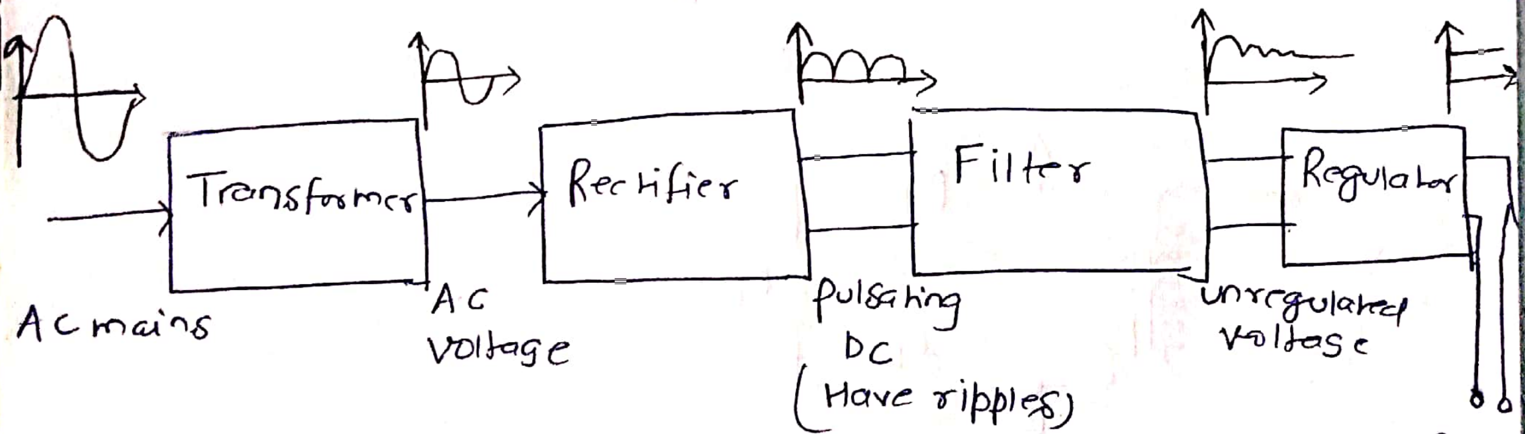
Regulated Power supply

In today's world, no. of Electronic devices operate fully or partially on DC power supply.

The DC power supply provides a smooth and constant DC voltage.

A typical DC power supply consist of various stages. The block diagram of the DC power supply is shown below.



Rectifiers

A rectifier is a device which converts an AC voltage to pulsating DC voltages. It uses p-n junction diodes to perform rectification. p-n Junction diodes allows the current to flow in only one direction and hence they make convert AC current to unidirection pulsating DC current.

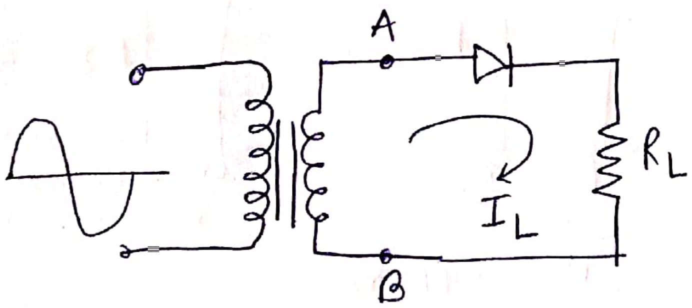
Types of Rectifiers

Depending on the no. of diodes used in rectifier, It is classified as

i) Half wave rectifier
ii) Full wave rectifier
iii) Bridge Rectifier.

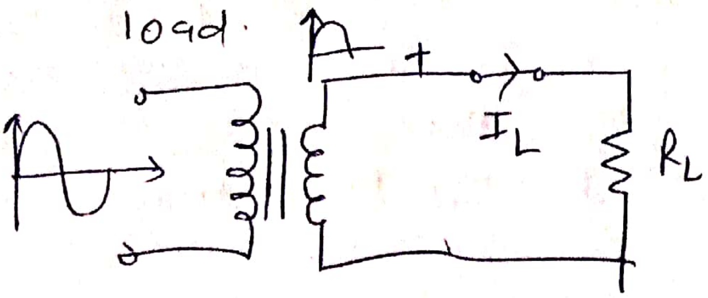
i) Half wave Rectifier

In half wave rectifier, only one diode is used. This diode conducts only during positive half cycle of the A.C supply.

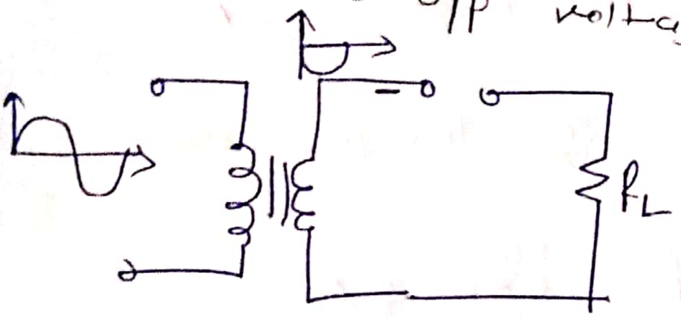


Operation

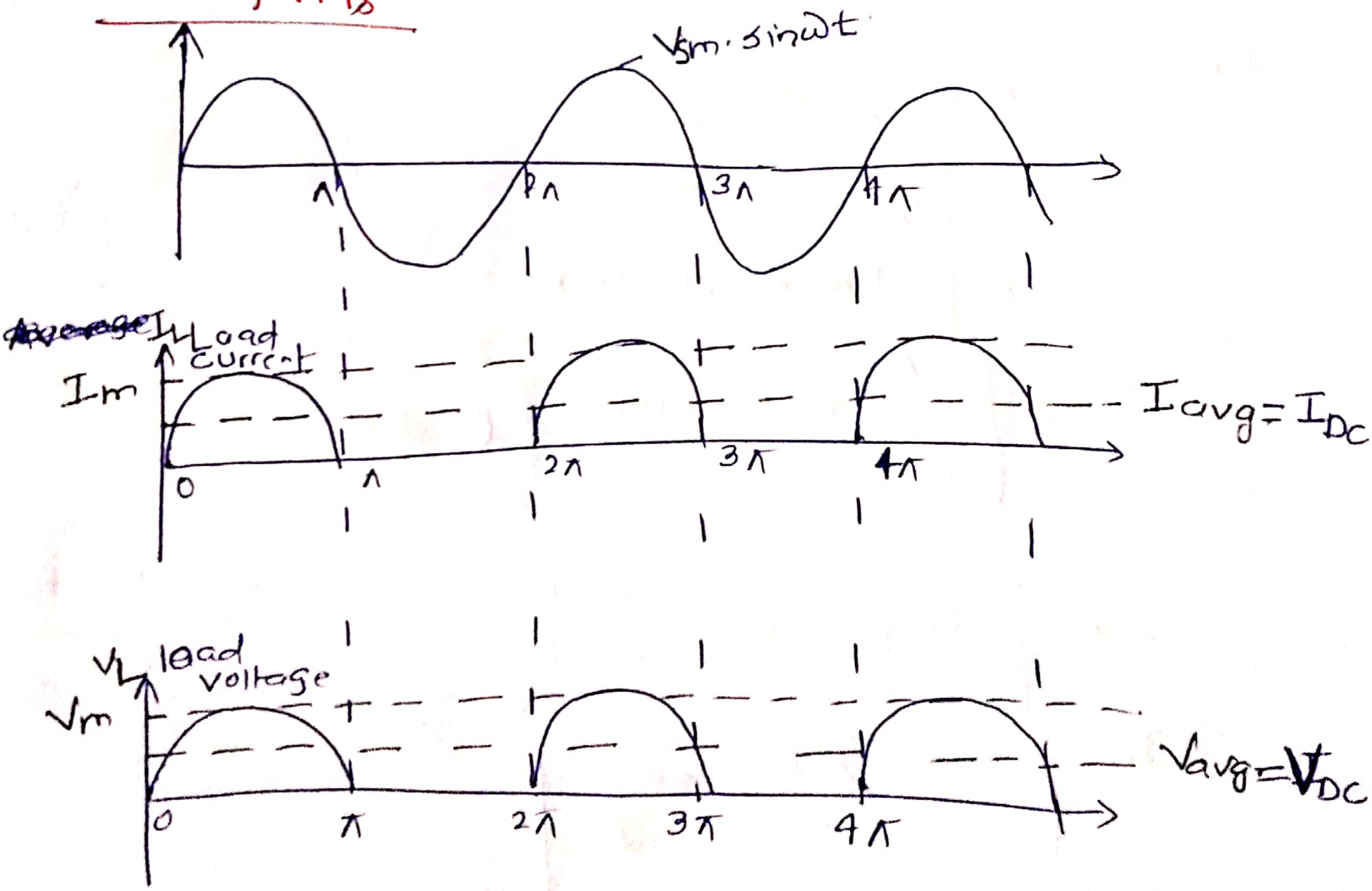
During positive half cycle of the AC voltage, the diode is forward biased and hence the circuit will allow the flow of current through load.



