B Sc-I Sem-I Paper-I (ELE-101) Sub-Electronics
Network Theorems and Semiconductor Devices
Network Theorems

1 Voltage divider theorem:

If a voltage divider circuit has N resistors (R_1, R_2, ….. R_N) connected in series with source voltage V then resistor R_i will have voltage drop

$$V_i = \frac{R_i}{R_1 + R_2 + ... + R_N} V \qquad (1)$$

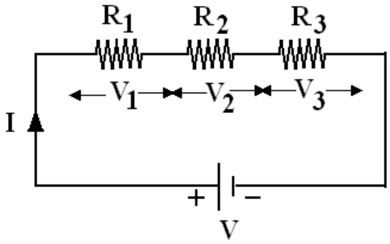


Fig. 1. Voltage divider circuit.

Consider the circuit shown in figure 1 in which three resistors R_1, R_2, R_3 are connected in series. Suppose V is the source voltage connected across the combination then total current I through the circuit is

$$I = \frac{V}{R_1 + R_2 + R_3} \qquad (2)$$

The voltage drop across R_1 is then

$$V_1 = R_1 I \qquad (4)$$

or

$$V_1 = \frac{R_1}{R_1 + R_2 + R_3} V \qquad (5)$$

Similarly the voltage drops across R_2 and R_3 respectively are

$$V_2 = \frac{R_2}{R_1 + R_2 + R_3} V \qquad (6)$$

and

$$V_3 = \frac{R_3}{R_1 + R_2 + R_3} V \qquad (7)$$

2 Current divider theorem:

If a current divider circuit has N resistors (R_1, R_2, …..R_N) connected in parallel with source current I then current through resistor R_i will be

$$I_i = \frac{\frac{1}{R_i}}{\frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_N}} I \qquad (1)$$

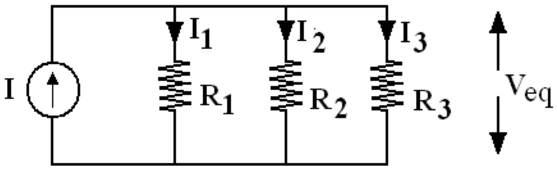


Fig. 1. Current divider circuit.

Consider the circuit shown in figure 1 in which three resistors R_1, R_2, R_3 are connected in parallel. Suppose I is the source current connected across the combination and Veq is the voltage drop across the combination then

$$V_{eq} = R_{eq} I \qquad (2)$$

But $$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \qquad (3)$$

Thus $$V_{eq} = \frac{I}{\left[\frac{1}{R_{eq}}\right]} = \frac{I}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} \qquad (4)$$

Therefore current through R_1 is

$$I_1 = \frac{V_{eq}}{R_1} \qquad (5)$$

Using equations (4) in equation (5), we get

$$I_1 = \frac{\frac{1}{R_1}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} I \qquad (6)$$

Similarly the currents through resistors R_2 and R_3 respectively are

$$I_2 = \frac{\frac{1}{R_2}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} I \qquad (7)$$

and $$I_3 = \frac{\frac{1}{R_3}}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} I \qquad (8)$$

3 Ideal constant voltage source:

The voltage source whose output voltage remains constant whatever the change in the load resistor is called ideal constant voltage source. Such voltage source possesses zero internal resistance so that internal voltage drop in the source is zero. In practice, none such ideal constant voltage source can be constructed. However attempts are made to reduce the internal resistance of the source.

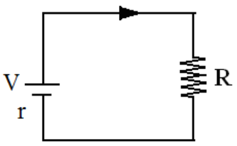


Fig. 1a.

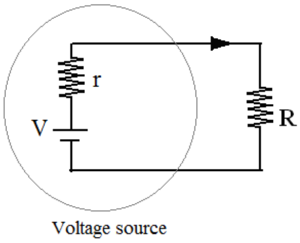


Fig. 1b.

Fig. 1a shows a resistor ‘R’ is connected across a voltage source. The internal resistance of a voltage source is always in series of the source. The equivalent circuit is shown in fig. 1b in which r indicates the internal resistance of the source. Therefore, the voltage drop across ‘R’ is $\frac{RV}{r+R}$ and can be close to ‘V’ if the internal resistance ‘r’ is very small in comparison with ‘R’.

4 Ideal constant current source:

The current source whose output current remains constant whatever the change in the load resistor is called ideal constant current source. Such current source possesses infinite or very internal resistance in comparison with the load resistance. In practice, none such ideal constant current source can be constructed.

Fig. 1a shows a resistor ‘R’ is connected across a current source. The internal resistance of a current source is always in parallel with the source. The equivalent circuit is shown in fig. 1b in which r indicates the internal resistance of the source. Therefore, the current through the resistor R is $\frac{rI}{r+R}$ and can be close to 'I' if the internal resistance 'r' is very high in comparison with 'R'.

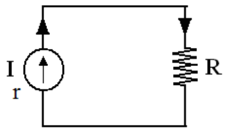


Fig. 1a.

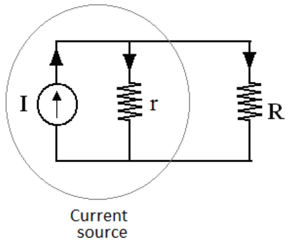


Fig. 1b.

5 Superposition theorem:

It states that in any linear circuit containing multiple independent energy sources, the current which flows at any point is the algebric sum of all the currents which would flow at that point if each source is considered separately and all the other sources are replaced by their internal resistances.

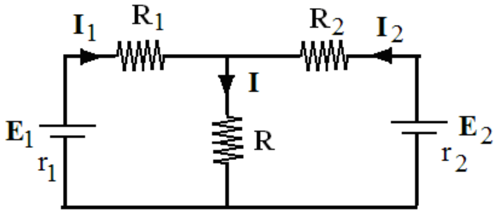


Fig. 1.

Consider the linear circuit as shown in fig. 1 in which I_1, I_2, I_3 represent the currents due to simultaneous action of the two voltage sources. To obtain current at any point in the circuit due to Source E_1 alone, we replace the source E_2 by its internal resistance r_2 and redraw the circuit as shown in fig. 2.

$$I_1' = \frac{E}{r_1 + R_1 + \left(\frac{R(R_2 + r_2)}{R + (R_2 + r_2)}\right)} \qquad (1)$$

$$I_2' = \frac{I_1' R}{R + (R_2 + r_2)} \qquad (2)$$

$$I' = \frac{I_1'(R_2 + r_2)}{R + (R_2 + r_2)} \qquad (3)$$

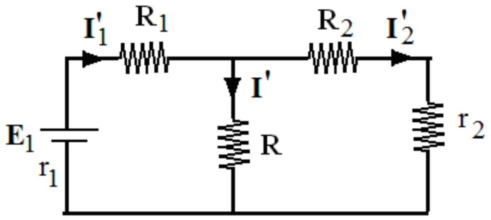


Fig. 2.

Similarly to obtain current at any point in the circuit due to Source E_2 alone, we replace the source E_1 by its internal resistance r_1 and redraw the circuit as shown in fig. 3.

$$I_2'' = \frac{E_2}{r_2 + R_2 + \left(\frac{R(R_1 + r_1)}{R + (R_1 + r_1)}\right)} \qquad (4)$$

$$I_1'' = \frac{I_2' R}{R + (R_1 + r_1)} \qquad (5)$$

$$I''=\frac{I_2''(R_1+r_1)}{R+(R_1+r_1)} \qquad (6)$$

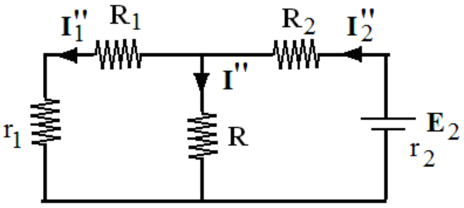


Fig. 3.

By combining the current values of fig. 2 and fig. 3, the actual current values in fig. 1 due to simultaneous action of both sources are

$$I_1 = I_1' - I_1'' \qquad (7)$$

$$I_2 = I_2'' - I_2' \qquad (8)$$

$$I = I' + I'' \qquad (9)$$

6 Thevenin’s Theorem:

Any linear electric network with current and voltage sources can be replaced by an equivalent circuit containing a single independent voltage source V_{TH} and a series resistance R_{TH}.

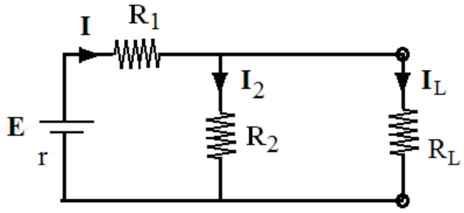


Fig. 1.

Consider the circuit as shown in fig. 1. Following are the simple steps to analyze electric circuit through Thevenin’s Theorem.

Open the load resistor (fig. 2).

Calculate the open circuit voltage. This is the Thevenin Voltage (V_{TH}).

$$V_{TH}=\frac{ER_2}{r+R_1+R_2} \qquad (1)$$

Replace energy sources by their internal resistances (fig. 3).

Calculate the open circuit resistance. This is the Thevenin Resistance (R_{TH}).

$$R_{TH}=\frac{(r+R_1)R_2}{(r+R_1)+R_2} \qquad (2)$$

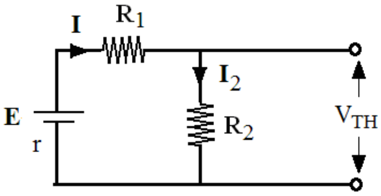


Fig. 2.

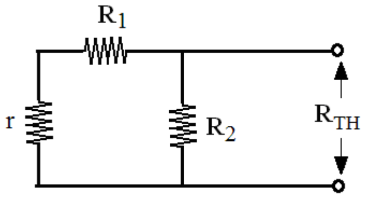


Fig. 3.

Now, redraw the circuit with measured open circuit voltage (V_{TH}) in Step (2) as voltage source and measured open circuit resistance (R_{TH}) in step (4) as a series resistance and connect the load resistor which we had removed in Step (1). This is the equivalent Thevenin Circuit (fig. 4) of the given Linear Electric Network.

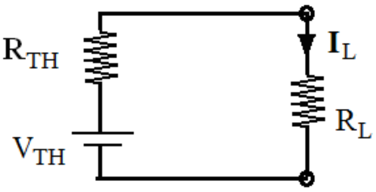


Fig. 4.

Now find the load current flowing through Load resistor by using the Ohm's Law

$$I_L = \frac{V_{TH}}{R_{TH} + R_L} \qquad (3)$$

7 Maximum Power transfer Theorem:

For any power source, the power transferred from the power source to the load is maximum when the resistance of the load R_L is equal to the internal resistance R_{in} of the source. The process used to make $R_L = R_{in}$ is called impedance matching.

Proof: Consider the circuit as shown in fig. 1.

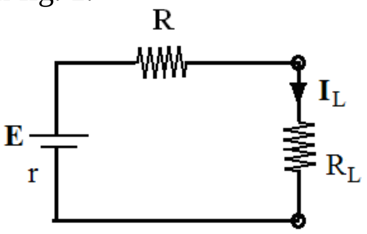


Fig. 1.

