SEC1205 - ELECTRONIC CIRCUITS - I

UNIT I RECTIFIERS AND POWER SUPPLIES

Half Wave Rectifier - Full Wave Rectifier - Bridge Rectifier - Performance of Rectifiers - Filters - Types of Filters - L, C, LC, π Filters - Ripple Factor Calculation for C, L, LC and π Filter - Regulators - Shunt and Series Voltage Regulator - IC Regulator - SMPS.

1.1 INTRODUCTION

A typical d.c. power supply consists of various stages. The Fig. 1.1 shows the block diagram of a typical d.c. power supply consisting of various circuits. The nature of voltages at various points is also shown in the Fig. 1.1

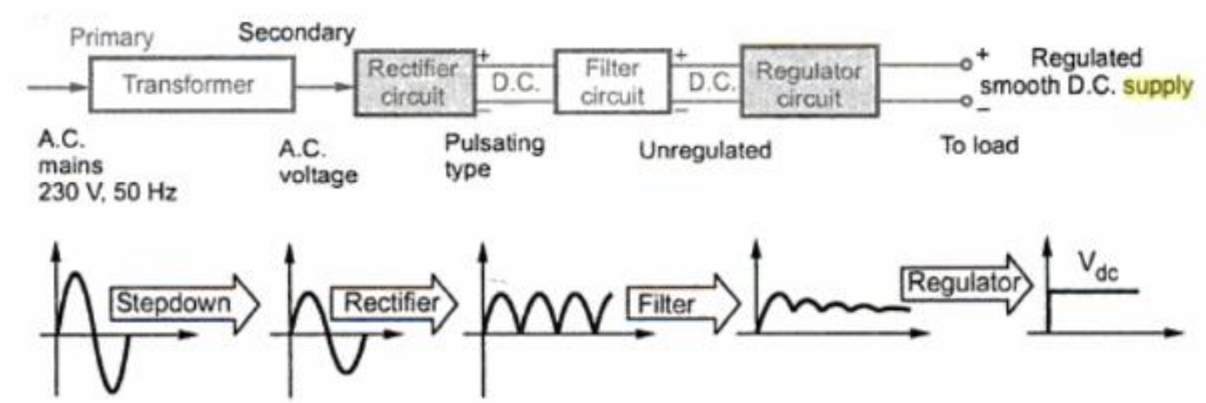


Fig. 1.1 Block diagram of Regulated Power supply with waveforms

The a.c. voltage (230 V, 50 Hz) is connected to the primary of the transformer. The transformer steps down the a.c. voltage, to the level required for the desired d.c. output. Thus, with suitable turns ratio we get desired a.c. secondary voltage. The rectifier circuit converts this a.c. voltage into a **pulsating d.c. voltage**. A pulsating d.c. voltage means a unidirectional voltage containing large varying component called **ripple** in it. The **filter** circuit is used after a rectifier circuit, which reduces the ripple content in the pulsating d.c. and tries to make it smoother. Still then the filter output contains some ripple. This voltage is called **unregulated d.c. voltage**. A circuit used after the filter is a regulator circuit which not only makes the d.c. voltage smooth and almost ripple free but it also keeps the d.c. output voltage constant though input d.c. voltage varies under certain conditions. It keeps the output voltage constant under variable load conditions, as well. The output of a regulator is called **d.c. supply**, to which the load can be connected. Nowadays, complete regulator circuits are available in the integrated circuit (IC) form.

1.2 RECTIFIER CIRCUIT

A **rectifier** is a device which converts a.c. voltage to pulsating d.c. voltage, using one or more p-n junction diode.

The p-n junction diode conducts only in one direction. It conducts when forward biased while practically it does not conduct when rever se biased. Thus if an alternating voltage is applied across a p-n junction diode, during positive half cycle the diode will be forward biased and will conduct successfully. While during the negative half cycle it will be reversed biased and will not conduct at all. Thus the conduction occurs only during positive half cycle. If the resistance is connected in series with the diode, the output voltage across the resistance will be unidirectional i.e. d.c.

1.2.1. Important Characteristics of Rectifier Circuits

a) **Waveform of the load current :** As rectifier converts a.c. to pulsating d.c., it is important to analyze the nature of the current through load which ultimately determines the waveform of the load voltage.

b) **Regulation of the output voltage :** As the load current changes, load voltage changes. Practically load voltage should remain constant. So concept of regulation is to study the effect of change in load current on the load voltage.

c) **Rectifier efficiency :** It signifies, how efficiently the rectifier circuit converts a.c. power into d.c. power.

d) **Peak value of current in the rectifier circuit :** The peak value is the maximum value of an alternating current in the rectifier circuit. This decides the rating of the rectifier circuit element which is diode.

e) **Peak value of voltage across the rectifier element in the reverse direction (PIV) :** When the diode is not conducting, the reverse voltage gets applied across the diode. The peak value of such voltage decides the peak inverse voltage i.e. PIV rating of a diode.

f) **Ripple factor :** The output of the rectifier is of pulsating d.c. type. The amount of a.c. content in the output can be mathematically expressed by a factor called ripple factor.

Using one or more diodes following rectifier circuits can be designed.

1. Half wave rectifier
2. Full wave rectifier
3. Bridge rectifier

1.3 HALF WAVE RECTIFIER

In half wave rectifier, rectifying element conducts only during positive half cycle of input a.c. supply. The negative half cycles of a.c. supply are eliminated from the output.

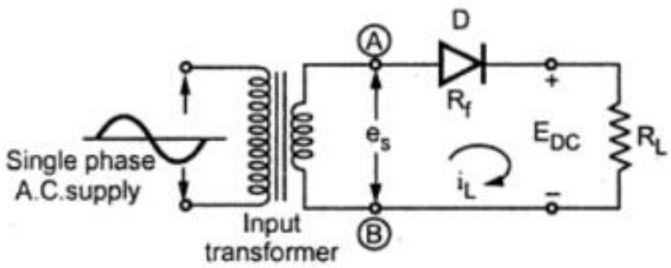


Fig. 1.2 Half wave rectifier

This rectifier circuit consists of resistive load, rectifying element, i.e. p-n junction diode, and the source of a.c. voltage, all connected in series. The circuit diagram is shown in the Fig. 1.2 Usually, the rectifier circuits are operated from a.c. mains supply. To obtain the desired d.c. voltage across the load, the a.c. voltage is applied to rectifier circuit using suitable step-up or step-down transformer, mostly a step-down one, with necessary turns ratio.

The input voltage to the half-wave rectifier circuit shown in the Fig. 1.2 is a sinusoidal a.c. voltage, having a frequency which is the supply frequency, 50 Hz.

The transformer decides the peak value of the secondary voltage. If N_1 are the primary number of turns and N_2 are the secondary number of turns and E_{pm} is the peak value of the primary voltage then,

$$\frac{N_2}{N_1} = \frac{E_{sm}}{E_{pm}}$$

where E_{sm} = The peak value of the secondary a.c. voltage.

As the nature of E_{sm} is sinusoidal the instantaneous value will be,

$$e_s = E_{sm} \sin \omega t$$

$$\omega = 2\pi f$$

$$f = \text{Supply frequency}$$

1.3.1 Operation

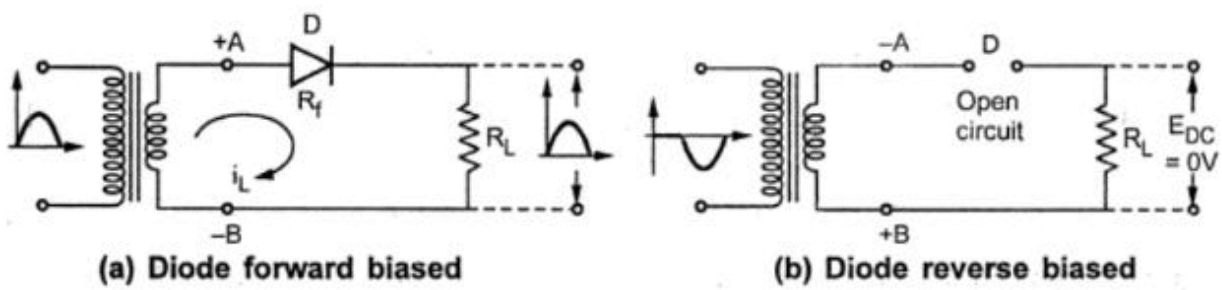


Fig. 1.3 Operation of half wave rectifier

During the positive half cycle of secondary a.c voltage, terminal (A) becomes positive with respect to terminal (B). The diode is forward biased and the current flows in the circuit in the clockwise direction, as shown in the Fig. 1.3 (a). The current will flow for almost full positive half cycle. This current is also flowing through load resistance R_L hence denoted as i_L, the load current.

During negative half cycle when terminal (A) is negative with respect to terminal (B), diode becomes reverse biased. Hence no current flows in the circuit as shown in the Fig. 1.3 (b). Thus the circuit current, which is also the load current, is in the form of half sinusoidal pulses.

The load voltage, being the product of load current and load resistance, will also be in the form of half sinusoidal pulses. The different waveforms are illustrated in Fig. 1.4.

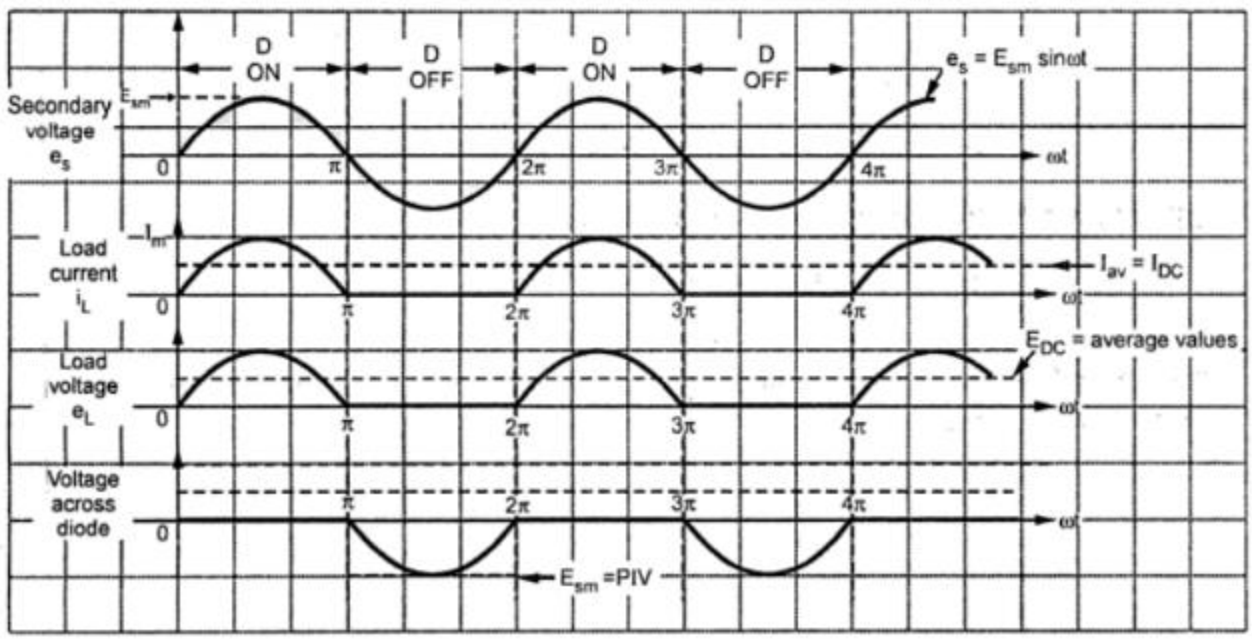


Fig. 1.4 Load current and Load voltage waveforms for half wave rectifier

The d.c. output waveform is expected to be a straight line but the half wave rectifier gives output in the form of positive sinusoidal pulses.

> **Key Point**: *Hence the output is called* ***pulsating d.c.*** *It is discontinuous in nature. Hence it is necessary to calculate the average value of load current and average value of output voltage.*

1.3.2 Average DC Load Current (I_{DC})

The average or d.c. value of alternating current is obtained by integration.

For finding out the average value of an alternating waveform, we have to determine the area under the curve over one complete cycle i.e. from 0 to 2π and then dividing it by the base i.e. 2π.

Mathematically, current waveform can be described as,

$$i_L = I_m \sin \omega t \qquad \text{for } 0 \le \omega t \le \pi$$

$$i_L = 0 \qquad \text{for } \pi \le \omega t \le 2\pi$$

where I_m = Peak value of load current

$$\therefore \quad I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} i_L \, d(\omega t) = \frac{1}{2\pi}\int_0^{2\pi} I_m \sin(\omega t)\, d(\omega t)$$

As no current flows during negative half cycle of a.c. input voltage, i.e. between $\omega t = \pi$ to $\omega t = 2\pi$, we change the limits of integration.

$$\therefore \quad I_{DC} = \frac{1}{2\pi}\int_0^{\pi} I_m \sin(\omega t)\, d(\omega t) = \frac{I_m}{2\pi}\left[-\cos(\omega t)\right]_0^{\pi}$$

$$= -\frac{I_m}{2\pi}\left[\cos(\pi) - \cos(0)\right] = -\frac{I_m}{2\pi}[-1-1] = \frac{I_m}{\pi}$$

$$\therefore \quad \boxed{I_{DC} = \frac{I_m}{\pi} = \text{average value}}$$

Applying Kirchhoff's voltage law we can write,

$$\boxed{I_m = \frac{E_{sm}}{R_f + R_L + R_s}}$$

where R_s = Resistance of secondary winding of transformer. If R_s is not given it should be neglected while calculating I_m.

1.3.3 Average DC Load Voltage (E_{DC})

It is the product of average D.C. load current and the load resistance R_L.

$$E_{DC} = I_{DC} R_L$$

Substituting value of I_{DC},

$$E_{DC} = \frac{I_m}{\pi} R_L = \frac{E_{sm}}{(R_f + R_L + R_s)\,\pi} R_L$$

The winding resistance R_s and forward diode resistance R_f are practically very **small** compared to R_L.

$$\therefore \quad \boxed{E_{DC} = \frac{E_{sm}}{\pi\left[\dfrac{R_f + R_s}{R_L} + 1\right]}}$$

But as R_f and R_s are small compared to R_L, $(R_f + R_s)/R_L$ is negligibly small compared to 1. So neglecting it we get,

$$\therefore \quad \boxed{E_{DC} \approx \frac{E_{sm}}{\pi}}$$

Note : When R_f and R_s are finite, calculate I_m, then I_{DC} and from that E_{DC} as $I_{DC}R_L$. Do not calculate E_{DC} as E_{sm}/π directly for finite R_f and R_s.

