Semiconductor Diode and Rectification

Introduction

A pn junction is known as a semiconductor diode. It is known that a pn junction conducts current easily when forward biased and practically no current flows when it is reverse biased. So, the outstanding property of a semiconductor diode is that it conducts current in one direction only. For this, it is used as a rectifier.

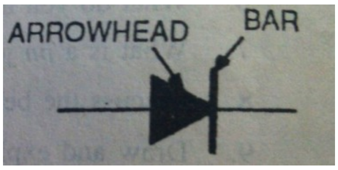

Figure 1.2.1

A semiconductor diode is represented by the schematic symbol shown in Figure 1.2.1. The arrow in the symbol indicates the direction of easier conventional current flow. When the diode is forward biased it permits current flow through it and while
it is reverse biased, it does not allow current flow through it.

Semiconductor diode as a Rectifier

Figure 1.2.2 illustrates the rectifying action of a semiconductor diode. The ac input voltage to be rectified; the diode and load R_L are connected in series. During the positive half cycle of ac input voltage, the arrowhead becomes positive w.r.t. bar. Therefore, the 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 ac voltage, the diode becomes reverse biased because now the arrowhead is negative w.r.t. bar. Therefore, the diode does not conduct and no voltage appears across load R_L. The result is that output consists of positive half cycles of input ac voltage while the negative half cycles are suppressed. In this way semiconductor diode has been able to do rectification i.e. change ac into dc.

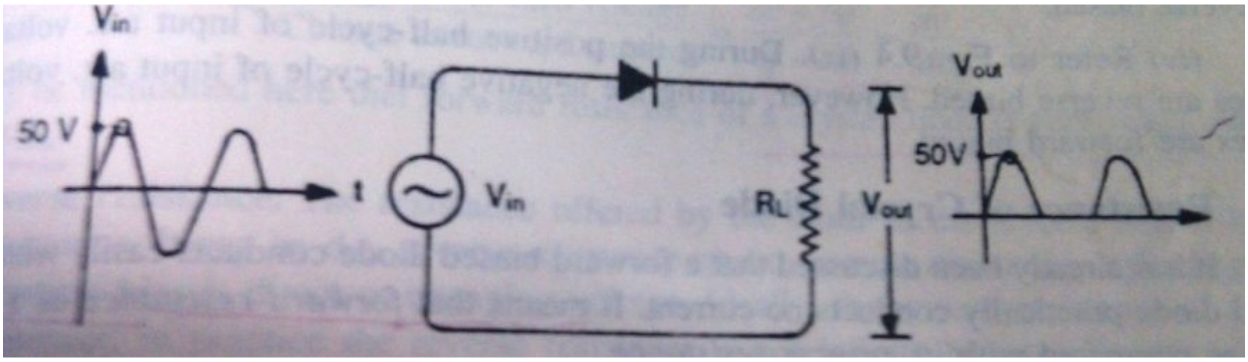

Figure 1.2.2

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

Resistance of a Semiconductor Diode

When the diode is forward biased it conducts easily whereas a reverse biased diode practically conducts no current. It means that forward resistance of a diode is quite small as compared to its reverse resistance.

1) Forward resistance: The resistance offered by the diode to forward bias is known as forward resistance. The resistance is not the same for the flow of direct current as for the changing current. Accordingly, this resistance is of two types, namely; dc forward resistance and ac forward resistance.

i) **dc forward resistance**: It is the opposition offered by the diode to the direct current. It is measured by the ratio of dc voltage across the diode to the resulting dc current through it. Refer to the Figure 1.2.3(a) which shows forward characteristic of a diode. When forward voltage is OA, the forward current is OB. So,

$$\textit{dc forward resistance, } R_f = \frac{OA}{OB}$$

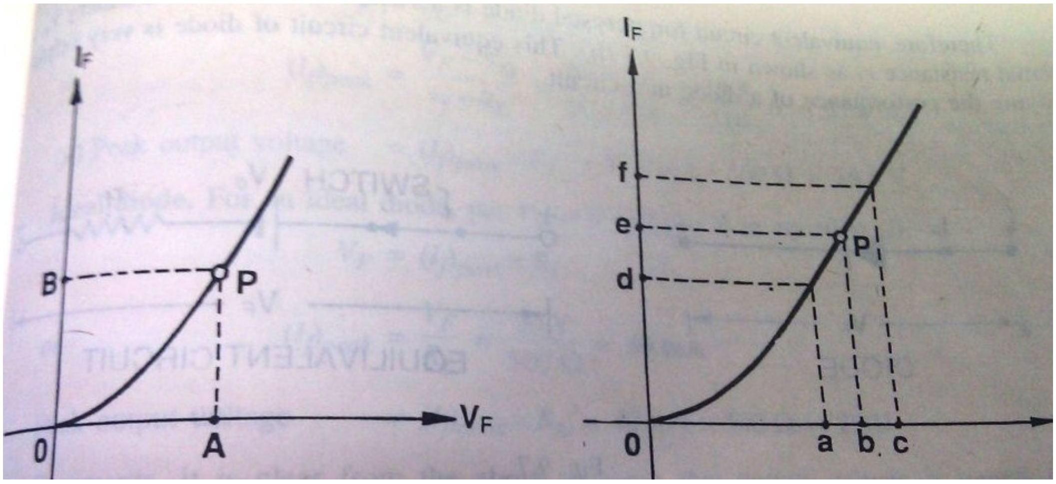

Figure 1.2.3

ii) **ac 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 the diode to the resulting change in current through it. i.e.

$$\textit{ac forward resistance} = \frac{\textit{Change in voltage across diode}}{\textit{Corresponding change in current}}$$

Refer to the Figure 1.2.3(b); $\textit{ac forward resistance, } R_f = \frac{ac}{df}$

Forward resistance of a semiconductor diode is very small, ranging from 1 to 25 Ω.

