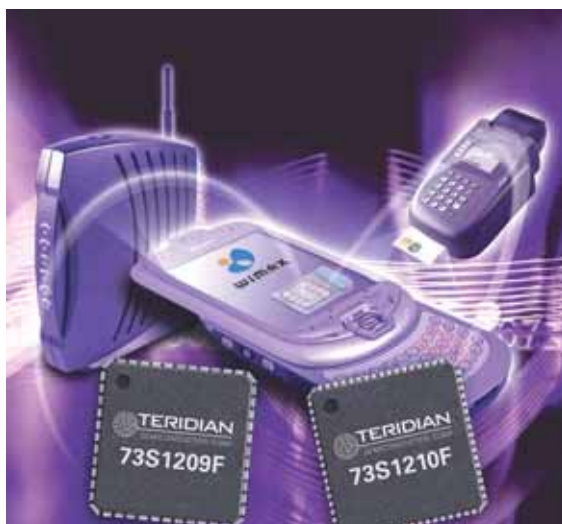


## 6

# Semiconductor Diode

- 6.1 Semiconductor Diode
- 6.3 Resistance of Crystal Diode
- 6.5 Crystal Diode Equivalent Circuits
- 6.7 Crystal Diode Rectifiers
- 6.9 Output Frequency of Half-Wave Rectifier
- 6.11 Full-Wave Rectifier
- 6.13 Full-Wave Bridge Rectifier
- 6.15 Efficiency of Full-Wave Rectifier
- 6.17 Nature of Rectifier Output
- 6.19 Comparison of Rectifiers
- 6.21 Types of Filter Circuits
- 6.23 Half-Wave Voltage Doubler
- 6.25 Zener Diode
- 6.27 Zener Diode as Voltage Stabiliser
- 6.29 Crystal Diodes versus Vacuum Diodes



## INTRODUCTION

It has already been discussed in the previous chapter that a  $pn$  junction conducts current easily when forward biased and practically no current flows when it is reverse biased. This unilateral conduction characteristic of  $pn$  junction (*i.e.* semiconductor diode) is similar to that of a vacuum diode. Therefore, like a vacuum diode, a semiconductor diode can also accomplish the job of *rectification* *i.e.* change alternating current to direct current. However, semiconductor diodes have become more \*popular as they are smaller in size, cheaper and robust and usually operate with greater efficiency. In this chapter, we shall focus our attention on the circuit performance and applications of semiconductor diodes.

\* On the other hand, vacuum diodes can withstand high reverse voltages and can operate at fairly high temperatures.

## 6.1 Semiconductor Diode

A *pn* junction is known as a **semi-conductor** or **\*crystal diode**.

The outstanding property of a crystal diode to conduct current in one direction only permits it to be used as a rectifier. A crystal diode is usually represented by the schematic symbol shown in Fig. 6.1. The arrow in the symbol indicates the direction of easier conventional current flow.

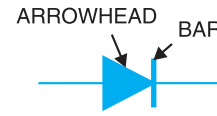


Fig. 6.1



A crystal diode has two terminals. When it is connected in a circuit, one thing to decide is whether the diode is forward or reverse biased. There is an easy rule to ascertain it. If the external circuit is trying to push the conventional current in the direction of arrow, the diode is forward biased. On the other hand, if the conventional current is trying to flow opposite to arrowhead, the diode is reverse biased. Putting in simple words :

(i) If *arrowhead* of diode symbol is *positive w.r.t. bar* of the symbol, the diode is forward biased.  
(ii) If the *arrowhead* of diode symbol is *negative w.r.t. bar*, the diode is reverse biased.

**Identification of crystal diode terminals.** While using a crystal diode, it is often necessary to know which end is arrowhead and which end is bar. For this purpose, the following methods are available :

(i) Some manufacturers actually paint the symbol on the body of the diode *e.g.* BY127, BY114 crystal diodes manufactured by BEL [See Fig. 6.2 (i)].



Fig. 6.2

(ii) Sometimes, red and blue marks are used on the body of the crystal diode. Red mark denotes arrow whereas blue mark indicates bar *e.g.* OA80 crystal diode [See Fig. 6.2 (ii)].

## 6.2 Crystal Diode as a Rectifier

Fig. 6.3 illustrates the rectifying action of a crystal diode. The a.c. input voltage to be rectified, the diode and load  $R_L$  are connected in series. The d.c. output is obtained across the load as explained in the following discussion. During the positive half-cycle of a.c. input voltage, the arrowhead becomes positive *w.r.t.* bar. Therefore, diode is forward biased and conducts current in the circuit. The result is that positive half-cycle of input voltage appears across  $R_L$  as shown. However, during the negative half-cycle of input a.c. voltage, the diode becomes reverse biased because now the arrowhead is negative *w.r.t.* bar. Therefore, diode does not conduct and no voltage appears across load  $R_L$ . The result is that output consists of positive half-cycles of input a.c. voltage while the negative half-cycles are suppressed. In this way, crystal diode has been able to do rectification i.e. change a.c. into d.c. It may be seen that output across  $R_L$  is pulsating d.c.

\* So called because *pn* junction is grown out of a crystal.

## 78 ■ Principles of Electronics

It is interesting to see that behaviour of diode is like a *switch*. When the diode is forward biased, it behaves like a closed switch and connects the a.c. supply to the load  $R_L$ . However, when the diode is reverse biased, it behaves like an open switch and disconnects the a.c. supply from the load  $R_L$ . This switching action of diode permits only the positive half-cycles of input a.c. voltage to appear across  $R_L$ .

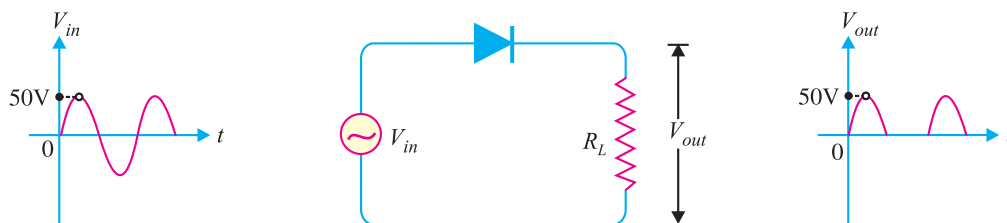


Fig. 6.3

**Example 6.1.** In each diode circuit of Fig. 6.4, find whether the diodes are forward or reverse biased.

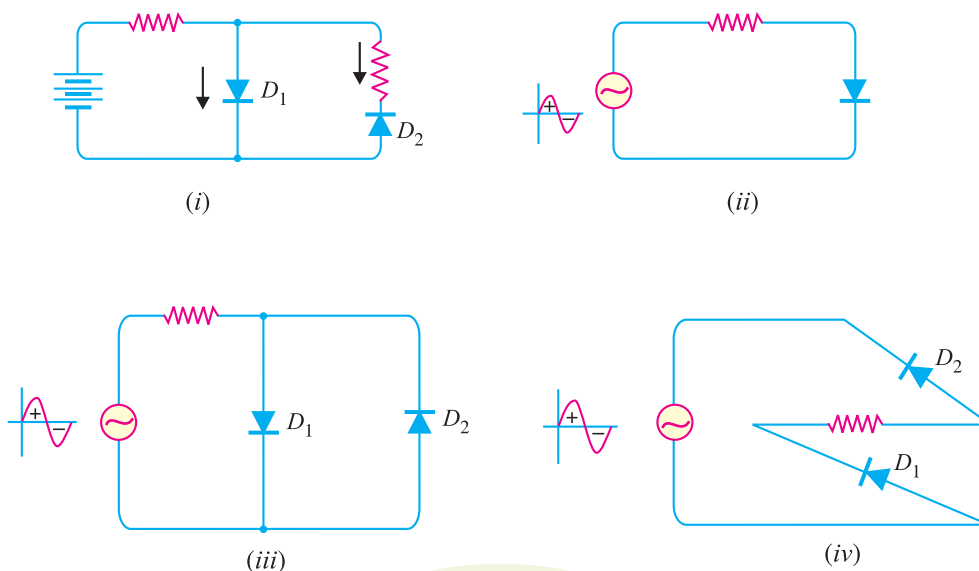


Fig. 6.4

### Solution.

(i) Refer to Fig. 6.4 (i). The conventional current coming out of battery flows in the branch circuits. In diode  $D_1$ , the conventional current flows in the direction of arrowhead and hence this diode is forward biased. However, in diode  $D_2$ , the conventional current flows opposite to arrowhead and hence this diode is reverse biased.

(ii) Refer to Fig. 6.4 (ii). During the positive half-cycle of input a.c. voltage, the conventional current flows in the direction of arrowhead and hence diode is forward biased. However, during the negative half-cycle of input a.c. voltage, the diode is reverse biased.

(iii) Refer to Fig. 6.4 (iii). During the positive half-cycle of input a.c. voltage, conventional current flows in the direction of arrowhead in  $D_1$  but it flows opposite to arrowhead in  $D_2$ . Therefore, during positive half-cycle, diode  $D_1$  is forward biased and diode  $D_2$  reverse biased. However, during the negative half-cycle of input a.c. voltage, diode  $D_2$  is forward biased and  $D_1$  is reverse biased.

(iv) Refer to Fig. 6.4 (iv). During the positive half-cycle of input a.c. voltage, both the diodes are reverse biased. However, during the negative half-cycle of input a.c. voltage, both the diodes are forward biased.

### 6.3 Resistance of Crystal Diode

It has already been discussed that a forward biased diode conducts easily whereas a reverse biased diode practically conducts no current. It means that *forward resistance* of a diode is quite small as compared with its *reverse resistance*.

**1. Forward resistance.** The resistance offered by the diode to forward bias is known as *forward resistance*. This resistance is not the same for the flow of direct current as for the changing current. Accordingly; this resistance is of two types, namely; *d.c. forward resistance* and *a.c. forward resistance*.

(i) *d.c. forward resistance.* It is the opposition offered by the diode to the direct current. It is measured by the ratio of d.c. voltage across the diode to the resulting d.c. current through it. Thus, referring to the forward characteristic in Fig. 6.5, it is clear that when forward voltage is  $OA$ , the forward current is  $OB$ .

$$\therefore \text{d.c. forward resistance, } R_f = \frac{OA}{OB}$$

(ii) *a.c. forward resistance.* It is the opposition offered by the diode to the changing forward current. It is measured by the ratio of change in voltage across diode to the resulting change in current through it *i.e.*

$$\text{a.c. forward resistance, } r_f = \frac{\text{Change in voltage across diode}}{\text{Corresponding change in current through diode}}$$

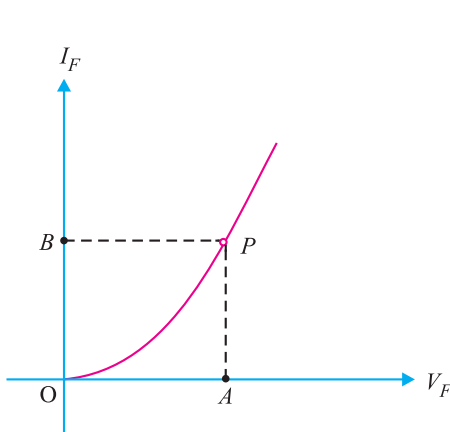


Fig. 6.5

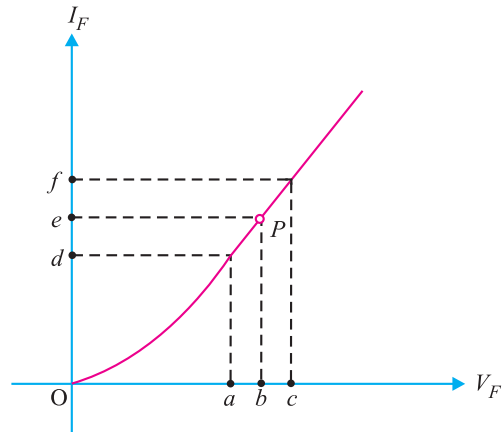


Fig. 6.6

The a.c. forward resistance is more significant as the diodes are generally used with alternating voltages. The a.c. forward resistance can be determined from the forward characteristic as shown in Fig. 6.6. If  $P$  is the operating point at any instant, then forward voltage is  $ob$  and forward current is  $oe$ . To find the a.c. forward resistance, vary the forward voltage on both sides of the operating point equally as shown in Fig. 6.6 where  $ab = bc$ . It is clear from this figure that :

For forward voltage  $oa$ , circuit current is  $od$ .

For forward voltage  $oc$ , circuit current is  $of$ .

$$\therefore \text{a.c. forward resistance, } r_f = \frac{\text{Change in forward voltage}}{\text{Change in forward current}} = \frac{oc - oa}{of - od} = \frac{ac}{df}$$

It may be mentioned here that forward resistance of a crystal diode is very small, ranging from 1 to 25  $\Omega$ .

**2. Reverse resistance.** The resistance offered by the diode to the reverse bias is known as *reverse resistance*. It can be d.c. reverse resistance or a.c. reverse resistance depending upon whether the reverse bias is direct or changing voltage. Ideally, the reverse resistance of a diode is infinite. However, in practice, the reverse resistance is not infinite because for any value of reverse bias, there does exist a small leakage current. It may be emphasised here that reverse resistance is very large compared to the forward resistance. In germanium diodes, the ratio of reverse to forward resistance is 40000 : 1 while for silicon this ratio is 1000000 : 1.

### 6.4 Equivalent Circuit of Crystal Diode

It is generally profitable to replace a device or system by its equivalent circuit. An equivalent circuit of a device (e.g. crystal diode, transistor etc.) is a combination of electric elements, which when connected in a circuit, acts exactly as does the device when connected in the same circuit. Once the device is replaced by its equivalent circuit, the resulting network can be solved by traditional circuit analysis techniques. We shall now find the equivalent circuit of a crystal diode.

**(i) \*Approximate Equivalent circuit.** When the forward voltage  $V_F$  is applied across a diode, it will not conduct till the potential barrier  $V_0$  at the junction is overcome. When the forward voltage exceeds the potential barrier voltage, the diode starts conducting as shown in Fig. 6.7 (i). The forward current  $I_f$  flowing through the diode causes a voltage drop in its internal resistance  $r_f$ . Therefore, the forward voltage  $V_F$  applied across the *actual* diode has to overcome :

(a) potential barrier  $V_0$

(b) internal drop  $I_f r_f$

$$\therefore V_F = V_0 + I_f r_f$$

For a silicon diode,  $V_0 = 0.7$  V whereas for a germanium diode,  $V_0 = 0.3$  V.

Therefore, approximate equivalent circuit for a crystal diode is a switch in series with a battery  $V_0$  and internal resistance  $r_f$  as shown in Fig. 6.7 (ii). This approximate equivalent circuit of a diode is very helpful in studying the performance of the diode in a circuit.

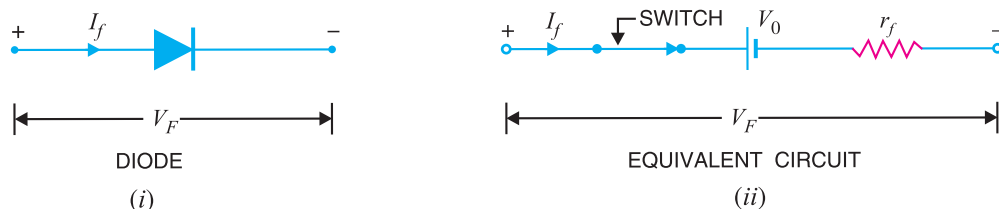


Fig. 6.7

**(ii) Simplified Equivalent circuit.** For most applications, the internal resistance  $r_f$  of the crystal diode can be ignored in comparison to other elements in the equivalent circuit. The equivalent circuit then reduces to the one shown in Fig. 6.8 (ii). This simplified equivalent circuit of the crystal diode is frequently used in diode-circuit analysis.



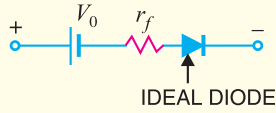
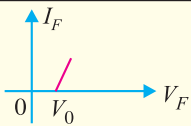
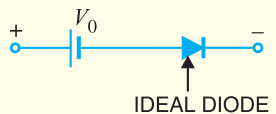
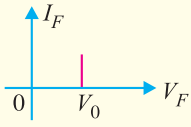

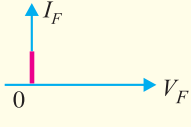
Fig. 6.8

\* We assume here that  $V/I$  characteristic of crystal diode is linear.

**(iii) Ideal diode model.** An ideal diode is one which behaves as a perfect conductor when forward biased and as a perfect insulator when reverse biased. Obviously, in such a hypothetical situation, forward resistance  $r_f = 0$  and potential barrier  $V_0$  is considered negligible. It may be mentioned here that although ideal diode is never found in practice, yet diode circuit analysis is made on this basis. *Therefore, while discussing diode circuits, the diode will be assumed ideal unless and until stated otherwise.*

### 6.5 Crystal Diode Equivalent Circuits

It is desirable to sum up the various models of crystal diode equivalent circuit in the tabular form given below:

S.No.	Type	Model	Characteristic
1.	Approximate model		
2.	Simplified model		
3.	Ideal Model		

**Example 6.2.** An a.c. voltage of peak value 20 V is connected in series with a silicon diode and load resistance of 500 Ω. If the forward resistance of diode is 10 Ω, find :

- (i) peak current through diode
  - (ii) peak output voltage
- What will be these values if the diode is assumed to be ideal ?

**Solution.**

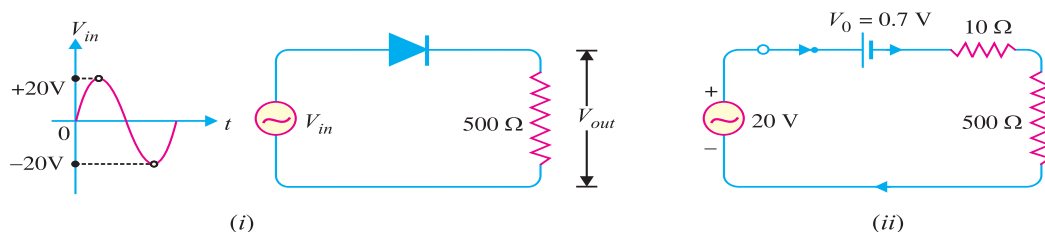
Peak input voltage = 20 V

Forward resistance,  $r_f = 10 \Omega$

Load resistance,  $R_L = 500 \Omega$

Potential barrier voltage,  $V_0 = 0.7 \text{ V}$

The diode will conduct during the positive half-cycles of a.c. input voltage only. The equivalent circuit is shown in Fig. 6.9 (ii).