1.3.4 R.M.S value of Load Current (I_{RMS})

The R.M.S means squaring, finding mean and then finding square root. Hence R.M.S. value of load current can be obtained as,

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{\pi}(I_m \sin \omega t)^2 \, d(\omega t)} = \sqrt{\frac{1}{2\pi}\int_0^{\pi}\left(I_m{}^2 \sin^2 \omega t \, d(\omega t)\right)}$$

$$= I_m \sqrt{\frac{1}{2\pi}\int_0^{\pi}\frac{[1-\cos(2\omega t)]\,d(\omega t)}{2}} = I_m \sqrt{\frac{1}{2\pi}\left\{\frac{\omega t}{2} - \frac{\sin(2\omega t)}{4}\right\}_0^{\pi}}$$

$$= I_m \sqrt{\frac{1}{2\pi}\left(\frac{\pi}{2}\right)} \qquad \text{as } \sin(2\pi) = \sin(0) = 0$$

$$= \frac{I_m}{2}$$

$$\therefore \quad \boxed{I_{RMS} = \frac{I_m}{2}}$$

1.3.5 DC Power Output (P_{DC})

The d.c. power output can be obtained as,

$$\boxed{P_{DC} = E_{DC} I_{DC} = I_{DC}^2 R_L}$$

$$\text{D.C. Power output} = I_{DC}^2 R_L = \left[\frac{I_m}{\pi}\right]^2 R_L = \frac{I_m^2}{\pi^2} R_L$$

$$\therefore \quad P_{DC} = \frac{I_m^2}{\pi^2} R_L$$

where $I_m = \dfrac{E_{sm}}{R_f + R_L + R_s}$

$$\therefore \quad \boxed{P_{DC} = \frac{E_{sm}^2 R_L}{\pi^2 [R_f + R_L + R_s]^2}}$$

1.3.6 AC Power Input (P_{AC})

The power input taken from the secondary of transformer is the power supplied to three resistances namely load resistance R_L , the diode resistance R_f and winding resistance R_s. The a.c. power is given by,

$$\boxed{P_{AC} = I_{RMS}^2 [R_L + R_f + R_s]}$$

but $I_{RMS} = \dfrac{I_m}{2}$ for half wave,

$$\therefore \quad \boxed{P_{AC} = \frac{I_m^2}{4} [R_L + R_f + R_s]}$$

1.3.7 Rectifier Efficiency (η)

The rectifier efficiency is defined as the ratio of output d.c. power to input a.c. power.

$$\therefore \quad \eta = \frac{\text{D.C. output power}}{\text{A.C. input power}} = \frac{P_{DC}}{P_{AC}}$$

$$\therefore \quad \eta = \frac{\frac{I_m^2}{\pi^2} R_L}{\frac{I_m^2}{4}[R_f + R_L + R_s]} = \frac{(4/\pi^2)R_L}{(R_f + R_L + R_s)}$$

$$\therefore \quad \boxed{\eta = \frac{0.406}{1 + \left(\frac{R_f + R_s}{R_L}\right)}}$$

If $(R_f + R_s) << R_L$ as mentioned earlier, we get the maximum theoretical efficiency of half wave rectifier as,

$$\boxed{\% \eta_{max} = 0.406 \times 100 = 40.6 \ \%}$$

Thus in half wave rectifier, maximum 40.6% a.c. power gets converted to d.c. power in the load. If the efficiency of rectifier is 40% then what happens to the remaining 60% power. It is present interms of ripples in the output which is fluctuating component present in the output. Thus more the rectifier efficiency, less are the ripple contents in the output.

1.3.8 Ripple Factor (γ)

It is seen that the output of half wave rectifier is not pure d.c. but a pulsating d.c. The output contains pulsating components called **ripples**. Ideally there should not be any ripples in the rectifier output. The measure of such ripples present in the output is with the help of a factor called **ripple factor** denoted by γ. It tells how smooth is the output. Smaller the ripple factor closer is the output to a pure d.c. The ripple factor expresses how much successful the circuit is, in obtaining pure d.c. from a.c. input.

Mathematically **ripple factor** is defined as the ratio of R.M.S. value of the a.c. component in the output to the average or d.c. component present in the output.

$$\boxed{\text{Ripple factor} \quad \gamma = \frac{\text{R.M.S. value of a.c. component of output}}{\text{Average or d.c. component of output}}}$$

Now the output current is composed of a.c. component as well as d.c. component.

Let I_{ac} = r.m.s. value of a. c. component present in output

I_{DC} = d.c. component present in output

I_{RMS} = R.M.S. value of total output current

$$\therefore \quad I_{RMS} = \sqrt{I_{ac}^2 + I_{DC}^2}$$

$$\therefore \quad I_{ac} = \sqrt{I_{RMS}^2 - I_{DC}^2}$$

Now

$$\text{Ripple factor} = \frac{I_{ac}}{I_{DC}} \quad \text{as per definition}$$

$$\therefore \quad \gamma = \frac{\sqrt{I_{RMS}^2 - I_{DC}^2}}{I_{DC}}$$

$$\therefore \quad \boxed{\gamma = \sqrt{\left(\frac{I_{RMS}}{I_{DC}}\right)^2 - 1}}$$

This is the general expression for ripple factor and can be used for any rectifier circuit.

Now for a half wave circuit,

$$I_{RMS} = \frac{I_m}{2} \quad \text{while} \quad I_{DC} = \frac{I_m}{\pi}$$

$$\therefore \quad \gamma = \sqrt{\left[\frac{\left(\frac{I_m}{2}\right)}{\left(\frac{I_m}{\pi}\right)}\right]^2 - 1} = \sqrt{\frac{\pi^2}{4} - 1} = \sqrt{1.4674}$$

$$\therefore \quad \boxed{\gamma = 1.211}$$

This indicates that the ripple contents in the output are 1.211 times the d.c. component i.e. 121.1 % of d.c. component. The ripple factor for half wave is very high which indicates that the half wave circuit is a poor converter of a.c. to d.c. The ripple factor is minimised using filter circuits along with the rectifiers.

1.3.9 Transformer Utilization Factor (TUF)

The factor which indicates how much is the utilization of the transformer in the circuit is called Transformer Utilization Factor (T.U.F.)

The T.U.F. is defined as the ratio of d.c. power delivered to the load to the a.c power rating of the transformer. While calculating the a.c. power rating, it is necessary to consider r.m.s. value of a.c. voltage and current.

The T.U.F. for half wave rectifier can be obtained as,

$$\text{A.C. power rating of transformer} = E_{RMS} I_{RMS}$$

$$= \frac{E_{sm}}{\sqrt{2}} \cdot \frac{I_m}{2} = \frac{E_{sm} I_m}{2\sqrt{2}}$$

Remember that the secondary voltage is purely sinusoidal hence its r.m.s. value is $1/\sqrt{2}$ times maximum while the current is half sinusoidal hence its r.m.s. value is 1/2 of the maximum, as derived earlier.

$$\text{D.C. power delivered to the load} = I_{DC}^2 R_L = \left(\frac{I_m}{\pi}\right)^2 R_L$$

$$\therefore \quad \text{T.U.F.} = \frac{\text{D.C. Power delivered to the load}}{\text{A.C. Power rating of the transformer}}$$

$$= \frac{\left(\frac{I_m}{\pi}\right)^2 R_L}{\left(\frac{E_{sm} I_m}{2\sqrt{2}}\right)}$$

Neglecting the drop across R_f and R_s we can write,

$$E_{sm} = I_m R_L$$

$$\therefore \quad \text{T.U.F} = \frac{I_m^2}{\pi^2} \cdot \frac{R_L . 2\sqrt{2}}{I_m^2 R_L} = \frac{2\sqrt{2}}{\pi^2} = 0.287$$

The value of T.U.F. is low which shows that in half wave circuit, the transformer is not fully utilized.

1.3.10 Load Current

The load current i_L which is composed of a.c. and d.c. components can be expressed using Fourier series as,

$$i_L = I_m \left[\frac{1}{\pi} + \frac{1}{2} \sin \omega t - \frac{2}{3\pi} \cos 2 \omega t - \frac{2}{15\pi} \cos 4 \omega t \ \ldots \right]$$

This expression shows that the current may be considered to be the sum of an infinite number of current components, according to Fourier series.

The first term of the series is the average or d.c. value of the load current. The second term is a varying component having frequency same as that of a.c. supply voltage. This is called fundamental component of the current having frequency same as the supply. The third term is again a varying component having frequency twice the frequency of supply voltage. This is called second harmonic component. Similarly all the other terms represent the a.c. components and are called harmonics.

Thus ripple in the output is due to the fundamental component alongwith the various harmonic components. And the average value of the total pulsating d.c. is the d.c. value of the load current, given by the constant term in the series, I_m/π

1.3.11 Peak Inverse Voltage (PIV)

The Peak Inverse Voltage is the peak voltage across the diode in the reverse direction i.e. when the diode is reverse biased. In half wave rectifier, the load current is ideally zero when the diode is reverse biased and hence the maximum value of the voltage that can exist across the diode is nothing but E_{sm}. This is shown in the Fig. 1.5

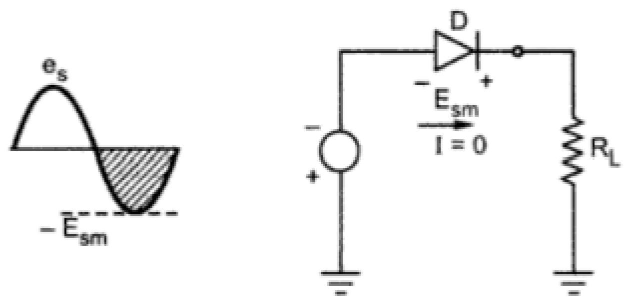


Fig. 1.5 PIV rating of Diode

Thus PIV occurs at the peak of each negative half cycle of the input, when **diode is** reverse biased and not conducting.

$\therefore$ PIV of diode = E_{sm} = Maximum value of secondary voltage = $\pi \, E_{DC}|_{I_{DC}=0}$

This is called PIV rating of a diode. So diode must be selected based on this PIV rating and the circuit specifications.

1.3.12 Voltage Regulation

The secondary voltage should not change with respect to the load current. The voltage regulation is the factor which tells us about the change in the d.c. output voltage as load changes from no load to full load condition.

If $(V_{dc})_{NL}$ = D.C. voltage on no load

$(V_{dc})_{FL}$ = D.C. voltage on full load

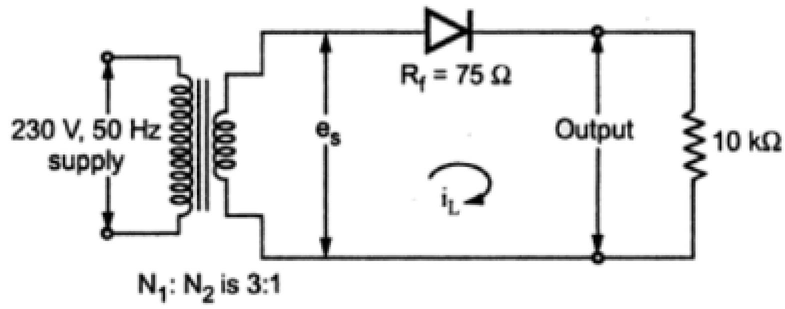
then voltage regulation is defined as,

$$\text{Voltage regulation} = \frac{(V_{dc})_{NL} - (V_{dc})_{FL}}{(V_{dc})_{FL}}$$

Key Point: *Less the value of voltage regulation, better is the performance of rectifier circuit.*

Example 1 : ***A half wave rectifier circuit is supplied from a 230 V, 50 Hz supply with a step down ratio of 3:1 to a resistive load of 10 kΩ. The diode forward resistance is 75 Ω while transformer secondary resistance is 10 Ω. Calculate maximum, average, RMS values of current, D.C. output voltage, efficiency of rectification and ripple factor.***

Solution:



The given values are,

$R_f = 75\ \Omega,\ R_L = 10\ k\Omega,\ R_s = 10\ \Omega$

The given supply voltages are always r.m.s. values.

$$E_p(RMS) = 230\ V,\quad \frac{N_1}{N_2} = \frac{3}{1}\ \text{i.e.}\ \frac{N_2}{N_1} = \frac{1}{3}$$

$$\frac{N_2}{N_1} = \frac{E_s(RMS)}{E_p(RMS)}$$

$$\therefore \quad \frac{1}{3} = \frac{E_s(RMS)}{230}$$

$$\therefore \quad E_s(RMS) = 76.667\ V$$

This is r.m.s. value of the transformer secondary voltage.

$$\therefore \quad E_{sm} = \sqrt{2}\,E_s(RMS) = \sqrt{2} \times 76.667 = 108.423\ V$$

$$\therefore \quad I_m = \frac{E_{sm}}{R_s + R_f + R_L} = \frac{108.423}{10 + 75 + 10 \times 10^3}$$

$$= \mathbf{10.75\ mA}$$

$$\therefore \quad I_{av} = I_{DC} = \frac{I_m}{\pi} = \frac{10.75}{\pi} = \mathbf{3.422\ mA}$$

$$I_{RMS} = \frac{I_m}{2} \quad \text{for half wave}$$

$$= \frac{10.75}{2} = \mathbf{5.375\ mA}$$

$$E_{DC} = \text{d.c output voltage} = I_{DC}\,R_L$$

$$= 3.422 \times 10^{-3} \times 10 \times 10^3 = \mathbf{34.22\ V}$$

$$P_{DC} = \text{d.c. output power} = E_{DC}\,I_{DC} = 34.22 \times 3.422 \times 10^{-3}$$

$$= 0.1171\ W$$

This also can be obtained as,

$$P_{DC} = \frac{I_m^2}{\pi^2} R_L = \frac{(10.75\times10^{-3})^2}{\pi^2}\times10\times10^3$$

$$= 0.1171 \text{ W}$$

$$P_{AC} = \text{a.c. input power} = I_{RMS}^2[R_s + R_f + R_L]$$

$$= (5.375\times10^{-3})^2[10+75+10\times10^3] = 0.2913 \text{ W}$$

$$\therefore \quad \% \eta = \frac{P_{DC}}{P_{AC}}\times100 = \frac{0.1171}{0.2913}\times100 = \mathbf{40.19\ \%}$$

The ripple factor is constant for half wave rectifier and is 1.21.

$$\therefore \quad \gamma = \mathbf{1.21}$$

Example 2 : *A half wave rectifier with $R_L = 1$ kΩ is given an input of 10 V peak from step down transformer. Calculate D.C. voltage and load current for ideal and silicon diode.*

Solution : Given values are $R_L = 1$ kΩ, $V_m = 10$ V peak

Case i) Ideal diode

Cut in voltage $V_\gamma = 0$ V, $R_f = 0\ \Omega$

$$\therefore \quad E_{DC} = \frac{V_m}{\pi} = \frac{10}{\pi} = \mathbf{3.18\ V}$$

$$\therefore \quad I_{DC} = \frac{E_{DC}}{R_L} = \frac{3.18}{1\times10^3} = \mathbf{3.18\ mA}$$

Case ii) Silicon diode

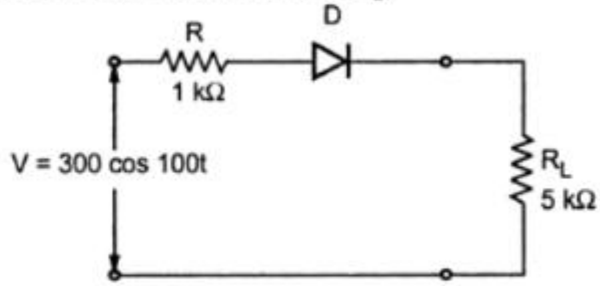
Cut in voltage $V_\gamma = 0.7$ V

$$\therefore \quad E_{DC} = \frac{V_m - V_\gamma}{\pi} = \frac{10-0.7}{\pi} = \mathbf{2.96\ V}$$

$$\therefore \quad I_{DC} = \frac{E_{DC}}{R_L} = \mathbf{2.96\ mA}$$

Example 3 : *A voltage $V = 300 \cos 100t$ is applied to a half wave rectifier, with $R_L = 5$ kΩ. The rectifier may be represented by ideal diode in series with a resistance of 1 kΩ. Calculate : i) I_m ii) D.C. power iii) A.C. power iv) Rectifier efficiency and v) Ripple factor.*

Solution : The diode circuit is as shown in the Fig.



