6

Semiconductor Diode

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.

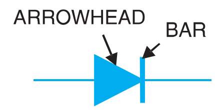
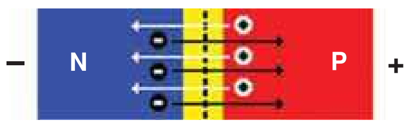


Fig. 6.1



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. BY*127, *BY*114 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.

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.

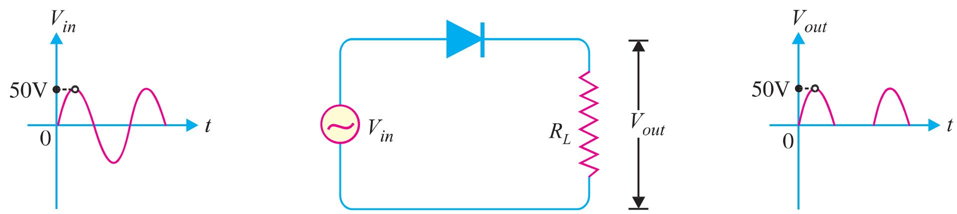


Fig. 6.3

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

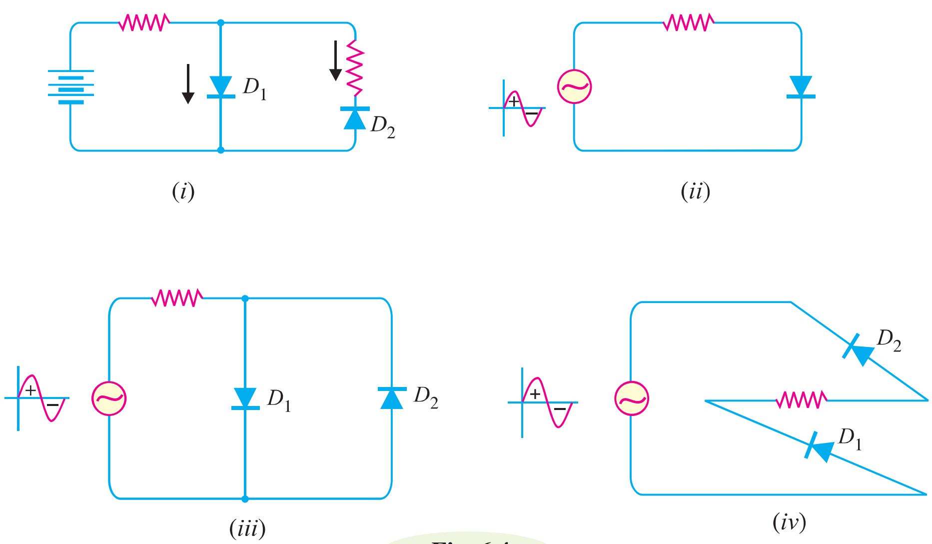


Fig. 6.4

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*.

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

(*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.*

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

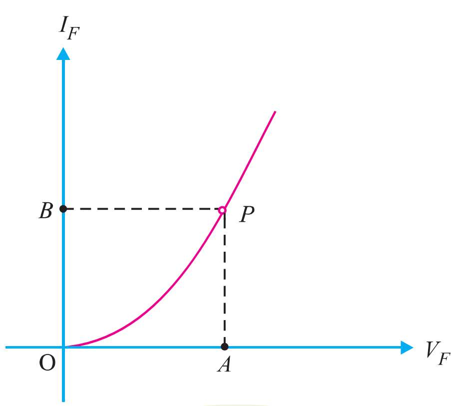


Fig. 6.5

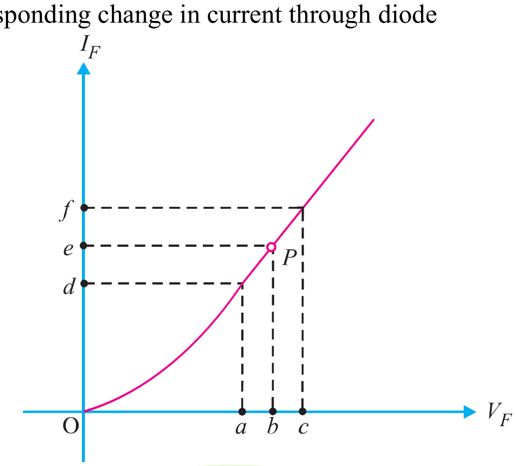


Fig. 6.6

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*.

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

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

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 $I_f r_f$

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

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.

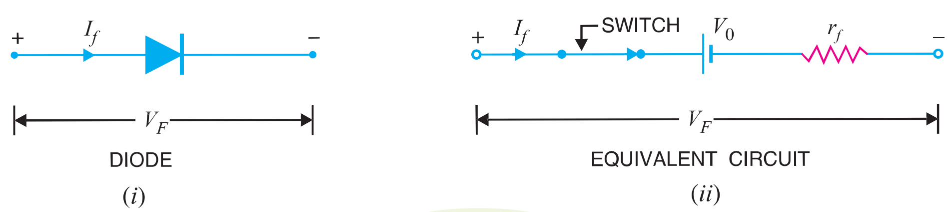


Fig. 6.7

(*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.

