UNIT-I
SEMICONDUCTOR DIODES AND APPLICATIONS

The p-n junction diode, Equivalent circuit of a diode, Zener diode, Zener diode as a voltage regulator, Rectification - Half wave rectifier, Full wave rectifier, Bridge rectifier, capacitor and choke filter circuit (only qualitative approach), 78XX based Fixed IC voltage regulator.

Formation of PN junction

A PN-junction is formed when an N-type material is fused together with a P-type material creating a semiconductor diode. When the N-type semiconductor and P-type semiconductor materials are first joined together a very large density gradient exists between both sides of the PN junction. The result is that some of the free electrons from the N-side begin to move across this newly formed junction to recombine with holes in the P-side. Similarly holes from the P-side begin to move across the junction to recombine with electrons in the N-side as shown in Fig.1.

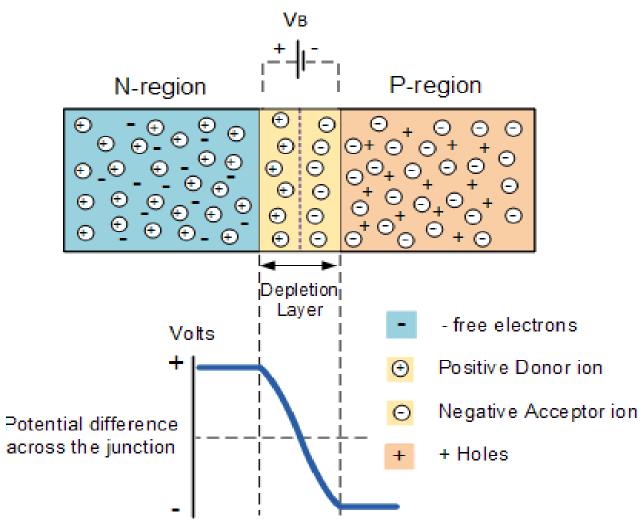


Fig.1 Formation of PN junction

PN Junction Diode Biasing

PN Junction Diode can be biased by an external voltage to either block or allow the flow of current through it.

Forward Bias

When positive terminal is connected to the P-type material and negative to the N-type material of the diode as shown in Fig.2, it is known as forward bias.

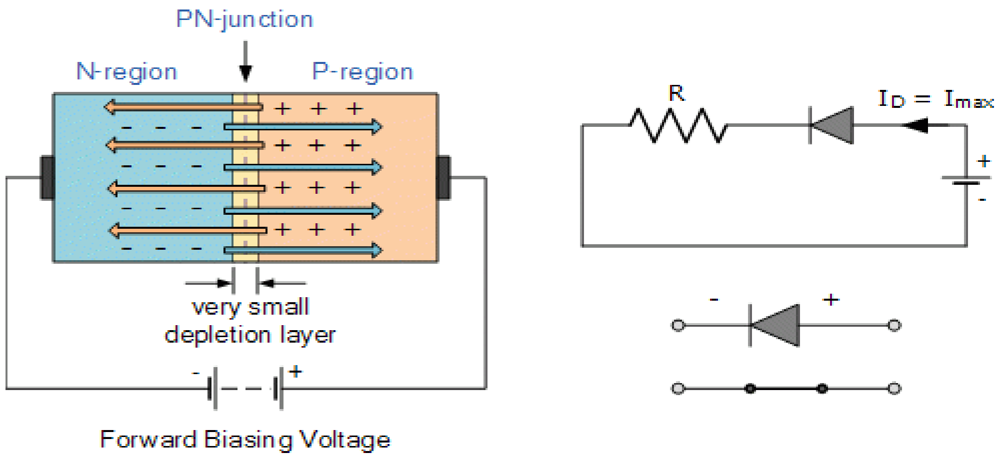


Fig.2 : Forward biased pn-junction diode

The effect of adding this additional energy source results in the electrons and holes being able to cross the depletion region from one side to the other. If this external voltage becomes greater than the value of the potential barrier, approx. 0.7 V for silicon and 0.3 V for germanium diodes, the holes from p-side and electrons from n-side get pushed towards the junction and current starts flowing. This voltage is called the “knee voltage”. After this, current increases with little increase in the external voltage as shown in the static V-I characteristics.

Reverse Bias

When negative terminal is connected to the P-type material and positive to the N-type material of the diode as shown in Fig.3, it is known as reverse bias.

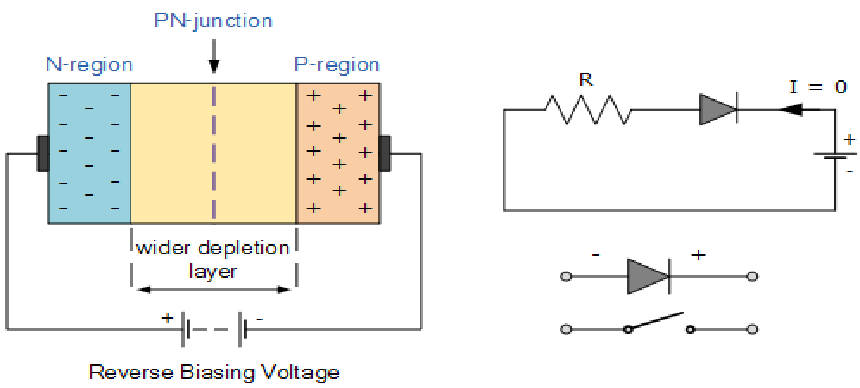


Fig.3: Reverse biased pn-junction diode

The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode. The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material. This condition represents a high resistance value to the PN junction and practically zero current flows through the junction diode with an increase in bias voltage. However, a very small leakage current does flow through the junction due to the minority electrons in P-side and electrons in N-side, which is measured in μA for germanium and nA for silicon.

If the reverse bias voltage V_R applied to the diode is increased to a sufficiently high value, PN junction will overheat and fail due to the *avalanche effect* around the junction. This may cause the diode to become shorted and will result in the flow of maximum circuit current which is shown as a step downward slope in the static V-I characteristics.

Diode Symbol and Static V-I Characteristics

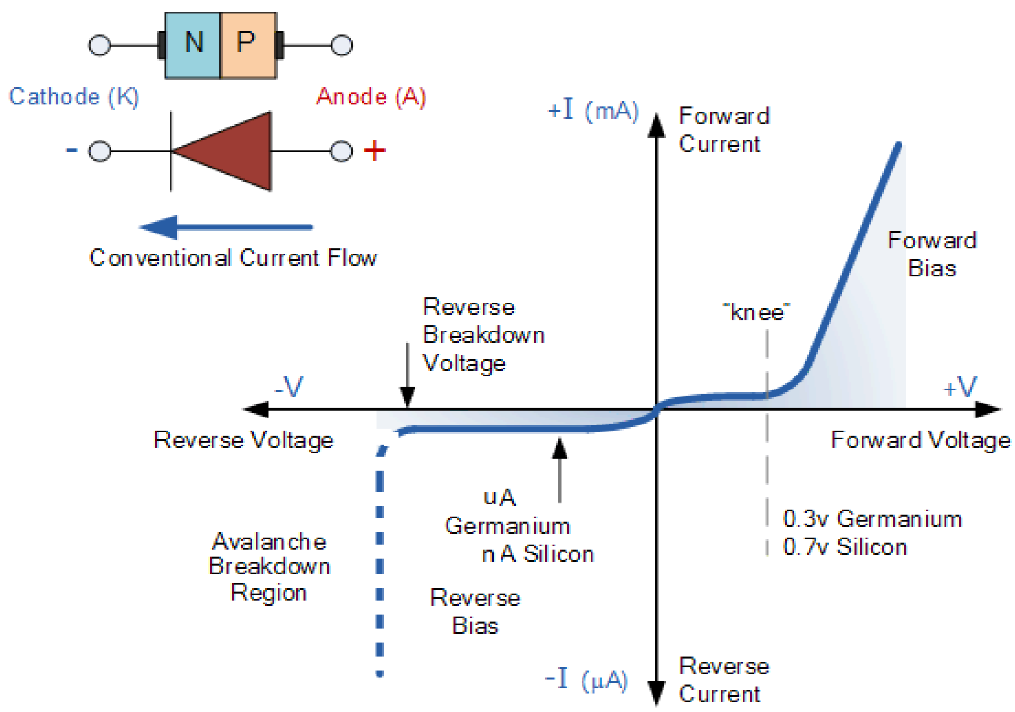


Fig.4: Diode static V-I characteristics

There are two operating regions and three possible "biasing" conditions for the standard **Junction Diode** and these are: Forward Bias and Reverse Bias.

