Module 1

Semiconductor Diodes and Applications

Syllabus

Semiconductor diodes: PN junction diode, Characteristics and Parameters, Diode rectifiers-Half wave rectifier, Full wave rectifier, Zener diode as voltage regulators, Block diagram of DC power Supply.

1. PN Junction Semiconductor:

Two blocks of PN Junction Semiconductor material are represented in Fig. 1-1; one block is p-type material, and the other is n-type. The small circles in the p-type material represent holes, which are the majority charge carriers in p-type. The dots in the n-type material represent the majority charge carrier free electrons within that material. Normally, the holes are uniformly distributed throughout the volume of the p-type semiconductor, and the electrons are uniformly distributed in the n-type.

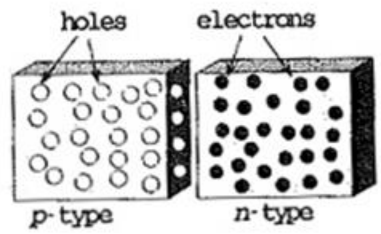

Figure 1-1 P-type and N-type semiconductor materials

In Figure 1-12, shows Semiconductor materials are shown representing a PN Junction. Holes and electrons are close together at the junction, so some free electrons from the n-side are attracted across the junction to fill adjacent holes on the p-side. They are said to diffuse across the junction from a region of high carrier concentration to one of low concentration. The free electrons crossing the junction create negative ions on the p-side by giving some atoms one more electron than their total number of protons. The electrons also leave positive ions (atoms with one fewer electron than the number of protons) behind them on the n-side.

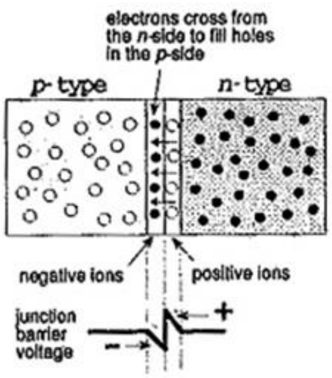

Figure 1-2 At a pn-junction, electrons cross from the n-side to fill holes in a layer of the p-side close to the junction

1.1.1 Barrier Voltage in PN Junction:

The n-type and p-type materials are both electrically neutral before the charge carriers diffuse across the junction. When negative ions are created on the p-side, the portion of the p-side close to the junction acquires a negative voltage, (see Fig.

1-2). Similarly, the positive ions created on the n-side gives the n-side a positive voltage close to the junction. The negative voltage on the p-side tends to repel additional electrons crossing from the n-side. Also, (thinking of the holes as positive particles) the positive voltage on the n-side tends to repel any hole movement from the p-side. Thus, the initial diffusion of charge carriers creates a barrier voltage in pn junction, which is negative on the p-side and positive on the n-side. The transfer of charge carriers and the resultant creation of the barrier voltage occur when the PN Junction Semiconductor are formed during the manufacturing

The magnitude of the barrier voltage in pn junction Semiconductor can be calculated from a knowledge of the doping densities, electronic charge, and junction temperature. Typical barrier voltages at 25°C are 0.3 V for germanium junctions and 0.7 V for silicon.

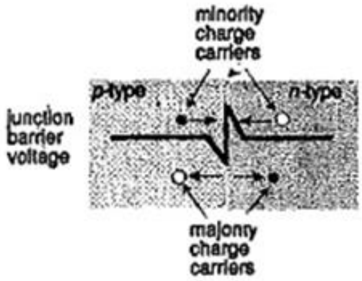

Figure 1-3 The barrier voltage at a pn junction assists the flow of minority charge carriers and opposes the flow of majority carriers

The barrier voltage in pn junction opposes both the flow of electrons from the n-side and the flow of holes from the p-side. Because electrons are the majority charge carriers in the n-type material, and holes are the majority charge carriers in the p-type, it is seen that the barrier voltage opposes the flow of majority carriers across the PN Junction Semiconductor, (see Fig. 1-3). Any free electrons generated by thermal energy on the p-side of the junction are attracted across the positive barrier to the n-side. Similarly thermally generated holes on the n-side are attracted to the p-side through the negative barrier presented to them at the junction. Electrons on the p-side and holes on the n-side are minority charge carriers. Therefore, the barrier voltage assists the flow of minority carriers across the junction, (Fig. 1-3).

1.1.2 Depletion Region in PN Junction:

The movement of charge carriers across the junction leaves a layer on each side which is depleted of charge carriers. This is the **Depletion Region in PN Junction** shown in Fig. 1-20(a). On the n-side, the depletion region consists of donor impurity atoms which, having lost the free electron associated with them, have become positively charged.

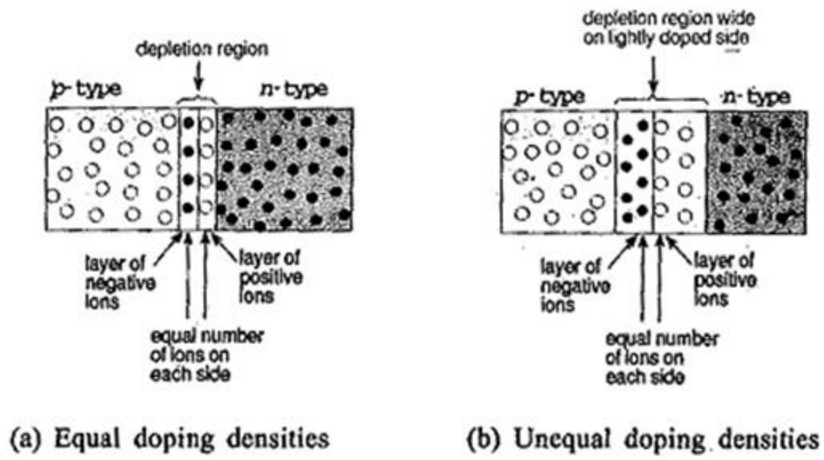

Figure 1-4 Charge carrier diffusion across a pn –junction creates a region depleted of charge carriers which penetrate deepest into the most lightly doped side.

The depletion region on the p-side is made up of acceptor impurity atoms which have become negatively charged by losing the hole associated with them. (The hole has been filled by an electron.)

On each side of the junction, equal numbers of impurity atoms are involved in the depletion region. If the two blocks of PN Junction Semiconductor material have equal doping densities, the depletion layers on each side have equal widths, (Fig 1-4(a)). If the p-side is more heavily doped than the n-side, as illustrated in Fig. 1-4(b), the depletion region penetrates more deeply into the n-side in order to include an equal number of impurity atoms on each side of the junction. Conversely, when the n-side is most heavily doped, the depletion region penetrates deepest into the p-type material.

1.1.3 Forward Bias PN Junction:

Consider the effect of an external bias voltage applied with the polarity of PN Junction Forward Bias shown in Fig. 1-5; positive on the p-side, negative on the n-side. The holes on the p-side, being positively charged particles, are repelled from the positive terminal and driven toward the junction. Similarly, the electrons on the n-side are repelled from the negative terminal toward the junction. The result is that the depletion region width and the barrier potential are both reduced.

