Unit 2
Phase-Controlled Rectifiers

OVERVIEW

- Rectification is the most common use for power electrical equipment. The process of changing an ac voltage and current to a dc voltage and current is known as rectifying.
- Input type: AC power source with set voltage and frequency.
- Output type: Pulsed controlled average dc output voltage
- An uncontrolled rectifier transforms a fixed ac voltage into a fixed average pulsed dc voltage.
- A controlled rectifier transforms a set ac voltage into a pulsed, changeable average dc voltage.
- A constant voltage, fixed frequency ac power source may be transformed into a variable dc output voltage using controlled rectifiers, which are line commutated ac to dc power converters.
- Thyristors are used in the design of phase-controlled converters.
- Thyristors' firing angle is changed to provide the necessary dc output voltage.

APPLICATIONS

- DC motor control is used in mills that produce steel, paper, and textiles.
- DC traction motor-powered AC-fed traction system.
- procedures using electrochemistry and electrometallurgy.
- controllers for reactors.
- Hand tool drivers that are portable.
- industrial drives with variable speeds.
- DC transmission at high voltage.
- UPS stands for uninterruptible power supply systems.

CATEGORIES

- Depending on the kind of input power source

1. Rectifiers that are single-phase controlled.
2. Three-phase rectifiers with control.

- One-phase rectifiers are categorized according to the rectification method as

1. rectifier with half wave control
2. Rectifiers with full wave control

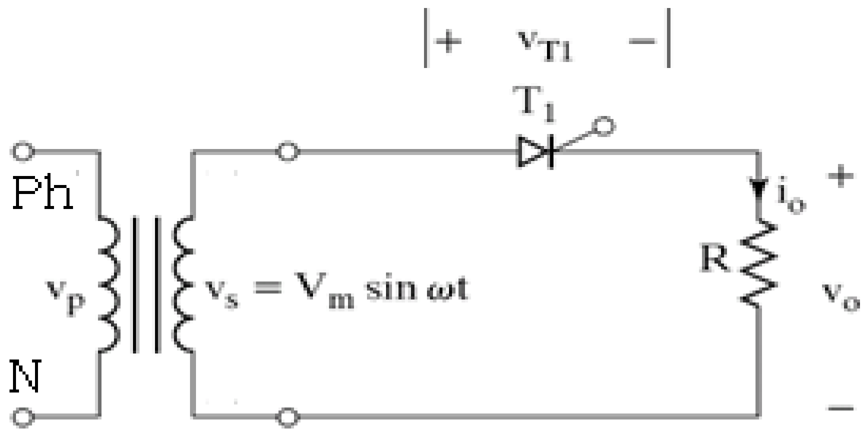
- Considering the design of power circuit full wave rectifiers, they are categorized as

1. Utilizing a center-tapped transformer, a full wave midpoint controlled rectifier
2. rectifiers with full wave bridge control (which do not need a transformer)

- Full wave bridge controlled rectifiers are categorized according to their quadrant functioning as

1. Full converter in single phase (two quadrant converter).
2. Single quadrant converter, or single phase semi-converter.

RECTIFIERS IN SINGLE PHASE (RESISTIVE LOAD) HALF WAVE CONVERTER

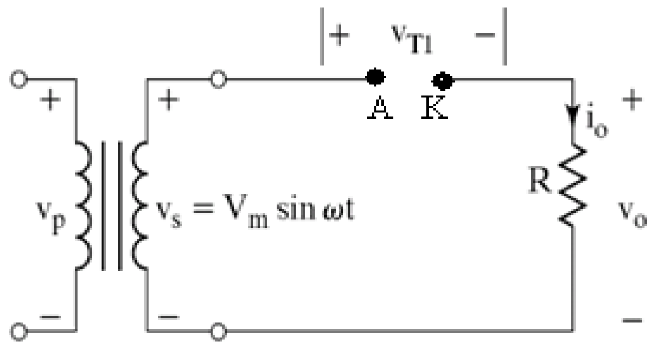


The transformer's primary is linked to the ac mains supply, as shown in the picture below, which causes the SCR to become forward bias during the positive half cycle. When T1 is activated at an angle α, it conducts and applies a voltage across R.

The voltage and current waveforms are seen above when the load current, i0, passes through "R." The output current has the same form as the output voltage because the load is resistive.