**Fig. 6.9**

## 82 ■ Principles of Electronics

(i) The peak current through the diode will occur at the instant when the input voltage reaches positive peak *i.e.*  $V_{in} = V_F = 20 \text{ V}$ .

$$\therefore V_F = V_0 + (I_f)_{peak} [r_f + R_L] \quad \dots(i)$$

$$\text{or} \quad (I_f)_{peak} = \frac{V_F - V_0}{r_f + R_L} = \frac{20 - 0.7}{10 + 500} = \frac{19.3}{510} \text{ A} = \mathbf{37.8 \text{ mA}}$$

(ii) Peak output voltage =  $(I_f)_{peak} \times R_L = 37.8 \text{ mA} \times 500 \Omega = \mathbf{18.9 \text{ V}}$

**Ideal diode.** For an ideal diode, put  $V_0 = 0$  and  $r_f = 0$  in equation (i).

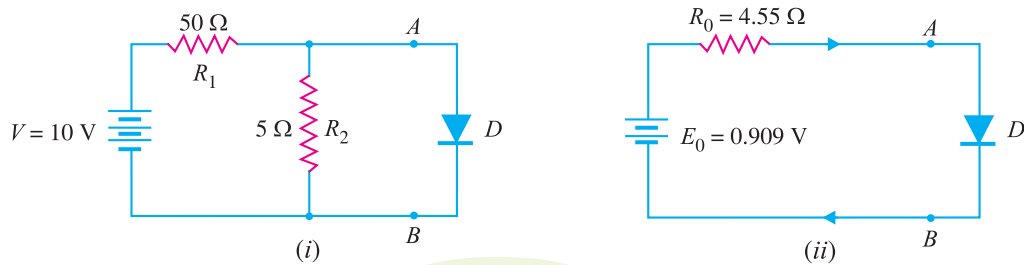
$$\therefore V_F = (I_f)_{peak} \times R_L$$

$$\text{or} \quad (I_f)_{peak} = \frac{V_F}{R_L} = \frac{20 \text{ V}}{500 \Omega} = \mathbf{40 \text{ mA}}$$

$$\text{Peak output voltage} = (I_f)_{peak} \times R_L = 40 \text{ mA} \times 500 \Omega = \mathbf{20 \text{ V}}$$

**Comments.** It is clear from the above example that output voltage is *nearly* the same whether the actual diode is used or the diode is considered ideal. This is due to the fact that input voltage is quite large as compared with  $V_0$  and voltage drop in  $r_f$ . Therefore, nearly the whole input forward voltage appears across the load. For this reason, diode circuit analysis is generally made on the ideal diode basis.

**Example 6.3.** Find the current through the diode in the circuit shown in Fig. 6.10 (i). Assume the diode to be ideal.



**Fig. 6.10**

**Solution.** We shall use Thevenin's theorem to find current in the diode. Referring to Fig. 6.10(i),

$$\begin{aligned} E_0 &= \text{Thevenin's voltage} \\ &= \text{Open circuited voltage across } AB \text{ with diode removed} \\ &= \frac{R_2}{R_1 + R_2} \times V = \frac{5}{50 + 5} \times 10 = 0.909 \text{ V} \end{aligned}$$

$$\begin{aligned} R_0 &= \text{Thevenin's resistance} \\ &= \text{Resistance at terminals } AB \text{ with diode removed and battery replaced by a short circuit} \\ &= \frac{R_1 R_2}{R_1 + R_2} = \frac{50 \times 5}{50 + 5} = 4.55 \Omega \end{aligned}$$

Fig. 6.10 (ii) shows Thevenin's equivalent circuit. Since the diode is ideal, it has zero resistance.

$$\therefore \text{Current through diode} = \frac{E_0}{R_0} = \frac{0.909}{4.55} = 0.2 \text{ A} = \mathbf{200 \text{ mA}}$$

**Example 6.4.** Calculate the current through  $48 \Omega$  resistor in the circuit shown in Fig. 6.11 (i). Assume the diodes to be of silicon and forward resistance of each diode is  $1 \Omega$ .

**Solution.** Diodes  $D_1$  and  $D_3$  are forward biased while diodes  $D_2$  and  $D_4$  are reverse biased. We can, therefore, consider the branches containing diodes  $D_2$  and  $D_4$  as "open". Replacing diodes  $D_1$  and  $D_3$  by their equivalent circuits and making the branches containing diodes  $D_2$  and  $D_4$  open, we get the circuit shown in Fig. 6.11 (ii). Note that for a silicon diode, the barrier voltage is  $0.7 \text{ V}$ .

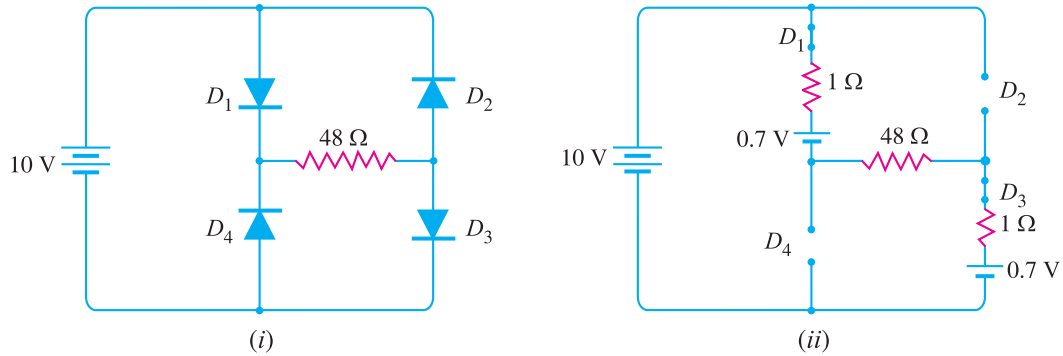


Fig. 6.11

Net circuit voltage =  $10 - 0.7 - 0.7 = 8.6 \text{ V}$

Total circuit resistance =  $1 + 48 + 1 = 50 \text{ } \Omega$

$\therefore$  Circuit current =  $8.6/50 = 0.172 \text{ A} = 172 \text{ mA}$

**Example 6.5.** Determine the current  $I$  in the circuit shown in Fig. 6.12 (i). Assume the diodes to be of silicon and forward resistance of diodes to be zero.

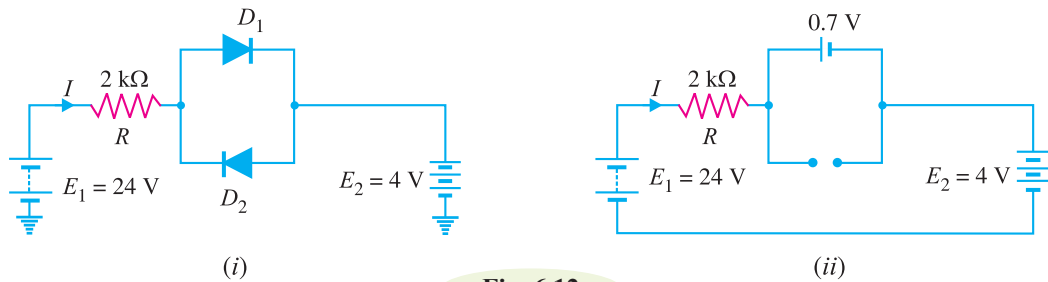


Fig. 6.12

**Solution.** The conditions of the problem suggest that diode  $D_1$  is forward biased and diode  $D_2$  is reverse biased. We can, therefore, consider the branch containing diode  $D_2$  as open as shown in Fig. 6.12 (ii). Further, diode  $D_1$  can be replaced by its simplified equivalent circuit.

$\therefore I = \frac{E_1 - E_2 - V_0}{R} = \frac{24 - 4 - 0.7}{2 \text{ k}\Omega} = \frac{19.3 \text{ V}}{2 \text{ k}\Omega} = 9.65 \text{ mA}$

**Example 6.6.** Find the voltage  $V_A$  in the circuit shown in Fig. 6.13 (i). Use simplified model.

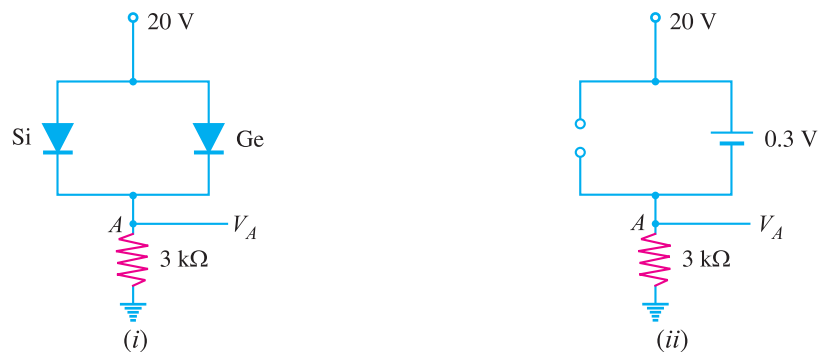


Fig. 6.13



## 84 ■ Principles of Electronics

**Solution.** It appears that when the applied voltage is switched on, both the diodes will turn “on”. But that is not so. When voltage is applied, germanium diode ( $V_0 = 0.3 \text{ V}$ ) will turn on first and a level of  $0.3 \text{ V}$  is maintained across the parallel circuit. The silicon diode never gets the opportunity to have  $0.7 \text{ V}$  across it and, therefore, remains in open-circuit state as shown in Fig. 6.13 (ii).

$$\therefore V_A = 20 - 0.3 = \mathbf{19.7 \text{ V}}$$

**Example 6.7.** Find  $V_Q$  and  $I_D$  in the network shown in Fig. 6.14 (i). Use simplified model.

**Solution.** Replace the diodes by their simplified models. The resulting circuit will be as shown in Fig. 6.14 (ii). By symmetry, current in each branch is  $I_D$  so that current in branch  $CD$  is  $2I_D$ . Applying Kirchhoff’s voltage law to the closed circuit  $ABCD$ , we have,

$$-0.7 - I_D \times 2 - 2I_D \times 2 + 10 = 0 \quad (I_D \text{ in mA})$$

$$\text{or} \quad 6I_D = 9.3$$

$$\therefore I_D = \frac{9.3}{6} = \mathbf{1.55 \text{ mA}}$$

$$\text{Also} \quad V_Q = (2I_D) \times 2 \text{ k}\Omega = (2 \times 1.55 \text{ mA}) \times 2 \text{ k}\Omega = \mathbf{6.2 \text{ V}}$$

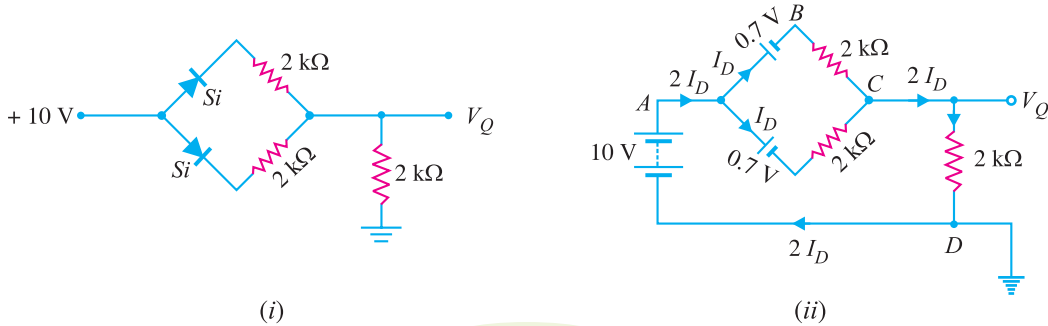


Fig. 6.14

**Example 6.8.** Determine current through each diode in the circuit shown in Fig. 6.15 (i). Use simplified model. Assume diodes to be similar.

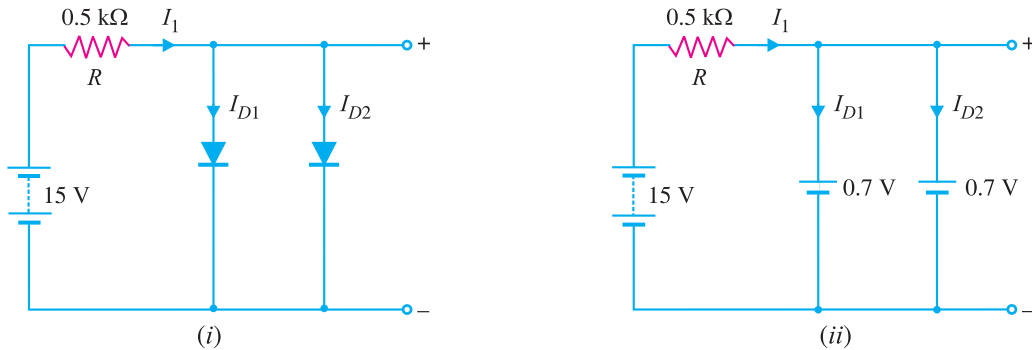


Fig. 6.15

**Solution.** The applied voltage forward biases each diode so that they conduct current in the same direction. Fig. 6.15 (ii) shows the equivalent circuit using simplified model. Referring to Fig. 6.15 (ii),

$$I_1 = \frac{\text{Voltage across } R}{R} = \frac{15 - 0.7}{0.5 \text{ k}\Omega} = 28.6 \text{ mA}$$

$$\text{Since the diodes are similar, } I_{D1} = I_{D2} = \frac{I_1}{2} = \frac{28.6}{2} = \mathbf{14.3 \text{ mA}}$$

**Comments.** Note the use of placing the diodes in parallel. If the current rating of each diode is  $20$

20 mA and a single diode is used in this circuit, a current of 28.6 mA would flow through the diode, thus damaging the device. By placing them in parallel, the current is limited to a safe value of 14.3 mA for the same terminal voltage.

**Example 6.9.** Determine the currents  $I_1$ ,  $I_2$  and  $I_3$  for the network shown in Fig. 6.16(i). Use simplified model for the diodes.

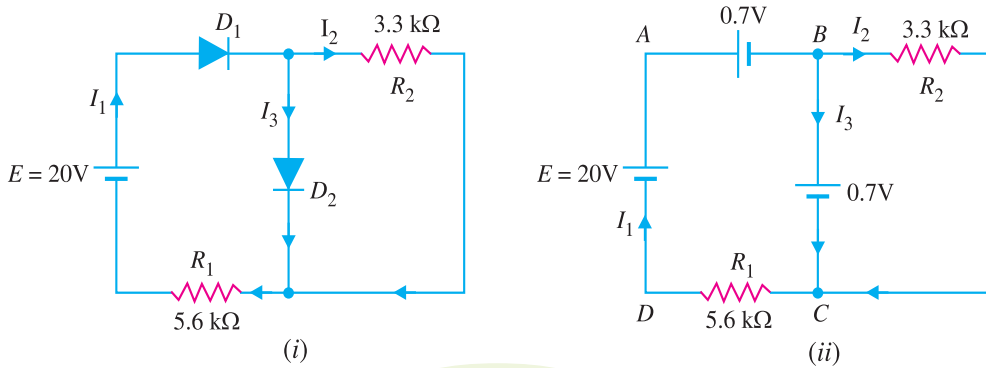


Fig. 6.16

**Solution.** An inspection of the circuit shown in Fig. 6.16 (i) shows that both diodes  $D_1$  and  $D_2$  are forward biased. Using simplified model for the diodes, the circuit shown in Fig. 6.16 (i) becomes the one shown in Fig. 6.16 (ii). The voltage across  $R_2$  ( $= 3.3 \text{ k}\Omega$ ) is 0.7V.

$$\therefore I_2 = \frac{0.7 \text{ V}}{3.3 \text{ k}\Omega} = 0.212 \text{ mA}$$

Applying Kirchhoff's voltage law to loop ABCDA in Fig. 6.16 (ii), we have,

$$-0.7 - 0.7 - I_1 R_1 + 20 = 0$$

$$\therefore I_1 = \frac{20 - 0.7 - 0.7}{R_1} = \frac{18.6 \text{ V}}{5.6 \text{ k}\Omega} = 3.32 \text{ mA}$$

Now  $I_1 = I_2 + I_3$

$$\therefore I_3 = I_1 - I_2 = 3.32 - 0.212 = 3.108 \text{ mA}$$

**Example 6.10.** Determine if the diode (ideal) in Fig. 6.17 (i) is forward biased or reverse biased.

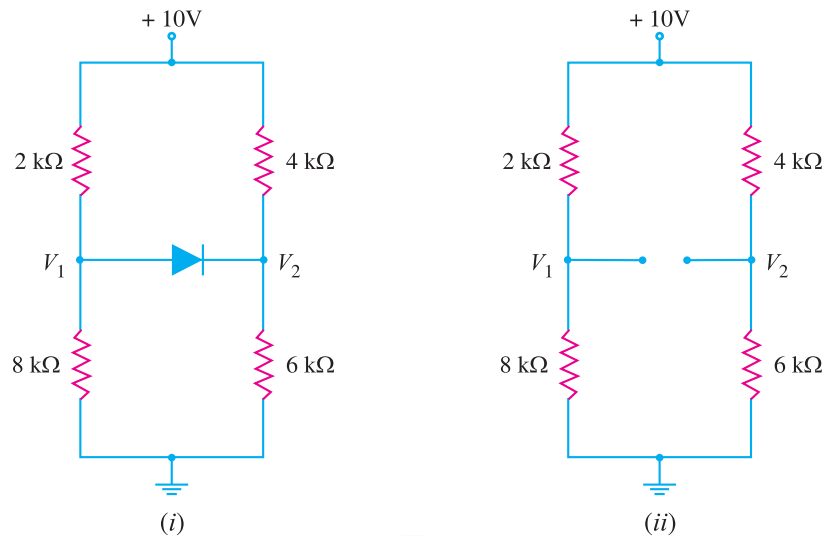


Fig. 6.17

## 86 ■ Principles of Electronics

**Solution.** Let us assume that diode in Fig. 6.17 (i) is *OFF* i.e. it is reverse biased. The circuit then becomes as shown in Fig. 6.17 (ii). Referring to Fig. 6.17 (ii), we have,

$$V_1 = \frac{10 \text{ V}}{2 \text{ k}\Omega + 8 \text{ k}\Omega} \times 8 \text{ k}\Omega = 8 \text{ V}$$

$$V_2 = \frac{10 \text{ V}}{4 \text{ k}\Omega + 6 \text{ k}\Omega} \times 6 \text{ k}\Omega = 6 \text{ V}$$

$$\therefore \text{Voltage across diode} = V_1 - V_2 = 8 - 6 = 2 \text{ V}$$

Now  $V_1 - V_2 = 2 \text{ V}$  is enough voltage to make the diode *forward biased*. Therefore, our initial assumption was wrong.

