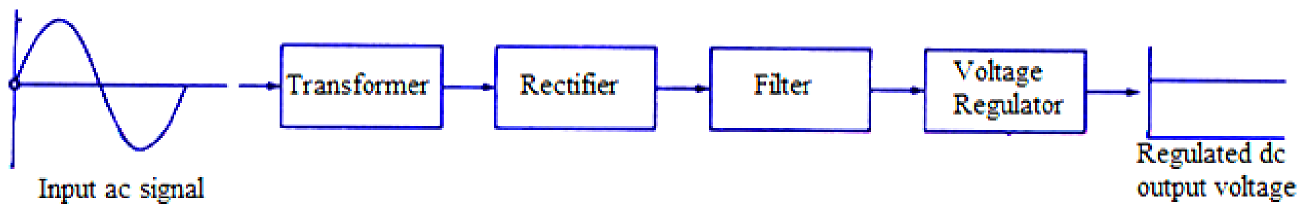
MODULE 1

POWER SUPPLIES

Power Supply

The primary function of a power supply is to convert one form of electrical energy to another and, as a result, power supplies are sometimes referred to as electric power converters. Power supplies are categorized in various ways. A regulated power supply is one that maintains constant output voltage or current despite variations in load current or input voltage. Conversely, the output of an unregulated power supply can change significantly when its input voltage or load current changes. Adjustable power supplies allow the output voltage or current to be programmed by mechanical controls (e.g., knobs on the power supply front panel), or by means of a control input, or both. A DC Power Supply Unit (commonly called a PSU) produces a DC supply from a pure AC wave.

Block Description of a DC Power Supply



1. Transformer

A transformer is a device which transforms high voltage AC into low voltage AC or vice versa. In a basic power supply the input power transformer has its primary winding connected to the main supply. A secondary winding, electro-magnetically coupled but electrically isolated from the primary is used to obtain an AC voltage of suitable amplitude. The power that we get from the wall outlet is 230 V 50 Hz. So a need arises to convert high voltage AC into low voltage. So a step-down transformer is used, which steps down the input AC voltage. The magnitude by which transformer steps down the voltage depends on the turn's ratio of primary and secondary winding.

2. Rectifier

After stepping down the ac voltage, it has to be converted to provide a suitable DC voltage. A rectifier is an electrical device composed of one or more diodes that converts alternating current (AC) to pulsating DC. A diode is like a one-way valve that allows an electrical current to flow in only one direction. This process is called rectification. Rectifiers are basically of two types:

i. Half wave rectifiers: Only the positive half cycle of the input is passed through and the other wave is blocked. It is not efficient because only half of the input wave form reaches the output.
ii. Full wave rectifiers: Passes the positive half cycle and reverses the negative part of the AC wave form and combines it with the positive cycle.

3. Filter

The output after being processed by a rectifier is not a pure DC. The output is a pulsating DC. The power supply that we intend to design must not have any variation in output voltage. The voltage from the rectifier fluctuates between 0 V and maximum value, and hence it contains AC components. These AC components need to be filtered out so as to obtain DC voltage. Filters, as the name suggests, filters out any AC component present and provides DC as the output. However, the output from the filter is still not a pure DC but filters remove the AC component in the voltage to a considerable extent. This increases the average DC value of the output voltage. The different classifications of filters are – Capacitor filter, Inductor filter, LC filters and CLC (π) filters.

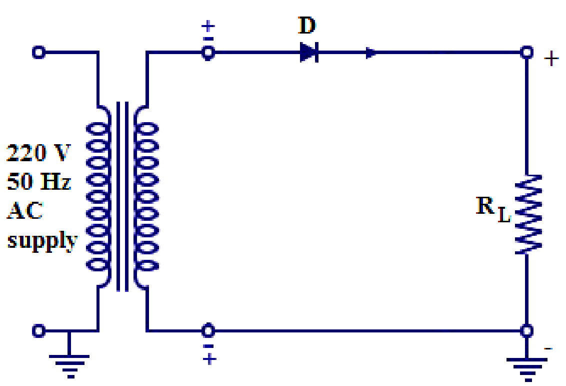
4. Voltage Regulator

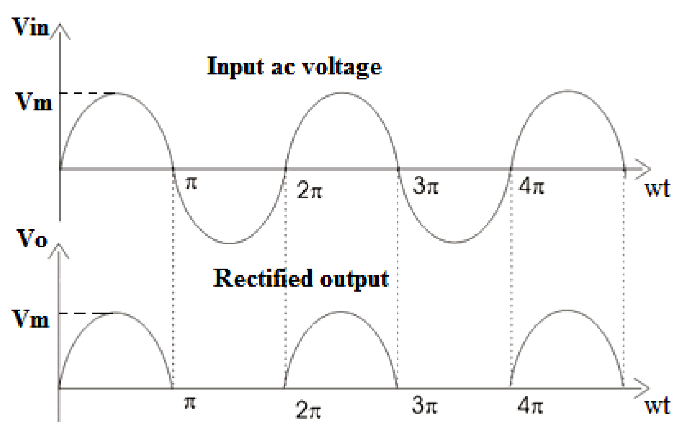
If there is a fluctuation in AC mains, there will be fluctuation in the output of transformer too. This output is passed on to the rectifier which again rectifies whatever is applied to it. Filter tries to eliminate the AC components as it is designed to do. However the average DC voltage may not be the same as it was intended to be. Hence a voltage regulator is needed to maintain the output at a constant level. Other case where a need of regulator arises is when there is a change in load current. For changes in load current, there is a change in output voltage. In order to maintain constant voltage irrespective of changes in load current, voltage regulator is used.

RECTIFIERS

A rectifier is an electrical device composed of one or more diodes that converts alternating current (AC) to pulsating DC. A diode is like a one-way valve that allows an electrical current to flow in only one direction. This process is called rectification. Rectifiers are basically of two types: Half wave and Full wave rectifiers.

1. Half Wave Rectifier

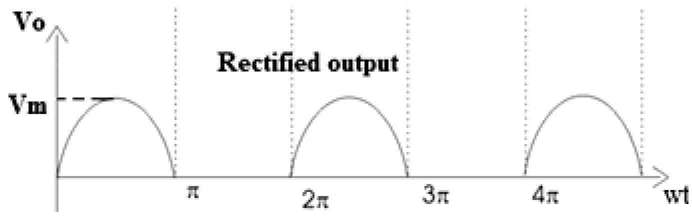




A simple Half Wave Rectifier is nothing more than a single p-n junction diode connected in series to the load resistor. A p-n junction diode conducts current only when it is forward biased. The same principle is made use of in a half wave rectifier to convert AC to DC. The input we give here is an alternating current. This input voltage is stepped down using a step down transformer. The ac voltage across the secondary winding changes polarities after every half cycle of input wave.

During the positive half-cycles of the input ac voltage *i.e.* when upper end of the secondary winding is positive w.r.t. its lower end, the diode is forward biased and therefore conducts current. If the forward resistance of the diode is assumed to be zero the input voltage during the positive half-cycles is directly applied to the load resistance R_L. The waveforms of the output current and output voltage are of the same shape as that of the input ac voltage. During the negative half cycles of the input ac voltage *i.e.* when the lower end of the secondary winding is positive w.r.t. its upper end, the diode is reverse biased and so does not conduct. Thus during the negative half cycles of the input ac voltage, the current through and voltage across the load remains zero. The reverse current, being very small in magnitude, is neglected. Thus for the negative half cycles no power is delivered to the load. Since only half-cycles of the input wave are used, it is called a half wave rectifier.

