6.2 P-N JUNCTION DIODE

A P-N junction diode is formed by introducing N-type impurity into one side and P-type impurity into the other side of a single crystal of semiconductor, as shown in Fig. 6.1.

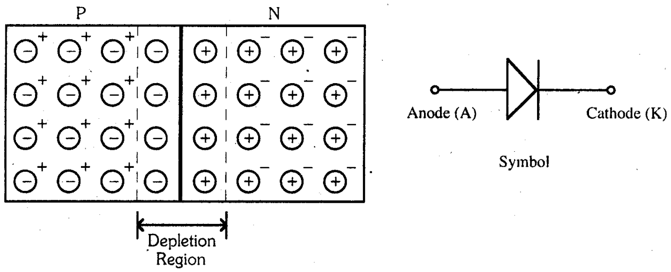

Fig. 6.1

We know that N-type material has a high concentration of free electrons while P-type material has a high concentration of holes. Therefore, at the P-N junction, there is a tendency for the free electrons to diffuse over to the P-side and holes to N-side. This process is called diffusion. As the free electrons move across the junction from N-type to P-type, a positive charge is built on the N-side of the junction. At the same time, the free holes cross the junction and a negative charge is established on the P-side of the junction. These recombinations near the junction do not continue for a long time because positive charge on N-side repels holes to cross from P-type to N-type and negative charge on P-side repels free electrons to enter from N-type to P-type. Thus the region at junction contains only negative and positive charge. This region is called depletion region or space charge region as the mobile charge carriers (free electrons and holes) have been depleted in this region.

Due to positive and negative charge in the depletion region, an electric field is formed. Therefore, an electric potential is established across the junction which is called as barrier potential. The potential is about 0.3 V for germanium and 0.7 V for silicon.

6.2.1 Working and Characteristics

Forward Biasing : A P-N junction is said to be forward biased when a positive terminal of the battery is connected to P-side and negative to N-side. This applied voltage establishes an electric field which acts against the field due to the potential barrier. Therefore resulting field is weakened. As potential barrier voltage is very small (0.3 V for Ge and 0.7 V for Si), a small forward voltage is sufficient to completely eliminate the barrier. Once the potential barrier is eliminated, current starts flowing in the circuit.

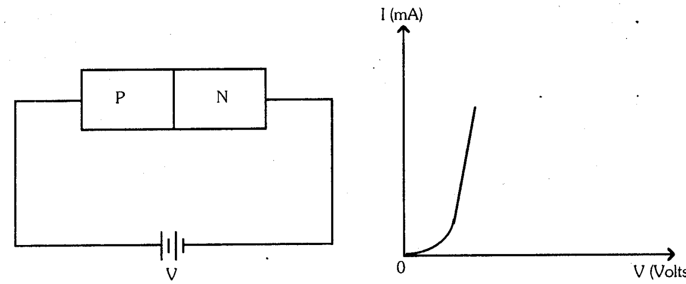

Fig. 6.2

Reverse Biasing : A P-N junction is said to be reverse biased when a negative terminal of the battery is connected to P-side and positive to N-side. The applied reverse voltage establishes an electric field which acts in the same direction as the field due to the potential barrier.

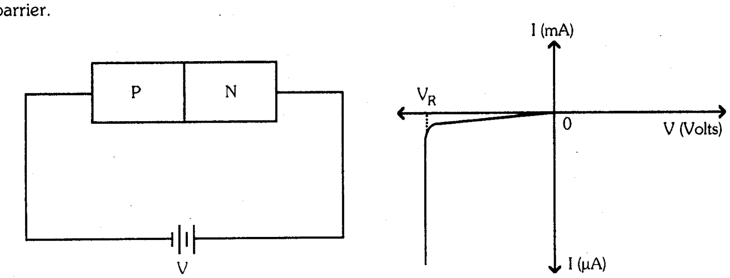

Fig. 6.3

Therefore resulting field is strengthened. The increased potential barrier prevents the flow of charge carriers across the junction. Hence no current flows in the circuit. However, in practice, a very small current flows due to minority carriers. If reverse voltage is increased continuously, at one stage junction breaks down and heavy current starts flowing.