2) **Reverse resistance**: The resistance offered by the diode to the reverse bias is known as reverse resistance. It can be dc reverse resistance or ac reverse resistance depending upon whether the reverse bias is direct or changing voltage. Ideally the reverse resistance of a diode is infinite. In Ge diodes, the ratio of reverse to forward resistance is 40000: 1 while for Si this ratio is 1000000: 1.

Equivalent circuit of a semiconductor diode

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 Figure 1.2.4(a). 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:

i. potential barrier V_0
ii. internal drop $I_f\, r_f$

So, $V_F = V_0 + I_f r_f$

For a Si diode, $V_0 = 0.7$ V whereas for Ge diode $V_0 = 0.3$ V.

Therefore, equivalent circuit for a diode is a switch in series with a battery V_0 and internal resistance r_f as shown in Figure 1.2.4(b).

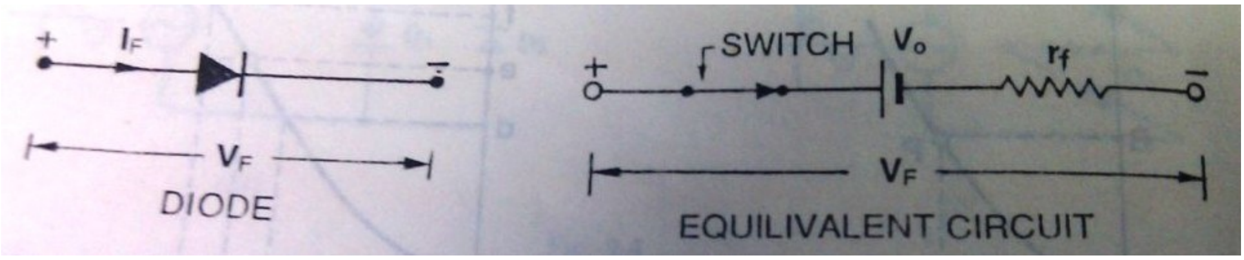

Figure 1.2.4

Ideal diode: An ideal diode is one which behaves as a perfect conductor when forward biased and as a perfect insulator when reverse biased. In such situation $r_f = 0$ and V_0 is negligible.

Important 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 carry. If this value exceeded, the diode may be destroyed due to excessive heat. For this reason, manufacturer's data sheet specifies the maximum forward current.

Peak Inverse voltage (PIV): It is maximum reverse voltage that a diode can withstand without destroying the junction. PIV 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 ac voltage.

Reverse current or Leakage current: It is the current that flows through a reverse biased diode. This current is due to minority carriers. The reverse current is small. For Si diode its value is extremely small (1µA) and for Ge diode it is appreciable (~100µA).

Semiconductor diode Rectifiers

The electric power available worldwide is usually an ac supply. The supply voltage varies sinusoidally and has a frequency of 50 or 60 Hz. But there are many applications e.g. electronic circuits, where dc supply is needed. When such a dc supply is required, the mains ac supply is rectified by using semiconductor diodes. Two types of rectifiers are used: (i) Half wave rectifier and (ii) Full wave rectifier.

Half-Wave Rectifier

In half wave rectification, the rectifier conducts current only during the positive half cycles of input ac supply. The negative half cycles of ac supply are suppressed. That is, during negative half cycles, no current is conducted and hence no voltage appears across the load. Therefore, current always flows in one direction.

Figure 1.2.5 shows the circuit where a single diode acts as half wave rectifier. The ac supply to be rectified is applied in series with the diode and load resistance R_L. Generally ac supply is given through a transformer. The use of transformer permits two advantages. Firstly, it allows to step up or step down the ac input voltage as the situation demands. Secondly, the transformer isolates the rectifier circuit from the power line and thus reduces the risk of electric shock.

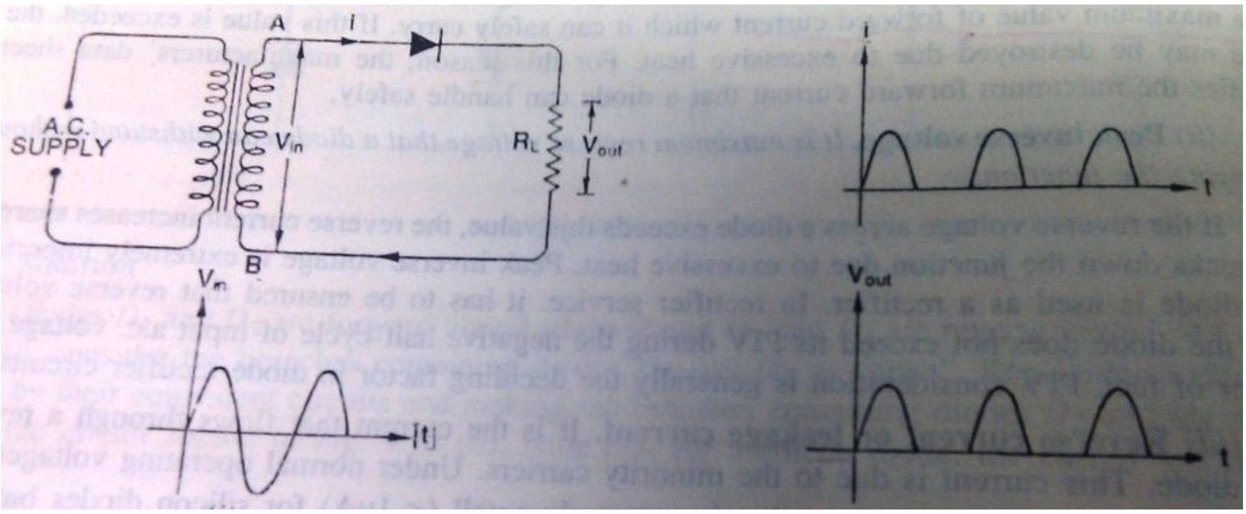

Figure 1.2.5

Operation:

The ac voltage across the secondary winding AB changes polarities after every half-cycles. During the positive half cycle of input ac 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 ac voltage only; it is blocked during the negative half cycles. In this way, current flows through the load R_L always in the same direction. Hence dc output is obtained across R_L. It may be noted that output across load is pulsating dc. These pulsations in the output are further smoothened with the help of filter circuits.

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

i. The pulsating current in the load contains alternating component whose basic frequency is equal to the supply frequency. So, filtering is required.
ii. The ac supply delivers power only half the time. Therefore, the output is low.

Efficiency of a Half Wave Rectifier

The ratio of dc power output to the applied input ac power is known as rectifier efficiency. i.e.

$$Rectifier\ efficiency,\ \eta = \frac{dc\ power\ output}{Input\ ac\ power}$$

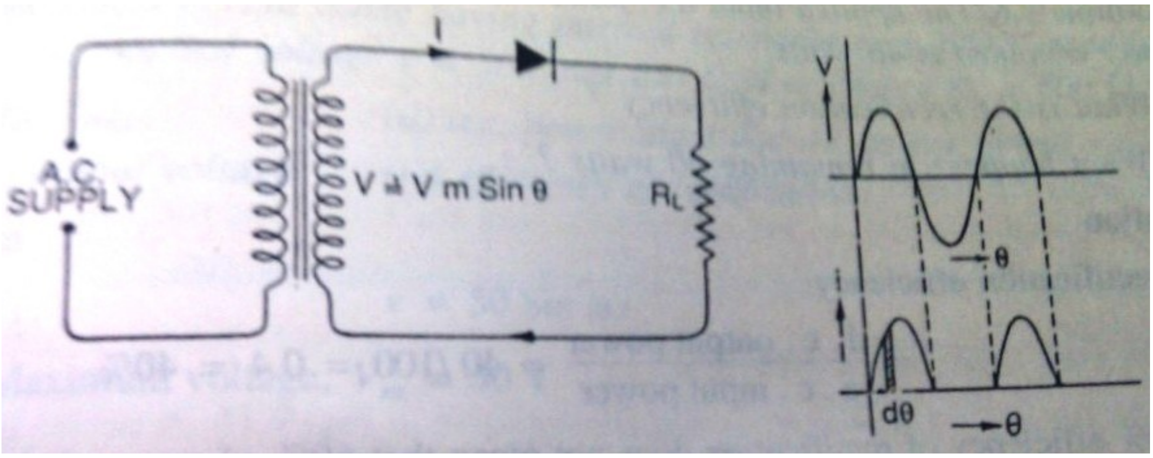

Figure 1.2.6

Consider a half wave rectifier shown in Figure 1.2.6. Let v = V_m Sin θ be the alternating voltage that appears across the secondary winding. Let r_f and R_L be the diode resistance and load resistance respectively. The diode conducts during positive half cycles of ac supply while no current conduction takes place during negative half cycles.

dc power: The output current is pulsating dc. So, average current,

$$I_{av} = I_{dc} = \frac{1}{2\pi}\int_0^{\pi} i d\theta = \frac{1}{2\pi}\int_0^{\pi} \frac{V_m sin\theta}{r_f+R_L} d\theta = \frac{V_m}{2\pi(r_f+R_L)}\int_0^{\pi} Sin\theta\ d\theta = \frac{I_m}{\pi}$$

So, dc power, $P_{dc} = I_{dc}^2 \times R_L = (I_m / \pi)^2 .R_L$.

ac power input: ac power input is given by

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

For a half wave rectified wave, $I_{rms} = I_m /2$. So, $P_{ac} = = [I_{rms}/2]^2 (r_f + R_L)$

So, Rectifier efficiency, $\eta = \frac{d.c.output\ power}{a.c.input\ power} = \frac{P_{dc}}{P_{ac}} = \frac{0.406}{1+\frac{r_f}{R_L}}$

The efficiency will be maximum if r_f is negligible as compared to R_L. So, maximum efficiency = 40.6%. This shows that in half wave rectification, a maximum of 40.6% of ac power is converted into dc power.

Full Wave Rectifier

In full wave rectification, current flows through the load in the same direction for both half cycles of input ac voltage. This can be achieved with two diodes working alternately. For the positive half cycle of input voltage, one diode supplies current to the load and for the negative

half cycle, the other diode does so; current being always in the same direction through the load. Therefore, a full wave rectifier utilizes both half cycles of input ac voltage to produce the dc output.
The following two circuits are commonly used for full wave rectification:

(i) Centre tap full wave rectifier and (ii) Full wave bridge rectifier.

Centre Tap Full Wave Rectifier

The circuit employs two diodes D_1 and D_2 as shown in Figure 1.2.7. A centre tapped secondary winding AB is used with two diodes connected so that each uses one half cycle of input ac voltage. In other words, diode D_1 utilizes the ac voltage appearing across the upper half OA of secondary winding for rectification while diode D_2 uses the lower half winding OB.