During negative half cycle, the diode will be reversed biased and hence the diode will act as open circuit. In this case, we will not be able to get any load current and hence o/p voltage will be zero.



wave forms



Average DC load current ($I_{DC} = I_{avg}$)

To find out average value of an AC waveform, we have to determine the area under the curve over one complete cycle i.e from 0 to 2π and the divide it by the base i.e 2π

current wave form passing through load resistance is

$I_L = I_m \cdot \sin\omega t$ for $0 \le \omega t \le \pi$

$I_L = 0$ for $\pi \le \omega t \le 2\pi$

$$I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} I_L \cdot d(\omega t).$$

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

$$= \frac{1}{2\pi}\left[\int_0^{\pi} I_m \cdot \sin\omega t\, d\omega t \int_{\pi}^{2\pi} 0 \cdot d\omega t\right]$$

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

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

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

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

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

9f

Average DC load voltage :-

$$V_{DC} = V_{avg} = \frac{1}{2\pi}\int_0^{2\pi} V_m \cdot \sin\omega t \cdot d\omega t$$

$$= \frac{1}{2\pi}\left[\int_0^{\pi} V_m \cdot \sin\omega t \cdot d\omega t + \int_{\pi}^{2\pi} 0 \cdot d\omega t\right]$$

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

RMS value of load current

The RMS means, squaring, finding mean and then finding square roots. Hence, RMS value can be given as

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

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

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

$$= \sqrt{\frac{I_m^2}{2\pi}\int_0^{\pi} \frac{(1-\cos 2\omega t)}{2} \cdot d\omega t.}$$

$$= \sqrt{\frac{I_m^2}{4\pi}\left[\omega t - \frac{\sin 2\omega t}{2}\right]_0^{\pi}}$$

$$= \sqrt{\frac{I_m^2}{4\pi}\left[(\pi - 0) - \frac{(\overset{\to 0}{\sin 2\pi} - \overset{\to 0}{\sin 0})}{2}\right]}$$

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$$= \sqrt{\frac{I_m^2}{4\cancel{\pi}} \times \cancel{\pi}}$$

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

RMS value of load voltage

$$V_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} (V_m \sin\omega t)^2 \cdot d\omega t}$$

If we solve it in similar manner as RMS current, then we will get

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

Rectifier Efficiency

It is defined as, ratio of o/p DC power to i/p AC power. If we neglect rectifier & secondary winding resistance then

P_{DC} = DC power = $I_{DC}^2 \cdot R_L$

P_{ac} = AC power = $I_{RMS}^2 \cdot R_L$

$$\eta = \frac{P_{DC}}{P_{ac}} = \frac{I_{DC}^2 \cdot \cancel{R_L}}{I_{RMS}^2 \cdot \cancel{R_L}}$$

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

$$\boxed{\eta\,\% = 40.6\,\%}$$

The remaining 60% of AC i/p power is present in terms of fluctuating ripples.

Ripple factor (γ)

The pulsating component of o/p is known as ripples. These ripples are measured by ripple factor. It tells that how smooth is the o/p. Smaller the ripple factor, the o/p is closer to the ~~pulsating~~ pure DC voltage.

It is given by the ratio of RMS value of the a.c component in the o/p to the average or D.C component of the o/p.

$$\gamma = \frac{\text{RMS value of AC component of the o/p}}{\text{Average or DC component of the o/p}}$$

Till now, the I_{RMS} is RMS value of combined AC and DC component.

I_{ac} = RMS value of a.c component

I_{DC} = Average value of DC component

I_{RMS} = RMS value of total o/p current (AC+DC)

$$I_{RMS}^2 = I_{ac}^2 + I_{DC}^2$$

$$I_{ac}^2 = I_{RMS}^2 - I_{DC}^2$$

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

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

$$= \sqrt{\frac{I_{RMS}^2}{I_{DC}^2} - 1}$$

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

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

$$= \sqrt{1.4674}$$

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

Peak Inverse Voltage (PIV)

It is the peak voltage across the diode in the reverse bias condition.

Hence, the maximum voltage across the diode in reverse bias will be equal to secondary voltage of the transformer.

$\boxed{PIV = V_{sm} = \text{Maximum voltage of secondary winding}}$

Transformer utilization factor (T.U.F)

The factor which indicates that how much utilization of transformer is taken place in the rectifier.

$$TUF = \frac{\text{DC power delivered to the load}}{\text{AC power rating of transformer}}$$

$$= \frac{I_{DC}^2 R_L}{I_{RMS}^2 \cdot R_L} = \frac{\left(\frac{I_m}{\pi}\right)^2 \cdot R_L}{\frac{V_{sm}}{2}}$$

purely sinusoidal

$$\text{AC power rating of transformer} = \underbrace{\frac{V_{sm}}{\sqrt{2}}}_{E_{RMS}} \cdot \underbrace{\frac{I_m}{2}}_{I_{RMS}}$$

half sinusoidal

$$\text{DC power to the load} = I_{DC}^2 \cdot R_L$$

$$TUF = \frac{I_{DC}^2 \cdot R_L}{\frac{V_{sm} \cdot I_m}{2\sqrt{2}}} = \frac{\left(\frac{I_m}{\pi}\right)^2 \cdot R_L}{\frac{V_{sm} \cdot I_m}{2\sqrt{2}}}$$

$$V_{sm} = I_m \cdot R_L$$

$$TUF = \frac{I_m^2 \cdot R_L}{\pi^2 \cdot \frac{I_m^2 \cdot R_L}{2\sqrt{2}}} = \frac{2\sqrt{2}}{\pi^2} = 0.287$$

DISAdvantages

i) High ripple factor

ii) Low efficiency

iii) Low transformer utilization factor

iv)

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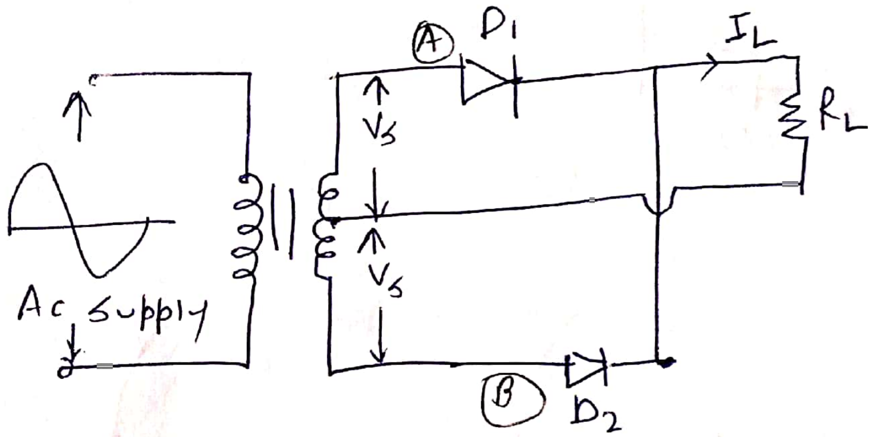
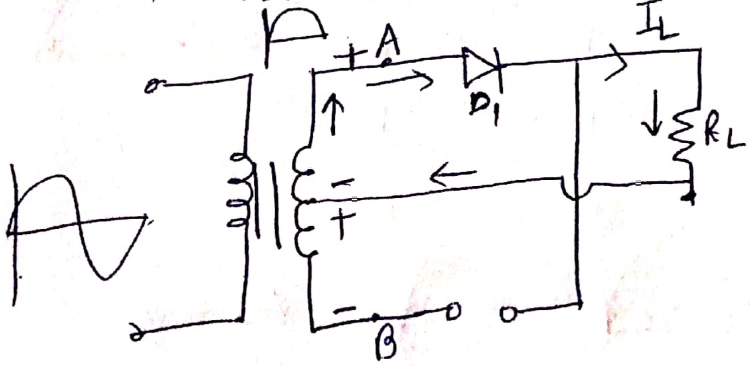
Full wave rectifier

In order to refine both positive and negative half cycles of a.c input voltage, two diody are used in full wave rectifier. The one diode conducts during positive half cycle and another conducts during negative half cycle. A center-tap transformer is used to ensure proper working of these diodes.



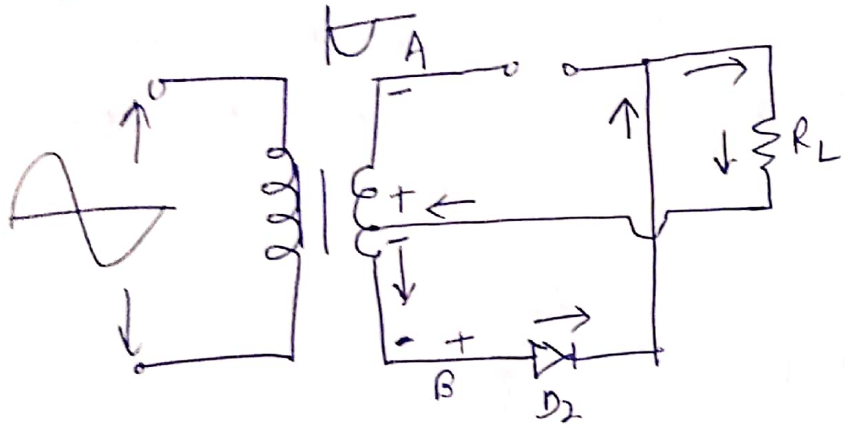
operation

During positive half cycle, terminal A is positive and D_1 is conducting. Terminal B is negative and D_2 is not conducting.