The given voltage is V = 300 cos 100t volts

Compare with, $E = E_{sm} \sin \omega t$

$$E_{sm} = 300 \text{ volts}$$

$$R = 1 \text{ k}\Omega = \text{resistance in series with diode}$$

$$R_L = 5 \text{ k}\Omega,\ R_s = R_f = 0\ \Omega$$

i) $$I_m = \frac{E_{sm}}{R + R_L + R_f + R_L} = \frac{300}{6\times10^3}$$

$$= \mathbf{50\ mA}$$

ii) $$I_{DC} = \frac{I_m}{\pi} = \frac{50}{\pi} = \mathbf{15.9154\ mA}$$

$\therefore$ $$P_{DC} = I_{DC}^2 R_L = (15.9154\times10^{-3})^2 \times 5 \times 10^3$$

$$= \mathbf{1.2665\ watts}$$

iii) $$P_{AC} = I_{RMS}^2 (R + R_L + R_s + R_f)$$

$$= \left(\frac{I_m}{2}\right)^2 (R + R_L + R_s + R_f) \quad \text{as } I_{RMS} = \frac{I_m}{2} \text{ for half wave}$$

$$= \left(\frac{50\times10^{-3}}{2}\right)^2 \times 6\times10^3 = \mathbf{3.75\ watts}$$

iv) $$\eta = \frac{P_{DC}}{P_{AC}}\times100 = \frac{1.2665}{3.75}\times100$$

$$= \mathbf{33.77\ \%}$$

v) $$\text{Ripple factor} = \sqrt{\left(\frac{I_{RMS}}{I_{DC}}\right)^2 - 1} = \sqrt{\left(\frac{25\times10^{-3}}{15.9154\times10^{-3}}\right)^2 - 1}$$

$$= \mathbf{1.211}$$

Disadvantages of half wave rectifier circuit

The various disadvantages of the half wave rectifier circuit are,

1. The ripple factor of half wave rectifier circuit is 1.21, which is quite high. The output contains lot of varying components.
2. The maximum theoretical rectification efficiency is found to be 40%. The practical value will be less than this. This indicates that half wave rectifier circuit is quite inefficient.

3. The circuit has low transformer utilization factor, showing that the transformer is not fully utilized.
4. The d.c. current is flowing through the secondary winding of the transformer which may cause dc saturation of the core of the transformer. To minimize the saturation, transformer size have to be increased accordingly. This increases the cost.

1.4 FULL WAVE RECTIFIER

The full wave rectifier conducts during both positive and negative half cycles of input a.c. supply. In order to rectify both the half cycles of a.c. input, two diodes are used in this circuit. The diodes feed a common load R_L with the help of a center tap transformer. The a.c. voltage is applied through a suitable power transformer with proper turns ratio.

The full wave rectifier circuit is shown in the Fig. 1.6

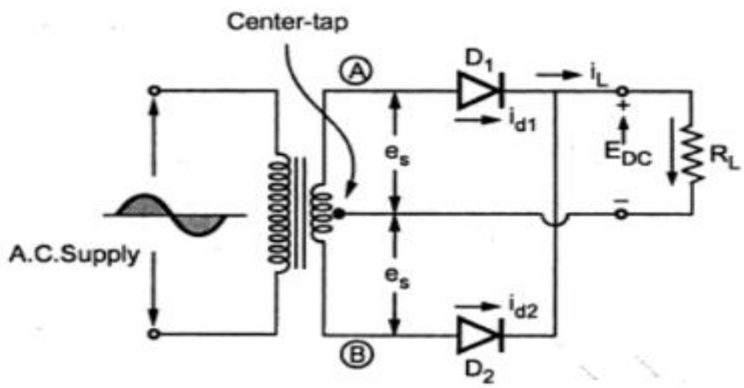


Fig. 1.6 Full Wave Rectifier Circuit

For the proper operation of the circuit, a **center-tap** on the secondary winding of the transformer is essential.

1.4.1 Operation of Full Wave Rectifier

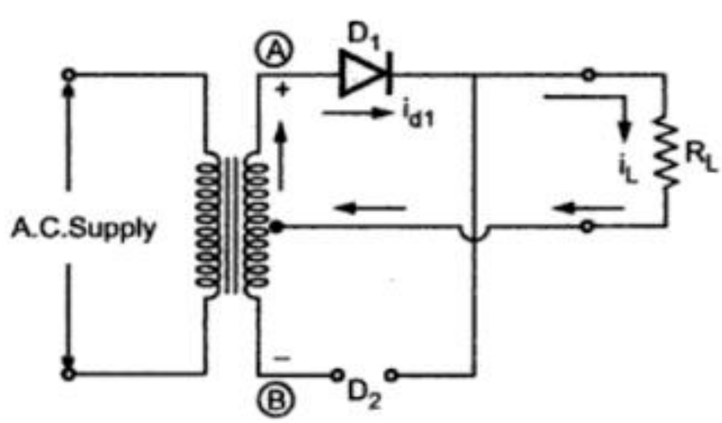


Fig. 1.7 Current flow during positive half cycle

Consider the positive half cycle of ac input voltage in which terminal (A) is positive and terminal (B) negative. The diode D_1 will be forward biased and hence will conduct; while diode D_2 will be reverse biased and will act as an open circuit and will not conduct. This is illustrated in the Fig. 1.7

The diode D_1 supplies the load current, i.e. $i_L = i_{d1}$ .This current is flowing through upper half of secondary winding while the lower half of secondary winding of the transformer carries no current since diode D_2 is reverse biased and acts as an open circuit.

In the next half cycle of ac voltage, polarity reverses and terminal (A) becomes negative and (B) positive. The diode D_2 conducts, being forward biased, while D_1 does not, being reverse biased. This is shown in the Fig. 1.8 .

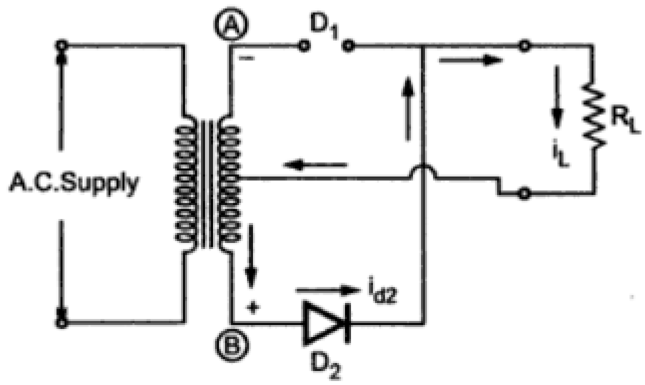


Fig. 1.8 Current flow during negative half cycle

The diode D_2 supplies the load current, i.e. $i_L = i_{d2}$. Now the lower half of the secondary winding carries the current but the upper half does not.

It is noted that the **load current flows in both the half cycles of ac voltage and in the same direction through the load resistance**. Hence we get rectified output across the load. The load current is sum of individual diode currents flowing in corresponding half cycles. It is also noted that the two diodes do not conduct simultaneously but in alternate half cycles.The individual diode currents and the load current are shown in the Fig. 1.9

Thus the full wave rectifier circuit essentially consists of two half-wave rectifier circuits working independently (working in alternate half cycles of a c) of each other but feeding a common load. The output load current is still pulsating d.c. and not pure d.c.

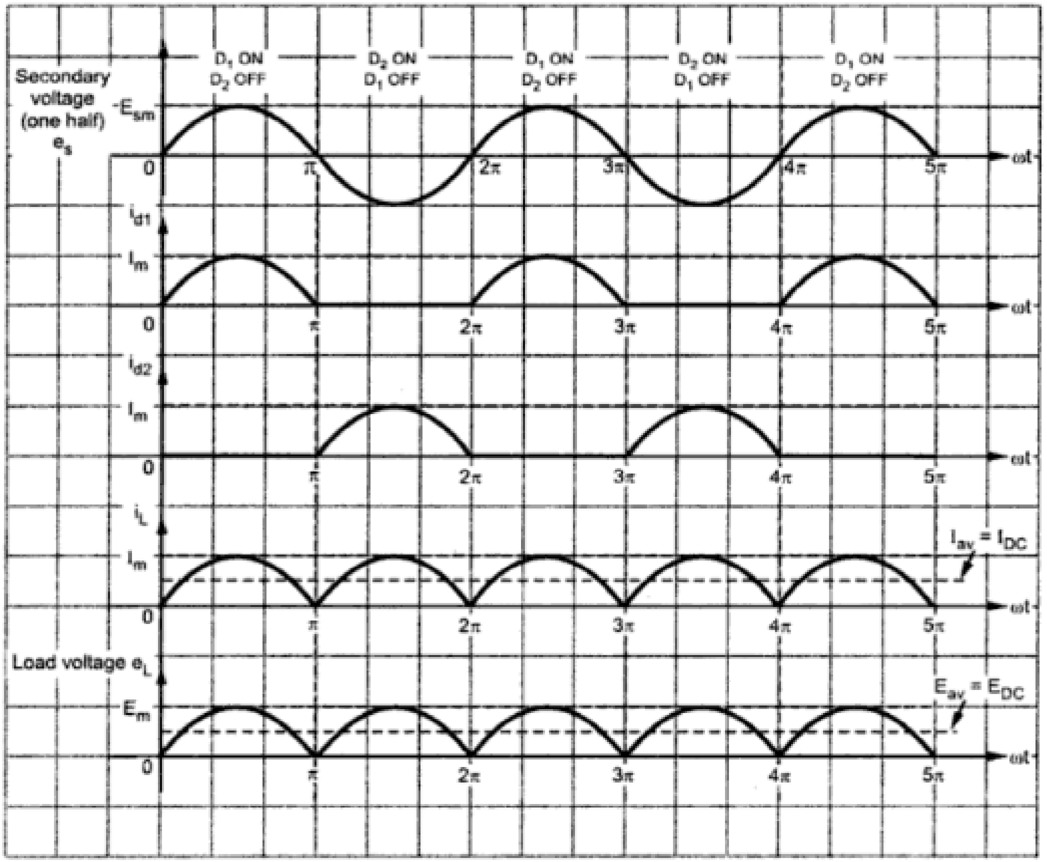
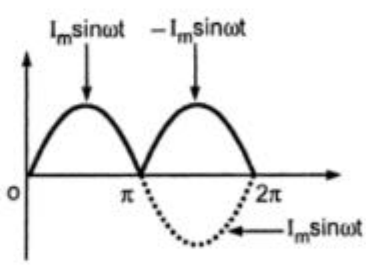


Fig. 1.9 Load current and voltage waveforms for full wave rectifier

1.4.2 Average DC Load Current (I_{DC})



Consider one cycle of load current i_L from 0 to 2π to obtain the average value which is d.c. value of load current.

$$i_L = I_m \sin \omega t \qquad 0 \le \omega t \le \pi$$

But for π to 2π, the current i_L is again positive while $\sin \omega t$ term is negative during π to 2π. Hence in the region π to 2π the positive i_L can be represented as negative of $I_m \sin(\omega t)$.

$$\therefore \quad i_L = -I_m \sin \omega t \qquad \pi \le \omega t \le 2\pi$$

$$\therefore \quad I_{av} = I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} i_L \, d(\omega t)$$

$$= \frac{1}{2\pi}\left[\int_0^{\pi} I_m \sin \omega t \, d(\omega t) + \int_{\pi}^{2\pi} -I_m \sin \omega t \, d(\omega t)\right]$$

$$= \frac{I_m}{2\pi}\left[\int_0^{\pi} \sin \omega t \, d(\omega t) - \int_{\pi}^{2\pi} \sin \omega t \, d(\omega t)\right]$$

$$= \frac{I_m}{2\pi}\left[(-\cos \omega t)_0^{\pi} - (-\cos \omega t)_{\pi}^{2\pi}\right]$$

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

but $\cos\pi = -1$

$$= \frac{I_m}{2\pi}[-(-1)+1+1-(-1)] = \frac{4I_m}{2\pi}$$

$$\therefore \quad \boxed{I_{DC} = \frac{2I_m}{\pi}} \quad \text{for full wave rectifier}$$

For half wave it is I_m/π and full wave rectifier is the combination of two half wave circuits acting alternately in two half cycles of input. Hence obviously the d.c. value for full wave circuit is $2\,I_m/\pi$.

1.4.3 Average DC Load Voltage (E_{DC})

The d.c. load voltage is,

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

Substituting value of I_m,

$$E_{DC} = \frac{2\,E_{sm}\,R_L}{\pi\,[R_f + R_s + R_L]} = \frac{2\,E_{sm}}{\pi\left[1+\frac{R_f+R_s}{R_L}\right]}$$

But as R_f and $R_s << R_L$ hence $\frac{R_f+R_s}{R_L} << 1$

$$\therefore \quad \boxed{E_{DC} = \frac{2E_{sm}}{\pi}}$$

1.4.4 R.M.S Value of Load Current (I_{RMS})

The R.M.S. value of current can be obtained as follows :

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i_L^2 d(\omega t)}$$

Since two half wave rectifier are similar in operation we can write,

$$I_{RMS} = \sqrt{\frac{2}{2\pi}\int_0^{\pi} [I_m \sin \omega t]^2 d(\omega t)}$$

$$= I_m\sqrt{\frac{1}{\pi}\int_0^{\pi}\left[\frac{1-\cos 2\omega t}{2}\right]d(\omega t)} \qquad \text{as } \sin^2 \omega t = \frac{1-\cos 2\,\omega t}{2}$$

$$\therefore \quad I_{RMS} = I_m \sqrt{\frac{1}{2\pi}\left[[\omega t]_0^{\pi} - \left(\frac{\sin 2\omega t}{2}\right)_0^{\pi}\right]} = I_m \sqrt{\frac{1}{2\pi}[\pi - 0]}$$

$$= I_m \sqrt{\frac{1}{2\pi}(\pi)} \qquad \text{as } \sin(2\pi) = \sin(0) = 0$$

$$\therefore \quad \boxed{I_{RMS} = \frac{I_m}{\sqrt{2}}}$$

1.4.5 DC Power output (P_{DC})

$$\boxed{\text{D.C. Power output} = E_{DC} I_{DC} = I_{DC}^2 R_L}$$

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

$$\therefore \quad P_{DC} = \frac{4}{\pi^2} I_m^2 R_L$$

Substituting value of I_m we get,

$$\boxed{P_{DC} = \frac{4}{\pi^2} \frac{E_{sm}^2}{(R_s + R_f + R_L)^2} \times R_L}$$

Note : Instead of remembering this formula, students can use the expression $E_{DC} I_{DC}$ or $I_{DC}^2 R_L$ to calculate P_{DC} while solving the problems.

1.4.6 AC Power input (P_{AC})

The a.c. power input is given by,

$$\boxed{P_{AC} = I_{RMS}^2 (R_f + R_s + R_L)}$$

$$= \left(\frac{I_m}{\sqrt{2}}\right)^2 (R_f + R_s + R_L)$$

$$\therefore \quad P_{AC} = \frac{I_m^2 (R_f + R_s + R_L)}{2}$$

Substituting value of I_m we get,

$$\therefore \quad P_{AC} = \frac{E_{sm}^2}{(R_f + R_s + R_L)^2} \times \frac{1}{2} \times (R_f + R_s + R_L)$$

$$\therefore \quad \boxed{P_{AC} = \frac{E_{sm}^2}{2(R_f + R_s + R_L)}}$$

1.4.7 Rectifier Efficiency (η)

$$\boxed{\eta = \frac{P_{DC} \text{ output}}{P_{AC} \text{ input}}}$$

$$\therefore \qquad \eta = \frac{\frac{4}{\pi^2} I_m^2 R_L}{\frac{I_m^2 (R_f + R_s + R_L)}{2}}$$

$$\therefore \qquad \eta = \frac{8 R_L}{\pi^2 (R_f + R_s + R_L)}$$

But if $R_f + R_s << R_L$, neglecting it from denominator

$$\eta = \frac{8 R_L}{\pi^2 (R_L)} = \frac{8}{\pi^2}$$

$$\therefore \qquad \boxed{\% \eta_{max} = \frac{8}{\pi^2} \times 100 = 81.2 \%}$$

This is the maximum theoretical efficiency of full wave rectifier.