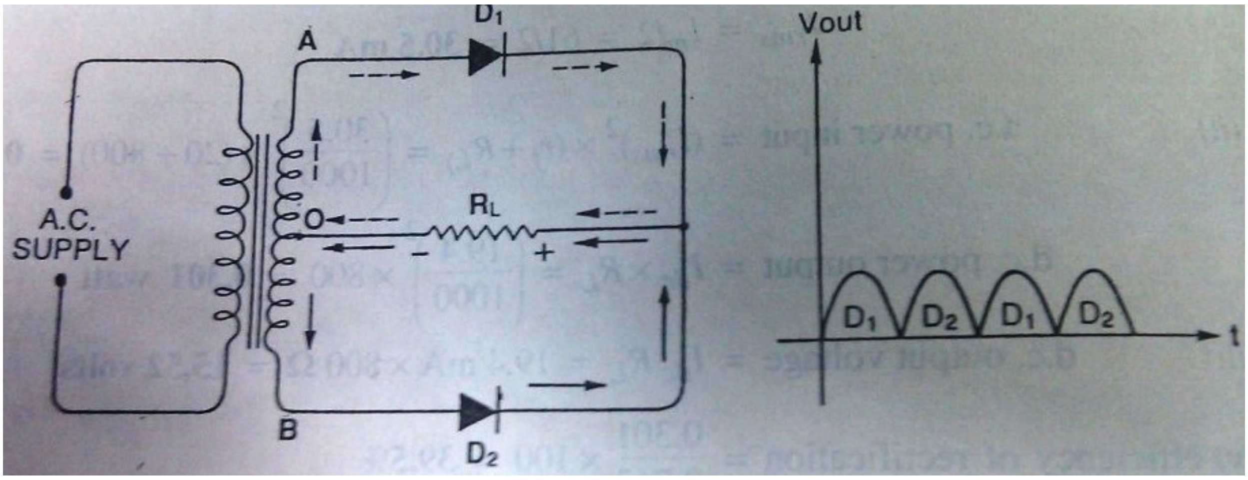

Figure 1.2.7.

Operation: During the positive half cycle of secondary voltage, end A of the secondary winding becomes positive and end B negative. This makes the diode D_1 forward biased and diode D_2 reverse biased. Therefore diode D_1 conducts while diode D_2 does not. The conventional current flow is through diode D_1, load resistor R_L, and the upper half of secondary winding as shown by the dotted arrows. During the negative half cycle, end A of the secondary becomes negative and end B positive. Therefore, diode D_2 conducts while diode D_1 does not. The conventional current flow is through diode D_2, load resistor R_L, and the lower half of secondary winding as shown by solid arrows. Referring to Figure 1.2.7, it may be seen that current in the load R_L is in the same direction for both half cycles of input ac voltage. Therefore, dc is obtained across the load R_L. Also, the polarities of the dc output across the load should be noted.

Peak Inverse Voltage: When the secondary voltage reaches its maximum value in the positive direction, diode D_1 is conducting and D_2 is non-conducting. So, whole the secondary voltage appears across the non conducting diode. Consequently the peak inverse voltage is twice the maximum voltage across the half secondary winding, i.e.

$$PIV = 2\ V_m$$

Disadvantages: (i) It is difficult to locate the centre tap on the secondary winding, (ii) The dc output is small as each diode utilizes only one half of the transformer secondary voltage, and (iii) The diodes used must have high peak inverse voltage.

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 Figure 1.2.8. The ac 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.

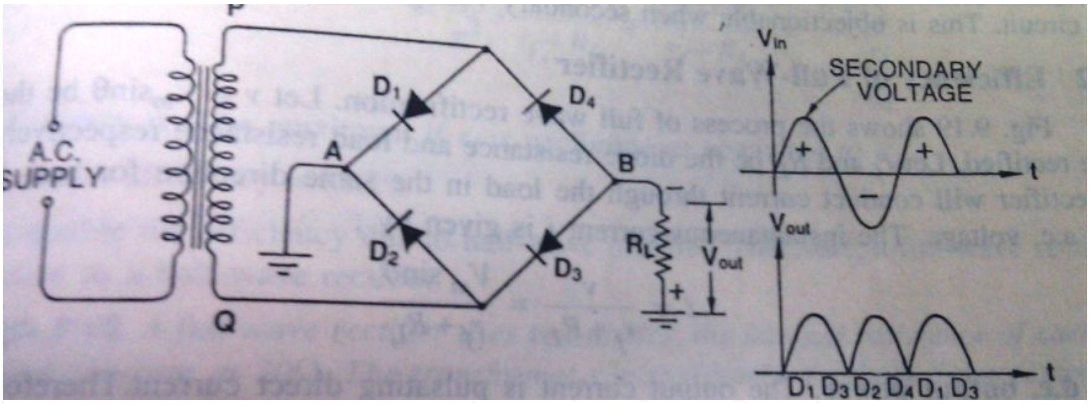

Figure 1.2.8

Operation: During the positive half cycle of secondary voltage, the end P of the secondary winding becomes positive and end Q negative. This makes diode D_1 and D_3 forward biased while diode 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 Figure 1.2.9(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, the end P of the secondary winding becomes negative and end Q positive. This makes diode D_2 and D_4 forward biased while diode 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 Figure 1.2.9(ii). The conventional current flow is shown by solid arrows. It may be seen that current flows from A to B through the load in the same direction as for the positive half cycle. Therefore, dc output is obtained across load R_L.

