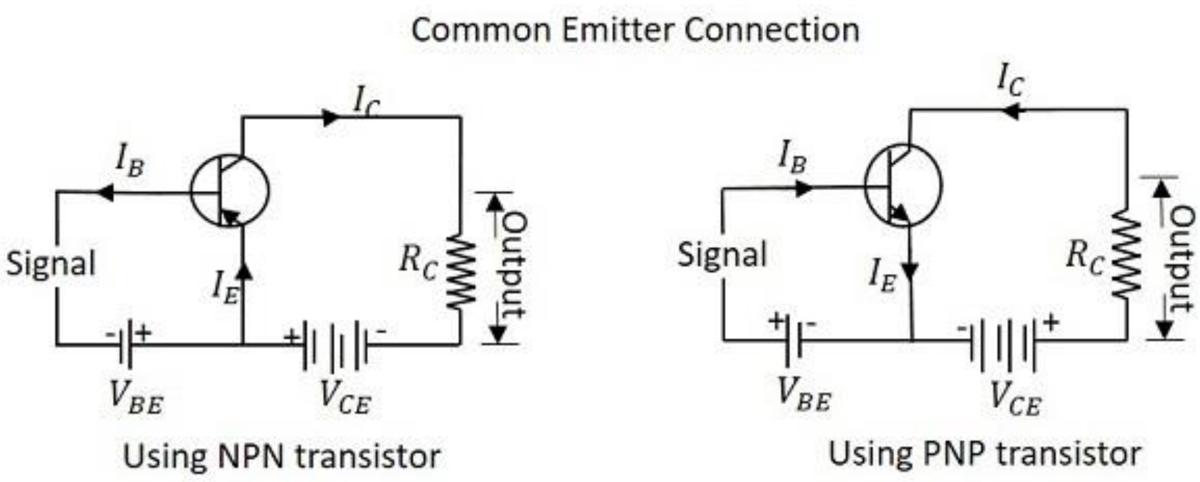
$$I_C(1 - \alpha) = \alpha I_B + I_{CBO}$$

$$I_C = \left(\frac{\alpha}{1 - \alpha}\right) I_B + \left(\frac{I_{CBO}}{1 - \alpha}\right)$$

$$I_C = \left(\frac{\alpha}{1 - \alpha}\right) I_B + \left(\frac{1}{1 - \alpha}\right) I_{CBO}$$

Hence the above derived is the expression for collector current. The value of collector current depends on base current and leakage current along with the current amplification factor of that transistor in use.

(ii) COMMON EMITTER (CE) CONFIGURATION:



The name itself implies that the Emitter terminal is taken as common terminal for both input and output of the transistor. The common emitter connection for both NPN and PNP transistors is as shown in the above figure.

Just as in CB configuration, the emitter junction is forward biased and the collector junction is reverse biased. The flow of electrons is controlled in the same manner. The input current is the base current I_B and the output current is the collector current I_C here.

Current Amplification Factor β:

The ratio of change in collector current ΔI_C to the change in base current ΔI_B is known as Base Current Amplification Factor. It is denoted by β.

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

Relation between β and α:

Let us try to derive the relation between base current amplification factor and emitter current amplification factor.

$$\beta = \frac{\Delta I_C}{\Delta I_B}$$

$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

$$I_E = I_B + I_C$$

$$\Delta I_E = \Delta I_B + \Delta I_C$$

$$\Delta I_B = \Delta I_E - \Delta I_C$$

We can write

$$\beta = \frac{\Delta I_C}{\Delta I_E - \Delta I_C}$$

Dividing by ΔI_E

$$\beta = \frac{\frac{\Delta I_C}{\Delta I_E}}{\frac{\Delta I_E}{\Delta I_E} - \frac{\Delta I_C}{\Delta I_E}}$$

We have

$$\alpha = \frac{\Delta I_C}{\Delta I_E}$$

Therefore

$$\beta = \frac{\alpha}{1-\alpha}$$

From the above equation, it is evident that, as α approaches 1, β reaches infinity. Hence, the current gain in Common Emitter connection is very high. This is the reason this circuit connection is mostly used in all transistor applications.

Expression for collector current:

In the Common Emitter configuration, I_B is the input current and I_C is the output current. We know

$$I_E = I_B + I_C$$

And

$$I_C = \alpha I_E + I_{CBO}$$

$$= \alpha(I_B + I_C) + I_{CBO}$$

$$I_C(1 - \alpha) = \alpha I_B + I_{CBO}$$

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBO}$$

If base circuit is open, i.e., if $I_B = 0$,

The collector emitter current with base open is I_{CEO}

$$I_{CEO} = \frac{1}{1-\alpha} I_{CBO}$$

Substituting the value of this in the previous equation, we get

$$I_C = \frac{\alpha}{1-\alpha} I_B + I_{CEO}$$

$$I_C = \beta I_B + I_{CEO}$$

Hence the equation for collector current is obtained.

4.7 INPUT – OUTPUT CHARACTERISTICS OF CE-CONFIGURATION

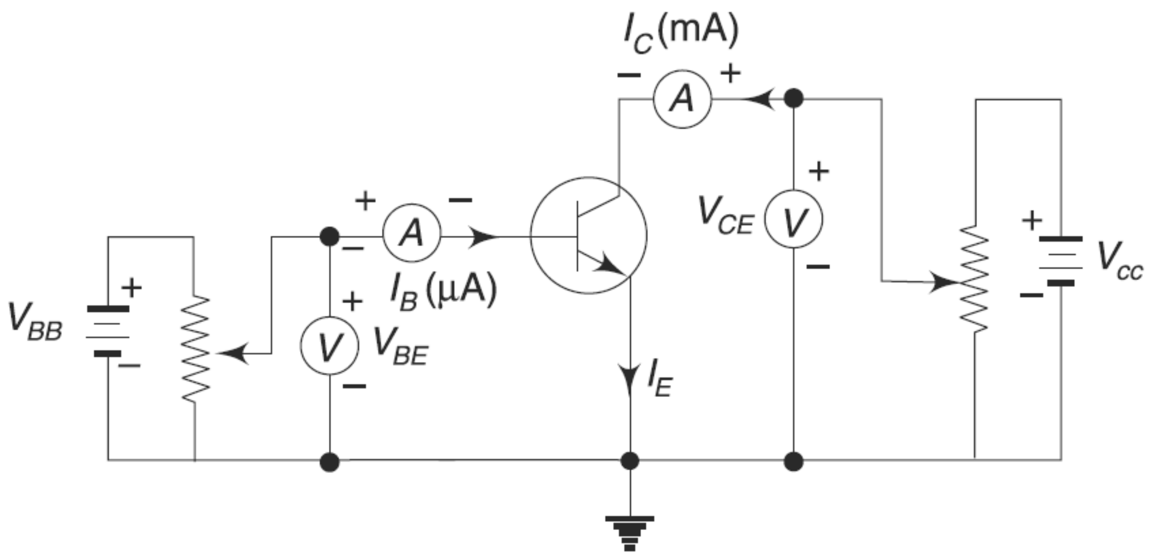


Fig. 4.17 Circuit to determine CE characteristics

Input Characteristics:

1. The input characteristics is a curve between input voltage V_{BE} and input current I_B with a constant output voltage V_{CE}. To determine the input characteristics, the collector to emitter voltage is kept constant at zero volt and base current is increased from zero in equal steps by increasing VBE in the circuit shown in Fig. 4.17.

2. The value of V_{BE} is noted for each setting of I_B. This procedure is repeated for higher fixed values of V_{CE}, and the curves of I_B Vs V_{BE} are drawn. The input characteristics thus obtained are shown in Fig. 4.18.

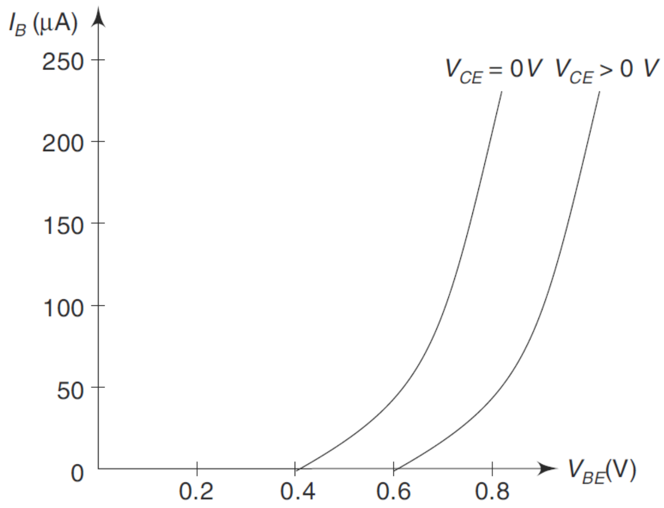


Fig. 4.18 CE input characteristics

3. When V_{CE} = 0, the emitter-base junction is forward biased and the junction behaves as a forward biased diode. Hence the input characteristic for V_{CE} = 0 is similar to that of a forward-biased diode.
4. When V_{CE} is increased, the width of the depletion region at the reverse biased collector base junction will increase. Hence the effective width of the base will decrease. This effect causes a decrease in the base current I_B. Hence, to get the same value of I_B as that for V_{CE} = 0, V_{BE} should be increased. Therefore, the curve shifts to the right as V_{CE} increases.

<u>Output Characteristics:</u>

1. The output characteristics is a curve between output voltage V_{CE} and output current I_C with a constant input current I_B. To determine the output characteristics, the base current I_B is kept constant at a suitable value by adjusting base-emitter voltage, V_{BE}. The magnitude of collector-emitter voltage V_{CE} is increased in suitable equal steps from zero and the collector current I_C is noted for each setting V_{CE}.
2. Now the curves of I_C versus V_{CE} are plotted for different constant values of I_B. The output characteristics thus obtained are shown in Fig. 4.19.

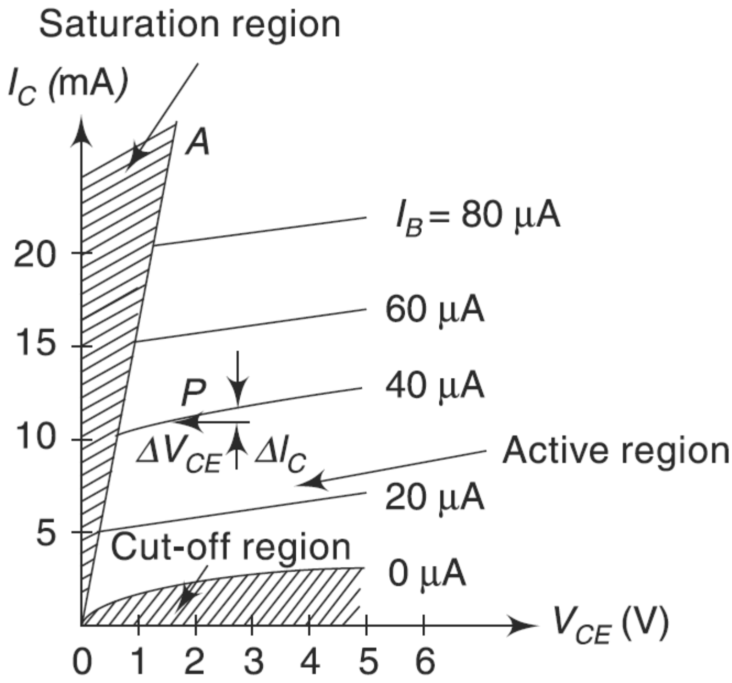


Fig. 4.19 CE output characteristics

3. The output characteristics have three regions, namely, saturation region, cut-off region and active region. The region of curves to the left of the line OA is called the saturation region (hatched), and the line OA is called the saturation line. In this region, both junctions are forward biased and an increase in the base current does not cause a corresponding large change in I_C. The ratio of $V_{CE(sat)}$ to I_C in this region is called saturation resistance.
4. The region below the curve for IB = 0 is called the cut-off region (hatched). In this region, both junctions are reverse biased. When the operating point for the transistor enters the cut-off region, the transistor is OFF.
5. The central region where the curves are uniform in spacing and slope is called the active region (unhatched). In this region, emitter-base junction is forward biased and the collector-base junction is reverse biased. If the transistor is to be used as a linear amplifier, it should be operated in the active region.