6.2.2 Important Terms in P-N Junction Diode

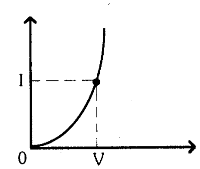

Fig. 6.4

(i) **DC or Static Resistance :** The resistance offered by the diode to dc supply, when forward biased is known as dc or static resistance. It is the ratio of dc voltage across the diode to the dc current flowing through it.

$$R_f = \frac{V}{I}$$

(ii) AC or Dynamic Resistance : The resistance offered by the diode to a changing signal, when forward biased, is known as ac or dynamic resistance. If ΔV is the change in voltage and ΔI is the change in current, the dynamic resistance r_f is given by,

$$r_f = \frac{\Delta V}{\Delta I}$$

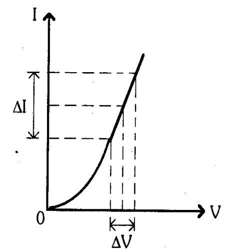

Fig. 6.5

(iii) Transition Capacitance : When a P-N junction is reversed biased, the majority carriers move away from the junction. Hence depletion region increases in size. As the reverse voltage increases, the depletion region consisting of positive and negative charge also increases. Thus capacitance exists across the junction due to the presence of immobile charges. This capacitance is called transition or space charge capacitance (C_T).

(iv) Diffusion Capacitance : When P-N junction is forward biased, electrons from N-side will move into P-side and holes from P-side will move into N-side. As the forward voltage increases, the number of majority carriers crossing the junction also increases. The change in the amount of charge Q due to change in applied voltage is called diffusion capacitance (C_D).

(v) Reverse Saturation Current : When a P-N junction is reverse biased, there is no current due to majority carriers, yet there is small amount of current due to flow of minority carriers across the junction. This current is called reverse saturation current. Since minority carriers are thermally generated, reverse saturation current is extremely temperature dependent.

Q.9 Explain breakdown effect.

Ans. As we increase the reverse bias across the diode the reverse saturation current remains almost unchanged. **However, at certain value of reverse voltage, suddenly large current flows from n side to p side inside the diode**. This effect is called **breakdown effect** and the corresponding voltage is called **breakdown voltage**. This effect can take place in following two ways depending upon doping level and applied voltage.

(A) **Zener breakdown : This effect takes place when doping level is large and applied voltage is small.** Due to large doping level there is a large electric field across the junction. This electric field is strong enough to remove electrons from the parent Si atoms within the depletion region. This creates large number of electron-hole pairs with in the depletion region. These minority carriers are swept away by the applied voltage and thus results in a large reverse current. During this the voltage across diode remains constant.

(B) **Avalanche breakdown : This effect takes place when doping level is small and applied voltage is large.** When the reverse voltage is increased the electric field across the junction increases and the electron are accelerated. The high energetic electrons, by collision, break covalent bonds and more electron-hole pairs are generated. This creates a chain reaction. These minority carriers are swept away by the applied voltage and thus results in a large reverse current. During this the voltage across diode remains constant.

6.3 ZENER DIODE

When reverse voltage across P-N junction diode is continuously increased, at one point junction breaks down and heavy current starts flowing.

There are two types of breakdown mechanism :

(i) Zener Breakdown

(ii) Avalanche Breakdown

Zener Breakdown : This phenomenon occurs in heavily doped P-N junction. The heavy doping makes the depletion layer very thin. When a reverse voltage is applied across P-N junction, a sufficiently strong force is exerted on a bound electron by the electric field. This field tears electrons out of its covalent bond. The new hole-electron pair which is created increases the reverse current. This process is called Zener breakdown. It does not involve collision of minority carriers.

Avalanche Breakdown : This phenomenon occurs in lightly doped P-N junctions where the depletion region is comparatively long. When applied reverse voltage increases, thermally generated minority carriers gain sufficient energy from the field and hence their velocity increases. They collide with the valence electrons and impart sufficient energy to disrupt a covalent bond. Therefore, in addition, to the original carrier a new electron-hole pair is generated. These carriers may also pick up sufficient energy from the applied field, collide with another valence electron, and create still another electron hole pair. Thus each new carrier may, in turn, produce additional carriers through collision and the action of disrupting bonds. This cumulative process is referred to as avalanche multiplication. It results in large reverse current and the diode is said to be in the region of avalanche breakdown.

In a Zener diode either or both breakdown mechanism may be present. At heavy doping levels and lower voltages the zener mechanism dominates. At low doping levels and higher voltages, the avalanche mechanism dominates.