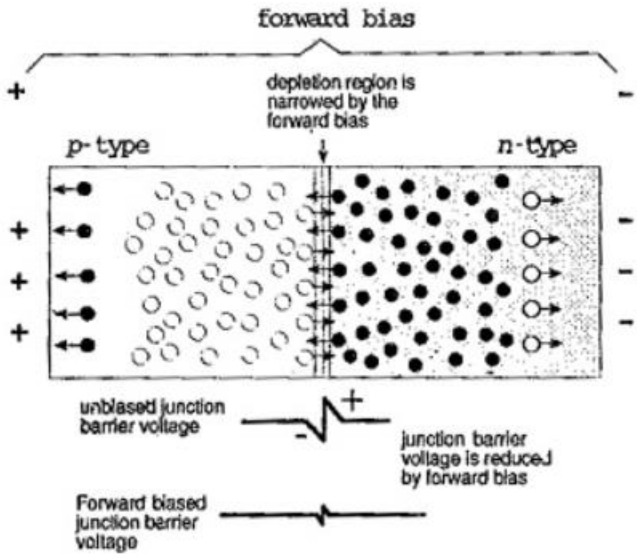

Figure 1.5- Forward biasing a pn-junction narrows the depletion region, reduces the barrier voltage, and causes a relatively large current to flow across the junction

When the applied bias voltage is progressively increased from zero, the barrier voltage gets smaller until it effectively disappears and charge carriers easily flow across the PN Junction Forward Bias. Electrons from the n-side are now attracted across to the positive bias terminal on the p-side, and holes from the p-side flow across to the negative terminal on the n-side, (thinking of holes as positively-charged particles). Thus, a majority carrier current flows, and the junction is said to be **PN Junction Forward Bias**.

Forward Bias Characteristics:

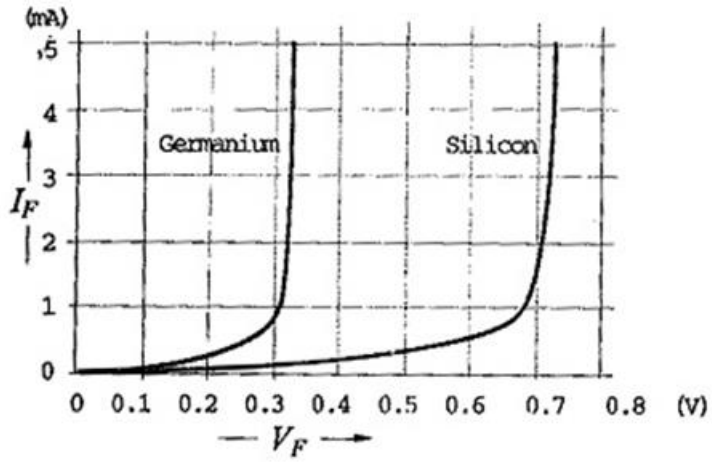

Figure 1-6 pn-junction forward characteristics. Germanium junction are forward biased at approximately 0.3V. A silicon junction requires approximately 0.7V for forward bias

The graph in Fig. 1-6 shows the forward current (I_F) plotted against forward voltage (V_F) for typical germanium and silicon pn-Junctions. In each case, the graph is known as the **forward characteristic** of the junction. It is seen that very little forward current flows until V_F exceeds the junction barrier, voltage (0.3 V for germanium, 0.7 V for silicon).

When V_F is increased from zero toward the knee of the characteristic, the barrier voltage is progressively overcome, allowing more majority charge carriers to flow across the junction. Above the knee of the characteristic I_F increases almost linearly with increase in V_F. The level of current that can be made to flow across a forward-biased pn-junction largely depends on the junction area.

1.1.4 Reverse Bias PN Junction:

When an external bias voltage is applied to a pn-junction, positive to the n-side and negative to the pride, electrons from the n-side are attracted to the positive terminal, and holes from the p-side are attracted to the negative terminal. As shown in Fig. 1-7, holes on the p-side of the junction are attracted away from the junction, and electrons are attracted away from the junction on the n-side. This causes the depletion region to be widened and the barrier voltage to be increased, as illustrated. With the barrier voltage increase there is no possibility of majority charge carrier current flow across the junction, and the junction is said to be Reverse Bias PN Junction. Because only a very small reverse current flows, a Reverse Bias PN Junction can be said to have a high resistance.

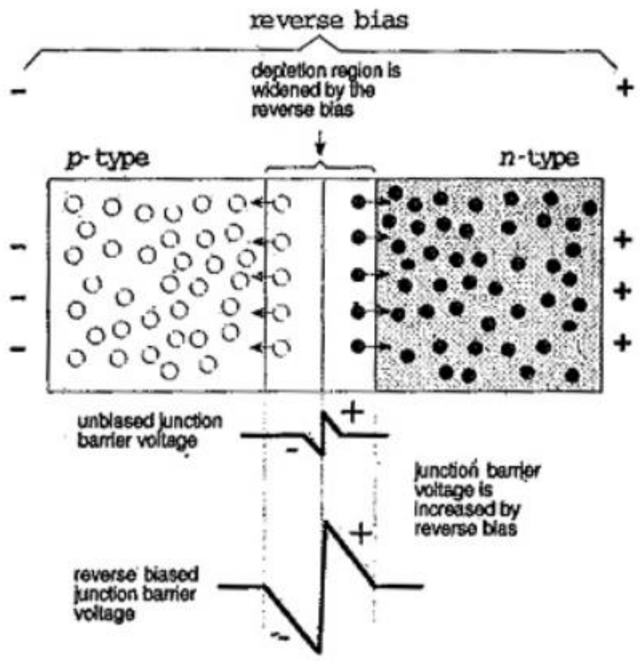

Figure 1-7 A reverse bias applied to a pn-junction causes the depletion region to widen, and increases the barrier voltage. Only a very small reverse current flows across the junction

Although there is no possibility of a majority charge carrier current flowing across a Reverse Bias PN Junction, minority carriers generated on each side can still cross the junction.

Electrons in the p-side are attracted across the junction to the positive voltage on the n-side. Holes on the n-side may flow across to the negative voltage on the p-side. This is shown by the junction reverse characteristic, or the graph of reverse current (I_R) versus reverse voltage (V_R), (Fig. 1-8).

VI Characteristics of Reverse Bias:

Only a very small reverse bias voltage is necessary to direct all available minority carriers across the junction, and further increases in bias voltage do not increase the current. This current is referred to as a R**everse Saturation Current**.

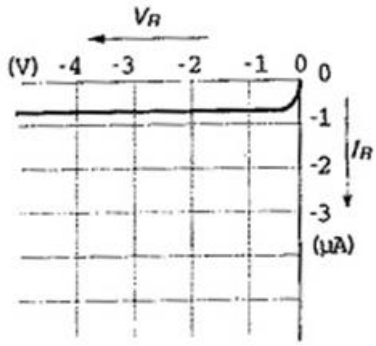

Figure 1-8 Current versus voltage characteristic for a reverse biased pn- junction

The reverse saturation current is normally a very small quantity, ranging from nano amps to micro amps, depending on the junction area, temperature, and semiconductor material.

1.1.5 PN Junction Diode Working Principle:

A PN Junction Diode Working Principle explains about the ability to permit substantial current flow when forward-biased, and to block current when reverse-biased. Thus, it can be used as a switch; on when forward-biased, and off when biased in reverse. In PN Junction Diode Working Principle, the copper wire connecting leads becomes an electronic device known as a **diode**.