4.8 INTRODUCTION TO FET (Field Effect Transistor)

The FET is a device in which the flow of current through the conducting region is controlled by an electric field. Hence the name Field Effect Transistor (FET). As current conduction is only by majority carriers, FET is said to be a unipolar device. Based on the construction, the FET can be classified into two types as Junction FET(JFET) and

Metal Oxide Semiconductor FET(MOSFET) or Insulated Gate FET (IGFET) or Metal Oxide Silicon Transistor(MOST).

Depending upon the majority carriers, JFET has been classified into two types, namely, (1) N-channel JFET with electrons as the majority carriers, and (2) P-Channel JFET with holes as the majority carriers.

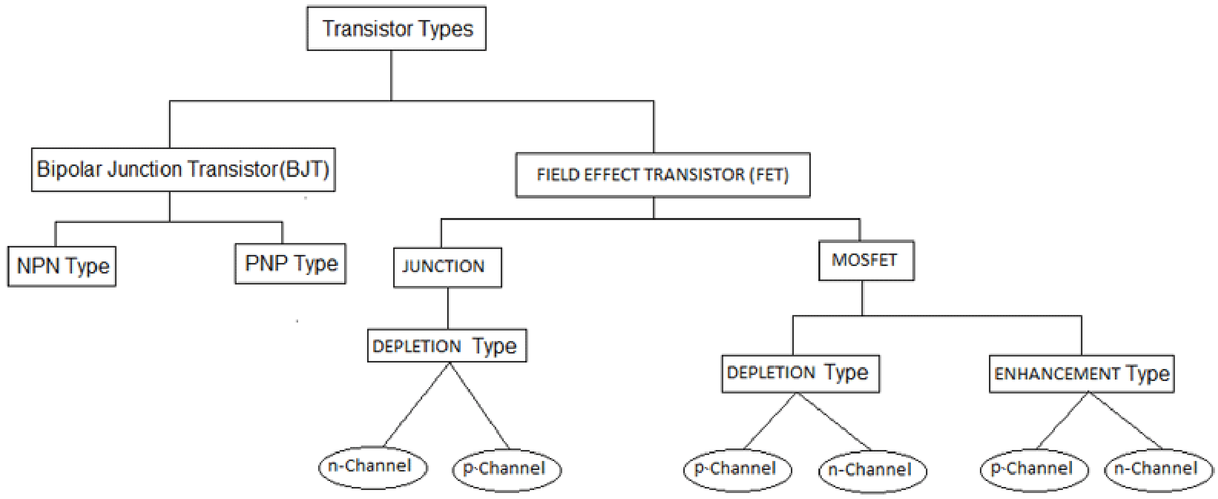


Fig. 4.20 Transistor classification

Construction of N-Channel JFET:

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

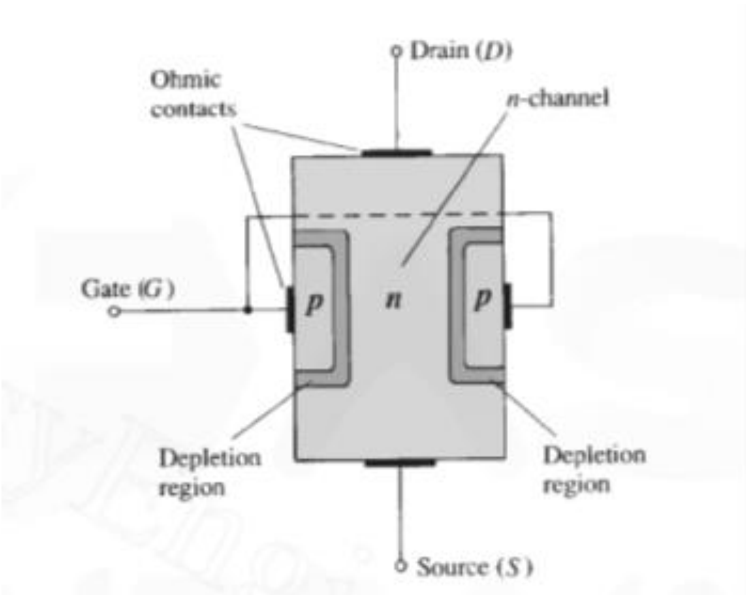


Fig. 4.21 Junction field effect transistor

Source (S): This terminal is connected to the negative pole of the battery. Electrons which are the majority carriers in the N-type bar enter the bar through this terminal.

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

Gate (G): 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 and called Gate G.

Channel: The region in N-type bar between source and drain 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 VDS = 0 and VGS = 0

When no voltage is applied between drain and source, and gate and source, the thickness of the depletion regions round the PN junction is uniform as shown in Fig. 4.22.

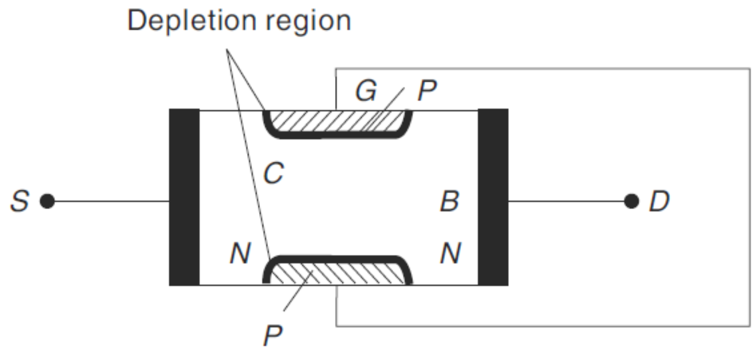


Fig. 4.22 JFET with no bias voltage

When VDS = 0 and VGS is decreased from zero

In this case, the PN junctions are reverse biased and hence the thickness of the depletion region increases. As Vgs 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 also increases until the two depletion regions make contact with each other. In this condition, the channel is said to be cut-off. The value of Vgs which is required to cut-off the channel is called the cut-off voltage V_C.

When VGS = 0 and VDS is increased from zero

Drain is positive with respect to the source with VGS = 0. Now the majority carriers (electrons) flow through the N-channel from source to drain. Therefore, the conventional current ID flows from drain to source. The magnitude of the current will depend upon the following factors:

1. The number of majority carriers (electrons) available in the channel, i.e., the conductivity of the channel.
2. The length L of the channel.
3. The cross-sectional area A of the channel at B.
4. The magnitude of the applied voltage VDS. Thus, the channel acts as a resistor of resistance R given by

$$R = \frac{\rho L}{A}$$

$$I_D = \frac{V_{DS}}{R} = \frac{A V_{DS}}{\rho L}$$

where ρ is the resistivity of the channel. Because of the resistance of the channel and the applied voltage VDS, there is a gradual increase of positive potential along the channel from source to drain. Thus, the reverse voltage across the PN junctions increases and hence the thickness of the depletion regions also increases. Therefore, the channel is wedge shaped as shown in Fig. 4.23.

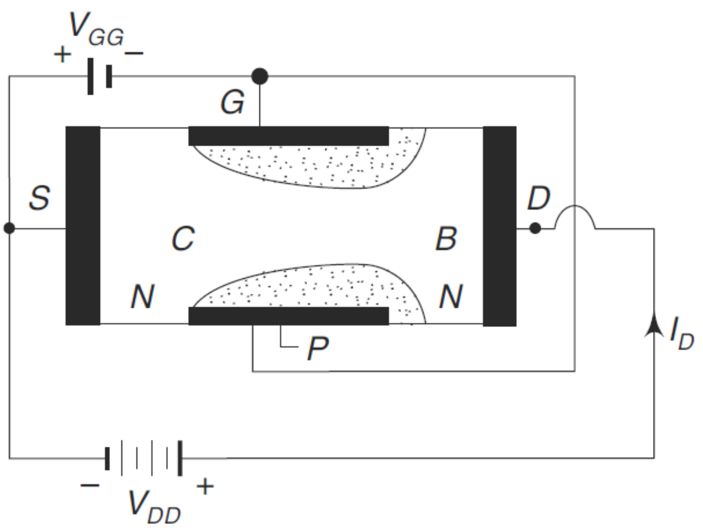


Fig. 4.23 JFET under applied bias

As V_{DS} is increased, the cross-sectional area of the channel will be reduced. At a certain value V_P of V_{DS}, the cross-sectional area at B becomes minimum. At this voltage, the channel is said to be pinched off and the drain voltage V_P is called the pinch-off voltage.

FET Drain Characteristics:

As a result of the decreasing cross-section of the channel with the increase of V_{DS}, the following results are obtained.

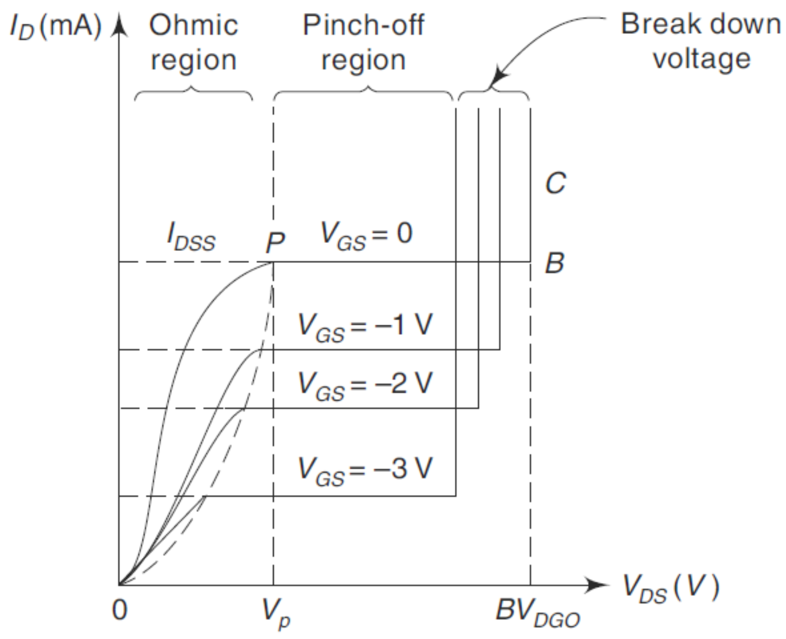


Fig. 4.24 FET drain characteristics

1. As V_{DS} is increased from zero, I_D increases along OP, and the rate of increase of I_D with V_{DS} decreases as shown in Fig. 4.24. The region from V_{DS} = 0 V to V_{DS} = VP is called the ohmic region.
2. When $V_{DS} = V_P$, I_D becomes maximum. When V_{DS} is increased beyond V_P, the length of the pinch-off or saturation region increases. Hence, there is no further increase of I_D.
3. At a certain voltage corresponding to the point B, I_D suddenly increases. This effect is due to the Avalanche multiplication of electrons caused by breaking of covalent bonds of silicon atoms in the depletion region between the gate and the drain. The drain voltage at which the breakdown occurs is denoted by BV_{DGO}. The variation of I_D with V_{DS} when Vgs = 0 is shown in Fig. 4.24 by the curve OPBC.

When VGS is negative and VDS is increased

When the gate is maintained at a negative voltage less than the negative cut-off voltage, the reverse voltage across the junction is further increased. Hence for a negative value of Vgs, the curve of I_D versus V_{DS} is similar to that for Vgs = 0, but the values of V_P and BV_{DGO} are lower, as shown in Fig. 4.24.

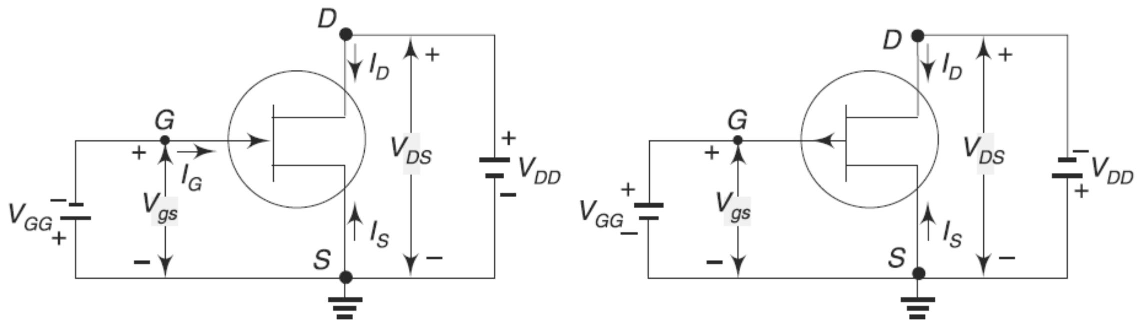
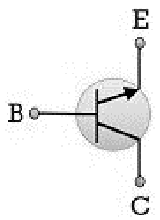
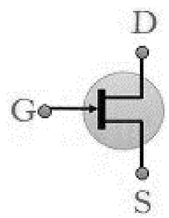


Fig. 4.25 Circuit symbols for N and P-channel JFET

Advantages of JFET:

1. The junction field effect transistor (JFET) is a majority charge carrier device hence it has less noise.
2. The JFET has high input impedance.
3. The JFET is a low power consumption device.
4. The JFET can be fabricated in small size area.
5. JFETs occupy less space in circuits due to its smaller size.
6. JFETs are protected to radiation.
7. The JFET has negative temperature coefficient of resistance, so they possess higher Temperature Stability.