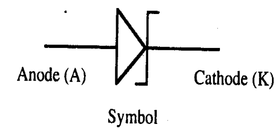

Fig. 6.12

Working and characteristics :

When forward biased, Zener diode behaves like a normal P-N junction diode. When reverse biased, it does not conduct until the applied reverse voltage reaches or exceeds Zener voltage V_Z and then current starts flowing through it.

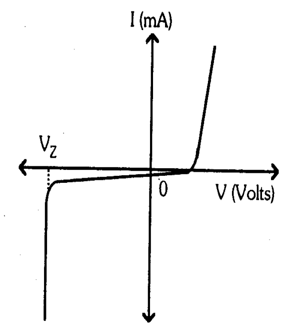

Fig. 6.13

6.5 RECTIFIERS

A rectifier is a device that converts ac voltage into dc voltage. The element used for rectification is a diode. The diode can be used as rectifier as it conducts in one direction only. When diode is forward biased, it allows the current to flow through it. When it is reverse biased, no current flows through it. There are two types of rectifiers :

(i) Half wave rectifier

(ii) Full wave rectifier

6.6 HALF WAVE RECTIFIER

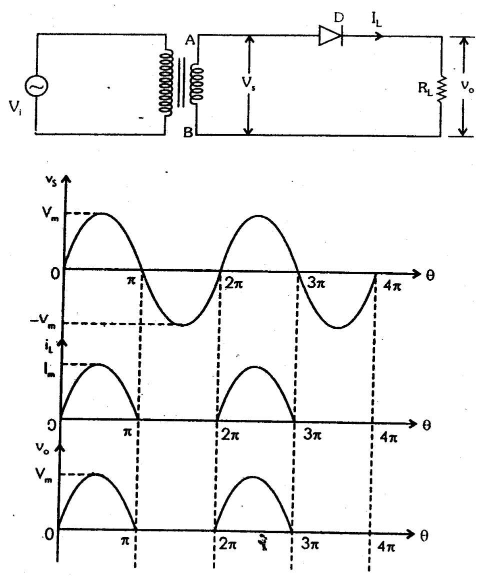

Fig. 6.35

Fig. 6.35 shows a half wave rectifier. It uses only one diode.

Working : During positive half cycle of ac supply, terminal A is positive w.r.t. B. Therefore liode D is forward biased and current flows through the load. During negative half cycle, erminal B is positive w.r.t. A. Therefore diode D is reverse biased and no current flows through ne load. The output voltage appears across the load during positive half cycle of ac supply only. lence circuit is called as half wave rectifier. The output of rectifier is pulsating in nature i.e. it ontains ac as well as dc components.

6.6.1 Analysis of Half Wave Rectifier

1. DC or average value of load current (I_{dc}) :

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i_L\, d\theta = \frac{1}{2\pi}\left[\int_0^{\pi} I_m \sin\theta\, d\theta + \int_{\pi}^{2\pi} 0\, d\theta\right]$$

$$= \frac{I_m}{2\pi}\,[-\cos\theta]_0^{\pi}$$

$$= \frac{I_m}{2\pi}\,[-\cos\pi + \cos 0] = \frac{I_m}{\pi}$$

2. RMS value of load current (I_{rms}) :

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

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

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

$$= \sqrt{\frac{I_m^2}{4\pi}\left[\pi - \frac{\sin 2\pi}{2} + \frac{\sin 0}{2}\right]} = \sqrt{\frac{I_m^2}{4}}$$

$$= \frac{I_m}{2}$$

3. Output voltage (V_{dc}) :

$$V_{dc} = I_{dc} R_L = \frac{I_m}{\pi} R_L$$

$$= \frac{1}{\pi}\frac{V_m}{(R_f + R_s + R_L)} R_L \qquad \left(\because I_m = \frac{V_m}{R_f + R_s + R_L}\right)$$

where $R_f \rightarrow$ Diode forward resistance

$R_s \rightarrow$ Secondary winding resistance

$R_L \rightarrow$ Load resistance

$$V_{dc} = \frac{V_m}{\pi}\left(\frac{R_f + R_s + R_L - R_f - R_s}{R_f + R_s + R_L}\right) = \frac{V_m}{\pi}\left(1 - \frac{R_f + R_s}{R_f + R_s + R_L}\right)$$