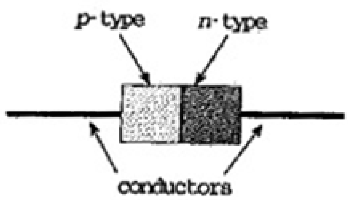

Figure 1-9 A semiconductor diode is a pn-junction with conductors for connecting the device to a circuit

The circuit symbol (or graphic symbol) for a diode is an arrowhead and bar, (Fig. 1-10). The arrowhead indicates the conventional direction of current flow when the diode is forward biased, (from the positive terminal through the device to the negative terminal). The p-side of the diode is always the positive terminal for forward bias and is termed the **anode**, The n-side, called the **cathode**, is the negative terminal when the device is forward biased.

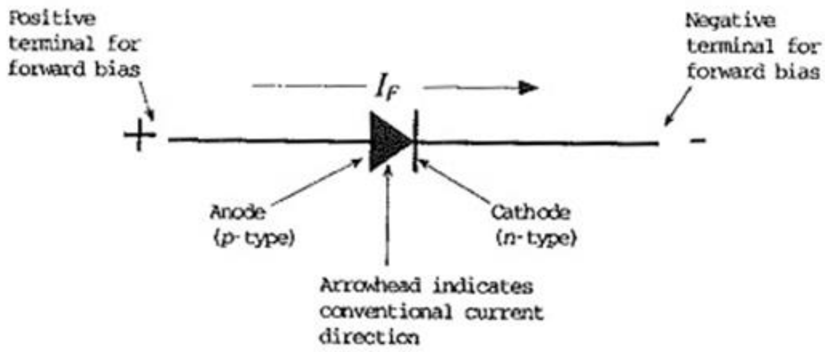

Figure 1-10 Diode circuit symbol. Current flows when the diode is forward biased: + on the anode, - on the cathode

1.1.6 Forward and Reverse Bias Characteristics of Diode:

Figures 1-11 and 1-12 show typical Forward and Reverse Bias Characteristics of Diode for low-current silicon and germanium diodes. From the silicon diode characteristics in Fig. 1-11, it is seen that the forward current (I_F) remains very low (less than microamps) until the diode forward-bias voltage (V_F) exceeds approximately 0.7 V. Above 0.7 V, I_F increases almost linearly with increase in V_F.

Forward and Reverse Bias Characteristics of Silicon Diode:

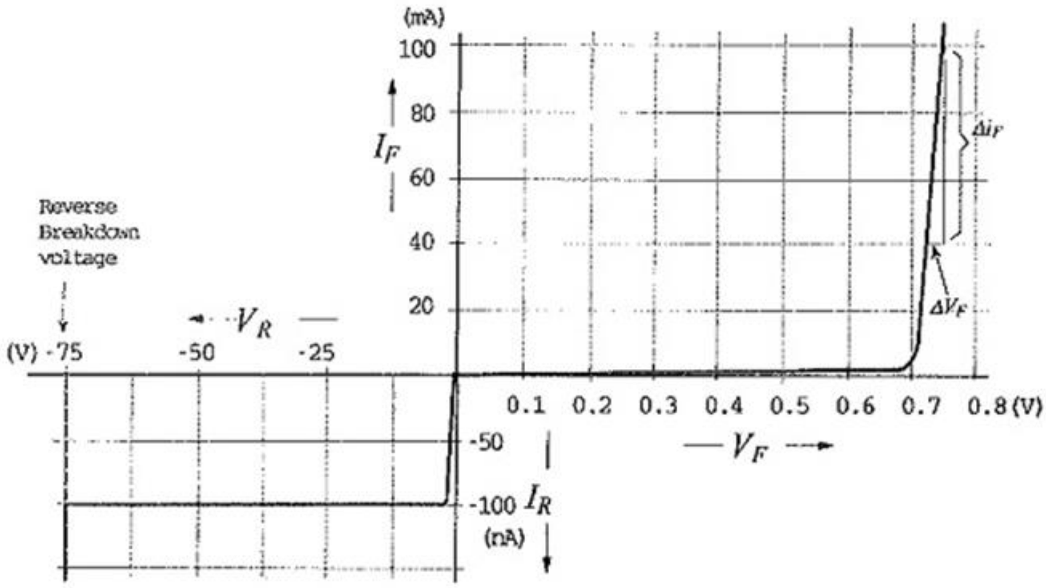

Figure 1-11 Typical forward and reverse characteristic for a silicon diode

Because the diode reverse current (I_R) is very much smaller than its forward current, the reverse characteristics are plotted with expanded current scales. For a silicon diode, I_R is normally less than 100 nA, and it is almost completely independent of the reverse-bias voltage. As already explained, I_R is largely a minority charge carrier **reverse saturation current**. A small increase in I_R can occur with increasing reverse-bias voltage, due to some minority charge carriers leaking along the junction surface. For a diode with the characteristics in Fig. 1-11, the reverse current is typically less than 1/10,000 of the lowest normal forward current level. Therefore, I_R is quite negligible when compared to I_F, and a reverse-biased diode may be treated almost as an open switch.

Forward and Reverse Bias Characteristics of Germanium Diode:

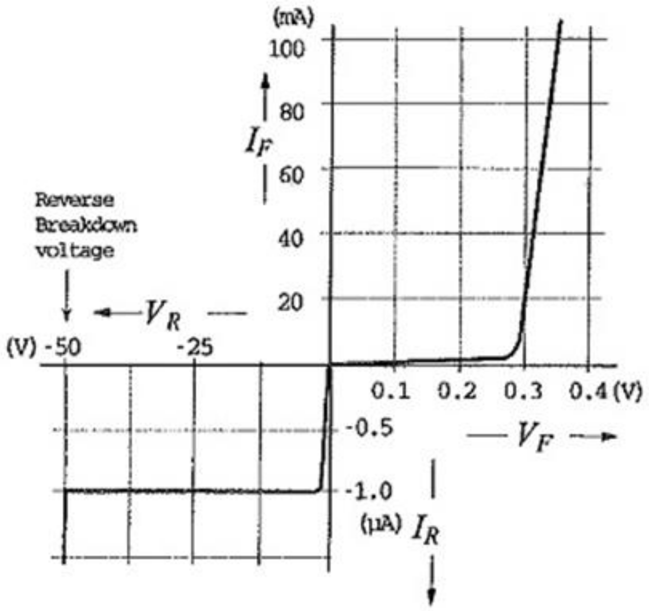

Figure 1-12 Typical forward and reverse characteristics for a germanium diode

When the diode reverse voltage (V_R) is sufficiently increased, the device goes into **reverse breakdown**. For the characteristics shown in Fig. 1-11, reverse breakdown occurs at 75 V. Reverse breakdown can destroy a diode unless the current is limited by a suitable series-connected resistor. Reverse breakdown is usefully applied in **Zener diodes**.

The Forward and Reverse Bias Characteristics of Germanium Diode are similar to those of a silicon diode, with some important differences. The forward voltage drop of a germanium diode is typically 0.3 V, compared to 0.7 V for silicon. For a germanium device, the reverse saturation current at 25°C may be around 1 µA, which is much larger than the reverse current for a silicon diode. Finally, the reverse breakdown voltage for germanium devices is likely to be substantially lower than that for silicon devices.

The lower forward voltage drop for germanium diodes can be a distinct advantage. However, the lower reverse current and higher reverse breakdown voltage of silicon diodes make them preferable to germanium devices for most applications.