When the diode is forward biased "Forward Current" I_F flows. Before the knee voltage the forward current is due to the diffusion of holes and electrons across the junction. After the knee voltage the current is mainly due to the drift of charge carriers. The potential difference or voltage across the diode is constant when the it conducts forward current I_F and is approximately 0.3 V for germanium and approximately 0.7 V for silicon diode. The $(\text{slope})^{-1}$ of the forward characteristics after the knee of the characteristics is the forward resistance of the diode when it is conducting as shown in Fig.4.

"Reverse Current" which is referred as I_R is the reverse saturation current which flows due to the minority carriers. The minority carriers are constantly generated due to thermal energy raising the temperature of the PN junction which in turn causing an increase in the generation of minority carriers, thereby resulting in an increase in leakage current. When the reverse voltage applied equals the reverse breakdown voltage V_{BR} a large reverse current flows destroying the PN junction. The resistors are used in series with the diode to limit its current flow. Exceeding its maximum forward current specification causes the device to dissipate more power in the form of heat.

Diodes are manufactured in a range of voltage and current ratings and care must be taken when choosing a diode for a certain application.

Some of the parameters of pn-diode are explained as follows

1. Maximum Forward Current (I_{Fmax})

The Maximum Forward Current I_{Fmax} is as its name implies the maximum forward current allowed to flow through the device. When the diode is conducting in the forward bias condition, it has a very small "ON" resistance across the PN junction and therefore, power is dissipated across this junction in the form of heat.

2. Forward Voltage drop/ Knee Voltage (V_F)

It is a forward voltage drop across a diode when it conducts. The forward bias voltage must exceed this voltage for the diode to conduct. Forward voltage drop for silicon diodes is 0.7Vand for germanium diodes is 0.3 V.

3. Reverse saturation current (I_R)

It is the nominal current which flows through the diode when it is reverse biased. It is in the order of nA for Si diodes and μA for Ge diodes.

4. Reverse breakdown voltage (V_{BR})

It is the reverse bias voltage at which the pn-junction breaks down and permanently damages the diode. $\mathbf{V_{BR}}$ is around 50V for Si diode and65 V for Ge.

5. Dynamic resistance (r_d)

The dynamic resistance or ac resistance of a diode is the reciprocal of the slope of the forward characteristics beyond knee.

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

Diode Models / Diode Equivalent Circuits

The three models of diode are as shown in Fig.5. The diode is two terminal non-linear device whose V-I characteristics are dependent on the polarity of the applied voltage. The diode is *Forward Biased* for $V_D > 0$, *Reverse Biased* for $V_D < 0$.

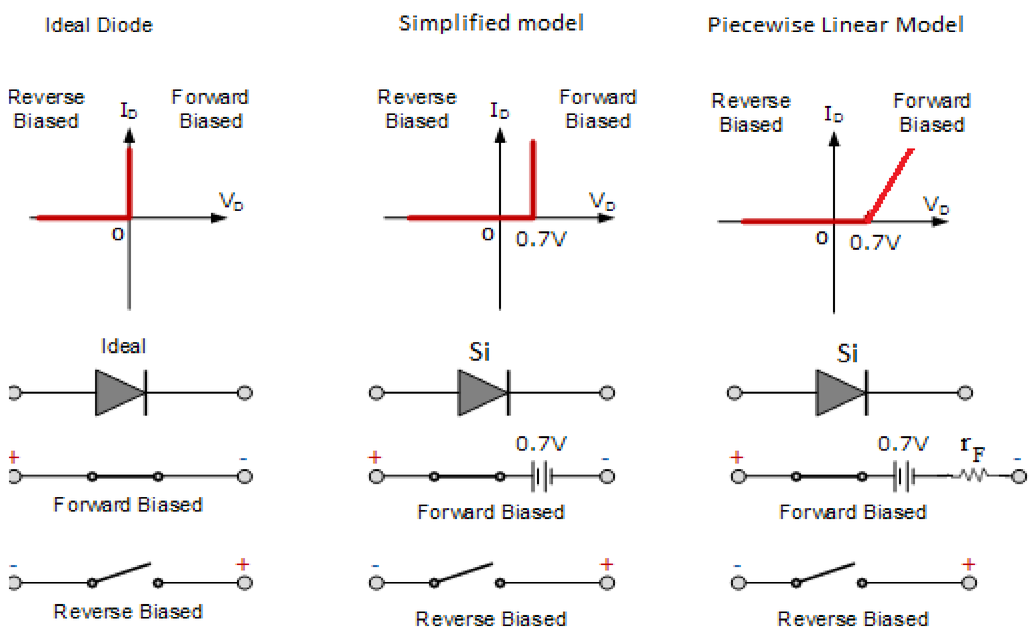


Fig.5 : Diode models

DC load line analysisi

A DC load line is a straight line drawn on the diode forward characteristics that describes all the dc conditions that exist in the operation of the circuit. Consider a diode series circuit as shown in Fig.6.

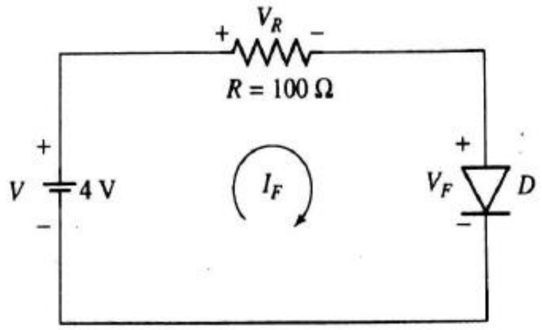


Fig.6: Diode series circuit

Here I_F is the current through the diode and V_F is the voltage across the diode. Applying KVL to the circuit we get,

$$-V + V_R + V_F = 0$$

$$\text{or} \quad V = I_F R + V_F \qquad (1)$$

Eq.1 is the equation of load line.

For $I_F = 0$, $V_F = V$. Hence when $I_F = 0$, $V_F = V$ is one of the points on load line at point A.

$$V_F = 4V,\ I_F = 0\,\text{mA}$$

From eq. 1, when $V_F = 0$, $\boldsymbol{I_F = \frac{V}{R}}$.

$V_F = 0, I_F = \frac{V}{R}$ is the second point on the DC load line at point B.

$\boldsymbol{V_F = 0, I_F = \frac{4}{100} = 40\ mA}$. Join the points A and B to get the DC load line. We can see that the DC load line intersects the diode characteristics at a point Q which corresponds to $\boldsymbol{I_F = 33\ mA}$ and $\boldsymbol{V_F = 0.7V}$. This can be shown by applying KVL to the circuit as $\boldsymbol{V - V_F - I_F R = 0}$ or

$$I_F = \frac{V - V_F}{R}$$

$$V_F = 0.7\,V \text{ for Silicon diode}$$

$$\therefore\ I_F = \frac{4 - 0.7}{100} = 33\,\text{mA}$$

The DC load line is drawn on the diode forward characteristics is as shown in Fig.7.

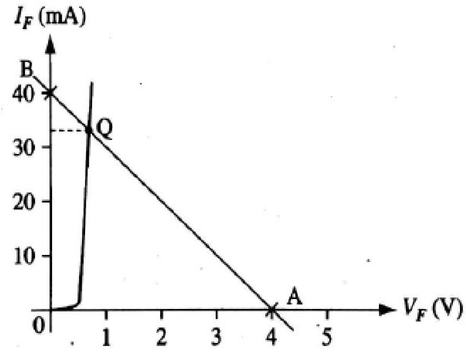


Fig.7: Plot of DC load line.