1.4.8 Ripple Factor (γ)

As derived earlier in case of half wave rectifier the ripple factor is given by a general expression,

$$\text{Ripple factor} = \sqrt{\left[\frac{I_{RMS}}{I_{DC}}\right]^2 - 1}$$

For full wave $I_{RMS} = I_m/\sqrt{2}$ and $I_{DC} = 2I_m/\pi$ so substituting in the above equation,

$$\text{Ripple factor} = \sqrt{\left[\frac{I_m/\sqrt{2}}{2I_m/\pi}\right]^2 - 1} = \sqrt{\frac{\pi^2}{8} - 1}$$

$$\therefore \qquad \boxed{\text{Ripple factor} = \gamma = 0.48}$$

Key Point : *This indicates that the ripple contents in the output are 48 % of the d.c. component which is much less than that for the half wave circuit.*

1.4.9 Peak Inverse Voltage (PIV)

$$\therefore \qquad \boxed{\text{PIV of diode} = 2 E_{sm} = \pi E_{DC}|_{I_{DC}=0}}$$

where E_{sm} = Maximum value of a.c. voltage across half the secondary of transformer.

If the diode drop is considered to be 0.7 V then the PIV of reverse biased diode is,

$$\boxed{\text{PIV of diode} = 2E_{sm} - 0.7}$$

This is because only one diode conducts at a time.

1.4.10 Transformer Utilization Factor (TUF)

In full wave rectifier, the secondary current flows through each half separately in every half cycle. While the primary of transformer carries current continuously. Hence T.U.F is calculated for primary and secondary windings separately and then the average T.U.F. is determined.

$$\text{Secondary T.U.F} = \frac{\text{D.C. power to the load}}{\text{A.C. power rating of secondary}}$$

$$= \frac{I_{DC}^2 R_L}{E_{RMS}\, I_{rms}} = \frac{\left(\frac{2}{\pi} I_m\right)^2 R_L}{\frac{E_{sm}}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}}}$$

Neglecting forward resistance R_f of diode, $E_{sm} \approx I_m R_L$.

$$\therefore \quad \text{Secondary T.U.F.} = \frac{\frac{4}{\pi^2} \times I_m^2 R_L}{\frac{I_m^2 R_L}{2}} = \frac{8}{\pi^2} = 0.812$$

The primary of the transformer is feeding two half-wave rectifiers separately. These two half-wave rectifiers work independently of each other but feed a common load. We have already derived the T.U.F. for half wave circuit to be equal to 0.287. Hence

$$\text{T.U.F. for primary winding} = 2 \times \text{T.U.F. of half wave circuit}$$

$$= 2 \times 0.287 = 0.574.$$

The average T.U.F for fullwave circuit will be

$$\text{Average T.U.F. for full wave rectifier circuit} = \frac{\text{T.U.F of primary} + \text{T.U.F of secondary}}{2}$$

$$= \frac{0.574 + 0.812}{2} = \mathbf{0.693}$$

∴ **Average T.U.F. for full-wave rectifier = 0.693**

Key Point: *Thus in full-wave circuit, transformer gets utilized more than the* ***half*** *wave rectifier circuit.*

Example 1 : *A full-wave rectifier circuit is fed from a transformer having a center-tapped secondary winding. The rms voltage from either end of secondary to center tap is 30 V. If the diode forward resistance is 2 Ω and that of the half secondary is 8 Ω, for a load of 1 kΩ, calculate, a) Power delivered to load, b) % Regulation at full load, c) Efficiency of rectification, d) TUF of secondary.*

Solution:

$$\text{Given}: E_s = 30\,V,\; R_f = 2\Omega,\; R_s = 8\Omega,\; R_L = 1k\Omega$$

$$E_s = E_{RMS} = 30\ V$$

$$E_{sm} = E_s\sqrt{2} = 30\sqrt{2}\ \text{volt} = 42.426\ V$$

$$I_m = \frac{E_{sm}}{R_f + R_L + R_s} = \frac{30\sqrt{2}}{2+1000+8}\ A$$

$$= 42\ mA$$

$$I_{DC} = \frac{2}{\pi} I_m = 26.74\ mA$$

a) Power delivered to the load $= I_{DC}^2\ R_L = (26.74 \times 10^{-3})^2\ (1\,k\Omega)$

$$= \mathbf{0.715\ W}$$

b) V_{DC}, no load $= \frac{2}{\pi}\ E_{sm} = \frac{2}{\pi} \times 30\sqrt{2} = 27\ V$

V_{DC}, full load $= I_{DC}\ R_L = (26.74\ mA)\ (1\ k\Omega)$

$$= 26.74\ V$$

% Regulation $= \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100 = \frac{27 - 26.74}{26.74} \times 100$

$$= \mathbf{0.97\ \%}$$

c) Efficiency of rectification $= \frac{\text{D.C. output}}{\text{A.C. input}}$

$$= \frac{8}{\pi^2} \times \frac{1}{1 + \frac{R_f + R_s}{R_L}} = \frac{8}{\pi^2} \times \frac{1}{1 + \frac{(2+8)}{1000}}$$

$= 0.802$ **i.e. 80.2%**

d) Transformer secondary rating $= E_{RMS}\ I_{RMS} = [30\ V]\left[\frac{42\ mA}{\sqrt{2}}\right]$

$$= \mathbf{0.89\ W}$$

$\therefore$ T.U.F. $= \frac{\text{D.C. power output}}{\text{A.C. rating}}$

$$= \frac{0.715}{0.89} = \mathbf{0.802}$$

1.5 Bridge Rectifier

The bridge rectifier circuits are mainly used as,

a) a power rectifier circuit for converting a.c. power to d.c. power, and

b) a rectifying system in rectifier type a.c. meters, such as a.c. voltmeter, in which the a.c. voltage under measurement is first converted into d.c. and measured with conventional meter. In this system, the rectifying elements are either copper oxide type or selenium type.

The basic bridge rectifier circuit is shown in Fig. 1.10

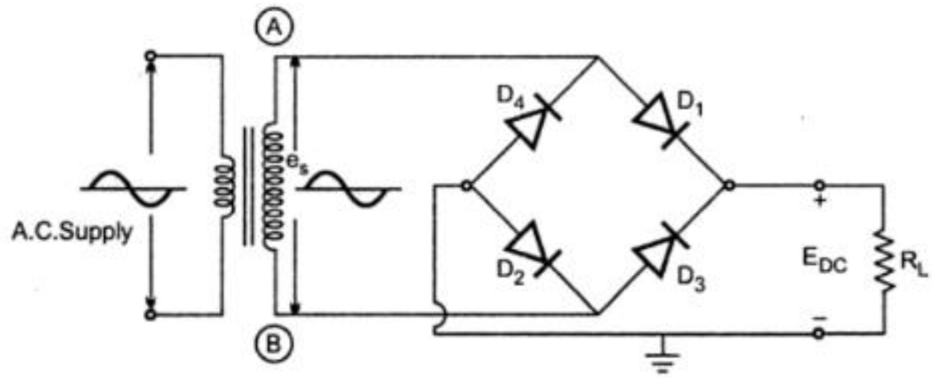


Fig. 1.10 Bridge rectifier circuit

The bridge rectifier circuit is essentially a full wave rectifier circuit, using four diodes, forming the four arms of an electrical bridge. To one diagonal of the bridge, the a.c. voltage is applied through a transformer if necessary, and the rectified d.c. voltage is taken from the other diagonal of the bridge. The main advantage of this circuit is that it does not require a center tap on the secondary winding of the transformer. Hence wherever possible, a.c. voltage can be directly applied to the bridge.

1.5.1 Operation of Bridge Rectifier

Consider the positive half of a.c. input voltage. The point A of secondary becomes positive. The diodes D_1 and D_2 will be forward biased, while D_3 and D_4 reverse biased. The two diodes D_1 and D_2 conduct in series with the load and the current flows as shown in Fig. 1.11

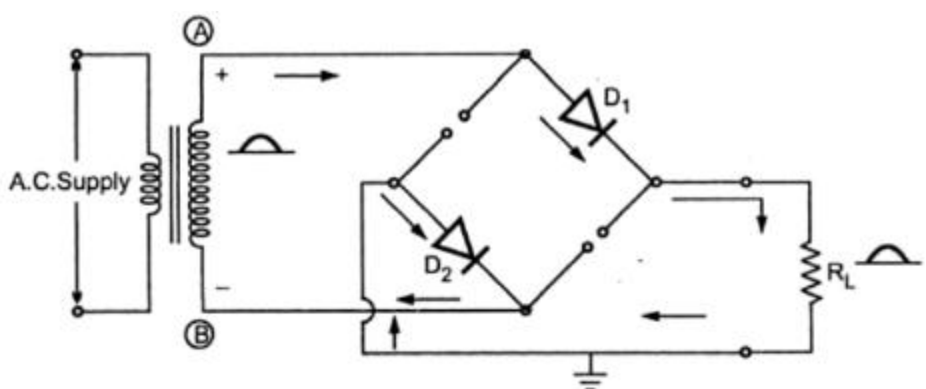


Fig. 1.11 Current flow during positive half cycle

In the next half cycle, when the polarity of a.c. voltage reverses hence point B becomes positive, diodes D_3 and D_4 are forward biased, while D_1 and D_2 reverse biased. Now the diodes D_3 and D_4 conduct is series with the load and the current flows as shown in Fig. 1.12

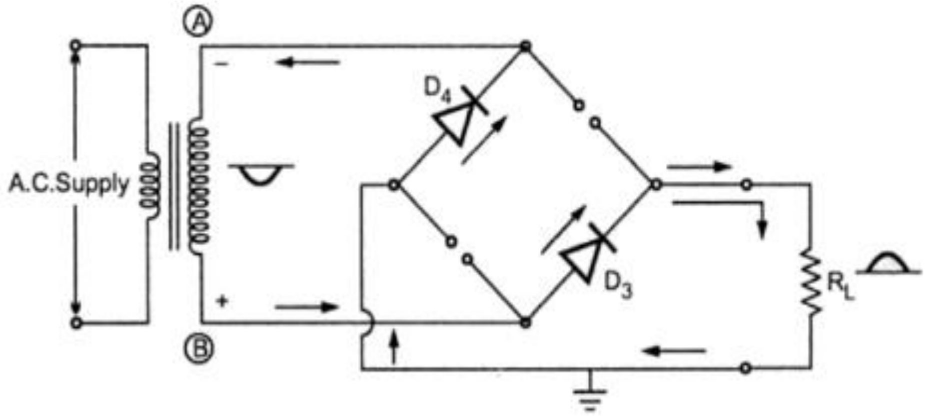


Fig. 1.12 Current flow during negative half cycle

It is seen that in both cycles of a.c., the load current is flowing in the same direction hence, we get a full wave rectified output.

The waveforms of load current and voltage remain exactly same as shown before for full wave rectifier.

1.5.2 Advantages of Bridge Rectifier

1) The current in both the primary and secondary of the power transformer flows for the entire cycle and hence for a given power output, power transformer of a small size and less cost may be used.

2) No center tap is required in the transformer secondary. Hence, wherever possible, ac voltage can directly be applied to the bridge.

3) The current in the secondary of the transformer is in opposite direction in two half cycles. Hence net d.c. component flowing is zero which reduces the losses and danger of saturation.

4) Due to pure alternating current in secondary of transformer, the transformer gets utilised effectively and hence the circuit is suitable for applications where large powers are required.

5) As two diodes conduct in series in each half cycle, inverse voltage appearing across diodes get shared. Hence the circuit can be used for high voltage applications. Such a peak reverse voltage appearing across diode is called peak inverse voltage rating (PIV) of diode.

1.5.3 Disadvantages of Bridge Rectifier

The only disadvantage of bridge rectifier is the use of four diodes as compared to two diodes in normal full wave rectifier. This causes additional voltage drop as indicated by term $2R_f$ present in expression of I_m instead of R_f. This reduces the output voltage.

Example 1 : *The four semiconductor diodes used in a bridge rectifier circuit each having a forward resistance of 0.1 Ω and infinite reverse resistance, feed a d.c. current of 10 A to a resistive load from a sinusoidally varying alternating supply of 30 V (r.m.s). Determine the resistance of the load and the efficiency of the circuit.*

Solution : The given values are,

$$R_f = 0.1\ \Omega,\ I_{DC} = 10A,\ R_s = 0\ \Omega,\ E_s(R.M.S.) = 30\ V$$

Now $$E_{sm} = E_{sm}(R.M.S.) \times \sqrt{2} = \sqrt{2} \times 30$$

$$= 42.4264\ V$$

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

∴ $$I_m = \frac{\pi \times I_{DC}}{2} = \frac{\pi \times 10}{2}$$

$$= 15.7079\ A$$

Now $$I_m = \frac{E_{sm}}{2R_f + R_s + R_L}$$

∴ $$15.7079 = \frac{42.4264}{2 \times 0.1 + R_L}$$

∴ $$R_L + 0.2 = 2.7$$

∴ $$R_L = \mathbf{2.5\ \Omega}$$

Now $$P_{DC} = I_{DC}^2 R_L = (10^2) \times 2.5 = 250\ W$$

$$P_{AC} = I_{RMS}^2 (2R_f + R_s + R_L)$$

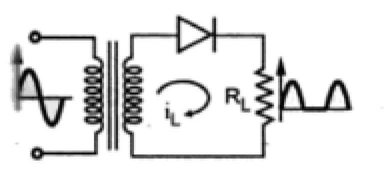
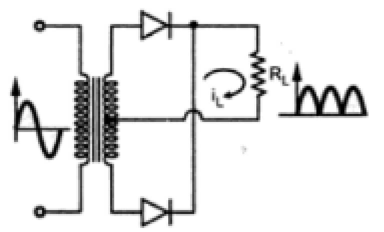
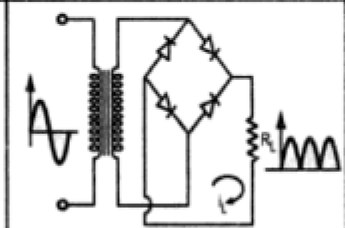
and $$I_{RMS} = \frac{I_m}{\sqrt{2}} = \frac{15.7079}{\sqrt{2}} = 11.1071\ A$$

∴ $$P_{AC} = (11.1071)^2\ [2 \times 0.1 + 2.5] = 333.092\ W$$

∴ $$\%\eta = \frac{P_{DC}}{P_{AC}} \times 100 = \frac{250}{333.092} \times 100$$

$$= \mathbf{75.05\ \%}$$

1.6 Comparision of Rectifier Circuits

Circuit Diagrams		
Half Wave	**Full Wave**	**Bridge**
		

S.R.	Parameter	Half Wave	Full Wave	Bridge
1.	Number of diodes	1	2	4
2.	Average D.C. current (I_{DC})	$\frac{I_m}{\pi}$	$\frac{2I_m}{\pi}$	$\frac{2I_m}{\pi}$
3.	Average D.C. voltage (E_{DC})	$\frac{E_{sm}}{\pi}$	$\frac{2E_{sm}}{\pi}$	$\frac{2E_{sm}}{\pi}$
4.	R.M.S. current (I_{RMS})	$\frac{I_m}{2}$	$\frac{I_m}{\sqrt{2}}$	$\frac{I_m}{\sqrt{2}}$
5.	D.C. power output (P_{DC})	$\frac{I_m^2 R_L}{\pi^2}$	$\frac{4}{\pi^2} I_m^2 R_L$	$\frac{4}{\pi^2} I_m^2 R_L$
6.	A.C. power input (P_{AC})	$\frac{I_m^2 (R_L + R_f + R_s)}{4}$	$\frac{I_m^2 (R_f + R_s + R_L)}{2}$	$\frac{I_m^2 (2R_f + R_s + R_L)}{2}$
7.	Maximum rectifier efficiency (η)	40.6 %	81.2 %	81.2 %
8.	Ripple factor (γ)	1.21	0.482	0.482
9.	Maximum load current (I_m)	$\frac{E_{sm}}{R_s + R_f + R_L}$	$\frac{E_{sm}}{R_s + R_f + R_L}$	$\frac{E_{sm}}{R_s + 2R_f + R_L}$

1.7 FILTER CIRCUITS

It is seen that the output a half-wave or full wave rectifier circuit is not pure d.c.; but it contains fluctuations or ripple, which are undesired. To minimize the ripple content in the output, filter circuits are used. These circuits are connected between the rectifier and load, as shown in the Fig. 1.13

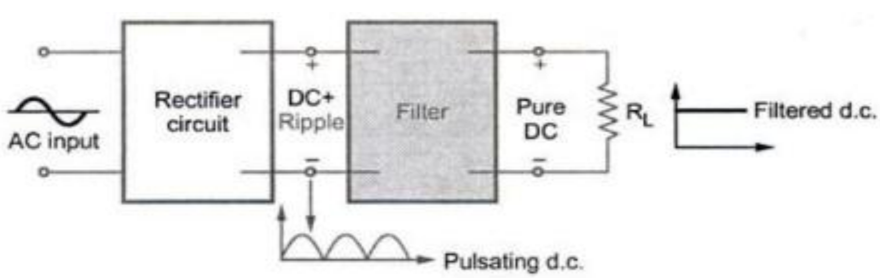


Fig. 1.13 Power supply using rectifier and filter

An a.c. input is applied to the rectifier. At the output of the rectifier, there will be d.c. and ripple voltage present, which is the input to the filter. Ideally the output of the filter should be pure d.c. Practically, the filter circuit will try to minimize the ripple at the output, as far as possible.