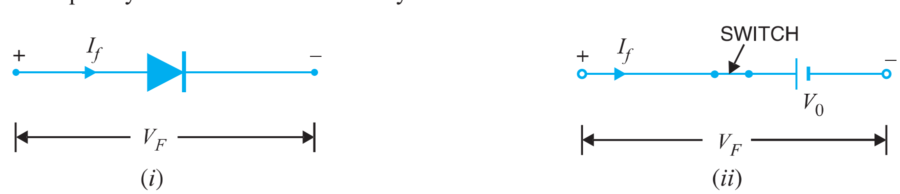


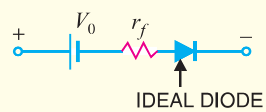
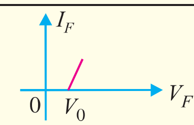
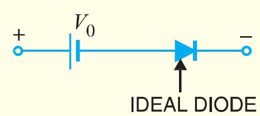
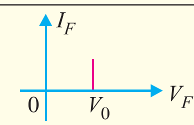
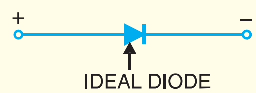
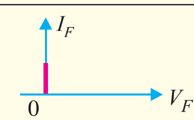
Fig. 6.8

* 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 Ω

Load resistance, R_L = 500 Ω

Potential barrier voltage, V_0 = 0.7 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*).

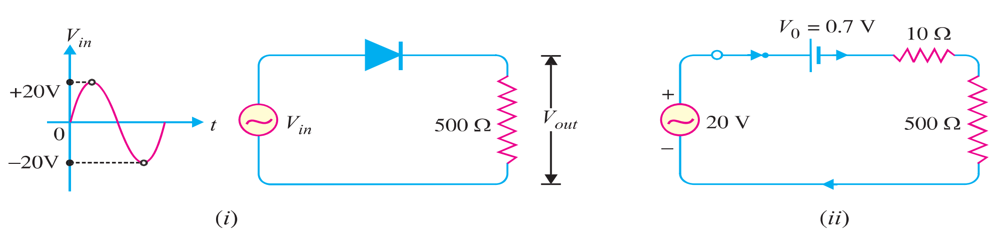


Fig. 6.9

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

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

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

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

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

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

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

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

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.*

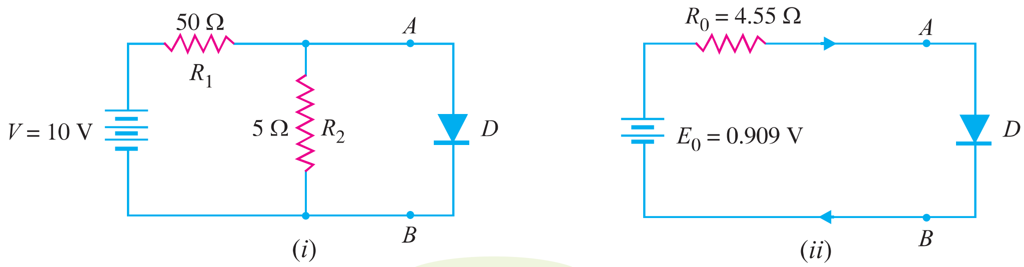


Fig. 6.10

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

E_0 = Thevenin's voltage

= Open circuited voltage across *AB* with diode removed

$$= \frac{R_2}{R_1 + R_2} \times V = \frac{5}{50 + 5} \times 10 = 0.909\ \text{V}$$

R_0 = Thevenin's resistance

= Resistance at terminals *AB* with diode removed and battery replaced by a short circuit

$$= \frac{R_1 R_2}{R_1 + R_2} = \frac{50 \times 5}{50 + 5} = 4.55\ \Omega$$

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

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

Example 6.4. *Calculate the current through 48 Ω 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 Ω.*

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 V.

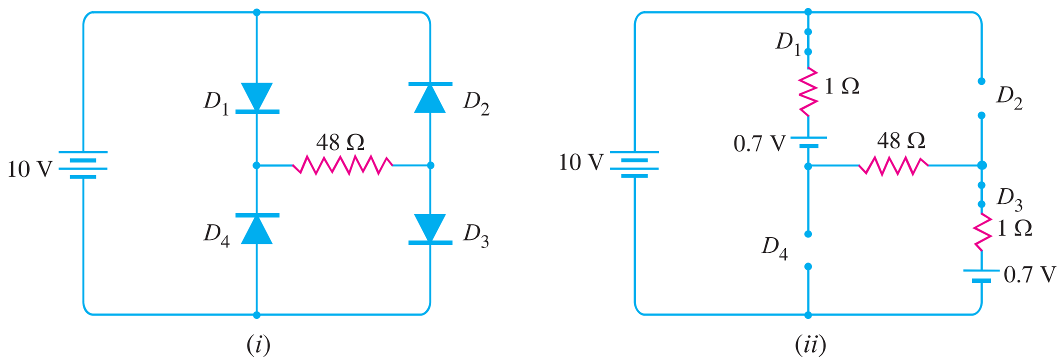


Fig. 6.11

Net circuit voltage = 10 − 0.7 − 0.7 = 8.6 V

Total circuit resistance = 1 + 48 + 1 = 50 Ω

∴ Circuit current = 8.6/50 = 0.172 A = **172 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.*