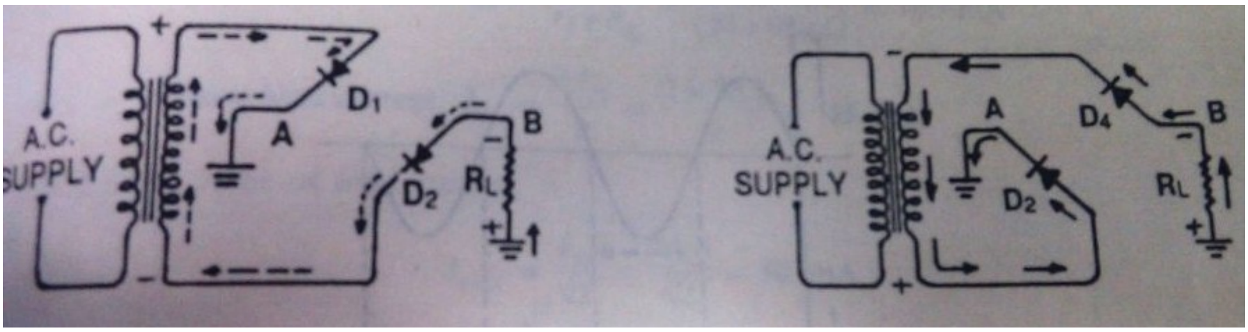

Figure 1.2.9

Peak Inverse Voltage: Referring to Figure 1.2.8., when end P is positive, diode D_1 conducts whereas diode D_2 does not conduct. By studying the circuit PD_1D_2Q it is easy to see that whole of the secondary voltage is applied in the reverse direction across D_2. Hence, PIV of each diode is equal to the maximum secondary voltage.

Advantages: (i) The need for centre tapped transformer is eliminated, (ii) The output is twice that of the centre tap circuit for the same secondary voltage, (iii) The PIV is one half that of the centre tap circuit.

Disadvantages: (i) It requires four diodes, (ii) Voltage drop in the internal resistance of the rectifying unit will be twice as great as in the centre tap circuit.

Efficiency of Full Wave Rectifier

Consider the full wave rectifier shown in Figure 1.2.9. Let v = V_m Sin θ be the alternating 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 ac voltage. The instantaneous current i is given by

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

dc output power: The output current is pulsating dc. So, average current,

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

So, dc power, $P_{dc} = I_{dc}^2 \times R_L$

ac input power: The ac input power is given by

$$P_{AC} = I_{rms}^2 \times (r_f + R_L)$$

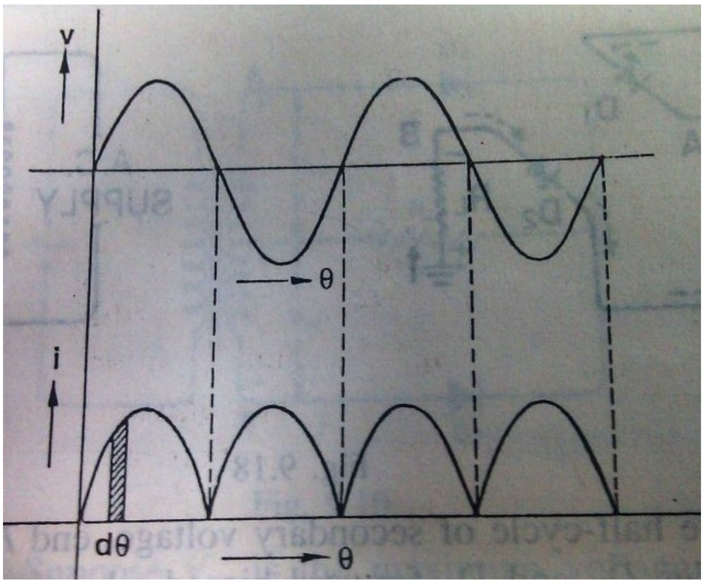

Figure 1.2.10

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

Nature of Rectifier Output

The output of a rectifier is pulsating dc as shown in Figure 1.2.10.Such a wave contains a dc component and an ac component. The ac component is responsible for the pulsation in the wave.

Ripple Factor

The effectiveness of a rectifier depends upon the magnitude of ac component in the output. So, ripple factor is very important. Smaller the ac component, the more effective is the rectifier. The ratio of rms value of ac component to the dc component in the rectifier output is known as ***ripple factor***. That is

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

Mathematical analysis:

The output of a rectifier contains a dc component and an ac component. The undesired ac component has a frequency of 100 Hz i.e. double the supply frequency 50 Hz and is called *ripple*, shown in Figure 1.2.11. It is a fluctuation superimposed on the dc component.

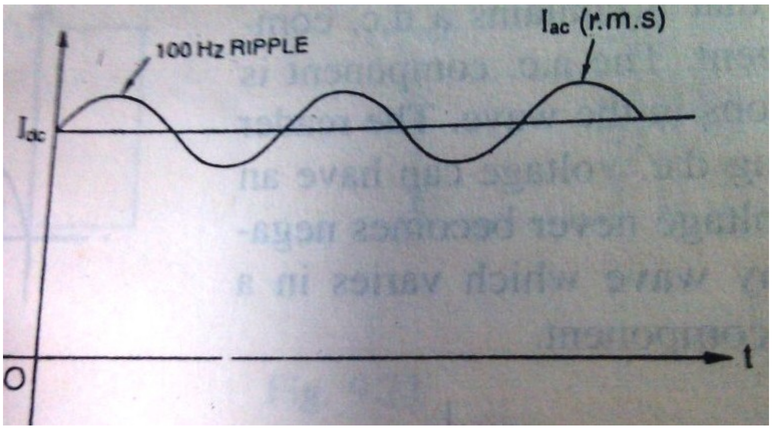

Figure 1.2.11

By definition, the effective i.e. rms value of total load current is given by:

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

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

For half wave rectification, $I_{rms} = I_m/2$ So, $I_{dc} = I_m/\pi$

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

So ac component exceeds dc component in the half wave rectifier. So it is ineffective.