**Example 6.11.** Determine the state of diode for the circuit shown in Fig. 6.18 (i) and find  $I_D$  and  $V_D$ . Assume simplified model for the diode.

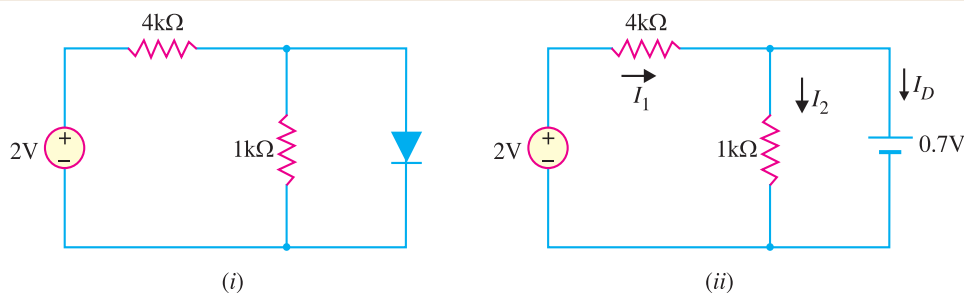


Fig. 6.18

**Solution.** Let us assume that the diode is *ON*. Therefore, we can replace the diode with a 0.7V battery as shown in Fig. 6.18 (ii). Referring to Fig. 6.18 (ii), we have,

$$I_1 = \frac{(2 - 0.7) \text{ V}}{4 \text{ k}\Omega} = \frac{1.3 \text{ V}}{4 \text{ k}\Omega} = 0.325 \text{ mA}$$

$$I_2 = \frac{0.7 \text{ V}}{1 \text{ k}\Omega} = 0.7 \text{ mA}$$

$$\text{Now } I_D = I_1 - I_2 = 0.325 - 0.7 = -0.375 \text{ mA}$$

Since the diode current is negative, the diode must be **OFF** and the true value of diode current is  $I_D = 0 \text{ mA}$ . Our initial assumption was wrong. In order to analyse the circuit properly, we should replace the diode in Fig. 6.18 (i) with an open circuit as shown in Fig. 6.19. The voltage  $V_D$  across the diode is

$$V_D = \frac{2 \text{ V}}{1 \text{ k}\Omega + 4 \text{ k}\Omega} \times 1 \text{ k}\Omega = 0.4 \text{ V}$$

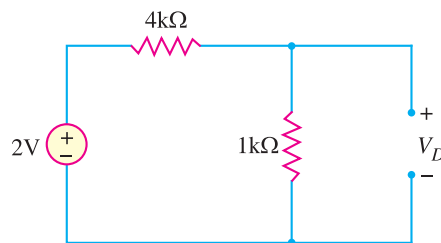


Fig. 6.19

We know that 0.7V is required to turn *ON* the diode. Since  $V_D$  is only 0.4V, the answer confirms that the diode is *OFF*.

## 6.6 Important Terms

While discussing the diode circuits, the reader will generally come across the following terms :

(i) **Forward current.** It is the current flowing through a forward biased diode. Every diode has a maximum value of forward current which it can safely carry. If this value is exceeded, the diode may be destroyed due to excessive heat. For this reason, the manufacturers' data sheet specifies the maximum forward current that a diode can handle safely.

**(ii) Peak inverse voltage.** It is the maximum reverse voltage that a diode can withstand without destroying the junction.

If the reverse voltage across a diode exceeds this value, the reverse current increases sharply and breaks down the junction due to excessive heat. Peak inverse voltage is extremely important when diode is used as a rectifier. In rectifier service, it has to be ensured that reverse voltage across the diode does not exceed its PIV during the negative half-cycle of input a.c. voltage. As a matter of fact, PIV consideration is generally the deciding factor in diode rectifier circuits. The peak inverse voltage may be between 10V and 10 kV depending upon the type of diode.

**(iii) Reverse current or leakage current.** It is the current that flows through a reverse biased diode. This current is due to the minority carriers. Under normal operating voltages, the reverse current is quite small. Its value is extremely small ( $< 1\mu\text{A}$ ) for silicon diodes but it is appreciable ( $\approx 100\mu\text{A}$ ) for germanium diodes.

It may be noted that the reverse current is usually very small as compared with forward current. For example, the forward current for a typical diode might range upto 100 mA while the reverse current might be only a few  $\mu\text{A}$ —a ratio of many thousands between forward and reverse currents.

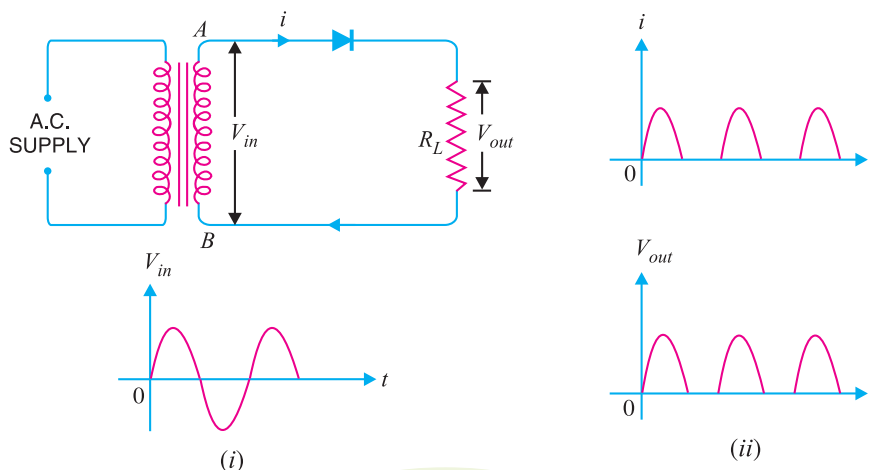
## 6.7 Crystal Diode Rectifiers

For reasons associated with economics of generation and transmission, the electric power available is usually an a.c. supply. The supply voltage varies sinusoidally and has a frequency of 50 Hz. It is used for lighting, heating and electric motors. But there are many applications (*e.g.* electronic circuits) where d.c. supply is needed. When such a d.c. supply is required, the mains a.c. supply is rectified by using crystal diodes. The following two rectifier circuits can be used :

- (i) Half-wave rectifier      (ii) Full-wave rectifier

### 6.8 Half-Wave Rectifier

In half-wave rectification, the rectifier conducts current only during the positive half-cycles of input a.c. supply. The negative half-cycles of a.c. supply are suppressed *i.e.* during negative half-cycles, no current is conducted and hence no voltage appears across the load. Therefore, current always flows in one direction (*i.e.* d.c.) through the load though after every half-cycle.



**Fig. 6.20**

**Circuit details.** Fig. 6.20 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  $R_L$ . Generally, a.c. supply is given through a transformer. The use of transformer permits two advantages. Firstly, it allows us to step up or step down the a.c. input voltage as the situation demands. Secondly, the transformer isolates the rectifier circuit from power line and thus reduces the risk of electric shock.

**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 *w.r.t.* end  $B$ . This makes the diode forward biased and hence it conducts current. During the negative half-cycle, end  $A$  is negative *w.r.t.* 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 ; it is blocked during the negative half-cycles [See Fig. 6.20 (ii)]. 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 the load is pulsating d.c. These pulsations in the output are further smoothed with the help of *filter circuits* discussed later.

**Disadvantages :** The main disadvantages of a half-wave rectifier are :

(i) The pulsating current in the load contains alternating component whose basic frequency is equal to the supply frequency. Therefore, an elaborate filtering is required to produce steady direct current.

(ii) The a.c. supply delivers power only half the time. Therefore, the output is low.

### 6.9 Output Frequency of Half-Wave Rectifier

The output frequency of a half-wave rectifier is equal to the input frequency (50 Hz). Recall how a complete cycle is defined. A waveform has a complete cycle when it repeats the same wave pattern over a given time. Thus in Fig. 6.21 (i), the a.c. input voltage repeats the same wave pattern over  $0^\circ - 360^\circ$ ,  $360^\circ - 720^\circ$  and so on. In Fig. 6.21 (ii), the output waveform also repeats the same wave pattern over  $0^\circ - 360^\circ$ ,  $360^\circ - 720^\circ$  and so on. This means that when input a.c. completes one cycle, the output half-wave rectified wave also completes one cycle. In other words, the output frequency is equal to the input frequency *i.e.*

$$f_{out} = f_{in}$$

For example, if the input frequency of sine wave applied to a half-wave rectifier is 100 Hz, then frequency of the output wave will also be 100 Hz.

### 6.10 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.*

$$\text{Rectifier efficiency, } \eta = \frac{\text{d.c. power output}}{\text{Input a.c. power}}$$

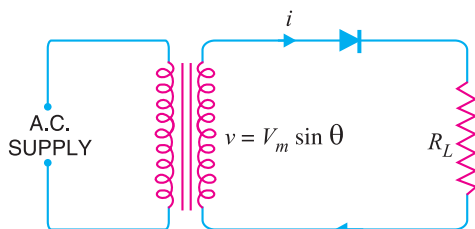


Fig. 6.22

Consider a half-wave rectifier shown in Fig. 6.22. Let  $v = V_m \sin \theta$  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.

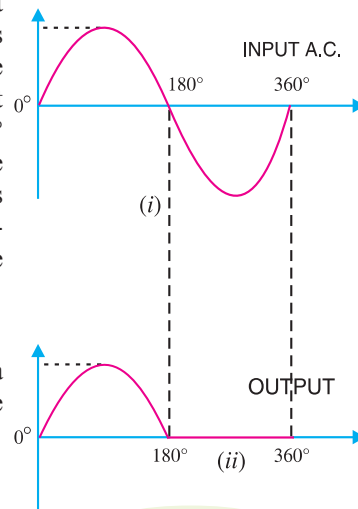
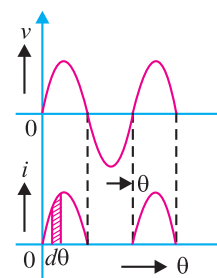


Fig. 6.21



**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.

$$\begin{aligned}
 *I_{av} = I_{dc} &= \frac{1}{2\pi} \int_0^\pi i \, d\theta = \frac{1}{2\pi} \int_0^\pi \frac{V_m \sin \theta}{r_f + R_L} \, d\theta \\
 &= \frac{V_m}{2\pi(r_f + R_L)} \int_0^\pi \sin \theta \, d\theta = \frac{V_m}{2\pi(r_f + R_L)} [-\cos \theta]_0^\pi \\
 &= \frac{V_m}{2\pi(r_f + R_L)} \times 2 = \frac{V_m}{(r_f + R_L)} \times \frac{1}{\pi} \\
 &= \frac{**I_m}{\pi} \quad \left[ \because I_m = \frac{V_m}{(r_f + R_L)} \right]
 \end{aligned}$$

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

**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,  $I_{rms} = I_m/2$

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

$$\begin{aligned}
 \therefore \text{Rectifier efficiency} &= \frac{\text{d.c. output power}}{\text{a.c. input power}} = \frac{(I_m / \pi)^2 \times R_L}{(I_m / 2)^2 (r_f + R_L)} \\
 &= \frac{0.406 R_L}{r_f + R_L} = \frac{0.406}{1 + \frac{r_f}{R_L}}
 \end{aligned}$$

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

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

(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 =  $\frac{\text{Area under the curve over a cycle}}{\text{Base}} = \frac{\int_0^\pi i \, d\theta}{2\pi}$

\*\* 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  $2 I_m$ .

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

## 90 ■ Principles of Electronics

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.

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

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.**

Primary to secondary turns is

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

R.M.S. primary voltage  
= 230 V

$\therefore$  Max. primary voltage is

$$\begin{aligned} V_{pm} &= (\sqrt{2}) \times \text{r.m.s. primary voltage} \\ &= (\sqrt{2}) \times 230 = 325.3 \text{ V} \end{aligned}$$

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

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

(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.

$$\therefore \text{Peak inverse voltage} = \mathbf{32.53 \text{ V}}$$

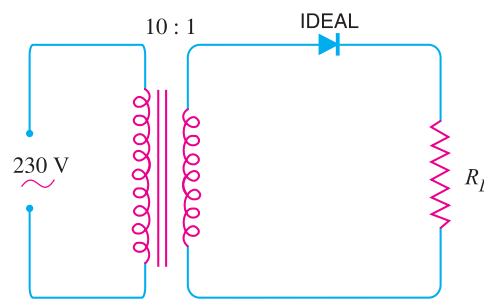


Fig. 6.23

**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.**

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

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

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

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

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

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

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

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

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

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

**Solution.**

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

$$\text{Diode resistance, } r_f = 25 \Omega$$

$$\text{Load resistance, } R_L = 800 \Omega$$

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

$$\begin{aligned} \therefore V_{dc} &= I_{dc} \times R_L \\ &= \frac{I_m}{\pi} \times R_L = \frac{V_m}{\pi(r_f + R_L)} \times R_L \quad \left[ \because I_m = \frac{V_m}{r_f + R_L} \right] \end{aligned}$$

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

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

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.



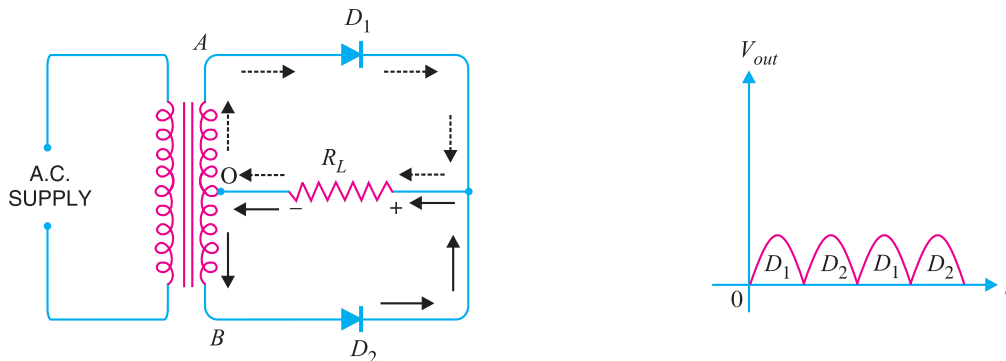


Fig. 6.24

**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.*

$$PIV = 2 V_m$$

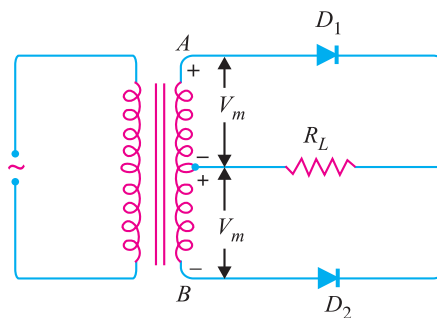


Fig. 6.25

**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.

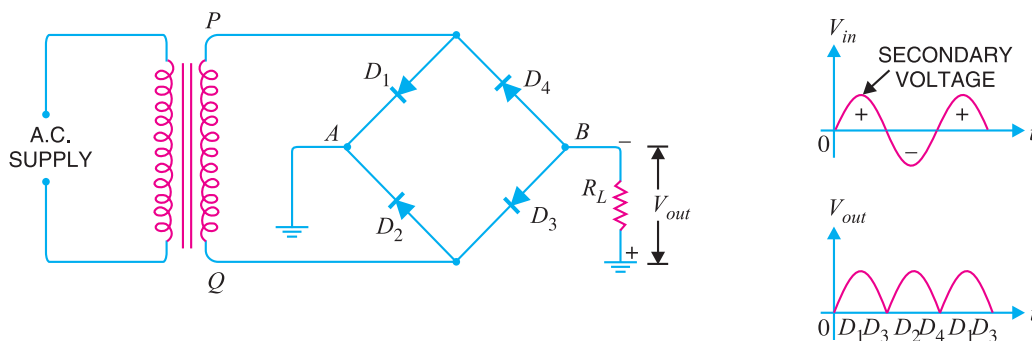


Fig. 6.26

**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  $R_L$ .

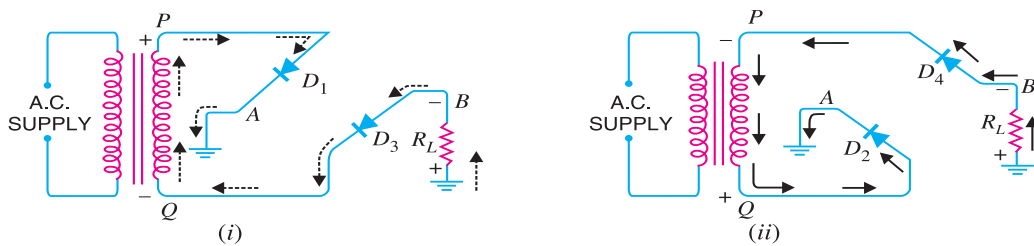


Fig. 6.27

**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).

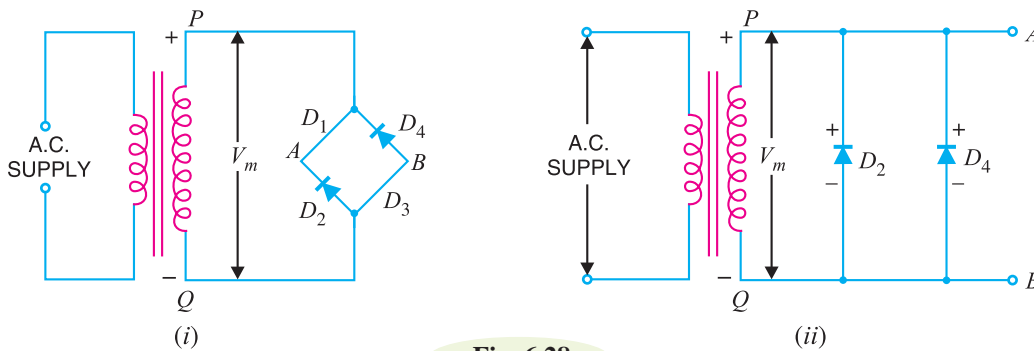


Fig. 6.28

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.

