SHIVAJI UNIVERSITY, KOLHAPUR
B.Sc. (Part III) Semester -V
Electronics (Paper-XII)
Power Electronic Devices and Applications

Unit 3:- Uncontrolled and Controlled rectifiers (12 Marks)

Uncontrolled rectifiers

Introduction:-

The ac to dc converters using diodes are termed as rectifiers. As the instant at which a diode can be turned on cannot be controlled, these rectifiers are uncontrolled rectifiers. The output voltage of an uncontrolled rectifier is always fixed and positive. The load current is also always positive. The flow of power will always be from the source to load. i.e. these converters are unidirectional in nature.

The three phase uncontrolled rectifiers are classified into two categories.

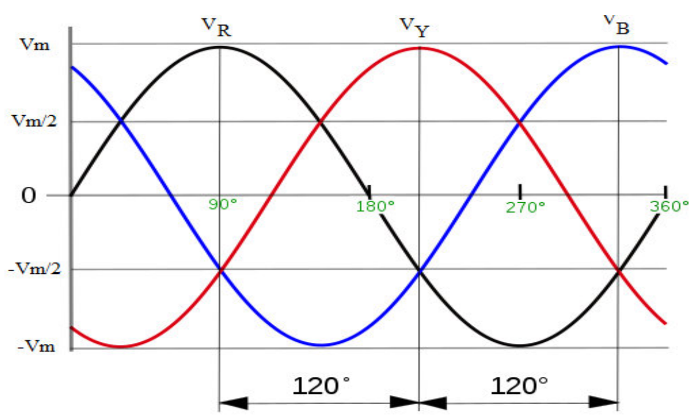
1. Half wave uncontrolled rectifier
2. Full wave uncontrolled rectifier
3. Bridge uncontrolled rectifier

Basic of Three phase supply:-

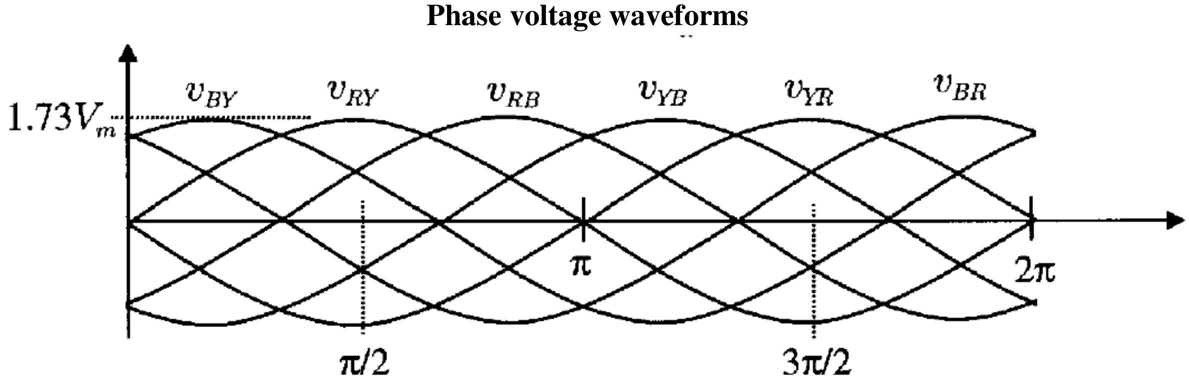
Certain basic concepts of three phase supply are as follows:

1. In a 4 wire three phase ac system, there are 3 phases namely R, Y, B and 4^{th} wire being the neutral N.
2. Phase voltage: - the voltage measured between a phase (R, Y, and B) and neutral (N) point is called as phase voltage. Then there are three phase voltages: V_{RN}, V_{YN} and $V_{BN.}$
3. Line voltage: - The voltage measured between any two phases is called as line voltage. Then there are six line voltages as follows: V_{RY}, V_{YB}, V_{BR}, V_{YR}, V_{BY}, and V_{RB}.
4. The phase voltages V_{RN}, V_{YN} and V_{BN} are phase shifted from each other by 120^{o}.
5. The line voltages are phase shifted from each other by 60^{o}.
6. If maximum peak voltage is V_m the maximum line voltage is $\sqrt{3}V_m$.
7. The frequency of each phase voltage and each line voltage is 50Hz.

Phase and line voltage waveforms:-



Phase voltage waveforms

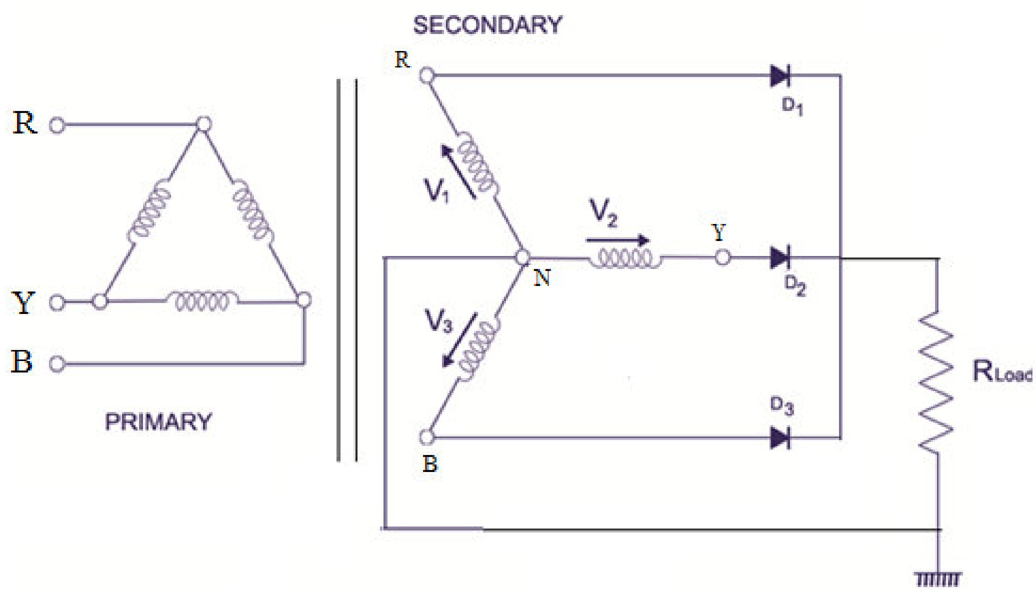


Line voltage waveforms

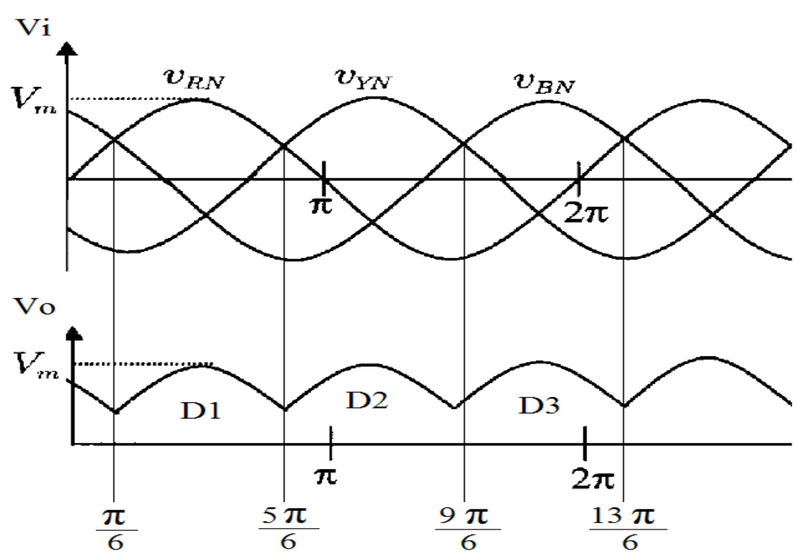
Three Phase Half Wave Rectifier:-

A three phase half wave rectifier, as the name implies, consists of a three phase transformer. Given below is a star connected secondary three phase transformer with three diodes connected to the three phases. As shown in the figure, the neutral point 'N' of the secondary is considered as the earth for the circuit and is given as the negative terminal for the load.

Circuit Diagram:-



Waveforms:-



Working: -

The operation of the rectifier is divided into three parts as follows:

1. $\frac{\pi}{6} < \omega t < \frac{5\pi}{6}$ **:-**

During this period V_{RN} is greater than other two voltages. Therefore diode D1 is forward biased and diode D2, D3 are reverse biased. So the load is connected to V_{RN} through diode D1 and output voltage equals to V_{RN}.

2. $\frac{5\pi}{6} < \omega t < \frac{9\pi}{6}$:-

During this period V_{YN} is greater than other two voltages. Therefore diode D2 is forward biased and diode D1, D3 are reverse biased. So the load is connected to V_{YN} through diode D1 and output voltage equals to V_{YN}.

3. $\frac{9\pi}{6} < \omega t < \frac{13\pi}{6}$:-

During this period V_{BN} is greater than other two voltages. Therefore diode D3 is forward biased and diode D1, D2 are reverse biased. So the load is connected to V_{BN} through diode D3 and output voltage equals to V_{BN}.