Performance of half wave rectifier



The time period of a half wave rectified signal is 2π. The half wave rectifier current waveform between 0 and 2π is given by

$$i_L = \begin{cases} I_m sinwt & 0 \le wt \le \pi \\ 0 & \pi \le wt \le 2\pi \end{cases}$$

$I_m = \frac{V_m}{r_f + R_L}$ ----------------------- (1) (r_f is the diode forward resistance)

1. DC output current and voltage (I_{dc} and V_{dc})

$$I_{dc} = \frac{1}{2\pi}\int_0^{2\pi} i_L \; d(wt)$$

$$I_{dc} = \frac{1}{2\pi}\left[\int_0^{\pi} I_m sinwt \; d(wt) + \int_{\pi}^{2\pi} 0 \; d(wt)\right]$$

$$I_{dc} = \frac{1}{2\pi}[-I_m coswt]_0^{\pi}$$

$$I_{dc} = \frac{I_m}{2\pi}[-cos\pi + \cos 0] = \frac{2I_m}{2\pi}$$

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

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

From equation (1) we have $I_m = \frac{V_m}{r_f + R_L}$

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

Since $R_L \gg r_f$, we can write

$$\boxed{V_{dc} = \frac{V_m}{\pi}}$$

2. RMS value of current and voltage

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i_L^2 \ d(wt)}$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\pi} {I_m}^2 sin^2 \ wt \ d(wt) + \int_{\pi}^{2\pi} 0 \ \ d(wt)\right]}$$

$$I_{rms} = \sqrt{\frac{{I_m}^2}{2\pi}\int_0^{\pi}\left(\frac{1 - cos2wt}{2}\right) \ d(wt)}$$

$$I_{rms} = \sqrt{\frac{{I_m}^2}{2\pi}\left[\frac{wt}{2} - \frac{\sin 2wt}{4}\right]_0^{\pi}}$$

$$I_{rms} = \sqrt{\frac{{I_m}^2}{2\pi} \times \frac{\pi}{2}} = \frac{I_m}{2}$$

$$\boxed{I_{rms} = \frac{I_m}{2}}$$

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

From equation (1) we have $I_m = \frac{V_m}{r_f + R_L}$

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

Since $R_L \gg r_f$, we can write

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

3. Ripple Factor

Ripple factor is the measure of purity of the dc output of the rectifier and is defined as

$$r = \frac{rms \ value \ of \ ac \ component \ of \ the \ wave}{average \ or \ dc \ component} = \frac{V_{rrms}}{V_{dc}}$$

$$V_{rrms} = \sqrt{V_{rms}^2 - V_{dc}^2}$$

$$r = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}} = \sqrt{\frac{V_{rms}^2 - V_{dc}^2}{{V_{dc}}^2}}$$

$$r = \sqrt{\frac{\left(\frac{V_m}{2}\right)^2 - \left(\frac{V_m}{\pi}\right)^2}{\left(\frac{V_m}{\pi}\right)^2}}$$

$$r = \sqrt{\frac{\pi^2}{4} - 1}$$

$$r = 1.21$$

4. Rectifier Efficiency

The rectifier efficiency tells us what percentage of the total input ac power is converted to useful dc output power. Rectification efficiency is defined as

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

$$P_{dc} = I_{dc}^2 R_L = \left(\frac{I_m}{\pi}\right)^2 R_L$$

The total ac power is given by

$P_{ac} = I_{rms}^2\ (r_f + R_L) = \left(\frac{I_m}{2}\right)^2 (r_f + R_L)$ (r_f is the forward diode resistance)

Therefore rectifier efficiency is given by

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{\left(\frac{I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{2}\right)^2 (r_f + R_L)} \times 100\%$$

$$\eta = \frac{\left(\frac{I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{2}\right)^2 R_L (\frac{r_f}{R_L} + 1)} \times 100\%$$

$$\eta = \frac{4}{\pi^2 (\frac{r_f}{R_L} + 1)} \times 100\% = \frac{40.6\%}{(\frac{r_f}{R_L} + 1)}$$

$R_L \gg r_f$. Therefore efficiency is

$\eta =$ 40.6 %.

5. Form Factor

Form factor is defined as the ratio of the rms value of the output voltage to the average value of the output voltage.

$$Form\ factor = \frac{rms\ value\ \ of\ \ output\ \ voltage}{Average\ \ value\ \ or\ dc\ value\ \ of\ \ output\ \ voltage}$$

$$Form\ factor = \frac{\frac{V_m}{2}}{\frac{V_m}{\pi}} = 1.56$$

6. Peak factor

Peak factor is defined as the ratio of the peak value of the output voltage to the rms value of the output voltage.

$$Peak\ factor = \frac{peak\ value\ of\ output\ voltage}{rms\ value\ of\ output\ voltage}$$

$$Peak\ factor = \frac{V_m}{\frac{V_m}{2}} = 2$$

7. Regulation

Regulation is defined as the variation of dc output voltage with change in dc load current. It is given as

$$Percentage\ Regulation = \frac{V_{no\ load} - V_{full\ load}}{V_{full\ load}} \times 100\%$$

$V_{no\ load}$ = dc voltage across load resistance, when minimum current flows through it.

$V_{full\ load}$ = dc voltage across load resistance, when maximum current flows through it.

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

$$V_{dc} = \frac{V_m}{\pi(r_f + R_L)}R_L$$

$$V_{dc} = \frac{V_m}{\pi}\left[1 - \frac{r_f}{(r_f + R_L)}\right] = \frac{V_m}{\pi} - \frac{V_m r_f}{\pi(r_f + R_L)}$$

$$V_{dc} = \frac{V_m}{\pi} - I_{dc}r_f - - - - - - - - - -(a)$$

$V_{no\ load} = \frac{V_m}{\pi}$ (no load when $I_{dc} = 0$)

$V_{full\ load} = I_{dc}R_L$

$$Percentage\ Regulation = \frac{\frac{V_m}{\pi} - I_{dc}R_L}{I_{dc}R_L} \times 100\%$$

$V_m = I_m(r_f + R_L)$ and $I_{dc} = \frac{I_m}{\pi}$

$$Percentage\ Regulation = \frac{\frac{I_m(r_f + R_L)}{\pi} - \frac{I_m}{\pi}R_L}{\frac{I_m}{\pi}R_L} \times 100\% = \frac{r_f + R_L - R_L}{R_L} \times 100\%$$

$$Percentage\ Regulation = \frac{r_f}{R_L} \times 100\%$$

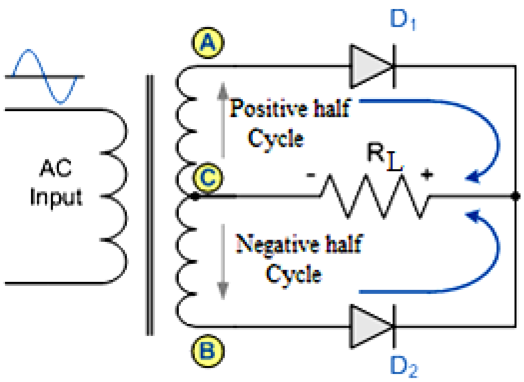
8. Peak Inverse Voltage (PIV)

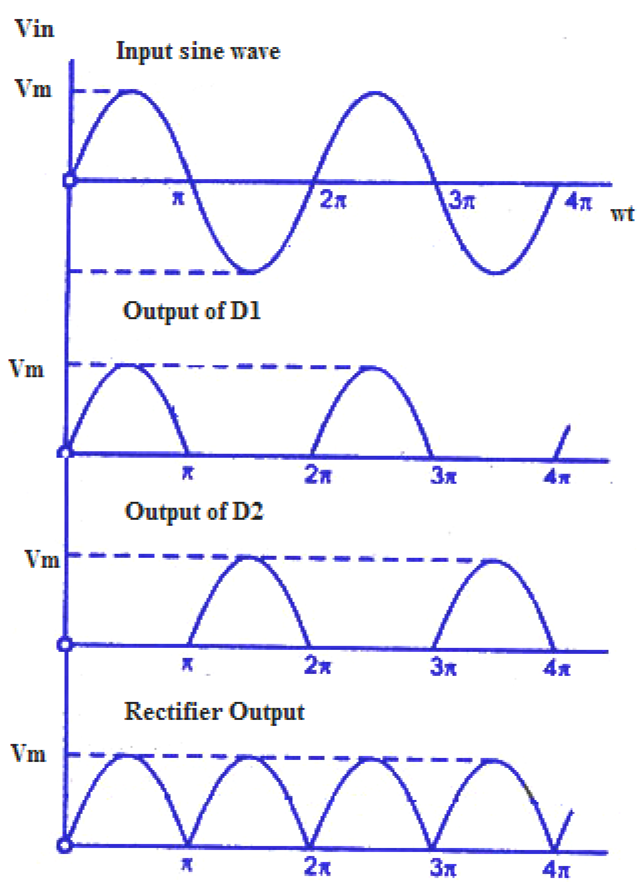
It is defined as the maximum reverse voltage that a diode can withstand without destroying the junction.
PIV for half wave rectifier = V_m

2. **<u>Full Wave Rectifier</u>**

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. A full wave rectifier circuit produces output during both half-cycles. Full wave rectifiers have some fundamental advantages over their 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. Full wave rectifiers are classified into two types namely- Centre tap rectifiers and Bridge rectifiers.

