

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.

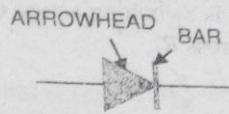
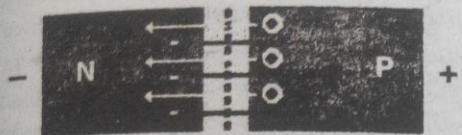


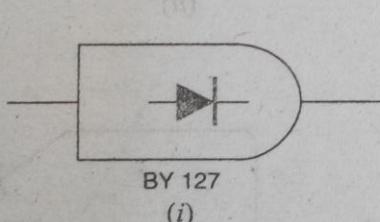
Fig. 6.1

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 :

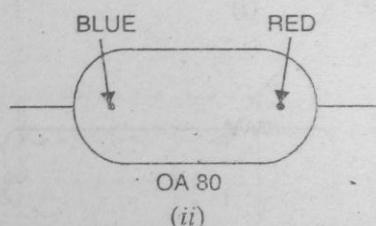
- (i) If arrowhead of diode symbol is *positive w.r.t. bar* of the symbol, the diode is forward biased.
- (ii) If the arrowhead of diode symbol is *negative w.r.t. bar*, the diode is reverse biased.

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)].



BY 127
(i)



OA 80
(ii)

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.

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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 .

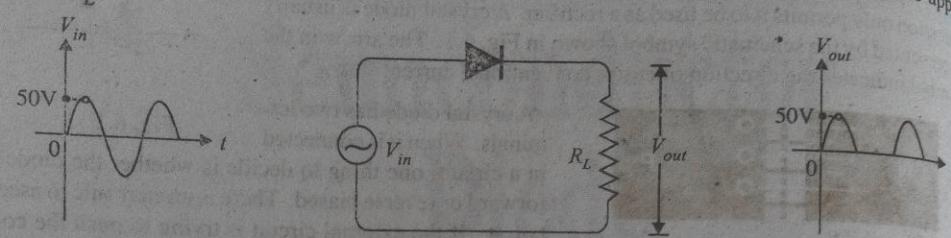


Fig. 6.3

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

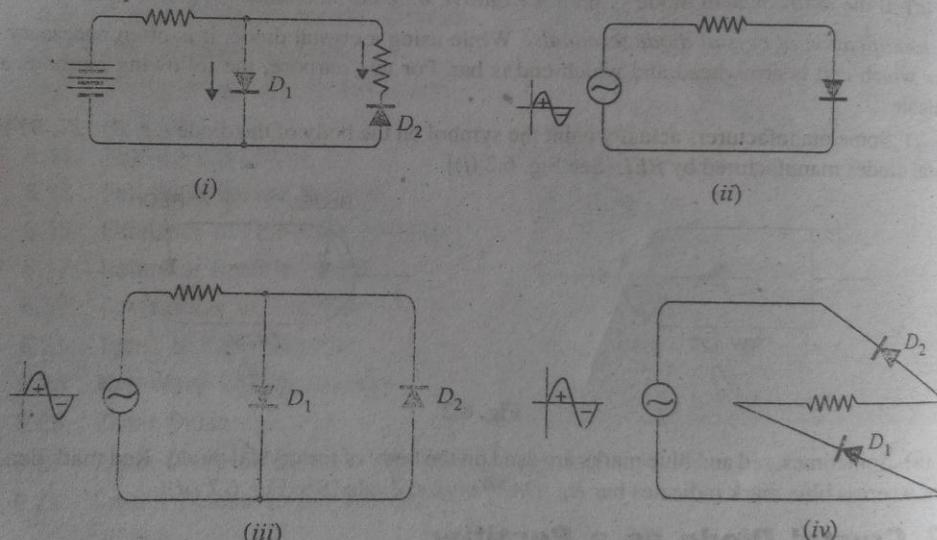


Fig. 6.4

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 the 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.

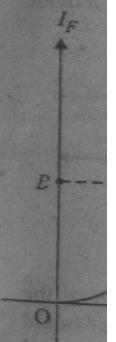
(iv) R
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6.3 Re
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(iv) Refer to Fig. 6.4 (iv). During the positive half-cycle of input a.c. voltage, both the diodes are reverse biased. However, during the negative half-cycle of input a.c. voltage,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

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

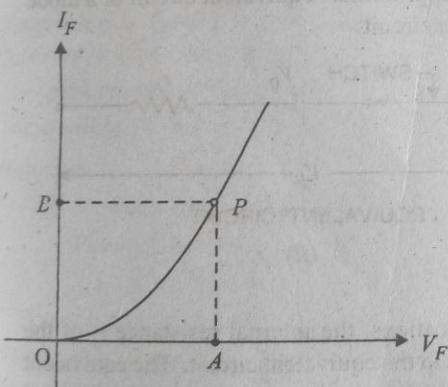


Fig. 6.5

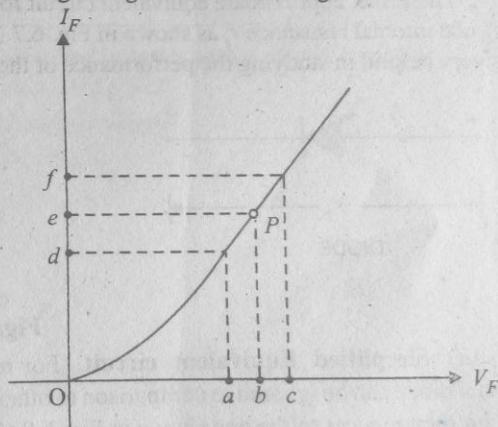


Fig. 6.6

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 $I_f r_f$

$$V_F = V_0 + I_f r_f$$

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.

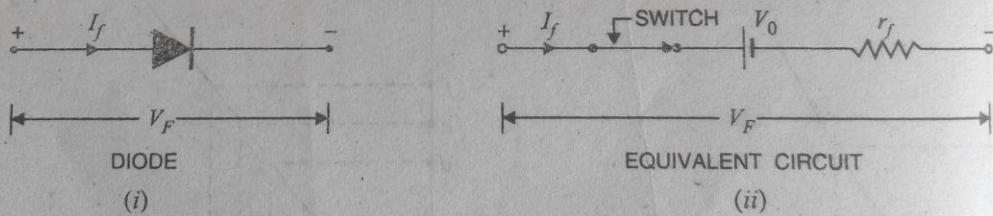


Fig. 6.7

(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

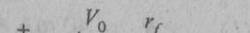
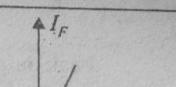
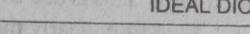
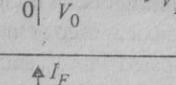
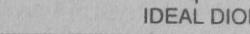
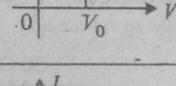
* We assume here that V/I characteristic of crystal diode is linear.

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(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	 IDEAL DIODE	
2.	Simplified model	 IDEAL DIODE	
3.	Ideal Model	 IDEAL DIODE	

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

What will be those 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).

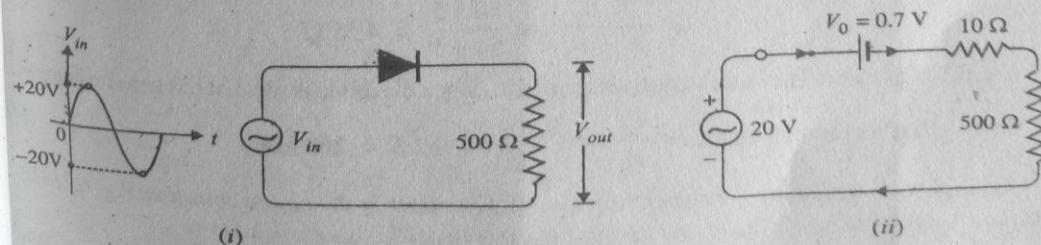


Fig. 6.9

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

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

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

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

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

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

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

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

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.