Analysis:-

1. Average DC voltage (V_{dc}):-

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} V_s \, dt$$

$$V_{dc} = \frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} V_m \sin \omega t \, dt$$

$$V_{dc} = \frac{3\,V_m}{2\pi}\,[-\cos \omega t]_{\pi/6}^{5\pi/6}$$

$$V_{dc} = -\frac{3\,V_m}{2\pi}\left[\cos\frac{5\pi}{6} - \cos\frac{\pi}{6}\right]$$

$$V_{dc} = -\frac{3\,V_m}{2\pi}\,[-0.866 - 0.866]$$

$$V_{dc} = -\frac{3\,V_m}{2\pi}\,[-1.732]$$

$$V_{dc} = \frac{3\,V_m}{2\pi}\,[1.732]$$

$$V_{dc} = \frac{5.196\,V_m}{2(3.14)}$$

$$V_{dc} = \frac{2.598\,V_m}{6.28}$$

$$V_{dc} = 0.8273\,V_m$$

2. RMS load voltage (V_{rms}):-

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_s^2 dt}$$

$$V_{rms} = \sqrt{\frac{3}{2\pi}\int_{\pi/6}^{5\pi/6} V_m^2 \sin^2 \omega t \, dt}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{2\pi}\int_{\pi/6}^{5\pi/6} \sin^2 \omega t \, dt}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{2\pi}\int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} \frac{1-\cos\,2\omega t}{2} dt}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{4\pi}\int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} (1-\cos 2\omega t)\, dt}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{4\pi}\left(\int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} 1\, dt - \int_{\frac{\pi}{6}}^{\frac{5\pi}{6}} \cos 2\omega t\, dt\right)}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{4\pi}\left([\,t\,]_{\pi/6}^{5\pi/6} - \left[\frac{\sin 2\omega t}{2}\right]_{\pi/6}^{5\pi/6}\right)}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{4\pi}\left(\left[\frac{5\pi}{6} - \frac{\pi}{6}\right] - \frac{1}{2}\left[\sin\frac{10\pi}{6} - \sin\frac{2\pi}{6}\right]\right)}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{4\,\pi}\left(\left[\frac{4\pi}{6}\right] - \frac{1}{2}\,[(-0.866) - (0.866)]\right)}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{4\,(3.14)}\left(\left[\frac{4(3.14)}{6}\right] + 0.866\right)}$$

$$V_{rms} = \sqrt{0.2388\,V_m^2\;(2.0933 + 0.866)}$$

$$V_{rms} = \sqrt{0.2388\,V_m^2\;(2.9593)}$$

$$V_{rms} = \sqrt{0.7067\,V_m^2}$$

$$V_{rms} = 0.8406\,V_m$$

3. Average DC current (I_{dc}):-

$$I_{dc} = \frac{V_{dc}}{R} = \frac{0.8273\ V_m}{R}$$

4. RMS load current (I_{rms}):-

$$I_{rms} = \frac{V_{rms}}{R} = \frac{0.8406\ V_m}{R}$$

5. Rectifier efficiency (η):-

DC load power $P_{dc} = V_{dc} \times I_{dc} = 0.8273\ Vm \times \frac{0.8273\ Vm}{R} = 0.6844\ V_m^2$

AC load power $Pac = V_{rms} \times I_{rms} = 0.8406\ Vm \times \frac{0.8406\ Vm}{R} = 0.7066\ V_m^2$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{0.6844\ V_m^2}{0.7066\ V_m^2} = 0.9685$$

$\eta\ \% = 0.9685 \times 100\ \% = 96.85\ \%$

6. Form factor :-

$$F.F. = \frac{V_{rms}}{V_{dc}} = \frac{0.8406\ V_m}{0.8273\ V_m} = 1.016$$

7. Ripple factor (R_f) :-

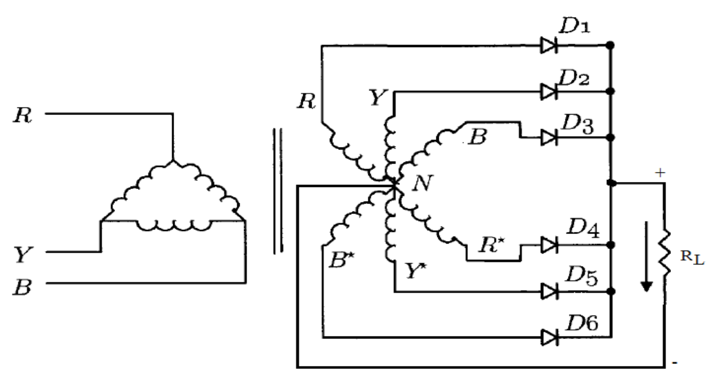
$$R_f = \sqrt{F.F.^2 - 1} = \sqrt{1.016^2 - 1} = \sqrt{1.0322 - 1} = \sqrt{0.0322} = 0.1794$$

$R_f\ \% = 0.1794 \times 100\ \% = 17.94\ \%$

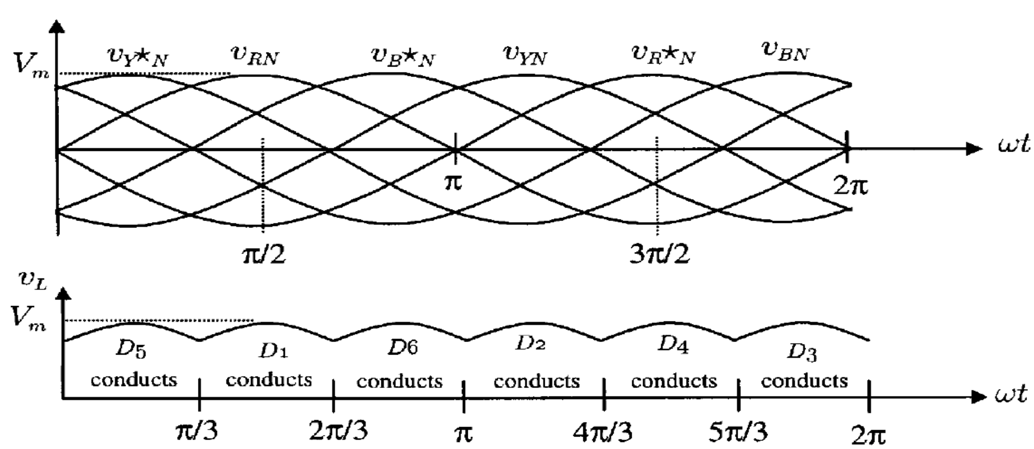
Three Phase Full Wave Rectifier:-

A basic full wave rectifier circuit is shown in Figure below. The six-phase voltages on the secondary are obtained by means of a center-tapped arrangement on a star-connected three-phase winding. Therefore, it is sometimes referred to as a six phase star rectifier.

Circuit diagram:-



Waveform:-



Working:-

The diode in a particular phase conducts during the period when the voltage on that phase is higher than that on the other phases. The voltage waveforms of each phase and the load are shown in Figure above. The conduction angle of each diode is π/3. Currents flow in only one diode at a time.

Analysis:-

1. Average DC voltage (V_{dc}):-

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} V_s \; dt$$

$$V_{dc} = \frac{6}{2\pi}\int_{\pi/3}^{2\pi/3} V_m \sin\omega t \, dt$$

$$V_{dc} = \frac{6\,V_m}{2\pi}\left[-\cos\omega t\right]_{\pi/3}^{2\pi/3}$$

$$V_{dc} = -\frac{3\,V_m}{\pi}\left[\cos\frac{2\pi}{3} - \cos\frac{\pi}{3}\right]$$

$$V_{dc} = -\frac{3\,V_m}{\pi}\left[-0.5 - 0.5\right]$$

$$V_{dc} = -\frac{3\,V_m}{\pi}\left[-1\right]$$

$$V_{dc} = \frac{3\,V_m}{3.14}\left[1\right]$$

$$V_{dc} = 0.9554\,V_m$$

2. RMS load voltage (V_{rms}):-

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_s^2 \, dt}$$

$$V_{rms} = \sqrt{\frac{6}{2\pi}\int_{\pi/3}^{2\pi/3} V_m^2 \sin^2\omega t \, dt}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{\pi}\int_{\pi/3}^{2\pi/3} \sin^2\omega t \, dt}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \frac{1-\cos 2\omega t}{2} dt}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{2\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} (1-\cos 2\omega t)\; dt}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{2\pi}\left(\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} 1\,dt - \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \cos 2\omega t\, dt\right)}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{2\pi}\left(\left[\;t\;\right]_{\pi/3}^{2\pi/3} - \left[\frac{\sin 2\omega t}{2}\right]_{\pi/3}^{2\pi/3}\right)}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{2\pi}\left(\left[\frac{2\pi}{3} - \frac{\pi}{3}\right] - \frac{1}{2}\left[\;\sin\frac{4\pi}{3} - \;\sin\frac{2\pi}{3}\right]\right)}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{2\,\pi}\left(\left[\frac{\pi}{3}\right] - \frac{1}{2}\left[(-0.866) - \;(0.866)\right]\right)}$$

$$V_{rms} = \sqrt{\frac{3\,V_m^2}{2\,(3.14)}\left(\left[\frac{3.14}{3}\right] + 0.866\right)}$$

$$V_{rms} = \sqrt{0.4777\,V_m^2\;\;(\;1.0466 + 0.866\;)}$$

$$V_{rms} = \sqrt{0.4777\,V_m^2\;\;(\;1.9126)}$$

$$V_{rms} = \sqrt{0.9136\,V_m^2}$$

$$V_{rms} = 0.9558\,V_m$$

3. Average DC current (I_{dc}):-

$$I_{dc} = \frac{V_{dc}}{R} = \frac{0.9554\,V_m}{R}$$

4. RMS load current (I_{rms}):-

$$I_{rms} = \frac{V_{rms}}{R} = \frac{0.9558\,V_m}{R}$$

8. Rectifier efficiency (η):-

DC load power $P_{dc} = V_{dc} \times I_{dc} = 0.9554\ V_m \times \frac{0.9554\ V_m}{R} = 0.9128\ V_m^2$