For full wave rectification, $I_{rms} = I_m/\sqrt{2}$ So, $I_{dc} = 2\,I_m/\pi$

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

So, dc component is more than the ac component. So, pulsation in the output is less than in half wave rectifier. For this reason full wave rectification is used for conversion of ac into dc.

Filter Circuits

The output of a rectifier contains a dc component and an ac component. But it is required to produce pure dc supply for using at various places in electronic circuits. To do so, a filter circuit is used which removes or filters out the ac components and allows only the dc component to reach the load.

A filter circuit is a device which removes the ac component of rectifier output but allows the dc component to reach the load.

So, a filter circuit should be installed between the rectifier and the load as shown in Figure 1.2.12.

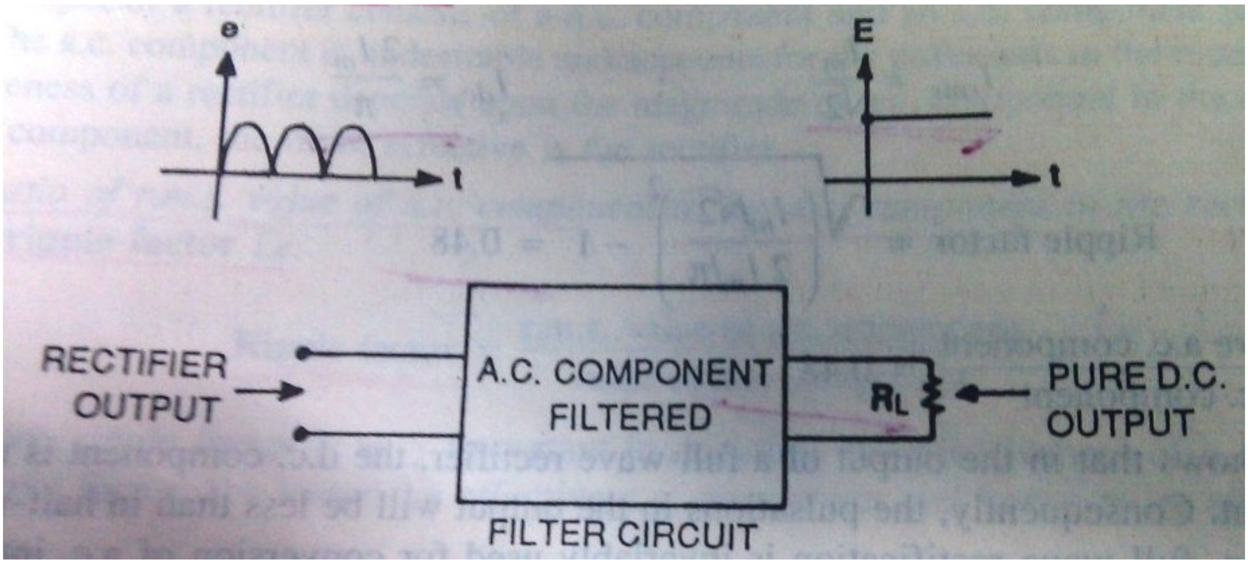

Figure 1.2.12

A filter circuit is generally a combination of inductors (L) and capacitors (C). A capacitor passes ac readily but does not pass dc. On the other hand an inductor opposes ac but allows dc to pass through it. So, a suitable network of L and C can effectively remove the ac component, allowing dc component to reach the load.

Types of Filter Circuits

The most commonly used filter circuits are capacitor filter, choke input filter and capacitor input π filter.

Capacitor Filter: Figure 1.2.13 shows a typical capacitor filter circuit. It consists of a capacitor C placed across the rectifier output in parallel with load R_L. Pulsating rectifier output 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, the 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 decreases. Immediately the next voltage peak comes and recharges the capacitor. This process is repeated again and again and very little ripple is left in the output voltage wave form. The capacitor filter circuit is very popular because of its low cost, small size, little weight and good characteristics. For small load currents, 50 mA, it is preferred. It is commonly used in small power supplies in transistor radio.

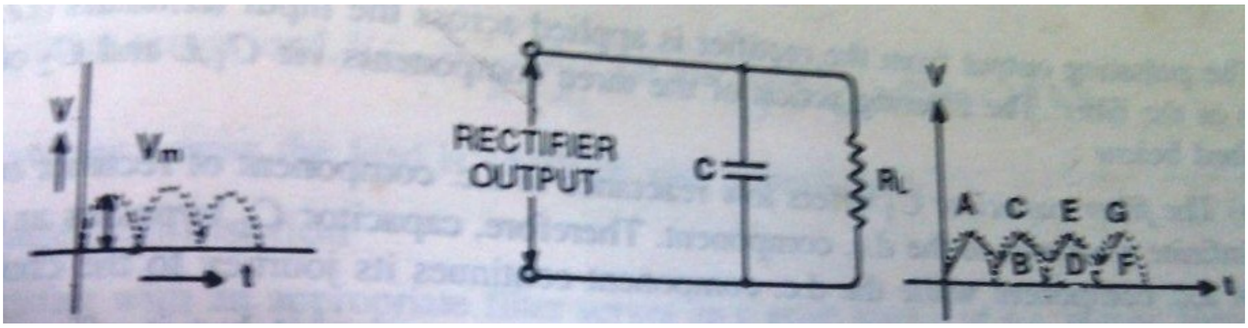

Figure 1.2.13

Choke input filter: Figure 1.2.14 shows a typical capacitor filter circuit. It consists of a choke L connected in series with the rectifier output and a filter capacitor C across the load R_L. Only a single filter section is shown, but several identical sections are often used to reduce the pulsation effectively.