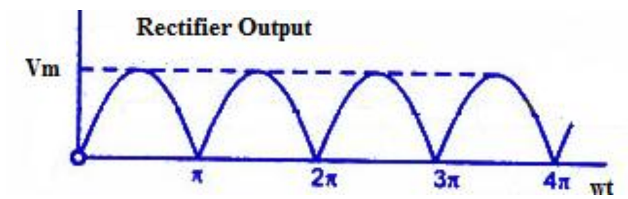
i. **<u>Centre Tap rectifier</u>**





In the case of centre-tap full wave rectifier, only two diodes are used, and are connected to the opposite ends of a centre-tapped secondary transformer as shown in the figure. The centre-tap is usually considered as the ground point or the zero voltage reference point. An ac input is applied to the primary coils of the transformer. This input makes the secondary ends A and B become positive and negative alternately. For the positive half of the ac signal, the secondary point A is positive, and B will be negative. At this instant diode D1 will be forward biased and diode D2 will be reverse biased. The diode D1 will conduct and D2 will not conduct during the positive half cycle. Thus the current flow will be in the direction A-D1- R_L-C. Thus, the positive half cycle appears across the load resistance R_L. During the negative half cycle, the secondary end A becomes negative and B becomes positive. At this instant, the diode D2 will be forward biased and D1 will be reverse biased. The diode D2 will conduct and D1 will not conduct during the negative half cycle. The current flow will be in the direction B-D2-R_L-C.

Performance of Centre tap full wave rectifier



The time period of a full wave rectified signal is π. The full wave rectifier current waveform between 0 and π is given by

$$i_L = I_m sinwt \qquad 0 \le wt \le \pi$$

$$I_m = \frac{V_m}{r_f + R_L}$$ ----------------------- (1) (r_f is the diode forward resistance)

1. DC output current and voltage ($I_{dc} and V_{dc}$)

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} i_L \; d(wt)$$

$$I_{dc} = \frac{1}{\pi}\int_0^{\pi} I_m sinwt \; d(wt)$$

$$I_{dc} = \frac{1}{\pi}[-I_m coswt]_0^{\pi}$$

$$I_{dc} = \frac{I_m}{\pi}[-cos\pi + \cos 0]$$

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

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

From equation (1) we have $I_m = \frac{V_m}{r_f + R_L}$

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

Since $R_L \gg r_f$, we can write

$$\boxed{V_{dc} = \frac{2V_m}{\pi}}$$

2. RMS value of current and voltage

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} i_L^2 \; d(wt)}$$

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} {I_m}^2 sin^2 \; wt \; d(wt)}$$

$$I_{rms} = \sqrt{\frac{{I_m}^2}{\pi}\int_0^{\pi} \left(\frac{1 - cos2wt}{2}\right) d(wt)}$$

$$I_{rms} = \sqrt{\frac{{I_m}^2}{\pi}\left[\frac{wt}{2} - \frac{\sin 2wt}{4}\right]\begin{matrix}\pi \\ 0\end{matrix}}$$

$$I_{rms} = \sqrt{\frac{{I_m}^2}{\pi} \times \frac{\pi}{2}} = \frac{I_m}{\sqrt{2}}$$

$$\boxed{I_{rms} = \frac{I_m}{\sqrt{2}}}$$

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

From equation (1) we have $I_m = \frac{V_m}{r_f + R_L}$

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

Since $R_L \gg r_f$, we can write

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

3. Ripple Factor

Ripple factor is the measure of purity of the dc output of the rectifier and is defined as

$$r = \frac{rms\ value\ of\ ac\ component\ of\ the\ wave}{average\ or\ dc\ component} = \frac{V_{rrms}}{V_{dc}}$$

$$V_{rrms} = \sqrt{V_{rms}^2 - V_{dc}^2}$$

$$r = \frac{\sqrt{V_{rms}^2 - V_{dc}^2}}{V_{dc}} = \sqrt{\frac{V_{rms}^2 - V_{dc}^2}{{V_{dc}}^2}}$$

$$r = \sqrt{\frac{\left(\frac{V_m}{\sqrt{2}}\right)^2 - \left(\frac{2V_m}{\pi}\right)^2}{\left(\frac{2V_m}{\pi}\right)^2}}$$

$$r = \sqrt{\frac{\pi^2}{8} - 1}$$

$$r = 0.482$$

4. Rectifier Efficiency

The rectifier efficiency tells us what percentage of the total input ac power is converted to useful dc output power. Rectification efficiency is defined as

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

$$P_{dc} = I_{dc}^2 R_L = \left(\frac{2I_m}{\pi}\right)^2 R_L$$

The total ac power is given by

$P_{ac} = I_{rms}^2\ (r_f + R_L) = \left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L)$ (r_f is the forward diode resistance)

Therefore rectifier efficiency is given by

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{\left(\frac{2I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 (r_f + R_L)} \times 100\%$$

$$\eta = \frac{\left(\frac{2I_m}{\pi}\right)^2 R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 R_L\left(\frac{r_f}{R_L} + 1\right)} \times 100\%$$

$$\eta = \frac{8}{\pi^2\left(\frac{r_f}{R_L} + 1\right)} \times 100\% = \frac{81.2\ \%}{\left(\frac{r_f}{R_L} + 1\right)}$$

$R_L \gg r_f$. Therefore efficiency is

$\eta =$ 81.2%.

5. Form Factor

Form factor is defined as the ratio of the rms value of the output voltage to the average value of the output voltage.

$$Form\ factor = \frac{rms\ value\ of\ output\ voltage}{Average\ value\ of\ output\ voltage}$$

$$Form\ factor = \frac{\frac{V_m}{\sqrt{2}}}{\frac{2V_m}{\pi}} = 1.11$$

6. Peak factor

Peak factor is defined as the ratio of the peak value of the output voltage to the rms value of the output voltage.

$$Peak\ factor = \frac{peak\ value\ of\ output\ voltage}{rms\ value\ of\ output\ voltage}$$

$$Peak\ factor = \frac{V_m}{\frac{V_m}{\sqrt{2}}} = \sqrt{2}$$

7. Regulation

Regulation is defined as the variation of dc output voltage with change in dc load current. It is given as

$$Percentage\ Regulation = \frac{V_{no\ load} - V_{full\ load}}{V_{full\ load}} \times 100\%$$

$V_{no\ load}$ = dc voltage across load resistance, when minimum current flows through it.

$V_{full\ load}$ = dc voltage across load resistance, when maximum current flows through it.

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

$$V_{dc} = \frac{2V_m}{\pi(r_f + R_L)}R_L$$

$$V_{dc} = \frac{2V_m}{\pi}\left[1 - \frac{r_f}{(r_f + R_L)}\right] = \frac{2V_m}{\pi} - \frac{2V_m r_f}{\pi(r_f + R_L)}$$

$$V_{dc} = \frac{2V_m}{\pi} - I_{dc}r_f - - - - - - - - - - (a)$$

$V_{no\ load} = \frac{2V_m}{\pi}$ (no load when $I_{dc} = 0$)

$V_{full\ load} = I_{dc}R_L$

$$Percentage\ Regulation = \frac{\frac{2V_m}{\pi} - I_{dc}R_L}{I_{dc}R_L} \times 100\%$$

$V_m = I_m(r_f + R_L)$ and $I_{dc} = \frac{2I_m}{\pi}$

$$Percentage\ Regulation = \frac{\frac{2I_m(r_f + R_L)}{\pi} - \frac{2I_m}{\pi} R_L}{\frac{2I_m}{\pi} R_L} \times 100\% = \frac{r_f + R_L - R_L}{R_L} \times 100\%$$

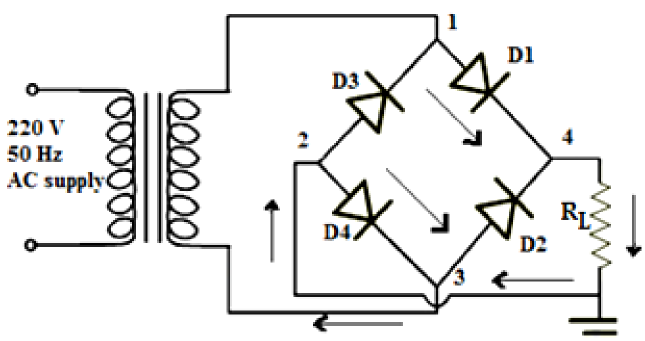
$$Percentage\ Regulation = \frac{r_f}{R_L} \times 100\%$$