Rectifiers using Diodes

Half wave rectifier, Full wave rectifier, Bridge rectifier, capacitor and choke filter circuit (only qualitative approach)

A rectifier is a circuit which converts the *Alternating Current* (AC) input power into a *Direct Current* (DC) output power. The input power supply may be either a single-phase or a multi-phase supply.

Half Wave Rectifier.

The simplest of all the rectifier circuits is Half Wave Rectifier. In a half wave rectifier circuit one half of each complete sine wave of the AC supply is converted to DC. That’s why this type of circuit is called a “half-wave” rectifier because it passes only half of the incoming AC power supply as shown in Fig.8.

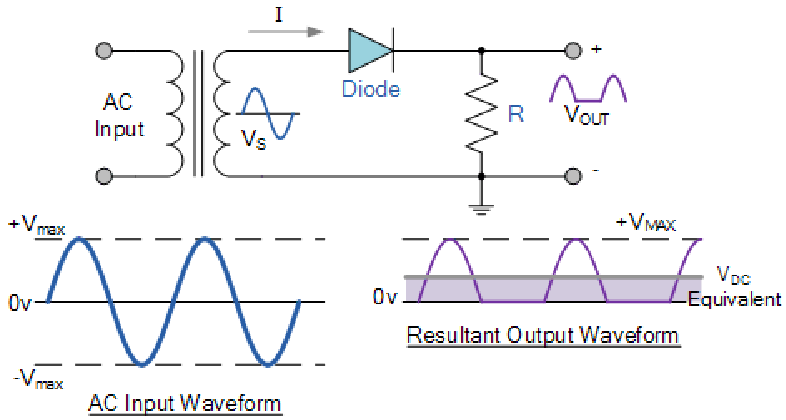


Fig.8: Half Wave Rectifier

During each "positive" half cycle of the AC sine wave, the diode is *forward biased* as the anode is positive with respect to the cathode resulting in current flowing through the diode. The voltage across the load resistor will therefore be the same as the supply voltage, Vs (V_S-V_F for Si or Ge diode), that is the "DC" voltage across the load is sinusoidal for the first half cycle only so V_{out} = Vs.

During each "negative" half cycle of the AC sinusoidal input waveform, the diode is *reverse biased* as the anode is negative with respect to the cathode. Therefore, NO current flows through the diode or circuit. Then in the negative half cycle of the supply, no current flows in the load resistor as no voltage appears across it so therefore, Vout = 0.

The current on the DC side of the circuit flows in one direction only making the circuit **Unidirectional**. As the load resistor receives from the diode a positive half of the waveform, zero volts, a positive half of the waveform, zero volts, etc.

Expressions for V_{DC}, V_{rms} and Rectification Efficiency, Ripple factor for Half Wave Rectifier

Consider output voltage,

$$V_o = V_m\, sinwt\ for\ 0 \leq \omega t \leq \pi$$

$$V_o = 0 \text{ for } \pi \leq \omega t \leq 2\pi$$

V_i is a sinusoidal waveform it can be represented as,

$$V_i = V_m\, sin\omega t = V_m\, sin\omega t$$

Load current,

$$I_L = \begin{cases} I_m \sin\omega t & for\ 0 \le \omega t \le \pi \\ 0 & \pi \le \omega t \le 2\pi \end{cases}$$

Where Max. load current, $I_m = \frac{V_m}{R_f + R_s + R_L}$

where R_f is the dynamic resistance of the diode

R_L is the load resistance & R_s transformer secondary winding resistance.

Derivation of V_{DC}

DC Average current I_{DC}

$$I_{DC} = \frac{Area\ under\ curve\ over\ full\ cycle}{Time\ period} = \frac{1}{2\pi}\int_0^{2\pi} I_m sin\omega t d\omega t$$

$$I_{DC} = \frac{1}{2\pi}\left[\int_0^{\pi} I_m sin\omega t d\omega t + \int_{\pi}^{2\pi} I_m sin\omega t d\omega t\right]$$

$$I_{DC} = \frac{1}{2\pi}\left[\int_0^{\pi} I_m sin\omega t d\omega t + \int_{\pi}^{2\pi} 0 d\omega t\right] \text{ since } I_L = 0, \pi \le \omega t \le 2\pi$$

$$I_{DC} = \frac{1}{2\pi}\left[\int_0^{\pi} I_m sin\omega t d\omega t\right]$$

$$I_{DC} = \frac{I_m}{2\pi}[-cos\omega t]_0^{\pi} = \frac{-I_m}{2\pi}[-1-1] = \frac{I_m}{\pi}$$

DC Average Voltage V_{DC}

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

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

$$V_{DC} = \frac{V_m}{R_f + R_S + R_L}\frac{R_L}{\pi} = \frac{V_m}{\pi}\frac{R_L}{R_f + R_S + R_L}$$

When the load resistor $R_L >> R_f\ and\ R_s$,

The dc value of the output voltage is $\boldsymbol{V_{dc} = \frac{V_m}{\pi}}$

Derivation of V_{rms}

Root mean square load current, I_{rms}

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} {I_L}^2\, d\omega t} \quad = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} {I_m}^2 sin^2 \omega t d\omega t}$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}[\int_0^{\pi} {I_m}^2 sin^2 \omega t d\omega t + \int_{\pi}^{2\pi} {I_m}^2 sin^2 \omega t d\omega t]}$$

$$= \sqrt{\frac{1}{2\pi}\int_0^{\pi} {I_m}^2 sin^2\, \omega t\ \ d\omega t} \qquad \text{since } I_L\text{=0}, \pi \leq \omega t \leq 2\pi$$

$$=\sqrt{\frac{{I_m}^2}{2\pi}\int_0^{\pi} \frac{1-cos2\omega t}{2} d\omega t} = \sqrt{\frac{{I_m}^2}{2\pi}[\frac{1}{2}\int_0^{\pi} d\omega t - \frac{1}{2}\int_0^{\pi} cos2\omega t d\omega t]}$$

$$=\sqrt{\frac{{I_m}^2}{2\pi}[\frac{1}{2}[\omega t]_0^{\pi} - \frac{1}{2}[\frac{sin2\omega t}{2}]_0^{\pi} d\omega t]}$$

$$=\sqrt{\frac{{I_m}^2}{2\pi}[\frac{\pi}{2} - 0]} = \boldsymbol{\frac{I_m}{2}}$$

Root mean square load voltage, V_{rms}

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

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

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

When the load resistor $R_L >> R_f\ and\ R_s$,

The rms value of the output voltage is $\boldsymbol{V_{rms} = \frac{V_m}{2}}$

Derivation of Ripple factor

The ripple factor is the measure of conversion from AC to DC of the half wave rectifier is

$$r = \frac{rms\ value\ of\ ac\ component\ of\ the\ output}{dC\ value\ of\ the\ output} = \frac{I_{ac}}{I_{dc}} \text{ ----(1)}$$

Where $I_{ac}^2 = I_{rms}^2 - I_{dc}^2$

Substituting in (1),

$$r = \frac{I_{ac}}{I_{dc}} = \frac{\sqrt{I_{rms}^2 - I_{dc}^2}}{I_{dc}} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

Substitute, $I_{rms} = \frac{I_m}{2}$ & $I_{dc} = \frac{I_m}{\pi}$

We get, $r = \sqrt{\left(\frac{\frac{I_m}{2}}{\frac{I_m}{\pi}}\right)^2 - 1} = \mathbf{1.21}$

Thus, the ripple factor of the half wave rectifier is 1.21 or the amount of ac present in the output is 121 % of the dc voltage.

Derivation of Rectification Efficiency

The efficiency of the half wave rectifier is

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

DC output power $P_{dc} = \boldsymbol{I_{dc}}^{\mathbf{2}} R_L$

AC input power $P_{ac} = \boldsymbol{I_{rms}}^{\mathbf{2}} (R_f + R_s + R_L)$

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

Substitute, $I_{rms} = \frac{I_m}{2}$ & $I_{dc} = \frac{I_m}{\pi}$

□ $\eta = \frac{(\frac{I_m}{\pi})^2 R_L}{(\frac{I_m}{2})^2 (R_f + R_s + R_L)}$ **= 0.406 = 40.6%**

If $R_L >> R_f$, the efficiency $\boldsymbol{\eta = 40.6}$ % or with no diode loss only 40.6% of the ac input power is converted into dc power in the load.