AC load power $P_{ac} = V_{rms} \times I_{rms} = 0.9558\ V_m \times \frac{0.9558\ V_m}{R} = 0.9135\ V_m^2$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{0.9128\ V_m^2}{0.9135\ V_m^2} = 0.9992$$

$\eta\ \% = 0.9992 \times 100\ \% = 99.92\ \%$

9. Form factor :-

$$F.F. = \frac{V_{rms}}{V_{dc}} = \frac{0.9558\ V_m}{0.9554\ V_m} = 1.0004$$

10. Ripple factor (R_f) :-

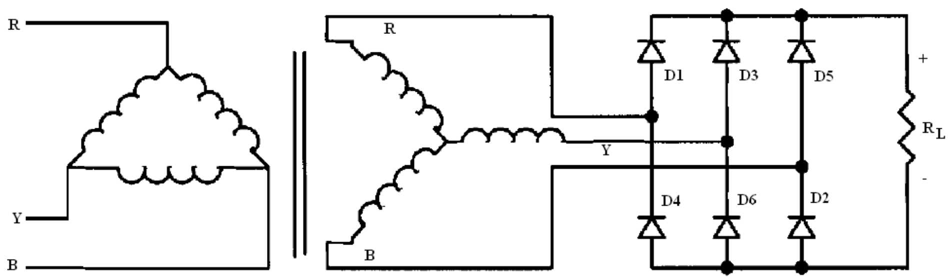
$$R_f = \sqrt{F.F.^2 - 1} = \sqrt{1.0004^2 - 1} = \sqrt{1.0008 - 1} = \sqrt{0.0008} = 0.0282$$

$R_f\ \% = 0.0282 \times 100\ \% = 2.82\ \%$

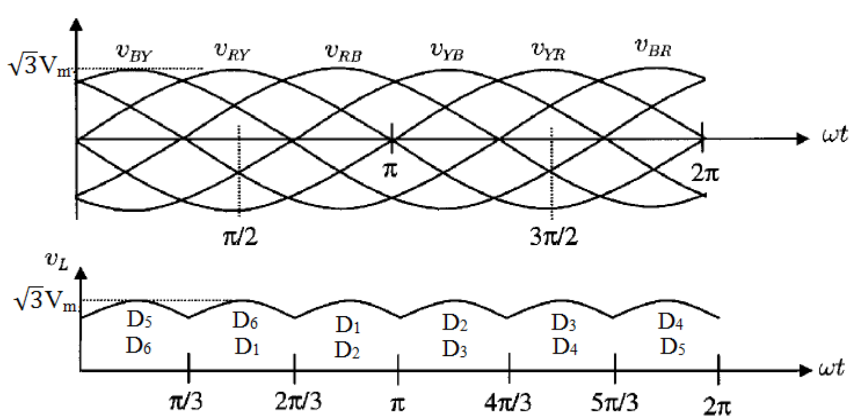
Three Phase Bridge Rectifier:-

Three-phase bridge rectifiers are commonly used for high power applications because they have the highest possible transformer utilization factor for a three-phase system. The circuit of a three-phase bridge rectifier is shown in Figure

Circuit diagram:-



Waveform:-



Working:-

The circuit arrangement is such that only two diodes conduct at a time and load is connected across phase line R & Y or Y & B or B & R. thus load voltage is equal to corresponding line voltage. The diodes are numbered in order of conduction sequence. The conduction sequence for diode is D_1D_2, D_2D_3, D_3D_4, D_4D_5, D_5D_6 and D_6D_1. The pair of diodes which are connected between these lines having highest amount of instantaneous line to line voltage will conduct.

The maximum line voltage is $\sqrt{3}V_m$.

Analysis:-

1. Average DC voltage (V_{dc}):-

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} V_s \, dt$$

$$V_{dc} = \frac{6}{2\pi}\int_{\pi/3}^{2\pi/3} \sqrt{3}V_m \sin\omega t \, dt$$

$$V_{dc} = \frac{6\sqrt{3}\,V_m}{2\pi}\,[-\cos\omega t]_{\pi/3}^{2\pi/3}$$

$$V_{dc} = -\frac{3\sqrt{3}\,V_m}{\pi}\left[\cos\frac{2\pi}{3} - \cos\frac{\pi}{3}\right]$$

$$V_{dc} = -\frac{3\sqrt{3}V_m}{\pi}\,[-0.5 - 0.5]$$

$$V_{dc} = -\frac{3\sqrt{3}V_m}{\pi}\,[-1]$$

$$V_{dc} = \frac{3\,(1.732)\,V_m}{3.14}\,[1]$$

$$V_{dc} = 1.6547\,V_m$$

2. RMS load voltage (V_{rms}):-

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_s^2 dt}$$

$$V_{rms} = \sqrt{\frac{6}{2\pi}\int_{\pi/3}^{2\pi/3} (\sqrt{3}V_m)^2 \sin^2\omega t \, dt}$$

$$V_{rms} = \sqrt{\frac{9\,V_m^2}{\pi}\int_{\pi/3}^{2\pi/3} \sin^2\omega t \, dt}$$

$$V_{rms} = \sqrt{\frac{9\,V_m^2}{\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \frac{1-\cos 2\omega t}{2} dt}$$

$$V_{rms} = \sqrt{\frac{9\,V_m^2}{2\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} (1-\cos 2\omega t)\, dt}$$

$$V_{rms} = \sqrt{\frac{9\,V_m^2}{2\pi}\left(\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} 1\, dt - \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} \cos 2\omega t \, dt\right)}$$

$$V_{rms} = \sqrt{\frac{9\,V_m^2}{2\pi}\left([\ t\ ]_{\pi/3}^{2\pi/3} - \left[\frac{\sin 2\omega t}{2}\right]_{\pi/3}^{2\pi/3}\right)}$$

$$V_{rms} = \sqrt{\frac{9\,V_m^2}{2\pi}\left(\left[\frac{2\pi}{3} - \frac{\pi}{3}\right] - \frac{1}{2}\left[\sin\frac{4\pi}{3} - \sin\frac{2\pi}{3}\right]\right)}$$

$$V_{rms} = \sqrt{\frac{9\,V_m^2}{2\,\pi}\left(\left[\frac{\pi}{3}\right] - \frac{1}{2}\,[(-0.866) - (0.866)]\right)}$$

$$V_{rms} = \sqrt{\frac{9\,V_m^2}{2\,(3.14)}\left(\left[\frac{3.14}{3}\right] + 0.866\right)}$$

$$V_{rms} = \sqrt{1.4331\,V_m^2\ (\ 1.0466 + 0.866\ )}$$

$$V_{rms} = \sqrt{1.4331\,V_m^2\ (\ 1.9126)}$$

$$V_{rms} = \sqrt{2.7409\,V_m^2}$$

$$V_{rms} = 1.6556\,V_m$$

3. Average DC current (I_{dc}):-

$$I_{dc} = \frac{V_{dc}}{R} = \frac{1.6547\,V_m}{R}$$

4. RMS load current (I_{rms}):-

$$I_{rms} = \frac{V_{rms}}{R} = \frac{1.6556\,V_m}{R}$$

5. Rectifier efficiency (η):-

DC load power $P_{dc} = V_{dc} \times I_{dc} = 1.6547\ Vm \ \times \frac{1.6547\ Vm}{R} = 1.6547\ V_m^2$

AC load power $Pac = V_{rms} \times I_{rms} = 1.6556\ Vm \ \times \frac{1.6556\ Vm}{R} = 1.6556\ V_m^2$

$$\eta = \frac{P_{dc}}{P_{ac}} = \frac{1.6547\ V_m^2}{1.6556\ V_m^2} = 0.9994$$

$\eta\ \% = 0.9994 \times 100\ \% = 99.94\ \%$

6. Form factor :-

$$F.F. = \frac{V_{rms}}{V_{dc}} = \frac{1.6556\ V_m}{1.6547\ V_m} = 1.0005$$

7. Ripple factor (R_f) :-

$$R_f = \sqrt{F.F.^2 - 1} = \sqrt{1.0005^2 - 1} = \sqrt{1.001 - 1} = \sqrt{0.001} = 0.0316$$

$R_f\ \% = 0.0316 \times 100\ \% = 3.61\ \%$

Comparison of HWR, FWR, and FWBR:-

Sr. No.	Points	HWR	FWR	FWDR
1	No. of Diodes	3	6	6
2	Average DC voltage	$0.8273\ V_m$	0.9554	$1.6547\ V_m$
3	RMS load voltage	$0.8406\ V_m$	$0.9558\ V_m$	$1.6556\ V_m$
4	Rectifier efficiency	96.85 %	99.92 %	99.94 %
5	Form factor	1.016	1.0004	1.0005
6	Ripple factor	17.92 %	2.82 %	3.61 %

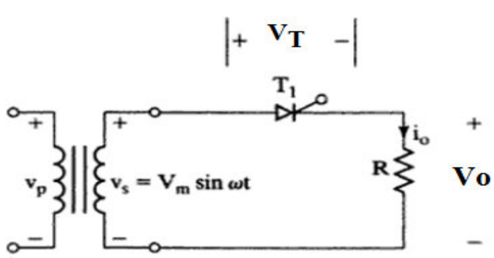
Controlled rectifiers

The rectifier circuit which converts AC into controlled DC is called as controlled rectifier. These rectifiers use SCR instead of diodes. The output voltage of thyristor rectifiers is varied by controlling the delay or firing angle of thyristors. A thyristor is turned on by applying a short pulse to its gate and turned off due to natural commutation.