The internal resistance of the network is

$$R_{in} = r + R \qquad (1)$$

Therefore current through the load resistance is

$$I_L = \frac{E}{R_{in} + R_L} \qquad (2)$$

The voltage drop across load is

$$V_L = R_L I_L = \frac{R_L E}{R_{in} + R_L} \qquad (3)$$

Therefore, the power supplied to the load by the source is

$$P_L = V_L I_L = \frac{R_L E}{R_{in} + R_L} \frac{E}{R_{in} + R_L} = \frac{R_L E^2}{(R_{in} + R_L)^2} \qquad (4)$$

If this power is to be maximum with respect to R_L then we must have

$$\frac{dP_L}{dR_L} = 0 \qquad (5)$$

Thus differentiating equation (4) with respect to R_L we get

$$\frac{dP_L}{dR_L} = \frac{d}{dR_L} \frac{R_L E^2}{(R_{in} + R_L)^2} = \frac{E^2}{(R_{in} + R_L)^2} + R_L E^2 \frac{d}{dR_L}(R_{in} + R_L)^{-2}$$

or $$\frac{dP_L}{dR_L} = \frac{E^2}{(R_{in} + R_L)^2} + \frac{R_L E^2(-2)}{(R_{in} + R_L)^3} \frac{d}{dR_L}(R_{in} + R_L)$$

or $$\frac{dP_L}{dR_L} = \frac{E^2}{(R_{in} + R_L)^2} + \frac{R_L E^2(-2)}{(R_{in} + R_L)^3} = \frac{E^2(R_{in} + R_L - 2R_L)}{(R_{in} + R_L)^3}$$

or $$\frac{dP_L}{dR_L} = \frac{E^2(R_{in} - R_L)}{(R_{in} + R_L)^3} = 0$$

For maximum power we put $\frac{dP_L}{dR_L} = 0$ which gives $R_{in} - R_L = 0$

or $$R_{in} = R_L \qquad (6)$$

Hence the proof.

Chapter 15

Diodes

1 Formation of p-n junction diode

Where the p-type and n-type regions meet is called pn junction and the complete pn crystal is called a junction diode. In n region, the majority carriers are electrons and minority carriers are holes on the other hand, in p region, the majority carriers are holes and minority carriers are electrons. Figure (1a) shows a junction diode On the formation of the pn junction the electrons on the n side tend to diffuse across the junction. When an electron enters the p region, it becomes a minority carrier. With so many holes around it this minority carrier has a short lifetime and soon after entering the p region that electron falls into a hole. When this happens the hole disappears and the conduction band electron becomes valance electron. Each time an electron diffuses across the junction it creates a pair of ion. Figure (1b) shows these ions on each side of the junction. The circled positive signs are of the positive ions and the circled minus signs are of the negative ions. Each pair of positive and negative ions is called a dipole. There are no movable charges in the region of dipoles. This charge empty region is called a **depletion layer**.

Each dipole has an electric field as shown in figure (1c). The arrow shows the direction of force on a positive charge. Therefore, when an electron enters the dipole region the field tries to push the electron back into the n region. The strength of the field increases with each crossing electron until the field will eventually stops the diffusion of electrons across the junction. The field between ions is equivalent to a difference of potential called the **barrier potential**. At 25° centigrade the barrier potential approximately equals 0.3 volt for germanium diodes and 0.7 volt for silicon diodes. Schematic symbol of a diode is shown in fig. 2.

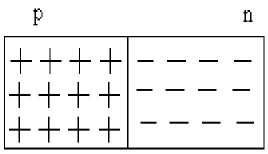


Fig 1a. Before diffusion

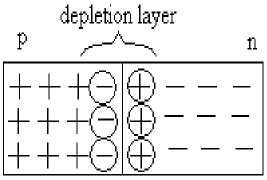


Fig 1b. After diffusion

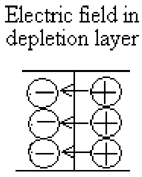


Fig 1c.

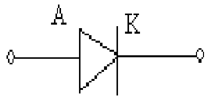


Fig. 2. Schematic symbol of a diode.

2 Biasing of a semiconductor diode

When an external battery is connected across the pn junction diode, it is called biasing of the diode. There are two methods to bias the diode, viz. the forward bias and the reverse bias.

i. Diode in forward bias:

In the forward bias the negative terminal of a dc source is connected to the n-type material and the positive terminal to the p-type material of the diode as shown in **figure 1**. In this case the electrons from the negative terminal of the source enter into the n region. The electrons in the n region move towards the junction. When they reach the junction get recombined with the holes and become valance electrons. Further, these electrons move towards the positive terminal of the battery through p region as valence electrons. Thus there appears a continuous flow of electrons with the help of external dc source. Note that in a forward bias, the external battery sets up an electrical field in opposite direction to the field setup by the barrier potential at the junction. A very small external voltage is needed to eliminate the field of barrier. Once the barrier potential is eliminated, the junction resistance becomes almost zero and a low resistance path is established for the entire circuit. Therefore, current flows in the circuit. This is called forward current.

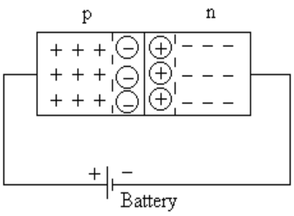


Fig. 1. Diode in forward bias.

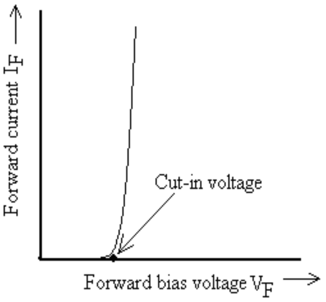


Fig. 2. Current-voltage characteristics.

The current voltage characteristic of a particular pn junction diode is as shown fig.2. It becomes a straight line after cut-in voltage. The cut-in voltage or offset voltage or threshold voltage is the voltage below which the current is very small and beyond which it raises very rapidly.

ii. Diode in reverse bias:

In reverse bias the positive terminal of the dc source is connected to the n p-type material and the negative terminal is connected to the p type material of the diode as shown in figure 3. The electric field produced by the external source is in the same direction to the depletion layer field. Because of this, holes and electrons move away from the junction. These moving electrons leave positive ions behind and departing holes leave negative ions. Therefore, the depletion layer gets wider. The greater reverse bias voltage, the wider the depletion layer becomes. While the depletion layer is adjusting to its new width, holes and electrons move from the junction. Therefore a current flows in the external circuit while the depletion layer is adjusted to its new width. This transient current drops to zero after the depletion layer stops growing. Further there is no current in the circuit.

If the reverse bias voltage is further increased, a critical voltage, known as breakdown voltage is reached, at which a rapid increase in reverse current occurs as shown in fig.4. In the breakdown region the diode may be damaged.

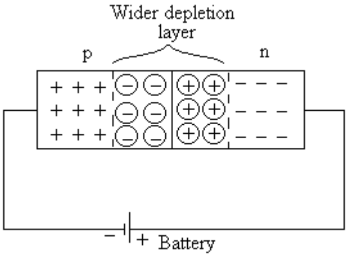


Fig. 3. Diode in reverse bias.

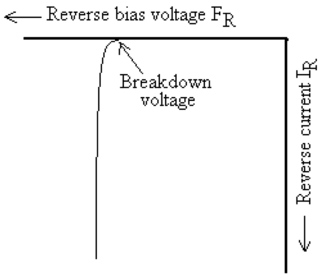


Fig.4. Diode characteristic in breakdown region.

3 Breakdown of a pn junction: avalanche breakdown and zener breakdown

All pn junctions have a limit of allowable maximum reverse-bias voltage, beyond which a rapid increase in the current occurs. This limiting voltage is known as breakdown voltage. There are two mechanisms responsible for this.

i. Avalanche breakdown: When the applied reverse voltage is large and reaches the breakdown value, minority carriers in the depletion layer of the diode are accelerated and reach high enough velocities to knockout a valance electron from outer orbits. This newly liberated electron can then get high enough velocities to free other valance electrons. In this way we get an avalanche of free electrons. Avalanche occurs for reverse voltages greater than 6 volt or so.

ii. Zener breakdown: The zener diode is made for operation in the breakdown region. The zener effect is different from the avalanche effect. When a diode is heavily doped, the depletion layer is very narrow. Because of this, the electric field across the depletion layer is very intense. In zener diode, the field is enough intense to pull electrons out of valence orbits. The creation of free electrons in this way is called zener breakdown. By varying the doping level a manufacturer can produce zener diodes with required breakdown voltages. Zener diodes are being used in regulated power supplies.

4 Ideal diode and first, second and third approximations of a semiconductor diode

An ideal diode acts like a perfect conductor when it is in forward bias and it acts like a perfect insulator when it is in reverse bias.

The first approximation: The ideal diode curve is as shown in figure 1a. From the curve it is clear that the ideal diode acts like an automatic switch. When the current tries to flow in the direction of the diode arrow, the switch is closed as shown in figure 1b. If the current tries to flow in opposite direction of the diode arrow, the switch is open. Such type of approximation of the diode as simply a switch is considered as the first approximation.

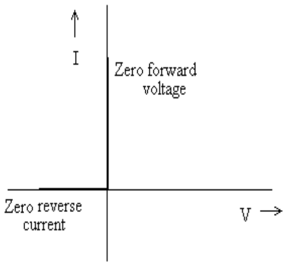


Fig 1a. Ideal Diode curve.

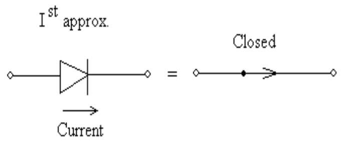


Fig 1b. Closed switch for forward current.

The second approximation: We know that a silicon diode conducts well when the forward voltage across it is greater than 0.7 volt and for a germanium diode it is 0.3 volt. Though these are very small in magnitude, one has to take into consideration. In the second approximation of the diode these knee voltage is taken into consideration and the corresponding volt-ampere curve of the diode is shown in figure 2a. The graph says no current flows until o.7 volt appears across the diode. At this point the diode turns on and acts as a short circuit with 0.7 volt drop across a silicon diode and o.3 volt for a germanium diode. Figure 2b shows the equivalent circuit for the second approximation. We think that when a diode is in forward bias, it acts as a switch in the series with a 0.7 volt battery. When the applied voltage is in forward bias, the switch is closed. When the forward voltage exceeds the o.7 volt the current flows. When the applied voltage is in reverse bias the switch is open.

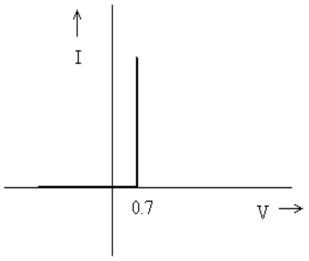


Fig.2a Second approximation diode curve

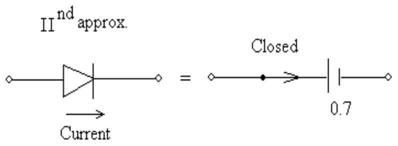


Fig.2b.

The third approximation:

In third approximation of a diode the resistance of the diode called bulk resistance is taken into consideration. The volt-ampere curve of the diode in third approximation is as shown in figure 3a. The equivalent circuit for the third approximation is a switch in series with a 0.7 volt battery and a resistance r_b as shown in figure 3b. After the external voltage in forward bias has overcome the barrier potential (0.7 volt for silicon diode and 0.3 volt for germanium diode) it forces to flow current in the direction of the diode arrow. Therefore, the total voltage across the silicon diode is $V_F = 0.7 + I_F r_b$

For a germanium diode 0.3 volt is to be used instead of 0.7 volt.