During the rectification process, the resultant output DC voltage and current are therefore both "ON" and "OFF" during every cycle. As the voltage across the load resistor is only present during the positive half of the cycle (50% of the input waveform), this results in a low average DC value being supplied to the load.

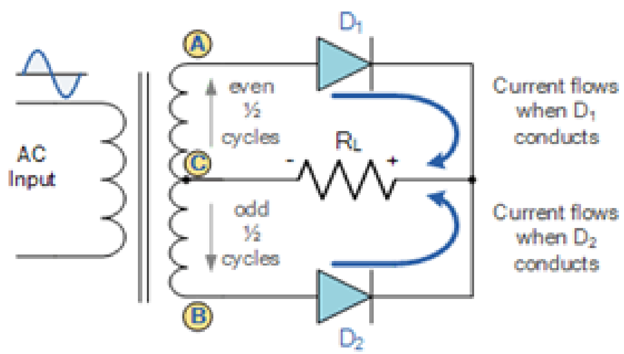
The variation of the rectified output waveform between this "ON" and "OFF" condition produces a waveform which has large amounts of "ripple" which is an undesirable feature. The resultant DC ripple has a frequency that is equal to that of the AC supply frequency.

Full Wave Rectifier.

Like the half wave circuit, a full wave rectifier circuit produces an output voltage or current which is purely DC or has some specified DC component. Full wave rectifiers have some fundamental advantages over the half wave rectifier counterparts. The average (DC) output voltage is higher than for half wave, the output of the full wave rectifier has much less ripple than that of the half wave rectifier producing a smoother output waveform.

Center-Tapped Transformer Full Wave Rectifier:

In a **Center tapped transformer Full Wave Rectifier** circuit two diodes are used, one for each half of the cycle. A multiple winding transformer is used whose secondary winding is split equally into two halves with a common centre tapped connection, (C). This configuration results in each diode conducting in turn when its anode terminal is positive with respect to the transformer centre point C producing an output during both half-cycles, twice that for the half wave rectifier so it is 100% efficient as shown in Fig.9.



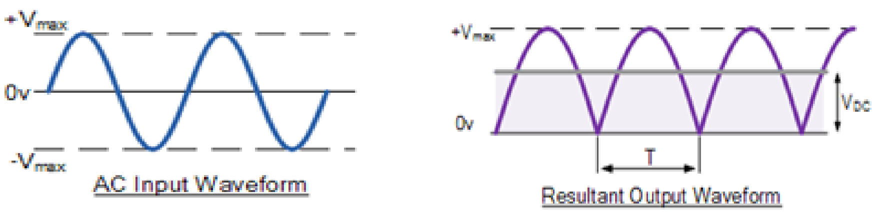


Fig.9: Full Wave Rectifier with 2 diodes

The full wave rectifier circuit consists of two diodes connected to a single load resistance (R_L) with each diode taking it in turn to supply current to the load. For the positive half cycle of input, point A of the transformer is positive with respect to point C, so diode D_1 conducts in the forward direction as indicated by the arrows.

For the negative half cycle of input, point B is positive with respect to point C, so diode D_2 conducts in the forward direction and the current flowing through resistor R_L is in the same direction for both half-cycles. As the output voltage across the resistor R_L is the phasor sum of the two waveforms combined, this type of full wave rectifier circuit is also known as a “bi-phase” circuit.

Full Wave Bridge Rectifier

Another type of circuit that produces the same output waveform as the center tapped transformer rectifier is the **Full Wave Bridge Rectifier**. This type of single phase rectifier uses four individual rectifying diodes connected in a closed loop “bridge” configuration to produce the desired output.

The main advantage of this bridge circuit is that it does not require a special centre tapped transformer, thereby reducing its size and cost. The single secondary winding is connected to one side of the diode bridge network and the load to the other side as shown in Fig.10.

The four diodes labelled D_1 to D_4 are arranged in “series pairs” with only two diodes conducting current during each half cycle.

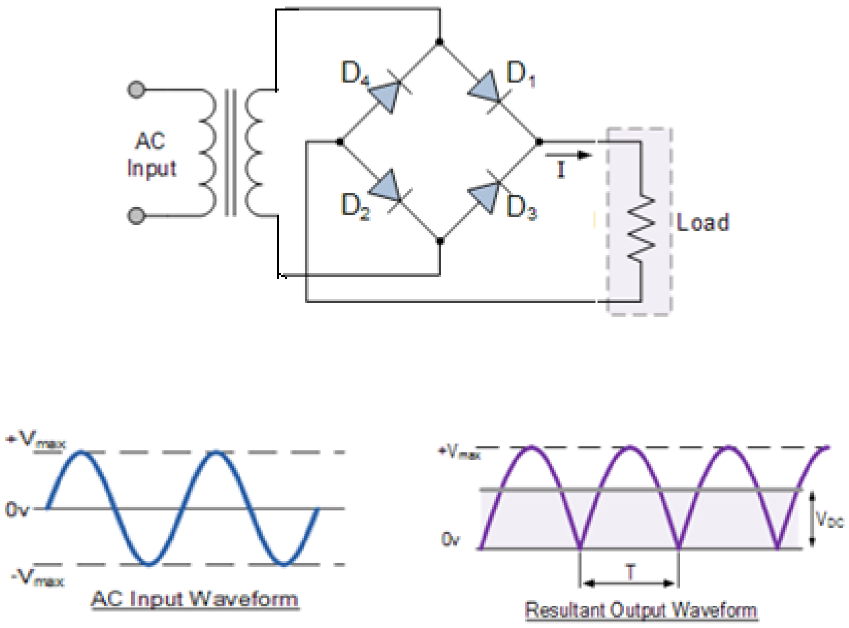


Fig.10: Bridge Rectifier

During the positive half cycle of the supply, diodes D1 and D2 conduct in series while diodes D3 and D4 are reverse biased and the current flows through the load as shown in the Fig.11.

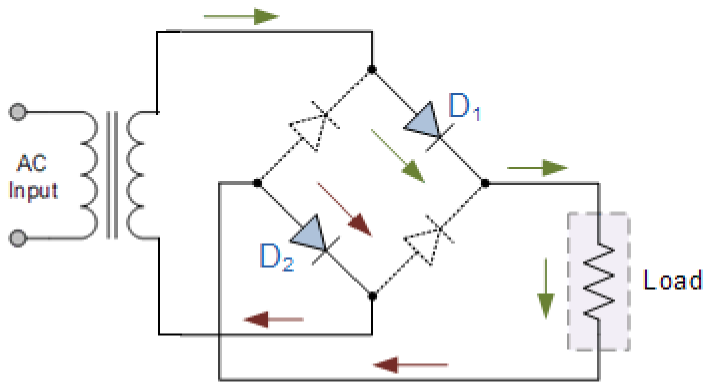


Fig.11: Working of Bridge Rectifier for Input Positive halfcycle

During the negative half cycle of the supply, diodes D3 and D4 conduct in series, but diodes D1 and D2 switch "OFF" as they are now reverse biased. The current flowing through the load is the same direction as before as shown in the Fig.12.

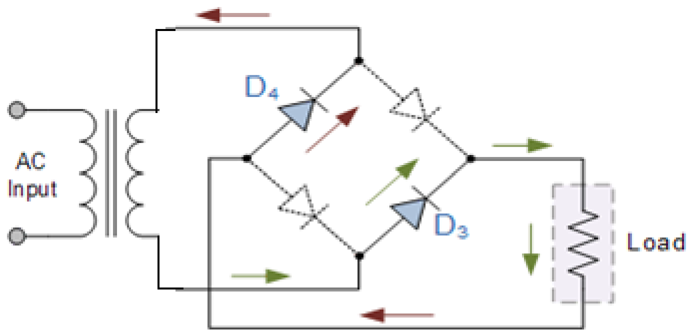


Fig.12: Working of Bridge Rectifier for Input Negative halfcycle

As the current flowing through the load is unidirectional, so the voltage developed across the load is also unidirectional and same as the previous two diode full-wave rectifier.