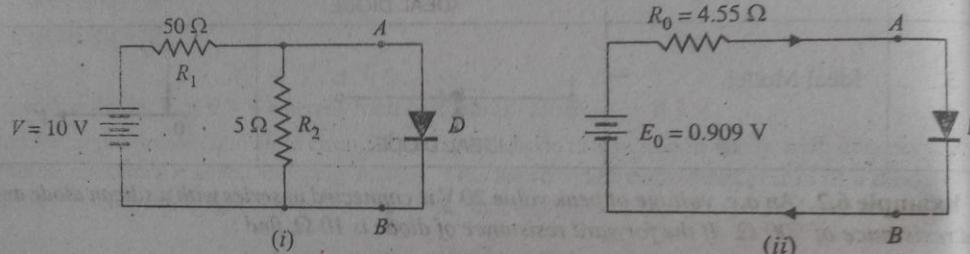


Fig. 6.10

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

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

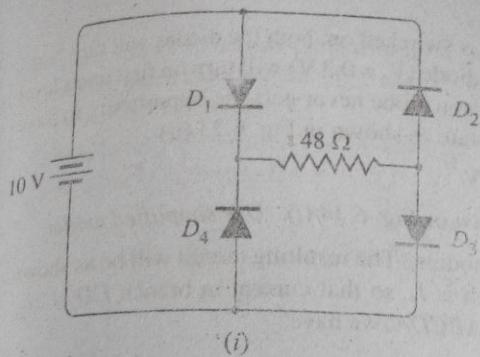
$$\begin{aligned} R_0 &= \text{Thevenin's resistance} \\ &= \text{Resistance at terminals } AB \text{ with diode removed and battery replaced by a short circuit} \\ &= \frac{R_1 R_2}{R_1 + R_2} = \frac{50 \times 5}{50 + 5} = 4.55 \Omega \end{aligned}$$

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

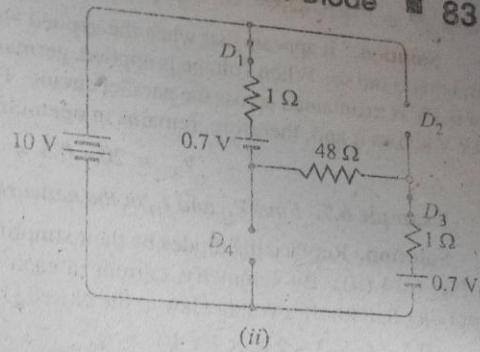
$$\therefore \text{Current through diode} = \frac{E_0}{R_0} = \frac{0.909}{4.55} = 0.2 \text{ A} = 200 \text{ mA}$$

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

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 .



(i)



(ii)

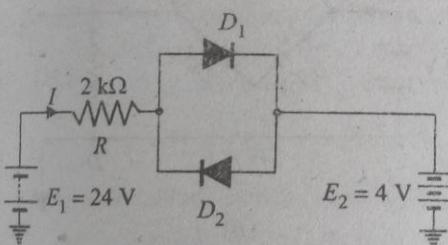
Fig. 6.11

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

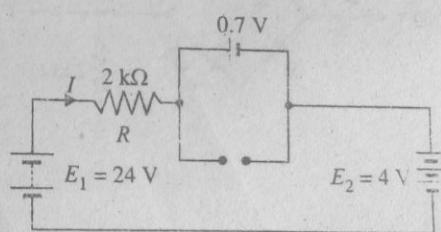
$$\text{Total circuit resistance} = 1 + 48 + 1 = 50 \Omega$$

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

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.



(i)



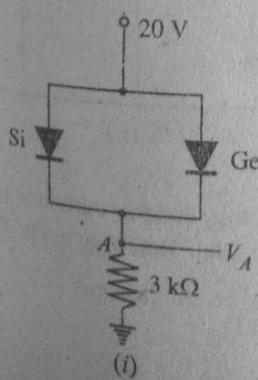
(ii)

Fig. 6.12

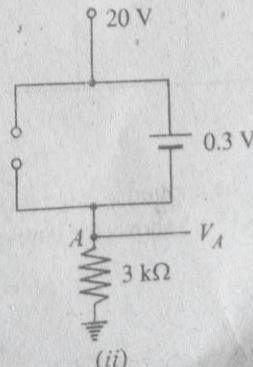
Solution. The conditions of the problem suggest that diode D_1 is forward biased and diode D_2 is reverse biased. We can, therefore, consider the branch containing diode D_2 as open as shown in Fig. 6.12 (ii). Further, diode D_1 can be replaced by its simplified model.

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

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



(i)



(ii)

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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 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).

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

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 ABCDA, we have,

$$-0.7 - I_D \times 2 - 2I_D \times 2 + 10 = 0$$

or

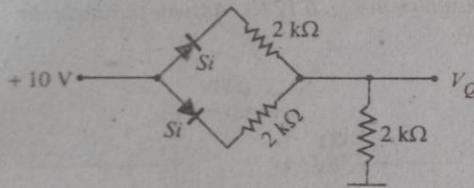
$$6I_D = 9.3$$

∴

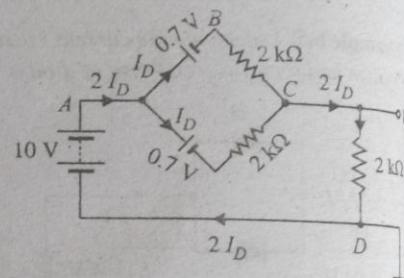
$$I_D = \frac{9.3}{6} = 1.55 \text{ mA}$$

Also

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



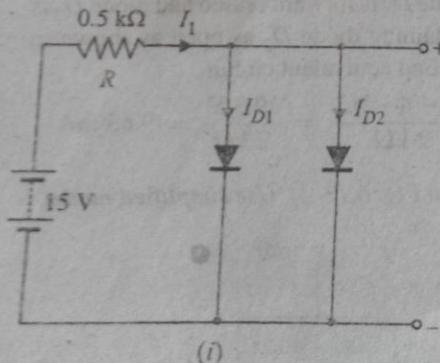
(i)



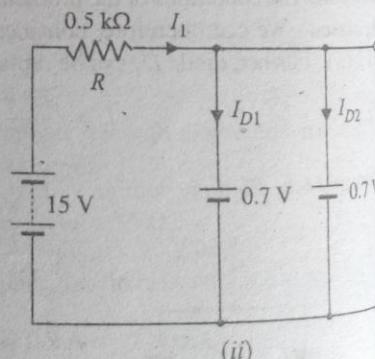
(ii)

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),

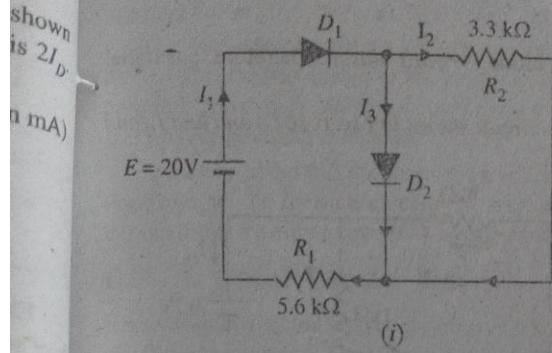
$$I_1 = \frac{\text{Voltage across } R}{R} = \frac{15 - 0.7}{0.5 \text{ k}\Omega} = 28.6 \text{ mA}$$

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

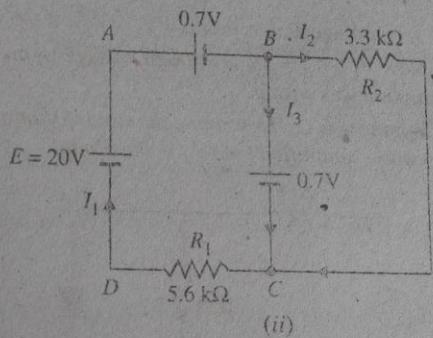
Comments. Note the use of placing the diodes in parallel. If the current rating of each

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.



(i)



(ii)

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 0.7 V.

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

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

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

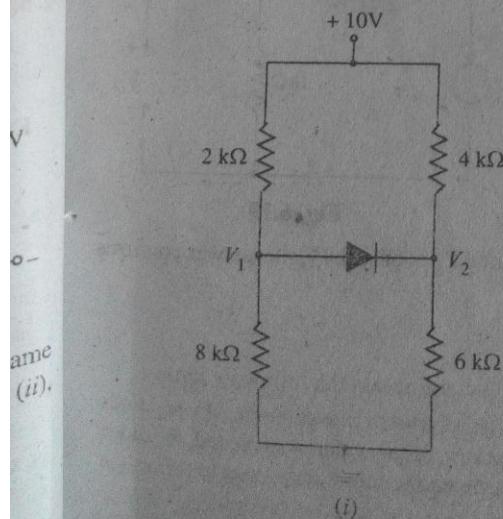
$$\therefore I_1 = \frac{20 - 0.7 - 0.7}{R_1} = \frac{18.6 \text{ V}}{5.6 \text{ k}\Omega} = 3.32 \text{ mA}$$

Now

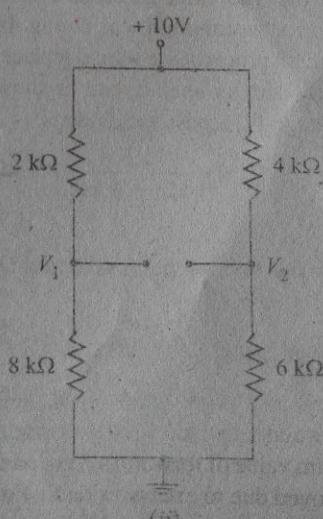
$$I_1 = I_2 + I_3$$

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

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



(i)



(ii)

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,

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

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

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

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 . Assume simplified model for the diode.