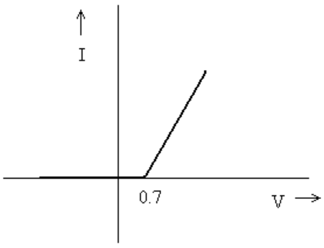


Fig.3a. Third approximation diode curve

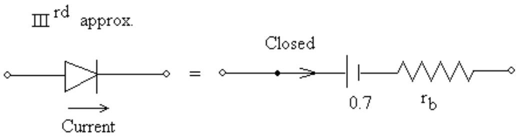


Fig.3b. Equivalent circuit.

5 Types of Diode

5.1 Zener Diode

The zener diode is made for operation in the breakdown region. By varying the doping level a manufacturer can produce zener diodes with required breakdown voltages. Zener diodes are being used in regulated power supplies.

Zener breakdown: When the applied reverse voltage reaches the breakdown value, minority carriers in the depletion layer of a diode are accelerated and reach high enough velocities to knockout a valance electron from outer orbits. This newly liberated electron can then get high enough velocities to free other valance electrons. In this way we get an avalanche of free electrons. Avalanche occurs for reverse voltages greater than 6 volt or so.

The zener effect is different. When a diode is heavily doped, the depletion layer is very narrow. Because of this, the electric field across the depletion layer is very intense. In zene diode the field is enough intense to pull electrons out of valence orbits. The creation of free electrons in this way is called zener breakdown. Figure 1 shows the schematic symbol of a zener diode.

By varying the doping level of silicon diodes, a manufacturer can produce zener diodes with breakdown voltages from about 2 to 200 volt. These diodes can operate in any of three regions: forward, leakage and breakdown. Figure 2 shows the I-V graph of a zener diode. In the forward region, it starts conducting around 0.7 volt just like an ordinary silicon diode. In the leakage region between zero and a breakdown it has only a small reverse current. In a zener diode break down has a very sharp knee voltage, followed by an almost vertical increase in the current. Note that the voltage is almost constant approximately equal to Vz over most of the break in our region. Hence in the breakdown region the zener resistance is very small or negligible.

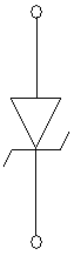


Fig. 1 Symbol of zener diode.

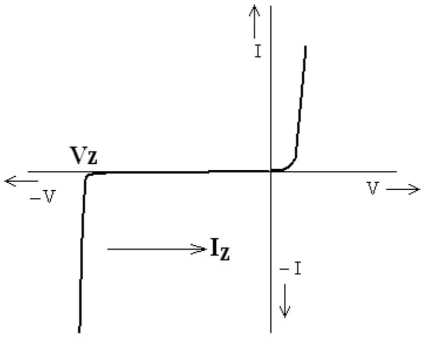


Fig. 2 Characteristic of zener diode

5.2 Tunnel Diode:

The symbol of turu1el diode is shown in fig. (a). It was found that if the depletion layer in a p-n junction was very thin, the electrons could penetrate through the junction barrier and thus could pass from one side of the depletion layer to the other with less energy than was apparently necessary. This quantummechanical phenomenon is known as tunneling and the p-n diode based upon this tunneling effect is known as a tunnel diode.

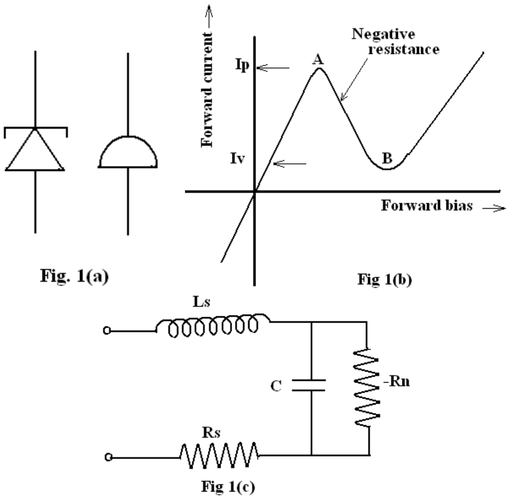


Fig. 1(a)

Fig 1(b)

Fig 1(c)

Fig. 1 Tunnel diode: (a) Symbol, (b) Voltage/current characteristic, (c) Equivalent circuit in negative resistance region.

In a tunnel diode, the width of the depletion layer is reduced by increasing the concentration of impurity atoms. With this impurity concentration, the width of the depletion layer is reduced to less than 100A.U. For potential barriers of this thickness, the probability of an electron to penetrate this barrier becomes very large, and the voltage/current characteristic of this diode is completely changed, as shown in fig. 1 (b). The tunnel diode shows a negative resistance for part of its characteristic [A to B in fig. 1 (b)] and therefore, is also called a negative resistance device. For currents between Ip (peak current) and Iv (valley current) the characteristic is triple valued because the same current can be achieved for three different applied voltages. The multivalued feature of the tunnel diode makes it a useful device in the high speed switching circuits. The equivalent circuit of a tunnel diode is shown in fig. l(c).

5.3 Photodiode:

The photodiode is a semiconductor p-n junction operating in the reverse-bias region and is based upon the phenomenon of the photovoltaic affect. A voltage is generated across the p-n junction when light falls upon it. Owing to this voltage, a current starts flowing in an external circuit, in a direction reverse to that usually flowing in a general-purpose diode. This current increases linearly with tile increase in the incident light. The symbol, biasing arrangement, and voltage/current characteristics of a photodiode are depicted in fig. 1. The dark current corresponds to the current flowing without incident light and obviously, it is the reverse saturation current of the diode.

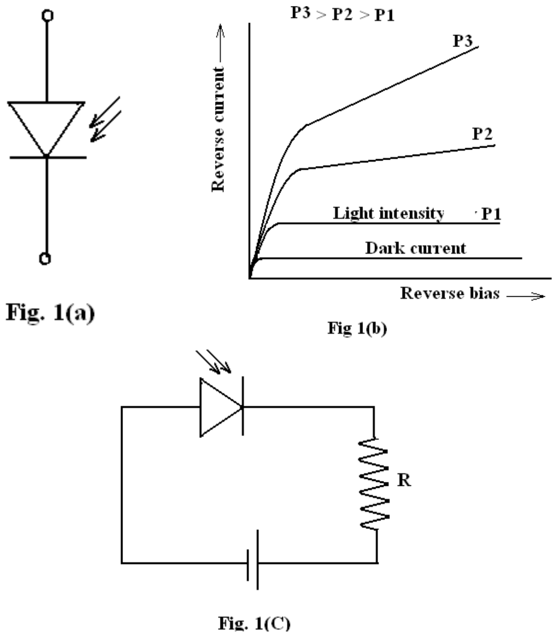


Fig. 1(a)

Fig 1(b)

Fig. 1(C)

Fig. 1. Photodiode: (a) Symbol, (b) Voltage/Current characteristic, (c) Biasing arrangement.

As we know that the current in a reverse-biased p-n junction owing to diffusing minority charge carriers. As the incident light produces electron-hole pairs in the reverse-biased diode, the electrons in the p-region and the holes in the n-region become additional minority charge carriers and the current increases. If the incident light falls at a distance from the p-n junction, the minority carriers produced due to light may recombine before diffusing across the junction and a small current will flow. This current will increase if the light falls near the junction because the probability of recombination is less. Hence, the photocurrent is a function of the distance from the junction at which the light falls, as shown in fig. 2. As the diffusion lengths of minority charge carriers in the p- and the n-regions are different, the curve is not symmetrical on both sides.

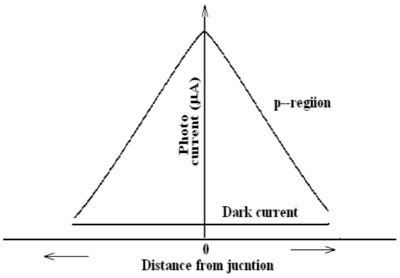


Fig. 2. Variation of photocurrent with distance from the junction at which light falls.

5.4 Light emitting diode (LED):

A diode that emits light when forward biased is called light emitting diode (LED). The typical structure of a light emitting diode (LED) is shown in figure l(a) and its electronic symbol is shown in fig. 1 (b). LEDs are made from elements like gallium, phosphorous and arsenic. By varying the quantities of these elements, it is possible to produce light of different colours that includes red, green, yellow and blue.

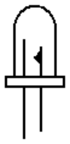


Fig. 1(a)

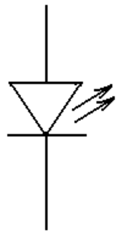


Fig. 1(b)

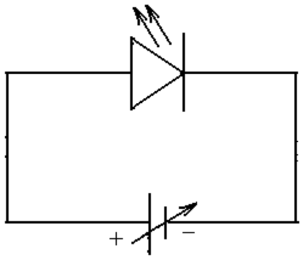


Fig. 2

LED Symbol of LED LED in forward bias

Working: When the LED is forward biased as shown in fig. 2, the electrons from n type material cross the p-n junction and recombine with holes in the p type material. The free electrons are in conduction band and they are at high energy level. The holes are in valence band and they are at low energy level. When electrons recombine with holes the energy is released in the form of light. Where as, in germanium and silicon diode the energy is released in the form of heat. Fig. 1 shows the symbol of LED. The arrows are in outward direction indicates that light is emitted from the diode when it is forward biased.

Application:

1) LED can be used to indicate whether the power is on or off. Thus LEDs are used as power indicator.
2) LEDs are often used in seven segment displays.

5.5 Varactor Diode:

The varactor diode is a semiconductor variable voltage capacitor. It is also called varicap diode or capacitor diode. When a p-n junction diode is reverse biased it has large resistance Rs and transition capacitance C_T. In fig. 1(a), the p-type semiconductor acts as one plate of the capacitor and the n-type semiconductor acts as the other plate of the capacitor and the depletion layer acts as the dielectric medium. Fig 1(b) shows the symbol of the varactor diode. The varactor diode means variable capacitor diode. When the reverse voltage across the diode increases, it increases the width of the depletion layer at the same time the transition capacitance C_T goes on decreasing as shown in fig 1(c).

Fig 1(d) shows the equivalent circuit of varactor diode in reverse bias. A large resistance Rs is in parallel with the transition capacitance C_T. The capacitive reactance is given by $\chi_T = \frac{1}{2\pi f C_T}$

At low frequency, the capacitive reactance is very high. Therefore, diode appears open because X_T and Rs are high.

At low frequencies, however X_T decreases and the equivalent circuit reduces to capacitance C_T. in other words at high frequencies a varactor is equivalent to voltage controlled capacitance.