The diode parameters of greatest interest are:

- **V_F – forward voltage drop**
- **I_R – reverse saturation current**
- **V_{BR} – reverse breakdown voltage**
- **r_d – dynamic resistance**
- **$I_{F(max)}$ – maximum forward current**

The values of these quantities are normally listed on the diode data sheet provided by device manufacturers. Some of the parameters can be determined directly from the Forward and Reverse Bias Characteristics of Diode. For the silicon diode characteristics in Fig. 1-11, $V_F \approx 0.7$ V, $I_R = 100$ nA, and $V_{BR} = 75$ V.

The **forward resistance** is a static quantity; it is a constant resistance ,of the diode at a particular constant forward current. The **dynamic resistance** of the diode is the resistance offered to changing levels of forward voltage. The dynamic resistance, also known as the **incremental resistance** or **ac resistance**, is the reciprocal of the slope of the forward characteristics beyond the knee.

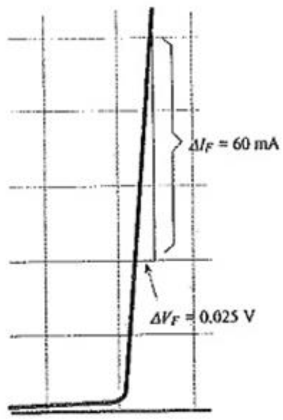

Figure 1-13 Determination of diode dynamic resistance from the forward characteristic

$$r_d = \frac{\Delta V_F}{\Delta I_F}$$

The dynamic resistance can also be calculate from the equation,

$$r'_d = \frac{26\ \text{mV}}{I_F}$$

where I_F is the dc forward current at the junction. Thus, for example, the dynamic resistance for a diode passing a 10 mA forward current is, r'_d = 26 mV/10 mA = 26 Ω.

1.2 Half Wave Rectifier Circuit:

A basic diode Half Wave Rectifier Circuit is shown in Fig. 1-14(a). An alternating input voltage is applied to a single diode connected in series with a load resistor R_L. The diode is forward biased during the positive half-cycles of the input waveform, and reverse biased during the negative half-cycles. Substantial current flows through R_L only during the positive half-cycles of the input. For the duration of the negative half-cycles, the diode behaves almost as an open switch. The output voltage waveform developed across R_L is a series of positive half-cycles of alternating voltage with intervening very small negative voltage levels produced by the diode reverse saturation current.

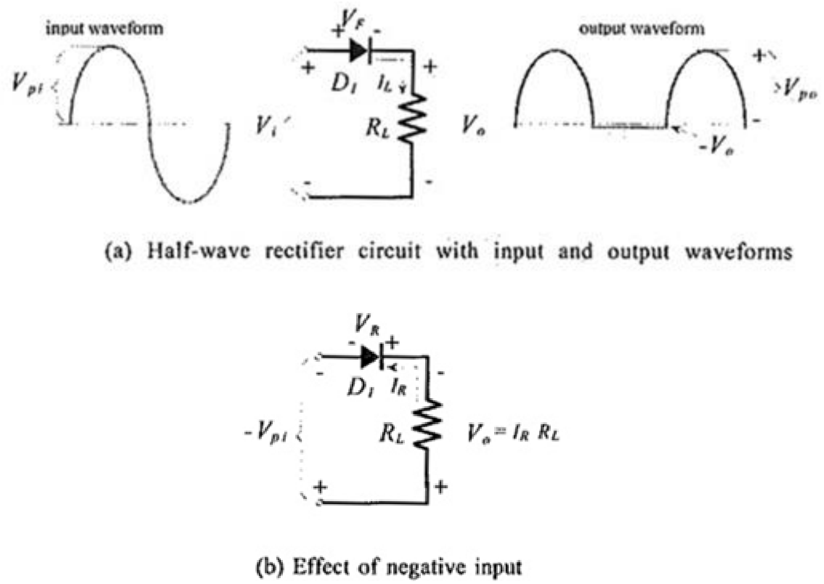

Figure1-14 Half wave rectifier circuit. The diode is forward biased during one half cycle of the applied waveform and reverse biased during the other half -cycle

Input voltage V_i is a sinusoidal waveform it can be represented mathematically as,

$$V_i = V_m \sin wt = V_m \sin \theta$$

During positive half cycle of V_i, the diode is forward biased and acts as short circuit. The current flows through R_L and V_O follows V_i. (Practically $V_o = V_i - V_F$ where V_F is voltage drop across the diode).

Output Voltage: $V_o = V_m \sin \theta$; for $0 \le \theta \le \pi$

Output Current: $i = I_m \sin \theta$; for $0 \le \theta \le \pi$

During negative half cycle of Vi, the diode is reverse biased and acts as open circuit and no current flows through R_L. Therefore no output voltage during this time. (Practically very small negative voltage levels produced by the diode reverse saturation current (I_R). So Vo=-$I_R R_L$

$$\text{Output Voltage:} \quad V_o = 0 \quad ;\text{for } \pi \leq \theta \leq 2\pi$$
$$\text{Output Current:} \quad i = 0 \quad ;\text{for } \pi \leq \theta \leq 2\pi$$

Maximum load current is given by,

$$I_m = \frac{V_m}{R_f + R_s + R_L}$$

Where

R_f= Forward resistance of the diode
R_s= Transformer secondary winding resistance
R_L= Load Resistance

Advantages:

1. Only one diode is required.
2. Centre tap transformer is not required

Disadvantages:

1. Ripple factor is too high (= 1.21).
2. Efficiency of rectification is low (η = 40.6%).
3. DC saturation of transformer secondary winding takes place.
4. Transformer utilization factor is low.
5. AC supply delivers power only during half of the time, therefore output is low.

1.3 Bridge Rectifier:

The bridge rectifier circuit in Fig. 1-15 is seen to consist of four diodes connected with their arrowhead symbols all pointing toward the positive output terminal of the circuit. Diodes D_1 and D_2 are series-connected, as are D_3 and D_4. The ac input terminals are the junction of D_1 and D_2 and the junction of D_3 and D_4. The positive output terminal is at the cathodes of D_1 and D_3, and the negative output is at the anodes of D_2 and D_4.

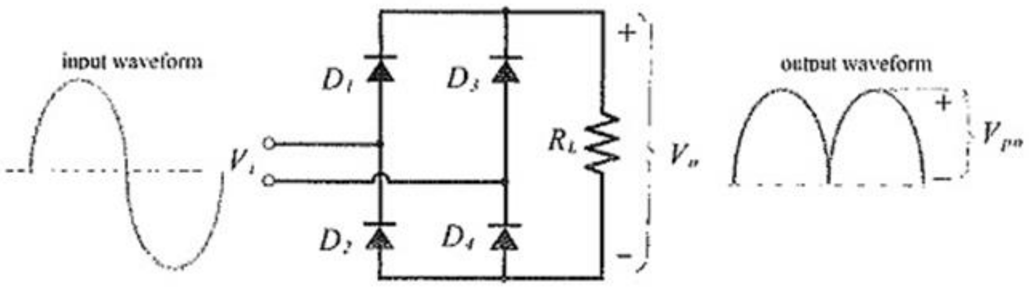

Figure 1-15 Full wave bridge rectifier circuit

During the positive half-cycle of input voltage, diodes D_1 and D_4 are in series with R_L, as illustrated in Figs. 1-16(a) and (b). Thus, load current (I_L) flows from the positive input terminal through D_1 to R_L, and then through R_L and D_4 back to the negative input terminal. Note that the direction of the load current through R_L is from top to bottom. During this time, the positive input terminal is applied to the cathode of D_2 and the negative output is at D_2 anode, [see Fig. 1-16(a)]. So, D_2 is reverse biased during the positive half-cycle of the input. Similarly, D_3 has the negative input at its anode and the positive output at its cathode during the positive input half-cycle, causing D_3 to be reverse biased.