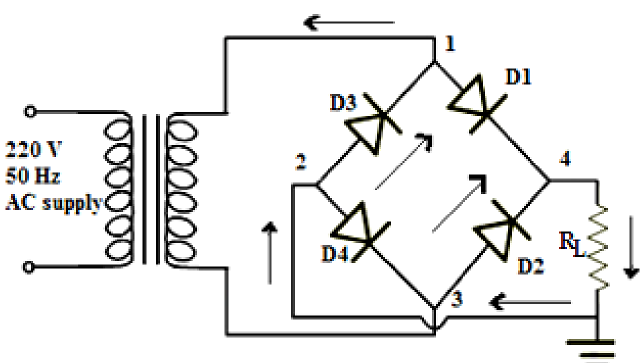
8. Peak Inverse Voltage (PIV)

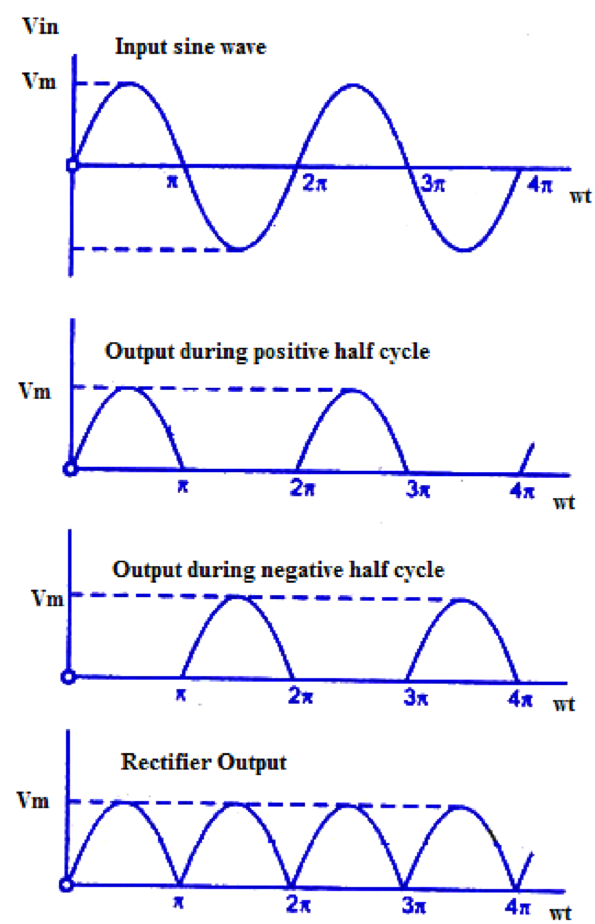
It is defined as the maximum reverse voltage that a diode can withstand without destroying the junction.
PIV for centre tap rectifier = $2V_m$

ii. Bridge Rectifier

Another type of circuit that produces the same output waveform as the full wave rectifier circuit is that of the full wave bridge rectifier. This type of 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 secondary winding of the transformer is connected to the two diametrically opposite points of the bridge at points 1 and 3. Assume that a load is connected at the output. The load R_L is connected to bridge through points 2 and 4.







During first half cycle of the AC input, the upper portion of the transformer secondary winding is positive with respect to the lower portion. Thus during the first half cycle diodes D1 and D_4 are forward biased. Current flows through the path 1-4, enters the load R_L and returns back flowing through path 2-3. During this half input cycle, the diodes D_2 and D_3 are reverse biased. Hence there is no current flow through the path 3-4 and 2-1. During the next cycle lower portion of the transformer is positive with respect to the upper portion. Hence during this cycle diodes D2 and D3 are forward biased. Current flows through the path 3-4 to load R_L and flows back through the path 2-1.The diodes D1 and D4 are reverse biased. So there is no current flow through the path 1-4 and 2-3.Thus negative cycle is rectified and it appears across the load.

<u>Performance of bridge rectifier</u>

The analysis of a bridge rectifier is same as that of a centre tap rectifier, except for PIV.

1. $I_{dc} = \frac{2I_m}{\pi}$
2. $V_{dc} = \frac{2V_m}{\pi}$
3. $I_{rms} = \frac{I_m}{\sqrt{2}}$
4. $V_{rms} = \frac{V_m}{\sqrt{2}}$
5. Ripple factor $r = 0.482$
6. Efficiency $\eta =$ 81.2%.
7. $Form\ factor = 1.11$
8. $Peak\ factor = \sqrt{2}$
9. $Percentage\ Regulation = \frac{r_f}{R_L} \times 100\%$
10. PIV for bridge rectifier = V_m

Advantages of bridge rectifier over centre tap rectifier

- No centre tap is required.
- Bridge rectifier is suited for high voltage applications because the output is twice that of the center-tap circuit for the same secondary voltage.
- The PIV is half that of the center tap circuit.
- Transformer utilization factor (TUF) is higher for bridge rectifier.

Disadvantages

- 4 diodes are used in a bridge rectifier. This increases the net voltage drop across diodes in a bridge rectifier (it is double to the value of center tap).

Comparison of half wave and full wave rectifier

	Half Wave	Full Wave	
		Centre Tap	Bridge
No of Diodes	1	2	4
PIV	V_m	$2V_m$	V_m
RMS Current	$\frac{I_m}{2}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$
RMS voltage	$\frac{V_m}{2}$	$\frac{V_m}{\sqrt{2}}$	$\frac{V_m}{\sqrt{2}}$
DC current	$\frac{I_m}{\pi}$	$\frac{2I_m}{\pi}$	$\frac{2I_m}{\pi}$
DC voltage	$\frac{V_m}{\pi}$	$\frac{2V_m}{\pi}$	$\frac{2V_m}{\pi}$
Ripple factor	1.21	0.482	0.482
Rectification efficiency	40.6%	81.2%	81.2%
Lowest ripple frequency	$f_i(input\ frequency)$	$2f_i$	$2f_i$
Peak factor	2	$\sqrt{2}$	$\sqrt{2}$
Transformer Utilization factor	0.287	0.693	0.812

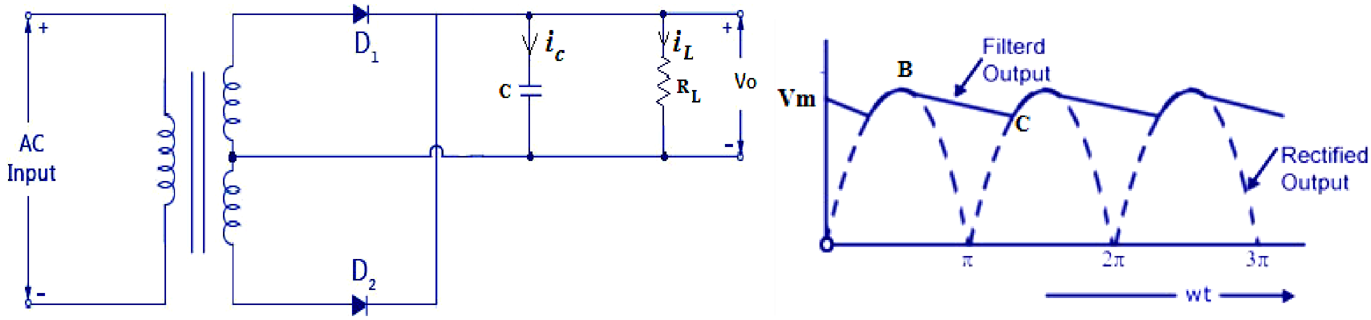
FILTERS

A power supply must provide ripple free source of power from an A.C. line. But the output of a rectifier is a pulsating dc. The filter is a device that allows the dc component to pass to the load and blocks the ac component of the rectifier output. Thus the output of the filter circuit will be a steady dc voltage. The filter circuit is mostly a combination of capacitors and inductors. Many types of passive filters are in use such as:

- Shunt capacitor filter
- Series inductor filter
- Chock input (LC) filter
- Pi(π) section filter or CLC filter or capacitor input filter

1. Shunt Capacitor Filter

This type of filter consists of large value of capacitor connected across the load resistor R_L as shown in figure. This capacitor offers a low reactance to the ac components and very high impedance to dc so that the ac components in the rectifier output find low reactance path through capacitor and only a small part flows through R_L, producing small ripple at the output. Here Xc (Xc =1/2πfC, the impedance of capacitor) should be smaller than R_L, because, current should pass through C and C should get charged. If C value is very small, Xc will be large and hence current flows through R_L only and no filtering action takes place.