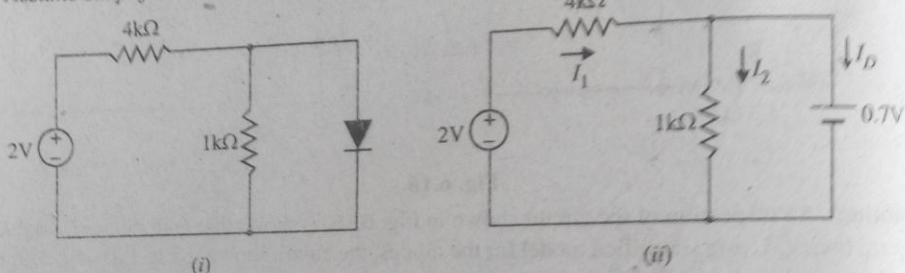


Fig. 6.18

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

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

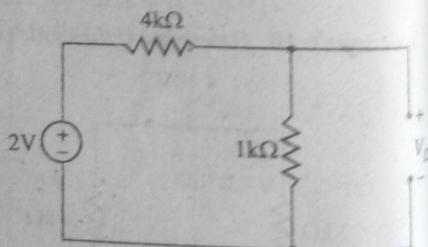


Fig. 6.19

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:

- 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 reverse current. If the reverse bias voltage exceeds the peak reverse voltage without destroying the diode, it is known as peak reverse current. This current is quite small (e.g. 100 μA) for a diode.

It may be noted that for example, the current in a diode is quite small (e.g. 100 μA) for a given voltage.

6.7 Characteristics

For reasons of convenience, usually an ideal diode is used for lighting where d.c. current is required. Using crystals, it is possible to obtain a current which is proportional to the voltage across the diode.

(i) Forward characteristics

6.8 Half-Wave Rectifier

In half-wave rectification, the alternating current is converted into direct current in one direction.

Circuit diagram of a half-wave rectifier. General circuit diagram of a half-wave rectifier. Firstly, it consists of a diode and a load resistor. The input is an AC source. The output is a DC source.

(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 ($\approx 100 \mu A$) 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 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.

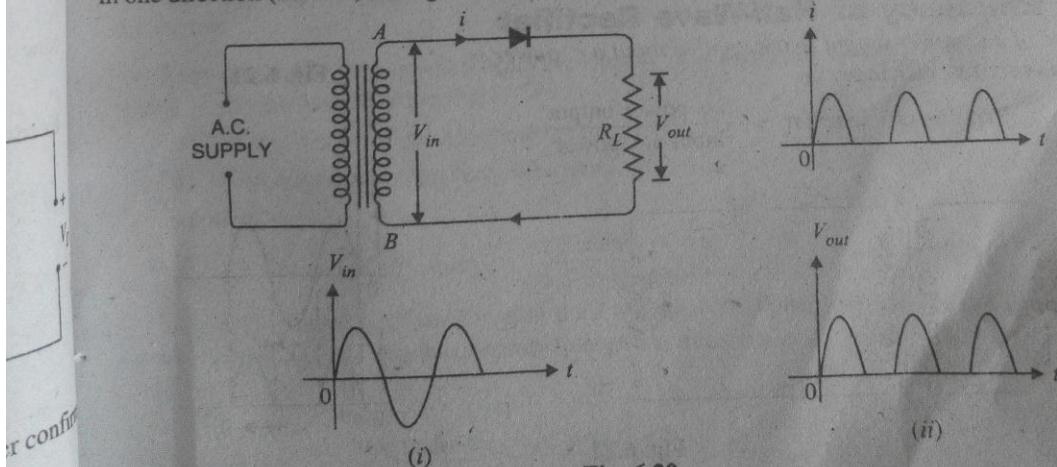


Fig. 6.20

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 smoothed with the help of filter circuits discussed later.

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

- 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 d.c. current.
- 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.

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

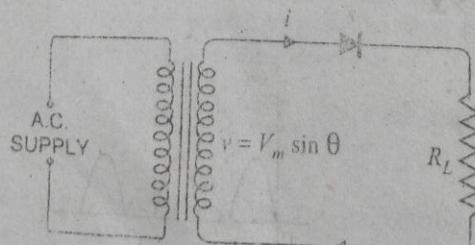


Fig. 6.22

Consider a half-wave rectifier shown in Fig. 6.22. Let $v = V_m \sin \theta$ be the alternating voltage appearing 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 v and no current con-

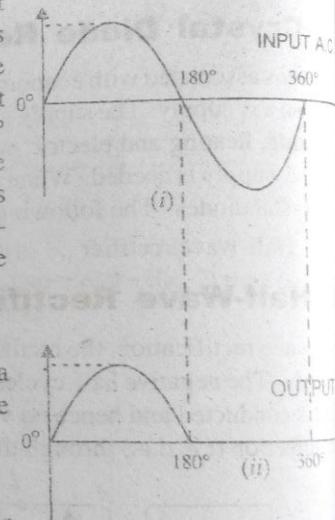
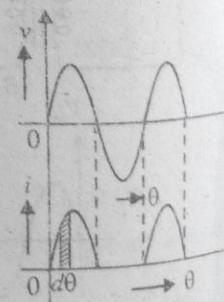


Fig. 6.21



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.

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

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

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.

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

(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

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

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 $2 I_m$.

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

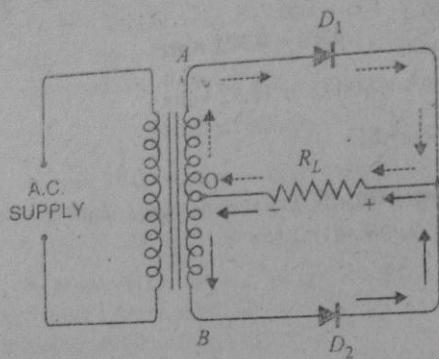
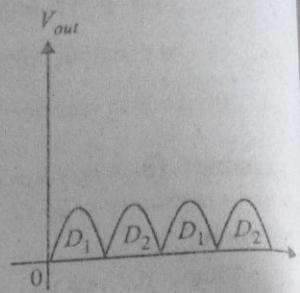


Fig. 6.24



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.

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

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.

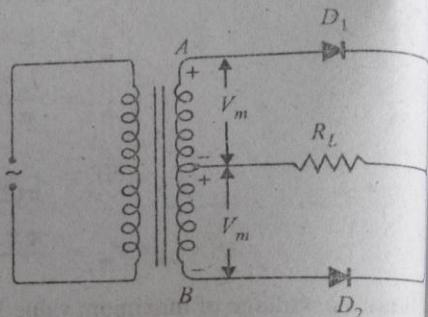


Fig. 6.25

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.

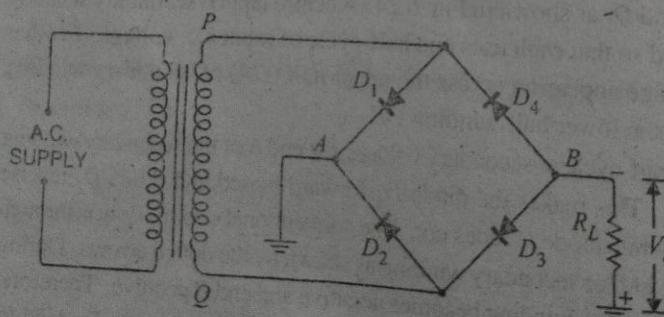
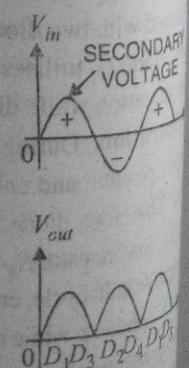


Fig. 6.26



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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 .

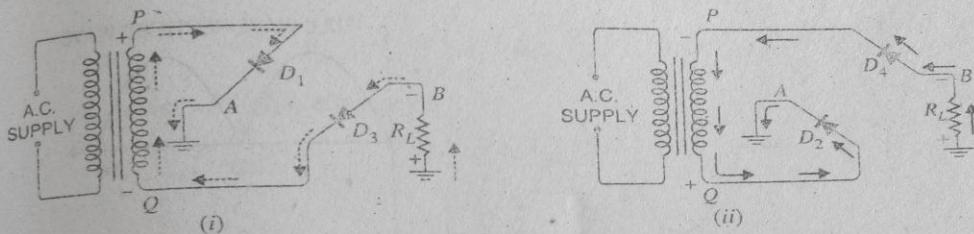


Fig. 6.27

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).