Comparison between JFET and BJT:

Parameter	BJT	JFET
Carrier	Bipolar (majority & minority carriers)	Unipolar (Majority carriers)
Symbol		
Device type	Current controlled device	Voltage controlled device
Input Impendence	Low	High
Gain	High gain	Low – medium gain
Power Consumption	It consumes more power	It consumes less power
Noise Level	High	Low
Thermal Stability	Low	High

Size	Large	Small
Application Preference	It is preferred in low current application.	It is preferred in low voltage application.

4.9 UNI – JUNCTION TRANSISTOR (UJT)

Construction:

UJT is a three terminal semiconductor switching device. As it has only one PN junction and three leads, it is commonly called as Unijunction transistor. The basic structure of UJT is shown in Fig. 4.26(a). It consists of a lightly doped N-type Silicon bar with a heavily doped P-type material alloyed to its one side closer to B2 for producing single PN junction. The circuit symbol of UJT is shown in Fig. 4.26(b). Here the emitter leg is drawn at an angle to the vertical and the arrow indicates the direction of the conventional current.

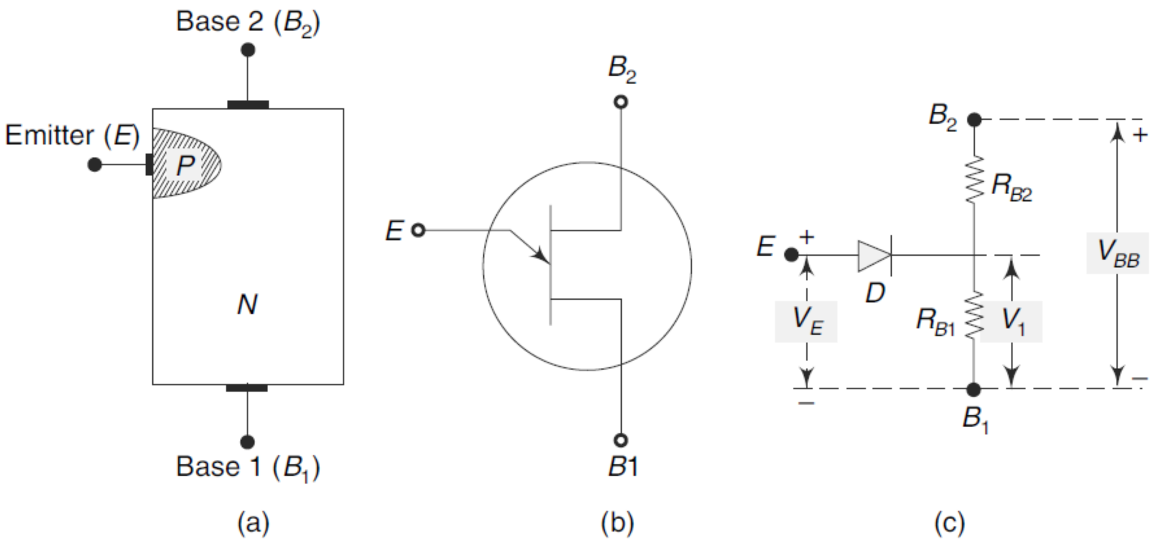


Fig. 4.26 (a) Basic structure (b) Circuit symbol and (c) Equivalent circuit

Working:

1. Referring to Fig. 4.26(c), the inter base resistance between B2 and B1 of the silicon bar is RBB = RB1 + RB2. With emitter terminal open, if voltage VBB is applied between the two bases, a voltage gradient is established along the N-type bar. The voltage drop across RB1 is given by V1 = ηVBB, where the intrinsic stand-off ratio η = RB1/(RB1 + RB2). The typical value of h ranges from 0.56 to 0.75. This voltage V1 reverse biases the PN junction and emitter current

is cut-off. But a small leakage current flows from B2 to emitter due to minority carriers.

2. If a positive voltage V_E is applied to the emitter, the PN junction will remain reverse biased so long as V_E is less than V_1. If V_E exceeds V_1 by the cut-in voltage $V\gamma$, the diode becomes forward biased. Under this condition, holes are injected into N-type bar. These holes are repelled by the terminal B2 and are attracted by the terminal B1.
3. Accumulation of holes in E to B1 region reduces the resistance in this section and hence emitter current IE is increased and is limited by VE. The device is now in the 'ON' state.
4. If a negative voltage is applied to the emitter, PN junction remains reverse biased and the emitter current is cut-off. The device is now in the 'OFF' state.

Characteristics:

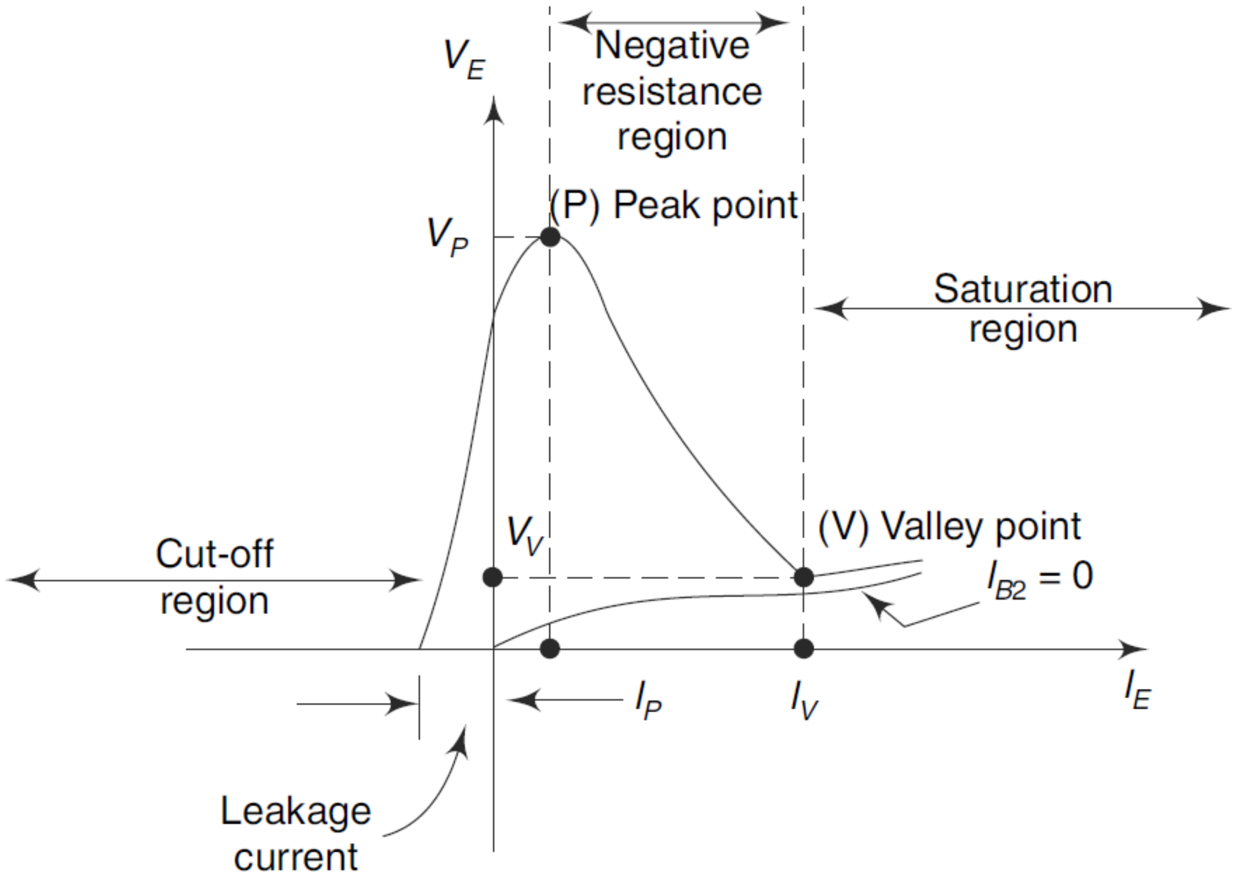


Fig. 4.27 Input characteristics of UJT

1. Figure 4.27 shows a family of input characteristics of UJT. Here, up to the peak point P, the diode is reverse biased and hence, the region to the left of the peak point is called cut-off region.
2. The UJT has a stable firing voltage V_P which depends linearly on VBB and a small firing current I_P (25 A). At P, the peak voltage $V_P = \eta VBB + V\gamma$, the diode starts conducting and holes are injected into N-layer. Hence, resistance decreases thereby decreasing V_E for the increase in I_E. So, there is a negative resistance region from peak point P to valley point V.
3. After the valley point, the device is driven into saturation and behaves like a conventional forward biased PN junction diode. The region to the right of the valley point is called saturation region. In the valley point, the resistance changes from negative to positive. The resistance remains positive in the saturation region.

UJT as Relaxation Oscillator:

The relaxation oscillator using UJT which is meant for generating sawtooth waveform is shown in Fig. 4.28. It consists of a UJT and a capacitor C_E which is charged through R_E as the supply voltage V_{BB} is switched ON.

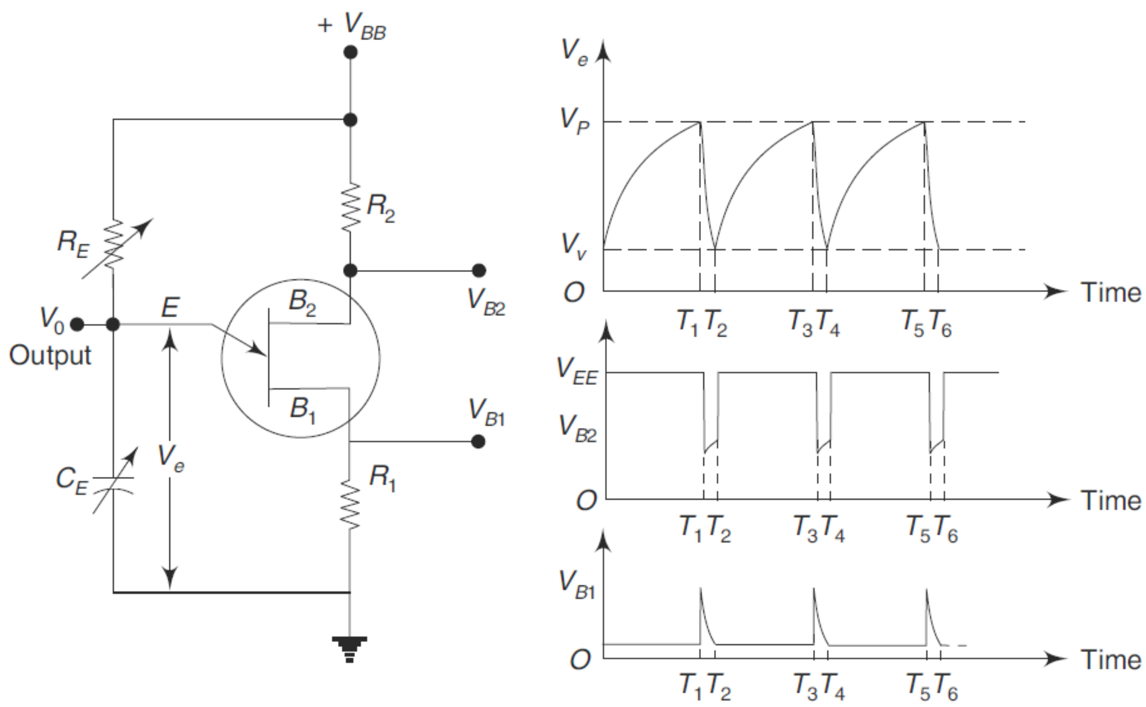


Fig. 4.28 UJT as relaxation oscillator

1. The voltage across the capacitor increases exponentially and when the capacitor voltage reaches the peak point voltage VP, the UJT starts conducting and the capacitor voltage is discharged rapidly through EB1 and R1.
2. After the peak point voltage of UJT is reached, it provides negative resistance to the discharge path which is useful in the working of the relaxation oscillator. As the capacitor voltage reaches zero, the device then cuts off and capacitor CE starts to charge again. This cycle is repeated continuously generating a sawtooth waveform across CE.
3. The inclusion of external resistors R2 and R1 in series with B2 and B1 provides spike waveforms. When the UJT fires, the sudden surge of current through B1 causes drop across R1, which provides positive going spikes. Also, at the time of firing, fall of VEBI causes I2 to increase rapidly which generates negative going spikes across R2.
4. By changing the values of capacitance CE or resistance RE, frequency of the output waveform can be changed as desired, since these values control the time constant RE CE of the capacitor charging circuit.
5. Therefore, the frequency of oscillations of sawtooth wave is

$$f_o = \frac{1}{T} = \frac{1}{2.303\, R_E\, C_E \log_{10} \frac{1}{(1-\eta)}}$$

UNIT-V: POWER SUPPLIES & PHOTOELECTRIC DEVICES
Rectifiers: Half wave, full wave rectifier, Bridge rectifier -Efficiency-ripple factor. Filters: L-section & π-section filters. I.C. regulators : Three Terminal Voltage Regulators (78XX & 79XX). Photo Electric Devices : Light Emitting Diode and Photo diode.