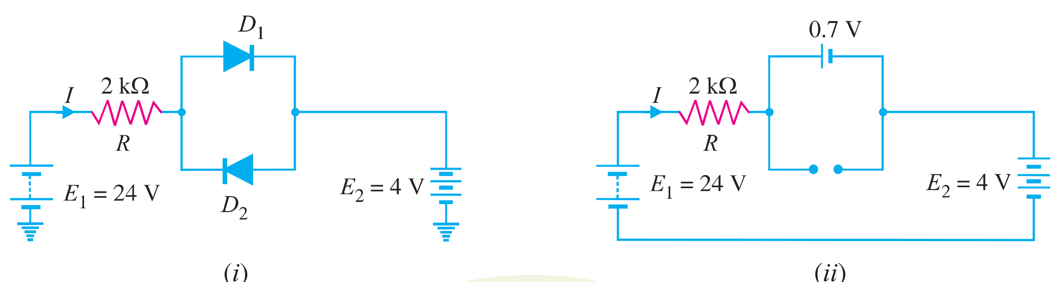


Fig. 6.12

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.

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

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

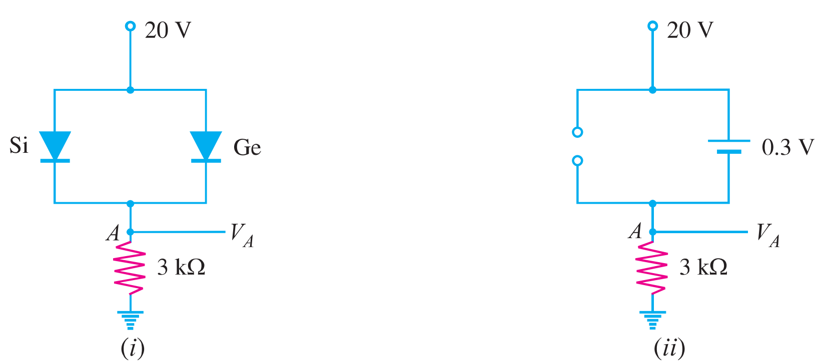


Fig. 6.13

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 ($V_0 = 0.3$ V) will turn on first and a level of 0.3 V is maintained across the parallel circuit. The silicon diode never gets the opportunity to have 0.7 V across it and, therefore, remains in open-circuit state as shown in Fig. 6.13 (*ii*).

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

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

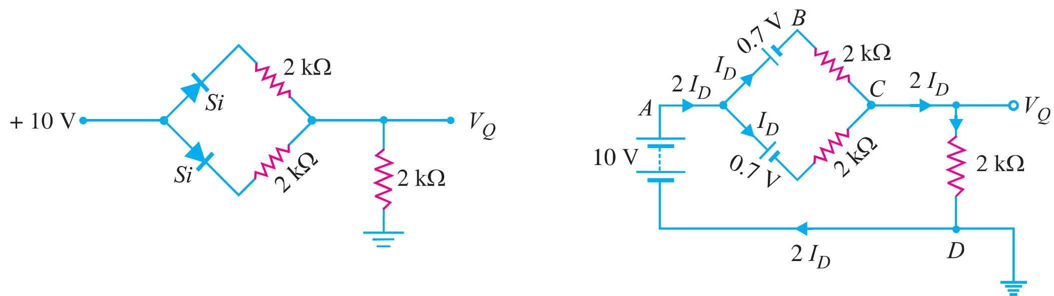
Solution. Replace the diodes by their simplified models. The resulting circuit will be as shown in Fig. 6.14 (*ii*). By symmetry, current in each branch is I_D so that current in branch *CD* is $2I_D$. Applying Kirchhoff's voltage law to the closed circuit *ABCDA*, we have,

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

or $$6\,I_D = 9.3$$

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

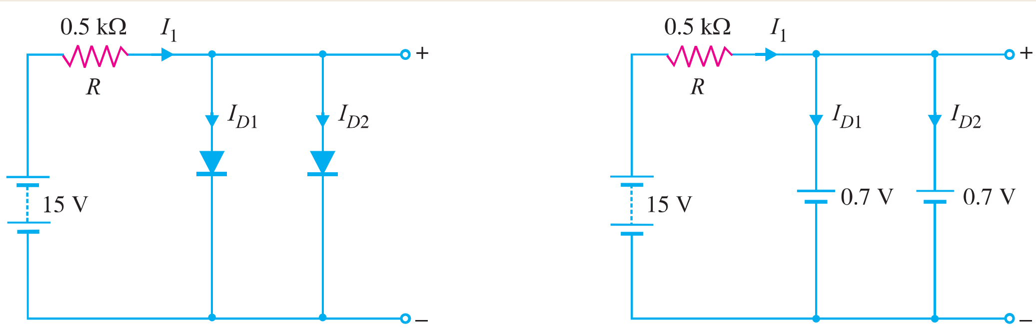
Also $$V_Q = (2\,I_D) \times 2\,\text{k}\Omega = (2 \times 1.55\ \text{mA}) \times 2\,\text{k}\Omega = \mathbf{6.2\ V}$$