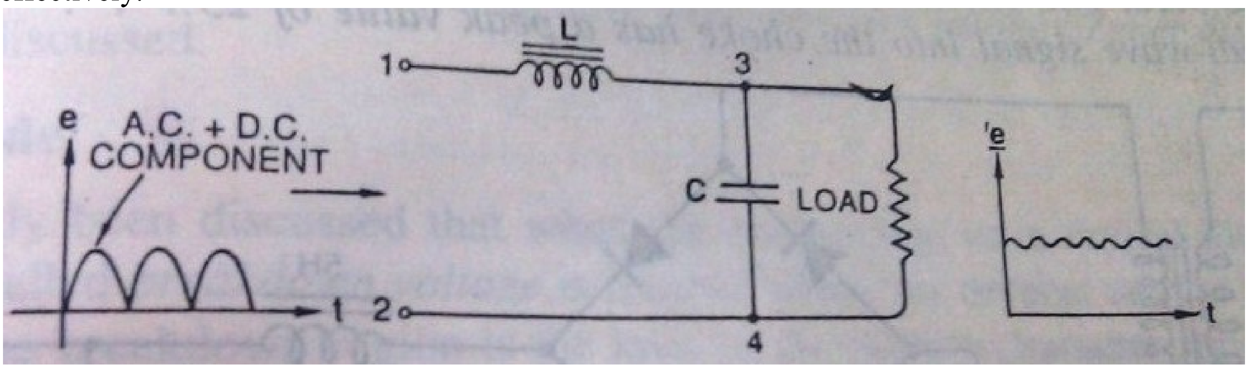

Figure1.2.14

Pulsating rectifier out put is applied across the input terminals of filter circuit. The choke offers high opposition to the passage of ac components while whole of dc component appears across the load. At terminal 3, the rectifier output contains dc component and the remaining part of ac component. Now the low reactance of filter capacitor by-passes the ac component. Therefore, only dc component reaches the load.

Capacitor input filter or π – filter: Figure 1.2.15 shows a typical capacitor input filter or π-filter. It consists of a capacitor C_1 connected across the rectifier output, a choke L in series and another filter capacitor C_2 connected across the load. Pulsating rectifier out put is applied across the input terminals of filter circuit. Capacitor C_1 offers low reactance to ac but offers infinite reactance to the dc. The choke offers high opposition to the passage of ac components while offers zero reactance to dc. Therefore, it allows dc component appears across the load.

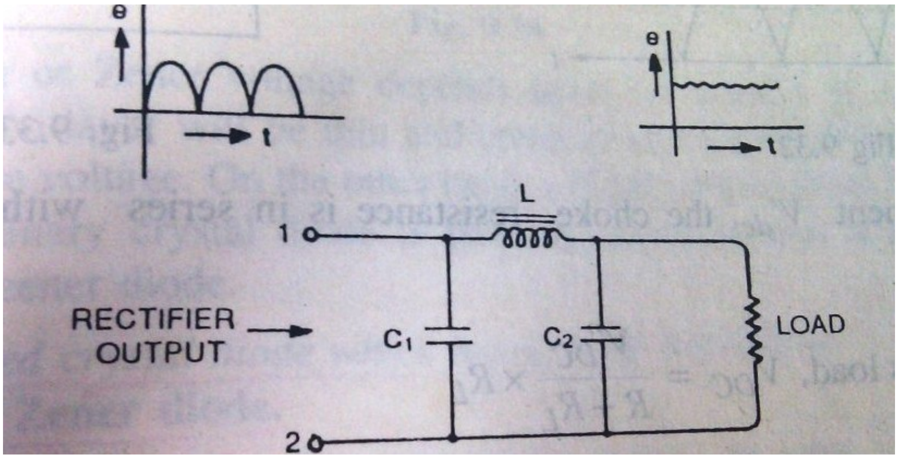

Figure 1.2.15

Voltage Stabilization

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 stabilizing device, called *stabilizer* is used. *Zener* diode is used for voltage stabilization.

Zener Diode

When the reverse bias on a semiconductor diode is increased, a critical voltage, called breakdown voltage is reached where the reverse current increases sharply to a high value as shown in Figure 1.2.16. The satisfactory explanation of this breakdown was first given by American Scientist C. Zener. Breakdown voltage is called Zener voltage andthe sudden increase in current is known as Zener current.