During the positive half cycle, the input voltage increases which forward biases the diode. The rectifier output also increases. The capacitor now begins to charge to the peak value V_m. Just past the positive peak, the rectifier output voltage falls below V_m. But at point B the capacitor has $+V_m$ volts across it. This reverse biases the diode, i.e., it becomes open circuited. The capacitor then starts discharging through the load. This prevents the load voltage from falling to zero. The capacitor continues to discharge until the source voltage becomes more than the capacitor voltage (at point C). The diode again starts conducting and capacitor is again charged to the peak value. During the charging period the rectifier supplies the charging current i_C as well as the load current i_L. During the discharging period, the rectifier does not supply any current, the capacitor sends current i_L through the load. The discharging of the capacitor depends upon the time constant CR_L. The longer the time constant, the steadier the output voltage. As the value of C increases the smoothness of the output also increases. But the maximum value of the capacitor is limited by the current rating of the diode. Also increase in the value of R_L decreases the load current and makes the output steady. These types of filters are used in circuits with small load currents like transistor radio receivers, calculators, etc. The ripple factor in capacitor filter is given by

$$\gamma = \frac{1}{4\sqrt{3}fCR_L}$$

Advantages

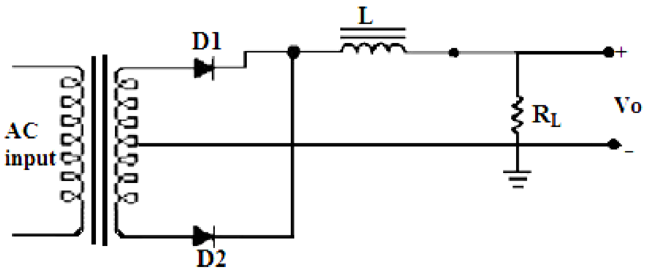
- Low cost
- Small size and weight
- Can be connected for both HW and FW rectifiers
- Improved dc output

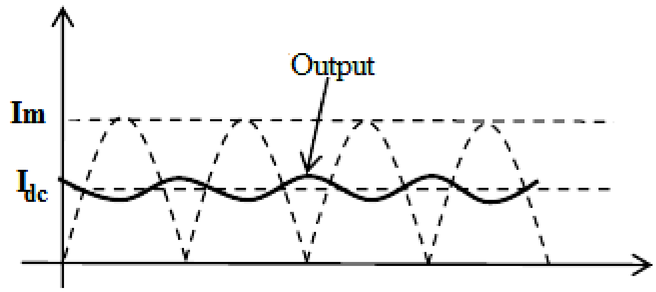
Disadvantages

- Capacitor draws more current

2. <u>Series Inductor Filter</u>

As the name of the filter circuit suggests, the Inductor L is connected in series between the rectifier circuit and the load. This type of filter is also known as choke filter. The working of series inductor filter depends on the inherent property of the inductor to oppose any variation in current. The reactance of the inductor is more for ac components and it offers more opposition to them. At the same time it provides no impedance for dc component. Therefore the inductor blocks ac components in the output of the rectifier and allows only dc component to flow through R_L.





When the rectifier output current increases above a certain value, energy is stored in the inductor in the form of a magnetic field and this energy is given up when the output current falls below the average value. Thus all the sudden changes in current that occurs in the circuit will be smoothened by placing the inductor in series between the rectifier and the load.

The action of an inductor depends upon the current through it and it requires current to flow through it at all the time. Therefore filter circuits consisting inductors can only be used together with full wave rectifiers. In inductor filter an increase in load current will improve the filtering action and results in reduced ripple. Series inductor filters are used in equipments of high load currents. The ripple factor in series inductor filter is given as

$$\gamma = \frac{R_L}{3\sqrt{2}wL}$$

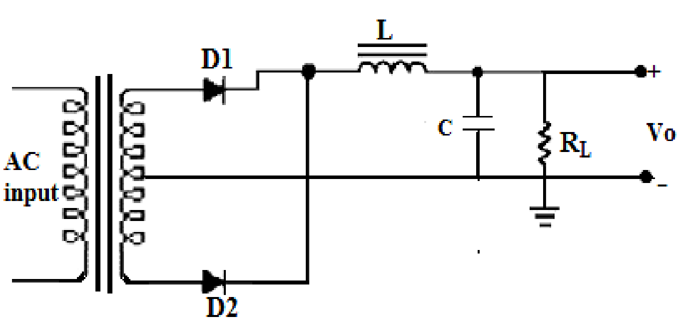
Advantages

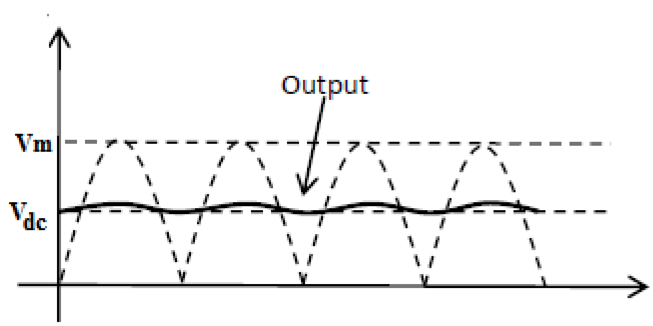
- Sudden changes in current is smoothened out
- Improved filtering action at high load currents

Disadvantages

- Reduced output voltage due to the drop across the inductor.
- Bulky and large in size
- Not suited for half wave rectifiers

3. <u>LC filter (Choke input LC filter)</u>





It is a combination of inductor and capacitor filter. Here an inductor is connected in series and a capacitor is connected in parallel to the load. As discussed earlier, a series inductor filter will reduce the ripple, when increasing the load current. But in case of a capacitor filter reverse happens. While increasing load current, the ripple also increases. So a combination of these two filters would make ripple independent of load current. Since the dc resistance of the inductor is very low it allows dc current to flow easily through it. The capacitor appears open for dc and so all dc components passes through the load resistor R_L. The ripple factor of a chock input filter is given by

$$\gamma = \frac{1}{6\sqrt{2}w^2 LC}$$

For optimum functioning, the inductor requires a minimum current to flow through, at all time. When the current falls below this rate, the output will increase sharply and hence the regulation becomes poor. To keep up the circuit current above this minimum value, a resistor is permanently connected across the filtering capacitor and is called **bleeder resistor**. This resistor always draws a minimum current even if the external load is removed. It also provides a path for the capacitor to discharge when power supply is turned off.

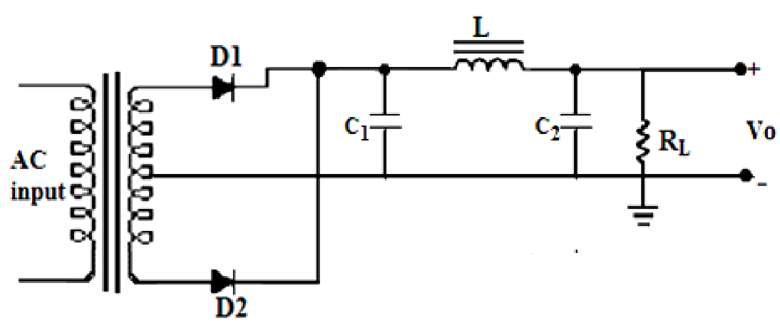
Advantages

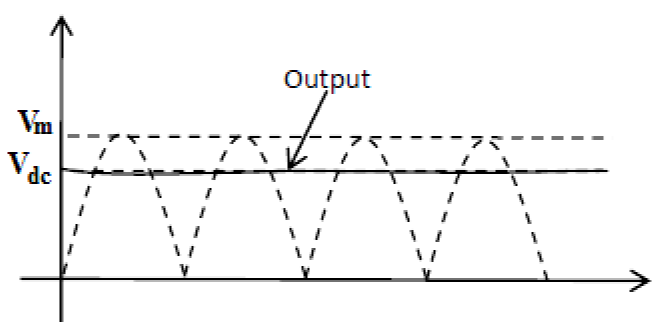
- Reduced ripples at the output
- Action is independent of load current

Disadvantages

- Low output voltage
- Bulky and large in size
- Not suited to connect with half wave rectifier.

