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.

$$^{*}I_{av} = I_{dc} = \frac{1}{2\pi}\int_0^{\pi} i \, d\theta = \frac{1}{2\pi}\int_0^{\pi} \frac{V_m \sin\theta}{r_f + R_L} \, d\theta$$

$$= \frac{V_m}{2\pi(r_f + R_L)}\int_0^{\pi} \sin\theta \, d\theta = \frac{V_m}{2\pi(r_f + R_L)}[-\cos\theta]_0^{\pi}$$

$$= \frac{V_m}{2\pi(r_f + R_L)} \times 2 = \frac{V_m}{(r_f + R_L)} \times \frac{1}{\pi}$$

$$= \frac{^{**}I_m}{\pi} \qquad \left[\because I_m = \frac{V_m}{(r_f + R_L)}\right]$$

$$\therefore \quad \text{d.c. power, } P_{dc} = I_{dc}^2 \times R_L = \left(\frac{I_m}{\pi}\right)^2 \times R_L \qquad ...(i)$$

a.c. power input : The a.c. power input is given by :

$$P_{ac} = I_{rms}^2 (r_f + R_L)$$

For a half-wave rectified wave, $I_{rms} = I_m/2$

$$\therefore \quad P_{ac} = \left(\frac{I_m}{2}\right)^2 \times (r_f + R_L) \qquad ...(ii)$$

$$\therefore \quad \text{Rectifier efficiency} = \frac{\text{d.c. output power}}{\text{a.c. input power}} = \frac{(I_m/\pi)^2 \times R_L}{(I_m/2)^2 (r_f + R_L)}$$

$$= \frac{0.406 \, R_L}{r_f + R_L} = \frac{0.406}{1 + \dfrac{r_f}{R_L}}$$

The efficiency will be maximum if r_f is negligible as compared to R_L.

∴ Max. rectifier efficiency = 40.6%

This shows that in half-wave rectification, a maximum of 40.6% of a.c. power is converted into d.c. power.

Example 6.12. *The applied input a.c. power to a half-wave rectifier is 100 watts. The d.c. output power obtained is 40 watts.*

(*i*) *What is the rectification efficiency ?*

(*ii*) *What happens to remaining 60 watts ?*

Solution.

$$(i) \quad \text{Rectification efficiency} = \frac{\text{d.c. output power}}{\text{a.c. input power}} = \frac{40}{100} = 0.4 = \mathbf{40\%}$$

(*ii*) 40% efficiency of rectification does not mean that 60% of power is lost in the rectifier circuit. In fact, a crystal diode consumes little power due to its small internal resistance. The 100 W

---

* Average value $= \dfrac{\text{Area under the curve over a cycle}}{\text{Base}} = \dfrac{\int_0^{\pi} i \, d\theta}{2\pi}$

** It may be remembered that the *area of one-half cycle of a sinusoidal wave* is twice the peak value. Thus in this case, peak value is I_m and, therefore, area of one-half cycle is $2\,I_m$.

$$\therefore \quad I_{av} = I_{dc} = \frac{2\,I_m}{2\pi} = \frac{I_m}{\pi}$$

a.c. power is contained as 50 watts in positive half-cycles and 50 watts in negative half-cycles. The 50 watts in the negative half-cycles are not supplied at all. Only 50 watts in the positive half-cycles are converted into 40 watts.

$$\therefore \quad \text{Power efficiency} = \frac{40}{50} \times 100 = 80\%$$

Although 100 watts of a.c. power was supplied, the half-wave rectifier accepted only 50 watts and converted it into 40 watts d.c. power. Therefore, it is appropriate to say that efficiency of rectification is 40% and *not* 80% which is power efficiency.

Example 6.13. *An a.c. supply of 230 V is applied to a half-wave rectifier circuit through a transformer of turn ratio 10 : 1. Find (i) the output d.c. voltage and (ii) the peak inverse voltage. Assume the diode to be ideal.*

Solution.

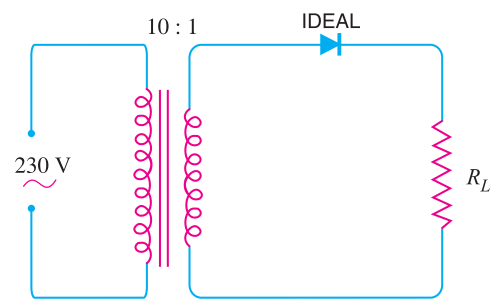

Fig. 6.23

Primary to secondary turns is

$$\frac{N_1}{N_2} = 10$$

R.M.S. primary voltage

$$= 230 \text{ V}$$

∴ Max. primary voltage is

$$V_{pm} = (\sqrt{2}) \times \text{r.m.s. primary voltage}$$

$$= (\sqrt{2}) \times 230 = 325.3 \text{ V}$$

Max. secondary voltage is

$$V_{sm} = V_{pm} \times \frac{N_2}{N_1} = 325.3 \times \frac{1}{10} = 32.53 \text{ V}$$

(i) $$I_{d.c.} = \frac{I_m}{\pi}$$

$$\therefore \quad V_{dc} = \frac{I_m}{\pi} \times R_L = \frac{V_{sm}}{\pi} = \frac{32.53}{\pi} = \mathbf{10.36\ V}$$

(ii) During the negative half-cycle of a.c. supply, the diode is reverse biased and hence conducts no current. Therefore, the maximum secondary voltage appears across the diode.