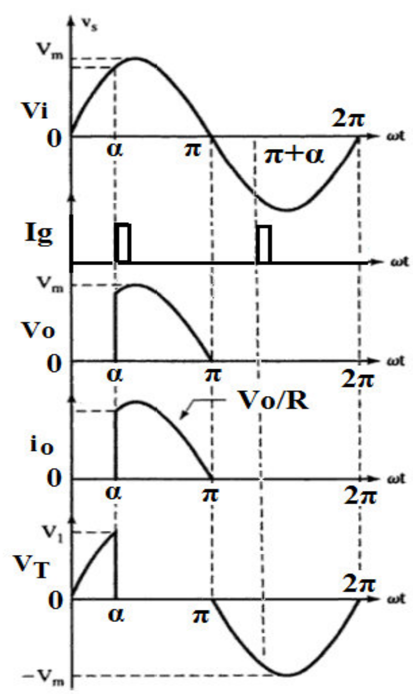
Concept of firing angle:-

The angle at which the rectifier device i.e. SCR is start to conduct is called as firing angle. OR
The angle at which the rectifier device i.e. SCR switches from OFF stat to ON state is called as firing angle.

Half convertor with resistive load (R) (Single phase half wave controlled rectifier):-



Circuit Digram



Waveform

The circuit diagram of half converter is as shown in figure above. It consists of thyristor connected in series with load R.

Working:-

The operation of half converter is divided into three parts.

1. **$0 < \omega t < \alpha$:-** During this period the anode of the thyristor is positive with respect to cathode. The thyristor is forward biased but it is not conducting any current. Therefore no current flows through the load and output becomes zero.

2. **$\alpha < \omega t < \pi$:-** At instant $\omega t = \alpha$, the firing pulse is applied to gate of thyristor. As thyristor is already forward biased, it will be turned ON. As the thyristor is turned on, current start to flows through it and also through load R. Thyristor act as closed switch, therefore load is directly connects to input. The output becomes equals to input voltage.

3. **$\pi < \omega t < 2\pi$:-** After $\omega t = \pi$, the input voltage becomes negative. So the thyristor anode becomes negative with respect to cathode. Therefore thyristor turns OFF. The current flowing through the thyristor becomes zero and also load current becomes zero. The output across load is zero.

Analysis:-

1. Average DC voltage (V_{dc}):-

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} V_s\ dt$$

$$V_{dc} = \frac{1}{2\pi}\left[\int_0^{\alpha} V_s\ dt + \int_{\alpha}^{\pi} V_s\ dt + \int_{\pi}^{2\pi} V_s\ dt\right]$$

$$V_{dc} = \frac{1}{2\pi}\left[0 + \int_{\alpha}^{\pi} V_s\ dt + 0\right]$$

$$V_{dc} = \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} V_s\ dt\right]$$

$$V_{dc} = \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} V_m\ \sin\omega t\, dt\right]$$

$$V_{dc} = \frac{V_m}{2\pi}[-\cos\omega t]_{\alpha}^{\pi}$$

$$V_{dc} = -\frac{V_m}{2\pi}(\cos\pi - \cos\alpha)$$

$$V_{dc} = -\frac{V_m}{2\pi}(-1 - \cos\alpha)$$

$$V_{dc} = \frac{V_m}{2\pi}(1 + \cos\alpha)$$

2. RMS load voltage (V_{rms}):-

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_s^2 dt}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\alpha} V_s^2 dt + \int_{\alpha}^{\pi} V_s^2 dt + \int_{\pi}^{2\pi} V_s^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\left[0 + \int_{\alpha}^{\pi} V_s^2 dt + 0\right]}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_{\alpha}^{\pi} V_s^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_{\alpha}^{\pi} V_m^2\ \sin^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\left[\int_{\alpha}^{\pi} \sin^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi} \frac{1 - \cos\ 2\omega t}{2} dt}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{4\pi}\int_{\alpha}^{\pi} (1 - \cos 2\omega t)\ dt}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{4\pi}\left(\int_{\alpha}^{\pi} 1\ dt - \int_{\alpha}^{\pi} \cos 2\omega t\, dt\right)}$$

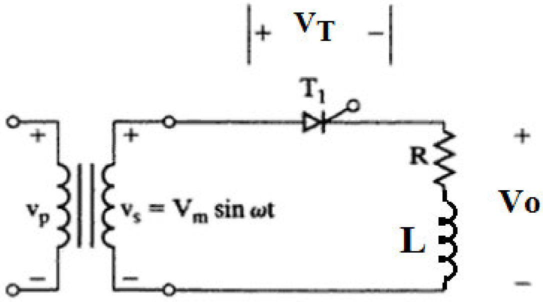
$$V_{rms} = \sqrt{\frac{V_m^2}{4\pi}\left([\ t\ ]_{\alpha}^{\pi} - \left[\frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}\right)}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{4\pi}\left([\pi - \alpha] - \frac{1}{2}[\ \sin 2\pi - \sin 2\alpha\ ]\right)}$$

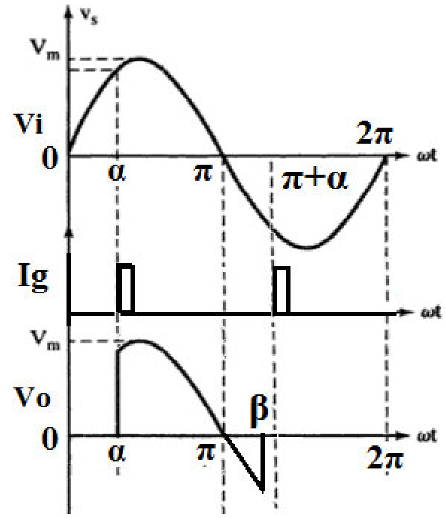
$$V_{rms} = \sqrt{\frac{V_m^2}{4\pi}\left([\pi - \alpha] - \frac{1}{2}[0 - \sin 2\alpha\ ]\right)}$$

$$V_{rms} = \frac{V_m}{2}\sqrt{\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)}$$

Half convertor with inductive load (R, L):-



Circuit Digram



Waveform

Working:-

The operation of half converter is divided into three parts.

1. **$0 < \omega t < \alpha$:-** During this period the anode of the thyristor is positive with respect to cathode. The thyristor is forward biased but it is not conducting any current. Therefore no current flows through the load and output becomes zero.

2. **$\alpha < \omega t < \beta$:-** At instant $\omega t = \alpha$, the firing pulse is applied to gate of thyristor. As thyristor is already forward biased, it will be turned ON. As the thyristor is turned on, current start to flows through it and also through load R & L. Thyristor act as closed switch, therefore load is directly connects to input. The output becomes equals to input voltage. After $\omega t = \pi$, the input voltage changes its polarity. As input current flowing through the thyristor start to decrease, the inductor start to discharge and maintain the current. Thyristor is not turned OFF because its anode current is not less than holding current even its anode is negative with respect to cathode. After some time at angle β, due to discharging of inductor current is reduced to zero and thyristor is turned OFF.

3. **$\beta < \omega t < 2\pi$:-** After $\omega t = \beta$, the input voltage becomes negative. So the thyristor anode becomes negative with respect to cathode. Therefore thyristor turns OFF. The current flowing through the thyristor becomes zero and also load current becomes zero. The output across load is zero.

Analysis:-

1. Average DC voltage (V_{dc}):-

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} V_s\, dt$$

$$V_{dc} = \frac{1}{2\pi}\left[\int_0^{\alpha} V_s\, dt + \int_{\alpha}^{\beta} V_s\, dt + \int_{\beta}^{2\pi} V_s\, dt\right]$$

$$V_{dc} = \frac{1}{2\pi}\left[0 + \int_{\alpha}^{\beta} V_s\, dt + 0\right]$$

$$V_{dc} = \frac{1}{2\pi}\left[\int_{\alpha}^{\beta} V_s\, dt\right]$$

$$V_{dc} = \frac{1}{2\pi}\left[\int_{\alpha}^{\beta} V_m \sin\omega t\, dt\right]$$

$$V_{dc} = \frac{V_m}{2\pi}[-\cos\omega t]_{\alpha}^{\beta}$$

$$V_{dc} = -\frac{V_m}{2\pi}(\cos\beta - \cos\alpha)$$

$$V_{dc} = \frac{V_m}{2\pi}(\cos\alpha - \cos\beta)$$

2. RMS load voltage (V_{rms}):-

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_s^2 dt}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\alpha} V_s^2 dt + \int_{\alpha}^{\beta} V_s^2 dt + \int_{\beta}^{2\pi} V_s^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\left[0 + \int_{\alpha}^{\beta} V_s^2 dt + 0\right]}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_{\alpha}^{\beta} V_s^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_{\alpha}^{\beta} V_m^2 \sin^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\left[\int_{\alpha}^{\beta} \sin^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\int_{\alpha}^{\beta} \frac{1-\cos\ 2\omega t}{2} dt}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{4\pi}\int_{\alpha}^{\beta} (1-\cos 2\omega t)\ dt}$$