(*i*) (*ii*)

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.*



(*i*) (*ii*)

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*),

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

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

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.*

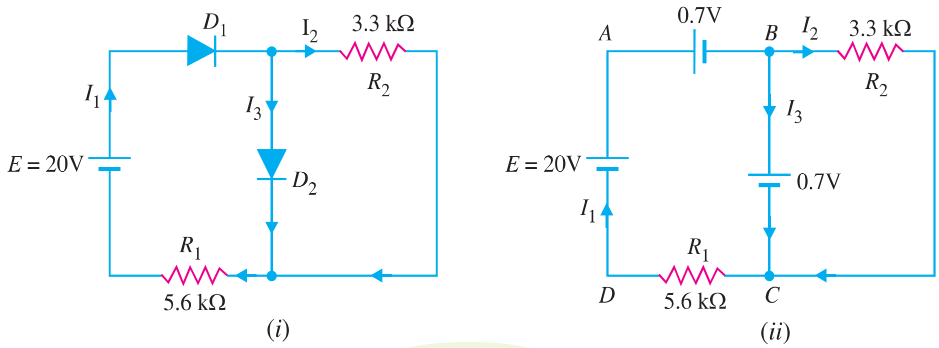


Fig. 6.16

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 k Ω) is 0.7V.

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

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

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

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

Now $\quad I_1 = I_2 + I_3$

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

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

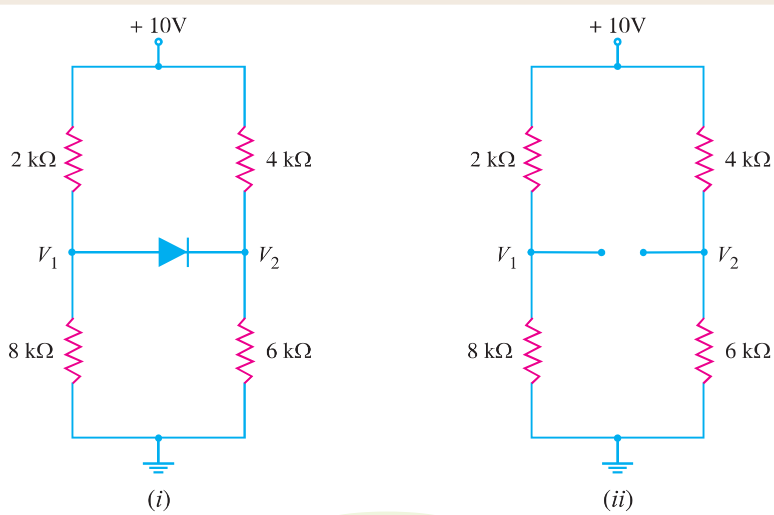


Fig. 6.17

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,

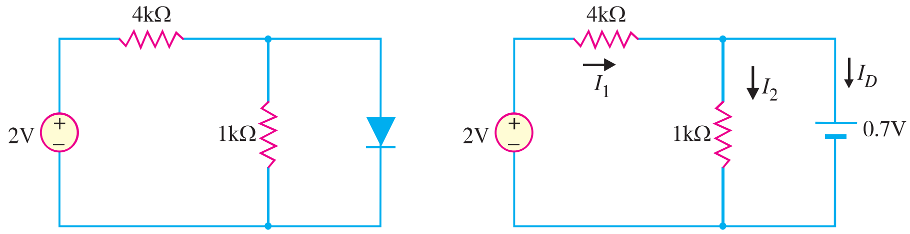
$$V_1 = \frac{10\text{ V}}{2\text{ k}\Omega + 8\text{ k}\Omega} \times 8\text{ k}\Omega = 8\text{V}$$

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

∴ 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.*



(*i*) (*ii*)

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,

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

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

Now $I_D = I_1 - I_2 = 0.325 - 0.7 = -0.375$ mA

Since the diode current is negative, the diode must be **OFF** and the true value of diode current is I_D = **0 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

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

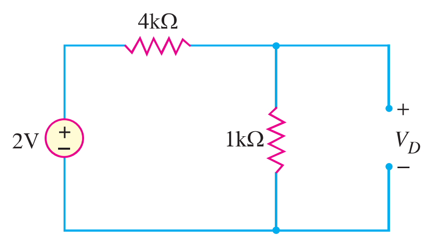


Fig. 6.19

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 ($< 1\mu$ A) for silicon diodes but it is appreciable ($\simeq$ 100 μA) 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 μA—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.