5.1 INTRODUCTION

All electronic circuits need d.c. power supply either from battery or power pack units. It may not be economical and convenient to depend upon battery power supply. Hence, many electronic equipment contains circuits which convert the a.c. supply voltage into d.c. voltage at the required level. The unit containing these circuits is called the Linear Mode Power Supply (LPS). In the absence of a.c. mains supply, the d.c. supply from battery can be converted into required a.c. voltage which may be used by computer and other electronic systems for their operation. Also, in certain applications, d.c. to d.c. conversion is required. Such a power supply unit that converts d.c. into a.c. or d.c. is called Switched Mode Power Supply (SMPS).

1. Linear power supply (LPS): a.c./d.c. power supply—Converter

2. Switched mode power supply (SMPS):

(i) d.c./d.c. power supply—Converter

(ii) d.c./a.c. power supply—Inverter

The basic building blocks of the linear power supply are shown in Fig. 5.1.

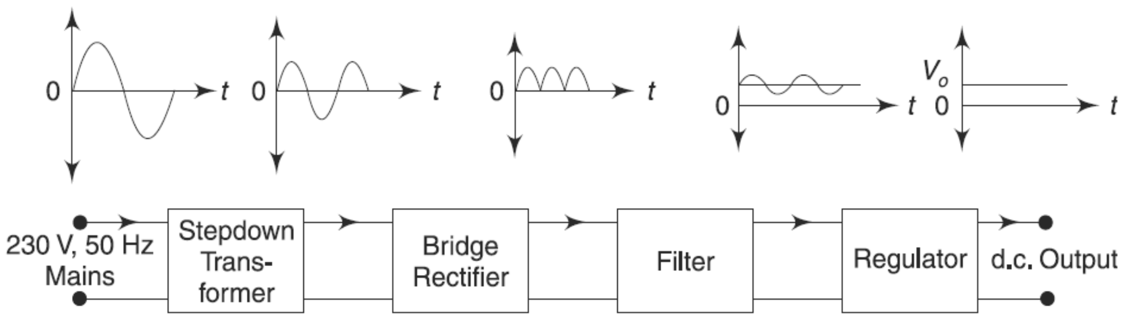


Fig. 5.1 Basic building blocks of linear mode power supply

A transformer supplies a.c. voltage at the required level. This bidirectional a.c. voltage is converted into a unidirectional pulsating d.c. using a rectifier. The unwanted ripple contents of this pulsating d.c. are removed by a filter to get pure d.c. voltage. The output of the filter is fed to a regulator which gives a steady d.c. output independent of load variations and input supply fluctuations.

5.2 RECTIFIERS

Rectifier is defined as an electronic device used for converting a.c. voltage into unidirectional voltage. A rectifier utilizes unidirectional conduction device like a vacuum diode or PN junction diode. Rectifiers are classified depending upon the period of conduction as Half-wave rectifier and Full-wave rectifier.

5.2.1 HALF-WAVE RECTIFIER

It converts an a.c. voltage into a pulsating d.c. voltage using only one half of the applied a.c. voltage. The rectifying diode conducts during one half of the a.c. cycle only. Figure 5.2 shows the basic circuit and waveforms of a half-wave rectifier.

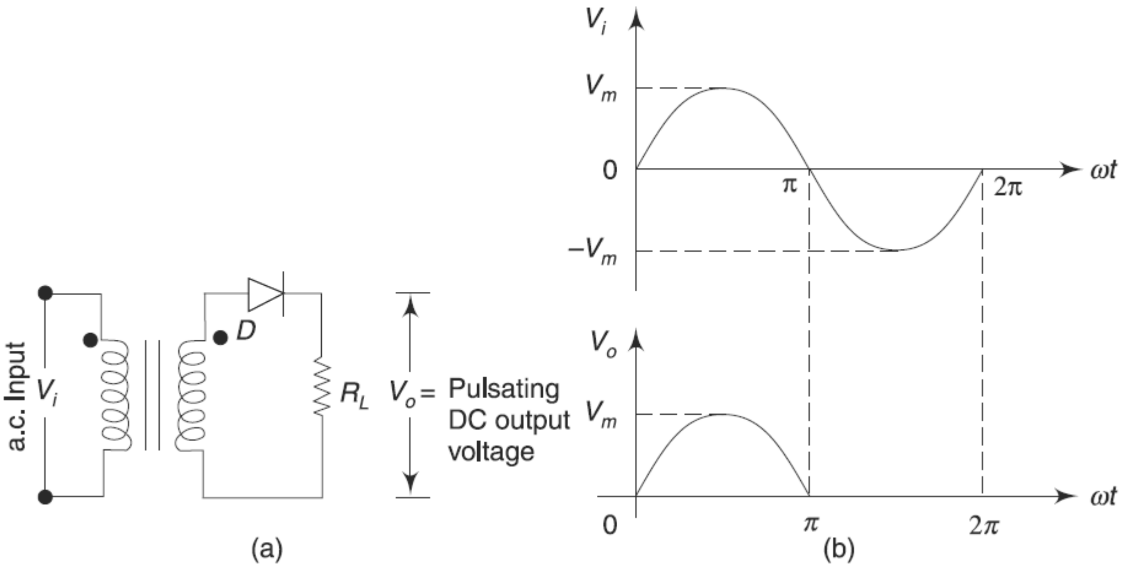


Fig. 5.2 (a) Basic structure of half-wave rectifier and (b) Input output waveforms of half-wave rectifier

Let Vi be the voltage to the primary of the transformer and given by the equation

$$V_i = V_m \sin wt;\ V_m >> V_\gamma$$

where V_γ is the cut-in voltage of the diode. During the positive half cycle of the input signal, the anode of the diode becomes more positive with respect to the cathode and hence, diode D conducts. For an ideal diode, the forward voltage drop is zero. So, the whole input voltage will appear across the load resistance, RL.

During negative half cycle of the input signal, the anode of the diode becomes negative with respect to the cathode and hence, diode D does not conduct. For an ideal diode, the impedance offered by the diode is infinity. So, the whole input voltage appears across diode D. Hence, the voltage drop across RL is zero.

Ripple factor ***(Γ)*** The ratio of rms value of a.c. component to the d.c. component in the output is known as ripple factor (Γ).

$$\Gamma = \frac{\text{rms value of a.c. component}}{\text{d.c. value of component}} = \frac{V_{r,\,\text{rms}}}{V_{\text{d.c.}}}$$

where $$V_{r,\,\text{rms}} = \sqrt{V_{\text{rms}}^2 - V_{\text{d.c.}}^2}$$

$$\Gamma = \sqrt{\left(\frac{V_{\text{rms}}}{V_{\text{d.c.}}}\right)^2 - 1}$$

V_{av} is the average or the d.c. content of the voltage across the load and is given by

$$V_{av} = V_{\text{d.c.}} = \frac{1}{2\pi}\left[\int_0^{\pi} V_m \sin \omega t d(\omega t) + \int_{\pi}^{2\pi} 0.\text{d}(\omega t)\right]$$

$$= \frac{V_m}{2\pi}[-\cos \omega t]_0^{\pi} = \frac{V_m}{\pi}$$

Therefore, $$I_{\text{d.c}} = \frac{V_{\text{d.c.}}}{R_L} = \frac{V_m}{\pi R_L} = \frac{I_m}{\pi}$$

If the values of diode forward resistance (r_f) and the transformer secondary winding resistance (R_s) are also taken into account, then

$$V_{\text{d.c.}} = \frac{V_m}{\pi} - I_{\text{d.c.}}(r_s + r_f)$$

$$I_{\text{d.c.}} = \frac{V_{\text{d.c.}}}{(r_s + r_f) + R_L} = \frac{V_m}{\pi(r_s + r_f + R_L)}$$

The rms voltage at the load resistance can be calculated as

$$V_{\text{rms}} = \left[\frac{1}{2\pi}\int_0^{\pi} V_m^2 \sin^2 \omega t \text{d}(\omega t)\right]^{\frac{1}{2}}$$

$$= V_m\left[\frac{1}{4\pi}\int_0^{\pi} (1 - \cos 2\,\omega t)\ \text{d}(\omega t)\right]^{\frac{1}{2}} = \frac{V_m}{2}$$

Therefore $$\Gamma = \sqrt{\left[\frac{V_m/2}{V_m/\pi}\right]^2 - 1} = \sqrt{\left(\frac{\pi}{2}\right)^2 - 1} = 1.21$$

From this expression it is clear that the amount of a.c. present in the output is 121% of the d.c. voltage. So the half-wave rectifier is not practically useful in converting a.c. into d.c.|

Efficiency ***(η)*** The ratio of d.c. output power to a.c. input power is known as rectifier efficiency (η).

$$\eta = \frac{\text{d.c. output power}}{\text{a.c. input power}} = \frac{P_{\text{d.c.}}}{P_{\text{a.c.}}}$$

$$= \frac{\dfrac{(V_{\text{d.c.}})^2}{R_L}}{\dfrac{(V_{\text{rms}})^2}{R_L}} = \frac{\left(\dfrac{V_m}{\pi}\right)^2}{\left(\dfrac{V_m}{2}\right)^2} = \frac{4}{\pi^2} = 0.406 = 40.6\%$$

The maximum efficiency of a half-wave rectifier is 40.6%.

Form Factor

$$\text{Form factor} = \frac{\text{rms value}}{\text{average value}}$$

$$= \frac{V_m/2}{V_m/\pi} = \frac{\pi}{2} = 1.57$$

Peak Factor

$$\text{Peak factor} = \frac{\text{peak value}}{\text{rms value}}$$

$$= \frac{V_m}{V_m/2} = 2$$

5.2.2 FULL-WAVE RECTIFIER

It converts an a.c. voltage into a pulsating d.c. voltage using both half cycles of the applied a.c. voltage. It uses two diodes of which one conducts during one half-cycle while the other diode conducts during the other half-cycle of the applied a.c. voltage. There are two types of full-wave rectifiers viz. (i) Full-wave rectifier with center tapped transformer and (ii) Full-wave rectifier without transformer (Bridge rectifier).