However in reality, during each half cycle the current flows through two diodes instead of just one so the amplitude of the output voltage is two voltage drops (2*0.7 = 1.4V) less than the input V_{MAX} amplitude. The ripple frequency is now twice the supply frequency (e.g. 100Hz for a 50Hz supply or 120Hz for a 60Hz supply.)

Although we can use four individual power diodes to make a full wave bridge rectifier, pre-made bridge rectifier components are available "off-the-shelf" in a range of different voltage and current sizes that can be soldered directly into a PCB circuit board or be connected by spade connectors.

Expressions for V_{dc}, V_{rms}, Ripple factor and Rectification efficiency for Full Wave Rectifier

Derivation of V_{DC}

DC Average current I_{DC}

$$I_{DC} = \frac{Area\ under\ curve\ over\ full\ cycle}{Time\ period} = \frac{1}{2\pi}\int_0^{2\pi} I_m sin\omega t d\omega t$$

$$I_{DC} = \frac{1}{2\pi}\left[\int_0^{\pi} I_m sin\omega t d\omega t + \int_{\pi}^{2\pi} I_m sin\omega t d\omega t\right]$$

$$I_{DC} = \frac{1}{2\pi}\left[2\int_0^{\pi} I_m sin\omega t d\omega t\right] = \frac{1}{\pi}\left[\int_0^{\pi} I_m sin\omega t d\omega t\right]$$

$$I_{DC} = \frac{I_m}{\pi}[-cos\omega t]_0^{\pi} = \frac{-I_m}{2\pi}[-1-1] = \frac{2I_m}{\pi}$$

DC Average Voltage V_{DC}

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

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

$$\Rightarrow V_{DC} = \frac{2V_m}{R_f + R_S + R_L} \frac{R_L}{\pi} = \frac{2V_m}{\pi} \frac{R_L}{R_f + R_S + R_L}$$

When the load resistor $R_L >> R_f$ *and* R_s ,

The dc value of the output voltage is $\boldsymbol{V_{dc} = \frac{2V_m}{\pi}}$

where R_s is the series resistance of the source V_s

R_f is the dynamic resistance of the diode

R_L is the load resistance.

Derivation of V$_{rms}$

Root mean square load current, I_{rms}

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} {I_L}^2\, d\omega t} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} {I_m}^2 sin^2\omega t d\omega t}$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}[\int_0^{\pi} {I_m}^2 sin^2\omega t d\omega t + \int_{\pi}^{2\pi} {I_m}^2 sin^2\omega t d\omega t]}$$

$$= \sqrt{\frac{1}{2\pi} 2 \int_0^{\pi} {I_m}^2 sin^2\, \omega t \;\, d\omega t}$$

$$= \sqrt{\frac{{I_m}^2}{\pi}\int_0^{\pi} \frac{1-cos2\omega t}{2} d\omega t} = \sqrt{\frac{{I_m}^2}{\pi}[\frac{1}{2}\int_0^{\pi} d\omega t - \frac{1}{2}\int_0^{\pi} cos2\omega t d\omega t]}$$

$$= \sqrt{\frac{{I_m}^2}{\pi}[\frac{1}{2}[\omega t]_0^{\pi} - \frac{1}{2}[\frac{sin2\omega t}{2}]_0^{\pi} d\omega t]} = \sqrt{\frac{{I_m}^2}{\pi}[\frac{\pi}{2} - 0]} = \boldsymbol{\frac{I_m}{\sqrt{2}}}$$

Root mean square load voltage, V_{rms}

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

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

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

When the load resistor $R_L >> R_f \ and \ R_s$,

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

Derivation of Ripple factor

The ripple factor, the measure of conversion from AC to DC of the full wave rectifier is

$$r = \frac{rms\ value\ of\ ac\ component\ of\ the\ output}{dC\ value\ of\ the\ output} = \frac{I_{ac}}{I_{dc}}$$

where $I_{ac}^2 = I_{rms}^2 - I_{dc}^2$

$$r = \frac{I_{ac}}{I_{dc}} = \frac{\sqrt{I_{rms}^2 - I_{dc}^2}}{I_{dc}} = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

Substitute, $I_{rms} = \frac{I_m}{\sqrt{2}}$ & $I_{dc} = \frac{2I_m}{\pi}$

We get, $r = \sqrt{\left(\frac{\frac{I_m}{\sqrt{2}}}{\frac{2I_m}{\pi}}\right)^2 - 1}$ = **0.482**

Thus, the ripple factor of the full wave rectifier is 0.482 or the amount of ac present in the output is 48.2 % of the dc voltage, which is a drastic improvement from 121 % of half wave rectifier.

Derivation of Rectification Efficiency

The efficiency of the full wave rectifier is

$$\%\eta = \frac{dc\ power\ delivered\ to\ the\ load}{ac\ input\ power\ from\ the\ transformer\ secondary}\ x\ 100 = \frac{P_{dc}}{P_{ac}}\ x\ 100$$

DC output power $P_{dc} = \boldsymbol{I_{dc}}^{\boldsymbol{2}} R_L$

AC input power $P_{ac} = \boldsymbol{I_{rms}}^{\mathbf{2}}(R_f + R_s + R_L)$

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

Substitute, $I_{rms} = \frac{I_m}{\sqrt{2}}$ & $I_{dc} = \frac{2I_m}{\pi}$

we get $\eta = \frac{(\frac{2I_m}{\pi})^2 R_L}{(\frac{I_m}{\sqrt{2}})^2 (R_f + R_s + R_L)}$ = **0.812 = 81.2 %**

If $R_L >> R_s + R_f$, the efficiency $\gamma = \mathbf{81.2}$ % or with no diode loss 81.2 % of the ac input power is converted into dc power in the load.

The main disadvantage of this type of full wave rectifier circuit is that a larger transformer for a given power output is required with two separate but identical secondary windings making this type of full wave rectifying circuit costly compared to the "Full Wave Bridge Rectifier" circuit equivalent.

Full-wave Rectifier with Capacitor filter

We saw in the previous section that the single phase half-wave rectifier produces an output wave every half cycle and that it was not practical to use this type of circuit to produce a steady DC supply. The full-wave bridge rectifier however, gives us a greater mean DC value (0.637 Vmax) with less superimposed ripple while the output waveform is twice that of the frequency of the input supply frequency.

The average DC output of the rectifier can be improved while at the same time reducing the AC variation of the rectified output by using smoothing capacitors to filter the output waveform. Smoothing or reservoir capacitors connected in parallel with the load across the output of the full wave bridge rectifier circuit increases the average DC output level even higher as the capacitor acts like a storage device as shown in Fig.13.

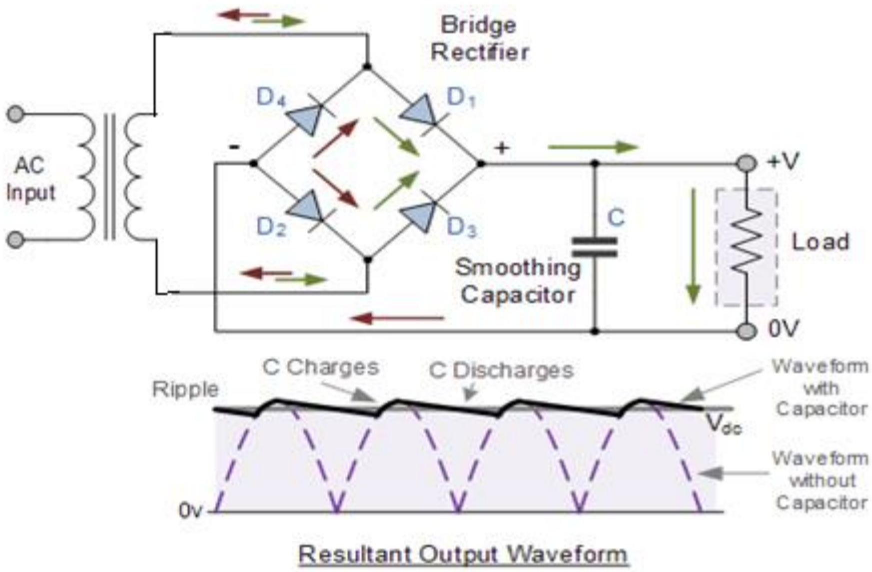


Fig13: Bridge rectifier with capacitor filter

The smoothing capacitor converts the full-wave rippled output of the rectifier into a more smooth DC output voltage. Here the capacitor is charged to the peak voltage of the output DC output, but when it drops from its peak voltage back down to zero volts, the capacitor cannot discharge as quickly due to the RC time constant of the circuit, maintaining the voltage across the load resistor until the capacitor re-charges once again on the next positive slope of the DC output. In other words, the capacitor only has time to discharge briefly before the next DC pulse recharges it back up to the peak value. Thus, the DC voltage applied to the load resistor drops only by a small amount. But we can improve this still by increasing the value of the smoothing capacitor.