∴ Peak inverse voltage = **32.53 V**

Example 6.14. *A crystal diode having internal resistance $r_f = 20\Omega$ is used for half-wave rectification. If the applied voltage $v = 50 \sin \omega t$ and load resistance $R_L = 800\ \Omega$, find :*

(i) I_m, I_{dc}, I_{rms} *(ii) a.c. power input and d.c. power output*

(iii) d.c. output voltage *(iv) efficiency of rectification.*

Solution.

$$v = 50 \sin \omega t$$

$$\therefore \quad \text{Maximum voltage, } V_m = 50 \text{ V}$$

(i) $$I_m = \frac{V_m}{r_f + R_L} = \frac{50}{20 + 800} = 0.061 \text{ A} = \mathbf{61\ mA}$$

$$I_{dc} = I_m/\pi = 61/\pi = \mathbf{19.4\ mA}$$

$$I_{rms} = I_m/2 = 61/2 = \mathbf{30.5\ mA}$$

(ii) $$\text{a.c. power input} = (I_{rms})^2 \times (r_f + R_L) = \left(\frac{30.5}{1000}\right)^2 \times (20 + 800) = \mathbf{0.763\ watt}$$

$$\text{d.c. power output} = I_{dc}^2 \times R_L = \left(\frac{19.4}{1000}\right)^2 \times 800 = \mathbf{0.301\ watt}$$

(*iii*) $$\text{d.c. output voltage} = I_{dc} R_L = 19.4\text{ mA} \times 800\ \Omega = \mathbf{15.52\ volts}$$

(*iv*) $$\text{Efficiency of rectification} = \frac{0.301}{0.763} \times 100 = \mathbf{39.5\%}$$

Example 6.15. *A half-wave rectifier is used to supply 50V d.c. to a resistive load of 800 Ω. The diode has a resistance of 25 Ω. Calculate a.c. voltage required.*

Solution.

Output d.c. voltage, $V_{dc} = 50$ V

Diode resistance, $r_f = 25\ \Omega$

Load resistance, $R_L = 800\ \Omega$

Let V_m be the maximum value of a.c. voltage required.

$$\therefore \quad V_{dc} = I_{dc} \times R_L$$

$$= \frac{I_m}{\pi} \times R_L = \frac{V_m}{\pi(r_f + R_L)} \times R_L \qquad \left[\because I_m = \frac{V_m}{r_f + R_L}\right]$$

or $$50 = \frac{V_m}{\pi(25 + 800)} \times 800$$

$$\therefore \quad V_m = \frac{\pi \times 825 \times 50}{800} = \mathbf{162\ V}$$

Hence a.c. voltage of maximum value 162 V is required.

6.11 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. This can be achieved with two diodes working alternately. For the positive half-cycle of input voltage, one diode supplies current to the load and for the negative half-cycle, the other diode does so ; current being always in the same direction through the load. Therefore, a full-wave rectifier utilises both half-cycles of input a.c. voltage to produce the d.c. output. The following two circuits are commonly used for full-wave rectification :

(*i*) Centre-tap full-wave rectifier (*ii*) Full-wave bridge rectifier

6.12 Centre-Tap Full-Wave Rectifier

The circuit employs two diodes D_1 and D_2 as shown in Fig. 6.24. A centre tapped secondary winding *AB* is used with two diodes connected so that each uses one half-cycle of input a.c. voltage. In other words, diode D_1 utilises the a.c. voltage appearing across the upper half (*OA*) of secondary winding for rectification while diode D_2 uses the lower half winding *OB*.

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 D_1 forward biased and diode D_2 reverse biased. Therefore, diode D_1 conducts while diode D_2 does not. The conventional current flow is through diode D_1, load resistor R_L 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 D_2 conducts while diode D_1 does not. The conventional current flow is through diode D_2, load R_L and lower half winding as shown by solid arrows. Referring to Fig. 6.24, it may be seen that current in the load R_L is *in the same direction* for both half-cycles of input a.c. voltage. Therefore, d.c. is obtained across the load R_L. Also, the polarities of the d.c. output across the load should be noted.