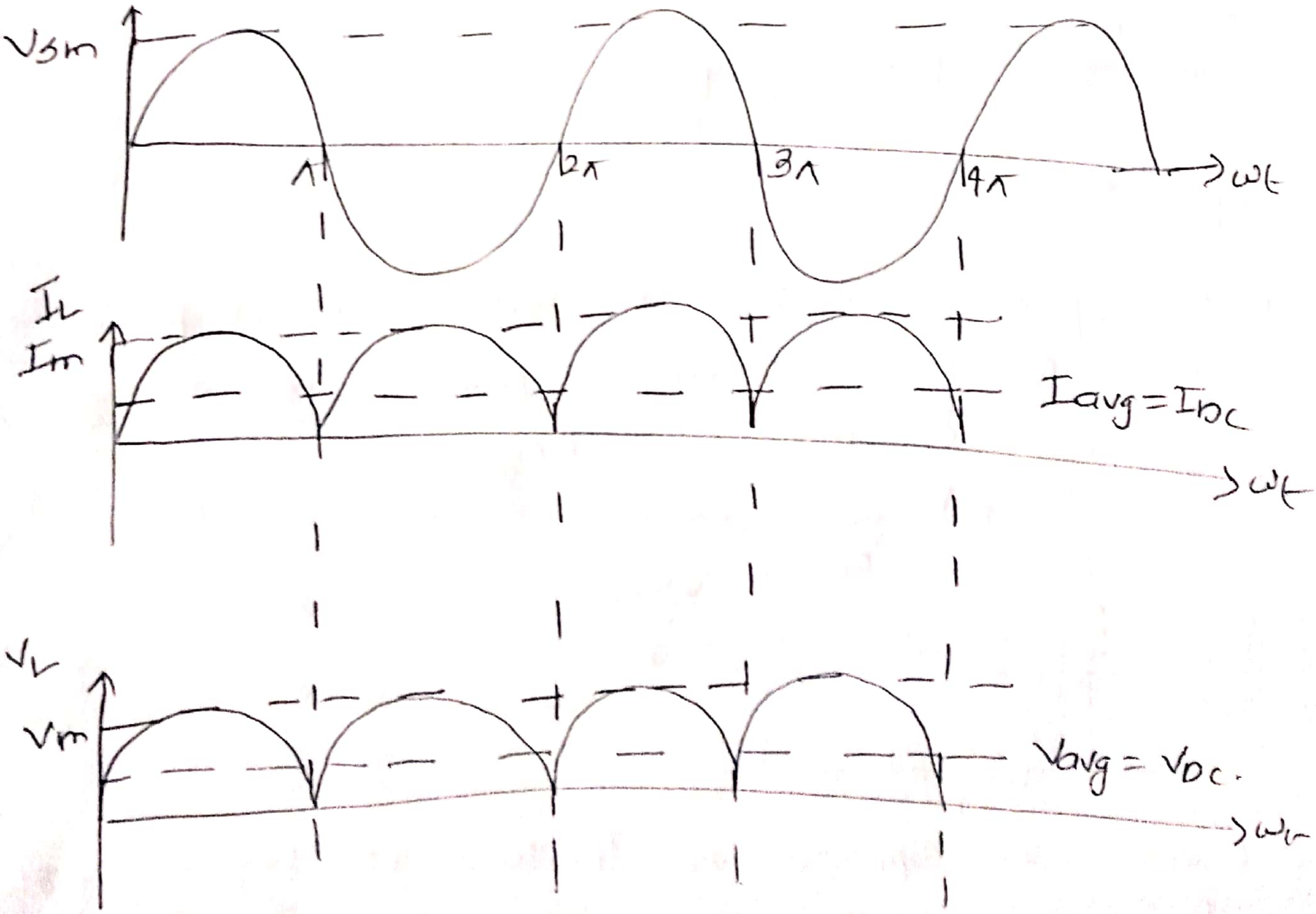


Current is supplied to the load resistance through D_1 and positive half cycles of the AC I/P is rectified.

During negative half cycle of AC voltage, point A will be negative and hence diode D_1 will be reverse biased, point B will be positive and diode D_2 will be forward biased. Hence, the Lower portion of secondary winding will be conducting and it will supply the load current to R_L.



wave forms



Average DC load current ($I_{DC} = I_{avg}$)

$$I_L = I_m \cdot \sin\omega t \qquad 0 \leq \omega t \leq 2\pi$$

$$I_{avg} = \frac{1}{2\pi}\int_0^{2\pi} I_L \cdot d\omega t$$

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

$$= \frac{2}{2\pi}\int_0^{\pi} I_m \cdot \sin\omega t \cdot d\omega t$$

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

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

$$= \frac{\cancel{2} I_m}{\cancel{2}\pi} \times 2$$

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

Average DC load voltage ($V_{DC} = V_{avg}$)

$$V_L = V_m \cdot \sin\omega t \qquad 0 \leq \omega t \leq 2\pi$$

$$V_{avg} = \frac{1}{2\pi}\int_0^{2\pi} V_m \cdot \sin\omega t \cdot d\omega t$$

$$= \frac{2}{2\pi}\int_0^{\pi} V_m \cdot \sin\omega t \cdot d\omega t$$

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

RMS value of load current

$$I_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} I_L^2 \cdot d\omega t}$$

$$= \sqrt{\frac{2}{2\pi}\int_0^{\pi} (I_m \cdot \sin\omega t)^2 \cdot d\omega t}$$

$$= \sqrt{\frac{I_m^2}{\pi}\int_0^{\pi} (\sin^2\omega t) \cdot d\omega t}$$

$$= \sqrt{\frac{I_m^2}{\pi}\int_0^{\pi} \left(\frac{1-\cos 2\omega t}{2}\right) \cdot d\omega t}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\int_0^{\pi} (1-\cos\omega t) \cdot d\omega t}$$

$$= \sqrt{\frac{I_m^2}{2\pi}\left\{\left[\omega t\right]_0^{\pi} - \underbrace{\left[\sin\omega t\right]_0^{\pi}}_{\text{zero}}\right\}}$$

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

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

RMS value of load voltage

$$V_{RMS} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_L^2 \cdot d\omega t}$$

$$= \sqrt{\frac{2}{2\pi}\int_0^{\pi} (V_m \cdot \sin\omega t)^2 \cdot d\omega t}$$

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

Rectifier Efficiency

$$\eta = \frac{P_{DC}}{P_{AC}}$$

$$P_{DC} = I_{DC}^2 \cdot R_L$$

$$P_{AC} = I_{RMS}^2 \cdot R_L$$

$$\eta = \frac{I_{DC}^2}{I_{RMS}^2} = \frac{\left(\frac{2I_m}{\pi}\right)^2}{\left(\frac{I_m}{\sqrt{2}}\right)^2} = \frac{4I_m^2}{\pi^2 \times I_m^2} \times 2 = \frac{8}{\pi^2} = 0.812$$

$$\boxed{\eta\% = 81.2\%}$$

Ripple factor

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

$$= \sqrt{\frac{\left(I_m/\sqrt{2}\right)^2}{\left(\frac{2I_m}{\pi}\right)^2} - 1}$$

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

$$= 0.48$$

$$\boxed{\gamma = 0.48}$$

Peak inverse voltage

Since one diode conducts during positive half cycle and another during negative half cycle

$$\boxed{PIV = 2V_{sm}}$$

Transformer utilization factor

In full wave rectifier, the secondary current flows through each half seprately in every half-cycle while the primary of the transformer carries current continiously. Hence, TUF is calculated for primary and secondary winding separately.

$$\text{Secondary TUF} = \frac{\text{DC power to the load}}{\text{AC power rating of secondary}}$$

$$= \frac{I_{DC}^2 \cdot R_L}{V_{RMS} \cdot I_{RMS}}$$

$$= \frac{I_{DC}^2 \cdot R_L}{\frac{V_{sm}}{\sqrt{2}} \cdot \frac{I_m}{\sqrt{2}}} = \frac{\left(\frac{2I_m}{\pi}\right)^2 \cdot R_L}{\frac{V_{sm} \cdot I_m}{2}}$$

$$V_{sm} = I_m \cdot R_L$$

$$TUF = \frac{4/\pi^2 \times I_m^2 \cdot R_L}{\frac{I_m^2 \cdot R_L}{2}} = \frac{8}{\pi^2} = 0.812$$

$$\text{TUF for primary} = 2 \times \text{TUF of half wave rectifier}$$

$$= 2 \times 0.287 = 0.574$$

$$\text{Average TUF} = \frac{\text{TUF of primary} + \text{TUF of secondary}}{2}$$

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

$$= 0.693$$

$$\boxed{TUF = 0.693}$$

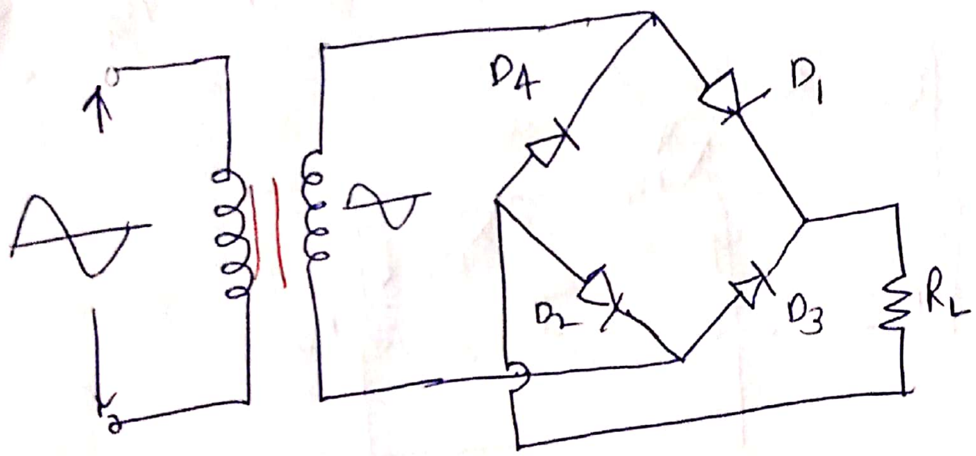
Advantages

i) Low ripple
ii) High efficiency
iii) High transformer utilization factor

Bridge Rectifier :-

Four diodes are used in bridge rectifier, forming four arms of a bridge, hence this is known as bridge rectifier. The one diagonal of the bridge is used by secondry of the transformer to supply voltage and another diagonal is used for o/p.