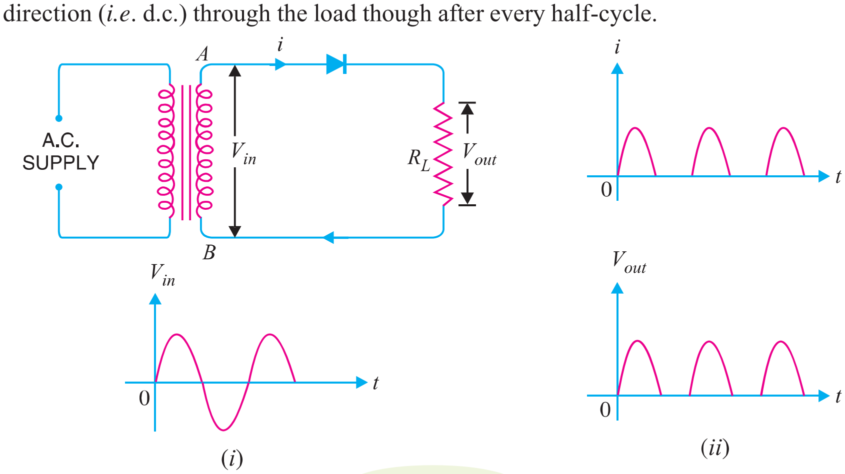


Fig. 6.20

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 smoothened 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° – 360°, 360° – 720° and so on. In Fig. 6.21 (*ii*), the output waveform also repeats the same wave pattern over 0° – 360°, 360° – 720° 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.

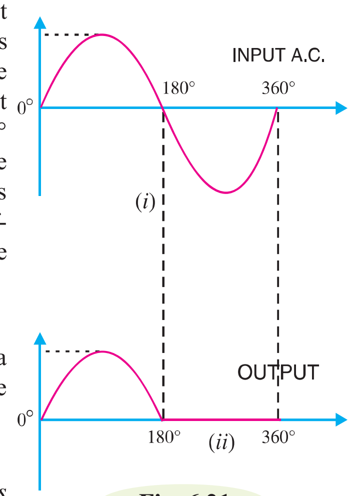


Fig. 6.21

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.*

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

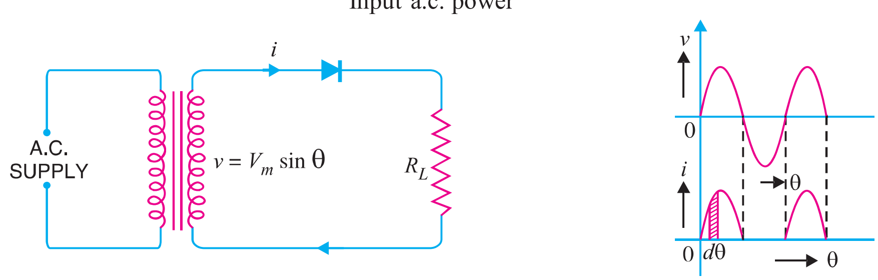


Fig. 6.22

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.

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

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

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

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

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

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

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

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

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

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

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

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

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

∴ Max. rectifier efficiency = 40.6%

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

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

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

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

Solution.

(***i***) Rectification efficiency $= \dfrac{\text{d.c. output power}}{\text{a.c. input power}} = \dfrac{40}{100} = 0.4 =$ **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 $= \dfrac{\text{Area under the curve over a cycle}}{\text{Base}} = \dfrac{\int_0^{\pi} i\, d\theta}{2\pi}$

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

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

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

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

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

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

Solution.

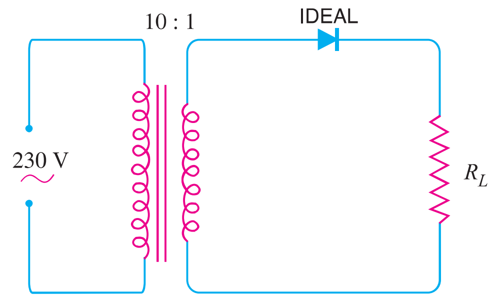


Fig. 6.23

Primary to secondary turns is

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

R.M.S. primary voltage

$$= 230 \text{ V}$$

∴ Max. primary voltage is

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

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

Max. secondary voltage is

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

(i)

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

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

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

∴ Peak inverse voltage = **32.53 V**

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

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

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

Solution.

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

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

(i)

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

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

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

(ii)

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

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

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

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

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

Solution.