Choke capacitor filter

It consists of an inductor connected in series with rectifier output circuit and a capacitor connected in parallel with the load resistor R_L as in Fig14.

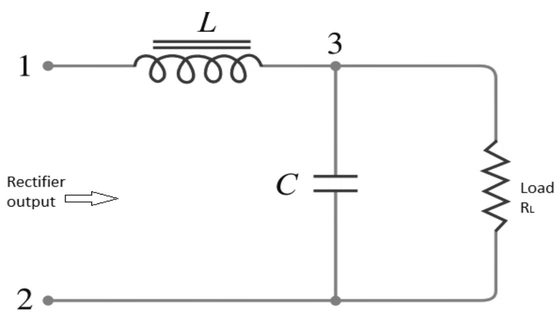


Fig.14: Choke capacitor filter

When the pulsating DC signal from the output of the rectifier circuit is fed into choke filter, the AC ripples present in the output DC voltage gets filtered by choke coil. The inductor has the property to block AC and pass DC. This is because DC resistance of an inductor is low and AC impedance of inductor coil is high. Thus, the AC ripples get blocked by inductor coil.

Although the inductor efficiently removes AC ripples, a small percentage of AC ripples is still present in the filtered signal. These ripples are then removed by the capacitor connected in parallel to the load resistor. Now, the DC output signal is free from AC components, and this regulated DC can be used in any application.

Zener Diode

The **Zener Diode** or "Breakdown Diode", as they are sometimes referred too, are basically the same as the standard PN junction diode but they are specially designed to have a low and specified **Reverse Breakdown Voltage** which takes advantage of any reverse voltage applied to it.

The **Zener diode** behaves just like a normal general-purpose diode consisting of a silicon PN junction and when biased in the forward direction, that is Anode positive with respect to its Cathode, it behaves just like a normal signal diode passing the rated current.

However, unlike a conventional diode that blocks any flow of current through itself when reverse biased, that is the Cathode becomes more positive than the Anode, as soon as the reverse voltage reaches a pre-determined value, the zener diode begins to conduct in the reverse direction.

This is because when the reverse voltage applied across the zener diode exceeds the rated voltage of the device a process called *Avalanche Breakdown* occurs in the semiconductor depletion layer and a current starts to flow through the diode to limit this increase in voltage.

The current now flowing through the zener diode increases dramatically to the maximum circuit value (which is usually limited by a series resistor) and once achieved, this reverse saturation current remains fairly constant over a wide range of reverse voltages. The voltage point at which the voltage across the zener diode becomes stable is called the "zener voltage", (Vz) and for zener diodes this voltage can range from less than one volt to a few hundred volts.

The point at which the zener voltage triggers the current to flow through the diode can be very accurately controlled (to less than 1% tolerance) in the doping stage of the diodes semiconductor construction giving the diode a specific *zener breakdown voltage*, (Vz) for example, 4.3V or 7.5V. This zener breakdown voltage on the I-V curve is almost a vertical straight line.

Zener Diode V-I Characteristics

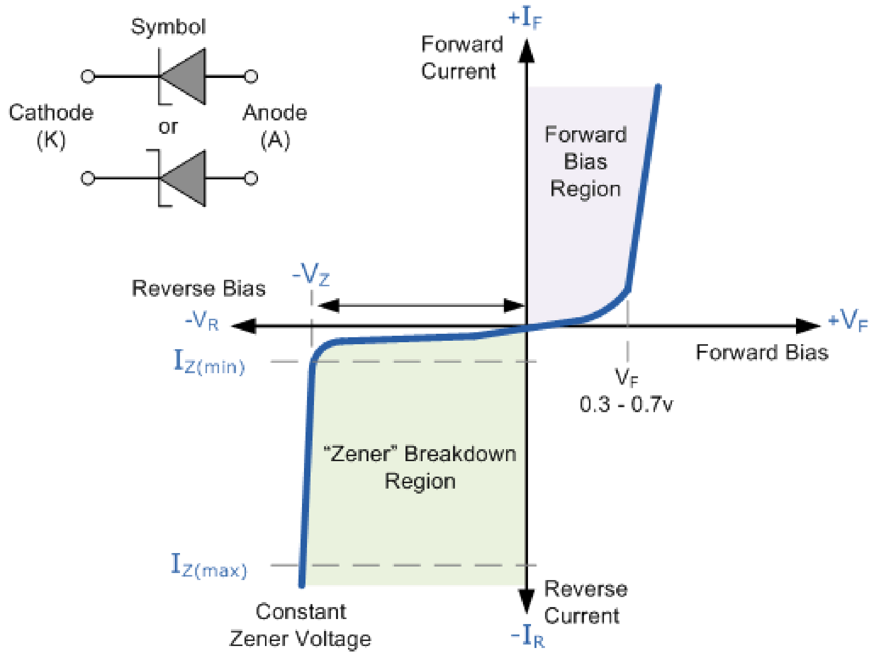


Fig.15: Zener Diode V-I Characteristics

The **Zener Diode** is used in its "reverse bias" or reverse breakdown mode, i.e. the diodes anode connects to the negative supply. From the I-V characteristics curve above, as seen in Fig.15, the zener diode has a region in its reverse bias characteristics of almost a constant negative voltage regardless of the value of the current flowing through the diode and remains nearly constant even with large changes in current as long as the zener diodes current remains between the breakdown current $I_{Z(min)}$ and the maximum current rating $I_{Z(max)}$.

This ability to control itself can be used to great effect to regulate or stabilise a voltage source against supply or load variations. The fact that the voltage across the diode in the breakdown region is almost constant turns out to be an important characteristic of the zener diode as it can be used in the simplest types of voltage regulator applications.

The function of a regulator is to provide a constant output voltage to a load connected in parallel with it in spite of the ripples in the supply voltage or the variation in the load current and the zener diode will continue to regulate the voltage until the diodes current falls below the minimum $I_{Z(min)}$ value in the reverse breakdown region.

The Zener Diode Regulator

Zener Diodes can be used to produce a stabilised voltage output with low ripple under varying load current conditions. By passing a small current through the diode from a voltage source, via a suitable current limiting resistor (R_S), the zener diode will conduct sufficient current to maintain a voltage drop of Vout.

We remember from the previous tutorials that the DC output voltage from the half or full-wave rectifiers contains ripple superimposed onto the DC voltage and that as the load value changes so to does the average output voltage. By connecting a simple zener stabiliser circuit as shown below across the output of the rectifier, a more stable output voltage can be produced.

Zener Diode Voltage Regulator

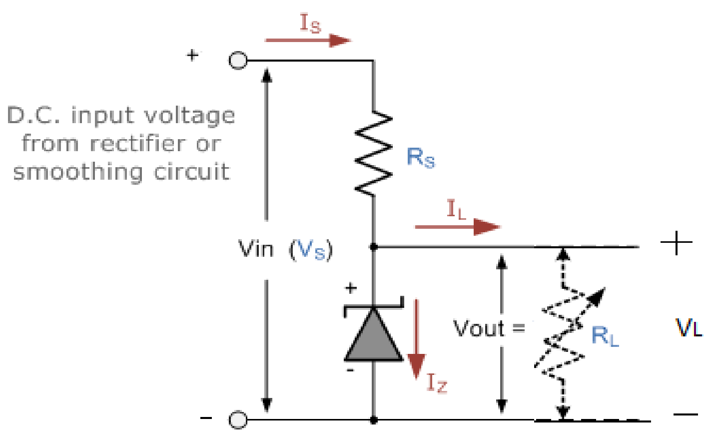


Fig.16: Zener Diode Voltage Regulator

The resistor, R_S is connected in series with the zener diode to limit the current flow through the diode with the voltage source, V_S being connected across the combination. The stabilised output voltage V_{out} is taken from across the zener diode. The zener diode is connected with its cathode terminal connected to the positive side of the DC supply so it is reverse biased and will be operating in its breakdown condition. Resistor R_S is selected so to limit the maximum current flowing in the circuit.