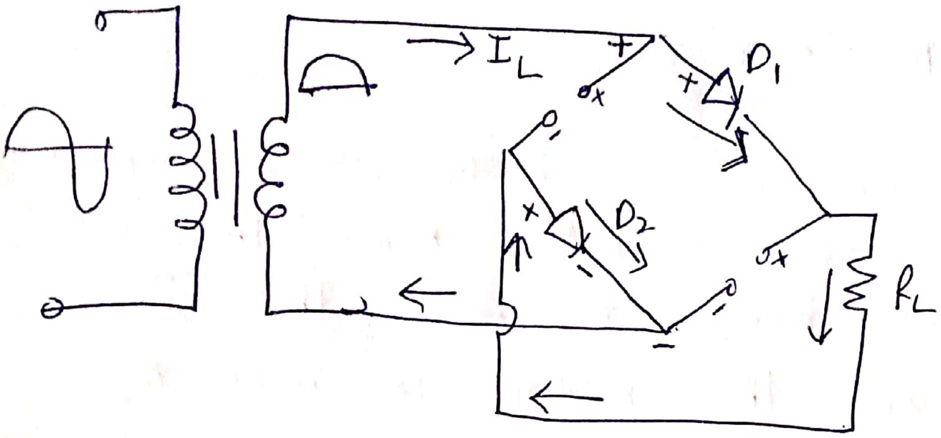
The major advantage is that it does not required a center tap transformer.



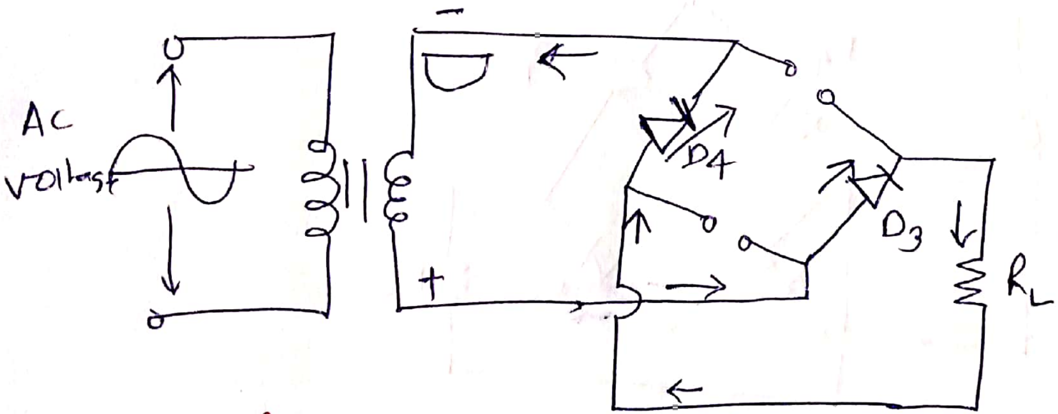
operation

During positive half of the secondry voltage Diodes D_1 and D_2 will be forward biased and hence will act as a closed switch. Diodes D_3 and D_4 will be reversed biased and hence no current will flow through them.

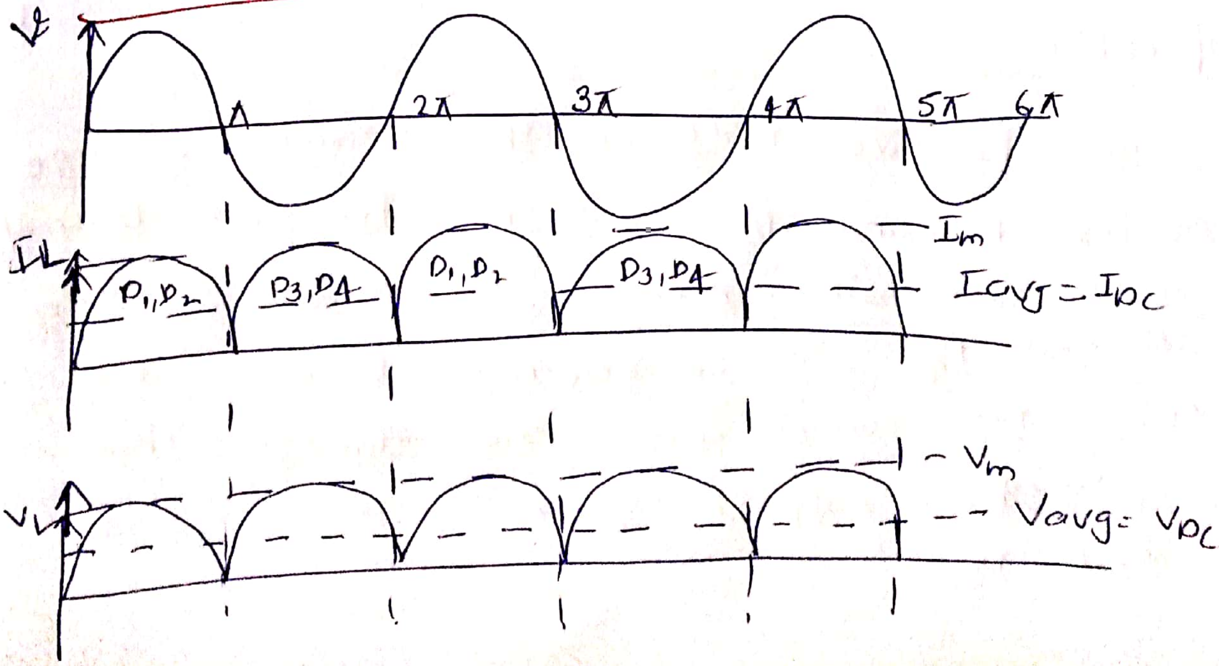
R_L will be supplied load current via D_1 and D_2.



During negative half cycle, Diodes D_1 & D_2 will be reversed biased and diodes D_3 and D_4 will be forward biased. Hence, R_L will be supplied load current through D_3 and D_4.



wave forms



Average load current

The derivations are similar to center tap full wave rectifier.

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

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

$$\eta = \frac{I^2_{DC}}{I^2_{RMS}} = 0.812$$

$$\boxed{\eta = 81.2\%}$$

Ripple factor $= \sqrt{\left(\frac{I_{RMS}}{I_{DC}}\right)^2 - 1}$

$$\boxed{\gamma = 0.48}$$

TUF = TUF of Secondry as the current flows through it through out of time.

$$\boxed{TUF = 0.812}$$

PIV = Two diodes conducts in series in each half cycle, hence inverse voltage gets shared among them. Here, the peak inverse voltage is V_{sm}, which is lower than center tap transformer. This property makes it useful for high voltage applications.

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FILTER CIRCUITS

The output from any of the rectifier circuits just discussed is not purely DC but also has some AC components, called ripples, along it. The ripples are maximum in the half-wave rectifier and being reduced in full-wave rectifier. Such supply is not useful for driving sophisticated electronic devices/circuits. For such applications, as well as for many more, the output DC developed will have to be much steady or smoother than that of the pulsating DC obtained directly from half-wave or full-wave rectifier circuits. Hence, it becomes essential to reduce the ripples from the pulsating DC supply available from rectifier circuits to the minimum. This is achieved by using a filter or smoothing circuit as shown in figure.

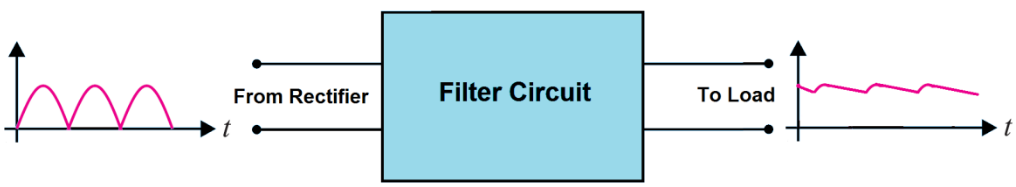


Figure: Filter input and output

A filter circuit is a device that converts pulsating output of a rectifier into a steady DC level. A filter circuit is generally a combination of inductors (L) and capacitors (C). The filtering action of L and C depends upon the facts that an inductor allows DC only and capacitor allows AC only to pass. So a suitable L and C network can effectively filter out (or remove) the ac components from the rectified output. Commonly used filter circuits are:

1. series inductor filter
2. shunt capacitor filter
3. capacitor input or π filter

Series Inductor (Choke) Filter

In this arrangement a high value inductor or choke L is connected in series with the rectifier element and the load, as illustrated in figure. The filtering action of an iductor filter depends upon its property of opposing any change in the current flowing through it. When the output current of the rectifier increases above a certain value, energy is stored in it in the form of magnetic field and this energy is given up when the output current falls below the average value. Thus by placing a choke coil in series with the rectifier output and load, any sudden change in current that might have occurred in the circuit without an inductor is smoothed out by the presence of the inductor L.