(i) Full-wave rectifier with center tapped transformer (Center tapped full-wave rectifier)

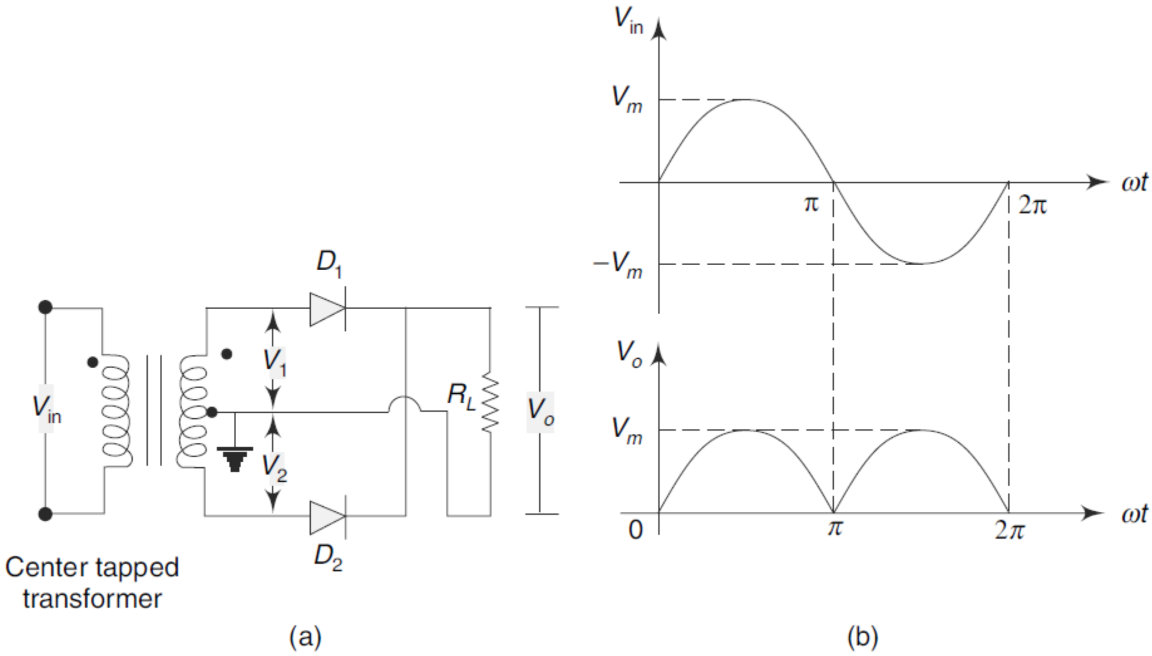


Fig. 5.3 (a) Center tapped full-wave rectifier and (b) Input output waveforms

Figure 5.3 shows the basic circuit and waveforms of full-wave rectifier. During positive half of the input signal, anode of diode D1 becomes positive and at the same time the anode of diode D2 becomes negative. Hence, D1 conducts and D2 does not conduct. The load current flows through D1 and the voltage drop across RL will be equal to the input voltage.

During the negative half-cycle of the input, the anode of D1 becomes negative and the anode of D2 becomes positive. Hence, D1 does not conduct and D2 conducts. The load current flows through D2 and the voltage drop across R_L will be equal to the input voltage.

Ripple factor (Γ)

$$\Gamma = \sqrt{\left(\frac{V_{\text{rms}}}{V_{\text{d.c.}}}\right)^2 - 1}$$

The average voltage or d.c. voltage available across the load resistance is

$$V_{\text{d.c.}} = \frac{1}{\pi}\int_0^{\pi} V_m \sin \omega t \, d(\omega t)$$

$$= \frac{V_m}{\pi}[-\cos \omega t]_0^{\pi} = \frac{2V_m}{\pi}$$

$$I_{\text{d.c.}} = \frac{V_{\text{d.c.}}}{R_L} = \frac{2V_m}{\pi R_L} = \frac{2I_m}{\pi} \text{ and } I_{\text{rms}} = \frac{I_m}{\sqrt{2}}$$

If the diode forward resistance (r_f) and the transformer secondary winding resistance (r_s) are included in the analysis, then

$$V_{\text{d.c}} = \frac{2V_m}{\pi} - I_{\text{d.c.}}(r_s + r_f)$$

$$I_{\text{d.c.}} = \frac{V_{\text{d.c.}}}{(r_s + r_f) + R_L} = \frac{2V_m}{\pi(r_s + r_f + R_L)}$$

RMS value of the voltage at the load resistance is

$$V_{\text{rms}} = \sqrt{\left[\frac{1}{\pi}\int_0^{\pi} V_m^2 \sin^2 \omega t \, d(\omega t)\right]} = \frac{V_m}{\sqrt{2}}$$

Therefore,

$$\Gamma = \sqrt{\left(\frac{V_m/\sqrt{2}}{2V_m/\pi}\right)^2 - 1} = \sqrt{\frac{\pi^2}{8} - 1} = 0.482$$

Efficiency (η) The ratio of d.c. output power to a.c. input power is known as rectifier efficiency (η).

$$\eta = \frac{\text{d.c. output power}}{\text{a.c. input power}} = \frac{P_{\text{d.c.}}}{P_{\text{a.c.}}}$$

$$= \frac{(V_{\text{d.c.}})^2/R_L}{(V_{\text{rms}})^2/R_L} = \frac{\left[\frac{2V_m}{\pi}\right]^2}{\left[\frac{V_m}{\sqrt{2}}\right]^2} = \frac{8}{\pi^2} = 0.812 = 81.2\%$$

The maximum efficiency of a full-wave rectifier is 81.2%.

(a) Form factor

$$\text{Form factor} = \frac{\text{rms value of the output voltage}}{\text{average value of the output voltage}}$$

$$= \frac{V_m/\sqrt{2}}{2V_m/\pi} = \frac{\pi}{2\sqrt{2}} = 1.11$$

(b) Peak factor

$$\text{Peak factor} = \frac{\text{peak value of the output voltage}}{\text{rms value of the output voltage}} = \frac{V_m}{V_m/\sqrt{2}} = \sqrt{2}$$

(ii) Bridge rectifier

The need for a center tapped transformer in a full-wave rectifier is eliminated in the bridge rectifier. As shown in Fig. 5.4, the bridge rectifier has four diodes connected to form a bridge. The a.c. input voltage is applied to the diagonally opposite ends of the bridge. The load resistance is connected between the other two ends of the bridge.

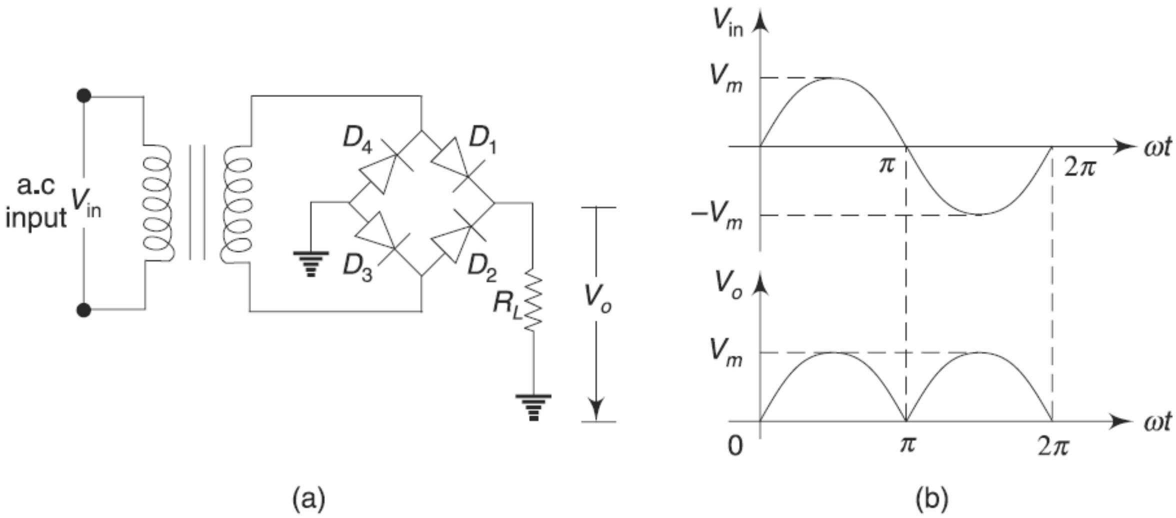


Fig. 5.4 (a) Bridge type full-wave rectifier and (b) Input output waveforms

For the positive half-cycle of the input a.c. voltage, diodes D1 and D3 conduct, whereas diodes D2 and D4 do not conduct. The conducting diodes will be in series through the load resistance RL. So, the load current flows through RL.

During the negative half-cycle of the input a.c. voltage, diodes D2 and D4 conduct, whereas diodes D1 and D3 do not conduct. The conducting diode D2 and D4 will be in series through the load RL and the current flows through RL in the same direction as in the previous half-cycle. Thus, a bidirectional wave is converted into a unidirectional one.

Note: Mathematical analysis of ripple factor, efficiency, form factor and peak factors for bridge rectifier is same as center tapped full-wave rectifier.

Comparison of Rectifiers:

Particulars	*Type of rectifier*		
	Half-wave	*Full-wave*	*Bridge*
No. of diodes	1	2	4
Maximum efficiency	40.6%	81.2%	81.2%
$V_{d.c.}$ (no load)	V_m/π	$2V_m/\pi$	$2V_m/\pi$
Average current/diode	$I_{d.c.}$	$I_{d.c.}/2$	$I_{d.c.}/2$
Ripple factor	1.21	0.48	0.48
Peak inverse voltage	V_m	$2V_m$	V_m
Output frequency	f	$2f$	$2f$
Transformer utilisation factor	0.287	0.693	0.812
Form factor	1.57	1.11	1.11
Peak factor	2	$\sqrt{2}$	$\sqrt{2}$

5.3 FILTERS

The output of a rectifier contains d.c. component as well as a.c. component. Filters are used to minimize the undesirable a.c., i.e., ripple leaving only the d.c. component to appear at the output. The ripple in the rectified wave being very high, the factor being 48% in the full-wave rectifier; majority of the applications which cannot tolerate this, will need an output which has been further processed.

Figure 5.5 shows the concept of a filter, where the full-wave rectified output voltage is applied at its input. The output of a filter is not exactly a constant d.c. level. But it also contains a small amount of a.c. component. Some important filters are:

I. Inductor filter
II. Capacitor filter
III. LC or L-section filter
IV. CLC or π-type filter

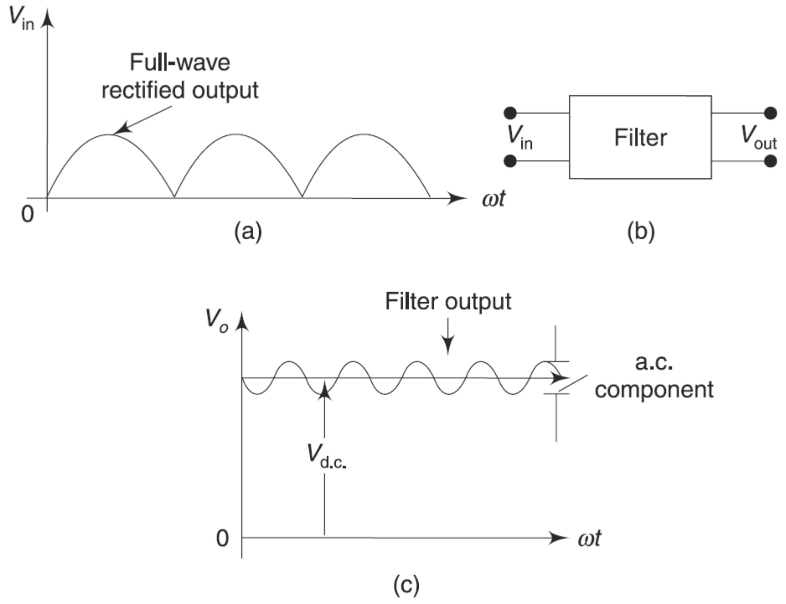
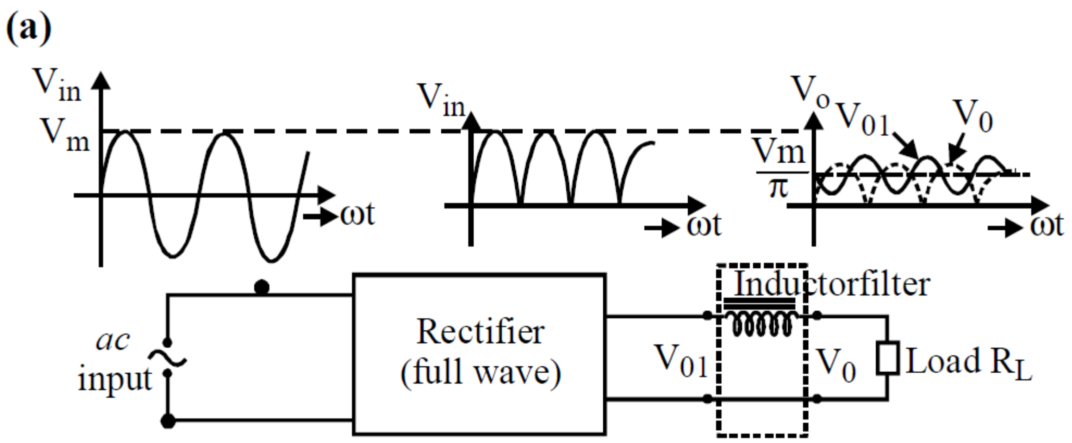


Fig. 5.5 Concept of filter

5.3.1 Inductor Filter:

It is also called as series inductor filter. Figure 5.6(a) shows the inductor filter. An inductor (choke) is just connected in series with the load. The inductors have the inherent property to oppose the change of current. This property of the inductor is utilized here to suppress the ac component (ripples) from the output of a rectifier.