4. π – filter (Capacitor input filter) or CLC filter





The capacitor-input filter is also called the pi filter due to its shape that looks like the Greek letter π. This filter is basically a capacitor filter followed by an LC filter. It is also called capacitor input filter because the rectifier feeds directly into the capacitor C1. Here the first capacitor C1 offers a low reactance to ac component of rectifier output but provide more reactance to dc components. Therefore most of the ac components will bypass through C1 and the dc component flows through choke L. The choke offers very high reactance to the ac component. Thus it blocks ac components while pass the dc. The capacitor C2 bypasses any other ac component appears across the load and we get study dc output. The ripple factor in a π-section filter is given by

$$\gamma = \frac{\sqrt{2}}{w^3 C_1 C_2 L R_L}$$

Advantages

- More output voltage
- Ripple less output
- Suitable to be used with both HWR and FWR

Disadvantages

- Large in size and weight
- High cost

<u>Voltage Regulators</u>

The purpose of every voltage regulator is to convert a given dc or ac input to a specific stable dc output and maintain that voltage despite changes in the input voltage or output load. In an ordinary power supply, the voltage regulation is poor i.e. dc output voltage changes appreciably with load current. Moreover, output voltage also changes due to variations in the input dc voltage. This is due to the following reasons:

(i) In practice, there are considerable variations in ac line voltage caused by outside factors beyond our control. This changes the dc output voltage. Most of the electronic circuits will refuse to work satisfactorily on such output voltage fluctuations.

(ii) The internal resistance of ordinary power supply is relatively large (> 30 Ω). Therefore, output voltage is affected by the amount of load current drawn from the supply. These variations in dc voltage may cause erratic operation of electronic circuits. Therefore, regulated dc power supply is the only solution in such situations.

There are mainly 2 types of regulation

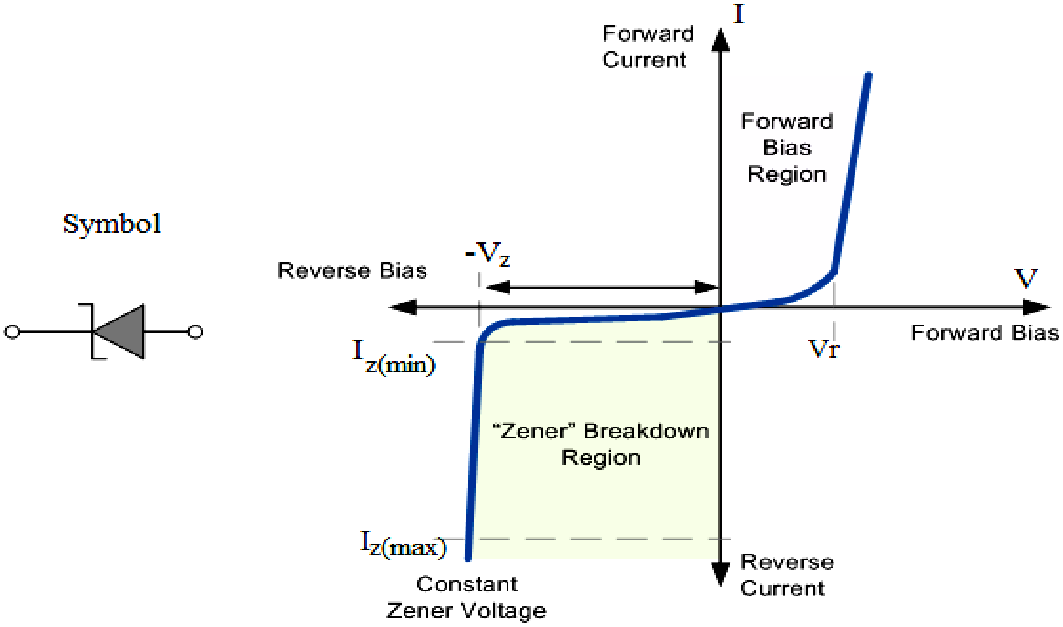
a. Load Regulation: It indicates the change in output voltage due to the change in load current.

$$Load\ Regulation = \frac{V_{no\ load} - V_{full\ \ load}}{V_{full\ load}}$$

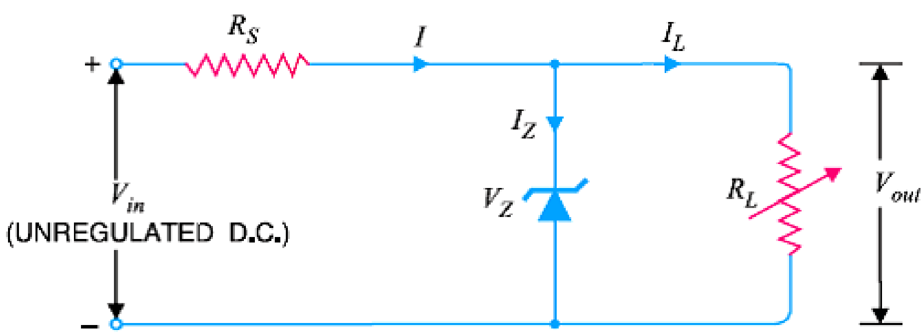
b. Line Regulation: It indicates the change in output voltage due to the change in input voltage.

1. <u>Zener diode voltage regulator</u>

The zener diode is like a general-purpose signal diode consisting of a silicon PN junction. When biased in the forward direction it behaves just like a normal signal diode passing the rated current. But as soon as the reverse voltage applied across the zener diode exceeds the rated voltage of the device, the diode breaks down and a current starts to flow through the diode to limit this increase in voltage. The voltage is maintained constant but the current starts rising significantly. Hence the voltage 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 property of zener diode is made use in voltage regulators.



Circuit working



As long as input voltage *Vin* is greater than zener voltage V_Z , the zener operates in the breakdown region and maintains constant voltage across the load. The series limiting resistance R_S limits the input current.The stabilized output voltage V_{out} is taken from across the zener diode. The zener diode is connected with its cathode terminal connected to the positive rail of the DC supply so it is reverse biased and will be operating in its breakdown condition. The load is connected in parallel with the zener diode, so the voltage across R_L is always the same as the zener voltage, ($V_{out} = V_Z$). 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 dependent upon the power rating of the device.

$I = I_Z + I_L$-----------------------(1)

Line regulation:
Assume that the load is fixed and the input voltage fluctuates. When the input voltage Vin increases, the current I increases. Since load is fixed, I_L is constant. Hence more current will flow through the zener. As long as the zener current is within the limits, the zener voltage remains constant. The voltage drop across R_S will increase but load voltage would remain constant. The reverse would be true when the input voltage decrease.

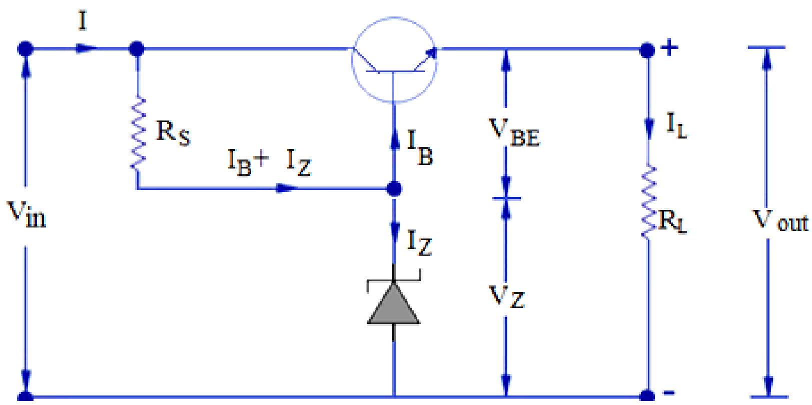
Load Regulation:
Assume that the load is varying and the input voltage is fixed. When the load R_L increases the output voltage Vout also increases. Since input is fixed, I is constant. Hence more current will flow through the zener. As long as the zener current is within the limits, the zener voltage remains constant. This leads to decrease in I_L in order to compensate for the increases in R_L so that Vout $(I_L R_L)$ remains constant. The operation is similar when R_L decreases.

Limitations

(i) It has low efficiency for heavy load currents. It is because if the load current is large, there will be considerable power loss in the series limiting resistance.

(ii) The output voltage slightly changes due to zener impedance. Changes in load current produce changes in zener current. Consequently, the output voltage also changes. Therefore, the use of this circuit is limited to only such applications where variations in load current and input voltage are small.