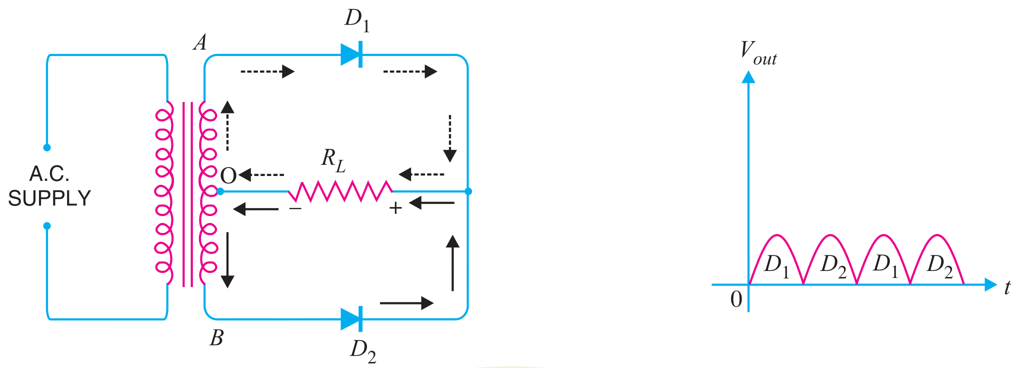

Fig. 6.24

Peak inverse voltage. Suppose V_m is the maximum voltage across the half secondary winding. Fig. 6.25 shows the circuit at the instant secondary voltage reaches its maximum value in the positive direction. At this instant, diode D_1 is conducting while diode D_2 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 half-secondary winding *i.e.*

$$\text{PIV} = 2\,V_m$$

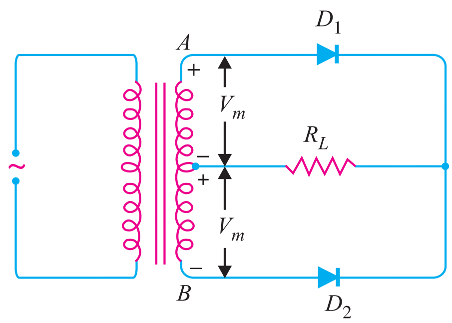

Fig. 6.25

Disadvantages

(i) It is difficult to locate the centre tap on the secondary winding.

(ii) The d.c. output is small as each diode utilises only one-half of the transformer secondary voltage.

(iii) The diodes used must have high peak inverse voltage.

6.13 Full-Wave Bridge Rectifier

The need for a centre tapped power transformer is eliminated in the bridge rectifier. It contains four diodes D_1, D_2, D_3 and D_4 connected to form bridge as shown in Fig. 6.26. 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 R_L is connected.

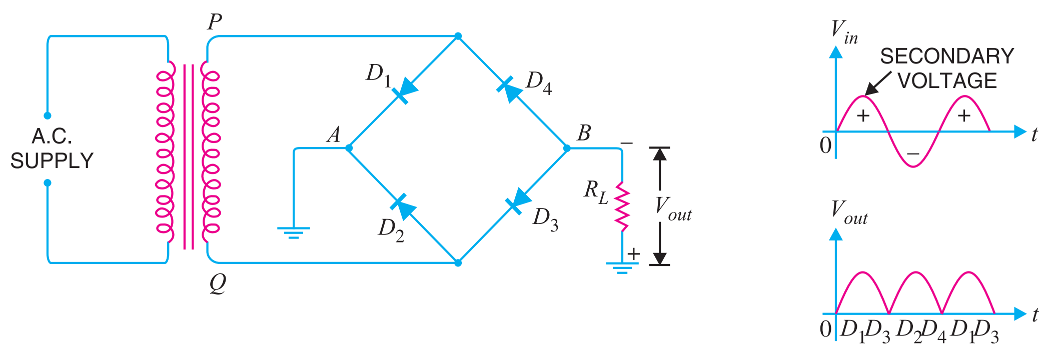

Fig. 6.26

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 D_1 and D_3 forward biased while diodes D_2 and D_4 are reverse biased. Therefore, only diodes D_1 and D_3 conduct. These two diodes will be in series through the load R_L as shown in Fig. 6.27 (*i*). The conventional current flow is shown by dotted arrows. It may be seen that current flows from A to B through the load R_L .

During the negative half-cycle of secondary voltage, end P becomes negative and end Q positive. This makes diodes D_2 and D_4 forward biased whereas diodes D_1 and D_3 are reverse biased. Therefore, only diodes D_2 and D_4 conduct. These two diodes will be in series through the load R_L as shown in Fig. 6.27 (*ii*). 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 is obtained across load R_L.

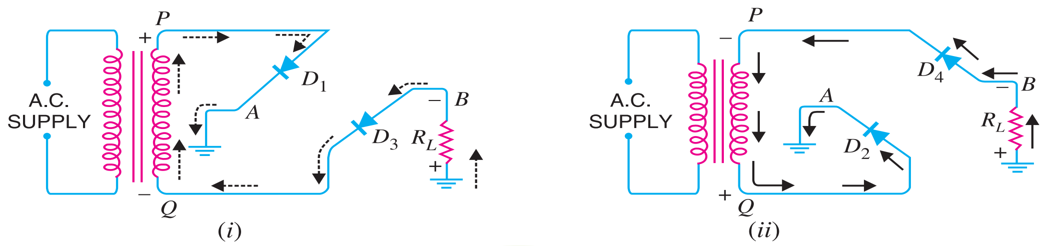

Fig. 6.27

Peak inverse voltage. The peak inverse voltage (PIV) of each diode is equal to the maximum secondary voltage of transformer. Suppose during positive half cycle of input a.c., end P of secondary is positive and end Q negative. Under such conditions, diodes D_1 and D_3 are forward biased while diodes D_2 and D_4 are reverse biased. Since the diodes are considered ideal, diodes D_1 and D_3 can be replaced by wires as shown in Fig. 6.28 (*i*). This circuit is the same as shown in Fig. 6.28 (*ii*).