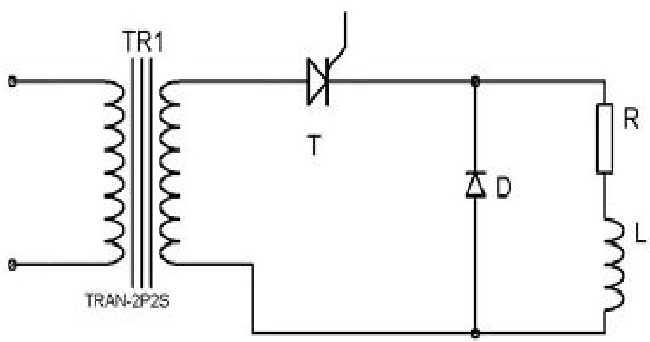
$$V_{rms} = \sqrt{\frac{V_m^2}{4\pi}\left(\int_{\alpha}^{\beta} 1\ dt - \int_{\alpha}^{\beta} \cos 2\omega t\, dt\right)}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{4\pi}\left([\ t\ ]_{\alpha}^{\beta} - \left[\frac{\sin 2\omega t}{2}\right]_{\alpha}^{\beta}\right)}$$

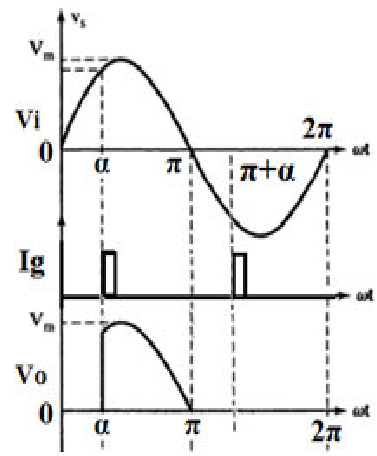
$$V_{rms} = \sqrt{\frac{V_m^2}{4\pi}\left([\beta-\alpha] - \frac{1}{2}\left[\ \sin 2\beta - \sin 2\alpha\right]\right)}$$

$$V_{rms} = \frac{V_m}{2}\sqrt{\frac{1}{\pi}\left([\beta-\alpha] - \frac{1}{2}\left[\ \sin 2\beta - \sin 2\alpha\right]\right)}$$

Use of freewheeling diode:-



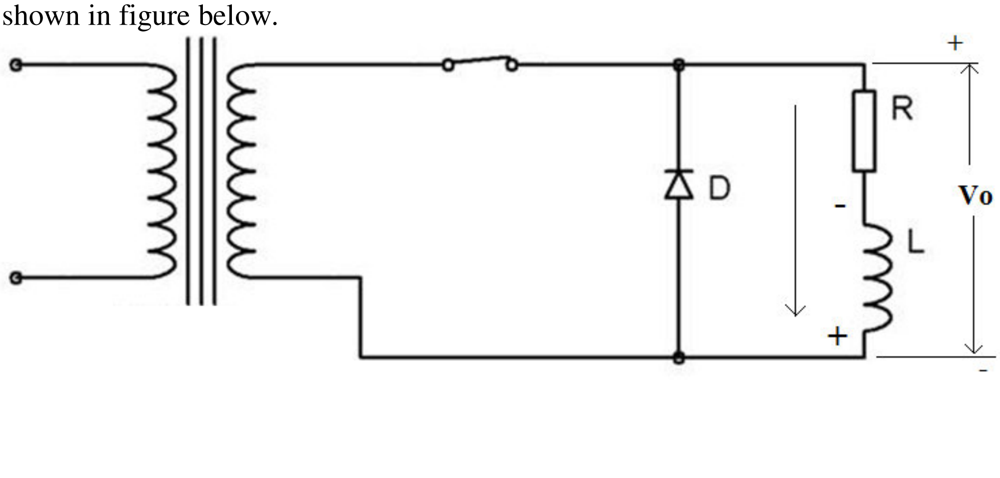
Circuit Digram



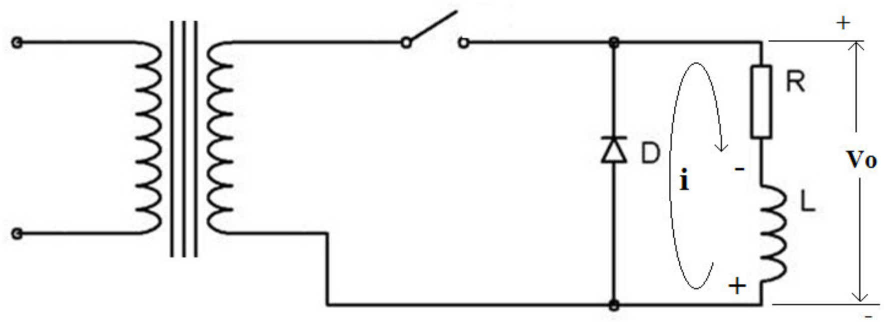
Waveform

The diode D is connected across load. This type of diode is called as freewheeling diode. The circuit operation divided into two parts.

1. **α < ωt < π: -** During this period the thyristor is in ON state, so it acts as closed switch. Diode D is reverse biased so all the current flows through load R and L. The inductor stores the charge and its polarity as shown in figure below.

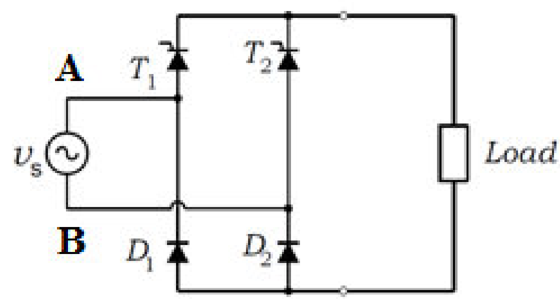


2. **π < ωt < β: -** After ωt = π, polarity of input voltage changes. This will forward bias freewheeling diode. Then inductor discharges through diode instead of thyristor. Therefore the current flowing through the thyristor decreases and it becomes turned OFF and it acts as closed switch as shown in figure below.

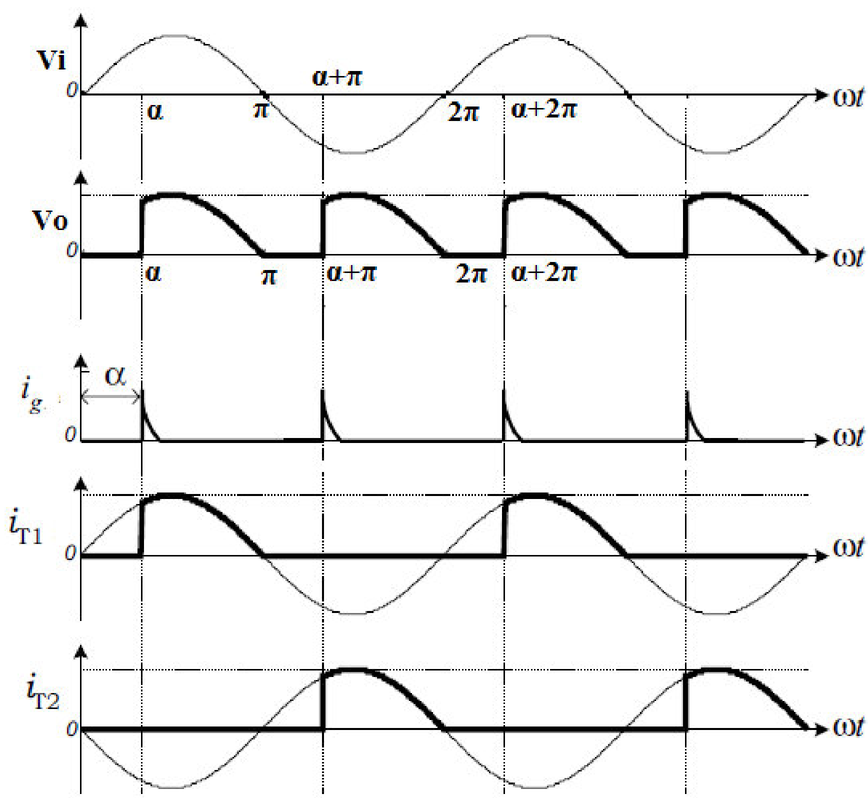


Semi-converter with resistive load (R):-

Semi converter or half controlled converter is a next step of half wave controlled rectifier. In semi converter circuit two thyristors and two diodes are connected in bridge configuration. The circuit is as shown in figure below.



Circuit diagram

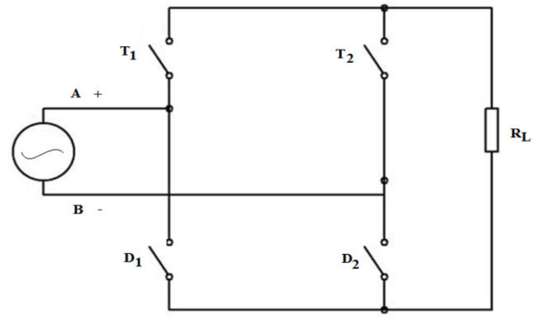


Waveform

Working: - The operation of this rectifier is divided into four parts.