The reactance $X_L = 2\pi fL$ of the inductor is large for high frequencies and offers more opposition to them but it allows the dc component of the rectifier to flow to the load at output. Thus, it smooths out the rectifier output from V_{01} to V_0, as shown in Fig. 5.6(b).



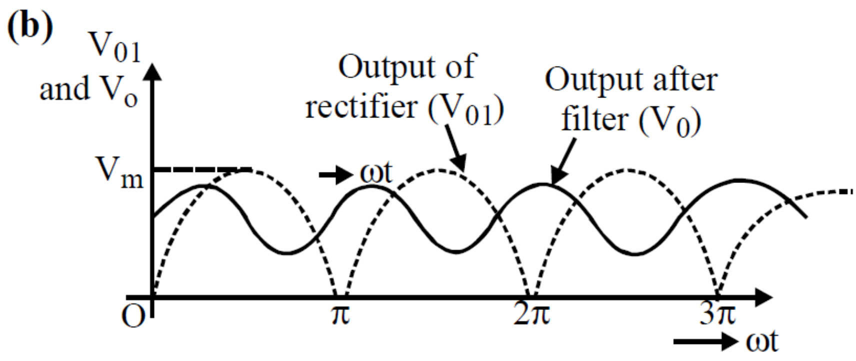


Fig. 5.6 (a) Inductor filter and (b) Filter output

The ripple factor of the Inductor filter is given by

$$\Gamma = \frac{R_L}{3\sqrt{2}\ \omega L}$$

5.3.2 Capacitor Filter:

It is also called as shunt capacitor filter. Figure 2.23a shows the capacitor filter. The capacitor is just connected in parallel (shunt) with the load. The property of a capacitor in series is that it allows ac component and blocks the dc compound. Thus, the operation of a shunt capacitor filter here is to short and bypass the ripple to ground, leaving the purer dc to appear at the output.

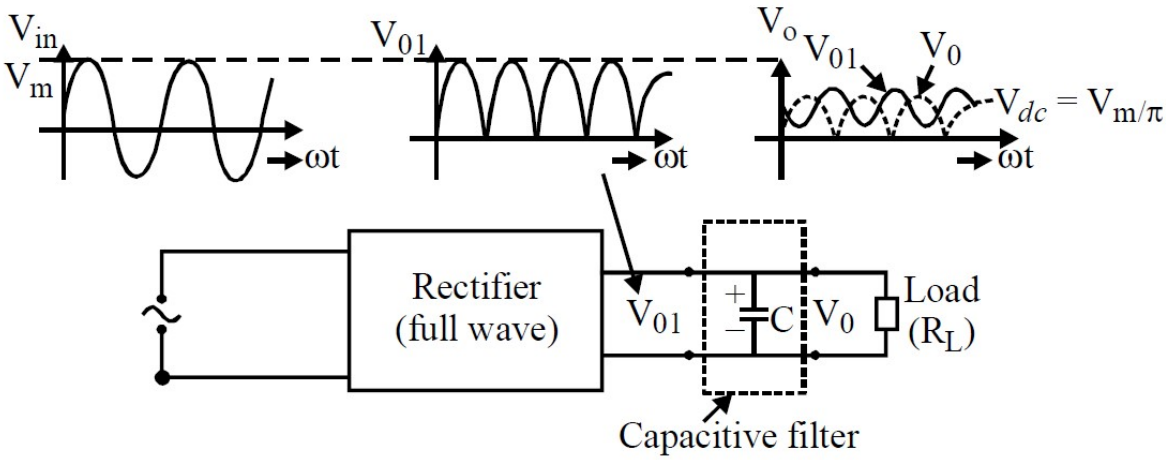


Fig. 5.7(a) Capacitor filter

During positive half cycle, the capacitor charges up to the peak value of the transformer secondary voltage Vm and will try to maintain this value (by supplying its charge current) when the full-wave input drops to zero. This requires large capacitor of 1000 µF or so.

Thus, this capacitor discharge through RL slowly until the transformer secondary voltage again increases to a value greater than the capacitor voltage. The diode conducts for a period which depends on the capacitor voltage (equal to the load voltage). The diode will conduct when the transformer secondary voltage becomes more than the 'cut-in' voltage of the diode. The diode stops conducting when the transformer voltage becomes less than the diode voltage. This is called cut-out voltage. The ripple voltage waveform across load resistance RL and charging and discharging of the capacitor during positive and negative half cycles of rectifier is shown in Fig. 5.7(b).

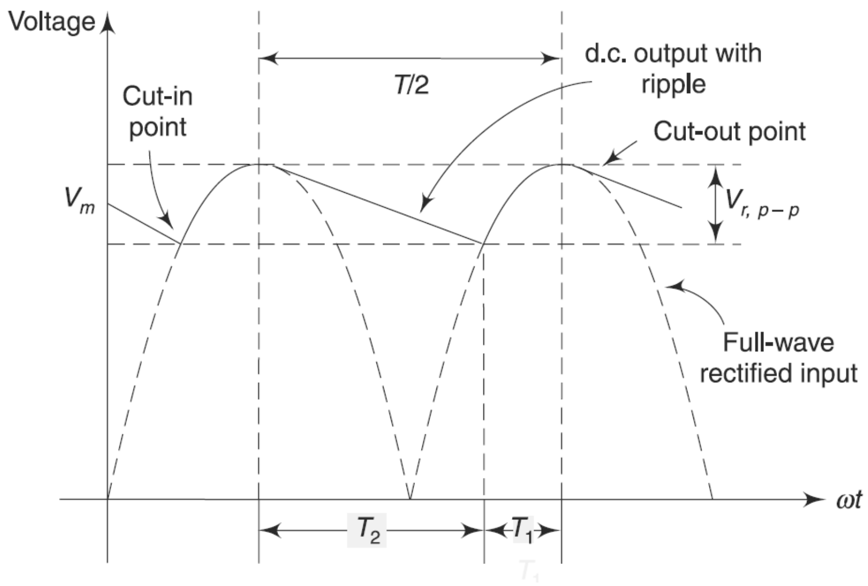


Fig. 5.7(b) Ripple voltage waveform across load R_L

Therefore, ripple factor $$\Gamma = \frac{V_{r,\,\text{rms}}}{V_{\text{d.c.}}} = \frac{1}{4\sqrt{3}\,fCR_L}$$

The ripple may be decreased by increasing C or R_L (or both) with a resulting increase in d.c. output voltage.

5.3.3 LC or L-Section Filter:

We know that the ripple factor is directly proportional to the load resistance RL in the inductor filter and inversely proportional to RL in capacitor filter. Therefore, if these two filters are combined as LC filter or L-section filter as shown in Fig. 5.8, the ripple factor will be independent of RL.

If the inductor value is increased, then it will increase the time of conduction. At some critical value of inductance, one diode D1 or D2 in full-wave center-tapped rectifier will always be conducting.

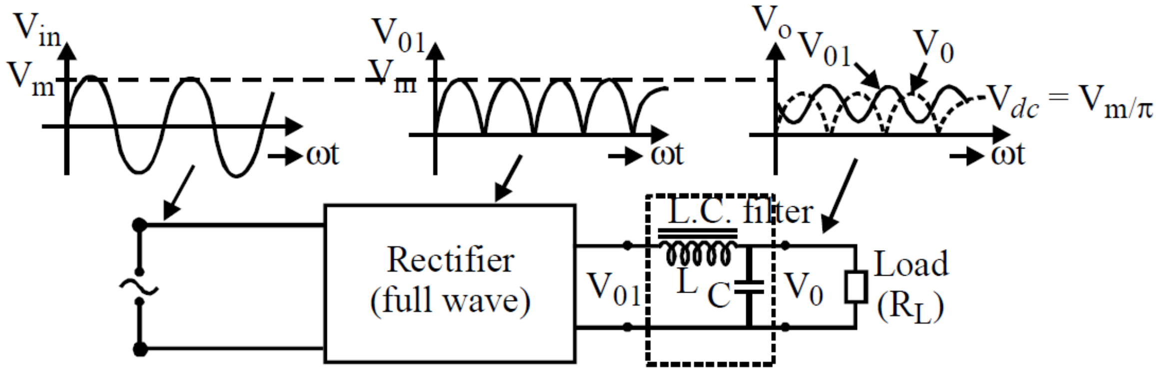


Fig. 5.8 LC or L-section filter

The ripple factor,
$$\Gamma = \frac{V_{r,\,\text{rms}}}{V_{\text{d.c.}}} = \frac{\sqrt{2}}{3}\cdot\frac{X_C}{X_L}$$
$$= \frac{\sqrt{2}}{3}\cdot\frac{1}{4\omega^2 C_L}, \text{ since } X_C = \frac{1}{2\omega C} \text{ and } X_L = 2\omega L$$

If f = 50 Hz, C is in μF and L is in Henry, ripple factor $\Gamma = \dfrac{1.194}{LC}$.

Advantages

(a) Ripple factor is very low (<1%).
(b) Ripple factor is independent of load resistance.
(c) Such filters are suitable for both heavy and low loads.

Disadvantages

(a) It cannot be used for half-wave rectifiers.
(b) The amplitude of output voltage is less.
(c) Inductances are more bulky and occupies more space.

5.3.4 CLC or π-Type Filter:

Figure 5.9 shows the CLC or π-type filter which basically consists of a capacitor filter followed by an LC section. The action of a π-section filter can best be understood by considering the inductor and the second capacitor as an L-section filter that acts upon the triangular output-voltage wave from the first capacitor. The output voltage is then approximately that from the input capacitor, decreased by the d.c. voltage drop in the inductor. The ripple contained in this output is reduced by the L-section filter.

Hence the ripple factor is

$$\Gamma = \frac{V_{\text{rms}}}{V_{\text{d.c.}}} = \frac{\sqrt{2} I_{\text{d.c.}} X_{C1}}{V_{\text{d.c.}}} \frac{X_{C2}}{X_{L1}} = \sqrt{2} \frac{X_{C1}}{R_L} \frac{X_{C2}}{X_{L1}}$$

where all reactance are calculated at the second-harmonic frequency.

For $f = 60$ Hz, the above equation reduces to

$$\Gamma = \frac{3{,}300}{C_1 C_2 L_1 R_L}$$

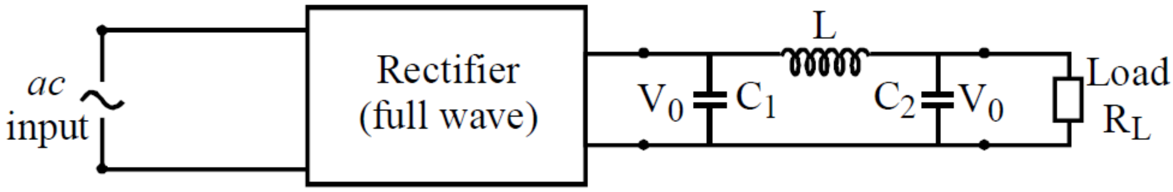


Fig. 5.9 CLC or π-type filter

5.4 IC (Integrated Circuit) VOLTAGE REGULATORS

5.4.1 Three Terminal Voltage Regulators:

Figure 5.10 shows the basic connection of a three-terminal voltage regulator IC to a load. The fixed voltage regulator has an unregulated dc input voltage V_i applied to one input terminal, a regulated output dc voltage V_o from a second terminal, and the third terminal connected to ground. For a selected regulator, IC device specifications list a voltage range over which the input voltage can vary to maintain a regulated output voltage over a range of load current.