Basically the ripple is a.c., i.e. varying with time, while d.c. is a constant w.r.t. time. Hence in order to separate d.c. from ripple, the filter circuit should use components which have widely different impedance for a.c. and d.c. Two such components are inductance and capacitance. Ideally, the inductance acts as a short circuit for d.c., but it has a large impedance for a.c.. Similarly, the capacitor acts as open for d.c. and almost short for a.c. if the value of capacitance is sufficiently large enough.

Since ideally, inductance acts as short circuit for d.c., it cannot be placed in shunt arm across the load, otherwise the d.c. will be shorted.

Key Point: *Hence, in a filter circuit, the inductance is always connected in series with the load.*

The inductance used in filter circuits is also called "**choke**".

Similarly, since the capacitance is open for d.c., i.e. it blocks d.c.; hence it cannot be connected in series with the load.

Key Point: *It is always connected in shunt arm, parallel to the load.*

Thus filter is an electronic circuit composed of capacitor, inductor or combination of both and connected between the rectifier and the load so as to convert pulsating d.c. to pure d.c.

There are basically two types of filter circuits,

- Capacitor input filter
- Choke input filter

Looking from the rectifier side, if the first element, in the filter circuit is capacitor then the filter circuit is called **capacitor input filter**. While if the first element is an inductor, it is called **choke input filter**. The choke input filter is not in use now a days as inductors are bulky, expensive and consume more power. Let us discuss the operation of a capacitor input filter.

1.8 Capacitor Input Filter

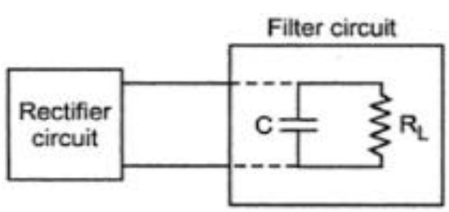


Fig. 1.14 Capacitor input filter

The block schematic of capacitor input filter is shown in the Fig. 1.14. Looking from the rectifier side the first element in filter is a capacitor.

1.8.1 Full wave rectifier with capacitor input filter

The same concept can now be extended to the capacitor filter used in full wave rectifier circuit as shown in the Fig. 1.19.

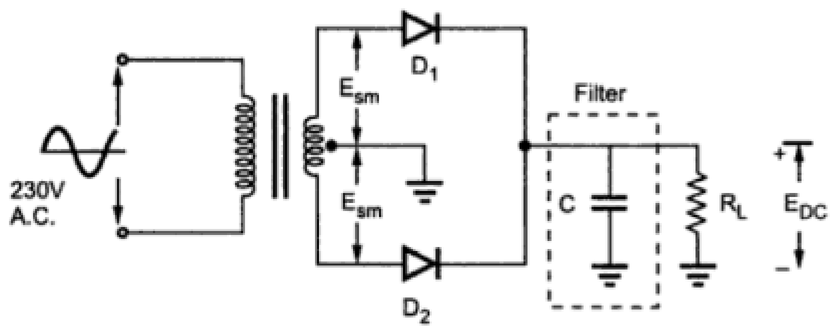


Fig.1.19 Full wave rectifier with capacitor input filter

Immediately when power is turned on, the capacitor C gets charged through forward biased diode D_1 to E_{sm}, during first quarter cycle of the rectified output voltage. In the next quarter cycle from $\frac{\pi}{2}$ to π, the capacitor starts discharging through R_L. Once capacitor gets charged to E_{sm}, the diode D_1 becomes reverse biased and stops conducting. So during the period from $\frac{\pi}{2}$ to π, the capacitor C supplies the load current. It discharges to point B shown in the Fig. 1.20. At point B, lying in the quarter π to $\frac{3\pi}{2}$ of the rectified output voltage, the input voltage exceeds capacitor voltage, making D_2 forward biased. This charges capacitor back to E_{sm} at point C.

The time required by capacitor C to charge to E_{sm} is quite small and only for this period, diode D_2 is conducting. Again at point C, diode D_2 stops conducting and capacitor supplies load and starts discharging upto point D in the next quarter cycle of the rectified output voltage as shown in the Fig. 1.20. At this point, the diode D_1 conducts to charge capacitor back to E_{sm}. The diode currents are shown shaded in the Fig. 1.20.

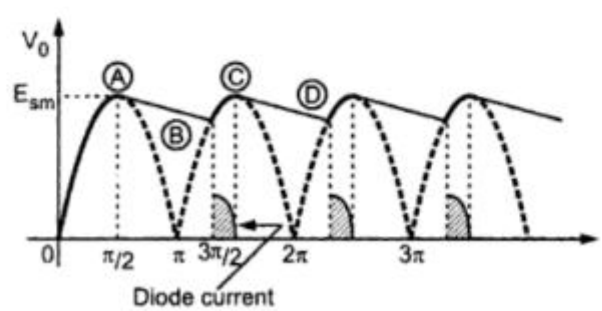


Fig.1.20 Charging and discharging of capacitor input filter

In this circuit, the two diodes are conducting in alternate half cycles of the output of the rectifier circuit. The diodes are not conducting for the entire half cycle but only for a part of the half cycle, during which the capacitor is getting charged. When the capacitor is discharging through the load resistance R_L, both the diodes are non-conducting. The capacitor supplies the load current. As the time required by capacitor to charge is very small and it discharges very little due to large time constant, hence ripple in the output gets reduced considerably. Though the diodes conduct partly, the load current gets maintained due to the capacitor. This filter is very popularly used in practice.

1.8.2 Expression for Ripple Factor

Consider an output waveform for a full wave rectifier circuit using a capacitor input filter, as shown in the Fig. 1.21.

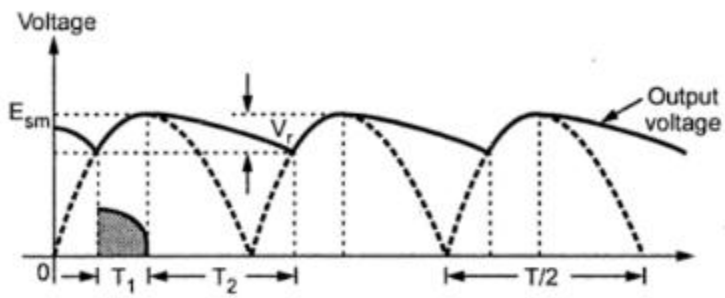


Fig.1.21 Derivation of ripple factor

Let T = Time period of the a.c. input voltage

$\frac{T}{2}$ = Half of the time period

T_1 = Time for which diode is conducting

T_2 = Time for which diode is nonconducting.

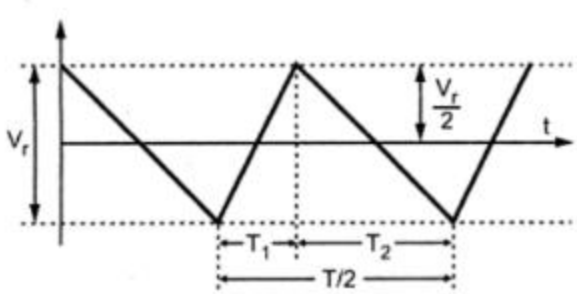


Fig. 1.22 Triangular approximation of ripple voltage

During time T_1, capacitor gets charged and this process is quick. During time T_2, capacitor gets discharged through R_L. As time constant R_LC is very large, discharging process is very slow and hence $T_2 >> T_1$.

Let V_r be the peak to peak value of ripple voltage, which is assumed to be triangular as shown in the Fig. 1.22

It is known mathematically that the r.m.s. value of such a **triangular waveform** is,

$$\boxed{V_{rms} = \frac{V_r}{2\sqrt{3}}}$$

During the time interval T_2, the capacitor C is discharging through the load resistance R_L. The charge lost is,

$$Q = CV_r$$

But $$i = \frac{dQ}{dt}$$

$\therefore$ $$Q = \int_0^{T_2} i\,dt = I_{DC}\,T_2$$

As integration gives average or d.c. value

Hence $$I_{DC}\,T_2 = CV_r$$

$\therefore$ $$V_r = \frac{I_{DC}\,T_2}{C}$$

Now, $$T_1 + T_2 = \frac{T}{2}$$ Normally, $T_2 >> T_1$

$\therefore$ $$T_1 + T_2 = T_2 = \frac{T}{2} \quad \text{where } T = \frac{1}{f}$$

$\therefore$ $$\boxed{V_r = \frac{I_{DC}}{C}\left[\frac{T}{2}\right] = \frac{I_{DC} \times T}{2C} = \frac{I_{DC}}{2\,fC}}$$

But $$I_{DC} = \frac{E_{DC}}{R_L}$$

$\therefore$ $$\boxed{V_r = \frac{E_{DC}}{2\,f\,C\,R_L} = \textbf{peak to peak ripple voltage}}$$

$$\text{Ripple factor} = \frac{V_{rms}}{E_{DC}} = \frac{\frac{E_{DC}}{2\,f\,C\,R_L}}{2\sqrt{3}} \times \frac{1}{E_{DC}}, \text{ Since } V_{rms} = \frac{V_r}{2\sqrt{3}}$$

$\therefore$ $$\boxed{\text{Ripple factor} = \frac{1}{4\sqrt{3}\,f\,C\,R_L} \quad \text{for } \textbf{full wave}}$$

For **half wave rectifier** with capacitor input filter the ripple factor is,

$$\boxed{\text{Ripple factor} = \frac{1}{2\sqrt{3}\,f\,C\,R_L} \quad \text{for } \textbf{half wave}}$$

The product CR_L is the time constant of the filter circuit.

1.8.3 Advantages and Disadvantages of Capacitor input filter

The **advantages** of capacitor input filter are,

1. Less number of components.
2. Low ripple factor hence low ripple voltage.
3. Suitable for high voltage at small load currents.

The **disadvantages** of capacitor input filter are,

1. Ripple factor depends on load resistance.
2. Not suitable for variable loads as ripple content increases as R_L decreases.
3. Regulation is poor.
4. Diodes are subjected to high surge currents hence must be selected accordingly.

Example 1 : *A full wave rectifier is operated from 50 Hz supply with 120 V (rms). It is connected to a load drawing 50 mA and using 100 μF filter capacitor. Calculate the d.c. output voltage and the r.m.s. value of ripple voltage. Also calculate the ripple factor.*

Solution : $E_{s(rms)} = 120$ V, f = 50 Hz, $I_{DC} = 50$ mA, C = 100 μF

$$E_{sm} = \sqrt{2}\, E_{s(rms)} = \sqrt{2} \times 120 = 169.7056 \text{ V}$$

For full wave rectifier,

$$E_{DC} = E_{sm} - I_{DC}\left[\frac{1}{4\,fC}\right]$$

$$= 169.7056 - \frac{50 \times 10^{-3}}{4 \times 50 \times 100 \times 10^{-6}} = \mathbf{167.2056\ V}$$

$$V_{r(rms)} = \frac{I_{DC}}{4\sqrt{3}\,fC} = \frac{50 \times 10^{-3}}{4 \times \sqrt{3} \times 50 \times 100 \times 10^{-6}}$$

$$= \mathbf{1.4433\ V}$$

The ripple factor is given by,

$$\gamma = \frac{V_{r(rms)}}{E_{DC}} = \frac{1.4433}{167.2056}$$

$$= 8.63 \times 10^{-3}$$

1.9 Inductor Filter or Choke Filter

In this type of filter, an inductor (choke) is connected in series with the load. It is known that the inductor opposes change in the current. So the ripple which is change in the current is opposed by the inductor and it tries to smoothen the output. Consider a full wave rectifier with inductor filter which is also called choke filter. Fig. 1.23 (a) shows the circuit diagram while Fig. 1.23 (b) shows the current waveform obtained by using choke filter with full wave rectifier.

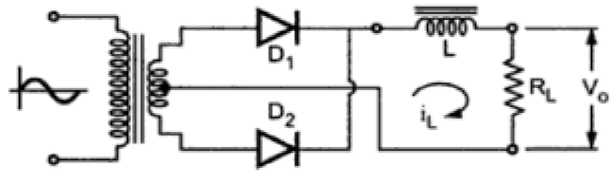


Fig.1.23 (a) Circuit diagram of choke filter

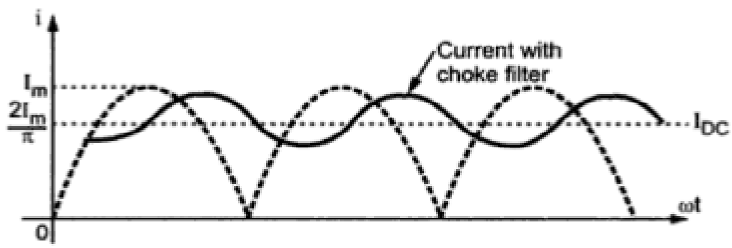


Fig.1.23 (a) Current waveform of choke filter

1.9.1 Operation of Inductor filter

In the positive half cycle of the secondary voltage of the transformer, the diode D_1 is forward biased. Hence the current flows through D_1, L and R_L. While in the negative half cycle, the diode D_1 is reverse biased while diode D_2 is forward biased. Hence the current flows through D_2, L and R_L. Hence we get unidirectional current through R_L. Due to inductor L which opposes change in current, it tries to make the output smooth by opposing the ripple content in the output.

We know that the fourier series for the load current for full wave rectifier as,

$$i_L = I_m \left[\frac{2}{\pi} - \frac{4}{3\pi} \cos 2\omega t - \frac{4}{15\pi} \cos 4\omega t \right]$$

Neglecting higher order harmonics we get,

$$i_L = \frac{2 I_m}{\pi} - \frac{4 I_m}{3\pi} \cos 2\omega t$$

Neglecting diode forward resistances and the resistance of choke and transformer secondary we can write the d.c. component of current as

$$\frac{2 I_m}{\pi} = \frac{2 V_m}{\pi R_L}$$

as $$I_m = \frac{V_m}{R_L}$$

While the second harmonic component represents a.c. component or ripple present and can be written as,

$$I_m = \frac{V_m}{Z} \quad \text{for a.c. component}$$

Now $$Z = R_L + j2X_L = \sqrt{R_L^2 + 4\omega^2 L^2} \angle \phi$$

where $$\phi = \tan^{-1} \frac{2\omega L}{R_L}$$

$$\therefore \quad \boxed{I_m = \frac{V_m}{\sqrt{R_L^2 + 4\omega^2 L^2}}}$$

The ripple present is the second harmonic component having frequency 2ω.