$$= \frac{V_m}{\pi} - \frac{V_m}{\pi\,(R_f + R_s + R_L)} \cdot (R_f + R_s)$$

$$= \frac{V_m}{\pi} - I_{dc} \cdot (R_f + R_s)$$

At no load, $I_{dc} = 0$

$$V_{dc} = \frac{V_m}{\pi}$$

4. Rectifier efficiency : It is defined as the ratio of dc output power to ac input power.

$$\eta = \frac{\text{DC output power}}{\text{AC input power}} = \frac{P_{dc}}{P_{ac}}$$

$$P_{dc} = I_{dc}^2 R_L = \frac{I_m^2}{\pi^2} R_L$$

$$P_{ac} = I_{rms}^2 (R_f + R_s + R_L) = \left(\frac{I_m}{2}\right)^2 (R_f + R_s + R_L)$$

$$= \frac{I_m^2}{4} (R_f + R_s + R_L)$$

$$\eta = \frac{\frac{I_m^2}{\pi^2} R_L}{\frac{I_m^2}{4}(R_f + R_s + R_L)} = \frac{4}{\pi^2} \frac{R_L}{R_f + R_s + R_L}$$

$$= \frac{4}{\pi^2} \frac{1}{\frac{R_f + R_s}{R_L} + 1}$$

$$= \frac{4}{\pi^2} \qquad (\because R_f + R_s << R_L)$$

$$= 0.406$$

$$\% \eta = 40.6\,\%$$

5. Ripple factor : The purpose of a rectifier is to convert ac into dc. The output of rectifier is pulsating in nature i.e. it contains dc as well as ac components. The ac component is called ripple which is removed with the help of filter circuit. The ratio of rms value of ac component of the waveform to the dc component of the waveform is known as ripple factor.

$$\text{Ripple factor } r = \frac{\text{RMS value of AC component of wave}}{\text{DC component of wave}}$$

$$= \frac{I_{ac,\,rms}}{I_{dc}}$$

The output current in half wave rectifier is given by,

$$i_L = I_{dc} + i_{ac}$$

RMS value of output current is given by,

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

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

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

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

For half wave rectifier,

$$r = \sqrt{\frac{\left(\frac{I_m}{2}\right)^2}{\left(\frac{I_m}{\pi}\right)^2} - 1} = 1.21$$

6. Peak Inverse Voltage (PIV) : It is defined as the maximum reverse voltage that can be applied across the diode without damaging it. For half wave rectifier,

$$PIV = V_m$$

7. Transformer Utilization Factor (TUF) :

$$TUF = \frac{\text{DC power delivered to the load}}{\text{AC rating of transformer secondary}}$$

$$= \frac{P_{dc}}{P_{ac}\,(\text{rated})}$$

The rated voltage of secondary is $\frac{V_m}{\sqrt{2}}$, but actual rms current flowing through the winding is only $\frac{I_m}{2}$, not $\frac{I_m}{\sqrt{2}}$.

$$TUF = \frac{\left(\frac{I_m}{\pi}\right)^2 R_L}{\frac{V_m}{\sqrt{2}} \frac{I_m}{2}}$$

$$= \frac{\frac{I_m^2}{\pi^2} R_L}{\frac{I_m (R_f + R_s + R_L)}{\sqrt{2}} \frac{I_m}{2}} \qquad [\because V_m = I_m (R_f + R_s + R_L)]$$

$$= \frac{2\sqrt{2}}{\pi^2} \frac{R_L}{R_f + R_s + R_L} = \frac{2\sqrt{2}}{\pi^2} \frac{1}{\frac{R_f + R_s}{R_L} + 1}$$

$$= \frac{2\sqrt{2}}{\pi^2} \qquad (\because R_f + R_s << R_L)$$

$$= 0.287$$

8. Voltage regulation : The variation of dc output voltage as a function of dc load current is called voltage regulation.

$$\%\text{ Regulation} = \frac{V_{dc_{no\ load}} - V_{dc_{full\ load}}}{V_{dc_{full\ load}}} \times 100$$

$$= \frac{\frac{V_m}{\pi} - \left[\frac{V_m}{\pi} - I_{dc} (R_f + R_s)\right]}{I_{dc} \cdot R_L} \times 100$$

$$= \frac{R_f + R_s}{R_L} \times 100$$

6.7 FULL WAVE RECTIFIER

Centre tap full wave rectifier :