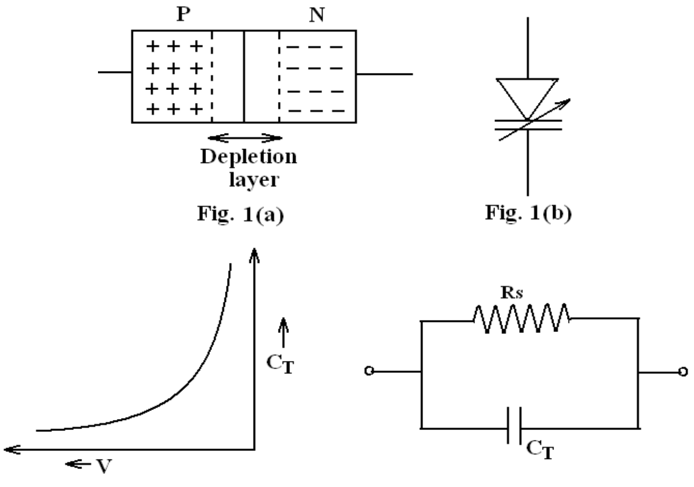


Fig. 1(a)

Fig. 1(b)

Fig. 1(c)

Fig. 1(d)

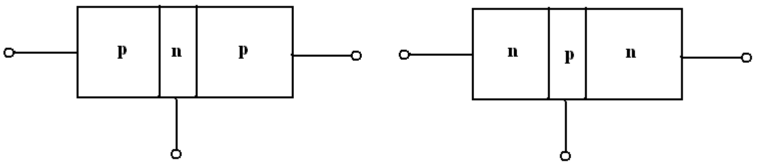
Fig. 1. Varactor diode: (a) Depletion layer, (b) symbol, (c) Characteristic, (d) Equivalent circuit.

Applications: The varactor diodes are widely used in television receivers, FM receivers and other communication systems in which high frequencies are involved.

Transistors

1 Transistor:

A transistor is a three-terminal sandwich of p and n type semiconductors. The three layers can be arranged in p-n-p or n-p-n form in a single crystalline wafer of a semiconductor as shown in Fig. 1.

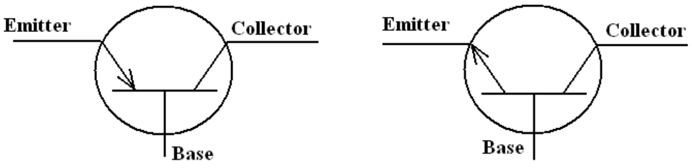


(a) p.n-p (b) n-p-n

Fig. 1. A junction transistor (a) p-n-p (b) n-p-n.

The three layers in the transistor are called emitter (E), base (B) and collector (C). The base is very thin and it is lightly doped. It is sandwiched between the collector and the emitter. The emitter is heavily doped and the collector is moderately doped. The collector is larger in size as compared to that of the emitter. The transistor has two junctions, one between the emitter and the base and another between the base and the collector.

The electrical symbol for the p-n-p and n-p-n transistors are as shown in Fig 2. The arrow on the emitter indicates the direction of the current that flows through the transistor.



p-n-p Transistor n-p-n Transosotor

Fig. 2. Electrical symbols of p-n-p and n-p-n transistors.

2 Action of a transistor:

The diffusion of the charge carriers across the junction produces two depletion layers in a transistor. The barrier potential is approximately 0.3 V for Ge and 0.7 V for Si transistors. For normal operation of a transistor, the emitter base junction is forward biased and the collector base junction is reversed biased. As there are two types of transistors as p-n-p and n-p-n, we consider each case for study.

(i) Working of n-p-n transistor: Fig. 1 shows the n-p-n transistor with forward bias to emitter-base junction and reverse bias to collector-base junction. The forward bias causes the electrons in the n-type emitter to flow towards the base. This constitutes the emitter current I_E. As these electrons flow through the p-type base, they tend to combine with holes. Since the base is lightly doped and very thin, therefore, only a few electrons (less than 5%) combine with holes to constitute base current I_B. The remainder (more than 95%) cross over into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. It is clear that emitter current is the sum of collector and base currents i.e.

$$I_E = I_B + I_C$$

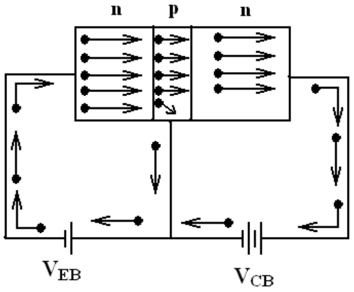


Fig. 1. Basic connection of n-p-n transistor.

(ii) Working of' p-n-p transistor: Fig. 2 shows the basic connection of a p-n-p transistor. The forward bias causes the holes in the p-type emitter to flow towards the base. This constitutes the emitter current I_E. As these holes cross into the n-type base, they tend to combine with the electrons. As the base is lightly doped and very thin, therefore only a few holes (less than 5%) combine with the electrons. The remainder (more than 95%) cross into the collector region to constitute collector current I_C. In this way, almost the entire emitter current flows in the collector circuit. It may be noted that current conduction within p-n-p transistor is by holes. However, in the external connecting wires, the current is still by electrons.

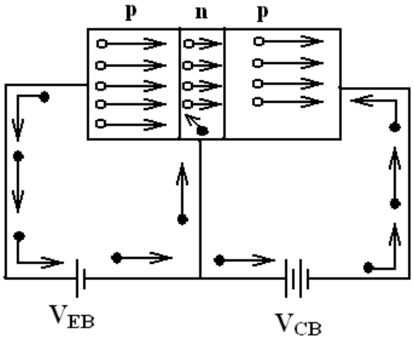


Fig. 2. Basic connection of p-n-p transistor.

The input circuit (i.e. emitter-base junction) has low resistance because of forward bias whereas output circuit (i.e. collector-base junction) has high resistance due to reverse bias.

3 Transistor connections:

There are three leads in a transistor viz. emitter, base and collector terminals. However, when a transistor is to be connected in a circuit, we require four terminals; two for the input and two for the output. This difficulty is overcome by making one terminal of the transistor common to both input and output terminals. The input is fed between this common terminal and one of the other two terminals, The output is obtained between the common terminal and the remaining terminal. Accordingly; a transistor can be connected a circuit in the following three ways;

(i) Common base connection,
(ii) Common emitter connection. and
(iii) Common collector connection.

Each circuit connection has specific advantages and disadvantages.

4 Transistor in common base connection (CB):

In this circuit arrangement, input is applied between emitter and base and output is taken from collector and base. Here base of the transistor is common to both input and output circuits and hence the name common base connection. In Fig. 1(i), a common base n-p-n transistor circuit is shown whereas Fig. 1(ii) shows the common base p-n-p transistor circuit.

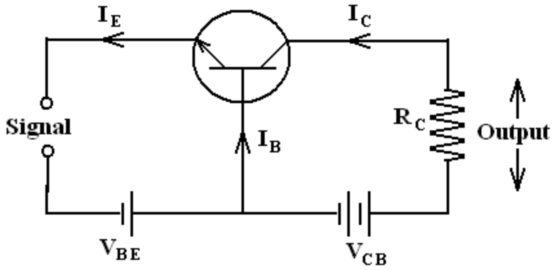


Fig. 1 (i)

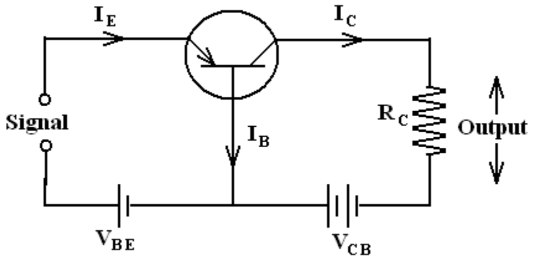


Fig. 1(ii)

Current amplification factor (β): It is the ratio of output current to input current. In a common base connection, the input current is the emitter current I_E and output current is the collector current I_C.

The ratio of change in collector current to the change in emitter current at constant collector – base voltage V_{CB} is known as current amplification factor i.e.,

$$\alpha = \frac{\Delta I_C}{\Delta I_E} \text{ at constant } V_{CB} \qquad (1)$$

It is clear that current amplification factor is less than unity.

Expression for collector current: The whole of emitter current does not reach the collector. It is because a small percentage of it, as a result of electron-hole combinations occurring in base area, gives rise to base current. Therefore,

$$I_E = I_C + I_B \qquad (2)$$

Also $$I_C = \alpha I_E \qquad (3)$$

These equations are useful in current determination.

Esample: In a common base connection, I_E = lmA, I_C = 0.95 mA. Calculate the value of I_B.

Solution: Given that I_E = l mA, and I_C = 0.95 mA.

Using the relation, $I_B = I_E - I_C$

we have I_B = 1 mA - 0.95 mA

or I_B = 0.05 mA (Ans.)

5 Characteristics of common base connection:

The interrelation of the various currents and voltages of a transistor can be displayed graphically and the curves obtained are known as the characteristics of the transistor. The most important characteristics of common base connection are input characteristics and output characteristics.

1. Input characteristic: It is the curve between emitter current I_E and emitter-base voltage V_{EB} at constant collector- base voltage V_{CD}. The emitter current is generally taken along y-axis and emitter-base voltage along x-axis. Fig. 1 shows the circuit used to determine the characteristics in common base configuration. Fig. 2(a) shows the input characteristics of a typical transistor in CB arrangement.

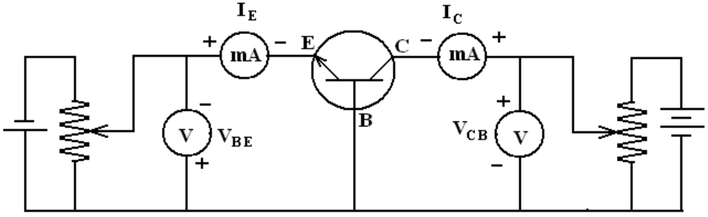


Fig. 1. Transistor in common base connection.

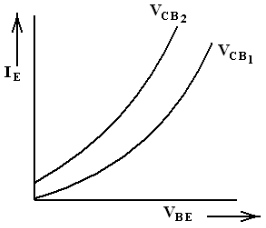


Fig. 2(a) Input characteristics.

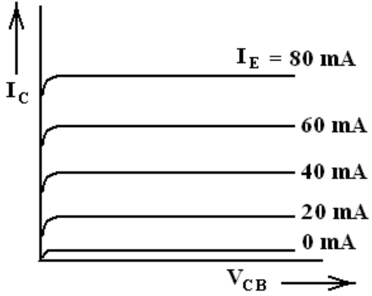


Fig. 2(b) Output characteristics.

The following points may be noted from these characteristics.

The emitter current I_E increases rapidly with small increase in emitter- base voltage V_{EB}. It means that input resistance is very small.

The emitter current is almost independent of collector-base voltage V_{CB}. This leads to the conclusion that emitter current (and hence collector current) is almost independent of collector voltage.

Input resistance: It is .the ratio of change in emitter-base voltage (ΔV_{EB}) to the resulting change in emitter current (ΔI_E) at constant collector-base voltage (V_{CB}) i.e.,

$$r_i = \frac{\Delta V_{EB}}{\Delta I_E} \text{ at constant } V_{CB}$$

In fact, input resistance is quite small, of the order of a few ohms.

2. Output characteristics: It is the curve between collector current I_C and collector-base voltage V_{CB} at constant emitter current I_E. Generally, collector current is taken along y-axis and collector-base voltage along x-axis. Fig. 2(b) shows the output characteristics of a typical transistor in CB arrangement. The following points may be noted from the characteristics.

The collector current I_C varies with V_{CB} on1y at very low voltages (<< 1 Volt). The transistor is never operated in this region.

When the value of V_{CB} is raised above 1-2 V, the collector current becomes constant as indicated by straight horizontal curves. It means that now I_C is independent of V_{CB} and depends upon I_E only. This is consistent with the theory that the emitter current flows almost entirely to the collector terminal. The transistor is always operated in this region.