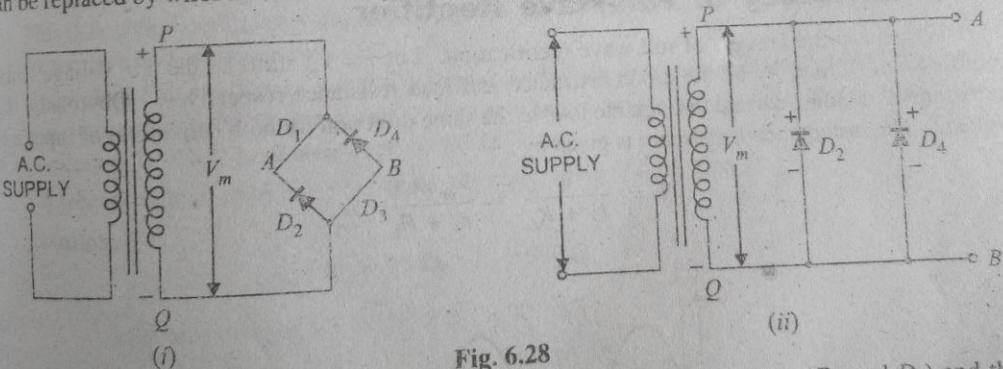


Fig. 6.28

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

- The need for centre-tapped transformer is eliminated.
- The output is twice that of the centre-tap circuit for the same secondary voltage.
- The PIV is one-half that of the centre-tap circuit (for same d.c. output).

Disadvantages

- 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.

$$f_{out} = 2 f_m$$

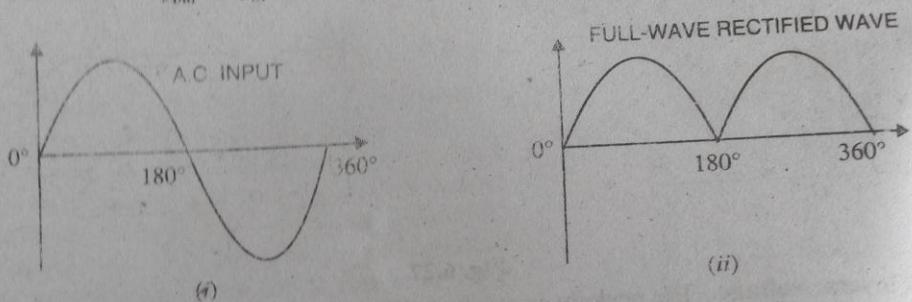


Fig. 6.29

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 voltage. The instantaneous current i is given by :

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

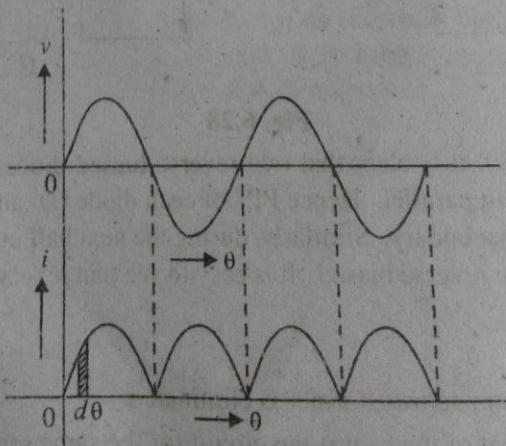


Fig. 6.30

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

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

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

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 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 20Ω . The transformer r.m.s. secondary voltage from centre tap to each end of secondary is 50 V and load resistance is 980Ω . Find :

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

Solution.

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

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

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

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

(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, $N_1/N_2 = 5$

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R.M.S. primary voltage = 230 V

\therefore 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

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

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

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

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

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

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

Since $r_f = 0$

\therefore 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.

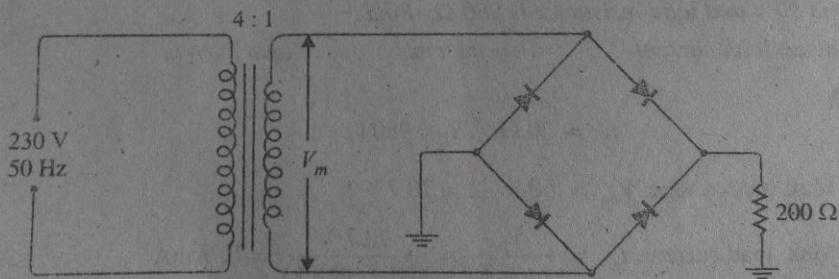


Fig. 6.32

Solution.

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

R.M.S. primary voltage = 230 V

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

Maximum voltage across secondary is

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

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

$$\therefore \text{d.c. output voltage} = 0.26 \times 200 = 52 \text{ V}$$

(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 frequency 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.

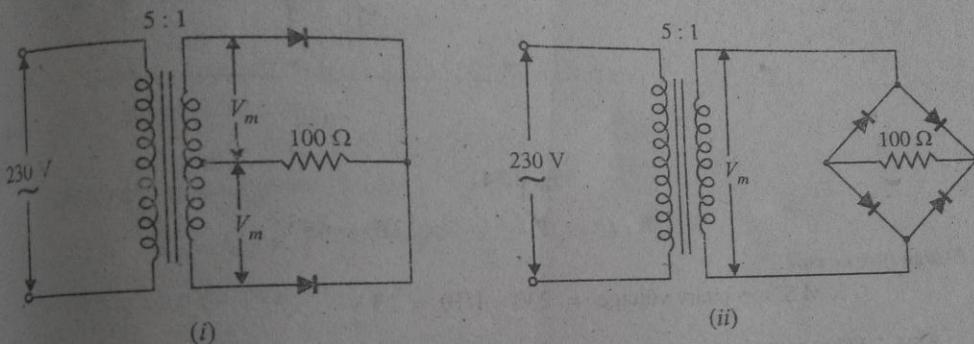


Fig. 6.33

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

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

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

Max. voltage across half secondary winding is

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

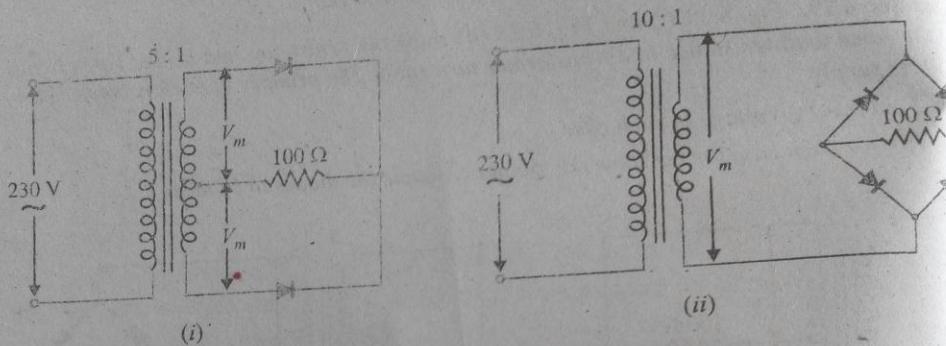


Fig. 6.34

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

Bridge type circuit

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

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

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

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

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

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

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

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

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

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

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

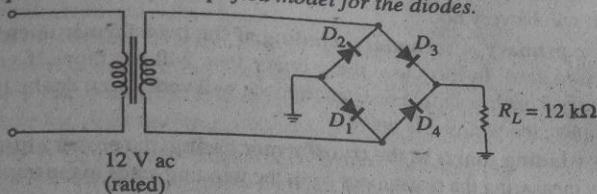


Fig. 6.35

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

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

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

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

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.

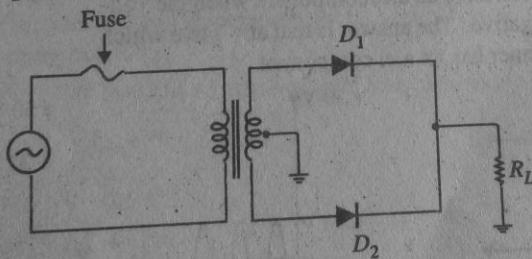


Fig. 6.36

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.
- (iv) In most cases, a shorted primary or shorted secondary will cause the fuse in the primary

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

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

(iii) If either winding shorts to the transformer casing, the primary fuse will blow. This can be checked by measuring the resistances from the winding leads to the transformer casing. A 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 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_1 will behave like a short-circuited diode. 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 rectifiers are the same as for centre-tap full-wave rectifier. Again symptoms for shorted and open diodes in a bridge rectifier are the same as those for the centre-tap circuit. In the case of bridge circuit, however, we 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.