When no load is connected (($I_L = 0$): With no load connected to the circuit, the load current will be zero, ($I_L = 0$), and all the circuit current passes through the zener diode which in turn dissipates its maximum power. Also a small value of the series resistor R_S will result in a greater diode current when the load resistance R_L is connected and large as this will increase the power dissipation requirement of the diode so care must be taken when selecting the appropriate value of series resistance so that the zener's maximum power rating is not exceeded under this no-load or high-impedance condition.

When the load R_L is connected across the diode: The load is connected in parallel with the zener diode, so the voltage across R_L is always the same as the zener voltage, ($V_R = V_Z$). There is a minimum zener current for which the stabilization of the voltage is effective and the zener current must stay above this value operating under load within its breakdown region at all times. The upper limit of current is of course dependant upon the power rating of the device. The supply voltage V_S must be greater than V_Z.

Voltage regulation can be done through two techniques:

1. Line regulation: In this case, series resistor R_s and load resistor R_L are kept constant. 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.

% regulation is given by

$$\frac{\Delta V_o}{\Delta V_{in}} \times 100$$

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

% regulation is given by $\frac{V_{NL}-V_{FL}}{V_{FL}} \times 100$

A zener diode is always operated in its reverse biased condition. A voltage regulator circuit can be designed using a zener diode to maintain a constant DC output voltage across the load in spite of variations in the input voltage or changes in the load current. The zener voltage regulator consists of a current limiting resistor R_S connected in series with the input voltage V_S with the zener diode connected in parallel with the load R_L in this reverse biased condition. The stabilized output voltage is always selected to be the same as the breakdown voltage V_Z of the diode.

Zener Diode Example 1:

A 5.0V stabilised power supply is required to be produced from a 12V DC power supply input source. The maximum power rating P_Z of the zener diode is 2W. Using the zener regulator circuit in Fig.16, calculate:

a). The maximum current flowing through the zener diode.

$$\text{Maximum Current} = \frac{\text{Watts}}{\text{Voltage}} = \frac{2w}{5v} = 400mA$$

b). The minimum value of the series resistor, R_S

$$R_S = \frac{V_S - V_Z}{I_Z} = \frac{12 - 5}{400mA} = 17.5\Omega$$

c). The load current I_L if a load resistor of 1kΩ is connected across the zener diode.

$$I_L = \frac{V_Z}{R_L} = \frac{5v}{1000\Omega} = 5mA$$

d). The zener current I_Z at full load.

$$I_Z = I_S - I_L = 400mA - 5mA = 395mA$$

A typical **zener diode** for general electronic circuits is the 500mW, *BZX55* series or the larger 1.3W, *BZX85* series were the zener voltage is given as, for example, *C7V5* for a 7.5V diode giving a diode reference number of *BZX55C7V5*.

Fixed Voltage Regulator

The fixed voltage regulator has an unregulated dc input voltage V_i applied to one input terminal, a regulated output dc voltage V_{OUT} from a second terminal, and the third terminal connected to ground. A popular example is the 7805 IC which provides a constant 5 volts output. A fixed voltage regulator can be a positive voltage regulator or a negative voltage regulator. A positive voltage regulator provides with constant positive output voltage. All those IC's in the 78XX series are fixed positive voltage regulators. In the IC nomenclature – 78XX; the part XX denotes the regulated output voltage the IC is designed for. Examples:- 7805, 7806, 7809 etc.

The series 78XX regulators are the three-terminal devices that provide a fixed positive output voltage as shown in figure.

78XX based Fixed IC voltage regulator

One of the important sources of DC supply are batteries. But using batteries in sensitive electronic circuits is not a good idea as batteries eventually drain out and loose their potential over time.

Also, the voltage provided by batteries are typically 1.2V, 3.7V, 9V and 12V. This is good for circuits whose voltage requirements are in that range. But, most of the TTL IC's work on 5V logic and hence we need a mechanism to provide a consistent 5V Supply.

For getting constant and steady output, the voltage regulators are implemented. The integrated circuits which are used for the regulation of voltage are termed as voltage regulator ICs. The 78XX family of linear voltage regulators that produce a regulated output. It is a fixed linear voltage regulator. The xx present in 78xx represents the value of the fixed output voltage that the particular IC provides.

IC 7805 is a three terminal linear voltage regulator IC with a fixed output voltage of 5V which is useful in a wide range of applications. Currently, the 7805 Voltage Regulator IC as shown in Fig.17 is manufactured by Texas Instruments, ON Semiconductor, STMicroelectronics, Diodes incorporated, Infineon Technologies, etc. Some of the important features of the 7805 IC are as follows:

- It can deliver up to 1.5 A of current (with heat sink).
- Has both internal current limiting and thermal shutdown features.
- Requires very minimum external components to fully function.

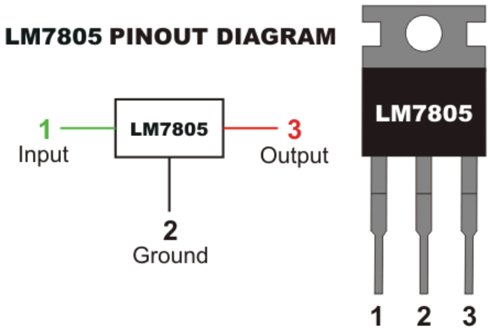


Fig.17: Pin Diagram of IC LM 7805

PIN 1-INPUT

The function of this pin is to give the input voltage. It should be in the range of 7V to 35V. We apply an unregulated voltage to this pin for regulation. For 7.2V input, the PIN achieves its maximum efficiency.

PIN 2-GROUND

We connect the ground to this pin. For output and input, this pin is equally neutral (0V).

PIN 3-OUTPUT

This pin is used to take the regulated output. It will be, $5V(4.8V - 5.2V)$.

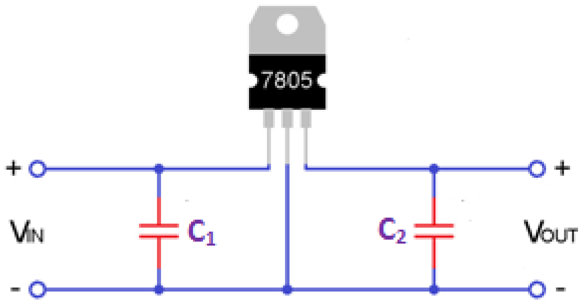


Fig.18: Circuit of 7805

The capacitor C_1 near the input is bypass capacitor, used to bypass very small extent spikes to the ground or earth. Also, the capacitor C_2 near the output is optional and if used, it helps in the transient response as shown in Fig.18.

Applications of Voltage Regulator 7805 IC

- Current regulator

- Regulated dual supply
- Building circuits for Phone charger, UPS power supply circuits, portable CD player etc
- Fixed output regulator
- Adjustable output regulator etc.

74XX series based fixed IC voltage regulator

A voltage regulator is one of the most widely used electronic circuitry in any device. A regulated voltage (without fluctuations & noise levels) is very important for the smooth functioning of many digital electronic devices. A common case is with micro controllers, where a smooth regulated input voltage must be supplied for the micro controller to function smoothly.IC regulators are available with fixed positive or negative output voltages or variable negative or positive output voltages.

Figure shows the functional diagram for 74XX series. Control element(pass transistor) in series with load between input and output. A reference voltage V_{ref} drives the non-inverting input of an amplifier. The resistor R_1 and R_2 sense a change in the output voltage and provide a feedback voltage. Output **sample circuit** senses a change in output voltage. The error detector compares the feedback voltage with a Zener diode reference voltage. **Error detector** compares sample voltage with reference voltage causes control element to compensate in order to maintain a constant output voltage. The resulting difference voltage causes the transistor Q_1 controls the conduction to compensate the variation of the output voltage. The block diagram of the IC voltage regulator is as shown in Fig.19.