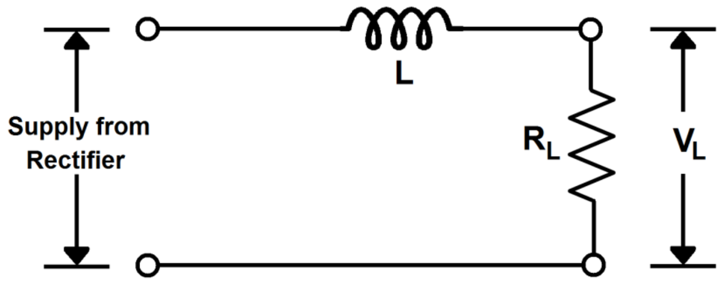


Figure: Circuit Diagram of Series Inductor Filter

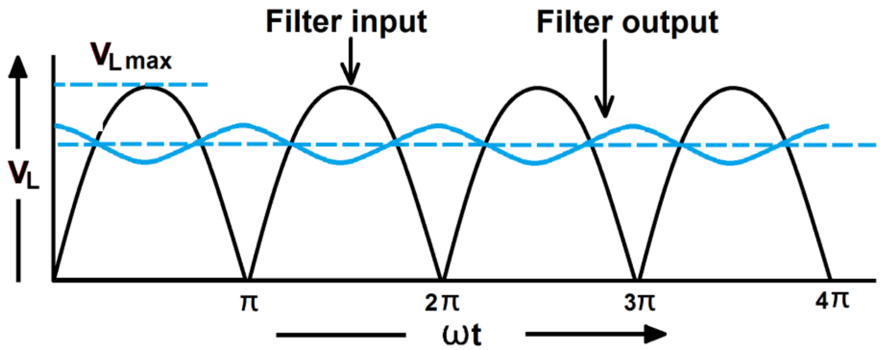


Figure: I/O Waveforms of Series Inductor Filter

The function of the inductor filter may be viewed in terms of impedances.

$$X_L = 2\pi f L$$

if f=0 (DC)

$$X_L = 0$$

if f=∞

$$X_L = \infty$$

The choke offers high impedance to the ac components but offers almost zero resistance to the desired dc components. Thus ripples are removed to a large extent. Nature of the output voltage without filter and with inductor (choke) filter is shown in figure. Inductor filter is more efficient for high load current or small load resistance R_L.

Shunt Capacitor Filter

This is the simplest form of the filter circuit and in this arrangement a high value capacitor C is placed directly across the output terminals, as shown in figure. During the conduction period it gets charged and stores up energy in the electrostatic field and discharges through the load resistance R_L delivering energy to it during non-conduction period. Through this process, the time duration during which current flows through the load resistance gets prolonged and AC components or ripples get considerably reduced. It is to be noted here that the capacitor C gets charged to the peak value of input voltage quickly because charging time constant is almost zero. It is so because there is no resistance (except the negligible forward resistance of diode) in the charging path. But the discharging time is quite large (roughly 100 times more than the charging time) depending upon the value of R_L because it discharges through load resistance R_L.

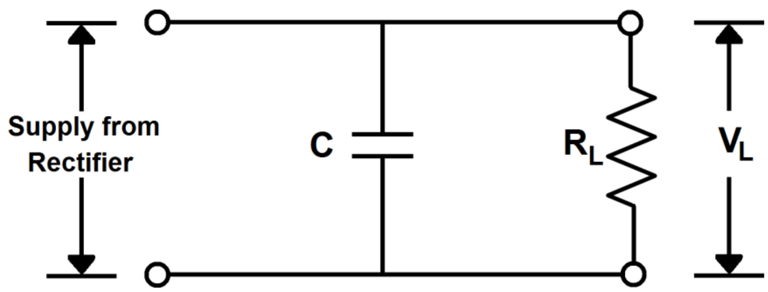


Figure: Circuit Diagram of Shunt Capacitor Filter

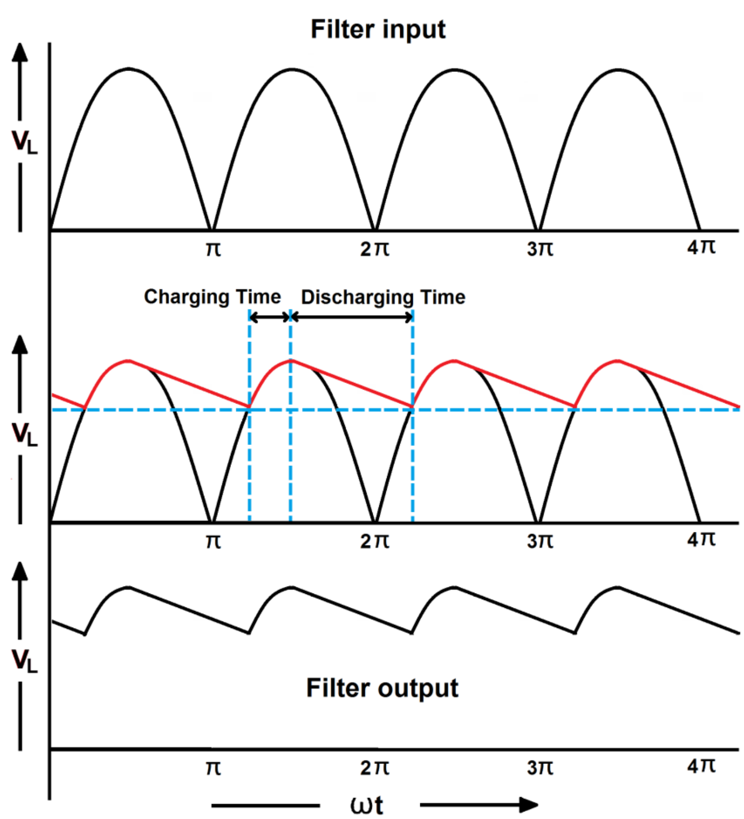


Figure: I/O Waveforms of Shunt Capacitor Filter

The function of the capacitor filter may be viewed in terms of impedances.

$$X_L = \frac{1}{2\pi f C}$$

if f=0 (DC)

$$X_L = \infty$$

if f=∞

$$X_L = 0$$

The large value capacitor C offers a low impedance shunt path to the ac components or ripples but offers high impedance to the de component. Thus ripples get bypassed through capacitor C and only de component flows through the load resistance R_L.

Capacitor filter is very popular because of its low cost, small size, light weight and good characteristics. It is quite useful for load up to 50 mA as in transistor radio, battery eliminators.

L Section (LC) Filter

Choke filter came into existence due to shortcomings of the series inductor and shunt capacitor filter. A series inductor filter filters the output current but reduces the output current (RMS value and Peak value) up to a large extent. And the shunt capacitor filter performs filtering efficiently but increases the diode current. The excess of current in a diode may lead to its destruction.

Thus, for better performance, we need a filter circuit in which ripple factor is low and do not vary with the variation in load resistance. This can be achieved by using the combination of series inductor filter and shunt capacitor filter. The voltage stabilization property of shunt capacitor filter and current smoothing property of series inductor filter is utilized for the formation of choke filter or L-section filter.

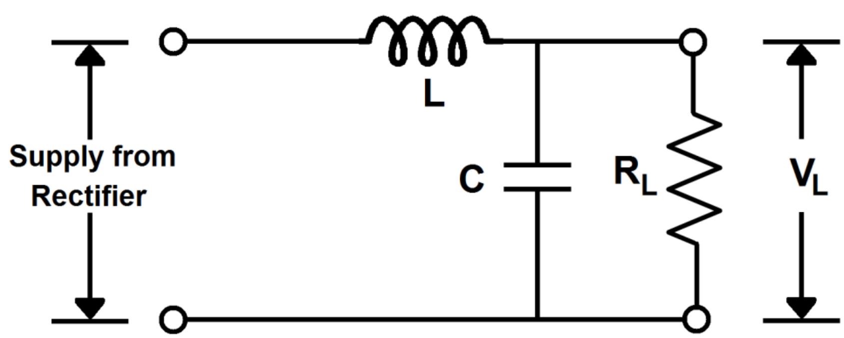


Figure: Circuit Diagram of L Section Filter

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

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

If the inductor of high inductive reactance (X_L), greater than the capacitive reactance at ripple frequency is used than filtering efficiency gets improved.

The waveform of DC output signal with a filter and without filter is shown in the below diagram.