Key Point: *Hence while calculations the effective inductive reactance must be calculated at* 2ω *hence represented as* $2X_L$ *in the above expression.*

Hence equation (1) modifies as,

$$\boxed{i_L = \frac{2V_m}{\pi R_L} - \frac{4V_m}{3\pi\sqrt{R_L^2 + 4\omega^2 L^2}} \cos(2\omega t - \phi)}$$

1.9.2 Expression for the ripple factor

Ripple factor is given by ,

$$\text{Ripple factor} = \frac{I_{rms}}{I_{DC}}$$

where $$I_{rms} = \frac{I_m}{\sqrt{2}} \text{ of a.c. component}$$

$$I_{rms} = \frac{4V_m}{3\sqrt{2}\,\pi\sqrt{R_L^2 + 4\omega^2 L^2}}$$

while $$I_{DC} = \frac{2V_m}{\pi R_L}$$

$$\therefore \text{Ripple factor} = \frac{\dfrac{4V_m}{3\sqrt{2}\,\pi\sqrt{R_L^2 + 4\omega^2 L^2}}}{\dfrac{2V_m}{\pi R_L}}$$

$$= \frac{2}{3\sqrt{2}} \cdot \frac{1}{\sqrt{1 + \dfrac{4\omega^2 L^2}{R_L^2}}}$$

Initially on no load condition, $R_L \to \infty$ and hence $\frac{4\omega^2 L^2}{R_L^2} \to 0$.

$$\therefore \text{Ripple factor} = \frac{2}{3\sqrt{2}} = 0.472$$

This is very close to normal full wave rectifier without filtering.

But as load increases, R_L decreases hence $\frac{4\omega^2 L^2}{R_L^2} >> 1$. So neglecting 1 we get,

$$\text{Ripple factor} = \frac{2}{3\sqrt{2}} \cdot \frac{1}{\sqrt{\frac{4\omega^2 L^2}{R_L^2}}}$$

$$\therefore \boxed{\gamma = \frac{R_L}{3\sqrt{2} \cdot \omega L}}$$

So as load changes, ripple charges which is inversely proportional to the value of the inductor.

Key Point: *Smaller the value of* R_L, *smaller is the ripple hence the filter is suitable for low load resistances i.e. for high load current applications.*

Example 1 (*a*). *What should be the value of inductance to use in an inductor filter connected to a full-wave rectifier operating at 50 Hz, if the ripple is not to exceed 5% for a 100 Ω load.*
(*b*). *Repeat the above problem for the standard aircraft power frequency of 400 Hz.*

Solution. (*a*) Given: $f = 50$ Hz; $\gamma = 5\% = 0.05$ and $R_L = 100\ \Omega$.

We know that ripple factor (γ),

$$0.05 = \frac{R_L}{3\sqrt{2} \cdot \omega \cdot L} = \frac{100}{3\sqrt{2} \times (2\pi \times 50) \times L} = \frac{0.075}{L}$$

$$\therefore \quad L = 0.075/0.05 = 1.5 \text{ H} \ \textbf{Ans.}$$

(*b*) Given: $f = 400$ Hz; $\gamma = 0.05$ and $R_L = 100\ \Omega$.

We also know that ripple factor (γ),

$$0.05 = \frac{R_L}{3\sqrt{2} \cdot \omega \cdot L} = \frac{100}{3\sqrt{2} \times (2\pi \times 400) \times L} = \frac{1}{106.6\, L}$$

$$\therefore \quad L = 1/(106.6 \times 0.05) = 0.188 \text{ H Ans.}$$

1.10 LC Filter or L section Filter

This is also called **choke input filter** as the filter element looking from the rectifier side is an inductance L. The d.c. winding resistance of the choke is R_x . The circuit is also called L-type filter or LC filter. The circuit is shown in the Fig. 1.24

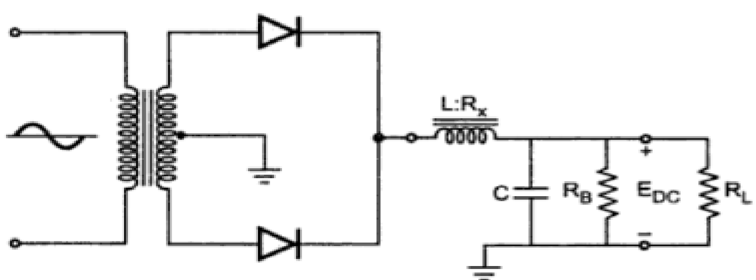


Fig. 1.24 Choke Input Filter

The basic requirement of this filter circuit is that the current through the choke must be continuous and not interrupted. An interrupted current through the choke may develop a large back e.m.f. which may be in excess of PIV rating of the diodes and /or maximum voltage rating of the capacitor C. Thus this back e.m.f. is harmful to the diodes and capacitor. To eliminate the back e.m.f. developed across the choke, the current through it must be maintained continuous.

This is assured by connecting a bleeder resistance, R_B across the output terminals.

We have seen that the lowest ripple frequency for a full wave rectifier circuit is twice the supply frequency of a.c. input voltage to the rectifier. Let f, in Hz, be the supply frequency. Then angular supply frequency will be ω rad/s, where $\omega = 2\pi f$. Then the lowest ripple angular frequency will be "2ω" rad/s.

1.10.1 Derivation of Ripple Factor

The analysis of the choke input filter circuit is based on the following assumptions :

Since the filter elements, L and C, are having reasonably large values, the reactance X_L of the inductance of L at 2ω i.e. $X_L = 2\omega L$ is much larger than R_x. Also the reactance X_L is much larger than the reactance of C, X_C at 2ω as,

$$X_C = \frac{1}{2\omega C}$$

Let R be the equivalent resistance of bleeder resistance R_B and the load resistance R_L connected in parallel. Then ,

$$R = R_B || R_L = \frac{R_B R_L}{R_B + R_L}$$

We will assume that reactance of C at '2ω' is much less than R, i.e. $X_C << R$.

The capacitance C is in parallel with R. Hence the equivalent impedance of X_C and R will be nearly equal to X_C, as per our assumption.

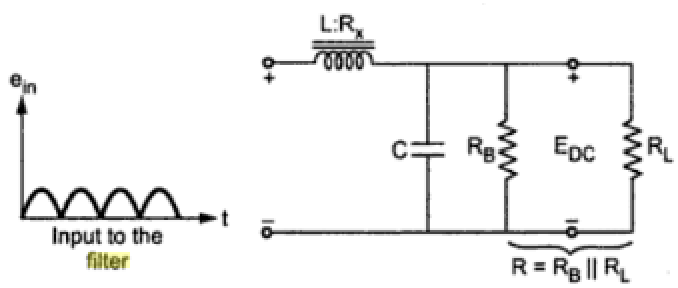


Fig. 1.25 Diagram for derivation of ripple factor

The input voltage e_{in}, to the choke-input filter is the output voltage of the full wave rectifier, having the waveform as illustrated in Fig. 1.25. Using Fourier series, the input voltage "e_{in}" can be written as,

$$e_{in} = E_{sm}\left[\frac{2}{\pi} - \frac{4}{3\pi}\cos 2\omega t - \frac{4}{15\pi}\cos 4\omega t \ldots\right]$$

where E_{sm} = the maximum value of half secondary voltage of the transformer.

The first term $\frac{2}{\pi} E_{sm}$, in the Fourier series indicates the d.c. output voltage of the rectifier, while the remaining terms ripple. The amplitude of the lowest ripple component, which is the second harmonic component of the supply frequency, is $\frac{4}{3\pi}$ while the amplitude of the fourth harmonic component, 5ω, is $\frac{4}{15\pi}$. The amplitude of the fourth harmonic is just one-fifth or 20% of the amplitude of second harmonic component. The higher harmonics will have still less amplitudes compared to the amplitude of the second harmonic component. Hence all harmonics, except the second harmonic, can be neglected. The equation for "e_{in}" can now be approximately written as,

$$e_{in} \approx E_{sm}\left[\frac{2}{\pi} - \frac{4}{3\pi}\cos 2\omega t\right]$$

The d.c. current in the circuit will be,

$$I_{DC} = \frac{\frac{2}{\pi} E_{sm}}{R_x + R}$$

$$R = R_B || R_L$$

$$\therefore \quad E_{DC} \text{ across the load} = I_{DC} R = \frac{2}{\pi} \frac{E_{sm}}{R_x + R} \times R$$

$$\therefore \quad E_{DC} = \frac{2}{\pi} \frac{E_{sm}}{1 + \frac{R_x}{R}}$$

Normally, R_x is much less than R, i.e. $R_x << R$

Then, $$E_{DC} \approx \frac{2}{\pi} E_{sm}$$

Thus the choke input filter circuit gives approximately constant d.c. voltage across the load. In other words, this filter circuit is having better load regulation compared to that of capacitor input filter in which case the d.c. load voltage depends upon the d.c. load current drawn. Let us calculate the ripple factor for choke input filter, based on the assumptions already made.

The impedance Z_2 of the filter circuit for second harmonic component of input, i.e. at 2ω, will be,

$$Z_2 = (R_x) + (j\,2\omega L) + \left[\frac{1}{j2\omega C} || R\right]$$

But, $\frac{1}{2\omega C} << R$, and $2\omega L >> R_x$, as per assumptions.

Hence, $|Z_2| \approx 2\omega L$

Second harmonic component of the current in the filter circuit, will be

$$I_{2m} = \frac{\frac{4}{3\pi} E_{sm}}{Z_2} \approx \frac{\frac{4}{3\pi} E_{sm}}{2\omega L}$$

The second harmonic voltage across the load is

$$E_{2m} = I_{2m} \times \left[\frac{1}{2\omega C} || R \right] \approx I_{2m} \times \frac{1}{2\omega C}$$

Since, $\frac{1}{2\omega C} << R$

$$\therefore \quad E_{2m} = I_{2m} \times \frac{1}{2\omega C} = \frac{\frac{4}{3\pi} E_{sm}}{2\omega L} \times \frac{1}{2\omega C}$$

$$\therefore \quad E_{2m} = \frac{4}{3\pi} \frac{E_{sm}}{4\omega^2 LC} = \frac{E_{sm}}{3\pi\omega^2 LC}$$

$$\therefore \quad E_{2rms} = \frac{E_{2m}}{\sqrt{2}} = \frac{E_{sm}}{3\sqrt{2}\pi\omega^2 LC}$$

Hence the ripple factor is given by,

$$\text{Ripple factor} = \frac{E_{2rms}}{E_{DC}}$$

$$= \frac{E_{sm}}{3\sqrt{2}\pi\omega^2 LC} \times \frac{1}{\frac{2}{\pi} \frac{E_{sm}}{1+\frac{R_x}{R}}}$$

$$= \frac{1}{6\omega^2 LC\sqrt{2}} \left(1 + \frac{R_x}{R} \right) \qquad \text{but } R_x << R$$

$$\therefore \quad \text{Ripple factor} \approx \frac{1}{6\sqrt{2}\omega^2 LC}$$

It is seen that the ripple factor for choke-input filter does not depend upon the load resistance unlike the capacitor input filter.

1.10.2 Advantages of Bleeder Resistor

1. It maintains the minimum current necessary for optimum operation of the inductor.
2. It improves voltage regulation of the supply by acting as preload on the supply.
3. It provides safety to the persons handling the equipment, by acting as a discharging path for capacitors.

Ex. 1 : *Determine the ripple factor of an L-type choke input filter comprising of a 10 H choke and 8 μF capacitor, used with a full-wave rectifier. Compare the above result with a simple 8 μ F capacitor input filter with a load current of 50 mA and also 150 mA, assuming the d.c. output voltage to be 50 V.*
Neglect d.c. resistance of choke and assume supply frequency of 50 Hz.

Sol. : The given values are

$$L = 10\,H,\ C = 8\,\mu F,\ I_{DC} = 50\,mA \text{ and } 150\,mA,\quad E_{DC} = 50\,V$$

i) For choke input filter

$$\gamma = \frac{1}{6\sqrt{2}\,\omega^2\,LC} = \frac{1}{6\sqrt{2}\,(2\pi f)^2\,LC}$$

$$= \frac{1}{6\sqrt{2}\,(2\pi\times 50)^2\times 10\times 8\times 10^{-6}}$$

$$= 0.01492$$

ii) For capacitor input filter

$$\gamma = \frac{1}{4\sqrt{3}\,f\,C\,R_L}$$

$$\text{For } I_{DC} = 50\,mA,\quad R_L = \frac{E_{DC}}{I_{DC}} = \frac{50}{50\times 10^{-3}} = 1\times 10^3\ \Omega$$

$$\gamma = \frac{1}{\sqrt{3}\times 50\times 8\times 10^{-6}\times 1\times 10^3}$$

$$= 0.36$$

$$\text{For } I_{DC} = 150\,mA,\quad R_L = \frac{E_{DC}}{I_{DC}} = \frac{50}{150\times 10^{-3}} = \frac{1}{3}\times 10^3\ \Omega$$

$$\gamma = \frac{1}{4\sqrt{3}\times 50\times 8\times 10^{-6}\times\left(\frac{1}{3}\right)\times 10^3}$$

$$= 1.082$$

It can be seen that as load current increases, the ripple content also increases in case of capacitor input filter.

1.11 CLC Filter or π Filter

This is a capacitor filter followed by a L section filter. The ripple rejection capability of π filter is very good. It is shown in the Fig. 1.26.

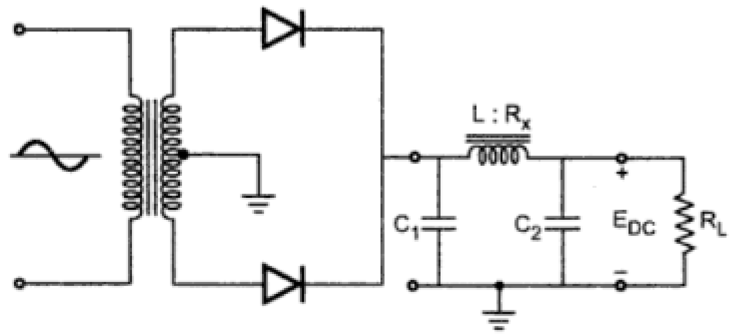


Fig. 1.26 π type filter

It consists of an inductance L with a d.c. winding resistance as R_x and two capacitors C_1 and C_2. The filter circuit is fed from full wave rectifier. Generally two capacitors are selected equal. This circuit is basically a capacitor input filter since the first element looking from the rectifier side is a capacitor. All the features, advantages, disadvantages discussed previously for the capacitor input filter using single capacitor are applicable equally to the π filter.

The rectifier output is given to the capacitor C_1. This capacitor offers very low reactance to the a.c. component but blocks d.c. component. Hence capacitor C_1 bypasses most of the a.c. component. The d.c. component then reaches to the choke L. The choke L offers very high reactance to a.c. component and low reactance to d.c. So it blocks a.c. component and does not allow it to reach to load while it allows d.c. component to pass through it. The capacitor C_2 now allows to pass remaining a.c. component and almost pure d.c. component reaches to the load. The circuit looks like a π hence called π filter. To obtain almost pure d.c. to the load, more such π sections may be used one after another.

The output voltage is given by,

$$E_{DC} = E_{sm} - \frac{V_r}{2} - I_{DC} R_x$$

where V_r = Peak to peak ripple voltage

R_x = D.C. resistance of choke

Now $V_r = \frac{I_{DC}}{2fC}$ for full wave

and $= \frac{I_{DC}}{fC}$ for half wave

1.11.1 Ripple factor for π filter

The ripple factor for this filter is given by ,

$$\text{Ripple factor} = \frac{\sqrt{2} \times X_{C1} \times X_{C2}}{X_L \, R_L}$$

The various reactances X_{C_1}, X_{C_2}, X_L are to be calculated at twice the supply frequency since the circuit is fed from a full wave rectifier circuit.