A very large change in collector-base voltage produces on1y a tiny change in collector current. This means that output resistance is very high.

Output resistance: It is the ratio of change in collector-base voltage (ΔV_{CB}) to the change in collector current (ΔI_C) at constant emitter current i.e.,

$$r_o = \frac{\Delta V_{CB}}{\Delta I_C} \text{ at constant } I_C$$

The output resistance of CB circuit is very high, of the order of several tens of kilo ohms.

6 Transistor in common emitter connection:

In this circuit arrangement, input is applied between base and emitter and output is taken from the collector and emitter. Here, emitter of the transistor is common to both input and output circuits and hence the name common emitter connection, Fig. 1(a) shows common emitter n-p-n transistor circuit whereas Fig 1(b) shows common emitter p-n-p transistor circuit.

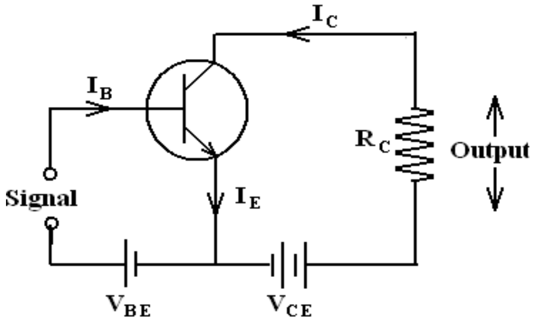


Fig. 1(a).

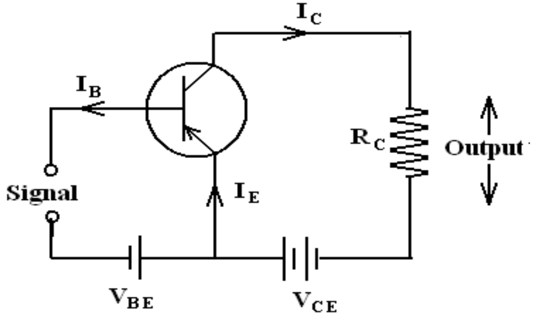


Fig. 1(b).

Base current amplification factor (β): In common emitter connection, input current is I_B and output current is I_C.

The ratio of change in collector current to the change in base current is known as current amplification factor i.e.,

$$\beta = \frac{\Delta I_C}{\Delta I_B} \qquad (1)$$

The current amplification factor or current gain is generally high in any transistor.

Relation between α and β: A simple relation exists between α and β. This can be derived by using the relations $\alpha = \frac{\Delta I_C}{\Delta I_E}$, $\beta = \frac{\Delta I_C}{\Delta I_B}$ and $\Delta I_E = \Delta I_C + \Delta I_B$. The relation is

$$\beta = \frac{\alpha}{1-\alpha} \qquad (2)$$

It is clear that as α approaches unity, β approaches infinity. In other words, the current gain in common emitter connection is very high.

7 Characteristics of a transistor in common emitter connection:

The important characteristics of this circuit arrangement are the input characteristics and output characteristics. Fig. 1 shows the circuit diagram for determining the characteristics for a common emitter n-p-n transistor circuit.

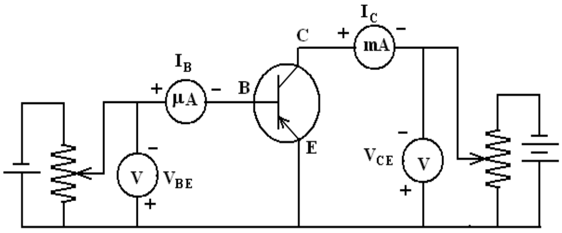


Fig. 1.

1. Input characteristics: It is the curve between base current I_B and base-emitter voltage V_{BE} at constant collector-emitter voltage V_{CE}.

The input characteristics of a CE connection can be determined by the circuit shown in Fig. 1. By keeping V_{CE} constant note the base current I_B for various values of V_{BE}. Then plot the readings obtained on the graph taking I_B along y-axis and V_{BE} along x-axis. This gives the input characteristic at particular V_{CB} as shown in Fig. 2(a). Following a similar procedure a family of input characteristics can be drawn.

The following points may be noted from the characteristics.

The characteristic resembles that of a forward biased diode curve. This is expected since the base-emitter section of transistor is a diode and it is forward biased.

As compared to CB arrangement. I_B increases less rapidly with V_{BE} Therefore, input resistance of a CE circuit is higher than that of CB circuit.

Input resistance: It is the ratio of change in base-emitter voltage (ΔV_{BE}) to the change in base current (ΔI_B) at constant V_{CB}. i.e., $r_i = \frac{\Delta V_{BE}}{\Delta I_B}$ at constant V_{CE}

The value of input resistance for a CE circuit is of the order of a few hundred ohms.

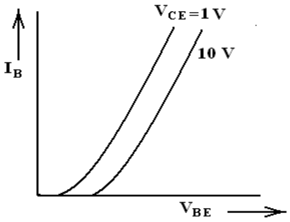


Fig. 2(a).

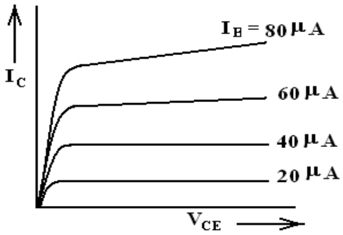


Fig. 2(b).

2. Output characteristics: It is the curve between collector current I_C and collector-emitter voltage V_{CE} at constant base current I_B.

With reference to Fig. 1, the output characteristics can be obtained by keeping the base current I_B fixed at some value, say 5μA, note the collector current I_C for various values of V_{CE}. Then plot the readings on a graph, taking I_C along y-axis and V_{CE} along x-axis. This gives the output characteristic at I_B= 5μA as shown in Fig. 2 (b). The procedure can be repeated for several values of I_B. The fol1owing points may be noted from the characteristics.

The collector current I_C varies with V_{CE} for V_{CB} between 0 and 1V only. After this, collector current becomes almost constant and independent of V_{CE}. This value of V_{CB} up to which col1ector current I_C changes is called the knee voltage (V_{knee}). The transistors are always operated in the region above the knee voltage.

Above knee voltage, I_C is almost constant. However, a small increase in I_C with increasing V_{CE} is caused by the collector depletion layer getting wider and capturing a few more majority carriers before electron-hole combinations occur in the base area.

For any value of V_{EC} above knee voltage, the collector current I_C is approximately equal to β × I_B.

Output resistance: It is the ratio of change in collector-emitter voltage (ΔV_{CE}) to the change in collector current (ΔI_C) at constant I_B. i.e.,

$$r_o = \frac{\Delta V_{CE}}{\Delta I_C} \text{ at constant } I_B$$

It may be noted that its value is of the order of 50 KΩ.

8 Construction and working of Junction Field Effect Transistor (JFET)

A junction field effect transistor (JFET) is a three terminal semiconductor device. These terminals are called as Source (S), Gate (G) and Drain (D). There are two types of JFET namely n-channel JFET and p-channel JFET.

Construction: A JFET consisting of a p-type or n-type silicon bar containing two p-n junctions at sides as shown in figure 1. The bar forms a conducting channel for the charge carriers. If the bar is of n-type then the JFET is called as n-channel JFET shown in figure 1(a). . If the bar is of p-type then the JFET is called as p-channel JFET shown in figure 1(b). the two p-type semiconductors in figure 1(a) or two n-type semiconductors in figure 1(b) are internally connected and a common terminal is brought out called as gate. The other two terminals brought out from the bar are called as source and drain.

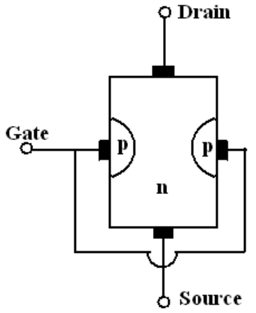


Fig 1(a) n-channel JFET

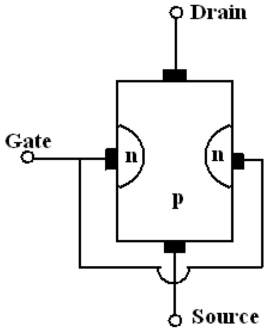


Fig 1(b) p-channel JFET

Working of JFET: Figure 2 shows the circuit diagram to study the working of a n-channel JFET. The circuit action is as follows.

When a potential difference or voltage V_{GS} is applied between drain and source with keeping zero voltage between gate and source, the two p-n junctions at the sides of the bar establishes two depletion layers. There is a plenty of region between these depletion layers through which the conduction of current can takes place. When the negative voltage is applied to the gate with respect to source as shown in figure 2(b), the width of depletion layers are increased due to which width of the region between the two depletion layers is decreased. This causes to less flow of electrons for the same drain voltage V_{DS}. Hence the drain current is decreased whenever the gate voltage V_{GS} is increased. The current conduction through n-channel JFET is due to electrons and in p-channel it is due to holes.

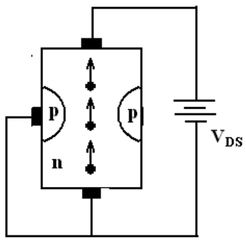


Fig. 2(a)

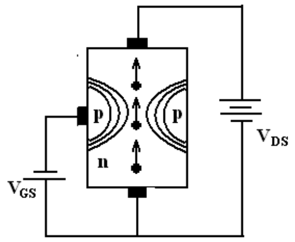


Fig. 2(b)

Symbol of JFET: Figure 3(a) shows the constructional structure of n-channel JFET and figure 3(b) shows its symbol. Similarly figure 4(a) represents the constructional structure of p-channel JFET and figure 4(b), its symbol.

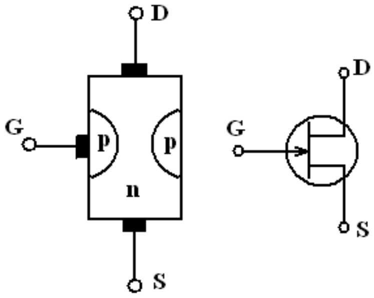


Fig. 3. n-channel JFET, (a) Constructional structure, (b) Symbol

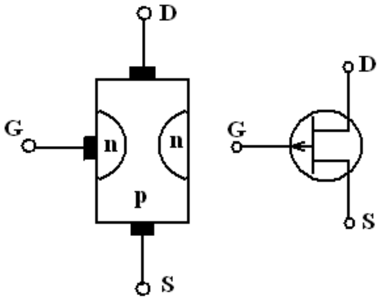


Fig. 4. p-channel JFET, (a) Constructional structure, (b) Symbol

9 Output and transfer characteristics of JFET:

Figure 1 shows the circuit diagram to determine the characteristics of an n-channel JFET. A characteristic relates the variation of current with respect to voltage of the given device. There are two types of characteristics for JFET namely output characteristic and transfer characteristic.

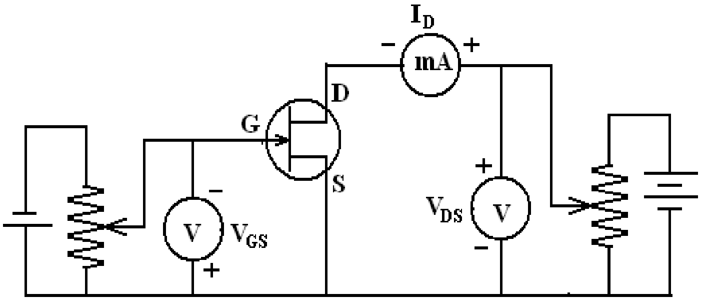


Fig. 1.