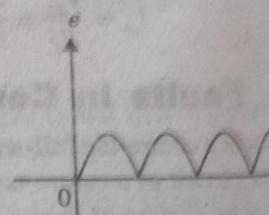
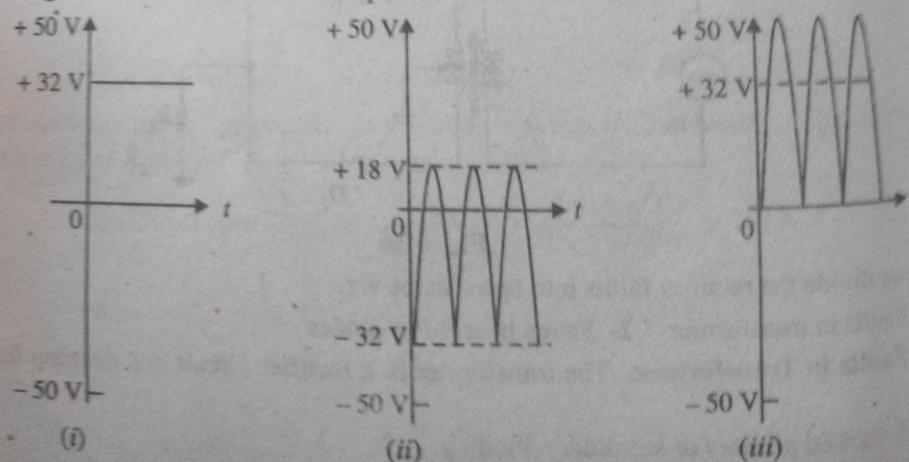


Fig. 6.37



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.

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.

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.



Rectifier

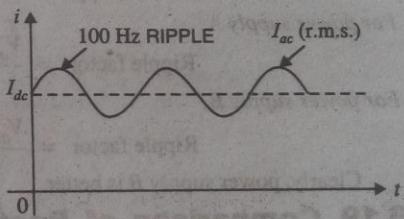


Fig. 6.39

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

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. This is the 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

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

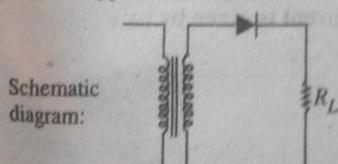
For power supply B

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

Clearly, power supply B is better.

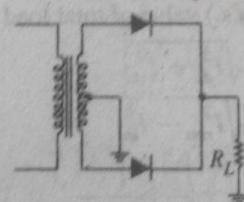
6.19 Comparison of Rectifiers

Rectifier type : Half-wave

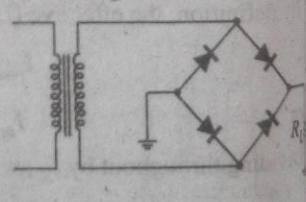


Schematic diagram:

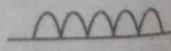
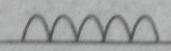
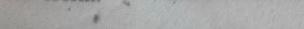
Full-wave Centre-tap



Bridge Rectifier



Typical output waveform:



S. No.	Particulars	Half-wave	Centre-tap	Bridge type
1	No. of diodes	1	2	4
2	Transformer necessary	yes	yes	no
3	Max. efficiency	40.6%	42%	51.2%
4	Ripple factor	1.21	0.48	0.48
5	Output frequency	f_m	$2f_m$	$2f_m$
6	Peak reverse voltage	V_m	V_m	$2V_m$

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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.

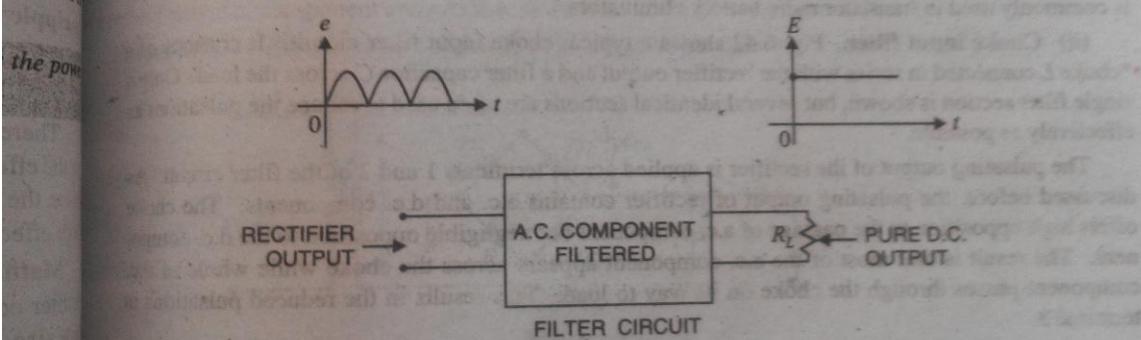


Fig. 6.40

6.21 Types of Filter Circuits

The most commonly used filter circuits are *capacitor filter*, *choke input filter* and *capacitor input filter or π -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., $f = 0$.

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

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.

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 the parallel combination of R - C) decreases as shown by the line AB in Fig. 6.41 (iii). The voltage across the 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 a smooth curve $ABCDEF$. It may be seen that very little ripple is left in the output. Moreover, output voltage is often higher as it remains substantially near the peak value of rectifier output voltage.

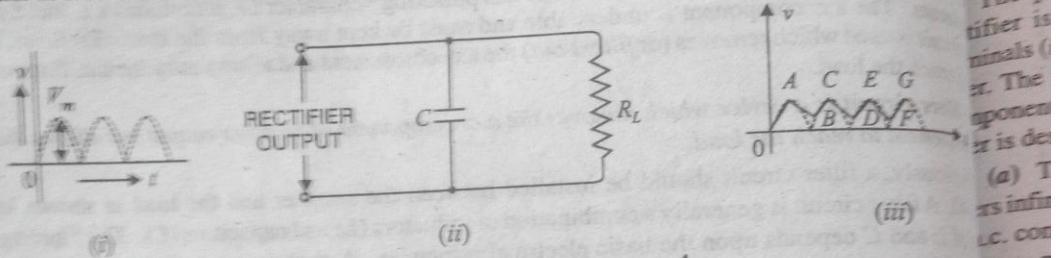


Fig. 6.41

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 one filter section is shown, but several identical sections are often used to reduce the pulsation 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 the d.c. component passes through the choke on its way to load. This results in the reduced pulsation at terminal 3.

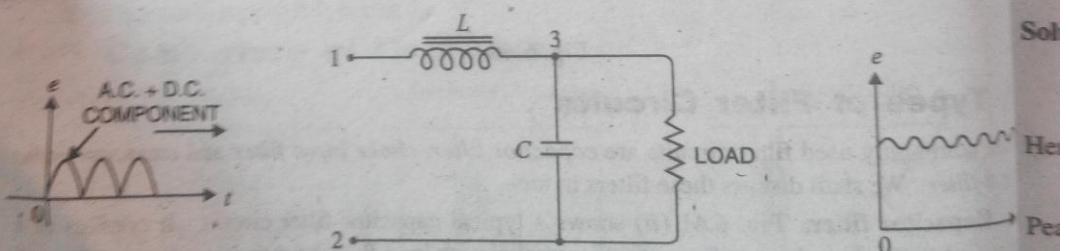


Fig. 6.42

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 C passes the a.c. component but prevents the d.c. component to flow through it. Therefore, only a.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 π -filter. Fig. 6.43 shows a typical capacitor input filter or π -filter. It consists of a filter capacitor C_1 connected across the rectifier output, a choke L in series

* The shorthand name of inductor coil is choke.

** The shape of the circuit diagram of this filter circuit appears like Greek letter π (pi) and hence called π -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 :

(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.