Hence,

$$X_{C_1} = \frac{1}{2\omega C_1}$$

$$X_{C_2} = \frac{1}{2\omega C_2}$$

$$X_L = 2\omega L$$

$$\therefore \quad \text{Ripple factor} = \frac{\sqrt{2}\left(\frac{1}{2\omega C_1}\right)\left(\frac{1}{2\omega C_2}\right)}{(2\omega L)(R_L)}$$

$$\therefore \quad \boxed{\gamma = \frac{\sqrt{2}}{8\omega^3 LC_1 C_2 R_L}}$$

Since this π type filter employes three fitering elements, the riple is reduced to the great extent.

If C_1 and C_2 are expressed in microfarads and frequency f is assumed to be 50 Hz then we get,

$$\gamma = \frac{\sqrt{2}}{8(2\pi \times 50)^3 \times \left(C_1 \times 10^{-6} \times C_2 \times 10^{-6} \times L \times R_L\right)}$$

$$\therefore \quad \boxed{\gamma \approx \frac{5700}{LC_1C_2R_L}}$$

where C_1 and C_2 are in μF, L in henries and R_L in ohms.

1.11.2 Advantages and Disadvantages of π Filter

Advantages

The various advantages of π filter are,

1. For a same total value of L and C, the ripple factor of π filter is much smaller than multiple LC section filter.
2. Higher d.c. output voltage at high load currents can be achieved.
3. The output is very much smoother.

Disadvantages

The various disadvantages of π filter are,

1. The voltage regulation is poor.
2. Higher values of PIV rating for the diodes.

Example 1 : *Calculate the ripple factor for a π type filter, employing 10 H choke and two equal capacitors 16 μF each and fed from a full wave rectifier and 50 Hz mains. The load resistance is 4 k Ω.*

Solution : The given values are,

$C_1 = C_2 = 16\ \mu F, \quad L = 10\ H, \quad R_L = 4\ k\Omega = 4000\ \Omega, \quad f = 50\ Hz$

$$\therefore \qquad \gamma = \frac{\sqrt{2}}{8\omega^3 L C_1 C_2 R_L} = \frac{\sqrt{2}}{8(2\pi f)^3 L C_1 C_2 R_L}$$

$$= \frac{\sqrt{2}}{8(2\pi\times 50)^3 \times 10 \times 16\times 10^{-6} \times 16 \times 10^{-6} \times 4000} = 5.56\times 10^{-4}$$

Thus the ripple is 0.055% which shows that with π filter the output is almost pure d.c.

1.12 Comparision of Filter Circuits

Parameter	Type of filter			
	L	C	LC	π
E_{DC}(no load)	0.636 E_{sm}	E_{sm}	E_{sm}	E_{sm}
E_{DC}(load I_{DC})	0.636 E_{sm}	$E_{sm} - \frac{I_{DC}}{4fC}$	0.636 E_{sm}	$E_{sm} - \frac{I_{DC}}{4fC}$
Ripple factor (γ)	$\frac{R_L}{3\sqrt{2}\omega L}$	$\frac{1}{4\sqrt{3}\,fRC}$	$\frac{1}{6\sqrt{2}\omega^2 LC}$	$\frac{\sqrt{2}}{8\omega^3 L C_1 C_2 R_L}$
PIV	2 E_{sm}	2 E_{sm}	2 E_{sm}	2 E_{sm}

Key Point: *Above comparison is for full wave rectifiers with filters and diode, transformer and filter element resistances are neglected.*

1.13 Regulators

None of the electronic circuits work properly with unregulated power supply. They require constant voltage supply regardless of the variations in the input voltage or load current. In order to ensure this, a voltage stabilizing device, called voltage regulator is used.

Key Point: *The **voltage regulator** circuit keeps the output voltage constant inspite of changes in load current or input voltage.*

Thus a voltage regulator is a must for every electronic circuit. But it is also necessary to build an unregulated supply before a voltage regulator is connected to a given circuit.

A voltage regulator is a device designed to keep the output voltage of a power supply as nearly constant as possible.

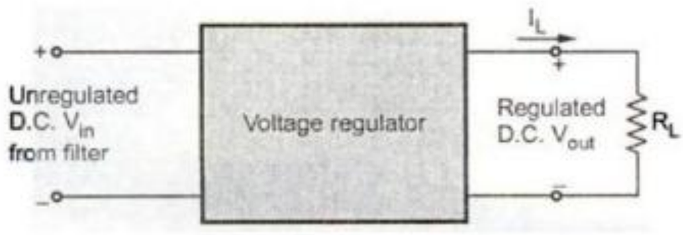


Fig. 1.27 Voltage regulator

As shown in the Fig. 1.27 the input to a voltage regulator circuit is unregulated d.c. input voltage, while the output of the voltage regulator circuit is regulated d.c. output voltage, V_{out}, which is almost constant.

1.13.1 Voltage Regulator Characteristics

1.13.1.1 Load Regulation:

The load regulation is the change in the regulated output voltage when the load current is changed from minimum (no load) to maximum (full load).

The load regulation is denoted as LR and mathematically expressed as,

$$LR = V_{NL} - V_{FL}$$

where V_{NL} = load voltage with no load current

V_{FL} = load voltage with full load current

The load regulation is often expressed as percentage by dividing the LR by full load voltage and multiplying result by 100.

$$\therefore \quad \boxed{\%\ LR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100}$$

1.13.1.2 Line Regulation or Source Regulation:

The SR is defined as the change in the regulated load voltage for a specified range of line voltage, typically 230 V ± 10 %.

Mathematically it is expressed as,

$$SR = V_{HL} - V_{LL}$$

where V_{HL} = load voltage with high line voltage

V_{LL} = load voltage with low line voltage

The percentage source regulation is defined as,

$$\boxed{\%\ SR = \frac{SR}{V_{nom}} \times 100}$$

where V_{nom} = nominal load voltage

1.13.2 Basic Voltage Regulator

The basic voltage regulator in its simplest form consists of,

1. Voltage reference, V_R
2. Error amplifier
3. Feedback network
4. Active series or shunt control element

The voltage reference generates a voltage level which is applied to the comparator circuit, which is generally error amplifier. The second input to the error amplifier is obtained through feedback network. Generally using the potential divider, the feedback signal is derived by sampling the output voltage. The error amplifier converts the difference between the output sample and the reference voltage into an error signal. This error signal inturn controls the active element of the regulator circuit, in order to compensate the change in the output voltage. Such an active element is generally a transistor.

1.13.3 Types of Voltage Regulators

Depending upon where the control element is connected in the regulator circuit, the regulators are basically classified as,

1. Series voltage regulator
2. Shunt voltage regulator

Each type provides a constant d.c. output voltage which is regulated.

1.13.4 Shunt Voltage Regulator

The heart of any voltage regulator circuit is a control element. If such a control element is connected in shunt with the load, the regulator circuit is called shunt voltage regulator. The Fig.1.28 shows the block diagram of shunt voltage regulator circuit.

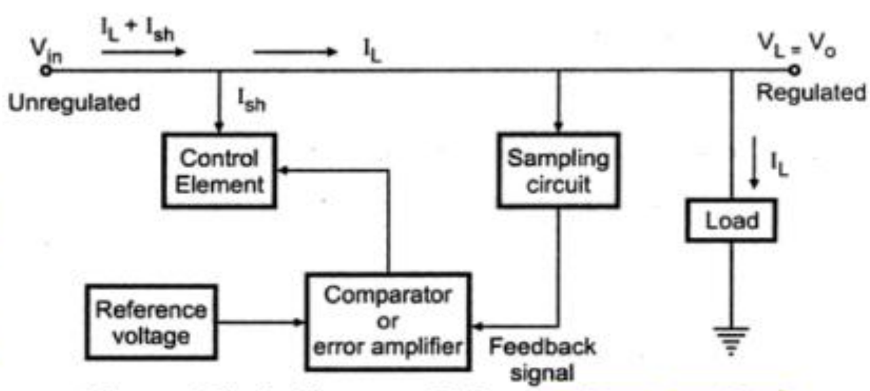


Fig.1.28 Block diagram of shunt voltage regulator

The unregulated input voltage V_{in}, tries to provide the load current. But part of the current is drawn by the control element, to maintain the constant voltage across the load. If there is any change in the load voltage, the sampling circuit provides a feedback signal to the comparator circuit. The comparator circuit compares the feedback signal with the reference voltage and generates a control signal which decides the amount of current required to be shunted to keep the load voltage constant. For example if the load voltage increases then the comparator circuit decides the control signal based on the feedback information, which draws the increased shunt current I_{sh}. Due to this the load current I_L decreases, hence the load voltage decreases to its normal value.

Key Point: *Thus the control element maintains the constant output voltage by shunting the current, hence the circuit is called shunt voltage regulator.*

1.13.5 Series Voltage Regulator

If in a voltage regulator circuit, the control element is connected in series with the load, the circuit is called series voltage regulator circuit. The Fig. 1.29 shows the block diagram of series voltage regulator circuit.

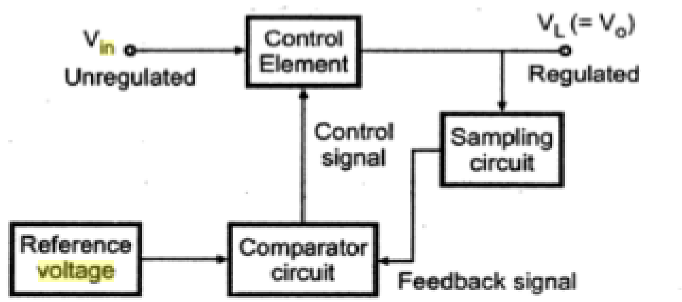


Fig. 1.29 Block diagram of series voltage regulator

The unregulated d.c. voltage is the input to the circuit. The control element, controls the amount of the input voltage, that gets to the output. The sampling circuit provides the necessary feedback signal. The comparator circuit compares the feedback with the reference voltage to generate the appropriate control signal.

For example, if the load voltage tries to increase, the comparator generates a control signal based on the feedback information. This control signal causes the control element to decrease the amount of the output voltage. Thus the output voltage is maintained constant.

Key Point: *Thus, control element which regulates the load voltage based on the control signal is in series with the load and hence the circuit is called series voltage regulator circuit.*

1.13.6 Zener diode as a shunt regulator

The simplest shunt voltage regulator circuit uses a zener diode, to regulate the load voltage. The Fig. 1.30 shows the arrangement of zener diode in a regulator circuit.

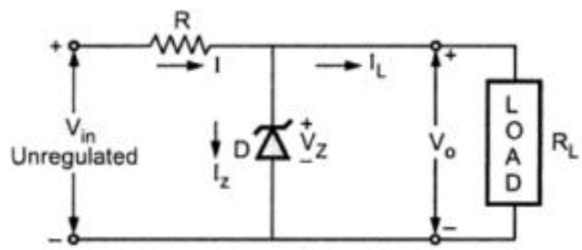


Fig. 1.30 Zener diode as a shunt regulator

1.13.6.1 Regulation with varying input voltage

The Fig. 1.31 shows a zener regulator under varying input voltage condition.

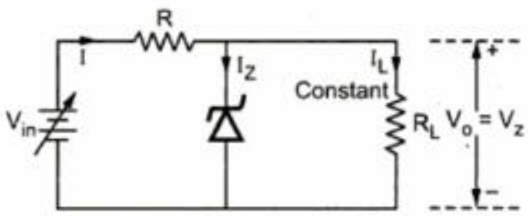


Fig. 1.31 Varying input condition

It can be seen that the output is

$V_o = V_Z$ is constant.

$$\therefore \quad I_L = \frac{V_o}{R_L} = \frac{V_Z}{R_L} = \text{constant}$$

And $I = I_Z + I_L$

Now if V_{in} increases, then the total current I increases. But I_L is constant as V_Z is constant. Hence the current I_Z increases to keep I_L constant.

But as long as I_Z is between I_{Zmin} and I_{Zmax}, the V_Z i.e. output voltage V_o is constant. Thus the changes in input voltage get compensated and output is maintained constant.

Similarly if V_{in} decreases, then current I decreases. But to keep I_L constant, I_Z decreases. As long as I_Z is between I_{Zmax} and I_{Zmin}, the output voltage remains constant.

Steps to Analyse Zener Regulator with Varying Input

The steps are,

1. Calculate the load current which is constant

$$\therefore \quad I_L = \frac{V_o}{R_L} = \frac{V_Z}{R_L}$$

2. To find $V_{in(min)}$, the current through zener must be I_{Zmin} to keep it reverse biased.

$$\therefore \quad I = I_L + I_{Zmin}$$

$$\therefore \quad V_{in}(min) = V_Z + I \times R$$

3. To find $V_{in}(max)$, the current through zener must be maximum equal to I_{Zmax}.

$$\therefore \quad I = I_L + I_{Zmax}$$

$$\therefore \quad V_{in(max)} = V_Z + I \times R$$

4. Hence the range of input is $V_{in(min)}$ to $V_{in(max)}$ for which output will be constant equal to V_Z.

Using the same steps, for given V_{in} range the resistance values can be obtained and zener regulator can be designed.

The maximum power dissipation in the zener diode is given by,

$$P_D = V_Z I_{Z(max)}$$

The zener diode must be selected with power dissipating rating higher than P_D.

1.13.6.2 Regulation with varying Load

The Fig. 1.32 shows a zener regulator under varying load condition and constant input voltage.

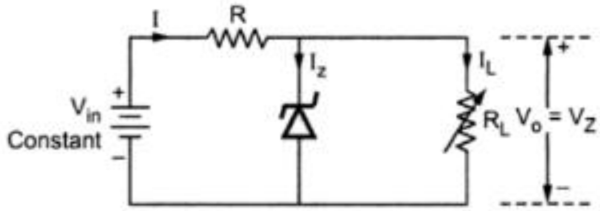


Fig. 1.32 Varying load condition

The input voltage is constant while the load resistance R_L is variable. As V_{in} is constant and
$V_o = V_Z$ is constant, then for constant R the current I is constant.

$$\therefore \qquad I = \frac{V_{in} - V_Z}{R} \text{ constant } = I_L + I_Z$$

Now if R_L decreases so I_L increases, to keep I constant I_Z decreases. But as long as it is between I_{Zmin} and I_{Zmax}, output voltage V_o will be constant. Similarly if R_L increases so I_L decreases, to keep I constant I_Z increases. But as long as it is between I_{Zmin} and I_{Zmax}, output voltage V_o will be constant.

Steps to Analyse Zener Regulator with Varying Load

The steps are,

1. Calculate total current I which is constant.

$$\therefore \qquad I = \frac{V_{in} - V_Z}{R}$$

2. To find $I_{L(min)}$, $I_Z = I_{Zmax}$

$$\therefore \qquad I_{L(min)} = I - I_{Zmax}$$

3. To find $I_{L(max)}$, $I_Z = I_{Zmin}$

$$\therefore \qquad I_{L(max)} = I - I_{Zmin}$$

4. Thus $I_{L(min)}$ to $I_{L(max)}$ is the range of load current for which output voltage remains constant.

The maximum power dissipation in zener remains same as,

$$P_D = V_Z \, I_{Zmax}$$

1.14 Advantages of IC Voltage Regulators

The various advantages of IC voltage regulators are,

1. Easy to use.
2. It greatly simplifies power supply design.
3. Due to mass production, low in cost.
4. IC voltage regulators are versatile.
5. Conveniently used for local regulation.
6. These are provided with features like built in protection, programmable output, current/voltage boosting, internal short circuit current limiting etc.

1.15 Classification of IC Voltage Regulators

The IC voltage regulators are classified as shown in the Fig.1.33 .