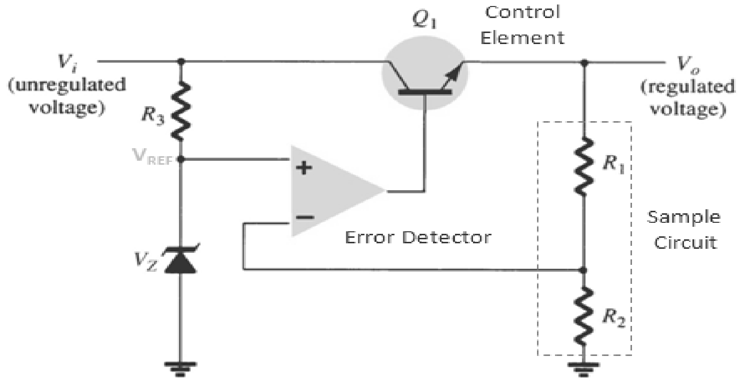


Fig.19: Circuit diagram of 74XX series based fixed IC voltage regulator

The output voltage will be maintained at a constant value of: $$Vo = \left(1 + \frac{R_1}{R_2}\right)V_Z$$

Light Emitting Diode (LED)

A LED is a semiconductor device that emits visible light when an electric current passes through it. The LED is a forward biased pn junction diode. When the diode is forward biased, the recombination of electrons and holes takes place. After recombination, electron goes into a new state, and its kinetic energy is given off as heat and light photons. This process of light emission in pn-junctions *Electroluminescence.* The metal contact of p-material is made much smaller to permit the emergence of maximum number of photons so that in an LED, the light generated per watt of electric power is high. Intensity of light increases linearly with forward current. Voltage levels of LED's are 1.2V to 3.2V. The response time is short. Symbol and construction of LED are as shown in Fig.20.

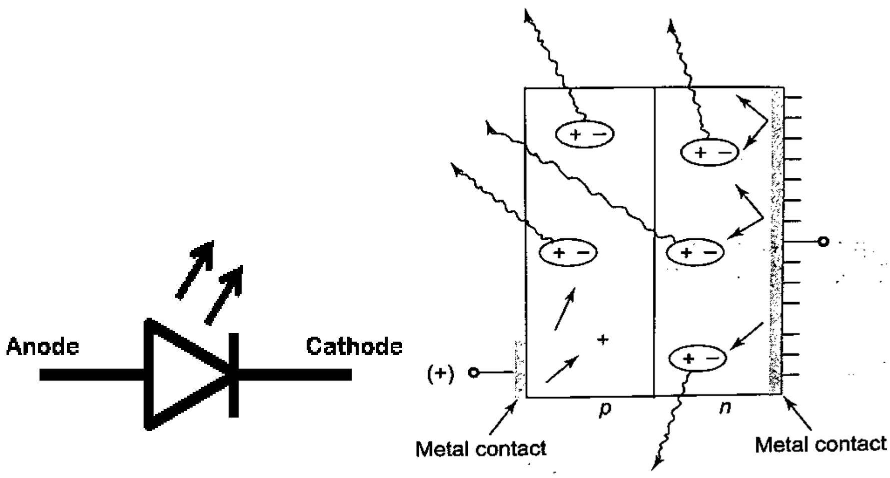


Fig.20: Symbol and construction of LED

Advantages of LED

1. Lower energy consumption
2. Longer life time
3. Improved physical robustness
4. Smaller size
5. Faster switching

Applications of LED

There are many applications of LED. Some are as explained:

1. LED used as bulb in homes and industries.
2. LED's are used in motor cycles and cars.
3. LED's are used in mobile phones and televisions as display.
4. LED's are used in automobile head lamps.

Photo Diode: It is a PN junction or PIN semiconductor device that consumes light energy to produce electric current. It is also called as photo detector, light detector or photo sensor. Diodes are designed to work in reverse bias condition. These diodes have slow response time. Symbol and circuit of diode as shown in Fig.21.

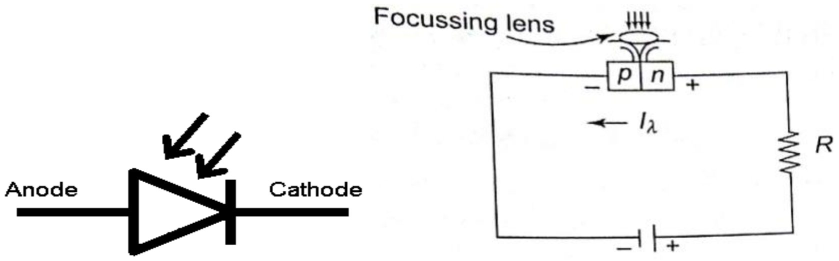


Fig.21: Symbol and construction of Photo Diode

When photons of sufficient energy strike the diode, electron-hole pairs are formed. When holes in p-region move towards n-side and electrons in n-region move towards the p-side and current is generated.

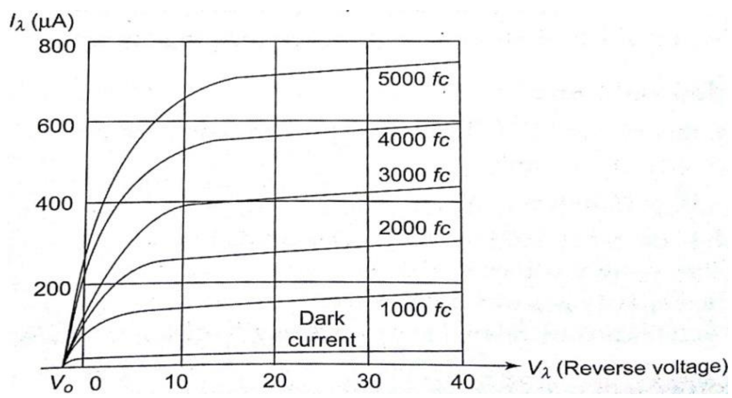


Fig.22: V-I Characteristics of Photo Diode

V-I Characteristics of Photodiode are as shown in Fig.22. where, current increases with increase in intensity of light, where f_c is unit of light intensity. Dark current is small reverse current of pn-diode when there is no light applied to the diode.

Applications of photodiodes:

There are many applications of photodiode. Some are as explained:

1. Optical communication systems
2. Automotive devices
3. Solar cell panels
4. Consumer electronics like CD players, TV and remote controls
5. Measurement of light intensity
6. Camera light meters and street lights
7. Photo detection circuits
8. Logic circuits and analysers

Photocoupler

Photocoupler is a device that uses a short optical path or link to couple a signal from one electrical circuit to another while providing electrical isolation.

It is a package of an LED and photodiode where as circuit is electrically isolated as shown in Fig.23. Interconnection is by means of a light sensitive optical interface.

Circuit consists of an LED that produces infra red light when forward biased. A semiconductor photosensitive diode acts as a receiver that is used to detect the emitted infra red beam from LED. Output is available across Resistor R_2.

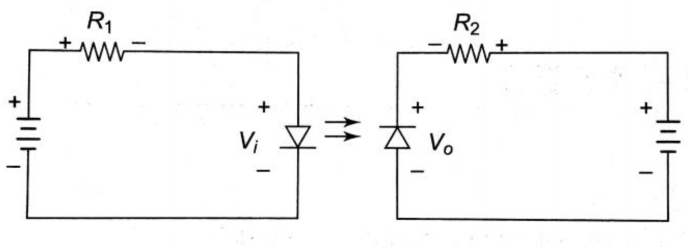


Fig.23: Block diagram of photocoupler

Advantages:

- Provides the required electrical isolation between a lower voltage control signal and a much higher voltage or mains current output signal.
- Used to detect the operation of the switch or another type of digital input signal.

Applications:

- Microprocessor input/output switching, DC and AC power control, PC communications, signal isolation and power supply regulation which suffer from current ground loops, etc.