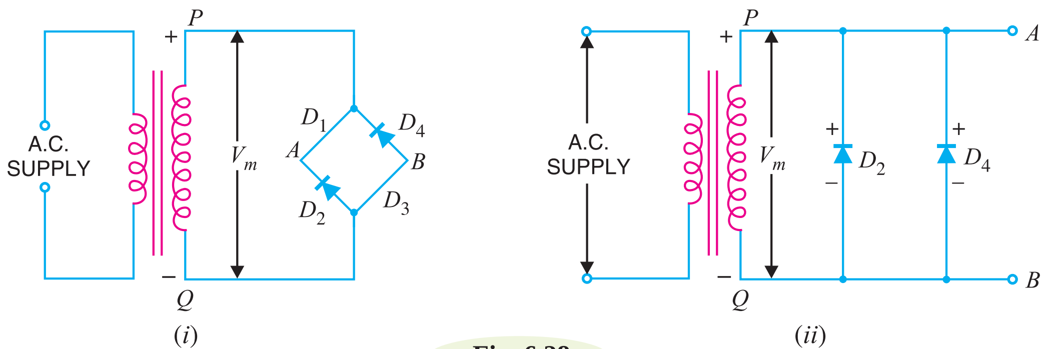

Fig. 6.28

Referring to Fig. 6.28 (*ii*), it is clear that two reverse biased diodes (*i.e.*, D_2 and D_4) and the secondary of transformer are in parallel. Hence PIV of each diode (D_2 and D_4) is equal to the maximum voltage (V_m) across the secondary. Similarly, during the next half cycle, D_2 and D_4 are forward biased while D_1 and D_3 will be reverse biased. It is easy to see that reverse voltage across D_1 and D_3 is equal to V_m.

Advantages

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

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

(*iii*) The PIV is one-half that of the centre-tap circuit (for same d.c. output).

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 in the internal resistance of the rectifying unit will be twice as great as in the centre tap circuit. This is objectionable when secondary voltage is small.

6.14 Output Frequency of Full-Wave Rectifier

The output frequency of a full-wave rectifier is double the input frequency. Remember that a wave has a complete cycle when it repeats the same pattern. In Fig. 6.29 (*i*), the input a.c. completes one cycle from 0° – 360°. However, the full-wave rectified wave completes 2 cycles in this period [See Fig. 6.29 (*ii*)]. Therefore, output frequency is twice the input frequency *i.e.*

$$f_{out} = 2\,f_{in}$$

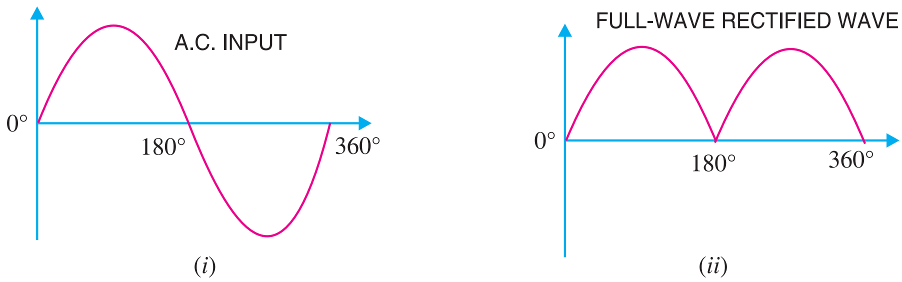

Fig. 6.29

For example, if the input frequency to a full-wave rectifier is 100 Hz, then the output frequency will be 200 Hz.

6.15 Efficiency of Full-Wave Rectifier

Fig. 6.30 shows the process of full-wave rectification. Let $v = V_m \sin\theta$ be the a.c. voltage to be rectified. Let r_f and R_L be the diode resistance and load resistance respectively. Obviously, the rectifier will conduct current through the load in the same direction for both half-cycles of input a.c. voltage. The instantaneous current i is given by :

$$i = \frac{v}{r_f + R_L} = \frac{V_m \sin\theta}{r_f + R_L}$$

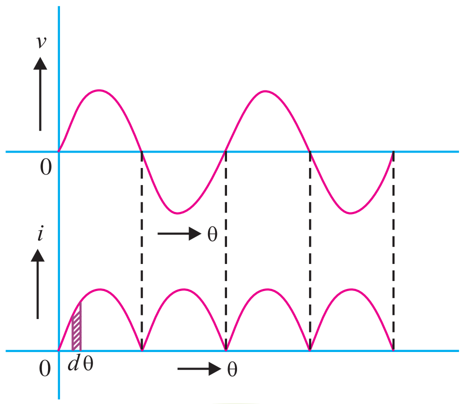

Fig. 6.30

d.c. output power. The output current is pulsating direct current. Therefore, in order to find the d.c. power, average current has to be found out. From the elementary knowledge of electrical engineering,