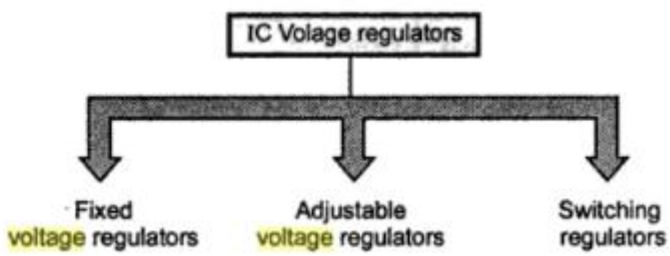


Fig. 1.33 Classification of IC regulators

1.15.1 Three terminal fixed voltage regulators

As the name suggests, three terminal voltage regulators have three terminals namely input which is unregulated (V_{in}), regulated output (V_o) and common or a ground terminal. These regulators do not require any feedback connections. The Fig. 1.34 shows the basic three terminal voltage regulator.

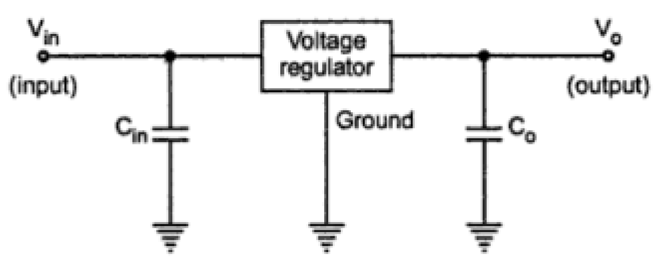


Fig. 1.34 Three terminal voltage regulators

The capacitor C_{in} is required if regulator is located at appreciable distance, more than 5 cm from a power supply filter. The output capacitor C_o may not be needed but if used it improves the transient response of the regulator i.e. regulator response to the transient changes in the load. This capacitor also reduces the noise present at the output. The difference between V_{in} and V_o ($V_{in} - V_o$) is called as dropout voltage and it must be typically 2.0 V even during the low point on the input ripple voltage, for the proper functioning of the regulator.

1.15.2 IC series of 3 terminal fixed voltage regulators

The popular IC series of three terminal regulators is μA78XX and μA79XX. The series μA78XX is the series of three terminal **positive** voltage regulators while μA79XX is the series of three terminal **negative** voltage regulators. The last two digits denoted as XX, indicate the output voltage rating of the IC.

Such series is available with seven voltage options as indicated in Table 1

Device type	Output Voltage	Device type	Output Voltage
7805	5.0 V	7905	– 5.0 V
7806	6.0 V	7906	– 6.0 V
7808	8.0 V	7908	– 8.0 V
7812	12.0 V	7912	– 12.0 V
7815	15.0 V	7915	– 15.0 V
7818	18.0 V	7918	– 18.0 V
7824	24.0 V	7924	– 24.0 V

Table 1

The 79XX series voltage regulators are available with same seven options as 78XX series, as indicated in Table 13.3. In addition, two extra voltages –2 V and –5.2 V are also available with ICs 7902 and 7905.2 respectively.

These ICs are provided with adequate heat sinking and can deliver output currents more than 1 A. These ICs do not require external components. These are provided with internal thermal protection, overload and short circuit protection.

1.15.3 Adjustable regulator using 78XX series

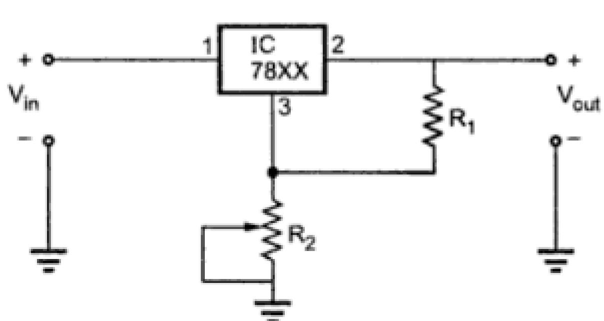


Fig. 1.35 Adjustable regulator using IC 78XX

Though IC 78XX series regulators have fixed value of the regulated output voltage, by connecting two resistances externally, an adjustable output voltage can be obtained.

The typical connection of 78XX IC regulator to obtain variable output voltage is shown in the Fig. 1.35.

$$V_{out} = V_{reg}\left[1+\frac{R_2}{R_1}\right]$$

where V_{reg} = Regulated fixed voltage of IC

By varying R_2, variable output voltage can be obtained.

1.15.4 Need of Switched Mode Power Supply

A linear regulator power supply has following limitations :

1. The required input step down transformer is bulky and expensive.
2. Due to low line frequency (50 Hz), large values of filter capacitors are required.
3. The efficiency is very low.
4. Input must be greater than the output voltage.
5. As large is the difference between input and output voltage, more is the power dissipation in the series pass transistor.
6. For higher input voltages, efficiency decreases.
7. The need for dual supply, is not economical and feasible to achieve with the help of linear regulators.

Thus in modern days, to overcome all these limitations Switched Mode Power Supplies (SMPS) are needed.

1.15.5 Block diagram of SMPS

A switching power supply is shown in Fig. 1.36 . The bridge rectifier and capacitor filters are connected directly to the ac line to give unregulated dc input. The thermistor R_t limits the high initial capacitor charge current. The reference regulator is a series pass regulator of the type .

Its output is a regulated reference voltage V_{ref} which serves as a power supply voltage for all other circuits. The current drawn from V_{ref} is usually very small (~ 10 mA), so the power loss in the series pass regulator does not affect the overall efficiency of the switched mode power supply (SMPS). Transistors Q_1 and Q_2 are alternately switched *off* and *on* at 20 kHz. These transistors are either fully *on* ($V_{CE\ sat}$ ~ 0.2V) or cut-off, so they dissipate very little power. These transistors drive the primary of the main transformer.

The secondary is centre-tapped and full wave rectification is achieved by diodes D_1 and D_2. This unidirectional square wave is next filtered through a two stage LC filter to produce output voltage V_o.

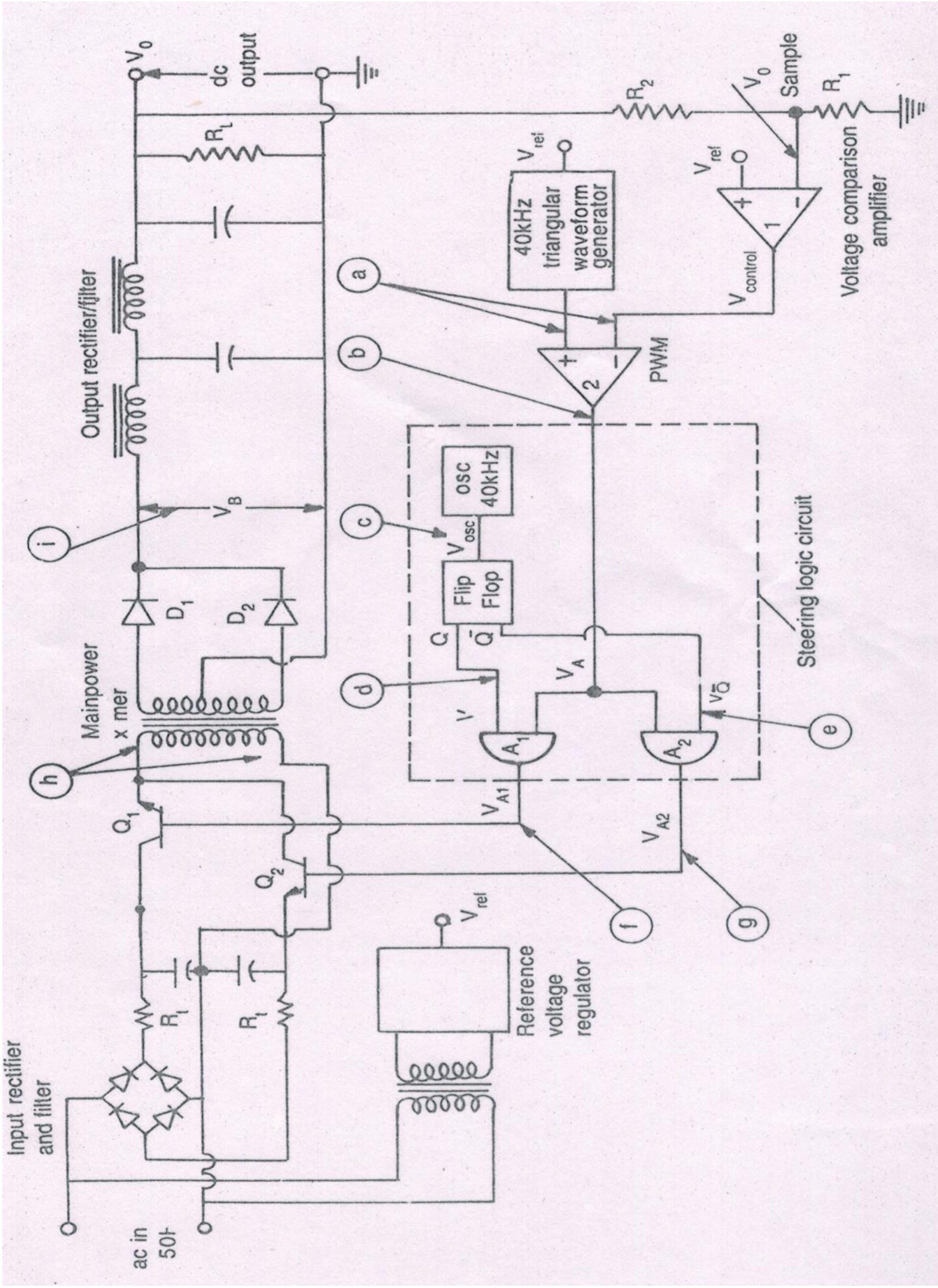


Fig.1.36 Block diagram of switched mode power supply

The regulation of V_o is achieved by the feedback circuit consisting of a pulse-width modulator and steering logic circuit. The output voltage V_o is sampled by a R_1R_2 divider and a fraction $R_1/(R_1+R_2)$ is compared with a fixed reference voltage V_{ref} in comparator 1. The output of this voltage comparison amplifier is called $V_{control}$ and is shown in Fig. 1.37(a)

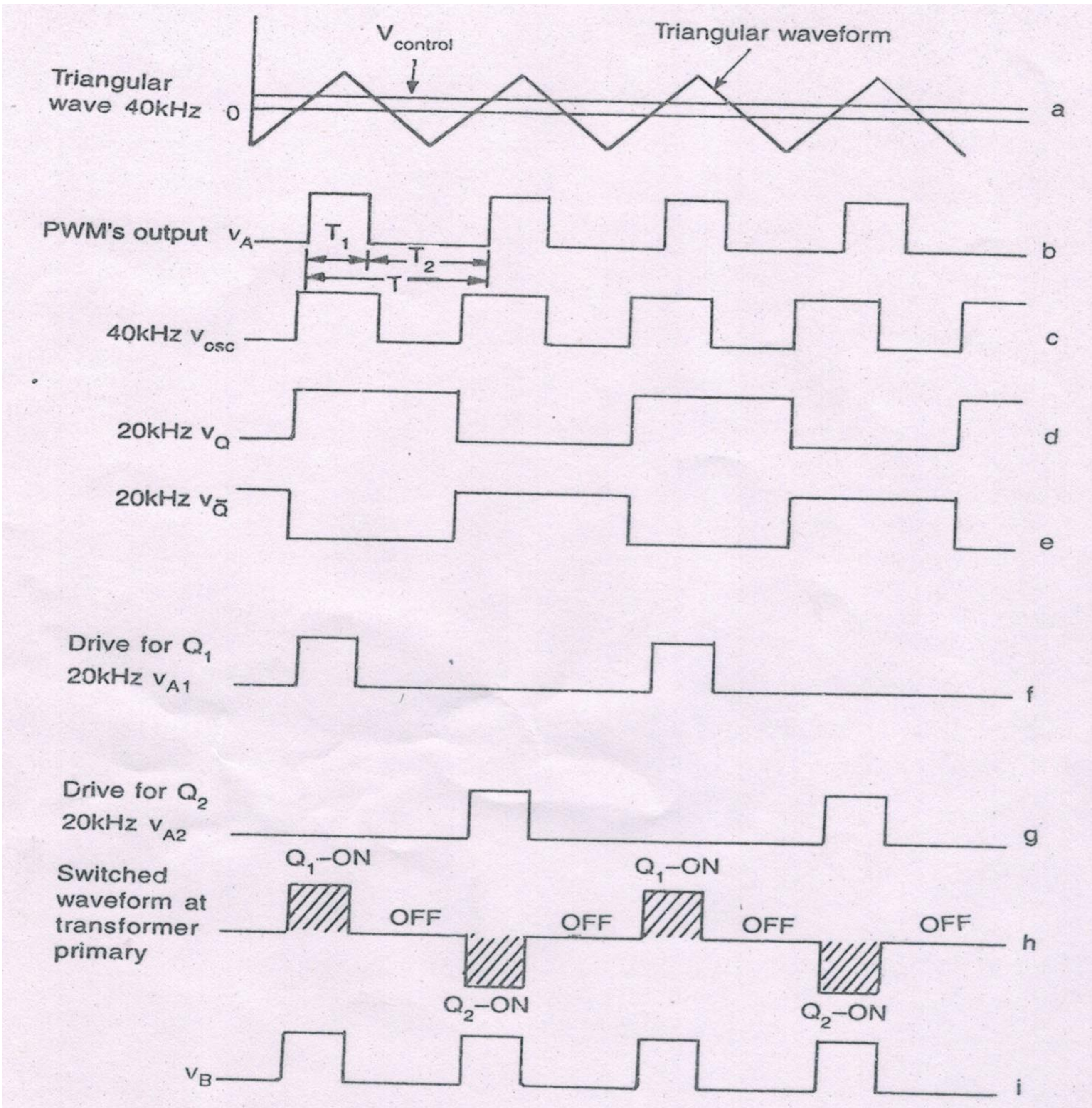


Fig.1.37 Waveforms of switched mode power supply

$V_{control}$ is applied to the (–) input terminal of comparator 2 and a triangular waveform of frequency 40 kHz (also shown in Fig. 1.37 (a)) is applied at the (+) input terminal. It may be noted that a high frequency triangular waveform is being used to reduce the ripple. The comparator 2 functions as a pulse width modulator and its output is a square wave v_A (Fig. 1.37 (b)) of period $T(f = 40$ kHz). The duty cycle of the square wave is $T_1/(T_1 + T_2)$ and varies with $V_{control}$ which in turn varies with the variation of v_o.

The output v_A drives a steering logic circuit shown in the dashed block. It consists of a 40 kHz oscillator cascaded with a flip-flop to produce two complementary outputs v_Q and $v_{\bar{Q}}$ shown in Fig. 1.37 (d) and (e). The output v_{A1} and v_{A2} of AND gates A_1 and A_2 are shown in Fig. 1.37 (f) and (g). These waveforms are applied at the base of transistor Q_1 and Q_2. Depending upon whether transistor Q_1 or Q_2 is ***on***, the waveform at the input of the transformer will be a square wave as shown in Fig. 1.37 (h). The rectified output v_B is shown in Fig. 1.37 (i).

An inspection of Fig. 1.36 shows that the output current passes through the power switch consisting of transistors Q_1 and Q_2, inductor having low resistance and the load. Hence using a switch with low losses (transistor with small $V_{CE\,(sat)}$ and high switching speed) and a filter with high quality factor, the conversion efficiency can easily exceed 90%.

If there is a rise in dc output voltage V_o, the voltage control $V_{control}$ of the comparator 1 also rises. This changes the intersection of the $V_{control}$ with the triangular waveform and in this case decreases the time period T_1 in the waveform of Fig. 1.37 (b). This in turn decreases the pulse width of the waveform driving the main power transformer. Reduction in pulse width lowers the average value of the dc output V_o. Thus the initial rise in the dc output voltage V_o has been nullified.