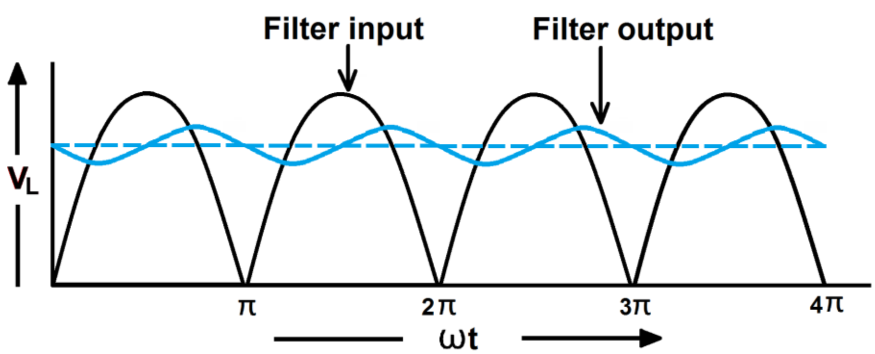


Figure: I/O Waveforms of L Section Filter

Advantages of Choke Filter or L-section Filter

1. It provides better voltage regulation.
2. The ripple factor can be varied according to the need.

Disadvantages of Choke Filter or L-Section filter

1. **Bulky Size:** These kinds of filters were popular in ancient time but it has become obsolete now due to bulky size of inductors and capacitors.
2. **Not suitable for low voltage power Supplies:** These are not suitable for low voltage power supplies. IC regulators or active filters are used in such devices.

Capacitor input π Filter

Pi filter *consists of a* ***shunt capacitor*** *at the input side, and it is followed by an* ***L-section filter****. The output from the rectifier is directly given across capacitor. The pulsating DC output voltage is filtered first by the capacitor connected at the input side and then by choke coil and then by another shunt capacitor. The construction arrangement of all the components resembles the shape of Greek letter Pi (π) as shown in figure. Thus it is called* ***Pi filter****. Besides, the capacitor is present at the input side. Thus, it is also called* ***capacitor input filter****.*

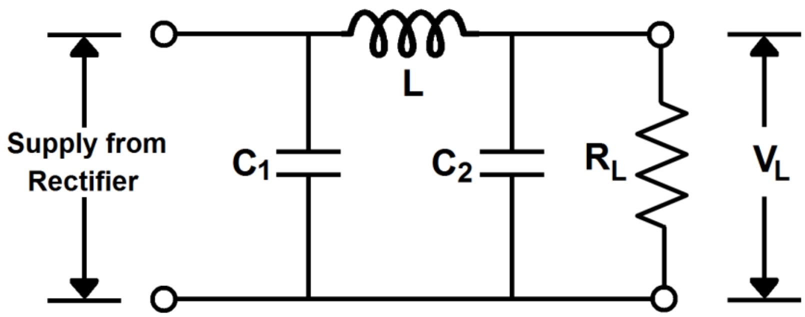


Figure: Circuit Diagram of π Filter

The output voltage coming from rectifier also consists of AC components. Thus it is a crucial need to remove these AC ripples to improve the performance of the device. The output from the rectifier is directly applied to the input capacitor. The capacitor provides low impedance to AC ripples present in the output voltage and high resistance to DC voltage. Therefore, most of the AC ripples get bypassed through the capacitor in input stage only.

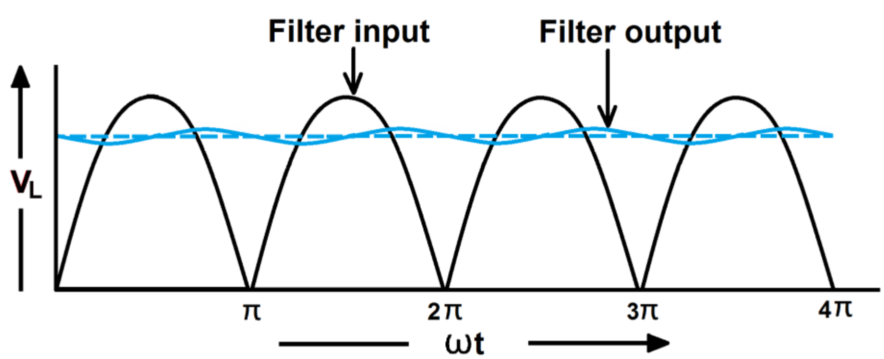


Figure: I/O Waveforms of π Filter

The residual AC components which are still present in filtered DC signal gets filtered when they pass through the inductor coil and through the capacitor connected parallel across the load. In this way, the efficiency of filtering increases multiple times. In pi-filters, the major filtering action is accomplished by the capacitor at input C_1. The residual AC ripples are filtered by inductor coil L and capacitor C_2.

Voltage Regulator

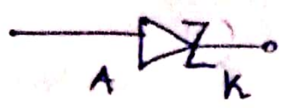
* Till now we have seen that o/p of rectifier circuit is pulsating DC which passes through filters and filters gives you unregulated DC supply. To Regulate this DC supply, we have to use voltage regulators.

* A Regulator circuit is a circuit which is used after the filter which makes DC voltage smooth and ripple free and also keeps output voltage constant though the i/p voltage is changing under certain conditions. It also keeps the o/p voltage constant if the load condition is varying.

Zener diode

Zener diode is a type of pn Junction diode which works in reverse biased condition. It was invented by a physicist Carl Zener in 1934. The breakdown voltage of zener diode ranges from 3V – 200V.

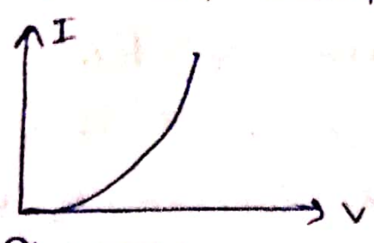
Symbol:-



voltage across Z.D ≥ V_Z

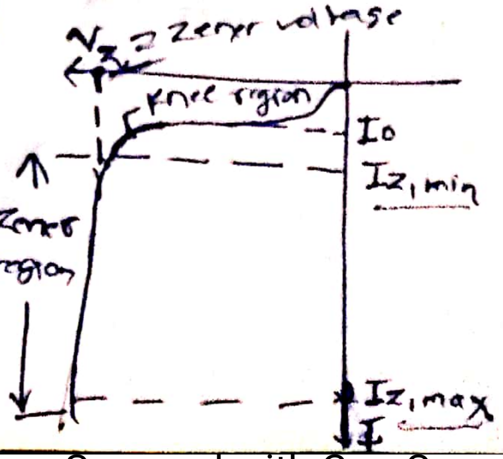
I-V characteristics

Forward biased



It works as a normal diode in forward biased condition.

Reversed biased



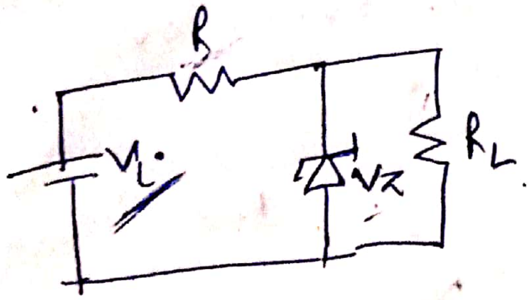
Initially when reverse voltage is applied across Zener diode, ~~to~~ a very small current starts flowing. This current is known as reverse saturation current and is denoted by I_0.

As the voltage is increased, the current starts increasing. A knee is observed in Zener diode characteristics and is denoted as Zener knee.

After that the current increases rapildly and breakdown is said to be occured. The reverse voltage at which breakdown occurs is known as Zener breakdown voltage and it is represented by V_Z.

After breakdown, the voltage drop across Zener diode remains constant ~~and~~ eventhough the applied reverse bias increases.

Zener diode also have a minimum and maximum current rating ($I_{Z,min}$ and $I_{Z,max}$) which gives it a power range.

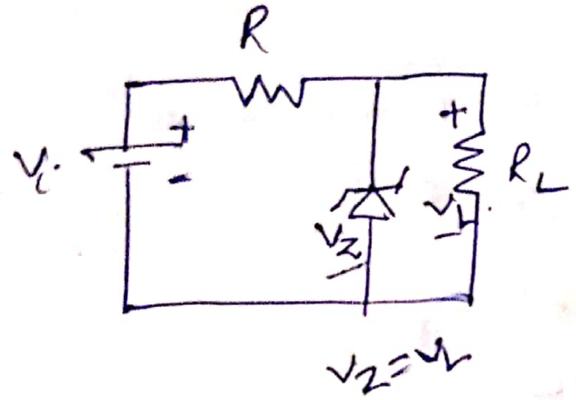


Conditions

i) V_i and R_L is fixed
ii) V_i fixed and R_L is variable
iii) V_i is variable and R_L fixed
iv) V_i and R_L both are variable.

Condition-1

V_i & R_L is fixed(Input voltage and load resistance are fixed).



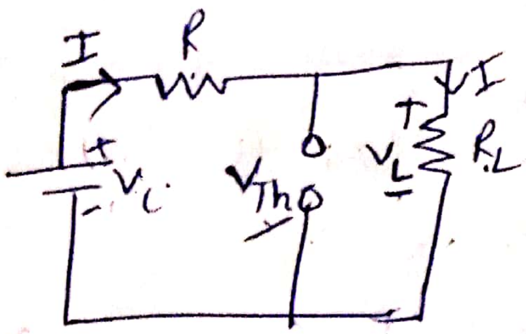
$R \rightarrow$ current limiting Resistor
$V_i \rightarrow$ Input voltage
$R_L \rightarrow$ Load resistance
$V_Z \rightarrow$ Zener voltage
$P_{ZM} \rightarrow$ Maximum power across Zener diode.

First we have to determine the state of Zener diode that whether it is ON or OFF.

To be ON, voltage across Zener diode $\geq V_Z$.

* we will use Thevenin's theorem to obtain the voltage across the diode.

we have to remove the Zener diode and find out voltage across the diode which will be represented by V_{th}.