$$I_{dc} = \frac{2\,I_m}{\pi}$$

$$\therefore \quad \text{d.c. power output, } P_{dc} = I_{dc}^2 \times R_L = \left(\frac{2\,I_m}{\pi}\right)^2 \times R_L \qquad ...(i)$$

a.c. input power. The a.c. input power is given by :

$$P_{ac} = I_{rms}^2\,(r_f + R_L)$$

For a full-wave rectified wave, we have,

$$I_{rms} = I_m/\sqrt{2}$$

$$\therefore \quad P_{ac} = \left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L) \qquad ...(ii)$$

∴ Full-wave rectification efficiency is

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{(2\,I_m/\pi)^2 R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L)}$$

$$= \frac{8}{\pi^2} \times \frac{R_L}{(r_f + R_L)} = \frac{0.812\,R_L}{r_f + R_L} = \frac{0.812}{1 + \frac{r_f}{R_L}}$$

The efficiency will be maximum if r_f is negligible as compared to R_L.

∴ Maximum efficiency = 81.2%

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

Example 6.16. *A full-wave rectifier uses two diodes, the internal resistance of each diode may be assumed constant at 20 Ω. The transformer r.m.s. secondary voltage from centre tap to each end of secondary is 50 V and load resistance is 980 Ω. Find :*

(*i*) *the mean load current* (*ii*) *the r.m.s. value of load current*

Solution.

$$r_f = 20\ \Omega, \quad R_L = 980\ \Omega$$

$$\text{Max. a.c. voltage, } V_m = 50 \times \sqrt{2} = 70.7\ \text{V}$$

$$\text{Max. load current, } I_m = \frac{V_m}{r_f + R_L} = \frac{70.7\ \text{V}}{(20 + 980)\ \Omega} = 70.7\ \text{mA}$$

(*i*) Mean load current, $I_{dc} = \frac{2\,I_m}{\pi} = \frac{2 \times 70.7}{\pi} = $ **45 mA**

(*ii*) R.M.S. value of load current is

$$I_{rms} = \frac{I_m}{\sqrt{2}} = \frac{70.7}{\sqrt{2}}\overrightarrow{AB} = \textbf{50 mA}$$

Example 6.17. *In the centre-tap circuit shown in Fig. 6.31, the diodes are assumed to be ideal i.e. having zero internal resistance. Find :*

(*i*) *d.c. output voltage* (*ii*) *peak inverse voltage* (*iii*) *rectification efficiency.*

Solution.

Primary to secondary turns, $N_1/N_2 = 5$

R.M.S. primary voltage = 230 V

∴ R.M.S. secondary voltage

$= 230 \times (1/5) = 46$ V

Maximum voltage across secondary

$= 46 \times \sqrt{2} = 65$V

Maximum voltage across half secondary winding is

$V_m = 65/2 = 32.5$ V

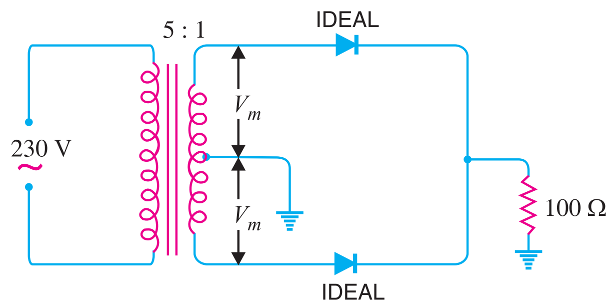

Fig. 6.31

(*i*) Average current, I_{dc} $= \dfrac{2V_m}{\pi R_L} = \dfrac{2 \times 32.5}{\pi \times 100} = 0.207$ A

∴ d.c. output voltage, $V_{dc} = I_{dc} \times R_L = 0.207 \times 100 =$ **20.7 V**

(*ii*) The peak inverse voltage is equal to the maximum secondary voltage, *i.e.*

$PIV =$ **65 V**

(*iii*) Rectification efficiency $= \dfrac{0.812}{1 + \dfrac{r_f}{R_L}}$

Since $r_f = 0$

∴ Rectification efficiency = **81.2 %**

Example 6.18. *In the bridge type circuit shown in Fig. 6.32, the diodes are assumed to be ideal. Find :* (*i*) *d.c. output voltage* (*ii*) *peak inverse voltage* (*iii*) *output frequency.* *Assume primary to secondary turns to be 4.*

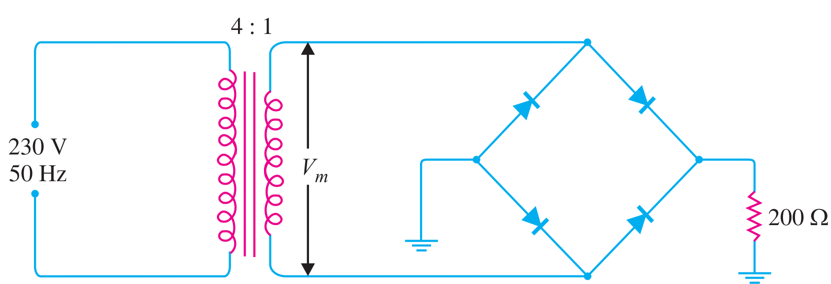

Fig. 6.32

Solution.