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

Diode resistance, r_f = 25 Ω

Load resistance, R_L = 800 Ω

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

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

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

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

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

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

6.11 Full-Wave Rectifier

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

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

6.12 Centre-Tap Full-Wave Rectifier

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

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

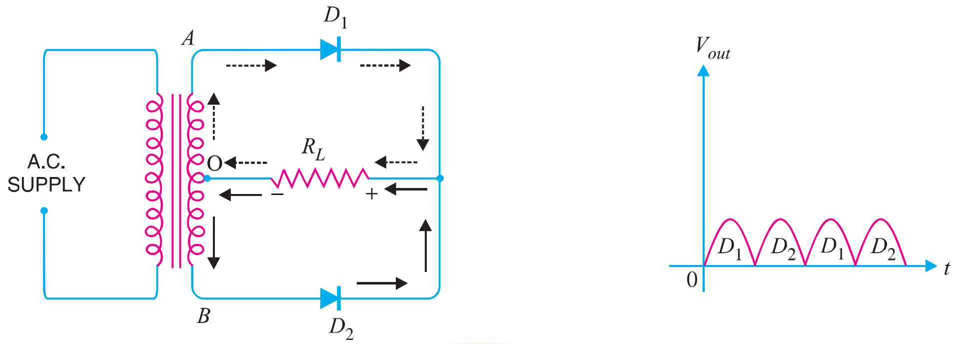


Fig. 6.24

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

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

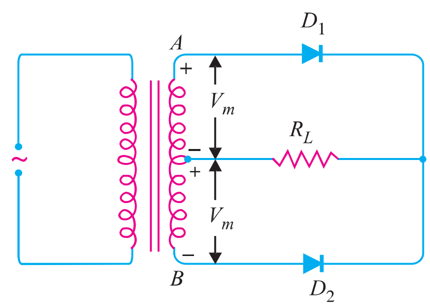


Fig. 6.25

Disadvantages

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

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

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

6.13 Full-Wave Bridge Rectifier

The need for a centre tapped power transformer is eliminated in the bridge rectifier. It contains four diodes D_1, D_2, D_3 and D_4 connected to form bridge as shown in Fig. 6.26. The a.c. supply to be rectified is applied to the diagonally opposite ends of the bridge through the transformer. Between other two ends of the bridge, the load resistance R_L is connected.

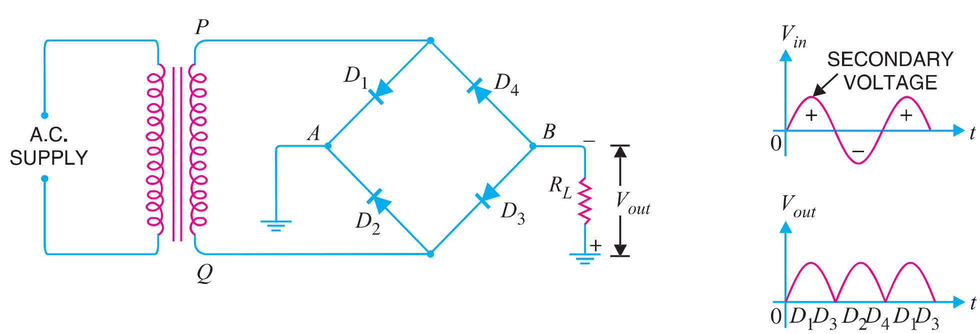


Fig. 6.26

Operation. During the positive half-cycle of secondary voltage, the end P of the secondary winding becomes positive and end Q negative. This makes diodes D_1 and D_3 forward biased while diodes D_2 and D_4 are reverse biased. Therefore, only diodes D_1 and D_3 conduct. These two diodes will be in series through the load R_L as shown in Fig. 6.27 (*i*). The conventional current flow is shown by dotted arrows. It may be seen that current flows from A to B through the load R_L .

During the negative half-cycle of secondary voltage, end P becomes negative and end Q positive. This makes diodes D_2 and D_4 forward biased whereas diodes D_1 and D_3 are reverse biased. Therefore, only diodes D_2 and D_4 conduct. These two diodes will be in series through the load R_L as shown in Fig. 6.27 (*ii*). The current flow is shown by the solid arrows. It may be seen that again current flows from A to B through the load *i.e.* in the same direction as for the positive half-cycle. Therefore, d.c. output is obtained across load R_L.

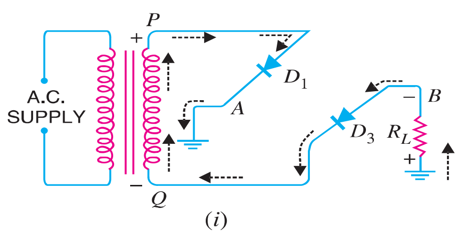


Fig. 6.27

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

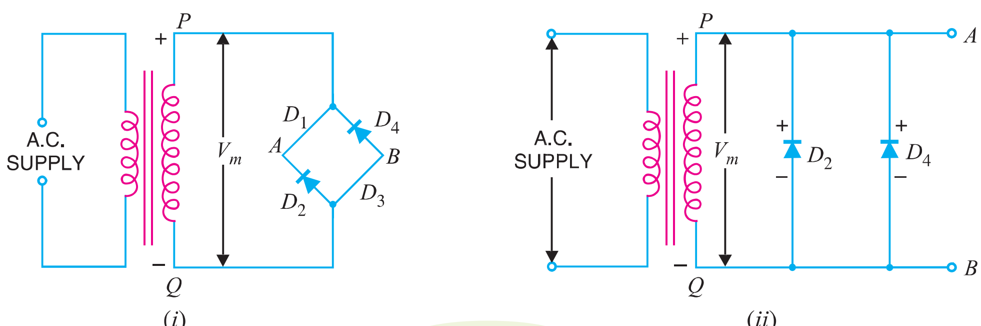


Fig. 6.28

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

Advantages

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

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

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

Disadvantages

(*i*) It requires four diodes.