Using KVL

$$V_i - IR - I \cdot R_L = 0.$$

$$V_i = I(R + R_L)$$

$$I = \frac{V_i}{R + R_L}$$

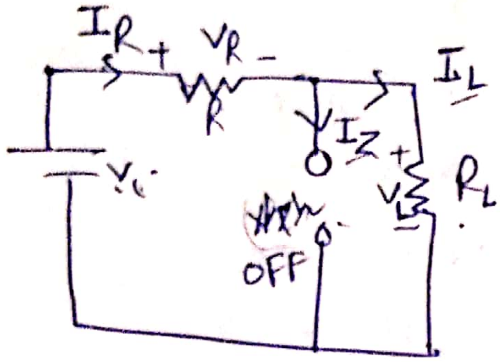
$$V_{Th} = V_L = I \cdot R_L = \frac{V_i}{R + R_L} \cdot R_L$$

* Now we have to compare V_{th} with V_Z.

Case-I if $V_{Th} \geq V_Z$ — Zener diode will be ON

Case-II $V_{Th} < V_Z$ — OFF

Case-II $V_{Th} < V_Z$



$I_Z = 0$ since Z.D is off

$P_Z = I_Z \cdot V_Z = 0$

$I_R = I_L + I_Z$

$I_R = I_L$

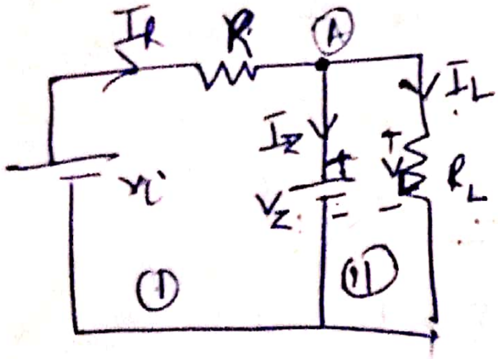
$I_R = \frac{V_i}{R+R_L} = I_L$

$V_R = I_R \cdot R$

$V_L = I_L \cdot R_L$

Case-I $V_{Th} \geq V_Z$

We have to replace zener diode with a voltage source.



$I_R = I_L + I_Z$

$I_Z = I_R - I_L$

Using KVL in loop (I)

$V_i - I_R \cdot R - V_Z = 0$

$$\boxed{I_R = \frac{V_i - V_Z}{R}}$$

Using KVL in loop (II)

$V_Z - I_L \cdot R_L = 0$

$$\boxed{I_L = \frac{V_Z}{R_L}}$$

$I_Z = I_R - I_L$

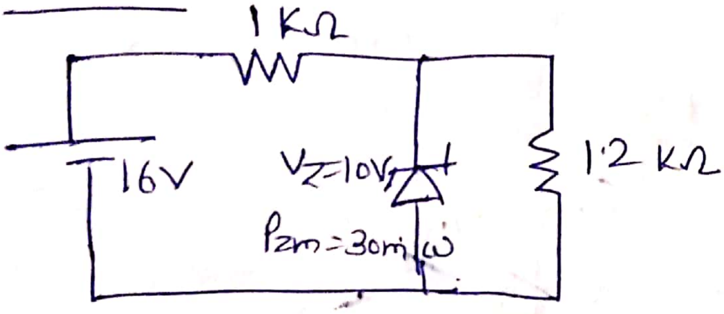
$= \left(\frac{V_i - V_Z}{R}\right) - \frac{V_Z}{R_L}$

$P_Z = I_Z \cdot V_Z$

$$\boxed{P_Z = \left\{ \left(\frac{V_i - V_Z}{R} \right) - \frac{V_Z}{R_L} \right\} \cdot V_Z}$$

$$\boxed{P_Z < P_{Zm}}$$

question



find V_L, V_R, I_Z and P_Z

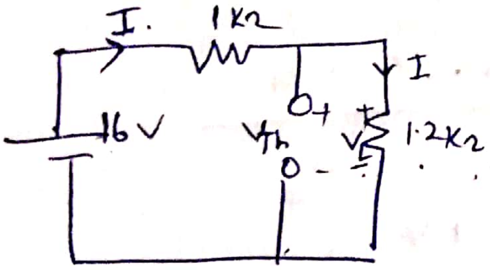
given

$V_i = 16V$, $R = 1K\Omega$, $R_L = 1.2K\Omega$, $V_Z = 10V$, $P_{Zm} = 30mW$

Solution

Find out whether zener diode is ON or OFF.

use thevenin's to find V_{Th} and compare it with V_Z.



$16 - I \times 1K\Omega - 1.2 \times I = 0$

$I = \frac{16}{2.2K\Omega} = 7.27 mA$

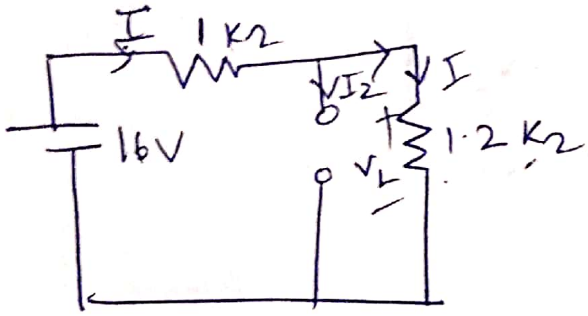
$V_{Th} = V_L = I \cdot R_L$

$= 7.27 \times 1.2 = \underline{8.72 V}$

Now $\underbrace{V_{Th} = 8.72 < V_Z (10V)}_{\text{diode is off}}$

$V_{Th} \geq V_Z$ for Zener diode to be ON.

This is case-2 $V_{th} < V_Z$ (diode off)



$I_Z = 0$, $P_Z = 0$

$I = \frac{16}{1+1.2} = 7.27\ mA$

$V_L = I \times 1.2$

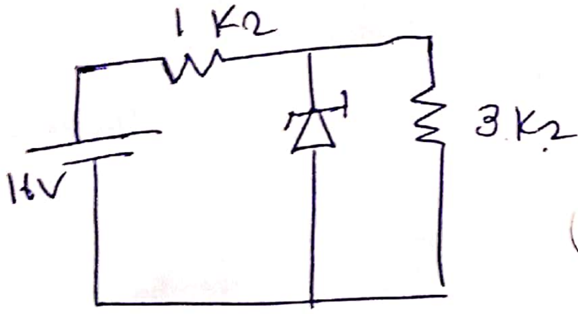
$= 7.27 \times 1.2$

$= 8.64\ V$

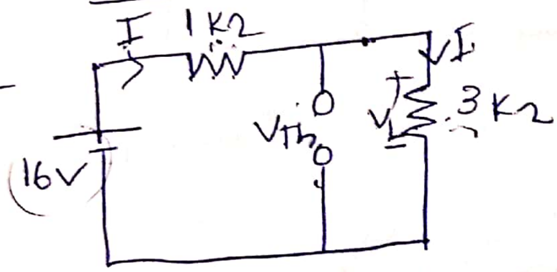
$V_R = I \cdot 1K\Omega$

$= 7.27 \times 1 = 7.27\ V$

what if $R_L = 3\ K\Omega$



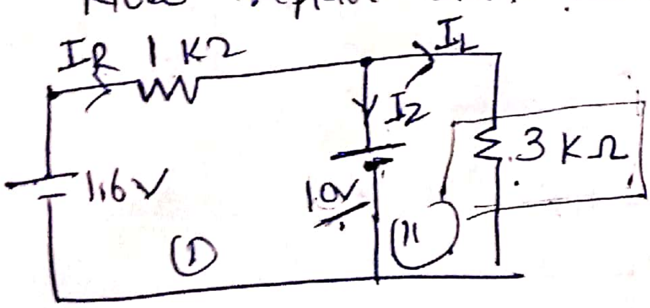
find V_{Th}



$I = \frac{16V}{4K\Omega} = 4mA$, $V_L = I \times 3 = 4 \times 3 = 12\ V$

$V_{Th} = V_L = 12V > V_Z(10V)$, Zener diode is ON.

Now replace zener diode with voltage source



use KVL in loop-1.

$16 - I_R \cdot 1 - 10 = 0$

$I_R = 6\ mA$.

use KVL in loop (II)

$10 - 3 \times I_L = 0$

$I_L = 10/3 = 3.33\ mA$

$I_Z = I_R - I_L$

$= 6 - 3.3 = 2.7\ mA$.

$\boxed{P_Z = I_Z \cdot V_Z = 2.7 \times 10V = 27\ mW}$

$V_R = I_R \cdot R$

$= 6 \times 1 = 6V$

$V_L = I_L \cdot R_L = 3.33 \times 3$

$= 10V$

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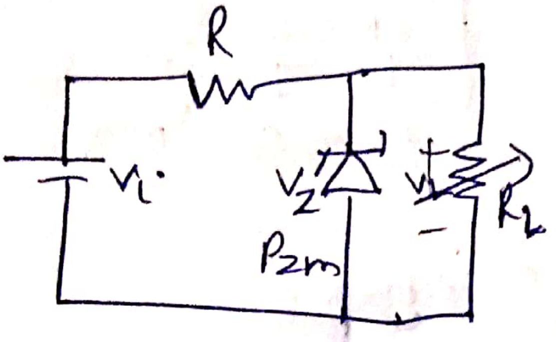
Condition – II

V_i is fixed and R_L is variable $\boxed{V_L \neq V_Z}$



If R_L is too small, since $V_L = V_Z$, and $V_L = I_L \cdot R_L$,
V_L will be smaller than V_Z and Zener diode will be off. So we have to find minimum value of R_L (R_{Lmin}) for which Zener diode will be ON. Similarly we have to find out R_{Lmax} for which diode will be turned ON.