## 94 ■ Principles of Electronics

(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  $0^\circ - 360^\circ$ . 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.*

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

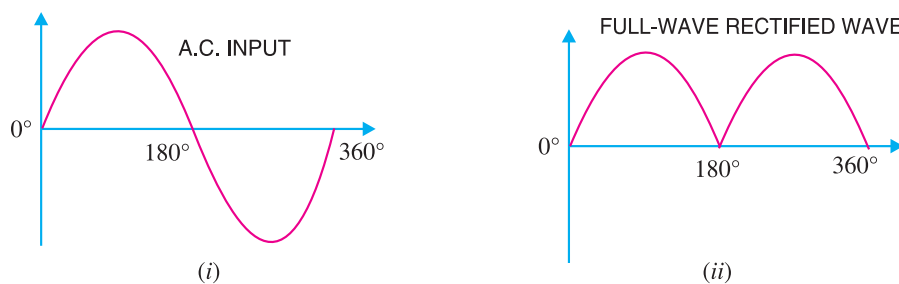


Fig. 6.29

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 :

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

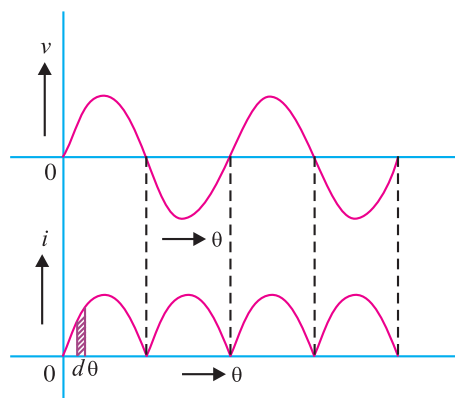


Fig. 6.30

**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,

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

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

**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,

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

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

$\therefore$  Full-wave rectification efficiency is

$$\begin{aligned} \eta &= \frac{P_{dc}}{P_{ac}} = \frac{(2 I_m / \pi)^2 R_L}{\left( \frac{I_m}{\sqrt{2}} \right)^2 (r_f + R_L)} \\ &= \frac{8}{\pi^2} \times \frac{R_L}{(r_f + R_L)} = \frac{0.812 R_L}{r_f + R_L} = \frac{0.812}{1 + \frac{r_f}{R_L}} \end{aligned}$$

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

$$\therefore \text{Maximum efficiency} = 81.2\%$$

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  $20 \Omega$ . The transformer r.m.s. secondary voltage from centre tap to each end of secondary is  $50 \text{ V}$  and load resistance is  $980 \Omega$ . 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,  $I_{dc} = \frac{2 I_m}{\pi} = \frac{2 \times 70.7}{\pi} = 45 \text{ mA}$

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

$$I_{rms} = \frac{I_m}{\sqrt{2}} = \frac{70.7}{\sqrt{2}} = 50 \text{ mA}$$

**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,  $N_1/N_2 = 5$

## 96 ■ Principles of Electronics

R.M.S. primary voltage = 230 V

∴ R.M.S. secondary voltage  
=  $230 \times (1/5) = 46 \text{ V}$

Maximum voltage across secondary  
=  $46 \times \sqrt{2} = 65 \text{ V}$

Maximum voltage across half secondary winding is

$$V_m = 65/2 = 32.5 \text{ V}$$

(i) Average current,  $I_{dc} =$   

$$\frac{2V_m}{\pi R_L} = \frac{2 \times 32.5}{\pi \times 100} = 0.207 \text{ A}$$

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

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

$$PIV = 65 \text{ V}$$

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

Since  $r_f = 0$

∴ Rectification efficiency = **81.2 %**

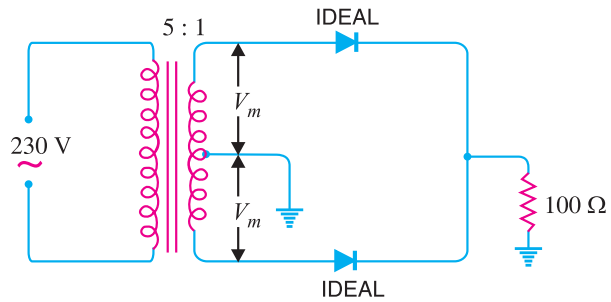


Fig. 6.31

**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.

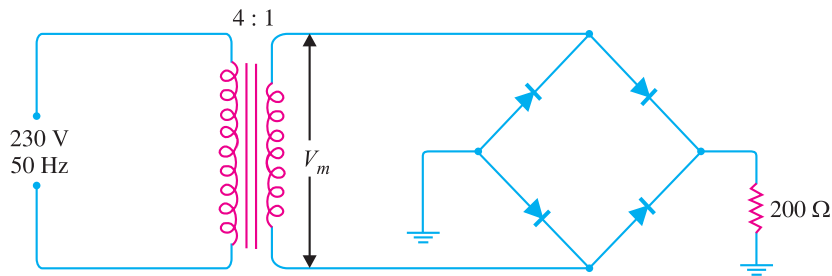


Fig. 6.32

**Solution.**

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

R.M.S. primary voltage = 230 V

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

Maximum voltage across secondary is

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

(i) Average current,  $I_{dc} =$   

$$\frac{2V_m}{\pi R_L} = \frac{2 \times 81.3}{\pi \times 200} = 0.26 \text{ A}$$

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

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

$$PIV = 81.3 \text{ V}$$

(iii) In full-wave rectification, there are two output pulses for each complete cycle of the input a.c. voltage. Therefore, the output frequency is twice that of the a.c. supply *i.e.*

$$f_{out} = 2 \times f_{in} = 2 \times 50 = 100 \text{ Hz}$$

**Example 6.19.** Fig. 6.33 (i) and Fig. 6.33 (ii) show the centre-tap and bridge type circuits having the same load resistance and transformer turn ratio. The primary of each is connected to 230V, 50 Hz supply.

(i) Find the d.c. voltage in each case.

(ii) PIV for each case for the same d.c. output. Assume the diodes to be ideal.

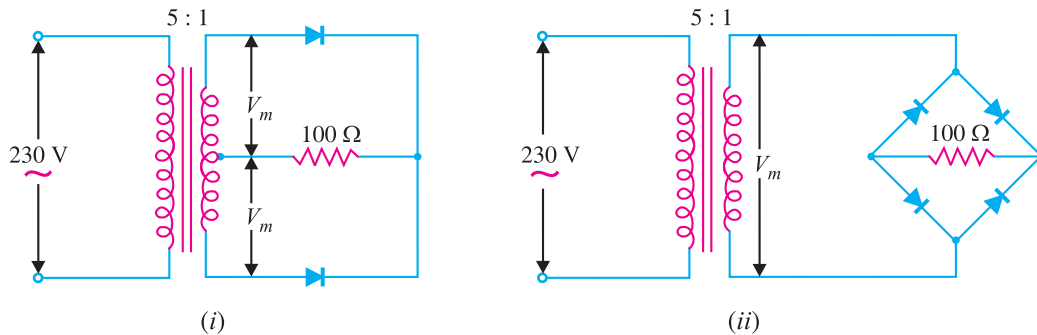


Fig. 6.33

**Solution.**

(i) **D.C. output voltage**

**Centre-tap circuit**

$$\text{R.M.S. secondary voltage} = 230 \times 1/5 = 46 \text{ V}$$

$$\text{Max. voltage across secondary} = 46 \times \sqrt{2} = 65 \text{ V}$$

Max. voltage appearing across half secondary winding is

$$V_m = 65/2 = 32.5 \text{ V}$$

$$\text{Average current, } I_{dc} = \frac{2V_m}{\pi R_L}$$

$$\begin{aligned} \text{D.C. output voltage, } V_{dc} &= I_{dc} \times R_L = \frac{2V_m}{\pi R_L} \times R_L \\ &= \frac{2V_m}{\pi} = \frac{2 \times 32.5}{\pi} = 20.7 \text{ V} \end{aligned}$$

**Bridge Circuit**

$$\text{Max. voltage across secondary, } V_m = 65 \text{ V}$$

$$\text{D.C. output voltage, } V_{dc} = I_{dc} R_L = \frac{2V_m}{\pi R_L} \times R_L = \frac{2V_m}{\pi} = \frac{2 \times 65}{\pi} = 41.4 \text{ V}$$

This shows that for the same secondary voltage, the d.c. output voltage of bridge circuit is twice that of the centre-tap circuit.

(ii) **PIV for same d.c. output voltage**

The d.c. output voltage of the two circuits will be the same if  $V_m$  (*i.e.* max. voltage utilised by each circuit for conversion into d.c.) is the same. For this to happen, the turn ratio of the transformers should be as shown in Fig. 6.34.

## 98 ■ Principles of Electronics

### Centre-tap circuit

$$\text{R.M.S. secondary voltage} = 230 \times 1/5 = 46 \text{ V}$$

$$\text{Max. voltage across secondary} = 46 \times \sqrt{2} = 65 \text{ V}$$

Max. voltage across half secondary winding is

$$V_m = 65/2 = 32.5 \text{ V}$$

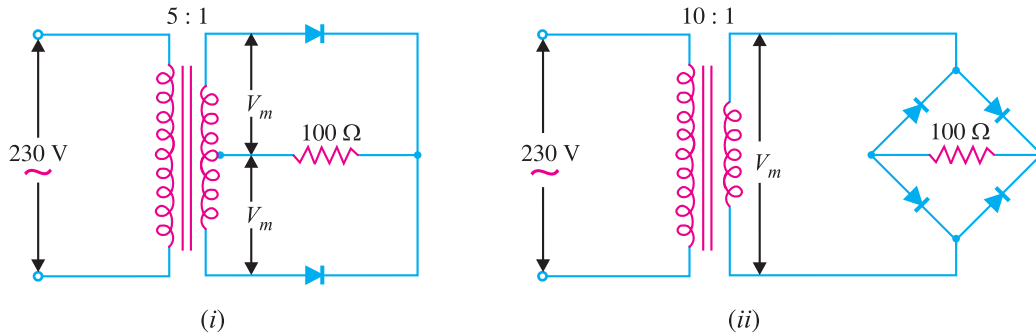


Fig. 6.34

$$\therefore PIV = 2 V_m = 2 \times 32.5 = \mathbf{65 \text{ V}}$$

### Bridge type circuit

$$\text{R.M.S. secondary voltage} = 230 \times 1/10 = 23 \text{ V}$$

$$\text{Max. voltage across secondary, } V_m = 23 \times \sqrt{2} = 32.5 \text{ V}$$

$$\therefore PIV = V_m = \mathbf{32.5 \text{ V}}$$

This shows that for the same d.c. output voltage, *PIV* of bridge circuit is half that of centre-tap circuit. This is a distinct advantage of bridge circuit.

**Example 6.20.** The four diodes used in a bridge rectifier circuit have forward resistances which may be considered constant at  $1 \Omega$  and infinite reverse resistance. The alternating supply voltage is  $240 \text{ V r.m.s.}$  and load resistance is  $480 \Omega$ . Calculate (i) mean load current and (ii) power dissipated in each diode.

#### Solution.

$$\text{Max. a.c. voltage, } V_m = 240 \times \sqrt{2} \text{ V}$$

(i) At any instant in the bridge rectifier, two diodes in series are conducting. Therefore, total circuit resistance =  $2 r_f + R_L$ .

$$\text{Max. load current, } I_m = \frac{V_m}{2 r_f + R_L} = \frac{240 \times \sqrt{2}}{2 \times 1 + 480} = 0.7 \text{ A}$$

$$\therefore \text{Mean load current, } I_{dc} = \frac{2 I_m}{\pi} = \frac{2 \times 0.7}{\pi} = \mathbf{0.45 \text{ A}}$$

(ii) Since each diode conducts only half a cycle, diode r.m.s. current is :

$$I_{r.m.s.} = I_m/2 = 0.7/2 = 0.35 \text{ A}$$

$$\text{Power dissipated in each diode} = I_{r.m.s.}^2 \times r_f = (0.35)^2 \times 1 = \mathbf{0.123 \text{ W}}$$

**Example 6.21.** The bridge rectifier shown in Fig. 6.35 uses silicon diodes. Find (i) d.c. output

voltage (ii) d.c. output current. Use simplified model for the diodes.

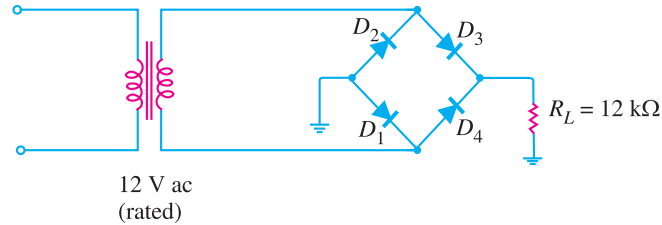


Fig. 6.35

**Solution.** The conditions of the problem suggest that the a.c. voltage across transformer secondary is 12V r.m.s.

∴ Peak secondary voltage is

$$V_{s(pk)} = 12 \times \sqrt{2} = 16.97 \text{ V}$$

(i) At any instant in the bridge rectifier, two diodes in series are conducting.

∴ Peak output voltage is

$$V_{out(pk)} = 16.97 - 2(0.7) = 15.57 \text{ V}$$

∴ Average (or d.c.) output voltage is

$$V_{av} = V_{dc} = \frac{2 V_{out(pk)}}{\pi} = \frac{2 \times 15.57}{\pi} = \mathbf{9.91 \text{ V}}$$

(ii) Average (or d.c.) output current is

$$I_{av} = \frac{V_{av}}{R_L} = \frac{9.91 \text{ V}}{12 \text{ k}\Omega} = \mathbf{825.8 \mu\text{A}}$$

## 6.16 Faults in Centre-Tap Full-Wave Rectifier

The faults in a centre-tap full-wave rectifier may occur in the transformer or rectifier diodes. Fig. 6.36 shows the circuit of a centre-tap full-wave rectifier. A fuse is connected in the primary of the transformer for protection purposes.

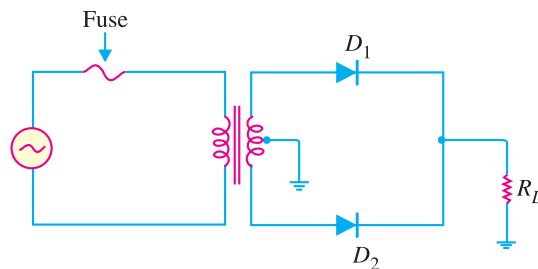


Fig. 6.36

We can divide the rectifier faults into two classes viz.

1. Faults in transformer    2. Faults in rectifier diodes

**1. Faults in Transformer.** The transformer in a rectifier circuit can develop the following faults :

- (i) A shorted primary or secondary winding.
- (ii) An open primary or secondary winding.
- (iii) A short between the primary or secondary winding and the transformer frame.
- (i) In most cases, a **shorted primary** or **shorted secondary** will cause the fuse in the primary



## 100 ■ Principles of Electronics

to blow. If the fuse does not blow, the d.c. output from the rectifier will be extremely low and the transformer itself will be very hot.

(ii) When the **primary or secondary winding of the transformer opens**, the output from the rectifier will drop to zero. In this case, the primary fuse will not blow. If you believe that either transformer winding is open, a simple resistance check will verify your doubt. If either winding reads a very high resistance, the winding is open.

(iii) If **either winding shorts to the transformer casing**, the primary fuse will blow. This fault can be checked by measuring the resistances from the winding leads to the transformer casing. A low resistance measurement indicates that a winding-to-case short exists.

**2. Faults in Rectifier Diodes.** If a fault occurs in a rectifier diode, the circuit conditions will indicate the type of fault.

(i) If **one diode in the centre-tap full-wave rectifier is shorted**, the primary fuse will blow. The reason is simple. Suppose diode  $D_2$  in Fig. 6.36 is shorted. Then diode  $D_2$  will behave as a wire. When diode  $D_1$  is forward biased, the transformer secondary will be shorted through  $D_1$ . This will cause excessive current to flow in the secondary (and hence in the primary), causing the primary fuse to blow.

(ii) If **one diode in the centre-tap full-wave rectifier opens**, the output from the rectifier will resemble the output from a half-wave rectifier. The remedy is to replace the diode.

**Bridge Rectifier Faults.** The transformer faults and their remedies for bridge rectifier circuits are the same as for centre-tap full-wave rectifier. Again symptoms for shorted and open diodes in the bridge rectifier are the same as those for the centre-tap circuit. In the case of bridge circuit, you simply have more diodes that need to be tested.

### 6.17 Nature of Rectifier Output

It has already been discussed that the output of a rectifier is pulsating d.c. as shown in Fig. 6.37. In fact, if such a waveform is carefully analysed, it will be found that it contains a d.c. component and an a.c. component. The a.c. component is responsible for the \*pulsations in the wave. The reader may wonder how a pulsating d.c. voltage can have an a.c. component when the voltage never becomes negative. The answer is that any wave which varies in a regular manner has an a.c. component.

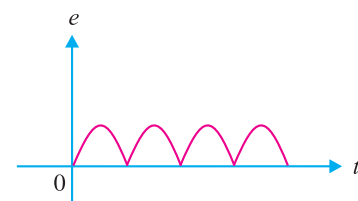


Fig. 6.37

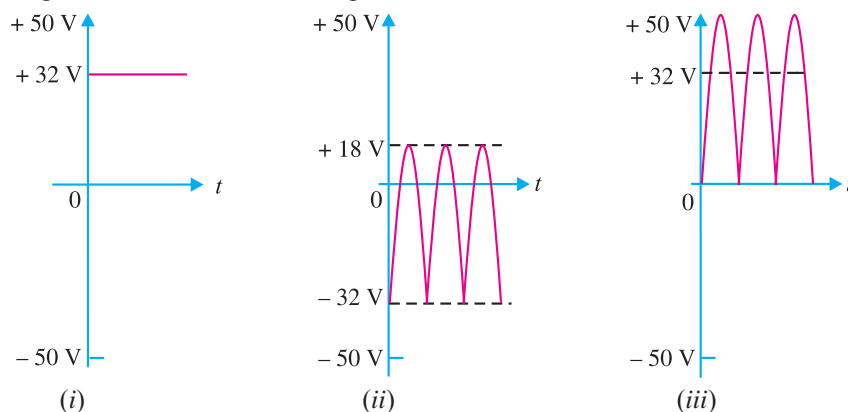


Fig. 6.38

\* Means changing output voltage.