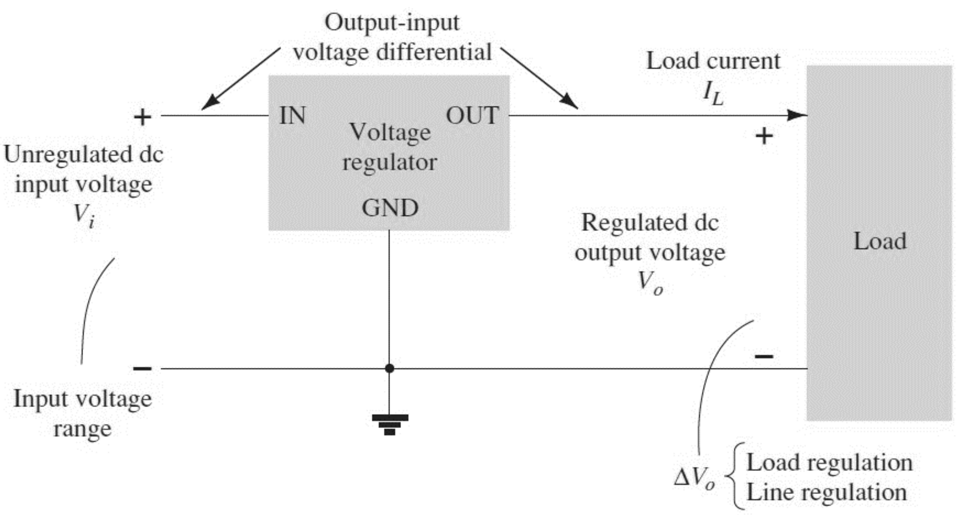


Fig. 5.10 Block diagram of three terminal voltage regulator

5.4.2 Fixed Positive Voltage Regulators (78XX):

The series 78 regulators provide fixed regulated voltages from 5 V to 24 V. Figure 5.11 shows how one such IC, a 7812, is connected to provide voltage regulation with output from this unit of +12 V dc. An unregulated input voltage V_i is filtered by capacitor C1 and connected to the IC's IN terminal. The IC's OUT terminal provides a regulated +12 V, which is filtered by capacitor C2 (mostly for any high-frequency noise). The third IC terminal is connected to ground (GND).

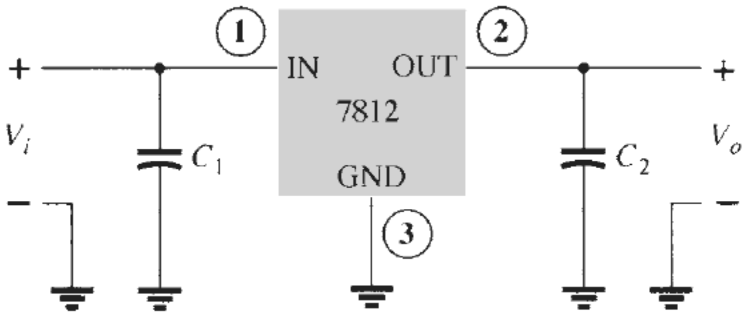


Fig. 5.11 Connections of a 7812 Voltage regulator

Whereas the input voltage may vary over some permissible voltage range and the output load may vary over some acceptable range, the output voltage remains constant within specified voltage variation limits. These limitations are spelled out in the manufacturer's specification sheets. A table of positive-voltage regulator ICs is provided in Table 5.1.

Table 5.1: Positive Voltage regulators in 7800 series

IC Part	Output Voltage (V)	Minimum V_i (V)
7805	+5	7.3
7806	+6	8.3
7808	+8	10.5
7810	+10	12.5
7812	+12	14.6
7815	+15	17.7
7818	+18	21.0
7824	+24	27.1

The connections of a 7812 in a complete voltage supply is shown in the connections of Fig. 5.12 . The ac line voltage (120 V rms) is stepped down to 18 V rms across each half of the center-tapped transformer. A full-wave rectifier and capacitor filter then provides an unregulated dc voltage, shown as a dc voltage of about 22 V, with ac ripple of a few volts as input to the voltage regulator. The 7812 IC then provides an output that is a regulated +12 V dc.

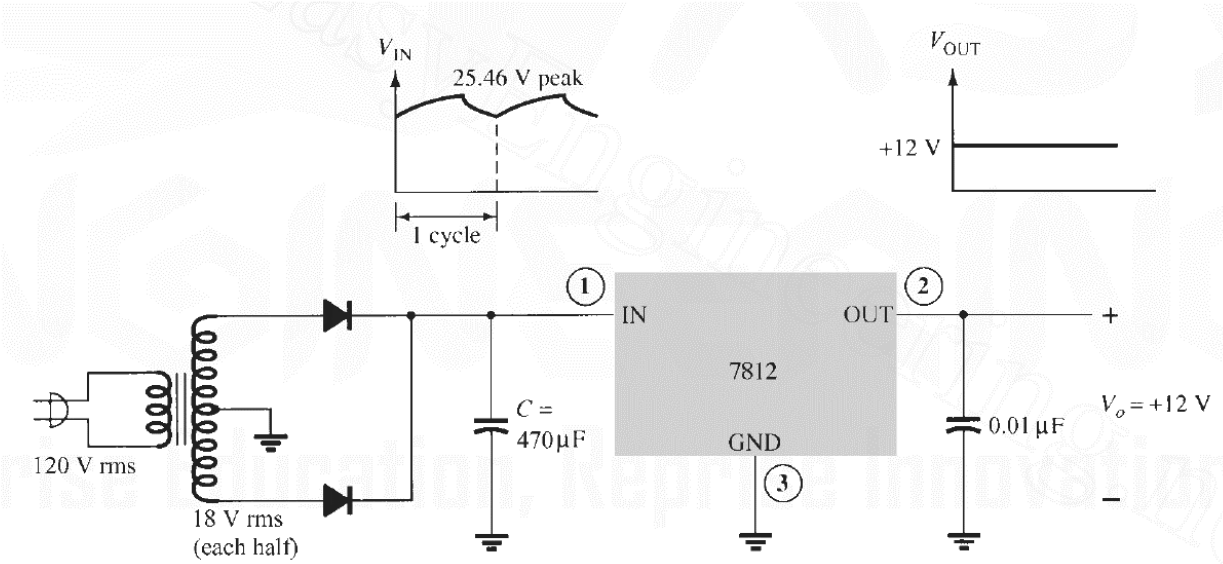


Fig. 5.12 A +12V Power supply

5.4.3 Fixed Negative Voltage Regulators (79XX):

The series 7900 ICs provide negative-voltage regulators, similar to those providing positive voltages. A list of negative-voltage regulator ICs is provided in Table 5.2 . As shown, IC regulators are available for a range of fixed negative voltages, the selected IC providing the rated output voltage as long as the input voltage is maintained greater than the minimum input value. For example, the 7912 provides an output of -12 V as long as the input to the regulator IC is more negative than -14.6 V.

Table 5.2: Negative Voltage regulators in 7900 series

IC Part	Output Voltage (V)	Minimum V_i (V)
7905	−5	−7.3
7906	−6	−8.4
7908	−8	−10.5
7909	−9	−11.5
7912	−12	−14.6
7915	−15	−17.7
7918	−18	−20.8
7924	−24	−27.1

5.5 Photo Electric Devices

5.5.1. Light-Emitting Diode (LED)

1. LED is an abbreviation of light-emitting diode. An LED-based display is perhaps the most important in the display devices used for various applications.
2. Some semiconductor materials used in LED manufacturing and their emitting colour of light is given in Table.

Colour	Semiconductor Material
Infrared (IR)	GaAs; GaAlAs; Si; Ge;
Red	GaAsP; CdSe;
Orange and yellow	InGaP; GaP, SiC

1. An LED is moderately doped pn junction made from some special materials like GaAs, GaP, GaN, InP, AlN, etc.
2. **Radiation emission:** When this diode is forward biased, then some of the electrons of the valence band (E_V) absorbs energy/get excited and jump to the conduction band (E_C), creating holes in valence band. At the same time, some of the excited electrons keep returning back to the valence band (E_V) to recombine with the holes they left, thereby losing energy (i.e. emitting earlier absorbed energy). In this process of recombination with holes (Fig.1), this energy (E_g = hv) emitted is equivalent to the optical radiation energy getting emitted having frequency v.
3. Recombination may be of two types:

   1. Direct recombination: E_C to E_V directly as shown in Fig.2a.

   2. Indirect recombination: E_C to E_V after stopping on a trap level (as shown in Fig.2b). This will lead to two types of radiations at frequencies v1 and v2.

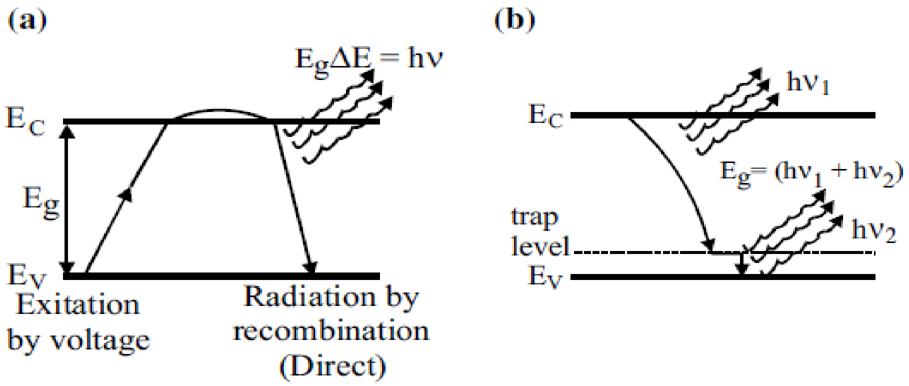


Fig. 2 a) Direct recombination, b) indirect recombination

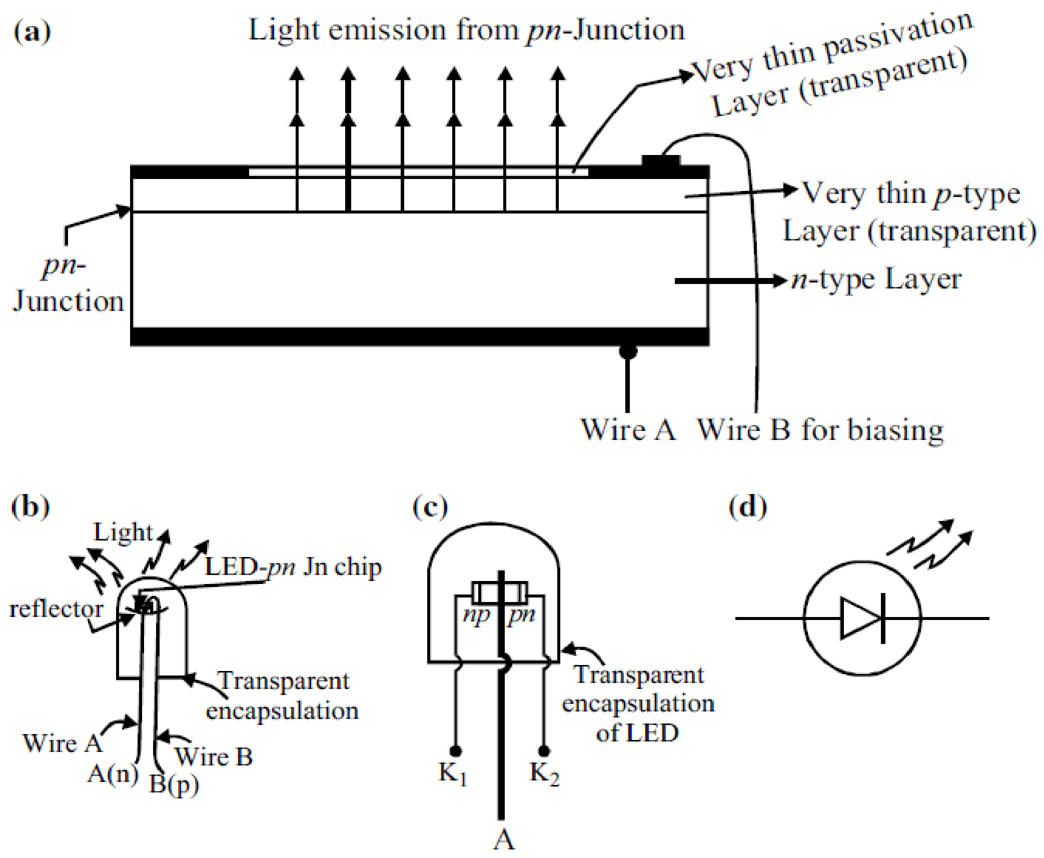


Fig. 3 a) Combination of an LED semiconductor pn junction, b) The active transparent encapsulated LED, c) Bi-colour LED and d) Symbol of LED

4. The construction of an LED is shown in Fig. 3a in chip form and in Fig.3b in the packaged form Fig. 3c shows the LED that can give two colours, when two chips (LEDs) are fixed on a single conductor A, with two wires for the two LED's, biasing. When AK_1 is forward biased, it gives one colour and with AK_2 biasing another colour. Therefore, a.c. signal of low frequency between AK_1 and AK_2 will give slow flickering of alternate colour, which will be visible to our eyes.