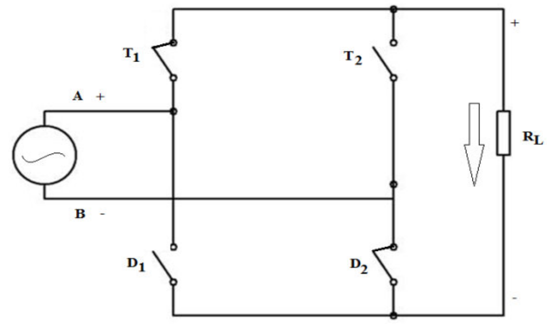
1. **0< ωt < α: -**

   During this period point A is positive and point B is negative. Therefore thyristor T_1 and diode D_2 are forward biased. But thyristor T_1 is in OFF state therefore it is not conducting any current. Therefore no current flows through the load and output becomes zero.



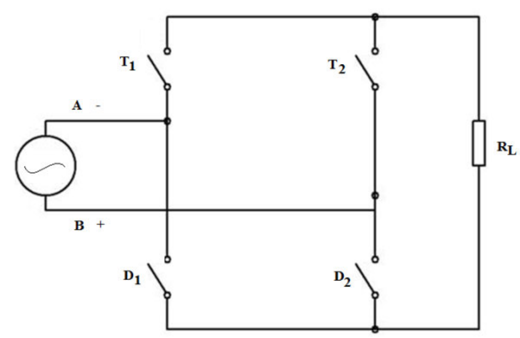
2. **α < ωt < π: -**

   At instant ωt = α, the firing pulse is applied to gate of thyristor T_1. As thyristor T_1 is already forward biased, it will be turned ON. As the thyristor is turned on, current start to flows and its path is A→ T_1 → R_L→ D_2 → B**.** Thyristor T_1 and diode D_2act as closed switch, therefore load is directly connects to input. The output becomes equals to input voltage.



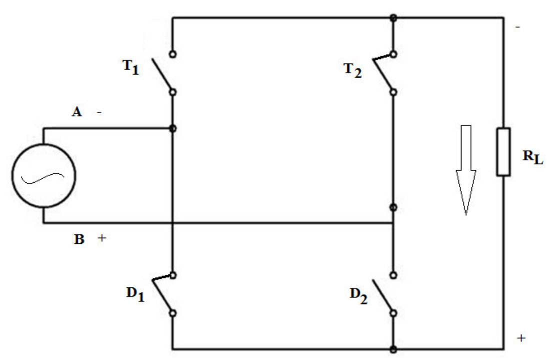
3. **π < ωt < α+ π: -**

   During this time period, point A is negative and point B is positive. Therefore thyristor T_1 and diode D_2 are reverse biased. So the current flowing through it becomes zero. The thyristor T_2 and diode D_1 are forward biased during this time period. But thyristor T_2 is in OFF state therefore it is not conducting any current. Therefore no current flows through the load and output becomes zero.



4. **α+ π < ωt < 2π: -**

   At instant ωt = α+ π, the firing pulse is applied to gate of thyristor T_2. As thyristor T_2 is already forward biased, it will be turned ON. As the thyristor is turned on, current start to flows and its path is B→ T_2 → R_L → D_1 → A**.** Thyristor T_2 and diode D_2 act as closed switch, therefore load is directly connects to input. The output becomes equals to input voltage but polarity is reversed.



Analysis:-

1. Average DC voltage (V_{dc}):-

$$V_{dc} = \frac{1}{2\pi}\int_0^{2\pi} V_s \, dt$$

$$V_{dc} = \frac{1}{2\pi}\left[\int_0^{\alpha} V_s \, dt + \int_{\alpha}^{\pi} V_s \, dt + \int_{\pi}^{\alpha+\pi} V_s \, dt + \int_{\alpha+\pi}^{2\pi} V_s \, dt\right]$$

$$V_{dc} = \frac{1}{2\pi}\left[0 + \int_{\alpha}^{\pi} V_s \, dt + \int_{\alpha+\pi}^{2\pi} V_s \, dt\right] + 0$$

$$V_{dc} = \frac{1}{2\pi}\left[\int_{\alpha}^{\pi} V_s \, dt + \int_{\alpha+\pi}^{2\pi} V_s \, dt\right]$$

$$V_{dc} = \frac{1}{2\pi}\left[2 \text{ x} \int_{\alpha}^{\pi} V_m \sin \omega t \, dt\right]$$

$$V_{dc} = \frac{2 V_m}{2\pi}[-\cos \omega t]_{\alpha}^{\pi}$$

$$V_{dc} = -\frac{V_m}{\pi}(\cos \pi - \cos \alpha)$$

$$V_{dc} = -\frac{V_m}{\pi}(-1 - \cos \alpha)$$

$$V_{dc} = \frac{V_m}{\pi}(1 + \cos \alpha)$$

4. RMS load voltage (V_{rms}):-

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} V_s^2 dt}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\alpha} V_s^2 dt + \int_{\alpha}^{\pi} V_s^2 dt + \int_{\pi}^{\alpha+\pi} V_s^2 dt + \int_{\alpha+\pi}^{2\pi} V_s^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{1}{2\pi}\left[0 + \int_{\alpha}^{\pi} V_s^2 dt + \int_{\pi}^{\alpha+\pi} V_s^2 dt + 0\right]}$$

$$V_{rms} = \sqrt{\frac{2}{2\pi}\left[\int_{\alpha}^{\pi} V_s^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{1}{\pi}\left[\int_{\alpha}^{\pi} V_m^2 \sin^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{\pi}\left[\int_{\alpha}^{\pi} \sin^2 dt\right]}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{\pi}\int_{\alpha}^{\pi} \frac{1 - \cos 2\omega t}{2} dt}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi} (1 - \cos 2\omega t) \, dt}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\left(\int_{\alpha}^{\pi} 1 \, dt - \int_{\alpha}^{\pi} \cos 2\omega t \, dt\right)}$$

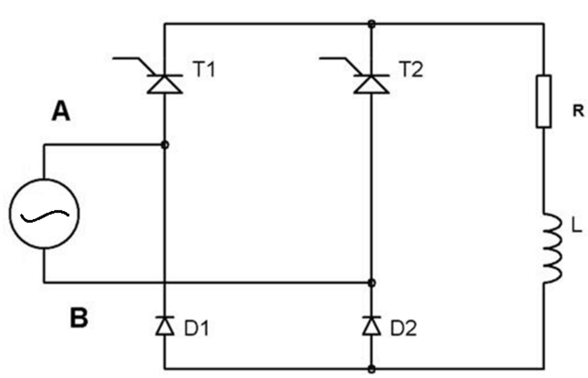
$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\left([\ t\ ]_{\alpha}^{\pi} - \left[\frac{\sin 2\omega t}{2}\right]_{\alpha}^{\pi}\right)}$$

$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\left([\pi - \alpha] - \frac{1}{2}[\ \sin 2\pi - \sin 2\alpha\ ]\right)}$$

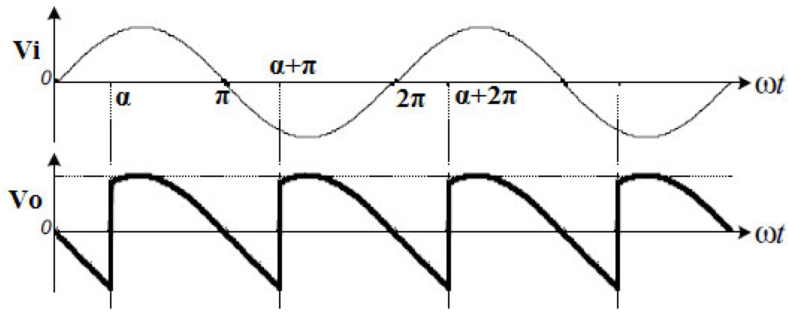
$$V_{rms} = \sqrt{\frac{V_m^2}{2\pi}\left([\pi - \alpha] - \frac{1}{2}[0 - \sin 2\alpha\ ]\right)}$$

$$V_{rms} = \frac{V_m}{\sqrt{2}}\sqrt{\frac{1}{\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2}\right)}$$

Semi-converter with resistive and inductive load (R, L):-



Circuit diagram



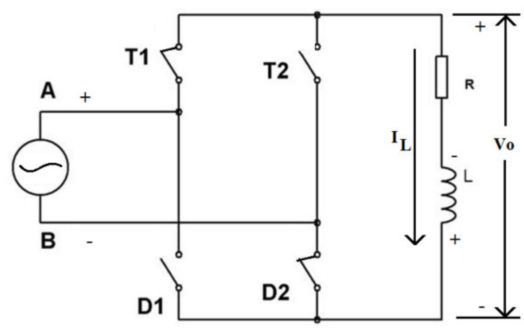
Waveform

Working:-

The operation of the circuit is divided into four parts.

1. $\alpha < \omega t < \pi$: -

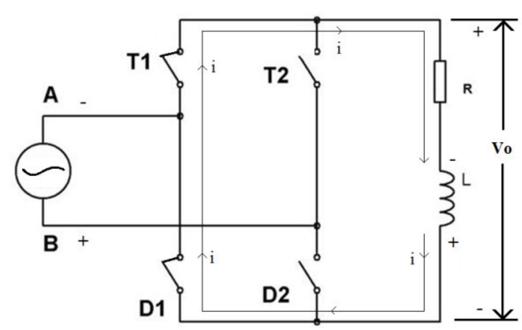
At instant $\omega t = \alpha$, the firing pulse is applied to gate of thyristor T_1. As diode D_2 and thyristor T_1 are already forward biased, it will be turned ON. As the thyristor is turned on, current start to flows and its path is A → T_1 → R → L→ D_2 → B**.** Thyristor T_1 and diode D_2 act as closed switch, therefore load is directly connects to input. The output becomes equals to input voltage. During this time period inductor stores the charge and its polarity as shown in figure.