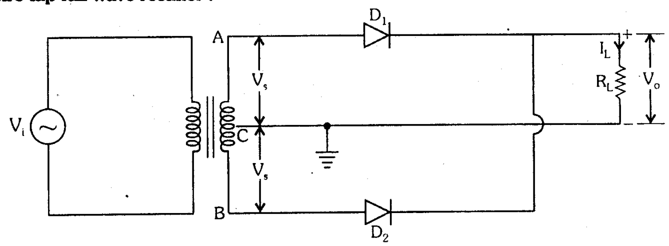

Fig. 6.36

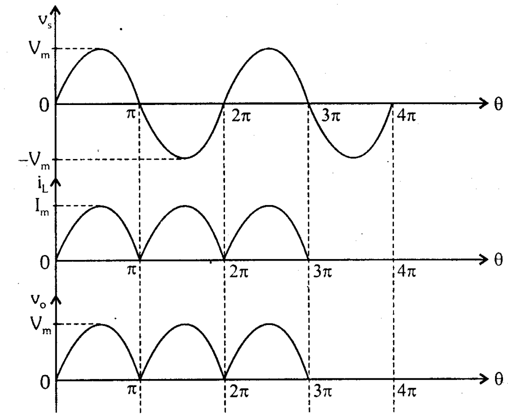

Fig. 6.37

Fig. 6.37 shows a centre tapped full wave rectifier. It uses two diodes.

Working : During positive half cycle, terminal A is positive w.r.t. C and terminal B is negative w.r.t. C. Therefore, diode D_1 is forward biased and D_2 is reverse biased. Therefore, current flows through diode D_1 and load.

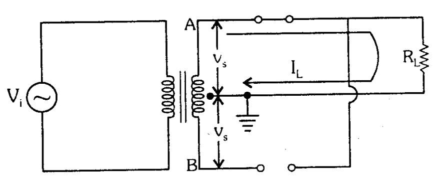

Fig. 6.38

During negative half cycle, terminal B is positive w.r.t. C and terminal A is negative w.r.t. C. Therefore, diode D_2 is forward biased and diode D_1 is reverse biased. Now, current flows through diode D_2 and load. Therefore, current flows through R_L in both half cycles. Thus, ac waveform is converted into dc and circuit is called full wave rectifier.

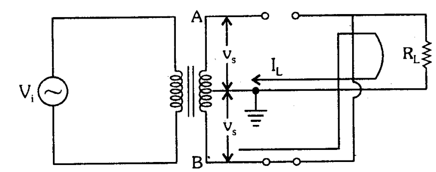

Fig. 6.39

Bridge rectifier : Fig. 6.40 (a) shows a bridge type full wave rectifier. It uses four diodes.

Working : During positive half cycle, terminal A is positive w.r.t. B, diodes D_1 and D_3 are forward biased and diodes D_2 and D_4 are reverse biased. Current flows through diode D_1, load R_L and diode D_3.

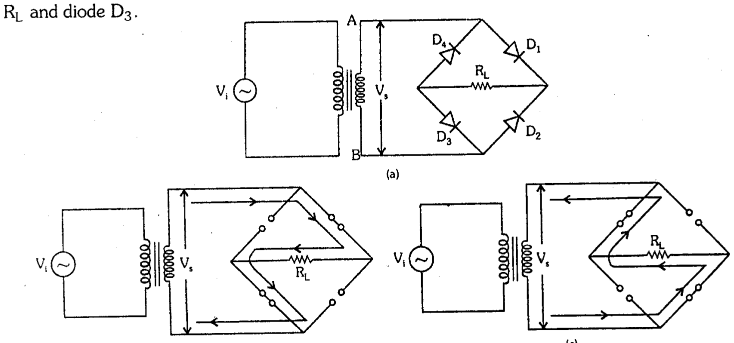

Fig. 6.40

During negative half cycle, terminal A is negative w.r.t. B. Diodes D_2 and D_4 are forward biased and diodes D_1 and D_3 are reverse biased. Current flows through D_2, load R_L and D_4. Thus current flows in both half cycles of ac supply. Output voltage is available in both half cycles and hence the circuit is called as full wave rectifier.