Primary/secondary turns, $N_1/N_2 = 4$

R.M.S. primary voltage = 230 V

∴ R.M.S. secondary voltage $= 230\,(N_2/N_1) = 230 \times (1/4) = 57.5$ V

Maximum voltage across secondary is

$$V_m = 57.5 \times \sqrt{2} = 81.3 \text{ V}$$

(*i*) Average current, $I_{dc} = \dfrac{2V_m}{\pi R_L} = \dfrac{2 \times 81.3}{\pi \times 200} = 0.26$ A

∴ d.c. output voltage, $V_{dc} = I_{dc} \times R_L = 0.26 \times 200 =$ **52 V**

$$I_{Lmin} = I - I_{ZM}$$

and $$R_{Lmax} = \frac{E_0}{I_{Lmin}} = \frac{V_Z}{I_{Lmin}}$$

If the load resistance exceeds this limiting value, the current through zener will exceed I_{ZM} and the device may burn out.

3. Fixed R_L and Variable E_i. This case is shown in Fig. 6.60. Here the load resistance R_L is fixed while the applied voltage (E_i) changes. Note that there is a definite range of E_i values that will ensure that zener diode is in the "on" state. Let us calculate that range of values.

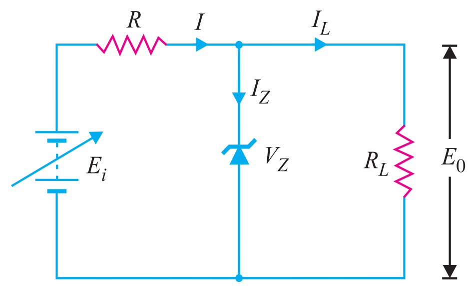

Fig. 6.60

(i) E_i (*min*). To determine the minimum applied voltage that will turn the zener on, simply calculate the value of E_i that will result in load voltage $E_0 = V_Z$ *i.e.*,

$$E_0 = V_Z = \frac{R_L\, E_i}{R + R_L}$$

$$\therefore \quad E_{i\,(min)} = \frac{(R + R_L)\, V_Z}{R_L}$$

(ii) E_i (*max*)

Now, current through R, $I = I_Z + I_L$

Since I_L $(= E_0/R_L = V_Z/R_L)$ is fixed, the value of I will be maximum when zener current is maximum *i.e.*,

$$I_{max} = I_{ZM} + I_L$$

Now $$E_i = I\,R + E_0$$

Since E_0 $(= V_Z)$ is constant, the input voltage will be maximum when I is maximum.

$$\therefore \quad E_{i\,(max)} = I_{max}\, R + V_Z$$

Example 6.25. *For the circuit shown in Fig. 6.61 (i), find :*

(i) the output voltage *(ii) the voltage drop across series resistance*

(iii) the current through zener diode.

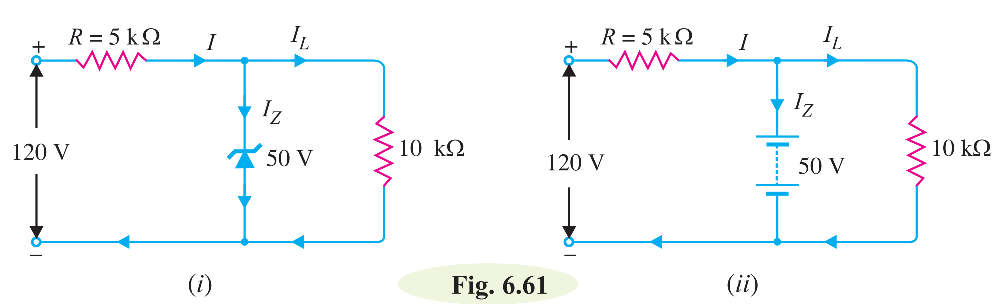

Fig. 6.61

Solution. If you remove the zener diode in Fig. 6.61 (*i*), the voltage V across the open-circuit is given by :

$$V = \frac{R_L E_i}{R + R_L} = \frac{10 \times 120}{5 + 10} = 80 \text{ V}$$

Since voltage across zener diode is greater than V_Z (= 50 V), the zener is in the "on" state. It can, therefore, be represented by a battery of 50 V as shown in Fig. 6.61 (*ii*).