2. <u>Transistor Series Voltage Regulator</u>



Such a circuit is also named an emitter follower voltage regulator. It is called so because the transistor used is connected in an emitter follower configuration. The circuit consists of an N-P-N transistor and a zener diode. As shown in the figure. The collector and emitter terminals of the transistor are in series with the load. Thus this regulator has the name series in it. The transistor used is a series pass transistor. The output of the rectifier that is filtered is then given to the input terminals and regulated output voltage V_{out} is obtained across the load resistor R_L. The reference voltage is provided by the zener diode and the transistor acts as a variable resistor, whose resistance varies with the operating conditions of base current, I_B.
The output voltage can thus be written as
$V_{out} = V_Z - V_{BE}$

Line Regulation

When the input supply voltage Vin increases the output voltage Vout also increases. This increase in Vout will cause a reduced voltage of the transistor base emitter voltage V_{BE} as the zener voltage V_Z is constant (according to equation 1). This reduction in V_{BE} causes a decrease in the level of conduction i.e., I_B decreases. This will further increase the collector-emitter resistance of the transistor which will slightly decrease the current $I_E(I_E = I_L)$ in order to compensate for the increases in Vin so that Vout $(I_L R_L)$ remains constant. The operation is similar when the input supply voltage decreases.

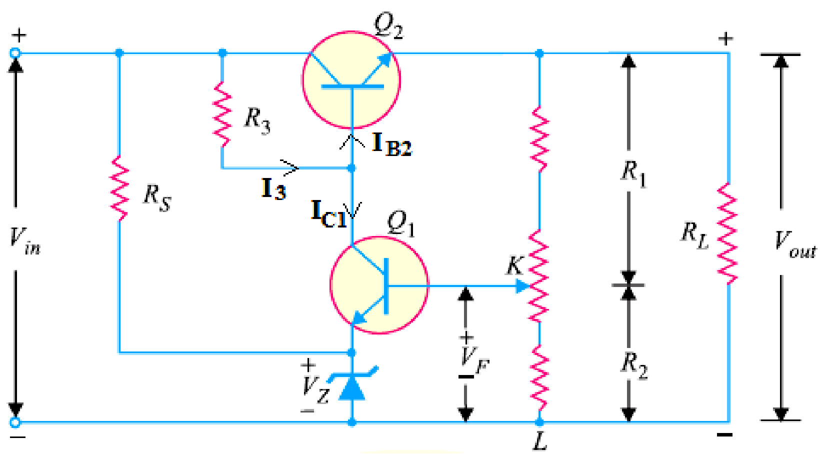
Load Regulation

The next condition would be the effect of the output load change in regard to the output voltage. Let us consider a case where the load resistance R_L increases. This causes an increase in the value of output voltage Vout and thus causes the transistor base emitter voltage V_{BE} to decrease. Hence I_B decreases. This causes the collector emitter resistance value to increase which will slightly decrease the current $I_E(I_E = I_L)$ in order to compensate for the increase in R_L so that Vout $(I_L R_L)$ remains constant.

The advantage of this circuit is that the changes in zener current are reduced by a factor β. Therefore, the effect of zener impedance is greatly reduced and much more stabilized output is obtained

Limitations
1. With the increase in room temperature, the values of V_{BE} and V_Z tend to decrease. Thus the output voltage cannot be maintained a constant.
2. There is no option to change the output voltage in the circuit.
3. Due to the small amplification process provided by only one transistor, the circuit cannot provide good regulation at high currents.
4. When compared to other regulators, this regulator has poor regulation and ripple suppression with respect to input variations.

3. Series Feedback Voltage Regulator



The figure shows the circuit of series feedback voltage regulator. It employs principles of negative feedback to hold the output voltage almost constant despite changes in line voltage and load current. The transistor Q_2 is called a pass transistor because the entire load current passes through it. The sample and adjust circuit is the voltage divider that consists of R_1 and R_2. The voltage divider samples the output voltage and delivers a negative feedback voltage to the base of Q_1. The feedback voltage V_F controls the collector current of Q_1.

<u>Circuit working</u>

The unregulated dc supply is fed to the voltage regulator. The circuit maintains constant output voltage irrespective of the variations in load or input voltage. Here is how the circuit operates.

(*i*) Suppose the output voltage increases due to any reason. This causes an increase in voltage across $R2$ as it is a part of the output circuit. The voltage across R2 is given by

$$V_{R2} = \frac{V_{out}\, R_2}{R_1 + R_2}$$

Also $V_{R2} = V_Z + V_{BE1}$

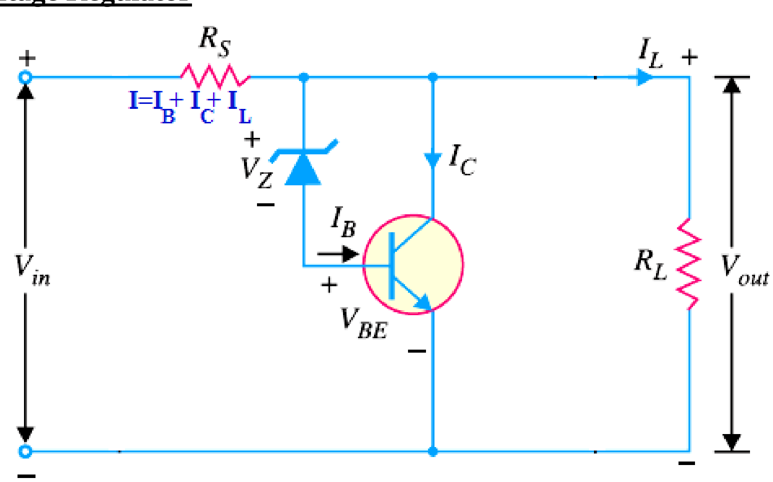
As V_{R2} increases, V_{BE1} also increases as V_Z is a constant. Therefore I_{B1} and I_{C1} increases. Assuming I_3 to be almost constant, the base current to Q2 decreases.

$$I_3 = I_{C1} + I_{B2}$$

This in turn causes the base voltage of $Q2$ to decrease. This result in increase of collector emitter resistance of Q2, thereby increasing V_{CE2} offsetting the increase in V_{out}. Thus output voltage is returned to its original value.

(*ii*) Similarly, if output voltage tries to decrease, voltage across $R2$ decreases as it is a part of the output circuit. As V_{R2} decreases, V_{BE1} also decreases as V_Z is a constant. Therefore I_{B1} and I_{C1} decreases. Assuming I_3 to be almost constant, the base current to Q2 increases. This in turn causes the base voltage of $Q2$ to increase. This result in decrease of collector emitter resistance of Q2, thereby decreasing V_{CE2} offsetting the decrease in V_{out}. Thus output voltage is returned to its original value.

4. <u>Transistor Shunt Voltage Regulator</u>



A shunt voltage regulator provides regulation by shunting current away from the load to regulate the output voltage. The circuit consists of an NPN transistor and a zener diode along with a series resistor R_S that is connected in series with the input supply. The zener diode is connected across the base and the collector of the transistor which is connected across the output. The output voltage is equal to the sum of zener voltage (V_Z) and transistor base-emitter voltage (V_{BE}) i.e.,

$V_{out} = V_Z + V_{BE}$----------------(1)

Also $I = I_B + I_C + I_L$---------------------(2)

Line Regulation:

Suppose the input voltage is varying. If the input voltage increases, the load voltage also increases. Since V_Z is constant, an increase in V_{out} causes an increase in V_{BE} also. Hence the current through base of transistor I_B increases. As a result, more collector current is shunted $(I_C = \beta I_B)$. Therefore according to equation 2, I_L decreases, thereby maintaining the regulated voltage across the load. Reverse happens when input voltage decreases.

Load Regulation:

If the load resistance increases, the load voltage also increases. Since V_Z is constant, an increase in V_{out} causes an increase in V_{BE} also. Hence the current through base of transistor I_B increases. As a result, more collector current is shunted $(I_C = \beta I_B)$. Therefore, since I is constant, the load current I_L decreases, thereby maintaining the regulated voltage across the load. Reverse happens if the load resistance decreases.

A shunt voltage regulator has the following drawbacks:

(*i*) A large portion of the total current through R_S flows through transistor rather than to the load.

(*ii*) There is considerable power loss in R_S.

(*iii*) There are problems of overvoltage protection in this circuit.