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

6.14 Output Frequency of Full-Wave Rectifier

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

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

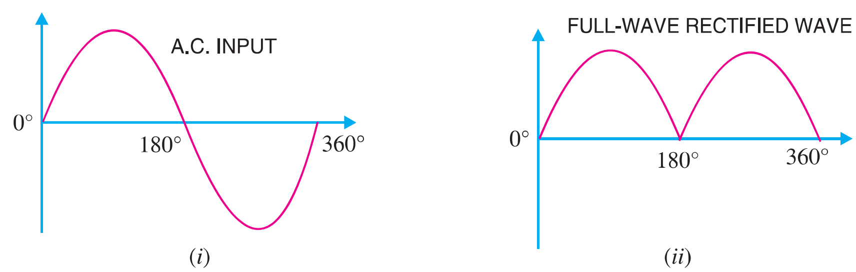


Fig. 6.29

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

6.15 Efficiency of Full-Wave Rectifier

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

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

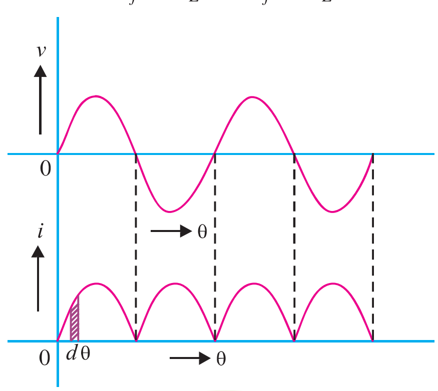


Fig. 6.30

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

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

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

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

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

For a full-wave rectified wave, we have,

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

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

$\therefore$ Full-wave rectification efficiency is

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

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

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

$\therefore$ Maximum efficiency = 81.2%

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

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

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

Solution.

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

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

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

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

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

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

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

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

Solution.

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

R.M.S. primary voltage = 230 V

∴ R.M.S. secondary voltage

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

Maximum voltage across secondary

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

Maximum voltage across half secondary winding is

$V_m = 65/2 = 32.5$ V

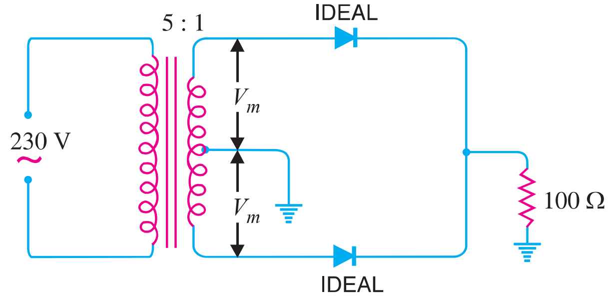


Fig. 6.31

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

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

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

$PIV =$ **65 V**

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

Since $r_f = 0$

∴ Rectification efficiency = **81.2 %**

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

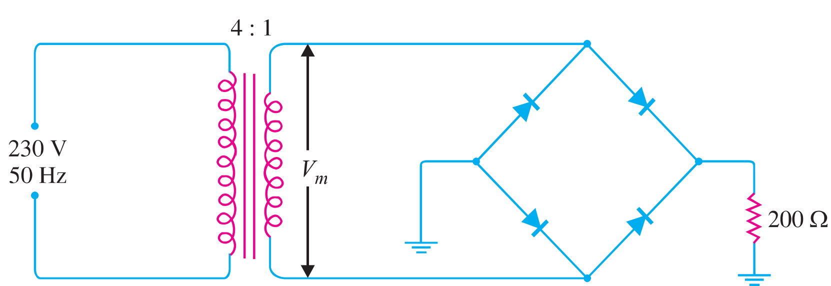


Fig. 6.32

Solution.

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

R.M.S. primary voltage = 230 V

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

Maximum voltage across secondary is

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

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

∴ d.c. output voltage, $V_{dc} = I_{dc} \times R_L = 0.26 \times 200 =$ **52 V** (*ii*) The peak inverse voltage is equal to the maximum secondary voltage *i.e.*

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

(*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 frequency *i.e.*

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

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.*

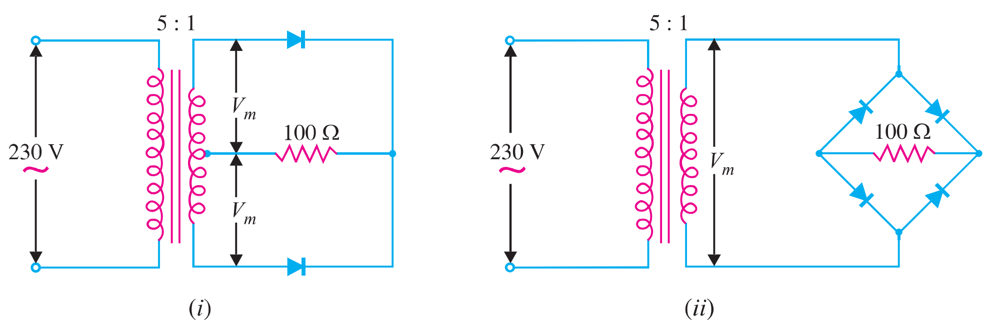


Fig. 6.33

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

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

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

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

$$= \frac{2V_m}{\pi} = \frac{2 \times 32.5}{\pi} = \mathbf{20.7\ V}$$

Bridge Circuit

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

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

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.