The fact that a pulsating d.c. contains both d.c. and a.c. components can be beautifully illustrated by referring to Fig. 6.38. Fig. 6.38 (i) shows a pure d.c. component, whereas Fig. 6.38 (ii) shows the \*a.c. component. If these two waves are added together, the resulting wave will be as shown in Fig. 6.38 (iii). It is clear that the wave shown in Fig. 6.38 (iii) never becomes negative, although it contains both a.c. and d.c. components. The striking resemblance between the rectifier output wave shown in Fig. 6.37 and the wave shown in Fig. 6.38 (iii) may be noted.



Rectifier

*It follows, therefore, that a pulsating output of a rectifier contains a d.c. component and an a.c. component.*

### 6.18 Ripple Factor

The output of a rectifier consists of a d.c. component and an a.c. component (also known as *ripple*). The a.c. component is undesirable and accounts for the pulsations in the rectifier output. The effectiveness of a rectifier depends upon the magnitude of a.c. component in the output ; the smaller this component, the more effective is the rectifier.

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

$$\text{Ripple factor} = \frac{\text{r.m.s. value of a.c. component}}{\text{value of d.c. component}} = \frac{I_{ac}}{I_{dc}}$$

Therefore, ripple factor is very important in deciding the effectiveness of a rectifier. The smaller the ripple factor, the lesser the effective a.c. component and hence more effective is the rectifier.

**Mathematical analysis.** The output current of a rectifier contains d.c. as well as a.c. component. The undesired a.c. component has a frequency of 100 Hz (*i.e.* double the supply frequency 50 Hz) and is called the *ripple* (See Fig. 6.39). It is a fluctuation superimposed on the d.c. component.

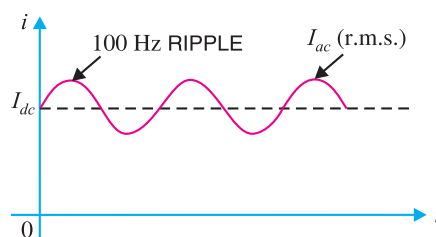


Fig. 6.39

By definition, the effective (*i.e.* r.m.s.) value of total load current is given by :

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

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

Dividing throughout by  $I_{dc}$ , we get,

$$\frac{I_{ac}}{I_{dc}} = \frac{1}{I_{dc}} \sqrt{I_{rms}^2 - I_{dc}^2}$$

But  $I_{ac}/I_{dc}$  is the ripple factor.

$$\therefore \text{Ripple factor} = \frac{1}{I_{dc}} \sqrt{I_{rms}^2 - I_{dc}^2} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

**(i) For half-wave rectification.** In half-wave rectification,

$$I_{rms} = I_m/2 \quad ; \quad I_{dc} = I_m/\pi$$

\* Although the a.c. component is not a sine-wave, yet it is alternating one.

## 102 ■ Principles of Electronics

$$\therefore \text{Ripple factor} = \sqrt{\left(\frac{I_m/2}{I_m/\pi}\right)^2} - 1 = 1.21$$

It is clear that a.c. component exceeds the 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.

**(ii) For full-wave rectification.** In full-wave rectification,

$$I_{rms} = \frac{I_m}{\sqrt{2}} \quad ; \quad I_{dc} = \frac{2 I_m}{\pi}$$

$$\therefore \text{Ripple factor} = \sqrt{\left(\frac{I_m/\sqrt{2}}{2 I_m/\pi}\right)^2} - 1 = 0.48$$

$$\text{i.e. } \frac{\text{effective a.c. component}}{\text{d.c. component}} = 0.48$$

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 in half-wave rectifier. For this reason, full-wave rectification is invariably used for conversion of a.c. into d.c.

**Example 6.22.** A power supply A delivers 10 V dc with a ripple of 0.5 V r.m.s. while the power supply B delivers 25 V dc with a ripple of 1 mV r.m.s. Which is better power supply ?

**Solution.** The lower the ripple factor of a power supply, the better it is.

*For power supply A*

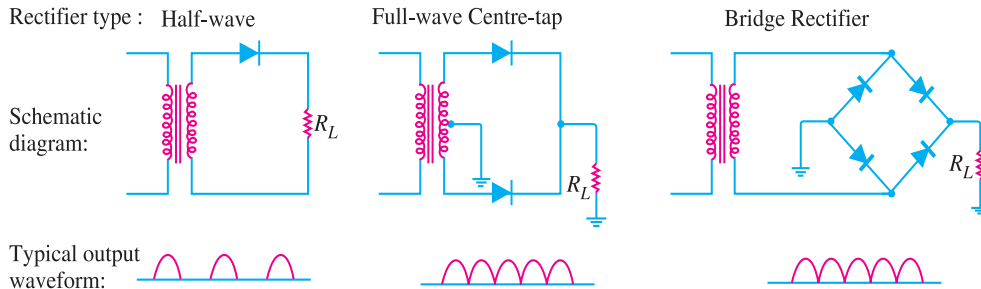
$$\text{Ripple factor} = \frac{V_{ac(r.m.s.)}}{V_{dc}} = \frac{0.5}{10} \times 100 = 5\%$$

*For power supply B*

$$\text{Ripple factor} = \frac{V_{ac(r.m.s.)}}{V_{dc}} = \frac{0.001}{25} \times 100 = 0.004\%$$

Clearly, power supply B is better.

### 6.19 Comparison of Rectifiers



S. No.	Particulars	Half-wave	Centre-tap	Bridge type
1	No. of diodes	1	2	4
2	Transformer necessary	no	yes	no
3	Max. efficiency	40.6%	81.2%	81.2%
4	Ripple factor	1.21	0.48	0.48
5	Output frequency	$f_{in}$	$2f_{in}$	$2f_{in}$
6	Peak inverse voltage	$V_m$	$2V_m$	$V_m$

A comparison among the three rectifier circuits must be made very judiciously. Although bridge circuit has some disadvantages, it is the best circuit from the viewpoint of overall performance. When cost of the transformer is the main consideration in a rectifier assembly, we invariably use the bridge circuit. This is particularly true for large rectifiers which have a low-voltage and a high-current rating.

## 6.20 Filter Circuits

Generally, a rectifier is required to produce pure d.c. supply for using at various places in the electronic circuits. However, the output of a rectifier has pulsating \*character *i.e.* it contains a.c. and d.c. components. The a.c. component is undesirable and must be kept away from the load. To do so, a *filter circuit* is used which removes (or *filters out*) the a.c. component and allows only the d.c. component to reach the load.

A **filter circuit** is a device which removes the a.c. component of rectifier output but allows the d.c. component to reach the load.

Obviously, a filter circuit should be installed between the rectifier and the load as shown in Fig. 6.40. A filter circuit is generally a combination of inductors ( $L$ ) and capacitors ( $C$ ). The filtering action of  $L$  and  $C$  depends upon the basic electrical principles. A capacitor passes a.c. readily but does not \*\*pass d.c. at all. On the other hand, an inductor †opposes a.c. but allows d.c. to pass through it. It then becomes clear that suitable network of  $L$  and  $C$  can effectively remove the a.c. component, allowing the d.c. component to reach the load.

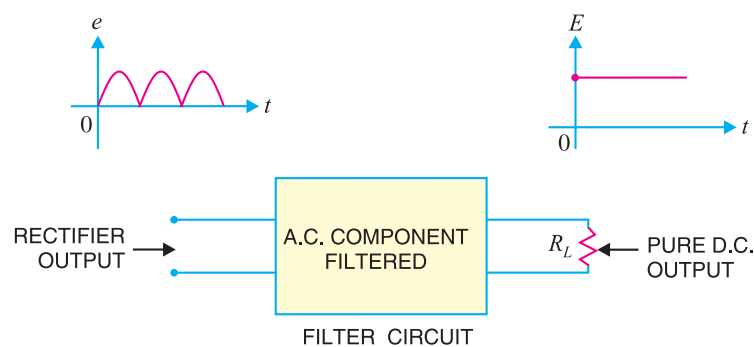


Fig. 6.40

## 6.21 Types of Filter Circuits

The most commonly used filter circuits are *capacitor filter*, *choke input filter* and *capacitor input filter or  $\pi$ -filter*. We shall discuss these filters in turn.

(i) **Capacitor filter.** Fig. 6.41 (ii) 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. 6.41 (iii)], the

\* If such a d.c. is applied in an electronic circuit, it will produce a *hum*.

\*\* A capacitor offers infinite reactance to d.c. For d.c.,  $f = 0$ .

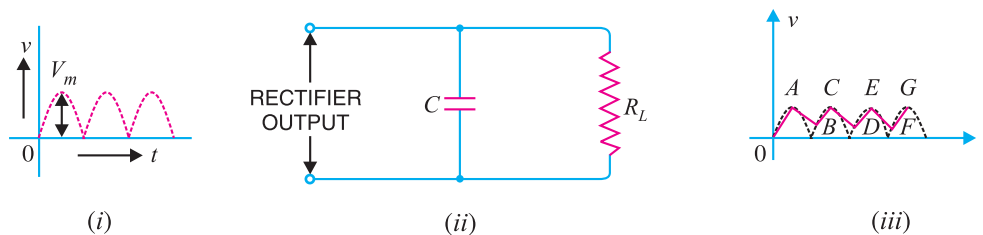
$$\therefore X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 0 \times C} = \infty$$

Hence, a capacitor does not allow d.c. to pass through it.

† We know  $X_L = 2\pi fL$ . For d.c.,  $f = 0$  and, therefore,  $X_L = 0$ . Hence inductor passes d.c. quite readily. For a.c., it offers opposition and drops a part of it.

## 104 ■ Principles of Electronics

capacitor is charged to the peak value  $V_m$  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  $R$ - $C$ ) decreases as shown by the line  $AB$  in Fig. 6.41 (iii). 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  $ABCDEFG$ . 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.

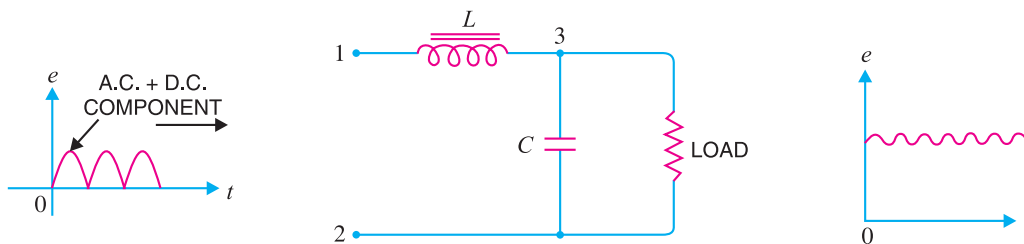


**Fig. 6.41**

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.

**(ii) Choke input filter.** Fig. 6.42 shows a typical choke input filter circuit. It consists of a \*choke  $L$  connected in series with the rectifier output and a filter capacitor  $C$  across the load. Only a single filter section is shown, but several identical sections are often used to reduce the pulsations as effectively as possible.

The pulsating output of the rectifier is applied across terminals 1 and 2 of the filter circuit. As discussed before, the pulsating output of rectifier contains a.c. and d.c. components. The choke offers high opposition to the passage of a.c. component but negligible opposition to the d.c. component. The result is that most of the a.c. component appears across the choke while whole of d.c. component passes through the choke on its way to load. This results in the reduced pulsations at terminal 3.



**Fig. 6.42**

At terminal 3, the rectifier output contains d.c. component and the remaining part of a.c. component which has managed to pass through the choke. Now, the low reactance of filter capacitor bypasses the a.c. component but prevents the d.c. component to flow through it. Therefore, only d.c. component reaches the load. In this way, the filter circuit has filtered out the a.c. component from the rectifier output, allowing d.c. component to reach the load.

**(iii) Capacitor input filter or  $\pi$ -filter.** Fig. 6.43 shows a typical capacitor input filter or \*\* $\pi$ -filter. It consists of a filter capacitor  $C_1$  connected across the rectifier output, a choke  $L$  in series and

\* The shorthand name of inductor coil is choke.

\*\* The shape of the circuit diagram of this filter circuit appears like Greek letter  $\pi$  (pi) and hence the name  $\pi$ -filter.

another filter capacitor  $C_2$  connected across the load. Only one filter 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*  $C_1$ ,  $L$  and  $C_2$  of this filter is described below :

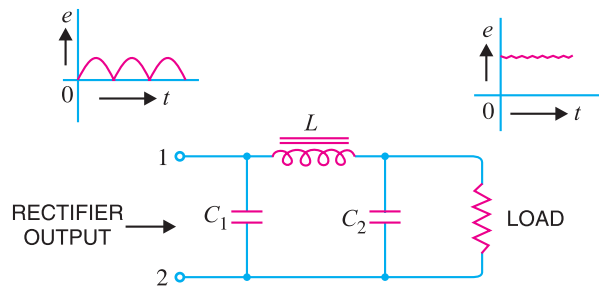


Fig. 6.43

(a) The *filter capacitor*  $C_1$  offers low reactance to a.c. component of rectifier output while it offers infinite reactance to the d.c. component. Therefore, capacitor  $C_1$  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*  $C_2$  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.

**Example 6.23.** For the circuit shown in Fig. 6.44, find the output d.c. voltage.

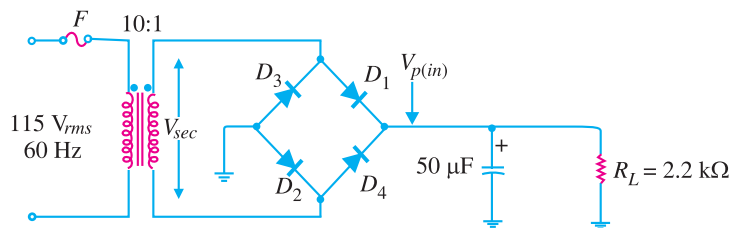


Fig. 6.44

**Solution.** It can be proved that output d.c. voltage is given by :

$$V_{dc} = V_{p(in)} \left( 1 - \frac{1}{2f R_L C} \right)$$

Here  $V_{p(in)}$  = Peak rectified full-wave voltage applied to the filter  
 $f$  = Output frequency

Peak primary voltage,  $V_{p(prim)} = \sqrt{2} \times 115 = 163\text{V}$

Peak secondary voltage,  $V_{p(sec)} = \left( \frac{1}{10} \right) \times 163 = 16.3\text{V}$

Peak full-wave rectified voltage at the filter input is

$$V_{p(in)} = V_{p(sec)} - 2 \times 0.7 = 16.3 - 1.4 = 14.9\text{V}$$

For full-wave rectification,  $f = 2 f_m = 2 \times 60 = 120\text{ Hz}$

$$\text{Now } \frac{1}{2f R_L C} = \frac{1}{2 \times 120 \times (2.2 \times 10^3) \times (50 \times 10^{-6})} = 0.038$$

\* That part of a.c. component which could not be bypassed by capacitor  $C_1$ .

## 106 ■ Principles of Electronics

$$\therefore V_{dc} = V_{p(in)} \left( 1 - \frac{1}{2f R_L C} \right) = 14.9 (1 - 0.038) = \mathbf{14.3V}$$

**Example 6.24.** The choke of Fig. 6.45 has a d.c. resistance of  $25 \Omega$ . What is the d.c. voltage if the full-wave signal into the choke has a peak value of  $25.7 \text{ V}$ ?

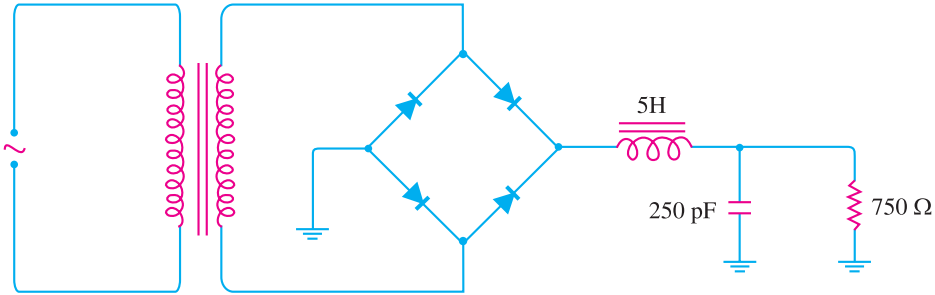


Fig. 6.45

**Solution.** The output of a full-wave rectifier has a d.c. component and an a.c. component. Due to the presence of a.c. component, the rectifier output has a pulsating character as shown in Fig. 6.46. The maximum value of the pulsating output is  $V_m$  and d.c. component is  $V'_{dc} = 2 V_m / \pi$ .

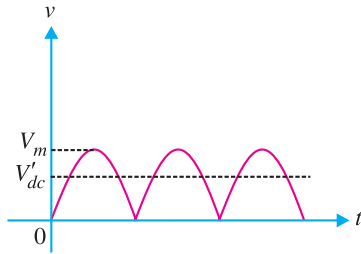


Fig. 6.46

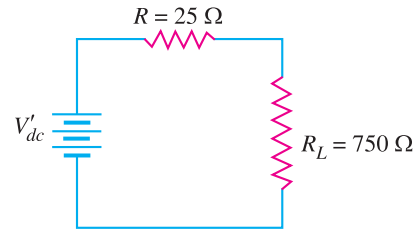


Fig. 6.47

For d.c. component  $V'_{dc}$ , the choke resistance is in series with the load as shown in Fig. 6.47.

$$\therefore \text{Voltage across load, } V_{dc} = \frac{V'_{dc}}{R + R_L} \times R_L$$

$$\text{In our example, } V'_{dc} = \frac{2V_m}{\pi} = \frac{2 \times 25.7}{\pi} = 16.4 \text{ V}$$

$$\therefore \text{Voltage across load, } V_{dc} = \frac{V'_{dc}}{R + R_L} \times R_L = \frac{16.4}{25 + 750} \times 750 = \mathbf{15.9 \text{ V}}$$

The voltage across the load is  $15.9 \text{ V}$  dc *plus* a small ripple.