1) Output characteristics: The curve between drain current I_D and drain-source voltage V_{DS} at constant gate-source V_{GS} voltage is called as output characteristic of a JFET. To obtain it, the V_{GS} voltage is kept constant and the V_{DS} voltage is increased by small steps and at each step the corresponding drain current

I_D is noted. The graph is plotted between them. This procedure is repeated for several other values of the gate-source voltage V_{GS}. A family of output characteristics of typical JFET is shown in figure 2.

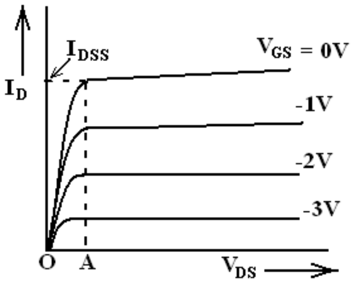


Fig. 2.

The following points may be noted from these characteristics.

Initially I_D increases rapidly with V_{DS} but then becomes almost constant. The drain-source voltage above which the drain current becomes constant is known as pinch off voltage V_P. Thus from figure 2, OA is the pinch off voltage.

After the pinch off voltage, the drain current becomes almost constant.

The drain current when V_{GS} = 0V and $V_{DS} = V_P$ is called shorted-gate drain current and is denoted by I_{DSS}.

Drain resistance: It is the ratio of the change in drain-source voltage (ΔV_{DS}) to the corresponding change in drain current (ΔI_D) at constant gate-source voltage V_{GS}. It is denoted by r_d. Therefore,

$$r_d = \frac{\Delta V_{DS}}{\Delta I_D} \text{ at constant } V_{GS} \qquad (1)$$

2) Transfer characteristics: The transfer characteristic of a JFET is the curve between the drain current I_D and the gate-source voltage V_{GS} with drain-source voltage V_{DS} is constant. To obtain it, the V_{DS} voltage is kept constant and the V_{GS} voltage is increased by small steps and at each step the corresponding drain current I_D is noted. The graph between I_D and V_{GS} is plotted. This procedure can be repeated for several values of V_{DS}. A transfer characteristic of a typical JFET is shown in figure 3. it is found that the drain current decreases with increase in gate-source voltage since the width of each depletion layer increases with increase in gate-source voltage. The value of V_{GS} at which the drain current becomes zero for given value of V_{DS} is called gate-source cutoff voltage $V_{GS(OFF)}$.

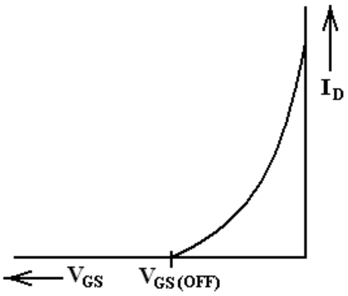


Fig. 3. Output characteristic of JFET.

Tranconductance (g_m): It is the ratio of the change in drain current (ΔI_D) to the corresponding change in gate-source voltage (ΔV_{GS}) at constant drain-source voltage V_{DS}. It is denoted by g_m. Therefore,

$$g_m = \frac{\Delta I_D}{\Delta V_{GS}} \text{ at constant } V_{DS} \qquad (2)$$

Amplification factor (μ): It is the ratio of the change in drain-source voltage (ΔV_{DS}) to the corresponding change in gate-source voltage (ΔV_{GS}) at constant drain I_D. It is denoted by μ. Therefore,

$$\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}} \text{ at constant } I_D \qquad (3)$$

Relation between μ, r_d and g_m: From equation (3), we arrange

$$\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}} = \frac{\Delta V_{DS}}{\Delta I_D} \times \frac{\Delta I_D}{\Delta V_{GS}} = r_d \times g_m$$

(from equations (1) and (2))

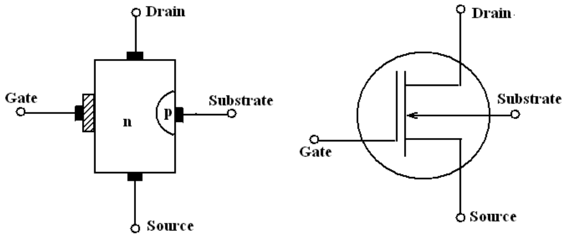
or $\mu = r_d \times g_m$ (4)

10 Construction and working of MOSFET

MOSFET means metal oxide semiconductor junction field effect transistor. The input impedance of MOSFET is much more than that of JFET because of very small gate leakage current.

Construction: Figure 1(a) shows the structural details of an n-channel MOSFET. It is similar to JFET except in the following modifications. There is only a single p-region. This is called a substrate. A thin layer of metal oxide usually silicon dioxide is deposited over the left side of the channel. A metallic gate is deposited over this oxide layer. As silicon dioxide is an insulator, therefore, the gate is insulated from the channel. Like JFET, MOSFET has three terminals, namely, source, gate and drain.

Figure 1(b) shows the schematic symbol of n-channel MOSFET. The arrow in p-channel MOSFET is outward in direction.



(a) Constructional structure (b) Symbol

Fig. 1 n-channel MOSFET

Working of MOSFET: Figure 2 shows the circuit to study the working of a MOSFET. Here the gate forms a small capacitor. One plate of the capacitor is the gate and the other is the channel and the metal oxide is the dielectric. When a negative voltage is applied to the gate with respect to the source, electrons accumulate on it. These electrons repel the conduction band electrons in the n-channel. Therefore, lesser number of conduction band electrons are made available for current conduction through the channel. The greater the negative voltage on gate, the lesser is the current conduction from source to drain. If the gate is given positive voltage, more electrons are made available in the channel, consequently, current from source to drain increases.

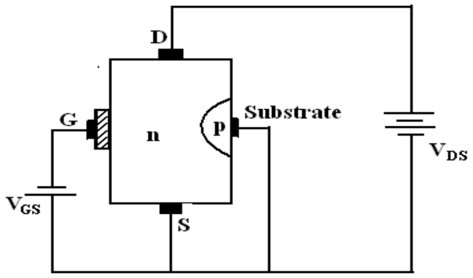


Fig. 2. Circuit of MOSFET.

The following points may be noted.

Unlike the JFET, MOSFET has no gate diode. This makes it possible to operate the device with negative as well as positive voltage.

In MOSFET the source to drain current is controlled by the field of the capacitor formed at the gate.

As the gate forms a capacitor, a negligible gate current flows through the gate. Consequently, the input impedance of the MOSFET becomes very high.

Power supplies

1 Half-wave rectifier:

A rectifier converts alternating current (ac) into direct current (dc). In half-wave rectification, the rectifier conducts current only during the positive half-cycles of input a.c. supply. During negative half-cycles, no current is conducted and hence no voltage appears across the load. Therefore current always flows in one direction through the load though after every half-cycle.

Circuit Diagram: Fig. 1 shows the circuit where a single crystal diode acts as a half-wave rectifier. The a.c. supply to be rectified is applied in series with the diode and load resistance R_L. The d.c. output is obtained across the load R_L. Generally, a.c. supply is given through a transformer.

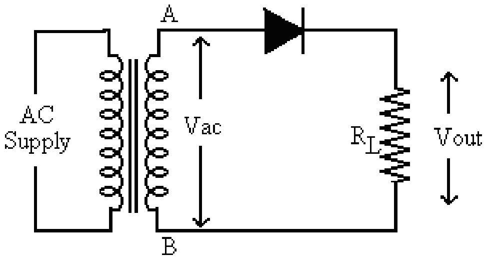
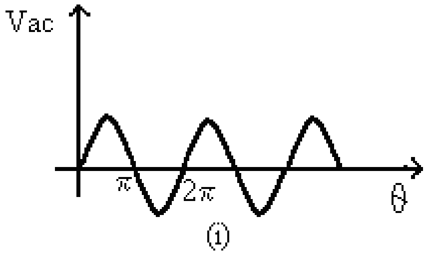
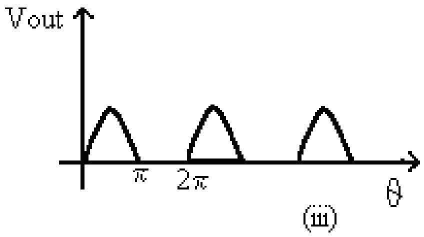


Fig. 1 Half-wave rectifier.



Input waveform



Output waveform

Operation: The a.c. voltage across the secondary winding AB changes polarities after every half cycle. During the positive half cycle of input a.c. voltage, end A becomes positive with respect to the end B. This makes the diode forward biased and hence it conducts current. During the negative half-cycle, end A is negative with respect to end B. Under this condition, the diode is reverse biased and it conducts no current. Therefore, current flows through the diode during positive half-cycles of input a.c. voltage only. In this way, current flows through load R_L always in the same direction. Hence d.c. output is obtained across R_L. It may be noted that output across load is pulsating d.c.. These pulsations in the output can be further smoothened with the help of filtering circuits.

2 Efficiency of half-wave rectifier:-

The ratio of d.c. power output to the applied input a.c. power is known as rectifier efficiency, i.e.

$$\eta = \frac{d.c.OutputPower}{a.c.InputPower}$$

Consider a half-wave rectifier shown in Fig. 1. Let $v = V_m \mathrm{Sin}\theta$ be the alternating voltage that appears across the secondary winding. Let r_f and R_L be the diode resistance and load resistance respectively. The diode conducts during positive half cycles of a.c. supply while no current conduction takes place during negative half-cycles.

d.c. power: The output current is pulsating direct current. Therefore, in order to find d.c. power, average current has to be found out.

$$I_{av} = I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i\,d\theta = \frac{1}{2\pi}\int_0^{\pi} \sin\theta\,d\theta + \frac{1}{2\pi}\int_{\pi}^{2\pi} 0\,d\theta$$

Since i = $I_m \sin\theta$ for $0 \le \theta \le \pi$ and i = 0 for $\pi \le \theta \le 2\pi$, and $I_m = \dfrac{Vm}{r_f + R_L}$

(1)

$$I_{dc} = \frac{I_m}{2\pi}\int_0^{\pi} \sin\theta\,d\theta = \frac{I_m}{2\pi}\left[-\cos\theta\right]_0^{\pi} = \frac{I_m}{2\pi}[2]$$

$$I_{dc} = \frac{I_m}{\pi} \qquad (2)$$

But the d.c. output power, $P_{dc} = I_{dc}^2 \times R_L$

or $$P_{dc} = \left(\frac{I_m}{\pi}\right)^2 \times R_L \qquad (3)$$

a.c. input power:

The average value of the input current is obtained in terms of root mean square (r.m.s.) value of it.

$$I_{rms} = \left[\frac{1}{2\pi}\int_0^{2\pi} i^2 d\theta\right]^{1/2} = \left[\frac{1}{2\pi}\int_0^{\pi} (I_m \sin\theta)^2 d\theta + \frac{1}{2\pi}\int_{\pi}^{2\pi} 0\,d\theta\right]^{1/2}$$

$$I_{rms} = I_m\left[\frac{1}{2\pi}\int_0^{\pi} \sin^2\theta\,d\theta\right]^{1/2} = \frac{I_m}{2} \qquad (4)$$

The a.c. input power, $P_{ac} = I_{rms}^2 \times (r_f + R_L)$

$$P_{ac} = \left(\frac{I_m}{2}\right)^2 (r_f + R_L) \qquad (5)$$

Efficiency:

Therefore half-wave Rectifier efficiency,

$$\eta = \frac{\left(\frac{I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{2}\right)^2 \times (r_f + R_L)}$$

$$\eta = \frac{0.406 \times R_L}{(r_f + R_L)} \qquad (6)$$

or $\eta = 0.406$

where r_f is neglected in comparison with R_L.