(*i*) Referring to Fig. 6.61 (*ii*),

Output voltage $= V_Z =$ **50 V**

(*ii*) Voltage drop across R = Input voltage $- V_Z = 120 - 50 =$ **70 V**

(*iii*) Load current, $I_L = V_Z/R_L = 50 \text{ V}/10 \text{ k}\Omega = 5 \text{ mA}$

Current through R, $I = \dfrac{70 \text{ V}}{5 \text{ k}\Omega} = 14 \text{ mA}$

Applying Kirchhoff's first law, $I = I_L + I_Z$

∴ Zener current, $I_Z = I - I_L = 14 - 5 =$ **9 mA**

Example 6.26. *For the circuit shown in Fig. 6.62 (i), find the maximum and minimum values of zener diode current.*

Solution. The first step is to determine the state of the zener diode. It is easy to see that for the given range of voltages (80 – 120 V), the voltage across the zener is greater than V_Z (= 50 V). Hence the zener diode will be in the "on" state for this range of applied voltages. Consequently, it can be replaced by a battery of 50 V as shown in Fig. 6.62 (*ii*).

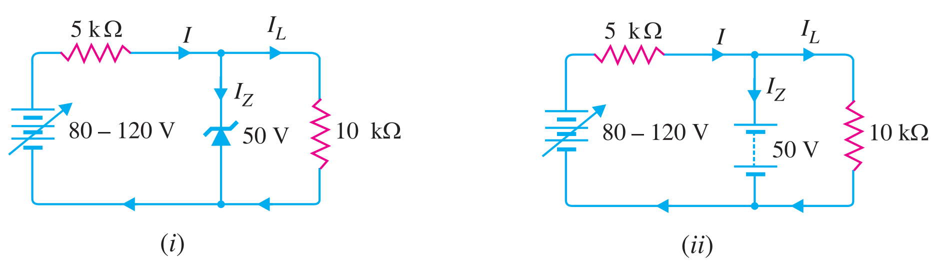

Fig. 6.62

Maximum zener current. The zener will conduct *maximum current when the input voltage is maximum *i.e.* 120 V. Under such conditions :

Voltage across 5 kΩ = 120 – 50 = 70 V

Current through 5 kΩ, $I = \dfrac{70 \text{ V}}{5 \text{ k}\Omega} = 14 \text{ mA}$

Load current, $I_L = \dfrac{50 \text{ V}}{10 \text{ k}\Omega} = 5 \text{ mA}$

Applying Kirchhoff's first law, $I = I_L + I_Z$

∴ Zener current, $I_Z = I - I_L = 14 - 5 =$ **9 mA**

* $I_Z = I - I_L$. Since I_L (= V_Z/R_L) is fixed, I_Z will be maximum when I is maximum.

Now, $I = \dfrac{E_i - E_0}{R} = \dfrac{E_i - V_Z}{R}$. Since V_Z (= E_0) and R are fixed, I will be maximum when E_i is maximum and *vice-versa*.

Minimum Zener current. The zener will conduct minimum current when the input voltage is minimum *i.e.* 80 V. Under such conditions, we have,

$$\text{Voltage across } 5\text{ k}\Omega = 80 - 50 = 30\text{ V}$$

$$\text{Current through } 5\text{ k}\Omega,\ I = \frac{30\text{ V}}{5\text{ k}\Omega} = 6\text{ mA}$$

$$\text{Load current, } I_L = 5\text{ mA}$$

$$\therefore \quad \text{Zener current, } I_Z = I - I_L = 6 - 5 = \mathbf{1\ mA}$$

Example 6.27. *A 7.2 V zener is used in the circuit shown in Fig. 6.63 and the load current is to vary from 12 to 100 mA. Find the value of series resistance R to maintain a voltage of 7.2 V across the load. The input voltage is constant at 12V and the minimum zener current is 10 mA.*

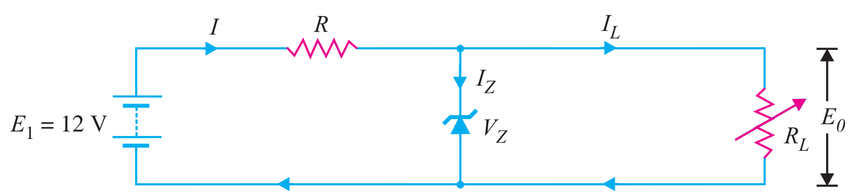

Fig. 6.63

Solution. $E_i = 12\text{ V}; \quad V_Z = 7.2\text{ V}$

$$R = \frac{E_i - E_0}{I_Z + I_L}$$

The voltage across R is to remain constant at 12 – 7.2 = 4.8 V as the load current changes from 12 to 100 mA. The minimum zener current will occur when the load current is maximum.

$$\therefore \quad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{12\text{ V} - 7.2\text{ V}}{(10 + 100)\text{ mA}} = \frac{4.8\text{ V}}{110\text{ mA}} = \mathbf{43.5\ \Omega}$$

If $R = 43.5\ \Omega$ is inserted in the circuit, the output voltage will remain constant over the regulating range. As the load current I_L decreases, the zener current I_Z will increase to such a value that $I_Z + I_L$ = 110 mA. Note that if load resistance is open-circuited, then I_L = 0 and zener current becomes 110 mA.