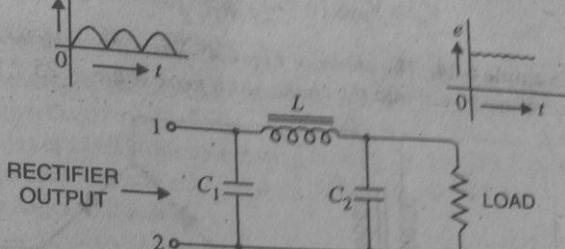


Fig. 6.43

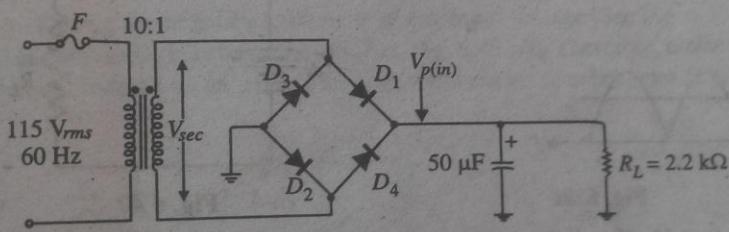


Fig. 6.44

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

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

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

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, $f = 2$. $f_{in} = 2 \times 60 = 120 \text{ Hz}$

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

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

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

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 V ?

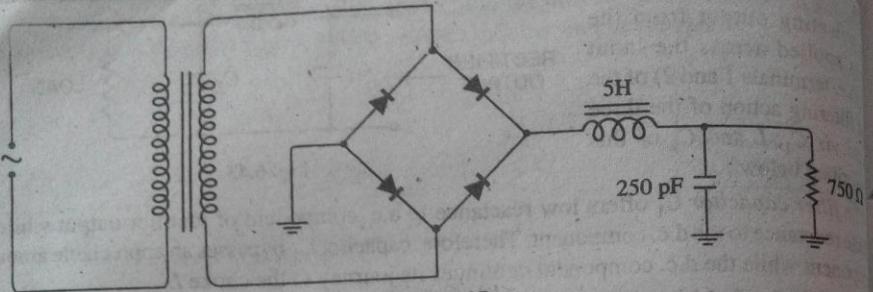


Fig. 6.45

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. The maximum value of the pulsating output is V_m and d.c. component is $V'_{dc} = 2 V_m / \pi$.

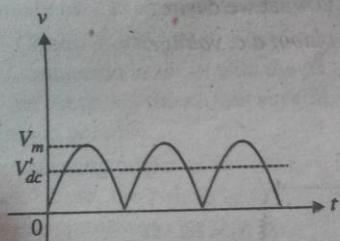


Fig. 6.46

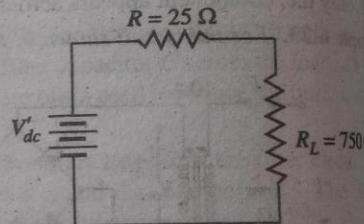


Fig. 6.47

For d.c. component V'_{dc} , the choke resistance is in series with the load as shown in Fig. 6.

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

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

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

The voltage across the load is 15.9 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 of input a.c. voltage. We can also use diodes and capacitors to build a circuit that will provide 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 voltage, there is no power amplification and law of conservation of energy holds good. When a multiplier increases the peak input voltage by a factor n , the peak input current is decreased approximately the same factor. Thus the actual power output from a voltage multiplier will be

greater than the
that the output

6.23 Hal

A half-wave voltage shown in Fig. 1 will be $2 V_S \sin(\omega t)$ if there are two capacitors so

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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.

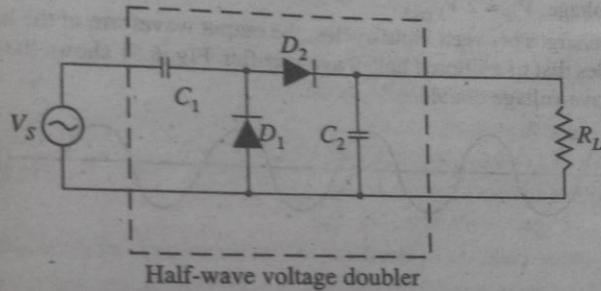


Fig. 6.48

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).

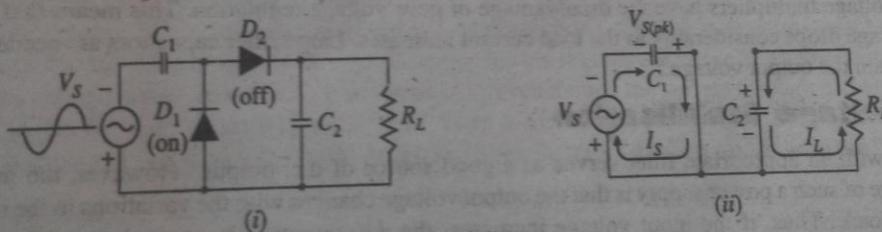


Fig. 6.49

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).

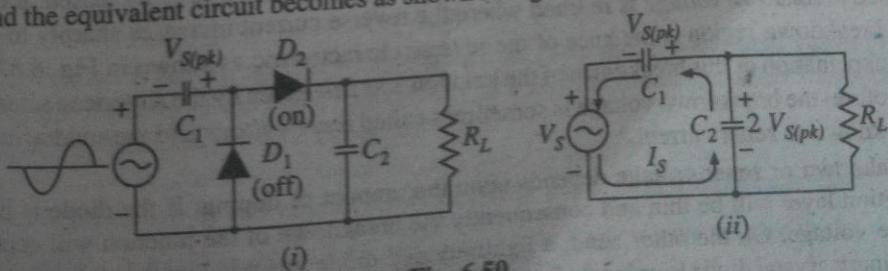


Fig. 6.50

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Referring to Fig. 6.20 (a), it is easy to see that C_1 charged to $V_{1(0)}$, and the source voltage V_{in} are both set an alternating voltage source. Thus C_1 will be charged to the sum of the source voltage and $V_{1(0)}$.

When C_1 discharges in its original polarity (i.e. negative half-cycle), P_1 is open because of diode forward bias. With P_1 turned off, the only discharge path for C_1 is through the load resistor R_L . The time constant for $R_L C_1$ of this circuit is so large that C_1 has little time to lose most of its charge before the next positive voltage comes. During the positive half-cycle, P_1 is turned on and voltage across voltage source is again raised to $\approx 2 V_{1(0)}$.

$$\text{D.C. output voltage, } V_{out} = 2 V_{1(0)}$$

Since C_1 hardly discharges between half-cycles, the output waveform of the full-wave voltage doubler closely resembles that of a diode half-wave rectifier. Fig. 6.21 shows the input and output waveforms for a full-wave voltage doubler.

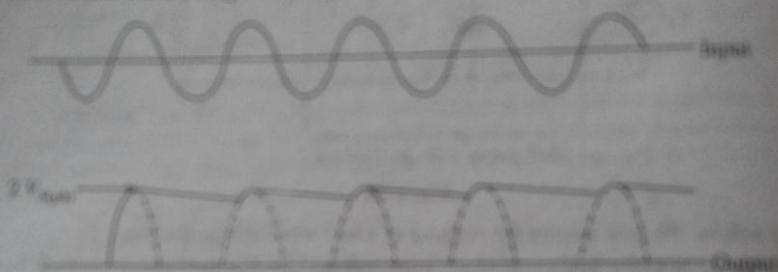


Fig. 6.21

The voltage multipliers have the disadvantage of poor voltage regulation. This means that the 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 multiplier with an appropriate filter source 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 multiplier also increases. Similarly, if the load current increases, the output voltage falls due to the voltage drop in the multiplying element, filter choke, 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 certain 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. 6.22. The satisfactory explanation of this breakdown of the junction was first given by the American scientist, Zener. Therefore, the breakdown voltage is sometimes called *zener voltage* and the junction current is known as *zener current*.

The breakdown of 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. Hence, an ordinary crystal diode is properly doped so that it has a sharp breakdown voltage, it is called

6.24
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6.27

The analysis
of the two

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The circuit
voltage V_{out}

than $0.5 V$
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page

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:

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

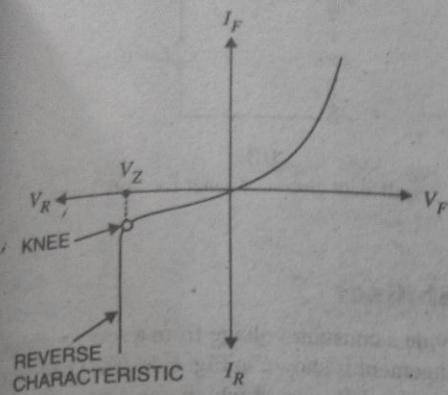


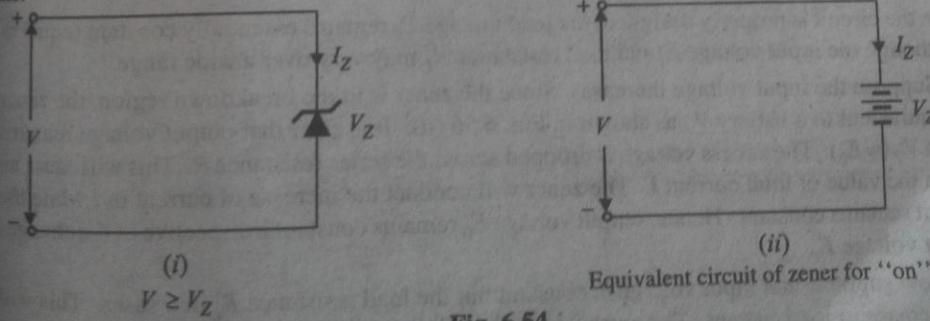
Fig. 6.52

- When forward biased, its characteristics are just those of ordinary diode.
- 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 breakdown 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.