## 6.22 Voltage Multipliers

With a diode, we can build a rectifier to produce a d.c. voltage that is nearly equal to the peak value of input a.c. voltage. We can also use diodes and capacitors to build a circuit that will provide a *d.c. output* that is multiple of the *peak input a.c. voltage*. Such a circuit is called a voltage multiplier. For example, a *voltage doubler* will provide a d.c. output that is *twice* the peak input a.c. voltage, a *voltage tripler* will provide a d.c. output that is three times the peak input a.c. voltage and so on.

While voltage multipliers provide d.c. output that is much greater than the peak input a.c. voltage, there is no power amplification and law of conservation of energy holds good. When a voltage multiplier *increases* the peak input voltage by a factor  $n$ , the peak input current is *decreased* by approximately the same factor. Thus the actual power output from a voltage multiplier will *never* be

greater than the input power. In fact, there are losses in the circuit (e.g. in diodes, capacitors etc.) so that the output power will actually be *less than* the input power.

### 6.23 Half-Wave Voltage Doubler

A half-wave voltage doubler consists of two diodes and two capacitors connected in a manner as shown in Fig. 6.48. It will be shown that if the peak input a.c. voltage is  $V_{S(pk)}$ , the d.c. output voltage will be  $2 V_{S(pk)}$  provided the diodes are ideal (this assumption is fairly reasonable). The basic idea in a voltage multiplier is to charge each capacitor to the peak input a.c. voltage and to arrange the capacitors so that their stored voltages will add.

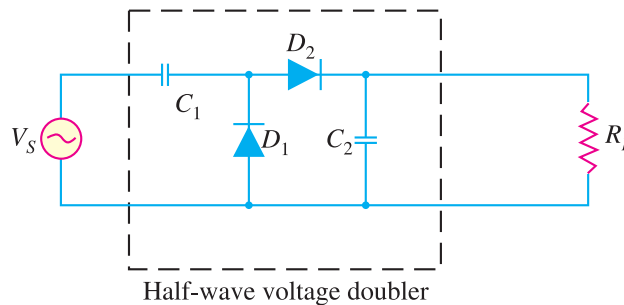


Fig. 6.48

**Circuit action.** We now discuss the working of a half-wave voltage doubler.

(i) During the negative half-cycle of a.c. input voltage [See Fig. 6.49 (i)], diode  $D_1$  is forward biased and diode  $D_2$  is reverse biased [See Fig. 6.49 (i)]. Therefore, diode  $D_1$  can be represented by a *short* and diode  $D_2$  as an *open*. The equivalent circuit then becomes as shown in Fig. 6.49 (ii).

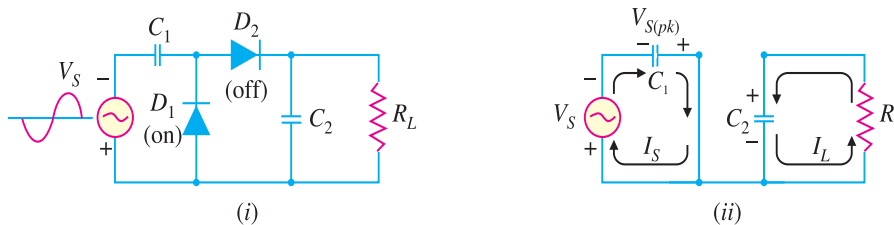


Fig. 6.49

As you can see [See Fig. 6.49 (ii)],  $C_1$  will charge until voltage across it becomes equal to peak value of source voltage [ $V_{S(pk)}$ ]. At the same time,  $C_2$  will be in the process of discharging through the load  $R_L$  (The source of this charge on  $C_2$  will be explained in a moment). *Note that in all figures electron flow is shown.*

(ii) When the polarity of the input a.c. voltage reverses (i.e. during positive half-cycle), the circuit conditions become as shown in Fig. 6.50 (i). Now  $D_1$  is reverse biased and  $D_2$  is forward biased and the equivalent circuit becomes as shown in Fig. 6.50 (ii).

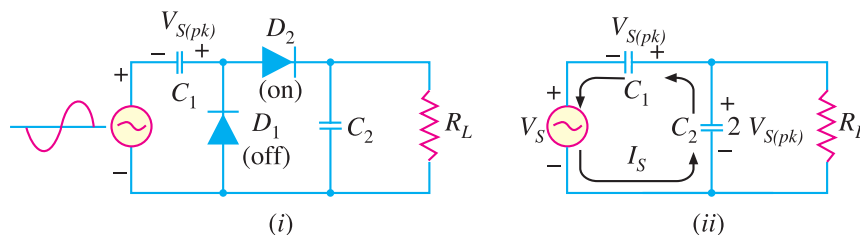


Fig. 6.50



## 108 ■ Principles of Electronics

Referring to Fig. 6.50 (ii), it is easy to see that  $C_1$  (charged to  $V_{S(pk)}$ ) and the source voltage ( $V_S$ ) now act as *series-aiding* voltage sources. Thus  $C_2$  will be charged to the sum of the series peak voltages *i.e.*  $2 V_{S(pk)}$ .

(iii) When  $V_S$  returns to its original polarity (*i.e.* negative half-cycle),  $D_2$  is again turned off (*i.e.* reverse biased). With  $D_2$  turned off, the only discharge path for  $C_2$  is through the load resistance  $R_L$ . The time constant ( $= R_L C_2$ ) of this circuit is so adjusted that  $C_2$  has little time to lose any of its charge before the input polarity reverses again. During the positive half-cycle,  $D_2$  is turned on and  $C_2$  recharges until voltage across it is again equal to  $2 V_{S(pk)}$ .

$$\therefore \text{D.C. output voltage, } V_{dc} = 2 V_{S(pk)}$$

Since  $C_2$  barely discharges between input cycles, the output waveform of the half-wave voltage doubler closely resembles that of a filtered half-wave rectifier. Fig. 6.51 shows the input and output waveforms for a half-wave voltage doubler.

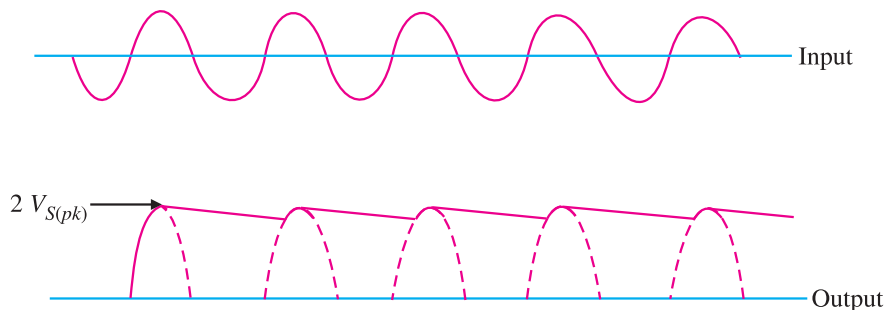


Fig. 6.51

The voltage multipliers have the disadvantage of poor voltage regulation. This means that d.c. output voltage drops considerably as the load current increases. Large filter capacitors are needed to help maintain the output voltage.

### 6.24 Voltage Stabilisation

A rectifier with an appropriate filter serves as a good source of d.c. output. However, the major disadvantage of such a power supply is that the output voltage changes with the variations in the input voltage or load. Thus, if the input voltage increases, the d.c. output voltage of the rectifier also increases. Similarly, if the load current increases, the output voltage falls due to the voltage drop in the rectifying element, filter chokes, transformer winding etc. In many electronic applications, it is desired that the output voltage should remain constant regardless of the variations in the input voltage or load. In order to ensure this, a voltage stabilising device, called voltage stabiliser is used. Several stabilising circuits have been designed but only *zener diode* as a voltage stabiliser will be discussed.

### 6.25 Zener Diode

It has already been discussed that when the reverse bias on a crystal diode is increased, a critical voltage, called *breakdown voltage* is reached where the reverse current increases sharply to a high value. The breakdown region is the knee of the reverse characteristic as shown in Fig. 6.52. The satisfactory explanation of this breakdown of the junction was first given by the American scientist C. Zener. Therefore, the breakdown voltage is sometimes called *zener voltage* and the sudden increase in current is known as *zener current*.

The breakdown or zener voltage depends upon the amount of doping. If the diode is heavily doped, depletion layer will be thin and consequently the breakdown of the junction will occur at a lower reverse voltage. On the other hand, a lightly doped diode has a higher breakdown voltage. When an ordinary crystal diode is properly doped so that it has a sharp breakdown voltage, it is called

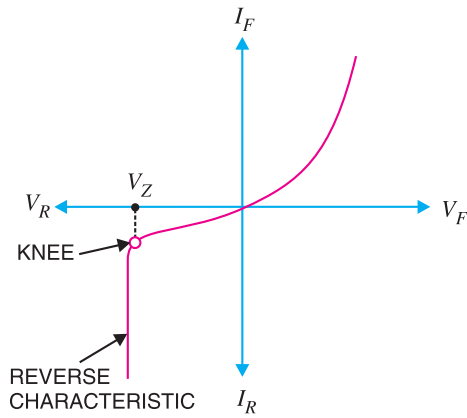


Fig. 6.52

- (iv) When forward biased, its characteristics are just those of ordinary diode.
- (v) The zener diode is not immediately burnt just because it has entered the \*breakdown region. As long as the external circuit connected to the diode limits the diode current to less than *burn out* value, the diode will not burn out.

### 6.26 Equivalent Circuit of Zener Diode

The analysis of circuits using zener diodes can be made quite easily by replacing the zener diode by its equivalent circuit.

(i) **“On” state.** When reverse voltage across a zener diode is equal to or more than break down voltage  $V_Z$ , the current increases very sharply. In this region, the curve is almost vertical. It means that voltage across zener diode is constant at  $V_Z$  even though the current through it changes. Therefore, in the breakdown region, an **\*\*ideal zener diode** can be represented by a battery of voltage  $V_Z$  as shown in Fig. 6.54 (ii). Under such conditions, the zener diode is said to be in the “ON” state.

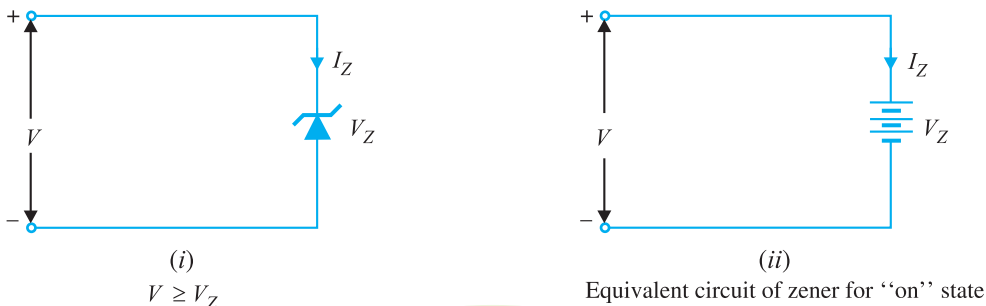


Fig. 6.54

(ii) **“OFF” state.** When the reverse voltage across the zener diode is less than  $V_Z$  but greater than 0 V, the zener diode is in the “OFF” state. Under such conditions, the zener diode can be represented by an open-circuit as shown in Fig. 6.55 (ii).

\* The current is limited only by both external resistance and the power dissipation of zener diode.  
 \*\* This assumption is fairly reasonable as the impedance of zener diode is quite small in the breakdown region.

a zener diode.

A properly doped crystal diode which has a sharp breakdown voltage is known as a **zener diode**.

Fig. 6.53 shows the symbol of a zener diode. It may be seen that it is just like an ordinary diode except that the bar is turned into z-shape. The following points may be noted about the zener diode:

- (i) A zener diode is like an ordinary diode except that it is properly doped so as to have a sharp breakdown voltage.
- (ii) A zener diode is always reverse connected i.e. it is always reverse biased.
- (iii) A zener diode has sharp breakdown voltage, called zener voltage  $V_Z$ .



Fig. 6.53

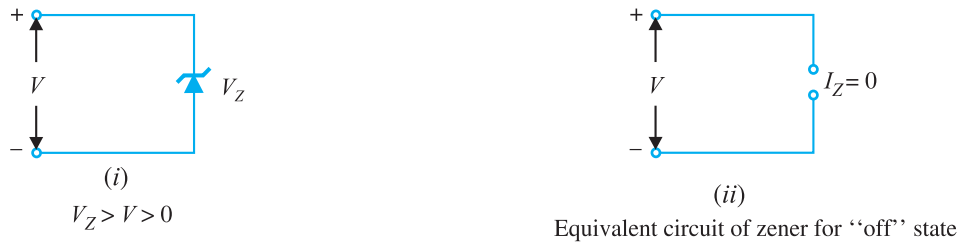


Fig. 6.55

### 6.27 Zener Diode as Voltage Stabiliser

A zener diode can be used as a voltage regulator to provide a constant voltage from a source whose voltage may vary over sufficient range. The circuit arrangement is shown in Fig. 6.56 (i). The zener diode of zener voltage  $V_Z$  is reverse connected across the load  $R_L$  across which constant output is desired. The series resistance  $R$  absorbs the output voltage fluctuations so as to maintain constant voltage across the load. It may be noted that the zener will maintain a constant voltage  $V_Z (= E_0)$  across the load so long as the input voltage does not fall below  $V_Z$ .

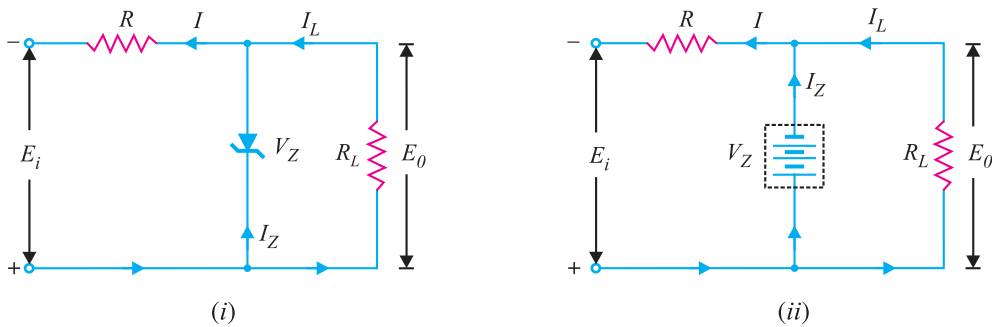


Fig. 6.56

When the circuit is properly designed, the load voltage  $E_0$  remains essentially constant (equal to  $V_Z$ ) even though the input voltage  $E_i$  and load resistance  $R_L$  may vary over a wide range.

(i) Suppose the input voltage increases. Since the zener is in the breakdown region, the zener diode is equivalent to a battery  $V_Z$  as shown in Fig. 6.56 (ii). It is clear that output voltage remains constant at  $V_Z (= E_0)$ . The excess voltage is dropped across the series resistance  $R$ . This will cause an increase in the value of total current  $I$ . The zener will conduct the increase of current in  $I$  while the load current remains constant. Hence, output voltage  $E_0$  remains constant irrespective of the changes in the input voltage  $E_i$ .

(ii) Now suppose that input voltage is constant but the load resistance  $R_L$  decreases. This will cause an increase in load current. The extra current cannot come from the source because drop in  $R$  (and hence source current  $I$ ) will not change as the zener is within its regulating range. The additional load current will come from a decrease in zener current  $I_Z$ . Consequently, the output voltage stays at constant value.

$$\text{Voltage drop across } R = E_i - E_0$$

$$\text{Current through } R, I = I_Z + I_L$$

Applying Ohm's law, we have,

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

### 6.28 Solving Zener Diode Circuits

The analysis of zener diode circuits is quite similar to that applied to the analysis of semiconductor diodes. The first step is to determine the state of zener diode *i.e.*, whether the zener is in the “on” state or “off” state. Next, the zener is replaced by its appropriate model. Finally, the unknown quantities are determined from the resulting circuit.

**1.  $E_i$  and  $R_L$  fixed.** This is the simplest case and is shown in Fig. 6.57 (i). Here the applied voltage  $E_i$  as well as load  $R_L$  is fixed. The first step is to find the state of zener diode. This can be determined by removing the zener from the circuit and calculating the voltage  $V$  across the resulting open-circuit as shown in Fig. 6.57 (ii).

$$V = E_0 = \frac{R_L E_i}{R + R_L}$$

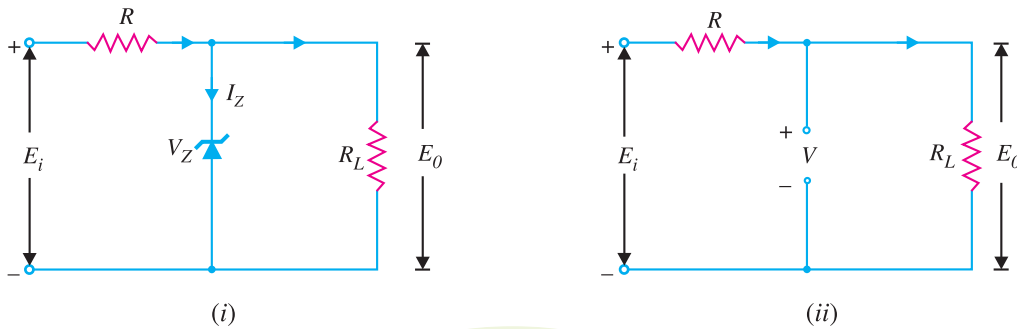


Fig. 6.57

If  $V \geq V_Z$ , the zener diode is in the “on” state and its equivalent model can be substituted as shown in Fig. 6.58 (i). If  $V < V_Z$ , the diode is in the “off” state as shown in Fig. 6.58 (ii).