6.7.1 Analysis of Full Wave Rectifier

1. **DC value of load current (I_{dc}) :**

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} i_L \, d\theta = \frac{1}{\pi}\int_0^{\pi} I_m \sin\theta \, d\theta$$

$$= \frac{I_m}{\pi}[-\cos\theta]_0^{\pi} = \frac{I_m}{\pi}[-\cos\pi + \cos 0]$$

$$= \frac{2I_m}{\pi}$$

2. RMS value of load current (I_{rms}) :

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

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2\theta \, d\theta} = \sqrt{\frac{I_m^2}{\pi}\int_0^{\pi}\left(\frac{1-\cos 2\theta}{2}\right)d\theta}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\left[\theta - \frac{\sin 2\theta}{2}\right]_0^{\pi}} = \frac{I_m}{\sqrt{2}}$$

3. Output voltage (V_{dc}) :

$$V_{dc} = I_{dc} R_L = \frac{2I_m}{\pi} R_L$$

$$= \frac{2}{\pi} \frac{V_m}{(R_f + R_s + R_L)} R_L$$

where $R_f \rightarrow$ Diode forward resistance

$R_s \rightarrow$ Secondary winding resistance

$R_L \rightarrow$ Load resistance

$$V_{dc} = \frac{2V_m}{\pi}\left(1 - \frac{R_f + R_s}{R_f + R_s + R_L}\right)$$

$$= \frac{2V_m}{\pi} - I_{dc} \cdot (R_f + R_s)$$

At no load, $I_{dc} = 0$

$$V_{dc} = \frac{2V_m}{\pi}$$

4. Rectifier efficiency :

$$\eta = \frac{\text{DC output power}}{\text{AC input power}} = \frac{P_{dc}}{P_{ac}}$$

$$P_{dc} = I_{dc}^2 R_L = \left(\frac{2I_m}{\pi}\right)^2 R_L = \frac{4I_m^2}{\pi^2} R_L$$

$$P_{ac} = I_{rms}^2 (R_f + R_s + R_L) = \left(\frac{I_m}{\sqrt{2}}\right)^2 (R_f + R_s + R_L)$$

$$= \frac{I_m^2}{2}(R_f + R_s + R_L)$$

$$\eta = \frac{\frac{4I_m^2}{\pi^2} R_L}{\frac{I_m^2}{2}(R_f + R_s + R_L)} = \frac{8}{\pi^2} \frac{R_L}{R_f + R_s + R_L}$$

$$= \frac{8}{\pi^2} \qquad (\because R_f + R_s << R_L)$$

$= 0.812$

$\% \eta = 81.2\%$

5. Ripple factor :

$$r = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} = \sqrt{\frac{\left(\frac{I_m}{\sqrt{2}}\right)^2}{\left(\frac{2I_m}{\pi}\right)^2} - 1}$$

$= 0.48$

6. Peak Inverse Voltage (PIV) :

PIV $= 2V_m$ (centre tap rectifier)

$= V_m$ (bridge rectifier)

7. Transformer Utilization Factor (TUF) :

$$TUF = \frac{\text{DC power delivered to the laod}}{\text{AC rating of transformer secondary}}$$

$$= \frac{I_{dc}^2 R_L}{V_{rms} I_{rms}} = \frac{\left(\frac{2I_m}{\pi}\right)^2 R_L}{\frac{V_m}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}}}$$

$$TUF = \frac{\frac{4I_m^2}{\pi^2} R_L}{\frac{I_m (R_f + R_s + R_L)}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}}}$$

$$= \frac{8}{\pi^2} \frac{R_L}{R_f + R_s + R_L} = \frac{8}{\pi^2} \qquad (\because R_f + R_s << R_L)$$

$= 0.812$

The primary of the transformer is feeding two half wave rectifiers separately.

TUF $= 2 \times$ TUF of half wave rectifier

$= 2 \times 0.287 = 0.574$

Average TUF for full wave rectifier $= \frac{0.574 + 0.812}{2} = 0.693$

TUF $= 0.693$ (centre tap rectifier)

$= 0.812$ (bridge rectifier)

8. Voltage regulation : The variation of dc output voltage as a function of dc load current s called voltage regulation.

$$= \frac{V_{dc_{no\ load}} - V_{dc_{full\ load}}}{V_{dc_{full\ load}}} \times 100$$

$$= \frac{\frac{2V_m}{\pi} - \left[\frac{2V_m}{\pi} - I_{dc}(R_f + R_s)\right]}{I_{dc} \cdot R_L} \times 100 = \frac{R_f + R_s}{R_L} \times 100$$