Equivalent circuit of zener for "on" state

Fig. 6.54

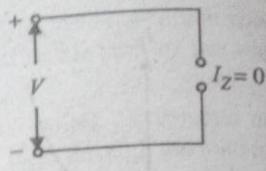
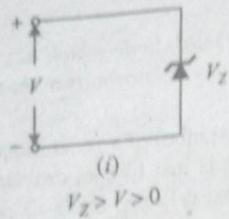
(ii) "OFF" state. When the reverse voltage across the zener diode is less than V_Z but greater than 0 V, the zener diode is in the "OFF" state. Under such conditions, the zener diode can be represented by an open-circuit as shown in Fig. 6.55 (ii).

* 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.



Fig. 6.53



Equivalent circuit of zener for "off" state

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 voltage 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 .

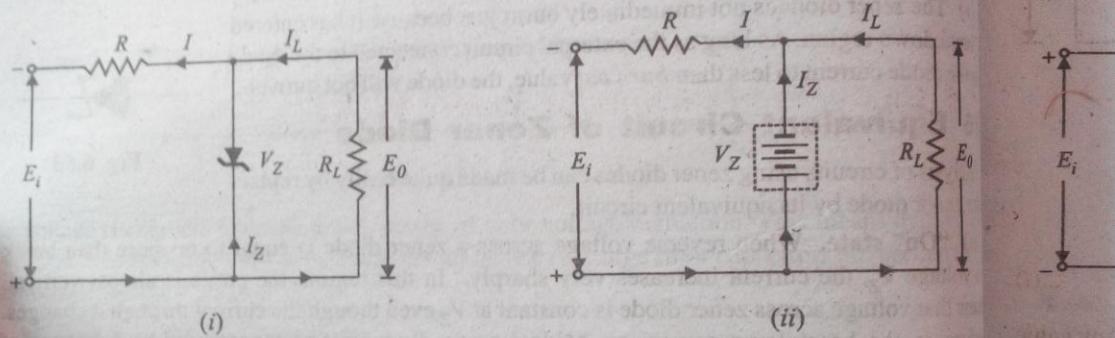


Fig. 6.56

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 its load current remains constant. Hence, output voltage E_0 remains constant irrespective of the change 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 ($\text{and hence source current } I$) 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 constant value.

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

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

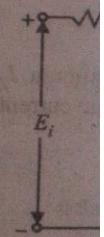
Appl

6.28

The analysis of diodes. The state or quantities

1. The voltage E determining open-circu

If V shown in
(i)



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).

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

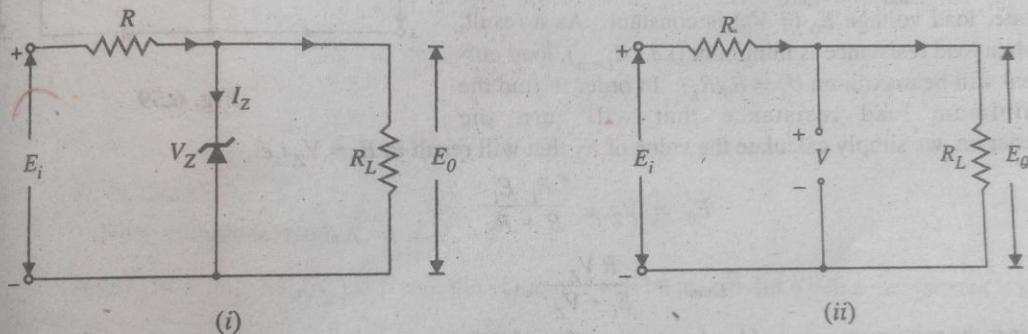


Fig. 6.57

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),

$$E_0 = V_Z$$

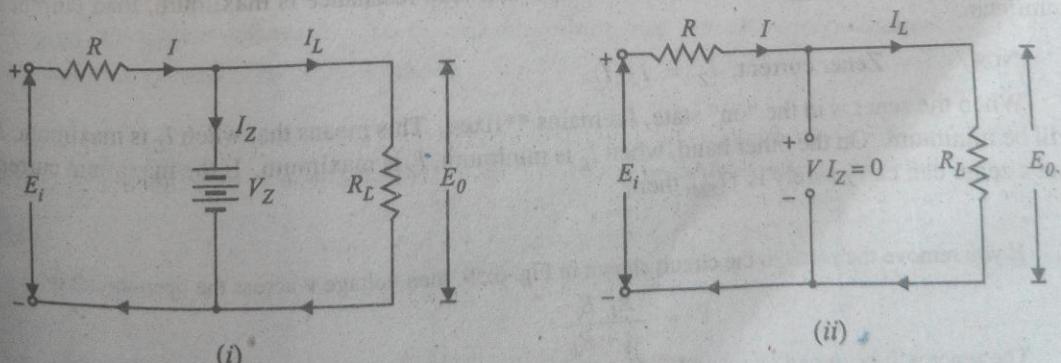


Fig. 6.58

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

Power dissipated in zener, $P_Z = V_Z I_Z$

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

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

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

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

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) $R_{L\min}$ and $I_{L\max}$. 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., $R_{L\min}$), 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.,

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

$$\therefore R_{L\min} = \frac{R V_Z}{E_i - V_Z}$$

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.

$$\text{Clearly; } I_{L\max} = \frac{E_0}{R_{L\min}} = \frac{V_Z}{R_{L\min}}$$

(ii) $I_{L\min}$ and $R_{L\max}$. 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 $\dagger I_{ZM}$, then,

* 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, $P_{ZM} = V_Z I_{ZM}$

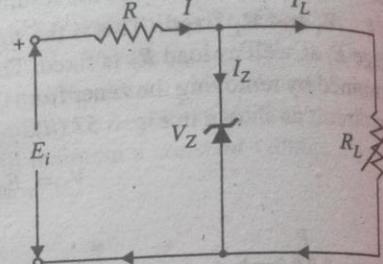


Fig. 6.59

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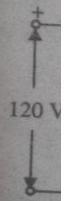
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(i)

(iii)



$$I_{L\min} = I - I_{ZM}$$

and

$$R_{L\max} = \frac{E_0}{I_{L\min}} = \frac{V_Z}{I_{L\min}}$$

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.

(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)

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

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

$$E_i = IR + E_0$$

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.

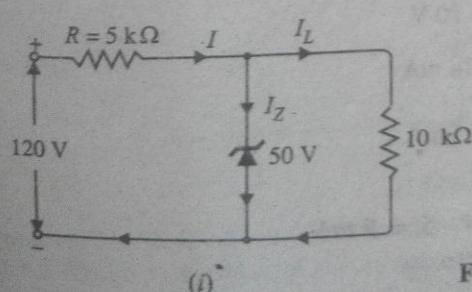
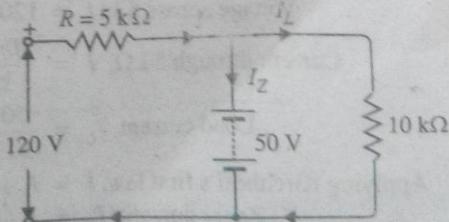


Fig. 6.61



(ii)

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),

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

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

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

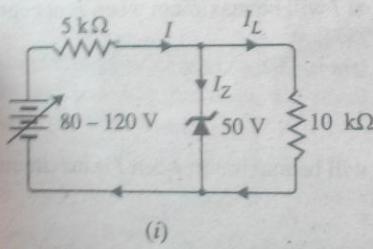
$$\text{Current through } R, I = \frac{70 \text{ V}}{5 \text{ k}\Omega} = 14 \text{ mA}$$

$$\text{Applying Kirchhoff's first law, } I = I_L + I_Z$$

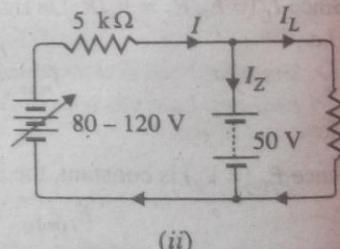
$$\therefore \text{Zener current, } I_Z = I - I_L = 14 - 5 = 9 \text{ mA}$$

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).