Thus the maximum efficiency of half-wave rectifier in percentage when r_f is neglected is

$$\eta = 40.6\,\% \qquad (7)$$

which is less than fifty percent.

3 Ripple factor of half-wave rectifier

From the output wave forms of the rectifier it is clear that the output voltage is pulsating and it contains a d.c. component and an a.c. component. The a.c. component is undesirable.

The ratio of r.m.s. value of a.c. component to the d.c. component in the rectified output is known as ripple factor, i.e.

r.m.s. value of a.c. component
Ripple factor = ---------------------------------

Value of d.c. component

By definition, the effective or r.m.s. value of total load current is given by

$$I_{rms} = \sqrt{I_{dc}^2 + I_{ac}^2}$$

or $$I_{rms}^2 = I_{dc}^2 + I_{ac}^2$$

$$I_{ac}^2 = I_{rms}^2 - I_{dc}^2$$

or $$I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$$

Dividing throughout by I_{dc}, we get

$$\frac{I_{ac}}{I_{dc}} = \sqrt{\frac{I_{rms}^2 - I_{dc}^2}{I_{dc}^2}}$$

or $$\frac{I_{ac}}{I_{dc}} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

But for half-wave rectifier we have $I_{rms} = I_m/2$ and $I_{dc} = I_m/\pi$. Substituting these in above equation we get, Ripple factor,

$$\gamma = \frac{I_{ac}}{I_{dc}} = \sqrt{\left(\frac{I_m/2}{I_m/\pi}\right)^2 - 1} = \sqrt{\left(\frac{\pi}{2}\right)^2 - 1} = \sqrt{\left(\frac{3.14}{2}\right)^2 - 1}$$

or $\gamma = 1.21$

It is clear that a.c. component exceeds tha d.c. component in the output of a half-wave rectifier. This results in greater pulsations in the output. Therefore, half-wave rectifier is ineffective for conversion of a.c. into d.c.

4 Centre-tap full-wave rectifier:

In full-wave rectification, current flows through the load in the same direction for both half cycles of input a.c. voltage. The centre-tap full-wave rectifier circuit employs two diodes D1 and D2 with a center tapped transformer as shown in Fig. 1.

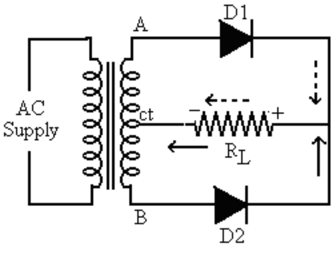
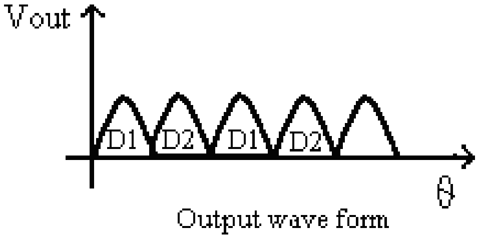


Fig. 1. Full-wave rectifier.



Operation:

During the positive half-cycle of secondary voltage the end A of the secondary winding becomes positive and end B negative. This makes the diode Dl forward biased and diode D2 reverse biased. Therefore diode Dl conducts while diode D2 does not. The conventional current flow is through diode Dl, load resistor RL and the upper half of secondary winding as shown by the dotted arrows. During the negative half cycle end A of the secondary winding becomes negative and end B positive. Therefore, diode D2 conducts' while diode D1 does not. The conventional current flows through diode D2, load RL and lower half winding as shown by solid arrows. Referring to Fig.1, it may be seen that current in the load RL is in the same direction for both half-cycles of input a.c. voltage. Therefore, d,c, output is obtained across the load RL. Also, the polarities of the d.c. output across the load should be noted.

Peak inverse voltage:

Suppose V is the maximum voltage across the half secondary winding. Fig. 1 shows the circuit at the instant the secondary voltage reaches its maximum value in the positive direction. At this instant, diode D1 is conducting while diode D2 is non-conducting. Therefore, whole of the secondary voltage appears across the non-conducting diode. Consequently, the peak inverse voltage is twice the maximum voltage across the ha1f secondary winding i.e.

PIV = 2V

Disadvantages:

Following are the disadvantages of the center tapped full-wave rectifier.

It is difficult to locate the center tap on the secondary winding.

The d.c. output is small as each diode utilizes only one half of the transformer secondary voltage.

The diodes used must have high peak inverse voltage.

5 Efficiency of full-wave rectifier:

The ratio of d.c. power output to the applied input a.c. power is known as rectifier efficiency, i.e.

$$\eta = \frac{d.c.OutputPower}{a.c.InputPower}$$

Consider a full-wave rectifier shown in Fig. 1. Let v = $V_m\text{Sin}\theta$ be the alternating voltage that appears across the secondary winding. Let r_f and R_L be the diode resistance and load resistance respectively. The diode conducts during positive half cycles of a.c. supply while no current conduction takes place during negative half-cycles.

d.c. power:

The output current is pulsating direct current. Therefore, in order to find d.c. power, average current has to be found out.

$$I_{av} = I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i\,d\theta = \frac{1}{2\pi}\int_0^{\pi} i_1 d\theta + \frac{1}{2\pi}\int_{\pi}^{2\pi} i_2 d\theta$$

$$I_{dc} = \frac{1}{2\pi}\int_0^{\pi} I_m \text{Sin}\theta d\theta - \frac{1}{2\pi}\int_{\pi}^{2\pi} I_m \text{Sin}\theta d\theta$$

Since $i = i_1 + i_2$ with

$i_1 = I_m\text{Sin}\theta$ for $0 \le \theta \le \pi$ and $i_1 = 0$ for $\pi \le \theta \le 2\pi$

$i_2 = 0$ for $0 \le \theta \le \pi$ and $i_2 = -I_m\text{Sin}\theta$ for $\pi \le \theta \le 2\pi$

and $$I_m = \frac{Vm}{r_f + R_L}$$

$$I_{dc} = \frac{I_m}{2\pi}\int_0^{\pi} \text{Sin}\theta d\theta - \frac{I_m}{2\pi}\int_{\pi}^{2\pi} \text{Sin}\theta d\theta \quad \text{or} \quad I_{dc} = \frac{I_m}{2\pi}[-\text{Cos}\theta]_0^{\pi} - \frac{I_m}{2\pi}[-\text{Cos}\theta]_{\pi}^{2\pi}$$

$$I_{dc} = \frac{I_m}{2\pi}[2] + \frac{I_m}{2\pi}[2]$$

$$I_{dc} = \frac{2I_m}{\pi} \qquad (1)$$

d.c. output power, $P_{dc} = I_{dc}^2 \times R_L$

$$P_{dc} = \left(\frac{2I_m}{\pi}\right)^2 \times R_L \qquad (2)$$

a.c. input power:

The average value of the input current is obtained in terms of root mean square (r.m.s.) value of it.

$$I_{rms} = \left[\frac{1}{2\pi}\int_0^{2\pi} i^2 d\theta\right]^{1/2} = \left[\frac{1}{2\pi}\int_0^{\pi} i_1^2 d\theta + \frac{1}{2\pi}\int_{\pi}^{2\pi} i_2^2 d\theta\right]^{1/2}$$

$$I_{rms} = \left[\frac{1}{2\pi}\int_0^{\pi} (I_m \mathrm{Sin}\,\theta)^2 d\theta + \frac{1}{2\pi}\int_{\pi}^{2\pi} (-I_m \mathrm{Sin}\,\theta)^2 d\theta\right]^{1/2}$$

$$I_{rms} = \left[\frac{I_m^2}{2\pi}\int_0^{\pi} \mathrm{Sin}^2\theta d\theta + \frac{I_m^2}{2\pi}\int_{\pi}^{2\pi} \mathrm{Sin}^2\theta d\theta\right]^{1/2}$$

$$I_{rms} = \frac{I_m}{\sqrt{2}} \qquad (3)$$

a.c. input power,

$Pac = I_{rms}^2 \times (r_f + R_L)$

or $$P_{ac} = \left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L) \qquad (6)$$

Efficiency:

Therefore half-wave Rectifier efficiency,

$$\eta = \frac{\left(\frac{2I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 \times (r_f + R_L)}$$

$$\eta = \frac{0.812 \times R_L}{(r_f + R_L)} \qquad (7)$$

or $\eta = 0.812$

where r_f is neglected in comparison with R_L.

Thus the maximum efficiency of half-wave rectifier in percentage when r_f is neglected is

$\eta = 81.2\ \%$ (8)

This is double the efficiency due to half-wave rectifier. Therefore, a full-wave rectifier is twice as effective as a half-wave rectifier.

6 Ripple factor of full-wave rectifier:

From the output wave forms rectifier it is clear that the output voltags is pulsating and it contains a d.c. component and an a.c. component. The a.c. component is undesirable.

The ratio of r.m.s. value of a.c. component to the d.c. component in the rectified output is known as ripple factor, i.e.

r.m.s. value of a.c. component
Ripple factor = ---------------------------------
Value of d.c. component

By definition, the effective or r.m.s. value of total load current is given by

$$I_{rms}^2 = I_{dc}^2 + I_{ac}^2$$

$$I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$$

Dividing throughout by I_{dc}, we get

$$\frac{I_{ac}}{I_{dc}} = \sqrt{\frac{I_{rms}^2 - I_{dc}^2}{I_{dc}^2}}$$

or $$\frac{I_{ac}}{I_{dc}} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

But for full-wave rectifier we have $I_{rms} = \frac{I_m}{\sqrt{2}}$ and $I_{dc} = \frac{2I_m}{\pi}$. Substituting these in above equation we get,

Ripple factor,

$$\gamma = \frac{I_{ac}}{I_{dc}} = \sqrt{\left(\frac{I_m/\sqrt{2}}{2I_m/\pi}\right)^2 - 1} = \sqrt{\left(\frac{\pi}{2\sqrt{2}}\right)^2 - 1} = \sqrt{\left(\frac{3.14}{2\sqrt{2}}\right)^2 - 1}$$

$\gamma = 0.48$

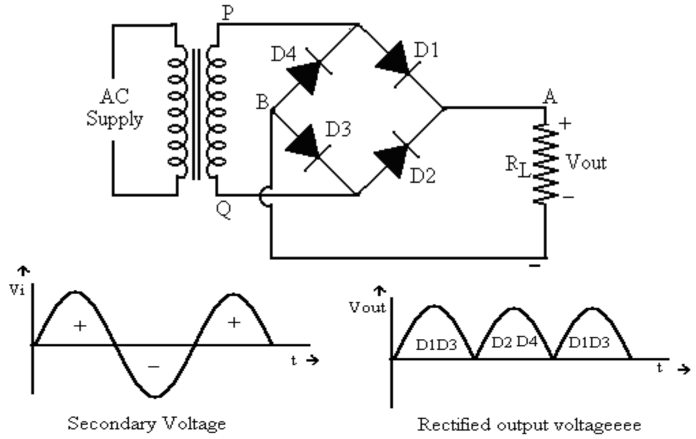
This shows that in the output of a full-wave rectifier, the d.c. component is more than the a.c. component. Consequently, the pulsations in the output will be less than that of half-wave rectification. For this reason, full-wave rectification is invariably used for conversion of a.c. into d.c.