6.8.1 Capacitor Filter

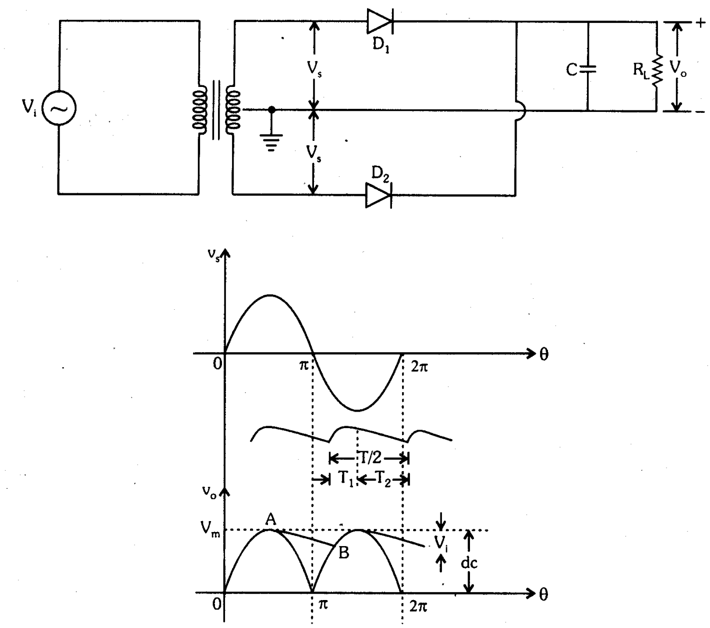

Fig. 6.41

In capacitor filter, capacitor is connected in parallel with the load R_L. During positive half cycle, diode D_1 is forward biased and diode D_2 is reverse biased. Therefore current flows through D_1, charging the capacitor C to the maximum value V_m. Since capacitor and load R_L are in parallel, the voltage across capacitor will appear as output voltage. Output voltage increases upto point A. After point A, input voltage starts decreasing but capacitor is already charged to the value V_m. Hence, diode D_1 is reverse biased in the positive half cycle itself and capacitor discharges slowly through R_L.

At the same time positive half cycle is over and negative half cycle begins. Due to this D_1 continues to be reverse biased. Now diode D_2 is also reverse biased due to voltage across capacitor. Therefore capacitor continues to discharge and reaches the point B. At this time, voltage at point B is more than the capacitor voltage and so diode D_2 is forward biased and again capacitor charges to value V_m. The process repeats. Thus amount of fluctuation is less at the output i.e. ac component is reduced after connecting the capacitor.

Ripple factor : From Fig.6.41 the amount of charge lost by the capacitor during interval T_2 is

$$Q_{discharge} = I_{dc}\, T_2$$

The amount of charge gained during interval T_1 in which voltage across capacitor changes by amount equal to the peak to peak voltage of ripple, V_r is given by

$$Q_{charge} = CV_r$$

But $$Q_{charge} = Q_{discharge}$$

$$CV_r = I_{dc}\, T_2$$

$$V_r = \frac{I_{dc}}{C} T_2.$$

Usually $T_2 >> T_1$ for a good filter.

$$T_1 + T_2 = \frac{T}{2}$$

$$T_2 = \frac{T}{2}$$ where T is time period of actual ac supply

$$= \frac{1}{2f}$$

$$V_r = \frac{I_{dc}}{2fC}$$

The ripple waveform is triangular in nature.

$$V_{ac,\,rms} = \frac{V_r}{2\sqrt{3}} = \frac{I_{dc}}{4\sqrt{3}\, fC}$$

$$= \frac{V_{dc}}{4\sqrt{3}\, f R_L\, C} \qquad (\because\ V_{dc} = I_{dc} \cdot R_L)$$

$$r = \frac{V_{ac,\,rms}}{V_{dc}} = \frac{1}{4\sqrt{3}\, f R_L\, C}$$

Thus for a good capacitor filter, r must be low. Hence C and R_L must be high.

Output voltage : The output voltage is given by,

$$V_{dc} = V_m - \frac{V_r}{2}$$

But $$V_r = \frac{I_{dc}}{2fC}$$

$$V_{dc} = V_m - \frac{I_{dc}}{4fC}$$

But $$V_{dc} = I_{dc} R_L$$

$$V_{dc} = V_m - \frac{V_{dc}}{4f R_L\, C}$$

$$= \frac{4V_m\, f R_L\, C}{1 + 4f R_L\, C}$$