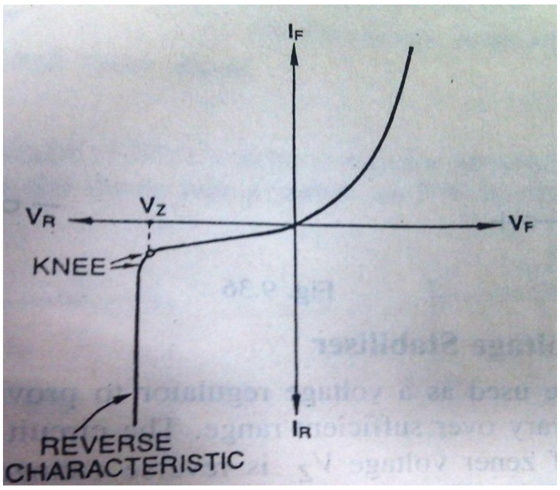

Figure 1.2.16

Breakdown or Zener voltage depends upon the amount of doping. If the diode is heavily doped, depletion layer will be thin and consequently the breakdown of the junction will occur at a lower reverse voltage. On the other hand, a lightly doped diode has a higher breakdown voltage.
A properly doped semiconductor diode which has a sharp breakdown voltage is known as a Zener diode. The symbol of a zener diode is shown in Figure 1.2.17.

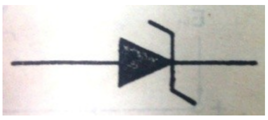
Figure 1.2.17

Equivalent Circuit of a Zener Diode

When the reverse voltage across a zener diode exceeds the breakdown voltage V_Z, the current increases 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 may be represented by a battery voltage V_Z as shown in Figure 1.2.18.

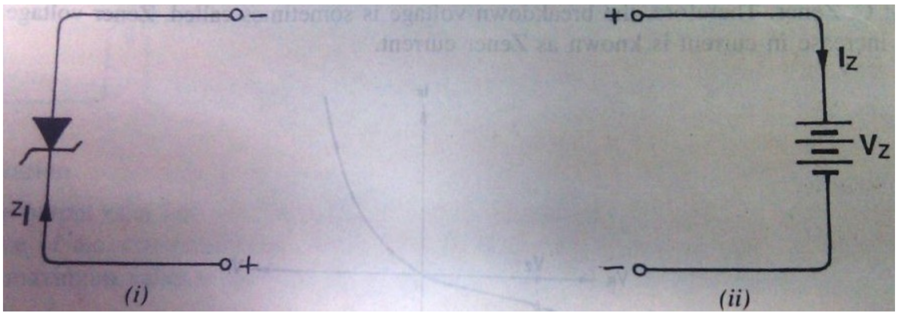

Figure 1.2.18

Zener Diode as Voltage Stabilizer

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 Figure 1.2.19. The zener diode of zener voltage V_Z is reverse connected across the load R_L across which constant output is desired. The series resistance R absorbs the output voltage fluctuations so as to maintain constant voltage across the load. Zener diode will maintain a constant voltage $V_Z = E_O$ across the load so long as the input voltage does not fall below V_Z.

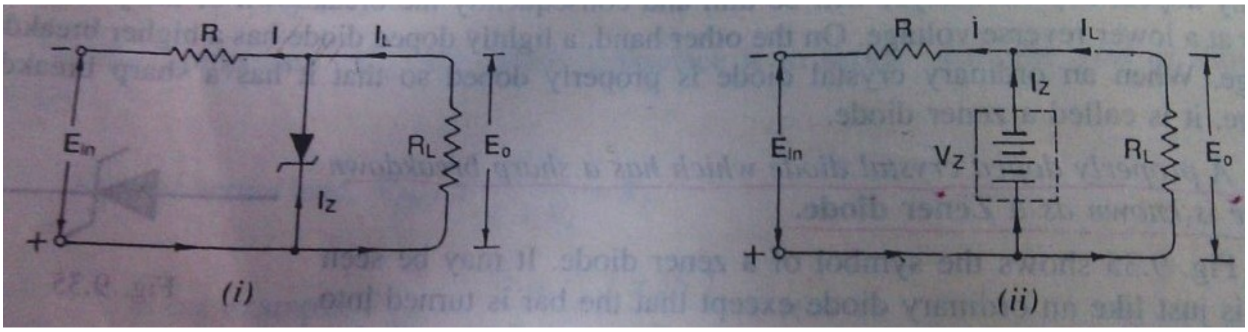

Figure 1.2.19.

When the circuit is properly designed, the load voltage E_O remains constant even though input voltage E_i and load resistance R_L may vary over a wide range.

1. **Input voltage increases**: Since the zener is in breakdown region, the zener diode is equivalent to a battery V_Z as shown in Figure 1.2.19(i). It is clear that output voltage remains constant at $V_Z = E_O$. 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 increased current while the load current remains constant. Hence, output voltage remains constant.

2. **Load resistance decreases**: This will increase in load current. The extra current can not come from the source because drop in R and hence source current 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. Hence, the output voltage stays at constant value.

Voltage drop across R $= E_i - E_O$

Current through R $I = I_Z + I_L$

Applying Ohm's law $R = (E_i - E_O) / (I_Z + I_L)$

Questions

1. What is a semiconductor or crystal diode? Explain its rectifying action.
2. What do you understand by dc and ac resistance of a semiconductor diode? How will you determine them from V-I characteristic of a crystal diode?
3. Draw the equivalent circuit of a crystal diode.
4. What is the importance of PIV in rectifier operation.
5. Describe a half wave rectifier. Derive its efficiency.
6. With a neat sketch, explain the working of i Centre-tap full wave rectifier ii full wave bridge rectifier.
7. Derive an expression for the efficiency of a full wave rectifier.
8. What is a ripple factor? What is its value for a half wav and full wave rectifier?
9. Describe the operation of i capacitor filter, ii choke input filter iii capacitor input filter.
10. What is a zener diode? Draw its equivalent circuit. Describe how a zener diode maintains constant voltage across the load.