7 Full-wave bridge rectifier:

The need for a center tapped power transformer is eliminated in the bridge rectifier. It contains four diodes Dl, D2, D3 and D4, connected to form bridge as shown in Fig. 1. The a.c. supply to be rectified is applied to the diagonally opposite ends of the bridge through the transformer. Between other two ends of the bridge, the load resistance RL is connected.

Operation:

During the positive half-cycle of secondary voltage, the end P of the secondary winding becomes positive and end Q negative. This makes diodes Dl and D3 forward biased while diodes D2 and D4, are reverse biased. Therefore, only diodes D1 and D2 conduct. These two diodes will be in series through the load RL as shown in Fig. 2(a). The conventiona1 current flow is shown by dotted arrows. It may be seen that current flows from A to B through the load BL.



Secondary Voltage

Rectified output voltageeee

Fig. 1. Bridge Rectiier.

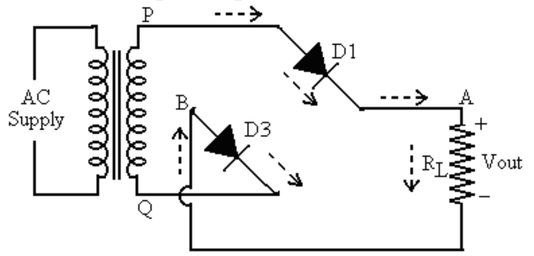


Fig. 2(i)

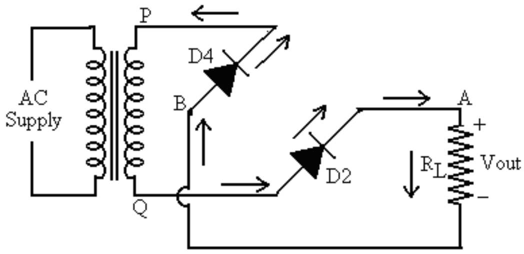


Fig. 2(ii).

During the negative half-cycle of secondary voltage, end P becomes negative and end Q positive. This makes diodes D2 and D4 forward biased whereas diodes D1 and D3 are reverse biased. Therefore, only diodes D2 and D4, conduct. These two diodes will be in series through the load RL as shown in Fig. 2 (b). The current flow is shown by the solid arrows. It may be seen that again current flows from A to B through the load i.e. in the same direction as for the positive half cycle. Therefore, d,c. output it obtained across load RL.

Peak inverse voltage:

Referring to Fig. 1, when end P is positive, diode D1,D3 conduct (i,e. its resistance is zero) whereas diode D2,D4 do not conduct. By studying the circuit, it is easy to see that whole of the secondary voltage is applied in the reverse direction across D2,D4. Hence, PIV of each diode is equal to the half of the maximum secondary voltage.

Advantages:

(i) The need for center-tapped transformer is eliminated.

(ii) The output is twice that of the center-tap circuit for the same secondary voltage.

(iii) The PIV is one-half that of the center-tap circuit.

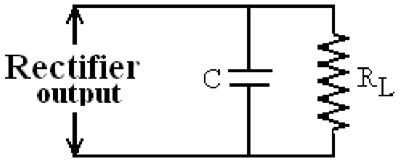
Disadvantages:

(i) It requires four diodes.

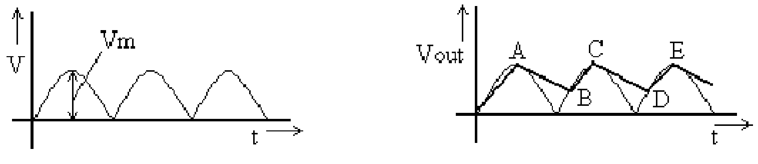
(ii) As during each half-cycle of a.c. input, two diodes that conduct are in series, therefore, voltage drop m the internal resistance of the rectifying unit will be twice as great as in the center-tap circuit. This is objectionable when secondary voltage is small.

8 Capacitor filter:

Fig. 1 shows a typical capacitor filter circuit. It consists of a capacitor C placed across the rectifier output in parallel with load R_L. The pulsating direct voltage of the rectifier is applied across the capacitor. As the rectifier voltage increases, it charges the capacitor and also supplies current to the load. At the end of quarter cycle [point A in Fig. 1 (ii)], the capacitor is charged to the peak value Vm of the rectifier voltage. Now, the rectifier voltage starts to decrease. As this occurs, the capacitor discharges through the load and voltage across it (i.e. across parallel combination of R_L) decreases as shown by the line AB in Fig. 1(ii). The voltage across load will decrease only slightly because immediately the next voltage peak comes and recharges the capacitor. This process is repeated again and again and the output voltage waveform becomes ABCDE. It may be seen that very little ripple is left in the output. Moreover, output voltage is higher as it remains substantially near the peak value of rectifier output voltage.



Sunt Capacitor Filter.



(i) Output voltage of a Full-wave rectifier.

(ii) Outout voltage of a shunt capacitor fiter.

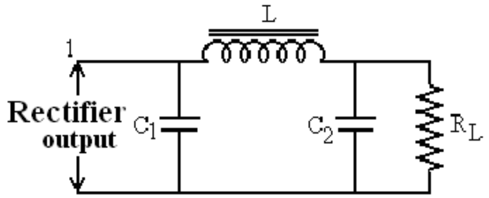
Fig. 1.

The capacitor filter circuit is extremely popular because of its low cost, small size, little weight and good characteristics. For small load currents (say upto 50 mA), this type of filter is preferred. It is commonly used in transistor radio battery eliminators.

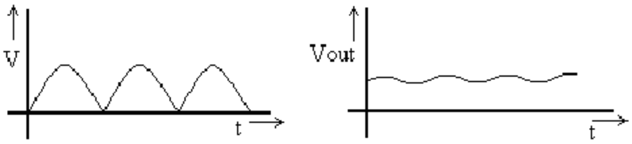
9 Capacitor input filter or π-filter:

Fig. 1 shows a typical capacitor input filter or π-filter. It consists of a filter capacitor C1 connected across the rectifier output, a choke L in series and another filter capacitor C2 connected across the load. Only one fi1ter section is shown, but several identical sections are often used to improve the smoothing action.

The pulsating output from the rectifier is applied across the input terminals (i.e. terminals 1 and 2) of the filter. The filtering action of the three components viz C1, L and C2 of this filter is described below.



Pi-filter.



(i) Output voltage of a Full-wave rectifier.

(ii) Outout voltage of a Pi-filter.

Fig. 1.

(a) The filter capacitor C1 offers low reactance to a.c. component of rectifier output while it offers infinite reactance to the d.c. component. Therefore, capacitor C1 bypasses an appreciable amount of a.c. component while the d.c. component continues its journey to the choke L.

(b) The choke L offers high reactance to the a.c. component but it offers almost zero reactance to the d.c. component. Therefore, it allows the d.c. component to flow through it, while the unbypassed a.c. component is blocked.

(c) The filter capacitor C2 bypasses the a.c. component, which the choke has failed to block. Therefore, only d.c. component appears across the load and that is what we desire.

10 Zener diode voltage regulator:

We know that when a zener diode is operated in the breakdown region, the voltage across it is substantially constant for a large change of current through it. This characteristic permits it to be used as a voltage regulator. Fig. 1 shows the circuit of a zener diode regulator. As long as input voltage V in is greater than zener voltage Vz, the zener operates in the breakdown region and maintains constant voltage across the load. The series limiting resistance R limits the input current.

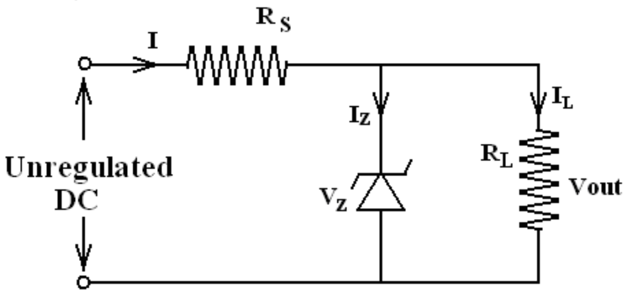


Fig. 1. Zener diode voltage regulator.

Operation: The zener will maintain constant voltage across the load in spite of changes in load current or input voltage. As the load current increases, the zener current decreases so that current through resistance R is constant. Since output voltage, Vo = Vin - IR, and I is constant, therefore, output voltage remains unchanged. The reverse would be true. The circuit will also correct for the changes in input voltages. If there is increase in the input voltage V, more current will flow through the zener, the voltage drop across Rs will increase but load voltage would remain constant. The reverse would be true.

Limitations: A zener diode regulator has the following draws backs.

(i) It has low efficiency for heavy load currents. It is because if the load current is large, there will be considerable power loss in the series limiting resistance.

(ii) The output voltage slightly changes due to zener impedance as Vout = Vz + IzZz. Changes in load current produce changes in zener current. Consequently, the output voltage also changes. Therefore, the use of this circuit is limited to only such applications where variations in load current and input voltage are small.

11 Transistor series voltage regulator:

Fig. 1 shows a simple series voltage regulator using a transistor and zener diode. The circuit is called a series voltage regulator because collector-emitter terminals are in series with the load. The unregulated d.c. supply is fed to the input terminals. So long as the input voltage is greater than Vz (zener voltage), the zener operates in the breakdown region and the output voltage remains constant.

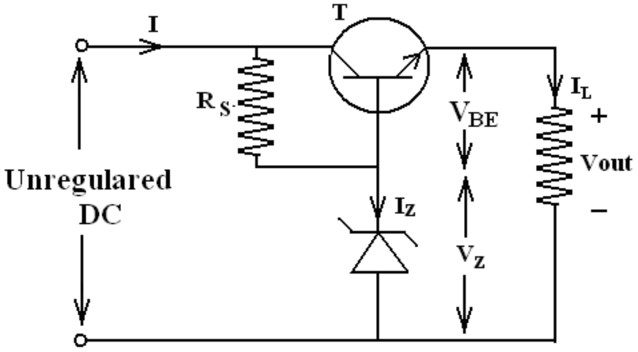


Fig. 1. Transistor voltage regulator.

From figure, it is clear that output voltage is equal to zener voltage minus the V_{BE} drop i.e.

$$Vout = Vz - V_{BE}$$

As V_{BE} is quite small, as compared to Vz, therefore, it can be neglected. Consequently, Vout = Vz. Now the zener diode operates in the breakdown region, therefore, Vz and hence Vout remains substantially constant. The advantage of this circuit is that the changes in zener current are reduced by a factor β. Therefore, the effect of zener impedance is greatly reduced and much more stabilized output voltage is ensured.

Limitation: A transistor series voltage regulator has the following draws backs.

(i) Although the changes in zener current are much reduced, yet the output is not absolutely constant. It is because both V_{BE} and Vz decrease with the increase in room temperature.

(ii) The output voltage cannot be changed easily as no such means is provided.