(i)



(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, $I = I_L + I_Z$

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

* $I_Z = I - I_L$. 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,

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

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

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

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

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.

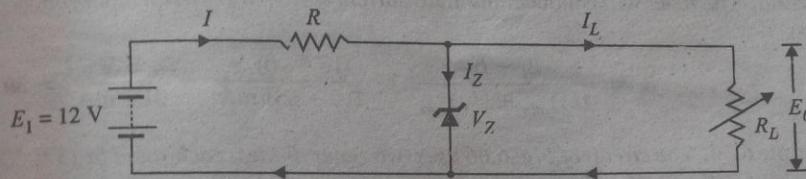


Fig. 6.63

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

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

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 28 V.

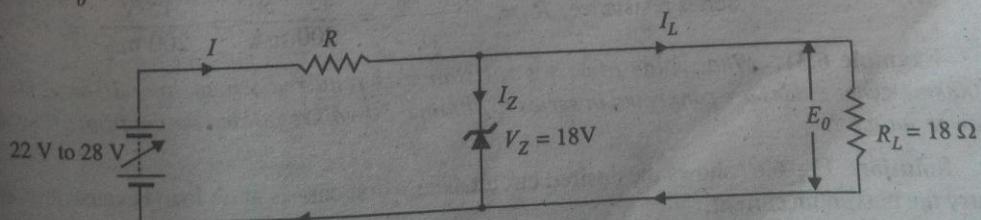


Fig. 6.64

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

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

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

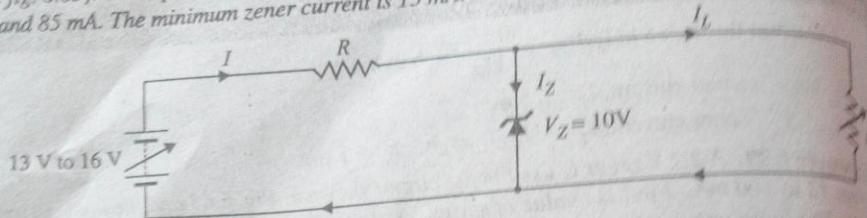


Fig. 6.65

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

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

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

(i) The regulated output voltage

(ii) The value of series resistance R

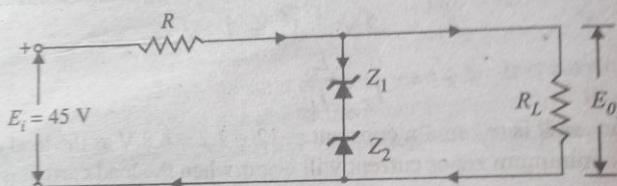


Fig. 6.66

Solution. When the desired regulated output voltage is higher than the rated voltage of a single zener, two or more zeners are connected in series as shown in Fig. 6.66. However, in such a case 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, 1000 mA zener diodes are connected in series to obtain a 30-volt regulated output from a 45-volt power source?

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

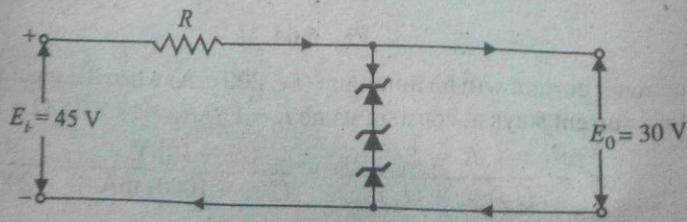


Fig. 6.67

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.

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

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

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

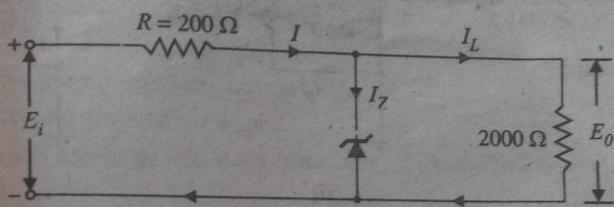


Fig. 6.68

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

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

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

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

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

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

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.

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

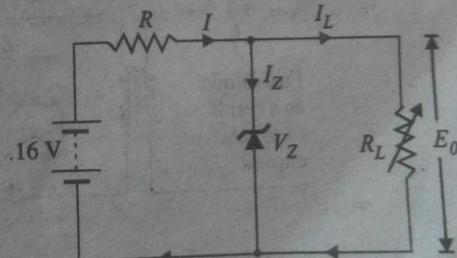


Fig. 6.69

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?

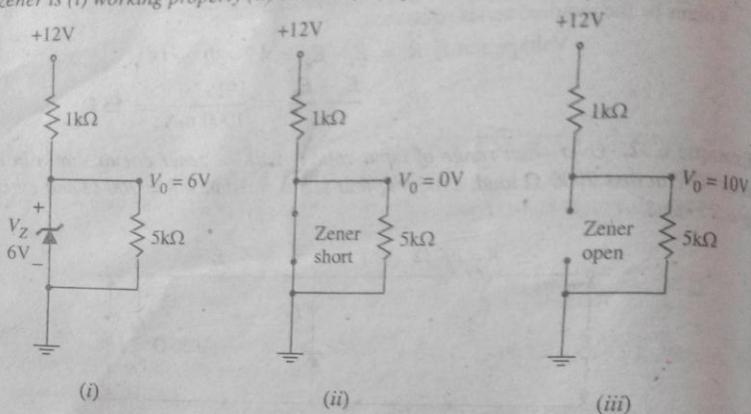


Fig. 6.70

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 near 6V [See Fig. 6.70 (i)].

(ii) If the zener diode is shorted [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?

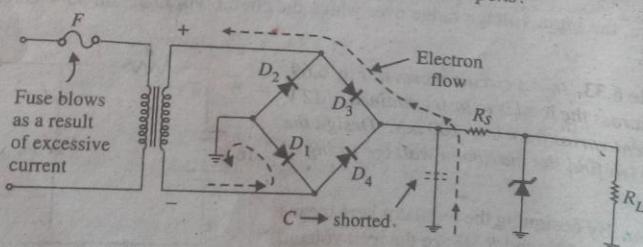


Fig. 6.71

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 voltage source through the secondary of the transformer, you will find that the current flows through the primary. Consequently, the power supply output to the load will be significantly lower than the input voltage.

6.29 Crystal Diodes

Semiconductor diodes (or crystal diodes) are similar to their electron-tube counterparts.

Advantages :

- (i) They are smaller.
- (ii) They are simpler.
- (iii) They require no vacuum diodes.

Disadvantages :

- (i) They are extremely expensive. Should the temperature may produce enough normally over a wide range.

It may be noted that silicon diode should not be used at temperatures above 100°C.

- (ii) They can handle small currents.

(iii) They cannot stand high voltage pulses. A transient pulse, may permanently damage the diode.

(iv) An overload for a short time may destroy the diode.

MUL

1. A crystal diode has
 (i) one pn junction
 (ii) two pn junctions
 (iii) three pn junctions
 (iv) none of the above

2. A crystal diode has forward bias voltage of
 (i) $k\Omega$
 (ii) $M\Omega$
 (iii) $M\Omega$
 (iv) $k\Omega$

3. If the arrow of crystal diode is pointing towards the bar, then diode is
 (i) p-n-p-n
 (ii) n-p-n-p
 (iii) p-n-p-n
 (iv) n-p-n-p

- Even when soldering the lead wires to reach the crystal diode, the heat must be applied to the lead wires and not to the crystal diode itself.

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.

1.29 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 :

It is because most of the crystal diodes are made of silicon which has a higher melting point than germanium. 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 withstand an overload for a short period and when the overload is removed, the tube will generally recover.

MULTIPLE-CHOICE QUESTIONS

1. A crystal diode has
 - (i) one *pn* junction
 - (ii) two *pn* junctions
 - (iii) three *pn* junctions
 - (iv) none of the above
2. A crystal diode has forward resistance of the order of
 - (i) kΩ
 - (ii) MΩ
 - (iii) Ω
 - (iv) none of the above
3. If the arrow of crystal diode symbol is positive, the diode is
 - (i) forward biased.
 - (ii) reverse biased.
 - (iii) either forward or reverse biased.
 - (iv) none of the above
4. The reverse current in a diode is of the order of
 - (i) kA
 - (ii) mA
 - (iii) μA
 - (iv) A
5. The forward voltage drop across a silicon diode is about
 - (i) 0.1 V
 - (ii) 0.3 V
 - (iii) 0.6 V
 - (iv) 1.2 V

In soldering of a crystal diode, care must be taken not to permit heat from the soldering iron to damage the diode.