Example 6.28. *The zener diode shown in Fig. 6.64 has V_Z = 18 V. The voltage across the load stays at 18 V as long as I_Z is maintained between 200 mA and 2 A. Find the value of series resistance R so that E_0 remains 18 V while input voltage E_i is free to vary between 22 V to 28V.*

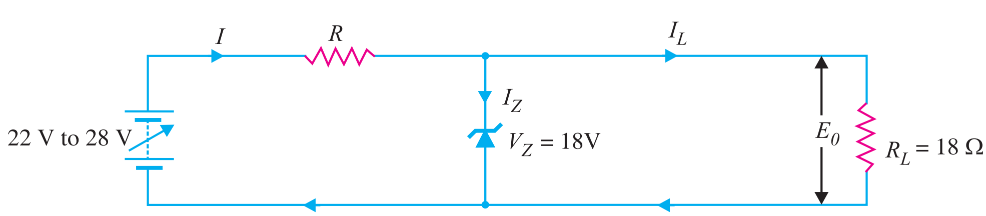

Fig. 6.64

Solution. The zener current will be minimum (*i.e.* 200 mA) when the input voltage is minimum (*i.e.* 22 V). The load current stays at constant value $I_L = V_Z / R_L$ = 18 V/18 Ω = 1 A = 1000 mA.

$$\therefore \quad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{(22 - 18)\text{ V}}{(200 + 1000)\text{ mA}} = \frac{4\text{ V}}{1200\text{ mA}} = \mathbf{3.33\ \Omega}$$

Example 6.29. *A 10-V zener diode is used to regulate the voltage across a variable load resistor [See fig. 6.65]. The input voltage varies between 13 V and 16 V and the load current varies between 10 mA and 85 mA. The minimum zener current is 15 mA. Calculate the value of series resistance R.*

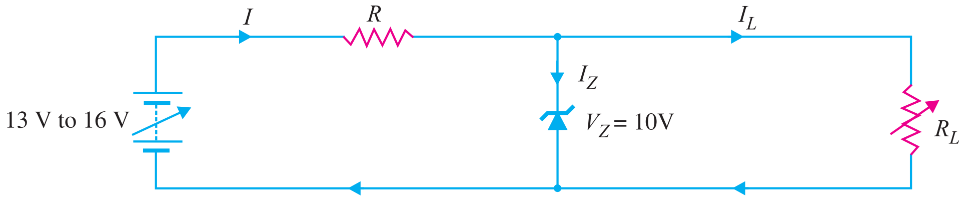

Fig. 6.65

Solution. The zener will conduct minimum current (*i.e.* 15 mA) when input voltage is minimum (*i.e.* 13 V).

$$\therefore \quad R = \frac{E_i - E_0}{(I_Z)_{min} + (I_L)_{max}} = \frac{(13-10)\text{ V}}{(15+85)\text{ mA}} = \frac{3\text{ V}}{100\text{ mA}} = \mathbf{30\ \Omega}$$

Example 6.30. *The circuit of Fig. 6.66 uses two zener diodes, each rated at 15 V, 200 mA. If the circuit is connected to a 45-volt unregulated supply, determine :*

(i) The regulated output voltage *(ii) The value of series resistance R*

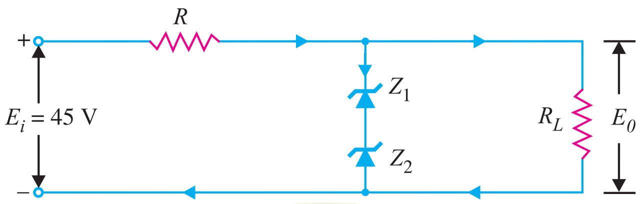

Fig. 6.66

Solution. When the desired regulated output voltage is higher than the rated voltage of the zener, two or more zeners are connected in series as shown in Fig. 6.66. However, in such circuits, care must be taken to select those zeners that have the same current rating.

Current rating of each zener, I_Z = 200 mA

Voltage rating of each zener, V_Z = 15 V

Input voltage, E_i = 45 V

(i) Regulated output voltage, E_0 = 15 + 15 = **30 V**

(ii) Series resistance, $R = \frac{E_i - E_0}{I_Z} = \frac{45-30}{200\text{ mA}} = \frac{15\text{ V}}{200\text{ mA}} = \mathbf{75\ \Omega}$

Example 6.31. *What value of series resistance is required when three 10-watt, 10-volt, 1000 mA zener diodes are connected in series to obtain a 30-volt regulated output from a 45 volt d.c. power source ?*

Solution. Fig. 6.67 shows the desired circuit. The worst case is at no load because then zeners carry the maximum current.

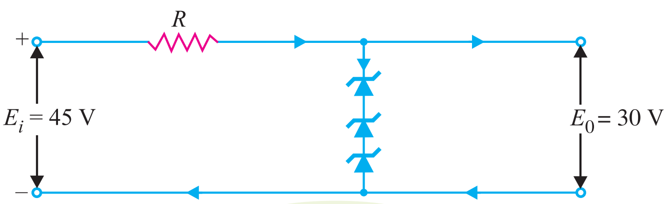

Fig. 6.67