Figures 1-16(c) and (d) show that diodes D_2 and D_3 are forward biased during the negative half-cycle of the input waveform, while D_1 and D_4 are reverse biased. Although the circuit input terminal polarity is reversed, I_L again flows through R_L from top to bottom, via D_3 and D_2.

It is seen that during both half-cycles of the input, the output terminal polarity is always positive at the top of R_L, negative at the bottom. Both positive and negative half-cycles of the input are passed to the output. The negative half-cycles are inverted, so that the output is a continuous series of positive half-cycles of sinusoidal voltage.

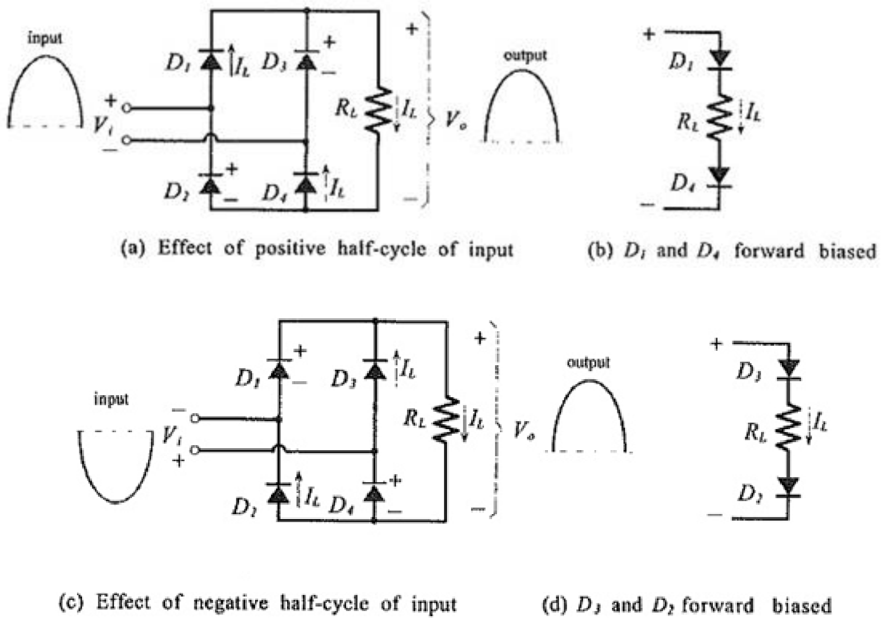

Figure 1-16 Operation of bridge rectifier circuit

The instantaneous value of current and voltage of transformer secondary is given by,

$V = V_m \sin\theta$ & $i = I_m \sin\theta$ where $I_m = \frac{V_m}{2R_f + R_S + R_L}$

Advantages:

1. Transformer cost is less.
2. Peak inverse voltage of diode is one half of the diode used in centre tapped rectifier.
3. Centre tapped transformer is not required.
4. It can be used in applications, where floating output terminals are allowed.

Disadvantages:

1. It requires four diodes.
2. During each half cycle of ac input, two diodes that conducts are in series and therefore voltage drop in the internal resistance of rectifying unit will be twice as compared to centre tapped circuit.

DC or Average Current (I_{DC}) and Voltage (V_{DC}):

$$Average\ value = \frac{Area\ under\ the\ curve\ over\ the\ full\ cycle}{Time\ Period}$$

For Half Wave Rectifier

Average Current (I_{DC}):

$$I_{DC} = \frac{[\int_0^{\pi} i.d\theta + \int_{\pi}^{2\pi} i.d\theta]}{2\pi}$$
$$= \frac{1}{2\pi}\int_0^{\pi} I_m sin\theta.d\theta$$
$$= \frac{I_m}{2\pi}[-cos\theta]_0^{\pi}$$
$$I_{DC} = \frac{I_m}{\pi} = 0.318I_m = 31.8\%I_m$$

Average DC voltage (V_{DC})

$$V_{dc} = I_{dc}R_L = \frac{I_m}{\pi}R_L$$

Where $I_{m} = \frac{V_m}{R_f+R_S+R_L}$

$$V_{dc} = \frac{V_m}{\pi(R_f + R_s + R_L)} * R_L$$

Divide numerator and denominator by R_L

$$V_{dc} = \frac{V_m}{\pi(\frac{R_f + R_s}{R_L} + 1)}$$

If $R_L >> R_f + R_S$, then

$$V_{dc} = \frac{V_m}{\pi} = 0.318V_m = 31.8\%V_m$$

Therefore the average or DC value of load voltage/ load current is 31.8% of the maximum ac input voltage or current.

For Full Wave Rectifier

Average Current (I_{DC}):

$$I_{DC} = \frac{[\int_0^{\pi} i.d\theta + \int_{\pi}^{2\pi} i.d\theta]}{2\pi}$$
$$= \frac{2}{2\pi}\int_0^{\pi} I_m sin\theta.d\theta$$
$$= \frac{I_m}{\pi}[-cos\theta]_0^{\pi}$$
$$I_{DC} = \frac{2I_m}{\pi} = 0.636I_m = 63.6\%I_m$$

Average DC voltage (V_{DC})

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

Where $I_{m} = \frac{V_m}{2R_f+R_S+R_L}$

$$V_{dc} = \frac{2V_m}{\pi(2R_f + R_s + R_L)} * R_L$$

Divide numerator and denominator by R_L

$$V_{dc} = \frac{2V_m}{\pi(\frac{2R_f + R_s}{R_L} + 1)}$$

If $R_L >> 2R_f + R_S$, then

$$V_{dc} = \frac{2V_m}{\pi} = 0.636V_m = 63.6\%V_m$$

Therefore the average or DC value of load voltage/ load current is 63.6% of the maximum ac input voltage or current.

Root Mean Square Value of Load current (I_{rms}) & Voltage (V_{rms})

The effective value of the output is the rms value

For Half Wave Rectifier:

RMS value of load current(I_{rms}):

$$I_{rms} = \sqrt{\frac{\int_0^{\pi} i^2.d\theta + \int_{\pi}^{2\pi} i^2 d\theta}{2\pi}} \text{ ; } \boldsymbol{substitute\ i = I_m sin\theta}$$

$$I_{rms} = \sqrt{\frac{\int_0^{\pi} I_m{}^2.sin^2\theta d\theta}{2\pi}}$$

WKT

$$sin^2\theta = \frac{1 - cos2\theta}{2}$$

Simplifying

$$I_{rms} = \sqrt{\frac{I_m{}^2}{2\pi}\frac{\int_0^{\pi}(1 - cos2\theta)d\theta}{2}} = \frac{I_m}{2} = 0.5I_m = 50\%I_m$$

RMS value of load voltage (V_{rms})

$$V_{rms} = I_{rms}R_L = \frac{I_m R_L}{2}$$

Where

$$I_m = \frac{V_m}{R_f + R_S + R_L}$$

$$V_{rms} = \frac{V_m R_L}{2(R_f + R_S + R_L)}$$

Divide numerator and denominator by R_L

$$V_{rms} = \frac{V_m}{2(\frac{R_f + R_s}{R_L} + 1)}$$

If $R_L >> R_f + R_S$, then

$$V_{rms} = \frac{V_m}{2} = 0.5V_m = 50\%V_m$$

Therefore the rms value of load voltage/ load current is 50% of the maximum ac input voltage or current.