**(i) On state.** Referring to circuit shown in Fig. 6.58 (i),

$$E_0 = V_Z$$

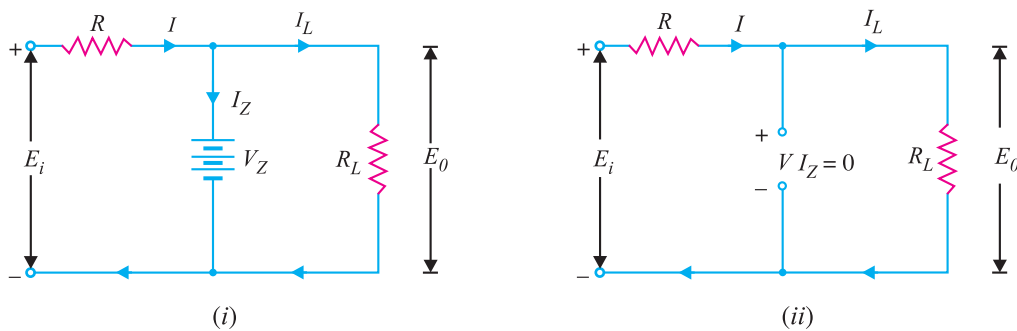


Fig. 6.58

## 112 ■ Principles of Electronics

$$I_Z = I - I_L \quad \text{where } I_L = \frac{E_0}{R_L} \text{ and } I = \frac{E_i - E_0}{R}$$

Power dissipated in zener,  $P_Z = V_Z I_Z$

**(ii) Off state.** Referring to the circuit shown in Fig. 6.58 (ii),

$$I = I_L \quad \text{and} \quad I_Z = 0$$

$$V_R = E_i - E_0 \quad \text{and} \quad V = E_0 \quad (V < V_Z)$$

$$\therefore P_Z = V I_Z = V(0) = 0$$

**2. Fixed  $E_i$  and Variable  $R_L$ .** This case is shown in Fig. 6.59. Here the applied voltage ( $E_i$ ) is fixed while load resistance  $R_L$  (and hence load current  $I_L$ ) changes. Note that there is a definite range of  $R_L$  values (and hence  $I_L$  values) which will ensure the zener diode to be in “on” state. Let us calculate that range of values.

**(i)  $R_{Lmin}$  and  $I_{Lmax}$ .** Once the zener is in the “on” state, load voltage  $E_0 (= V_Z)$  is constant. As a result, when load resistance is minimum (i.e.,  $R_{Lmin}$ ), load current will be maximum ( $I_L = E_0/R_L$ ). In order to find the minimum load resistance that will turn the zener on, we simply calculate the value of  $R_L$  that will result in  $E_0 = V_Z$  i.e.,

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

$$\therefore R_{Lmin} = \frac{R V_Z}{E_i - V_Z} \quad \dots(i)$$

This is the minimum value of load resistance that will ensure that zener is in the “on” state. Any value of load resistance less than this value will result in a voltage  $E_0$  across the load less than  $V_Z$  and the zener will be in the “off” state.

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

**(ii)  $I_{Lmin}$  and  $R_{Lmax}$ .** It is easy to see that when load resistance is maximum, load current is minimum.

Now, Zener current,  $I_Z = I - I_L$

When the zener is in the “on” state,  $I$  remains \*\*fixed. This means that when  $I_L$  is maximum,  $I_Z$  will be minimum. On the other hand, when  $I_L$  is minimum,  $I_Z$  is maximum. If the maximum current that a zener can carry safely is † $I_{ZM}$ , then,

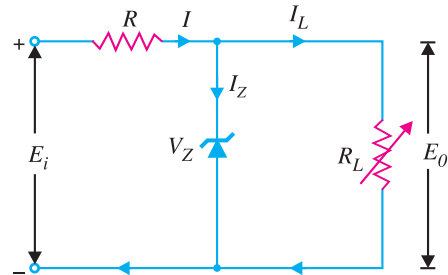


Fig. 6.59

\* If you remove the zener in the circuit shown in Fig. 6.59, then voltage  $V$  across the open-circuit is

$$V = \frac{R_L E_i}{R + R_L}$$

The zener will be turned on when  $V = V_Z$ .

\*\* Voltage across  $R$ ,  $V_R = E_i - E_0$  and  $I = V_R/R$ . As  $E_i$  and  $E_0$  are fixed,  $I$  remains the same.

† Max. power dissipation in zener,  $P_{ZM} = V_Z I_{ZM}$

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

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.

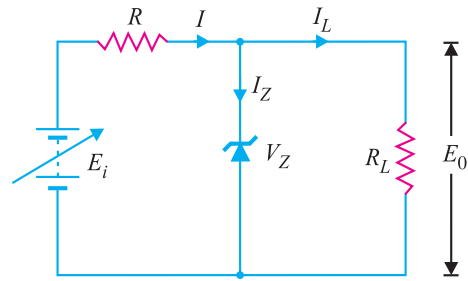


Fig. 6.60

**(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.,

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

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

**(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.

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

**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.

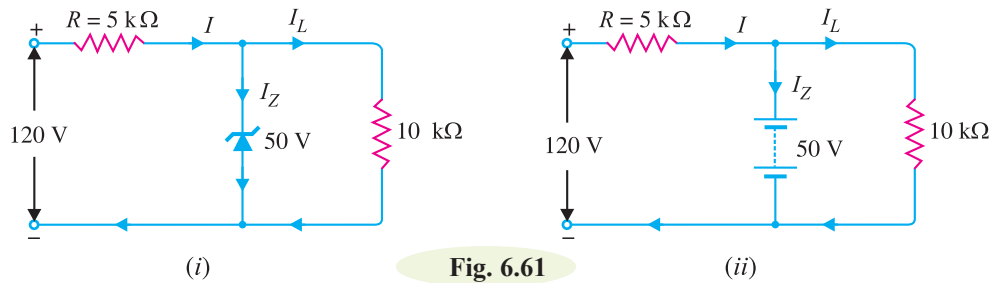


Fig. 6.61

## 114 ■ Principles of Electronics

**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  $V_Z (= 50 \text{ V})$ , 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),

$$\text{Output voltage} = V_Z = \mathbf{50 \text{ V}}$$

(ii) Voltage drop across  $R = \text{Input voltage} - V_Z = 120 - 50 = \mathbf{70 \text{ V}}$

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

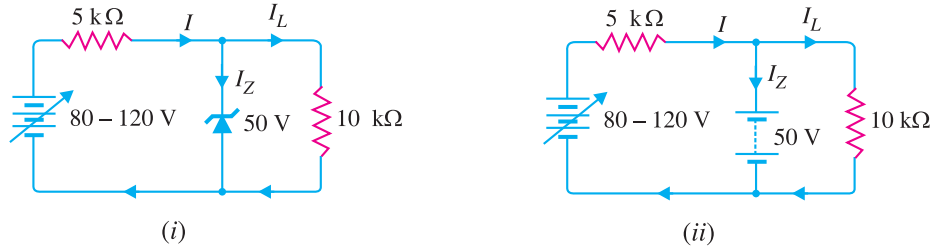
$$\text{Current through } R, I = \frac{70 \text{ V}}{5 \text{ k}\Omega} = 14 \text{ mA}$$

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

$$\therefore \text{Zener current, } I_Z = I - I_L = 14 - 5 = \mathbf{9 \text{ mA}}$$

**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  $V_Z (= 50 \text{ V})$ . 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 :

$$\text{Voltage across } 5 \text{ k}\Omega = 120 - 50 = 70 \text{ V}$$

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

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

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

$$\therefore \text{Zener current, } I_Z = I - I_L = 14 - 5 = \mathbf{9 \text{ mA}}$$

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

Now,  $I = \frac{E_i - E_0}{R} = \frac{E_i - V_Z}{R}$ . 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,

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

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

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

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

**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.

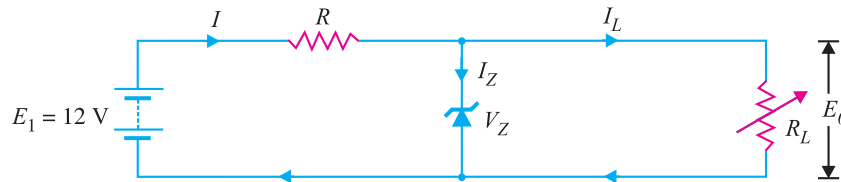


Fig. 6.63

**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  $12 - 7.2 = 4.8 \text{ V}$  as the load current changes from 12 to 100 mA. The minimum zener current will occur when the load current is maximum.

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

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  $I_Z + I_L = 110 \text{ mA}$ . 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  $V_Z = 18 \text{ V}$ . 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.

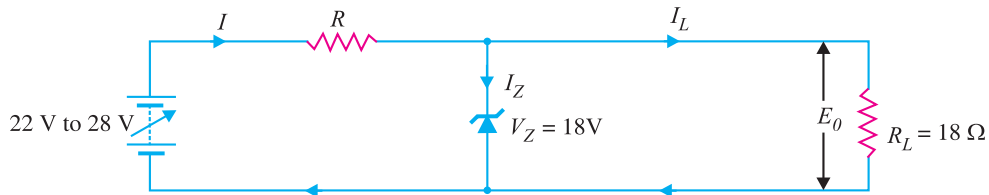


Fig. 6.64

**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  $I_L = V_Z / R_L = 18 \text{ V} / 18 \Omega = 1 \text{ A} = 1000 \text{ mA}$ .

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



116 ■ Principles of Electronics

**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  $R$ .

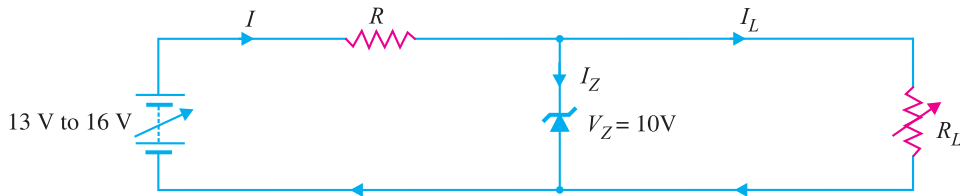


Fig. 6.65

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

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

**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  $R$

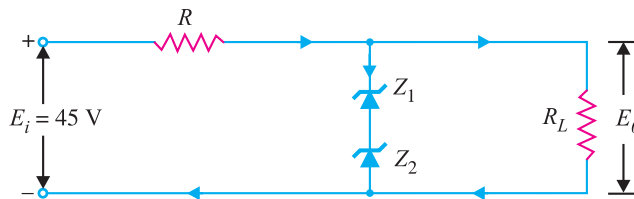


Fig. 6.66

**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,  $I_Z = 200 \text{ mA}$

Voltage rating of each zener,  $V_Z = 15 \text{ V}$

Input voltage,  $E_i = 45 \text{ V}$

(i) Regulated output voltage,  $E_0 = 15 + 15 = 30 \text{ V}$

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

**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.

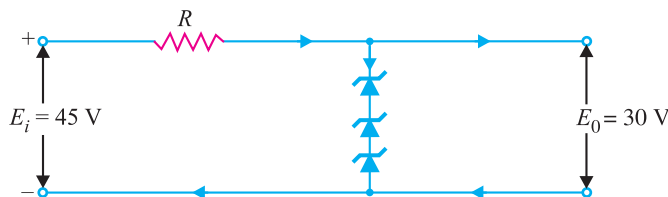


Fig. 6.67

Voltage rating of each zener,  $V_Z = 10\text{ V}$

Current rating of each zener,  $I_Z = 1000\text{ mA}$

Input unregulated voltage,  $E_i = 45\text{ V}$

Regulated output voltage,  $E_0 = 10 + 10 + 10 = 30\text{ V}$

Let  $R$  ohms be the required series resistance.

$$\text{Voltage across } R = E_i - E_0 = 45 - 30 = 15\text{ V}$$

$$\therefore R = \frac{E_i - E_0}{I_Z} = \frac{15\text{ V}}{1000\text{ mA}} = 15\ \Omega$$

**Example 6.32.** Over what range of input voltage will the zener circuit shown in Fig. 6.68 maintain 30 V across 2000  $\Omega$  load, assuming that series resistance  $R = 200\ \Omega$  and zener current rating is 25 mA ?

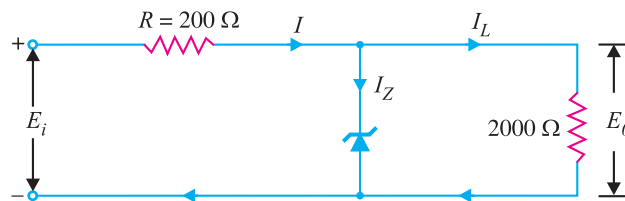


Fig. 6.68

**Solution.** The minimum input voltage required will be when  $I_Z = 0$ . Under this condition,

$$I_L = I = \frac{30\text{ V}}{2000\ \Omega} = 15\text{ mA}$$

$$\begin{aligned} \therefore \text{Minimum input voltage} &= 30 + IR = 30 + 15\text{ mA} \times 200\ \Omega \\ &= 30 + 3 = 33\text{ V} \end{aligned}$$

The maximum input voltage required will be when  $I_Z = 25\text{ mA}$ . Under this condition,

$$I = I_L + I_Z = 15 + 25 = 40\text{ mA}$$

$$\begin{aligned} \therefore \text{Max. input voltage} &= 30 + IR \\ &= 30 + 40\text{ mA} \times 200\ \Omega \\ &= 30 + 8 = 38\text{ V} \end{aligned}$$

Therefore, the input voltage range over which the circuit will maintain 30 V across the load is **33 V to 38 V**.

**Example 6.33.** In the circuit shown in Fig. 6.69, the voltage across the load is to be maintained at 12 V as load current varies from 0 to 200 mA. Design the regulator. Also find the maximum wattage rating of zener diode.

**Solution.** By designing the regulator here means to find the values of  $V_Z$  and  $R$ . Since the load voltage is to be maintained at 12 V, we will use a zener diode of zener voltage 12 V i.e.,

$$V_Z = 12\text{ V}$$

The voltage across  $R$  is to remain constant at  $16 - 12 = 4\text{ V}$  as the load current changes from 0 to 200 mA. The minimum zener current will occur when the load current is maximum.

$$\therefore R = \frac{E_i - E_0}{(I_Z)_{\min} + (I_L)_{\max}} = \frac{16 - 12}{(0 + 200)\text{ mA}} = \frac{4\text{ V}}{200\text{ mA}} = 20\ \Omega$$

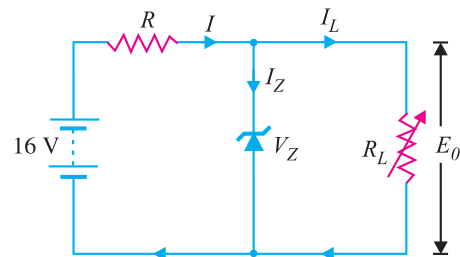


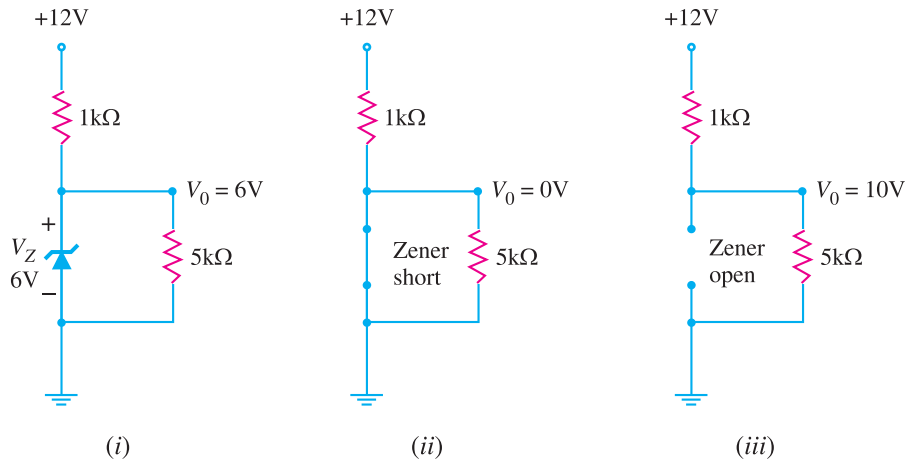
Fig. 6.69

## 118 ■ Principles of Electronics

Maximum power rating of zener is

$$P_{ZM} = V_Z I_{ZM} = (12 \text{ V})(200 \text{ mA}) = 2.4 \text{ W}$$

**Example 6.34.** Fig. 6.70 shows the basic zener diode circuits. What will be the circuit behaviour if the zener is (i) working properly (ii) shorted (iii) open-circuited?



**Fig. 6.70**

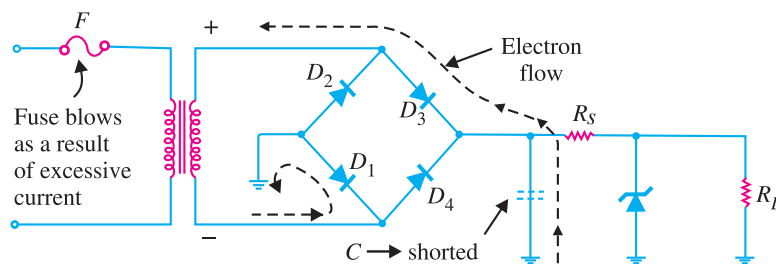
**Solution.** Zener diodes cannot be tested individually with a multimeter. It is because multimeters usually do not have enough input voltage to put the zener into breakdown region.

(i) If the zener diode is working properly, the voltage  $V_0$  across the load ( $= 5 \text{ k}\Omega$ ) will be nearly 6V [See Fig. 6.70 (i)].

(ii) If the zener diode is short [See Fig. 6.70 (ii)], you will measure  $V_0$  as 0V. The same problem could also be caused by a shorted load resistor ( $= 5 \text{ k}\Omega$ ) or an opened source resistor ( $= 1 \text{ k}\Omega$ ). The only way to tell which device has failed is to remove the resistors and check them with an ohmmeter. If the resistors are good, then zener diode is bad.

(iii) If the zener diode is open-circuited, the voltage  $V_0$  across the load ( $= 5 \text{ k}\Omega$ ) will be 10V.

**Example 6.35.** Fig. 6.71 shows regulated power supply using a zener diode. What will be the circuit behaviour if (i) filter capacitor shorts (ii) filter capacitor opens?



**Fig. 6.71**

**Solution.** The common faults in a zener voltage regulator are shorted filter capacitor or opened filter capacitor.

(i) **When filter capacitor shorts.** When the filter capacitor shorts, the primary fuse will blow. The reason for this is illustrated in Fig. 6.71. When the filter capacitor shorts, it shorts out the load resistance  $R_L$ . This has the same effect as wiring the two sides of the bridge together (See Fig. 6.71).

If you trace from the high side of the bridge to the low side, you will see that the only resistance across the secondary of the transformer is the forward resistance of the two *ON* diodes. This effectively shorts out the transformer secondary. The result is that excessive current flows in the secondary and hence in the primary. Consequently, the primary fuse will blow.

**(ii) When filter capacitor opens.** When the filter capacitor opens, it will cause the ripple in the power supply output to increase drastically. At the same time, the d.c. output voltage will show a significant drop. Since an open filter capacitor is the only fault that will cause *both* of these symptoms, no further testing is necessary. If both symptoms appear, replace the filter capacitor.