2. **$\pi < \omega t < \alpha + \pi$: -**

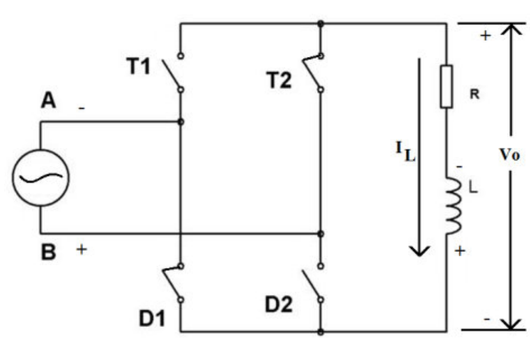
After $\omega t = \pi$, point A becomes negative and point B is positive. Diode D_2 is now reverse biased because its cathode is positive with respect to anode. So it acts as open switch. Diode D_1 is forward biased because its cathode is negative with respect to anode. So it acts as closed switch.

As input current flowing through the thyristor T_1 start to decrease, the inductor start to discharge through diode D_1 and thyristor T_1 and maintain the current. Thyristor is not turned OFF because its anode current is not less than holding current even its anode is negative with respect to cathode. The thyristor T_1 is remains in ON state until next gate pulse is applied.



3. $\alpha + \pi < \omega t < 2\pi$: -

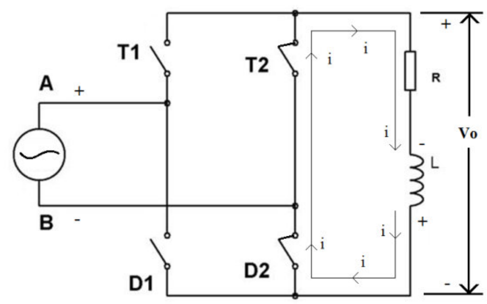
At instant $\omega t = \alpha + \pi$, the firing pulse is applied to gate of thyristor T_2. As diode D_1 and thyristor T_2 are already forward biased, it will be turned ON. As the thyristor is turned on, current start to flows and its path is B → T_2 → R → L→ D_1 → A**.** Thyristor T_2 and diode D_1 act as closed switch, therefore load is directly connects to input. The output becomes equals to input voltage. During this time period inductor stores the charge and its polarity as shown in figure.



4. 2π < ωt < α + 2π: -

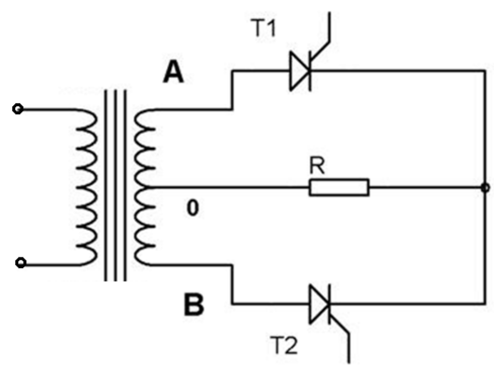
After ωt= 2π, point A becomes positive and point B is negative. Diode D_1 is now reverse biased because its cathode is positive with respect to anode. So it acts as open switch. Diode D_2 is forward biased because its cathode is negative with respect to anode. So it acts as closed switch.

As input current flowing through the thyristor T_2 start to decrease, the inductor start to discharge through diode D_2 and thyristor T_2 and maintain the current. Thyristor is not turned OFF because its anode current is not less than holding current even its anode is negative with respect to cathode. The thyristor T_2 is remains in ON state until next gate pulse is applied.

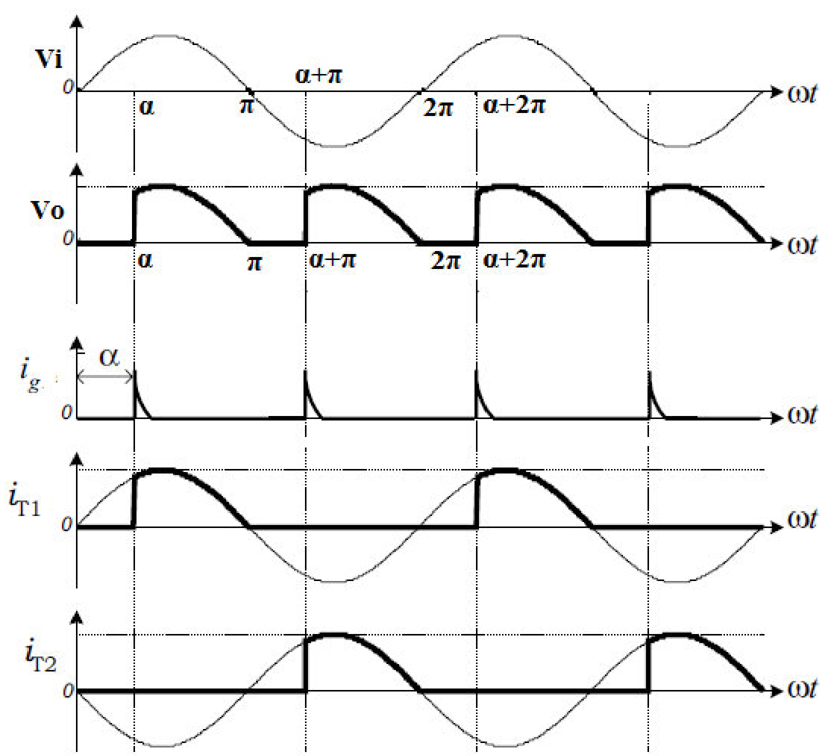


Full converter with resistive load (R):-

The circuit diagram of full converter with mid-point configuration is as shown in figure below. It consists of center tapped transformer, thyristors T1 and T2 and load is connected between common cathode point of thyristors T1 and T2 and center tap of transformer.



Circuit diagram

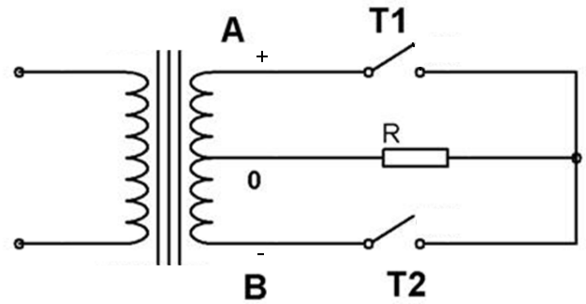


Waveform

Working: - The operation of this rectifier is divided into four parts.

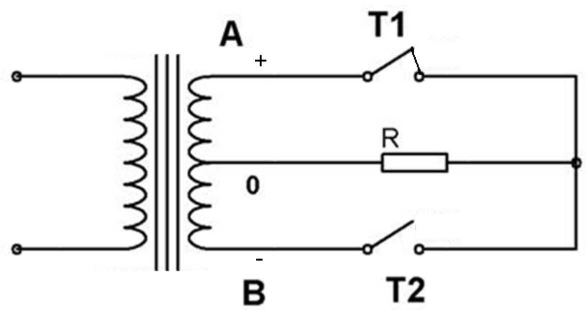
1. 0< ωt < α: -

During this period point A is positive and point B is negative. Therefore thyristor T_1 and is forward biased. But thyristor T_1 is in OFF state therefore it is not conducting any current. Therefore no current flows through the load and output becomes zero.



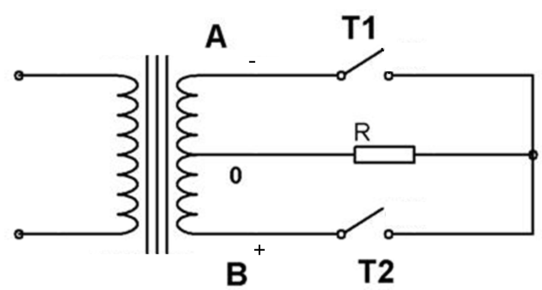
2. α < ωt < π: -

At instant ωt = α, the firing pulse is applied to gate of thyristor T_1. As thyristor T_1 is already forward biased, it will be turned ON. As the thyristor is turned on, current start to flows and its path is A→ T_1 → R→ 0**.** Thyristor T_1 act as closed switch, therefore load is directly connects to input. The output becomes equals to input voltage.



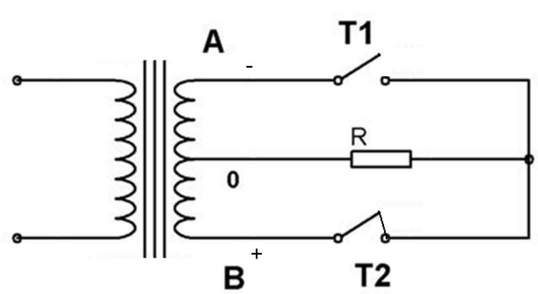
3. π < ωt < α+ π: -

During this time period, point A is negative and point B is positive. Therefore thyristor T_1 is reverse biased. So the current flowing through it becomes zero. The thyristor T_2 is forward biased during this time period. But thyristor T_2 is in OFF state therefore it is not conducting any current. Therefore no current flows through the load and output becomes zero.



4. α+ π < ωt < 2π: -

At instant ωt = α+ π, the firing pulse is applied to gate of thyristor T_2. As thyristor T_2 is already forward biased, it will be turned ON. As the thyristor is turned on, current start to flows and its path is B→ T_2 → R → 0**.** Thyristor T_2 act as closed switch, therefore load is directly connects to input. The output becomes equals to input voltage but polarity is reversed.