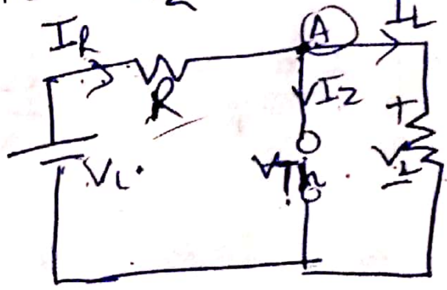
Condition for minimum Load resistance (R_{Lmin}).

$V_{th} \geq V_Z \mid V_{th} = V_Z$

Voltage across Zener diode $= V_Z$

$$V_{Th} = V_i \cdot \frac{R_{Lmin}}{R + R_{Lmin}}$$

$$= V_Z = V_L$$



$V = IR$

$I_{max} = V / R_{Lmin}$

$I = I_R = I_L$

$$I = \frac{V_i}{R + R_{Lmin}}$$

$$V_Z = \frac{V_i \cdot R_{Lmin}}{R + R_{Lmin}}$$

$$V_Z (R + R_{Lmin}) = V_i \cdot R_{Lmin}$$

$$\boxed{R_{Lmin} = \frac{V_Z \cdot R}{V_i - V_Z}}$$

$$\boxed{I_{Lmax} = \frac{V_L}{R_{Lmin}} = \frac{V_Z}{R_{Lmin}}}$$

→ Apply KCL at node A.

$$I_R = I_Z + I_L$$

$$\text{freq} \qquad \text{Imax}$$

$$I_R = I_{Zmin} + I_{Lmax}$$

$$I_{Zmin} = I_R - I_{Lmax}$$

$$= \frac{(V_i - V_Z)}{R} - \frac{V_Z}{R_{Lmin}}$$

Maximum load resistance (R_{Lmax}) :-

$R_{Lmax} \rightarrow I_{Lmin} \rightarrow I_{Zmax}$

$$I_R = I_Z + I_L$$
fixed max min

$P_{Zm} = I_{Zmax} \cdot V_Z$

$I_{Zmax} = \boxed{\frac{P_{Zm}}{V_Z}} \rightarrow$ provided by manufacturer

again

$I_R = I_Z + I_L$

$I_R = I_{Zmax} + I_{Lmin}$

$I_{Lmin} = I_R - I_{Zmax}$

$= \frac{(V_i - V_Z)}{R} - \frac{P_{Zm}}{V_Z}$

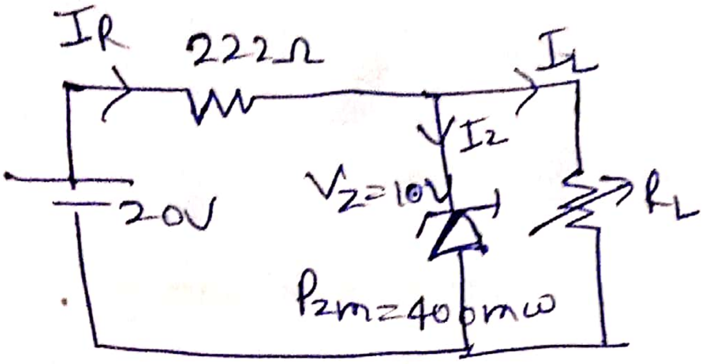
$V_L = I_{Lmin} \cdot R_{Lmax}$

Now

$$\boxed{R_{Lmax} = \frac{V_L}{I_{Lmin}} = \frac{V_Z}{\left(\frac{V_i - V_Z}{R}\right) - \frac{P_{Zm}}{V_Z}}}$$

questions

Determine the maximum and minimum value of R_L



given, $V_i = 20V$, $R = 222\,\Omega$, $V_z = 10\,V$, $P_{zm} = 400\,mW$

$R_{L\,min} = ?$ $\quad R_{L\,max} = ?$

Case – I (To find R_L min)

$$R_{L\,min} = \frac{V_Z \cdot R}{V_i - V_Z} = \frac{10 \cdot (222)}{(20-10)} = \underline{222\,\Omega}$$

$$\boxed{R_{L\,min} = 222\,\Omega}$$

$$I_{L\,max} = \frac{V_Z}{R_{L\,min}} = \frac{10}{222} = 45\,mA$$

Case – II (R_L max)

$P_{zm} = 400\,mW$

$= I_{zm} \cdot V_z$

$= I_{zm} \cdot 10$

$I_{zm} = 40\,mA$

$I_R = I_Z + I_L$

fixed max min

$I_{L\,min} = I_R - I_{Z\,max}$

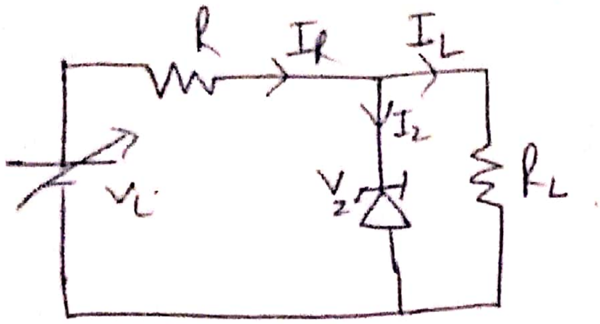
$$I_R = \frac{V_i - V_Z}{R} = \frac{20-10}{222} = 45\,mA$$

$I_{L\,min} = 45 - 40 = 5\,mA$ | $V_L = I_{L\,min} \times R_{L\,max}$

$$R_{L\,max} = \frac{V_Z}{I_{L\,max}} = \frac{10}{5\,mA} = \underline{2\,k\Omega}$$

Condition 3

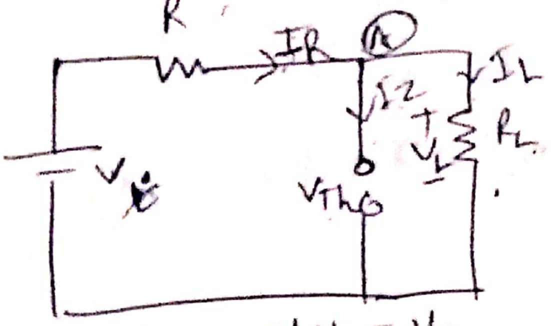
when V_i is variable and R_L is fixed.



Condition for minimum V_i

if $V_{Th} \geq V_Z$, Z.D will be turned on

$V_{Th} = V_Z$



$V_{th} = V_Z$

$$I = \frac{V_i}{R+R_L}$$

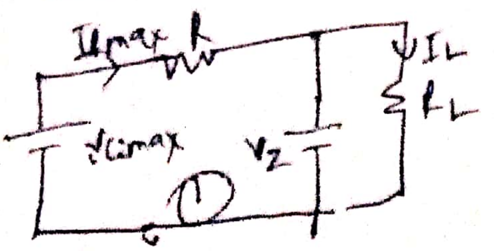
$$V_{Th} = V_L = I \cdot R_L$$

$$= \frac{V_i \cdot R_L}{R+R_L}$$

$$\frac{V_i \cdot R_L}{R+R_L} = V_Z$$

$$V_{i\,min} \cdot R_L = V_Z(R+R_L)$$

$$\boxed{V_{i\,min} = \frac{V_Z(R+R_L)}{R_L}}$$



Condition for $V_{i\,max}$

$V_{i\,max}$ is limited by $I_{Z\,max}$

$I_R = I_Z + I_L$,

$I_R = I_{Z\,max} + I_L$

$I_R \to max$, $I_L \to$ fixed $\left(\frac{V_L}{R_L}\right)$

$I_{R\,max} = I_{Z\,max} + I_L$

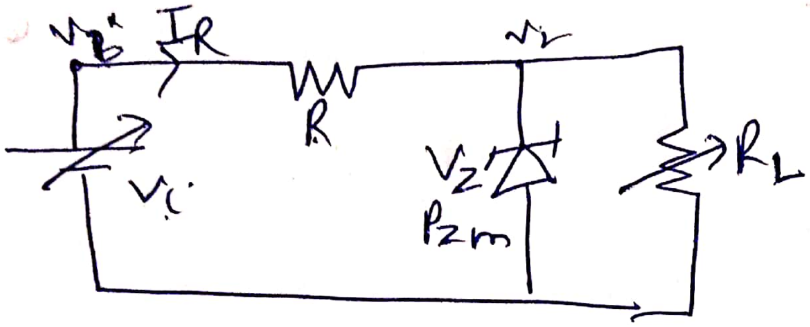
using KVL

$V_{i\,max} - V_{R\,max} - V_Z = 0$

$V_{i\,max} = V_Z + V_{R\,max}$

$$\boxed{V_{i\,max} = V_Z + I_{R\,max} \cdot R}$$

Condition-4 Both V_i and R_L is varying.



Dynamic Range of R, it will vary between R_{min} and R_{max}.

$R_{min} \rightarrow I_{R max}$

$$R_{min} = \frac{V_{i max} - V_Z}{I_{R max}}$$

$$R_{max} = \frac{V_{i min} - V_Z}{I_{R min}}$$

$I_R \geq I_Z + I_L$

$$\frac{V_i - V_Z}{R} \geq I_Z + I_L$$