## 6.29 Crystal Diodes versus Vacuum Diodes

Semiconductor diodes (or crystal diodes) have a number of advantages and disadvantages as compared to their electron-tube counterparts (*i.e.*, vacuum diodes).

### Advantages :

- (i) They are smaller, more rugged and have a longer life.
- (ii) They are simpler and inherently cheaper.
- (iii) They require no filament power. As a result, they produce less heat than the equivalent vacuum diodes.

### Disadvantages :

(i) They are extremely heat sensitive. Even a slight rise in temperature increases the current appreciably. Should the temperature \*exceed the rated value of the diode, the increased flow of current may produce enough heat to ruin the *pn* junction. On the other hand, vacuum diodes function normally over a wide range of temperature changes.

It may be noted that silicon is better than germanium as a semiconductor material. Whereas a germanium diode should not be operated at temperatures higher than 80°C, silicon diodes may operate safely at temperatures upto about 200°C.

- (ii) They can handle small currents and low inverse voltages as compared to vacuum diodes.
- (iii) They cannot stand an overload even for a short period. Any slight overload, even a transient pulse, may permanently damage the crystal diode. On the other hand, vacuum diodes can stand an overload for a short period and when the overload is removed, the tube will generally recover.

## MULTIPLE-CHOICE QUESTIONS

- |  |   |
|--|---|
| <p>1. A crystal diode has .....</p> <ul style="list-style-type: none"> <li>(i) one <i>pn</i> junction</li> <li>(ii) two <i>pn</i> junctions</li> <li>(iii) three <i>pn</i> junctions</li> <li>(iv) none of the above</li> </ul> <p>2. A crystal diode has forward resistance of the order of .....</p> <ul style="list-style-type: none"> <li>(i) <math>k\Omega</math>                      (ii) <math>\Omega</math></li> <li>(iii) <math>M\Omega</math>                      (iv) none of the above</li> </ul> <p>3. If the arrow of crystal diode symbol is positive w.r.t. bar, then diode is ..... biased.</p> | <ul style="list-style-type: none"> <li>(i) forward</li> <li>(ii) reverse</li> <li>(iii) either forward or reverse</li> <li>(iv) none of the above</li> </ul> <p>4. The reverse current in a diode is of the order of .....</p> <ul style="list-style-type: none"> <li>(i) kA                      (ii) mA</li> <li>(iii) <math>\mu A</math>                      (iv) A</li> </ul> <p>5. The forward voltage drop across a silicon diode is about .....</p> |
|--|---|

\* Even when soldering the leads of a crystal diode, care must be taken not to permit heat from the soldering device to reach the crystal diode.

## 120 ■ Principles of Electronics

- (i) 2.5 V                      (ii) 3 V  
(iii) 10 V                      (iv) 0.7 V
6. A crystal diode is used as .....
- (i) an amplifier      (ii) a rectifier  
(iii) an oscillator      (iv) a voltage regulator
7. The d.c. resistance of a crystal diode is ..... its a.c. resistance.
- (i) the same as      (ii) more than  
(iii) less than      (iv) none of the above
8. An ideal crystal diode is one which behaves as a perfect ..... when forward biased.
- (i) conductor  
(ii) insulator  
(iii) resistance material  
(iv) none of the above
9. The ratio of reverse resistance and forward resistance of a germanium crystal diode is about .....
- (i) 1 : 1                      (ii) 100 : 1  
(iii) 1000 : 1                      (iv) 40000 : 1
10. The leakage current in a crystal diode is due to .....
- (i) minority carriers  
(ii) majority carriers  
(iii) junction capacitance  
(iv) none of the above
11. If the temperature of a crystal diode increases, then leakage current .....
- (i) remains the same  
(ii) decreases  
(iii) increases  
(iv) becomes zero
12. The PIV rating of a crystal diode is ..... that of equivalent vacuum diode.
- (i) the same as      (ii) lower than  
(iii) more than      (iv) none of the above
13. If the doping level of a crystal diode is increased, the breakdown voltage .....
- (i) remains the same  
(ii) is increased  
(iii) is decreased  
(iv) none of the above
14. The knee voltage of a crystal diode is approximately equal to .....
- (i) applied voltage  
(ii) breakdown voltage  
(iii) forward voltage  
(iv) barrier potential
15. When the graph between current through and voltage across a device is a straight line, the device is referred to as .....
- (i) linear                      (ii) active  
(iii) nonlinear                      (iv) passive
16. When the crystal diode current is large, the bias is .....
- (i) forward                      (ii) inverse  
(iii) poor                      (iv) reverse
17. A crystal diode is a ..... device.
- (i) non-linear                      (ii) bilateral  
(iii) linear                      (iv) none of the above
18. A crystal diode utilises ..... characteristic for rectification.
- (i) reverse                      (ii) forward  
(iii) forward or reverse  
(iv) none of the above
19. When a crystal diode is used as a rectifier, the most important consideration is .....
- (i) forward characteristic  
(ii) doping level  
(iii) reverse characteristic  
(iv) PIV rating
20. If the doping level in a crystal diode is increased, the width of depletion layer .....
- (i) remains the same  
(ii) is decreased  
(iii) is increased  
(iv) none of the above
21. A zener diode has .....
- (i) one *pn* junction  
(ii) two *pn* junctions  
(iii) three *pn* junctions  
(iv) none of the above
22. A zener diode is used as .....
- (i) an amplifier      (ii) a voltage regulator  
(iii) a rectifier      (iv) a multivibrator
23. The doping level in a zener diode is ..... that of a crystal diode.

- (i) the same as      (ii) less than  
(iii) more than      (iv) none of the above
24. A zener diode is always ..... connected.  
(i) reverse  
(ii) forward  
(iii) either reverse or forward  
(iv) none of the above
25. A zener diode utilises ..... characteristic for its operation.  
(i) forward  
(ii) reverse  
(iii) both forward and reverse  
(iv) none of the above
26. In the breakdown region, a zener diode behaves like a ..... source.  
(i) constant voltage  
(ii) constant current  
(iii) constant resistance  
(iv) none of the above
27. A zener diode is destroyed if it .....  
(i) is forward biased  
(ii) is reverse biased  
(iii) carries more than rated current  
(iv) none of the above
28. A series resistance is connected in the zener circuit to .....  
(i) properly reverse bias the zener  
(ii) protect the zener  
(iii) properly forward bias the zener  
(iv) none of the above
29. A zener diode is ..... device.  
(i) a non-linear      (ii) a linear  
(iii) an amplifying      (iv) none of the above
30. A zener diode has ..... breakdown voltage.  
(i) undefined      (ii) sharp  
(iii) zero      (iv) none of the above
31. .... rectifier has the lowest forward resistance.  
(i) solid state      (ii) vacuum tube  
(iii) gas tube      (iv) none of the above
32. Mains a.c. power is converted into d.c. power for .....  
(i) lighting purposes  
(ii) heaters  
(iii) using in electronic equipment  
(iv) none of the above
33. The disadvantage of a half-wave rectifier is that the .....  
(i) components are expensive  
(ii) diodes must have a higher power rating  
(iii) output is difficult to filter  
(iv) none of the above
34. If the a.c. input to a half-wave rectifier has an r.m.s. value of  $400/\sqrt{2}$  volts, then diode PIV rating is .....  
(i)  $400/\sqrt{2}$  V      (ii) 400 V  
(iii)  $400 \times \sqrt{2}$  V      (iv) none of the above
35. The ripple factor of a half-wave rectifier is .....  
(i) 2      (ii) 1.21  
(iii) 2.5      (iv) 0.48
36. There is a need of transformer for .....  
(i) half-wave rectifier  
(ii) centre-tap full-wave rectifier  
(iii) bridge full-wave rectifier  
(iv) none of the above
37. The PIV rating of each diode in a bridge rectifier is ..... that of the equivalent centre-tap rectifier.  
(i) one-half      (ii) the same as  
(iii) twice      (iv) four times
38. For the same secondary voltage, the output voltage from a centre-tap rectifier is ..... than that of bridge rectifier.  
(i) twice      (ii) thrice  
(iii) four times      (iv) one-half
39. If the PIV rating of a diode is exceeded, .....  
(i) the diode conducts poorly  
(ii) the diode is destroyed  
(iii) the diode behaves as zener diode  
(iv) none of the above
40. A 10 V power supply would use ..... as filter capacitor.  
(i) paper capacitor      (ii) mica capacitor  
(iii) electrolytic capacitor  
(iv) air capacitor

## 122 ■ Principles of Electronics

41. A 1000 V power supply would use ..... as a filter capacitor.
- paper capacitor
  - air capacitor
  - mica capacitor
  - electrolytic capacitor
42. The ..... filter circuit results in the best voltage regulation.
- choke input
  - capacitor input
  - resistance input
  - none of the above
43. A half-wave rectifier has an input voltage of 240 V r.m.s. If the step-down transformer has a turns ratio of 8 : 1, what is the peak load voltage ? Ignore diode drop.
- 27.5 V
  - 86.5 V
  - 30 V
  - 42.5 V
44. The maximum efficiency of a half-wave rectifier is .....
- 40.6%
  - 81.2%
  - 50%
  - 25%
45. The most widely used rectifier is .....
- half-wave rectifier
  - centre-tap full-wave rectifier
  - bridge full-wave rectifier
  - none of the above

### Answers to Multiple-Choice Questions

- |           |           |           |          |           |
|-----------|-----------|-----------|----------|-----------|
| 1. (i)    | 2. (ii)   | 3. (i)    | 4. (iii) | 5. (iv)   |
| 6. (ii)   | 7. (iii)  | 8. (i)    | 9. (iv)  | 10. (i)   |
| 11. (iii) | 12. (ii)  | 13. (iii) | 14. (iv) | 15. (i)   |
| 16. (i)   | 17. (i)   | 18. (ii)  | 19. (iv) | 20. (iii) |
| 21. (i)   | 22. (ii)  | 23. (iii) | 24. (i)  | 25. (ii)  |
| 26. (i)   | 27. (iii) | 28. (ii)  | 29. (i)  | 30. (ii)  |
| 31. (i)   | 32. (iii) | 33. (iii) | 34. (ii) | 35. (iv)  |
| 36. (ii)  | 37. (i)   | 38. (iv)  | 39. (ii) | 40. (iii) |
| 41. (i)   | 42. (i)   | 43. (iv)  | 44. (i)  | 45. (iii) |

### Chapter Review Topics

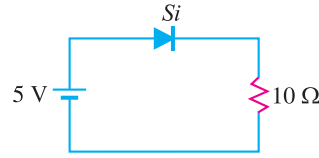
- What is a crystal diode ? Explain its rectifying action.
- Draw the graphic symbol of crystal diode and explain its significance. How the polarities of crystal diode are identified ?
- What do you understand by the d.c. and a.c. resistance of a crystal diode ? How will you determine them from the  $V-I$  characteristic of a crystal diode ?
- Draw the equivalent circuit of a crystal diode.
- Discuss the importance of peak inverse voltage in rectifier service.
- Describe a half-wave rectifier using a crystal diode.
- Derive an expression for the efficiency of a half-wave rectifier.
- With a neat sketch, explain the working of (i) Centre-tap full-wave rectifier (ii) Full-wave bridge rectifier.
- Derive an expression for the efficiency for a full-wave rectifier.
- Write a short note about the nature of rectifier output.
- What is a ripple factor ? What is its value for a half-wave and full-wave rectifier ?
- Describe the action of the following filter circuits : (i) capacitor filter (ii) choke input filter (iii) capacitor input filter.
- What is a zener diode ? Draw the equivalent circuit of an ideal zener in the breakdown region.
- Explain how zener diode maintains constant voltage across the load.

**Problems**

1. What is the current in the circuit in Fig. 6.72 ? Assume the diode to be ideal. [10 mA]

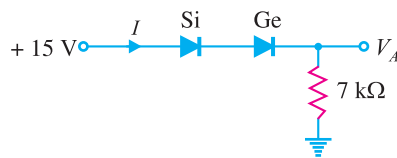


**Fig. 6.72**

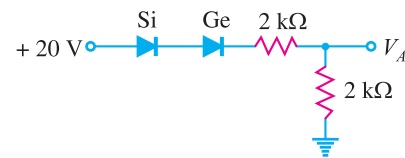


**Fig. 6.73**

2. Using equivalent circuit, determine the current in the circuit shown in Fig. 6.73. Assume the forward resistance of the diode to be  $2\ \Omega$ . [358 mA]
3. Find the voltage  $V_A$  and current  $I$  in the circuit shown in Fig. 6.74. Use simplified model. [14 V; 2 mA]
4. Determine the magnitude of  $V_A$  in the circuit shown in Fig. 6.75. [9.5 V]
5. A half-wave rectifier uses a transformer of turn ratio 4 : 1. If the primary voltage is 240 V (r.m.s.), find (i) d.c. output voltage (ii) peak inverse voltage. Assume the diode to be ideal. [(i) 27 V (ii) 85 V]

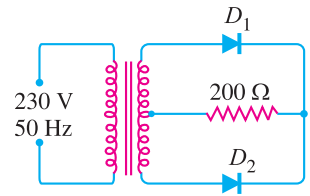


**Fig. 6.74**

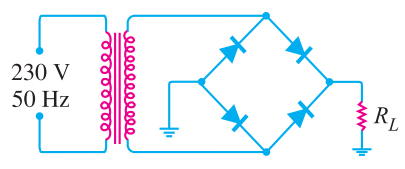


**Fig. 6.75**

6. A half-wave rectifier uses a transformer of turn ratio 2 : 1. The load resistance is  $500\ \Omega$ . If the primary voltage (r.m.s.) is 240 V, find (i) d.c. output voltage (ii) peak inverse voltage. [(i) 54 V (ii) 170 V]



**Fig. 6.76**



**Fig. 6.77**

7. In Fig. 6.76, the maximum voltage across half of secondary winding is 50 V. Find (i) the average load voltage (ii) peak inverse voltage (iii) output frequency. Assume the diodes to be ideal. [(i) 31.8 V (ii) 100 V (iii) 100 Hz]
8. In Fig. 6.77, the maximum secondary voltage is 136 V. Find (i) the d.c. load voltage (ii) peak inverse voltage (iii) output frequency. [(i) 86.6 V (ii) 136 V (iii) 100 Hz]
9. A semiconductor diode having ideal forward and reverse characteristics is used in a half-wave rectifier circuit supplying a resistive load of  $1000\ \Omega$ . If the r.m.s. value of the sinusoidal supply voltage is 250 V, determine (i) the r.m.s. diode current and (ii) power dissipated in the load. [(i) 177 mA (ii) 31.3W]
10. The four semiconductor diodes used in a bridge rectifier circuit have forward resistance which can be considered constant at  $0.1\ \Omega$  and infinite reverse resistance. They supply a mean current of 10 A to a resistive load from a sinusoidally varying alternating supply of 20V r.m.s. Determine the resistance of the load and the efficiency of the circuit. [1.6Ω ; 72%]
11. Find the average value of each voltage in Fig. 6.78. [(i) 1.59 V (ii) 63.7 V (iii) 16.4 V (iv) 10.5 V]



124 ■ Principles of Electronics

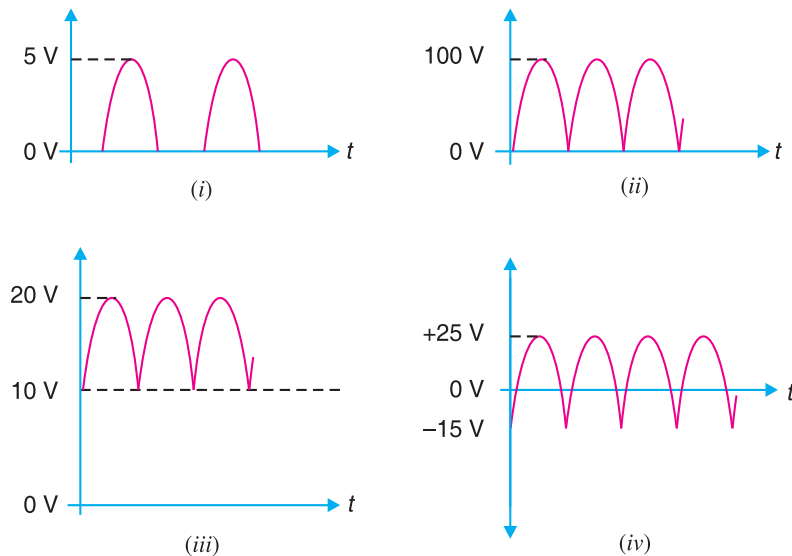


Fig. 6.78

12. Calculate the peak voltage across each half of a centre-tapped transformer used in a full-wave rectifier that has an average output voltage of 110V. [173V]
13. What PIV rating is required for the diodes in a bridge rectifier that produces an average output voltage of 50V? [78.5 V]
14. In the circuit shown in Fig. 6.79, is zener diode in the on or off state? [Off]

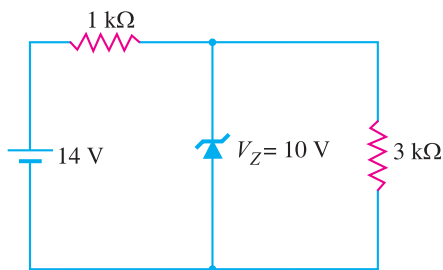


Fig. 6.79

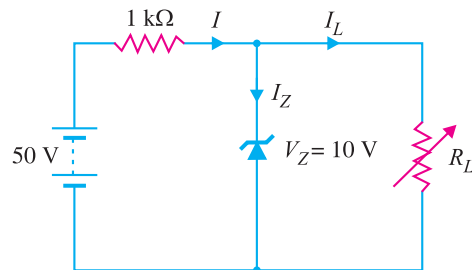


Fig. 6.80

15. In the circuit shown in Fig. 6.80, determine the range of  $R_L$  that will result in a constant voltage of 10 V across  $R_L$ . [250  $\Omega$  to 1.25 k $\Omega$ ]

**Discussion Questions**

1. Why are diodes not operated in the breakdown region in rectifier service ?
2. Why do we use transformers in rectifier service ?
3. Why is PIV important in rectifier service ?
4. Why is zener diode used as a voltage regulator ?
5. Why is capacitor input filter preferred to choke input filter ?