For Full Wave Rectifier:

RMS value of load current(I_{rms}):

$$I_{rms}=\sqrt{\frac{\int_0^{\pi} i^2.d\theta+\int_{\pi}^{2\pi} i^2 d\theta}{2\pi}} \ ; substitute\ i = I_m sin\theta$$

$$I_{rms}=\sqrt{\frac{2\int_0^{\pi} {I_m}^2.sin^2\theta d\theta}{2\pi}}$$

WKT

$$sin^2\theta = \frac{1-cos2\theta}{2}$$

Simplifying

$$I_{rms}=\sqrt{\frac{{I_m}^2}{\pi}\frac{\int_0^{\pi}(1-cos2\theta)d\theta}{2}} = \frac{I_m}{\sqrt{2}} = 0.707I_m = 70.7\%I_m$$

RMS value of load voltage (V_{rms})

$$V_{rms} = I_{rms}R_L = \frac{I_m R_L}{\sqrt{2}}$$

Where

$$I_{m}= \frac{V_m}{2R_f + R_S + R_L}$$

$$V_{rms} = \frac{V_m R_L}{\sqrt{2}(2R_f + R_S + R_L)}$$

Divide numerator and denominator by R_L

$$V_{rms} = \frac{V_m}{\sqrt{2}(\frac{2R_f + R_s}{R_L} + 1)}$$

If $R_L >> 2R_f + R_S$, then

$$V_{rms} = \frac{V_m}{\sqrt{2}} = 0.707V_m = 70.7\%V_m$$

Therefore the rms value of load voltage/ load current is 70.7% of the maximum ac input voltage or current.

Efficiency of Rectification (η)

$$\eta=\frac{DC\ Power\ delivered\ to\ the\ load}{AC\ input\ power\ from\ the\ transformer\ secondary} = \frac{P_{dc}}{P_{ac}}$$

$$P_{dc} = I_{dc}^2 R_L$$
$$P_{ac} = I_{rms}^2(R_f + R_s + R_L)$$

$$\eta=\frac{I_{dc}^2 R_L}{I_{rms}^2(R_f+R_s+R_L)}$$

Divide Numerator & Denominator by R_L

$$\eta=\frac{I_{dc}^2}{I_{rms}^2}$$

For Half Wave Rectifier

$I_{DC} = \frac{I_m}{\pi}$ **and** $I_{rms} = \frac{I_m}{2}$

$$\eta = \frac{\left(\frac{I_m}{\pi}\right)^2}{\left(\frac{I_m}{2}\right)^2} = \frac{4}{\pi^2} = 0.406 = 40.6\%$$

Maximum efficiency η=0.406=40.6%

For Full Wave Rectifier

$I_{DC} = \frac{2I_m}{\pi}$ **and** $I_{rms} = \frac{I_m}{\sqrt{2}}$

$$\eta = \frac{\left(\frac{2I_m}{\pi}\right)^2}{\left(\frac{I_m}{\sqrt{2}}\right)^2} = \frac{8}{\pi^2} = 0.812 = 81.2\%$$

Maximum efficiency η=0.812=81.2%

Ripple Factor(ϒ)

Rectifier converts AC power to DC power and is described quantitatively by a term called ripple factor.

$$\Upsilon = \frac{rms\ value\ of\ ac\ component\ of\ output}{dc\ component\ of\ output} = \frac{I_{ac}}{I_{dc}}$$

rms value of the ac component of the current is given by

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

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

For Half Wave rectifier

$I_{DC} = \frac{I_m}{\pi}$ **and** $I_{rms} = \frac{I_m}{2}$

$$\Upsilon = \sqrt{\frac{\frac{I_m^2}{4}}{\frac{I_m^2}{\pi^2}} - 1} = \sqrt{\frac{\pi^2}{4} - 1} = 1.21 = 121\%$$

For Full Wave rectifier

$I_{DC} = \frac{2I_m}{\pi}$ **and** $I_{rms} = \frac{I_m}{\sqrt{2}}$

$$\Upsilon = \sqrt{\frac{\frac{I_m^2}{2}}{\frac{4I_m^2}{\pi^2}} - 1} = \sqrt{\frac{\pi^2}{8} - 1} = 0.482 = 48.2\%$$

Voltage Regulation:

It is the factor which tells about the change in dc output voltage as load changes from no load to full load condition.

$$\% \text{ Regulation}=\frac{V_{No-Load}-V_{Full-Load}}{V_{Full-Load}} * 100$$

$$\% \text{ R} =\frac{V_{NL}-V_{FL}}{V_{FL}} * 100$$

1.4 Comparison of Half wave rectifier, Full wave Bridge rectifier:

Sl. No:	Parameter:	Half-Wave Rectifier:	Bridge Rectifier:
1	Diodes:	1	4
2	Peak Inverse Voltage (PIV):	V_m	V_m
3	Ripple Frequency:	f	2f
4	Ripple Factor ( ):	1.21=121%	0.482=48.2%
5	Maximum Efficiency ( ):	0.406=40.6%	0.812=81.2%
6	Average Current (I_{DC}):	$I_m/\pi = 0.318 I_m$	$2I_m/\pi = 0.636 I_m$
7	Average Voltage (V_{dc}):	$V_m/\pi = 0.318 V_m$	$2V_m/\pi = 0.636 V_m$
8	RMS Current (I_{rms}):	$\frac{I_m}{2}$	$I_{rms} = \frac{I_m}{\sqrt{2}}$
9	RMS Voltage (V_{rms}):	$\frac{V_m}{2}$	$\frac{V_m}{\sqrt{2}}$

1. A half wave rectifier uses a diode whose internal resistance is 30Ω to supply power to 1.1 KΩ load from 110V (rms) source of supply. Calculate: i) DC load voltage; ii) DC load current; iii) AC load current

Solution : Given V_{rms}=110 V, R_L=1.1KΩ, R_f=30Ω

$$V_{rms} = \frac{V_m}{\sqrt{2}}$$

$$V_m = \sqrt{2}V_{rms} = \sqrt{2} * 110V = 155.56V$$

$$I_m = \frac{V_m}{R_f + R_s + R_L} = \frac{155.56V}{30 + 1100} = 137.66mA$$

$$I_{rms} = \frac{I_m}{2} = \frac{137.66mA}{2} = 68.83mA$$

(i) DC Load Voltage

$$V_{dc} = \frac{V_m}{\pi} = 49.46V$$

(ii) DC Load Current

$$I_{dc} = \frac{I_m}{\pi} = 43.77mA$$

(iii) AC Load Current

$$I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2} = 53.12mA$$

2. A full wave bridge rectifier with a load of 1 KΩ. The ac voltage applied to the diode is 200 V, if diode resistance is neglected. Calculate: i) Average dc current; ii) Average dc voltage.