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

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

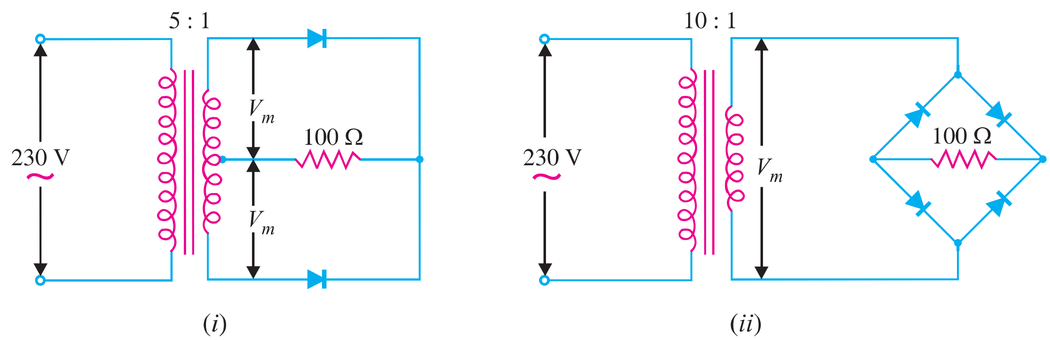


Fig. 6.34

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

Bridge type circuit

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

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

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

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 1Ω and infinite reverse resistance. The alternating supply voltage is 240 V r.m.s. and load resistance is 480 Ω. 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 = $2\,r_f + R_L$.

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

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

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

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

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

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.*

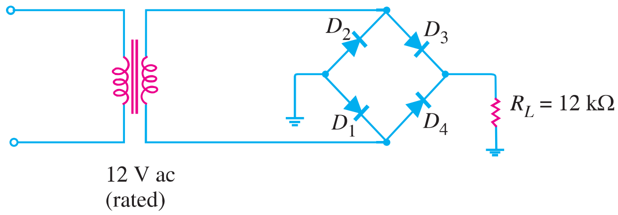


Fig. 6.35

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

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

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

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

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.

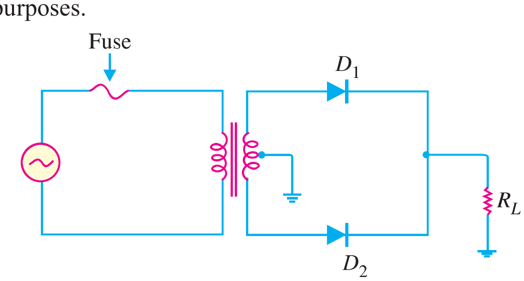


Fig. 6.36

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 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.

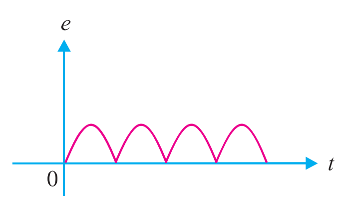


Fig. 6.37

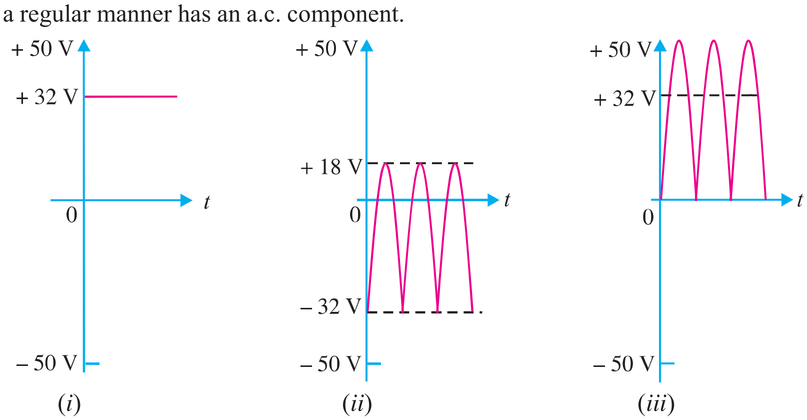


Fig. 6.38

* 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.

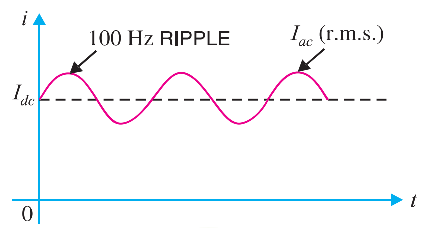


Fig. 6.39

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.

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

(*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.

$\therefore$ 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,

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

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

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

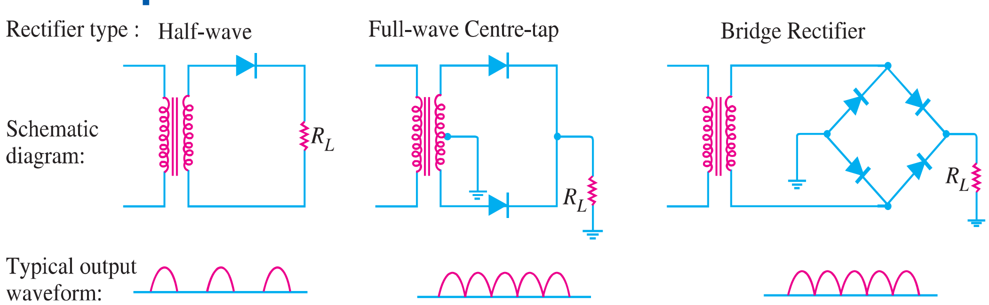
Ripple factor $= \frac{V_{ac(r.m.s.)}}{V_{dc}} = \frac{0.5}{10} \times 100 = 5\%$

For power supply B

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}	$2\,f_{in}$	$2\,f_{in}$
6	Peak inverse voltage	V_m	$2\,V_m$	V_m