Analysis:-

1. Average DC voltage (V_{dc}):-

$$V_{dc}=\frac{1}{2\pi}\int_0^{2\pi}V_s\ dt$$

$$V_{dc}=\frac{1}{2\pi}\left[\int_0^{\alpha}V_s\ dt+\int_{\alpha}^{\pi}V_s\ dt+\int_{\pi}^{\alpha+\pi}V_s\ dt+\int_{\alpha+\pi}^{2\pi}V_s\ dt\right]$$

$$V_{dc}=\frac{1}{2\pi}\left[0+\int_{\alpha}^{\pi}V_s\ dt+\int_{\alpha+\pi}^{2\pi}V_s\ dt\right]+0$$

$$V_{dc}=\frac{1}{2\pi}\left[\int_{\alpha}^{\pi}V_s\ dt+\int_{\alpha+\pi}^{2\pi}V_s\ dt\right]$$

$$V_{dc}=\frac{1}{2\pi}\left[2\ x\int_{\alpha}^{\pi}V_m\ \sin\omega t\,dt\right]$$

$$V_{dc}=\frac{2\ V_m}{2\pi}[-\cos\omega t]_{\alpha}^{\pi}$$

$$V_{dc}=-\frac{V_m}{\pi}(\cos\pi-\cos\alpha)$$

$$V_{dc}=-\frac{V_m}{\pi}(-1-\cos\alpha)$$

$$V_{dc}=\frac{V_m}{\pi}(1+\cos\alpha)$$

2. RMS load voltage (V_{rms}):-

$$V_{rms}=\sqrt{\frac{1}{2\pi}\int_0^{2\pi}V_s^2dt}$$

$$V_{rms}=\sqrt{\frac{1}{2\pi}\left[\int_0^{\alpha}V_s^2dt+\int_{\alpha}^{\pi}V_s^2dt+\int_{\pi}^{\alpha+\pi}V_s^2dt+\int_{\alpha+\pi}^{2\pi}V_s^2dt\right]}$$

$$V_{rms}=\sqrt{\frac{1}{2\pi}\left[0+\int_{\alpha}^{\pi}V_s^2dt+\int_{\pi}^{\alpha+\pi}V_s^2dt+0\right]}$$

$$V_{rms}=\sqrt{\frac{2}{2\pi}\left[\int_{\alpha}^{\pi}V_s^2dt\right]}$$

$$V_{rms}=\sqrt{\frac{1}{\pi}\left[\int_{\alpha}^{\pi}V_m^2\ \sin^2dt\right]}$$

$$V_{rms}=\sqrt{\frac{V_m^2}{\pi}\left[\int_{\alpha}^{\pi}\sin^2dt\right]}$$

$$V_{rms}=\sqrt{\frac{V_m^2}{\pi}\int_{\alpha}^{\pi}\frac{1-\cos\ 2\omega t}{2}dt}$$

$$V_{rms}=\sqrt{\frac{V_m^2}{2\pi}\int_{\alpha}^{\pi}(1-\cos2\omega t)\ \ dt}$$

$$V_{rms}=\sqrt{\frac{V_m^2}{2\pi}\left(\int_{\alpha}^{\pi}1\ dt-\int_{\alpha}^{\pi}\cos2\omega t\,dt\right)}$$

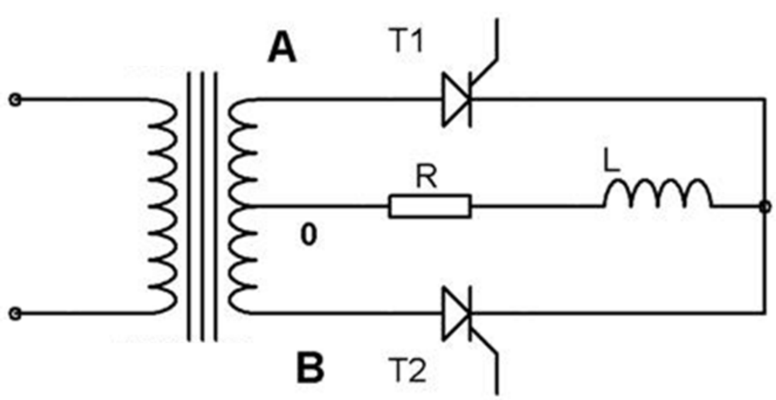
$$V_{rms}=\sqrt{\frac{V_m^2}{2\pi}\left([\ t\ ]_{\alpha}^{\pi}-\left[\frac{\sin2\omega t}{2}\right]_{\alpha}^{\pi}\right)}$$

$$V_{rms}=\sqrt{\frac{V_m^2}{2\pi}\left([\pi-\alpha]-\frac{1}{2}\ [\ \sin2\pi-\ \sin2\alpha\,]\right)}$$

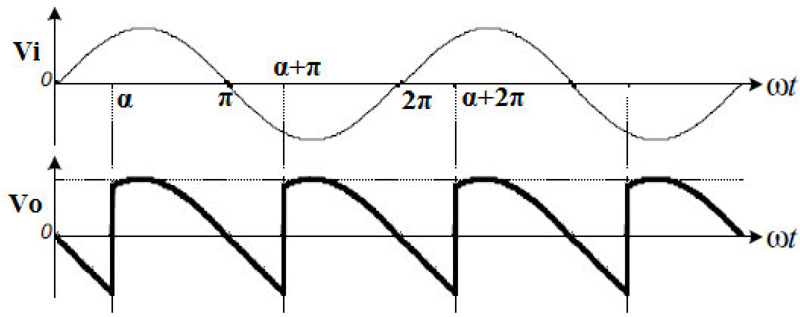
$$V_{rms}=\sqrt{\frac{V_m^2}{2\pi}\left([\pi-\alpha]-\frac{1}{2}\ [0-\ \sin2\alpha\,]\right)}$$

$$V_{rms}=\frac{V_m}{\sqrt{2}}\sqrt{\frac{1}{\pi}\left(\pi-\alpha+\frac{\sin2\alpha}{2}\right)}$$

Full converter with resistive and inductive load (R, L):-



Circuit diagram



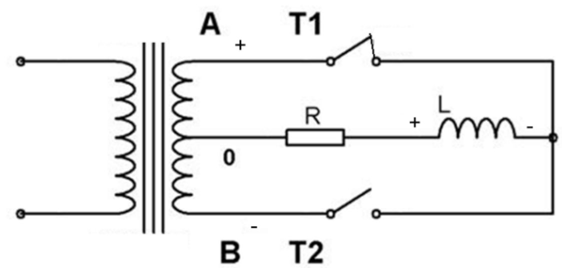
Waveform

Working:-

The operation of the circuit is divided into four parts.

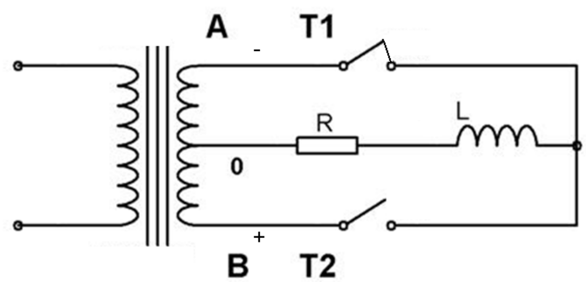
1. α < ωt < π: -

At instant ωt = α, the firing pulse is applied to gate of thyristor T_1. As thyristor T_1 is already forward biased, it will be turned ON. As the thyristor is turned on, current start to flows and its path is A → T_1 → L → R→0**.** Thyristor T_1 act as closed switch, therefore load is directly connects to input. The output becomes equals to input voltage. During this time period inductor stores the charge and its polarity as shown in figure.



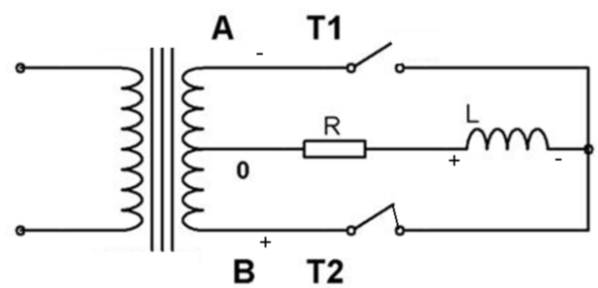
2. π < ωt < α + π: -

After ωt= π, point A becomes negative and point B is positive. As input current flowing through the thyristor T_1 start to decrease, the inductor start to discharge through diode thyristor T_1 and maintain the current. Thyristor is not turned OFF because its anode current is not less than holding current even its anode is negative with respect to cathode. The thyristor T_1 is remains in ON state until next gate pulse is applied.



3. α + π < ωt < 2π: -

At instant ωt = α+ π, the firing pulse is applied to gate of thyristor T_2. As thyristor T_2 is already forward biased, it will be turned ON. As the thyristor is turned on, current start to flows and its path is B → T_2 → R → L→ 0**.** Thyristor T_2 act as closed switch, therefore load is directly connects to input. The output becomes equals to input voltage. During this time period inductor stores the charge and its polarity as shown in figure.



4. 2π < ωt < α + 2π: -

After ωt= 2π, point A becomes positive and point B is negative. As input current flowing through the thyristor T_2 start to decrease, the inductor start to discharge through thyristor T_2 and maintain the current. Thyristor is not turned OFF because its anode current is not less than holding current even its anode is negative with respect to cathode. The thyristor T_2 is remains in ON state until next gate pulse is applied.