Given V_{rms}=200V, R_L=1KΩ,

$$V_m = \sqrt{2}V_{rms} = \sqrt{2} * 200V = 282.84V$$

$$I_m = \frac{V_m}{2R_f + R_s + R_L} = \frac{282.84}{1000} = 282.84mA$$

(i) Average dc current

$$I_{DC} = \frac{2I_m}{\pi} = 0.693 * 282.84mA = 179.88mA$$

(ii) Average DC voltage

$$V_{DC} = \frac{2V_m}{\pi} = 0.693 * 282.84V = 179.88\ V$$

3. A bridge rectifier supplies a power to a 1 KΩ load. The AC voltage applied to the diode is 300 V. If diode resistance is 25Ω and that of the transformer secondary is negligible. Determine average load current, average load voltage and rectification efficiency

Given V_{rms}=300V, R_L=1KΩ, R_f=25Ω

$$V_m = \sqrt{2}V_{rms} = \sqrt{2} * 300V = 424.26V$$

$$I_m = \frac{V_m}{2R_f + R_s + R_L} = \frac{424.26}{50 + 1000} = 404.05mA$$

(i) Average dc current

$$I_{DC} = \frac{2I_m}{\pi} = 0.693 * 404.05mA = 280mA$$

(ii) Average DC voltage

$$V_{DC} = \frac{2V_m}{\pi} = 0.693 * 424.26V = 294.01\ V$$

(iii) Rectification Efficiency

$$\eta = \frac{8}{\pi^2} * \frac{R_L}{(2R_f + R_s + R_L)} = 0.812 * \frac{1000\Omega}{50 + 1000} = 0.7733 = 77.33\%$$

4. A half wave rectifier from a supply 230 V 50 Hz with step down transformer ratio 3:1 to a resistive load of 10 KΩ. The diode forward resistance is 75 Ω and transformer secondary is 10 Ω. Calculate the DC current, DC voltage, efficiency and ripple factor.

Solution: Given $N_1 : N_2 = 3 : 1$, V_P = 230 V, R_L = 10 KΩ, R_f = 75 Ω and R_s = 10 Ω

$$\frac{N_1}{N_2} = \frac{V_P}{V_S} \Rightarrow N_1V_S = N_2V_P \Rightarrow V_S(rms) = \frac{N_2}{N_1}V_P = \frac{1}{3}V_P = \frac{230}{3} = 76.66V$$

$$V_m = \sqrt{2} \times V_S(rms) = \sqrt{2} \times 76.66 = 108.41\ V$$

$$I_m = \frac{V_m}{(R_f + R_s + R_L)} = \frac{108.41}{(75 + 10 + 10K)} = 10.75\ mA$$

$$I_{dc} = \frac{I_m}{\pi} = 0.318I_m = 0.318 \times 10.75\ mA = 3.418\ mA$$

$$V_{dc} = V_m/\pi \quad 0.318V_m = 0.318 \times 108.41 = 34.47\ V$$

$$\eta = \frac{4}{\pi^2} \times \frac{R_L}{(R_f + R_s + R_L)} = 0.406 \times \frac{10K}{75 + 10 + 10K} = 0.4025 = 40.25\%$$

$$I_{rms} = \frac{V_{rms}}{(R_f + R_s + R_L)} = \frac{76.66}{(75 + 10 + 10K)} = 7.6\ mA$$

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1} = \sqrt{\left(\frac{7.6\ mA}{3.418\ mA}\right)^2 - 1} = 1.22$$

5. A sinusoidal wave of Vi = 600 sin 30t is applied to a half wave rectifier. The load resistance is 2 KΩ and forward resistance of the diode is 60 Ω. Find:
   I. DC current through the diode
   II. AC or rms value of current through the circuit
   III. DC output voltage
   IV. AC power input
   V. DC power output
   VI. Rectifier efficiency

Solution: Given $V_i = 600 \sin 30t = V_m \sin wt$, $R_L = 2\ K\Omega$, $R_f = 60\ \Omega$

(i) $I_{DC} = \frac{I_m}{\pi}$ and $I_m = \frac{V_m}{R_f+R_s+R_L} = \frac{V_m}{R_f+R_L} = \frac{600}{60+2x10^3} = 291.2mA$

$$I_{DC} = \frac{I_m}{2V_m} = \frac{291.2mA}{[illegible]} = 92.71\ mA$$

(ii) $I_{rms} = \frac{I_m}{2} = \frac{291.2mA}{2} = 145.6\ mA$

(iii) DC output voltage: $V_{DC} = I_{DC} \times R_L = 92.71\ mA \times 2\ K\Omega = 185.4\ V$

(iv) AC power input: $P_{ac} = I_{rms}^2 (R_f + R_L) = (145.6\ mA)^2 (60\ \Omega + 2\ K\Omega) = 43.67\ W$

(v) DC power output: $P_{dc} = I_{dc}^2 (R_L) = (92.71\ mA)^2 (2\ K\Omega) = 17.1\ W$

(vi) Rectifier efficiency:

$$\eta = \frac{P_{dc}}{P_{ac}} \times 100 = \frac{17.1\ W}{43.67\ W} \times 100 = 39.3\%$$

6. If the input voltage for a bridge rectifier is 50 V and each diode has a forward resistance of 25Ω. Find the current through a load resistance of 2950Ω and the dc voltage.

Current through a load resistance

$$I_m = \frac{V_m}{2R_f + R_s + R_L} = \frac{50}{50 + 2950} = 16.6mA$$

(i) Average DC voltage

$$V_{DC} = \frac{2V_m}{\pi} = 0.693 * 50V = 31.83\ V$$

1.5 Half Wave Rectifier with Capacitor Filter

When a sinusoidal alternating voltage is rectified, the resultant waveform is a series of positive (or negative) half-cycles of the input waveform; it is not direct voltage. To convert to direct voltage (dc), a **smoothing circuit** or **filter** must be employed.

Figure 1-17(a) shows a Half Wave Rectifier with Capacitor Filter (C_1) and a load resistor (R_L). The capacitor, termed a reservoir capacitor, is charged almost to the peak level of the circuit input voltage when the diode is forward biased. This occurs at V_{pi} as shown in Fig. 1-17(b), giving a peak capacitor voltage,

$$V_C = V_{pi} - V_F$$

When the instantaneous level of input (at the diode anode) falls below V_{pi} the diode becomes reverse biased, because the capacitor voltage (V_C) (at the diode cathode) remains close to ($V_{pi} - V_F$), [see Fig. 1-17(c)]. With the diode reverse biased, the capacitor begins to discharge through the load resistor (R_L). So, V_C falls slowly, as shown by the capacitor voltage waveform in Fig. 1-17(a).

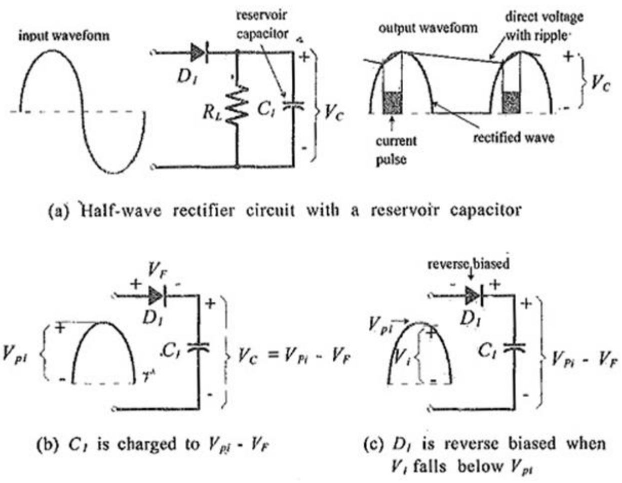

Figure 1-17 A reservoir capacitor smoothes the output from the rectifier circuit by charging upto the peak output voltage and retaining most of its charge between voltage peaks

The diode remains reverse biased through the remainder of the input positive half-cycle, the negative half-cycle, and the first part of the positive half-cycle again until the instantaneous level of V_1 becomes greater than V_C once more. At this point current flows through the diode to recharge the capacitor, causing the capacitor voltage to return to ($V_{pi} - V_F$). The charge and discharge of the capacitor causes the small increase and decrease in the capacitor voltage, which is also the circuit output voltage. It is seen that the circuit output is a .direct voltage with a small **ripple voltage** waveform superimposed, fig. 1-17(a)].