For these reasons, a series voltage regulator is preferred over the shunt voltage regulator.

IC Voltage Regulators

We can also use integrated circuits (IC) to produce voltage regulators. One advantage of IC voltage regulators is that properties like thermal compensation, short circuit protection and surge protection can be built into the device. Most of the commonly used IC voltage regulators are three-terminal devices.

There are basically four types of IC voltage regulators:

(i) Fixed positive voltage regulators

(ii) Fixed negative voltage regulators

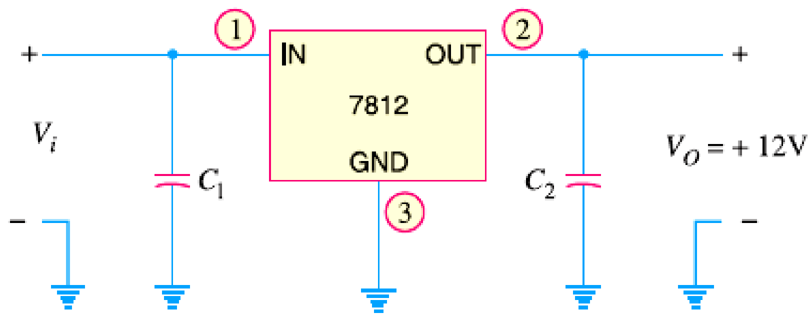
(iii) Adjustable voltage regulators

(iv) Dual-tracking voltage regulators

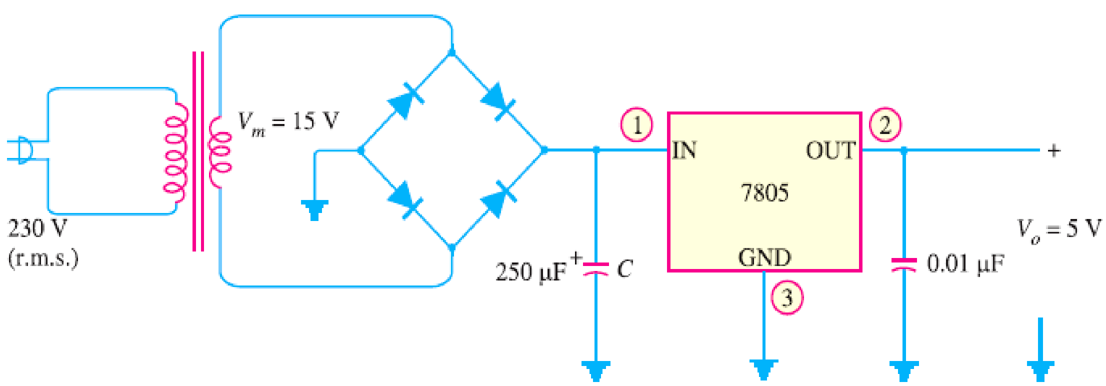
1. Fixed Positive Voltage Regulators (78XX)

This IC regulator provides a fixed positive output voltage. Although many types of IC regulators are available, the 78XX series of IC regulators is the most popular. These ICs are designed as fixed voltage regulators and with adequate heat sinks that can deliver output currents in excess of 1 A. Although these devices do not require any external component, such components can be employed for providing adjustable voltages and currents. The last two digits in the part number indicate the dc output voltage. For example, the 7812 is a + 12V regulator whereas the 7805 is a + 5V regulator. This series (78XX series) provides fixed regulated voltages from + 5 V to + 24V.

Type number	Output voltage
7805	+5.0 V
7806	+6.0 V
7808	+8.0 V
7809	+9.0 V
7812	+12.0 V
7815	+15.0 V
7818	+18.0 V
7824	+24.0 V



The 7812 IC is connected to provide a fixed dc output of + 12V. The unregulated input voltage Vi is connected to the IC’s IN terminal and the IC’s OUT terminal provides + 12V. Capacitors, although not always necessary, are sometimes used on the input and output as shown in figure. The output capacitor (C2) acts basically as a line filter to improve transient response. The input capacitor (C1) is used to prevent unwanted oscillations. The input voltage must always be higher than the output voltage by some minimum amount typically 2V. For example, the 7812 is a + 12V regulator for which the input must be 10 V. The minimum difference between input and output voltage is called drop out voltage.The figure below shows a bridge rectifier connected along with 7805 to provide a regulated supply of 5 volts.



Advantages

- 78xx series ICs do not require additional components to provide a constant, regulated source of power, making them, economical and efficient.
- 78xx series ICs have built-in protection against a circuit drawing too much power.

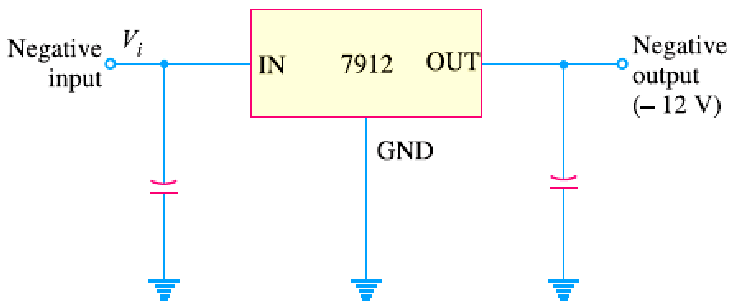
Disadvantages

- The input voltage must always be higher than the output voltage by some minimum amount (typically 2 volts). This can make these devices unsuitable for powering some devices from certain types of power sources.

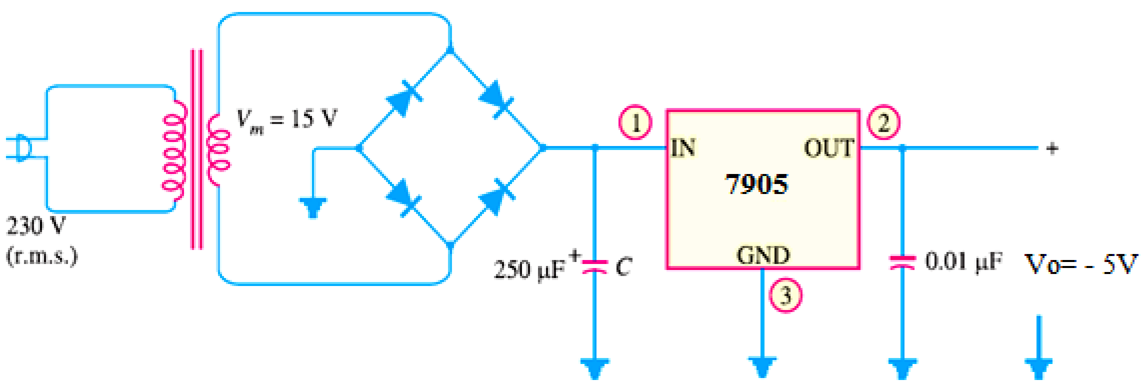
2. Fixed Negative Voltage Regulators (79XX)

These are three terminal regulators and are available with fixed negative output voltage. This series is the negative voltage counterpart of the78XX series. The 79XX series provides fixed regulated voltages from – 5V to – 24 V. The number 79 indicates that it is a negative voltage regulator and XX indicates the output voltage of the IC. ‘XX’ can be replaced by the controlled output voltage provided by the regulator, for example, if it is 7905, then the output voltage of the IC is -5 V.

Type number	Output voltage
7905	−5.0 V
7905.2	−5.2 V
7906	−6.0 V
7908	−8.0 V
7912	−12.0 V
7915	−15.0 V
7918	−18.0 V
7924	−24.0 V



The 7912 IC is connected to provide a fixed dc output of - 12V. The unregulated input voltage Vi is connected to the IC’s IN terminal and the IC’s OUT terminal provides - 12V. Capacitors, although not always necessary, are sometimes used on the input and output as shown in figure. The output capacitor (C2) acts basically as a line filter to improve transient response. The input capacitor (C1) is used to prevent unwanted oscillations. The input voltage must always be higher than the output voltage by some minimum amount typically 2V. The figure below shows a bridge rectifier connected along with 7905 to provide a regulated supply of -5 volts.



Advantages

- 79xx series ICs do not require additional components to provide a constant, regulated source of power, making them, economical and efficient.
- 79xx series ICs have built-in protection against a circuit drawing too much power.

Disadvantages

- The input voltage must always be higher than the output voltage by some minimum amount (typically 2 volts). This can make these devices unsuitable for powering some devices from certain types of power sources.