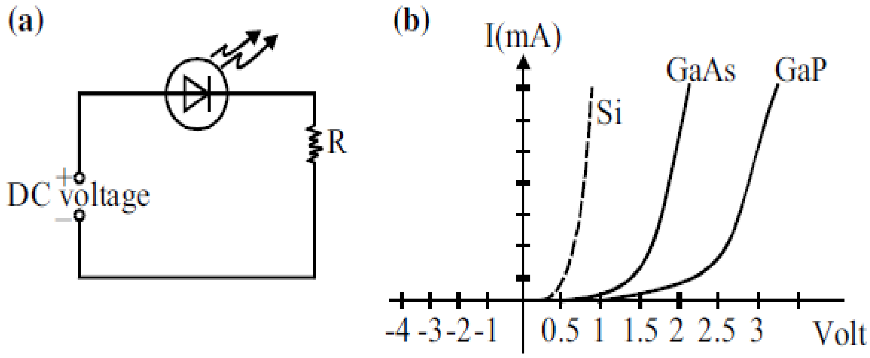


Fig. 4 a) LED connected with series resistance R showing biasing b) LED V-I characteristics

5. Forward biasing of a LED is normally through a series resistance for protecting against heavy current flow, which will damage it, as shown in Fig. 4a. The turn-on voltage of LED is basically from 1.5 to 5V with the current varying from 10 to 15 mA with power dissipation of 10 mW to 150 mW depending upon the semiconductor used. Being moderately to highly doped, the reverse breakdown voltage is less than 10 V. The properties of LED are as follows:

   (a) It can emit different colours with different semiconductor materials.

   (b) Intensity is proportional to the forward bias current.

   (c) Switching speed of ON to OFF and OFF to ON is as low as 1 n-s.

   (d) Life longevity period is as high as 100,000 hrs.

6. The LEDs are widely used as ON/OFF power indicator light in burglar alarm systems, phone, multimeters, calculators, digital meters, microprocessors, digital computers, electronic telephone exchange, intercom, electronic panels, digital watches, video displays and optical communication systems.

5.5.2. Photodiode

Photodiode detector is a pn junction (or PIN) diode used with −ve bias for detection of light intensity. Its property of dependence of reverse bias leakage current on light is used as light detector. Here, reverse bias leakage minority current (I_S) is directly proportional light intensity (I_L).

Construction:

These are made of semiconductor materials and the effective light entry area of a photodiode is about 0.2 mm^2. Schematic diagram of a photodiode is shown in Fig. 4.9a–e. An ordinary pn junction can be used as a basic photodiode, but PIN junction provides more satisfactory performance with middle i layer being intrinsic, as an intrinsic layer has very high generation/recombination rate of e–h pairs. The main requirement of a photodiode is to ensure maximum amount of light to reach the intrinsic layer. The substrate (the base semiconductor) is n+ (heavily n doped).

Light can enter from the top thin p layer (Fig. 4.9a) or from the side in mesa structure (Fig. 4.9b). It is packaged with transparent window (Fig. 4.9c). A schematic circuit with photodiode detector with reverse bias is shown in Fig. 4.9d. The symbol is given in Fig. 4.9e.

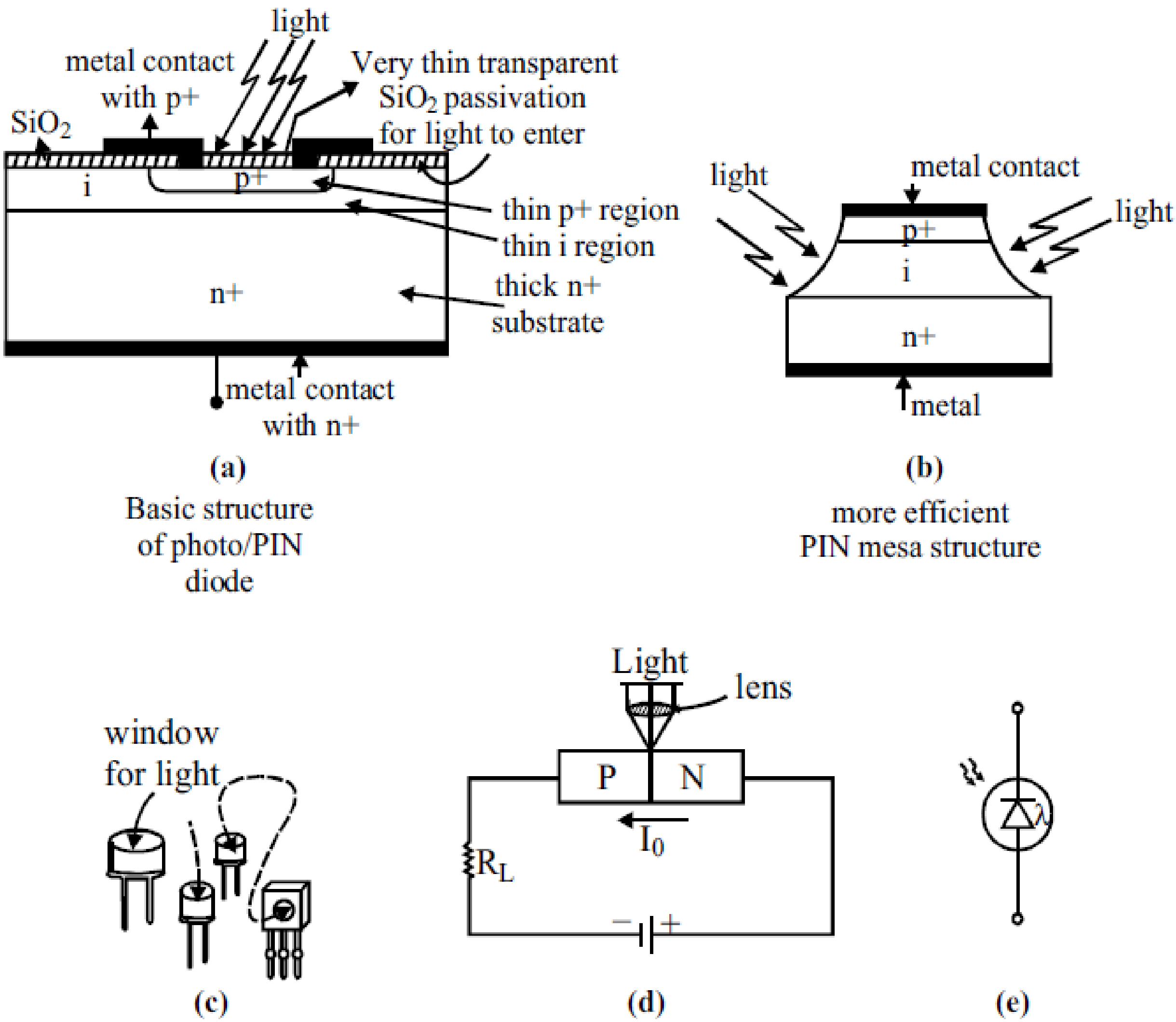


Fig. 4.9 a) Basic structure of photo/PIN diode, b) high-efficient PIN mesa structure for light entering directly into region, c) packaged photodiodes with windows, d) schematic circuit of photodiode detectors with reverse biased, e) symbol of photodiode detector

Working of Photodiode

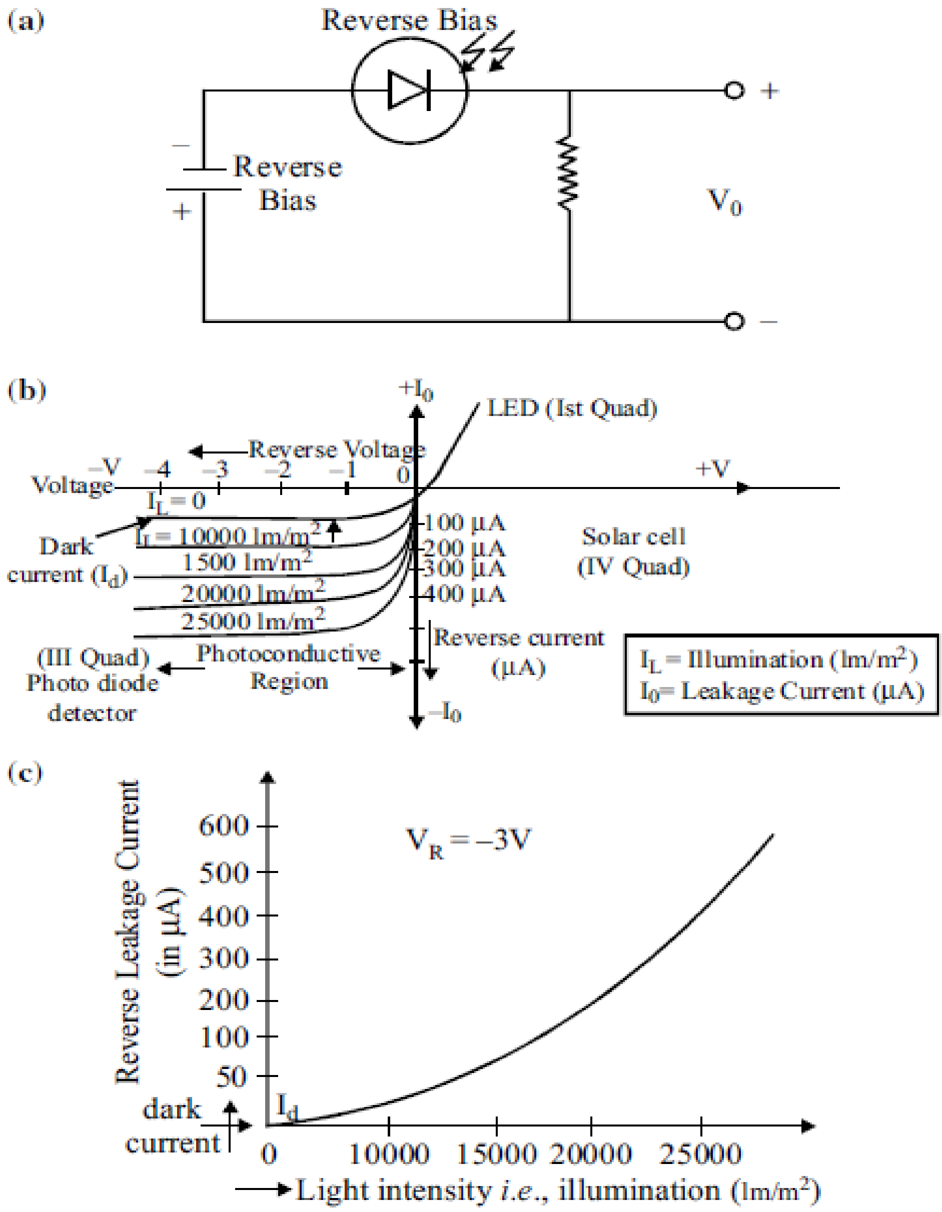


Fig. 4.10 a) Circuit connection of photodiode detector for seeing I versus V characteristic. b) V-I characteristics of photodiode detector where I_L = Illumination and I_0 = Leakage current. c) Illumination versus reverse leakage current characteristics of photodiode detector for $V_R = -3$ V

When a photodiode is reverse biased, there is a leakage current in µA range. This current increase, when light is incident on the i region of the diode due to extra generation of electron–hole pair (EHP) as shown in Fig. 4.10b, c.

Properties of Photodiode

Positive properties

1. Linearity is good.
2. Fast switching time.
3. Better frequency response.
4. Excellent spectral response.

Negative properties

1. Small active area.
2. Dark current, i.e., leakage current increases with temperature.

Application of Photodiode

1. Detection of both visible and invisible spectrum of lights. (IR + UV + optical radiations).
2. Switching application.
3. Optical communication.
4. Encoders and decoders.
5. Logic circuits with required stability and high speed.