1.6 Zener Diode Voltage Regulator Circuit:

1.6.1 Regulator Circuit With No Load – The most important application of Zener Diode Voltage Regulator Circuit is dc voltage regulator circuits. These can be the simple regulator circuit shown in Fig. 1-18, or the more complex regulators.

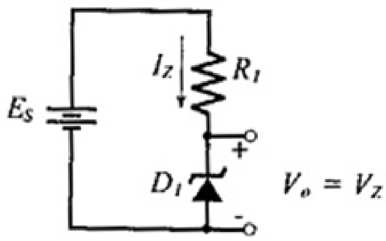

Figure 1-18 Zener diode reference voltage source or voltage regulator

The circuit in Fig. 1-18 is usually employed as a voltage reference source that supplies only a very low current (much lower than I_Z) to the output. Resistor R_1 in Fig. 1-18 limits the Zener diode current to the desired level.

$$I_Z = \frac{E_S - V_Z}{R_1}$$

The Zener current may be just greater than the diode knee current (I_{ZK}). However, for the most stable reference voltage, I_Z should be selected as I_{ZT} (the specified test current).

1.6.2 Loaded Regulator:

When a Zener diode regulator is required to supply a load current (I_L), as shown in Fig. 1-19, the total supply current (flowing through resistor R_1) is the sum of I_L and I_Z Care must be taken to ensure that the minimum Zener diode current is large enough to keep the diode in reverse breakdown.

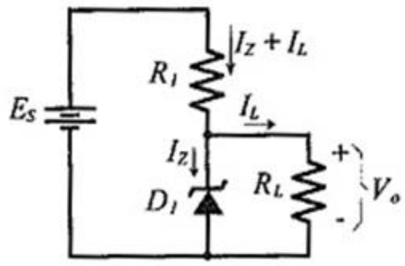

Figure 1-19 Zener diode voltage regulator circuit supplying a load current. The diode must be able to pass a current of (I_L+I_z)

Typically, $I_{Z(min)}$ = 5 mA for a Zener diode with I_{ZT} = 20 mA. The circuit current equation is,

$$I_Z + I_L = \frac{E_S - V_Z}{R_1}$$

In some cases, the load current in the type of circuit shown in Fig. 3-21 may be reduced to zero. Because the voltage drop across R_1 remains constant, the supply current remains

constant at,

$$I_{R1} = I_Z + I_L$$

All of this current flows through the Zener diode when R_L is disconnected. The circuit design must ensure that the total current does not exceed the maximum Zener diode current.

1. A 9V reference source is to use a series connected Zener diode and resistor of 1k ohm is connected to a 30 V supply. Calculate the circuit current when the supply voltage drops to 27V.

Solution: From the data sheet V_Z=9.1 V and I_{ZT}=20mA

With Es=30V;

$$R_1 = \frac{E_S - V_Z}{I_Z} = \frac{30V - 9.1V}{20mA} = 1.05k\Omega$$

P_D for R_1

$$P_{R1} = I_1^2 R_1 = (20mA)^2 X\ 1k\Omega = 0.4W$$

When E_S=27V:

$$I_Z = \frac{E_S - V_Z}{R_1} = \frac{27V - 9.1V}{1k\Omega} = 17.9mA$$

The voltage regulation can be done through two techniques

1. Line regulation

In this case, series resistance and load resistance are kept constant and it is assumed that all the variations in voltage arise due to fluctuations in input power supply. The regulated output voltage is achieved for input voltage above certain minimum level.

The percentage of regulation is given by

$$\frac{\Delta Vo}{\Delta Vin} * 100$$

Where

V_o is the output voltage,

V_{IN} is the input voltage and ΔVo is the change in output voltage for a particular change in input voltage ΔV_{IN}.

2. Load Regulation

In this, the input voltage is fixed while the load resistance is varied. The constant output voltage is obtained as long as the load resistance is maintained above a minimum value.

The percentage of regulation is given by

$$\frac{V_{NL} - V_{FL}}{V_{FL}} * 100$$

Where V_{NL} is the voltage across the zener diode when no load is applied and V_{FL} is the full resistor voltage.

1.7 DC POWER SUPPLY

The block diagram of a d.c. power supply is shown in Fig. 1-20. Since the mains input is at a relatively high voltage, a step-down transformer of appropriate turns ratio is used to convert this to a low voltage. The a.c. output from the transformer secondary is then rectified using conventional silicon rectifier diodes to produce an unsmoothed (sometimes referred to as pulsating d.c.) output. This is then smoothed and filtered before being applied to a circuit which will regulate (or stabilize) the output voltage so that it remains relatively constant in spite of variations in both load current and incoming mains voltage. Fig. 1-21 shows how some of the electronic components that we have already met can be used in the realization of the block diagram in Fig. 1-20. The iron-cored step-down transformer feeds rectifier arrangement (often based on a bridge circuit). The output of the rectifier is then applied to a high-value reservoir capacitor. This capacitor stores a considerable amount of charge and is being constantly topped-up by the rectifier arrangement. The capacitor also helps to smooth out the voltage pulses produced by the rectifier. Finally, a stabilizing circuit (often based on a series transistor regulator and a zener diode voltage reference) provides a constant output voltage.

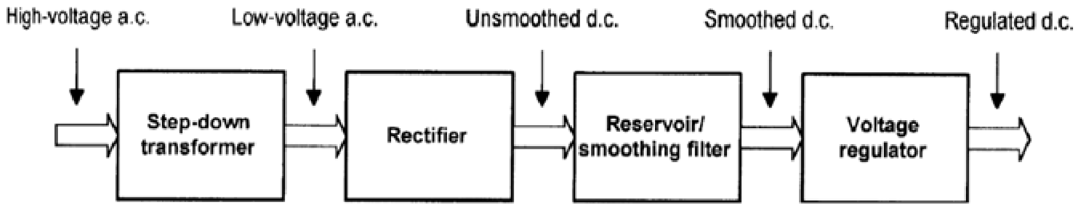

Figure 1-20 Block diagram of a d.c. power supply

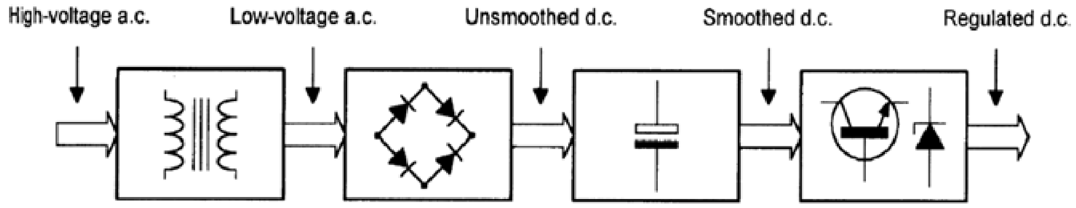

Figure 1-21 Block diagram of a d.c. power showing principal components

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2. Mike Tooley.(2015) Electronic Circuits, Fundamentals & Application (4th ed). Elsevier.
3. D. P. Kothari, I .J. Nagarath , “Basic Electronics”, 2nd edition, Mc Graw Hill, 2018.