Waveforms

equivalent circuit in the event that T1 is not in use



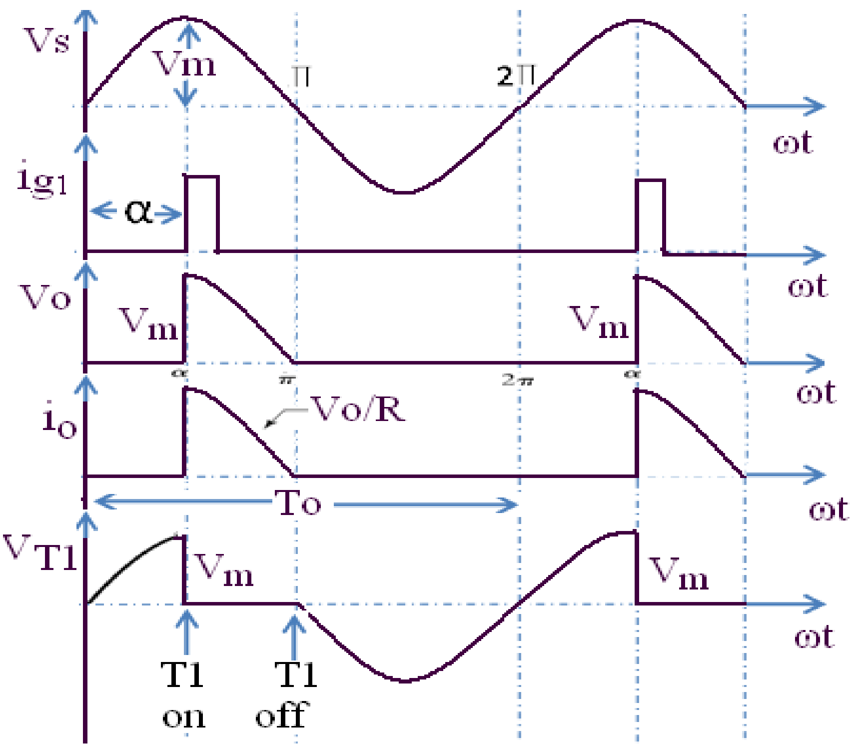
The thyristor is in a forward biased condition during the +ve half cycle of the i/p supply when the higher end of the transformer secondary winding is at a +ve potential relative to the lower end.

An adequate gate trigger pulse is applied to the thyristor's gate terminal to activate it at a delay angle of ωt = α. The thyristor behaves and assumes a perfect thyristor when it is triggered at a delay angle of ωt = α. When conducting from ωt = α to π radians, the i/p supply voltage works across the load, and the thyristor functions as a closed switch. For a purely resistive load, the formula provides the load current io that flows when the thyristor T1 is turned on.

Considering α≤ ωt ≤ π, Io= vo/RL

equivalent circuit in the condition of T1 being on

Thyristor γ's conduction angle is equal to O-α.



OVER THE LOAD, THE AVERAGE (DC) OUTPUT VOLTAGE:

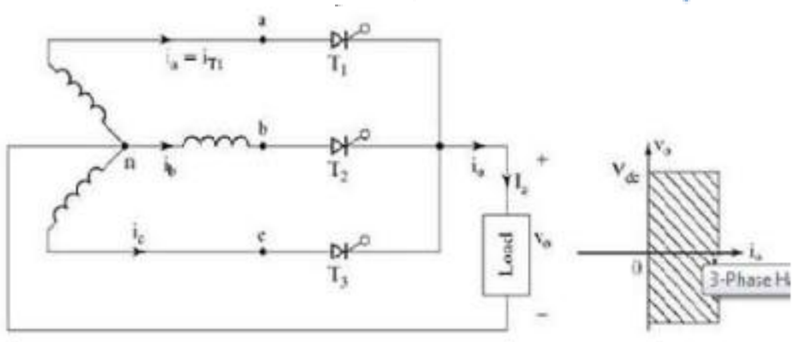


Figure: 2.16 circuit diagram three phase half wave rectifier

$$V_0(Avg) = \frac{1}{T} \int_0^T V_0(wt)\, dwt$$

i.e Area under one cycle.

Therefore T=2π&Vo(ωt) = Vm sinωt from α to π& for rest of the period Vo(ωt)=0

$$\therefore V_0(Avg) = \frac{1}{2\pi} \int_0^{2\pi} V_m \sin(wt)\, dwt$$

$$= \frac{V_m}{2\pi} [-\cos wt]_\alpha^\pi$$

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

Power transferred to load,

$$P_0(Avg) = \frac{V_0^2(Avg)}{R}$$

Thus, power & voltage can be controlled by firing angle.

When α = 0, the highest average (dc) output voltage is achieved.

Half wave rectifier control characteristics with R-load
The maximum average (dc) output voltage is obtained when α = 0
Control Characteristics of Half wave rectifier with R-load

For $\alpha = 0^0$; $V_0 = \frac{V_m}{\pi}$

For $\alpha = 90^0$; $V_0 = \frac{V_m}{2\pi}$

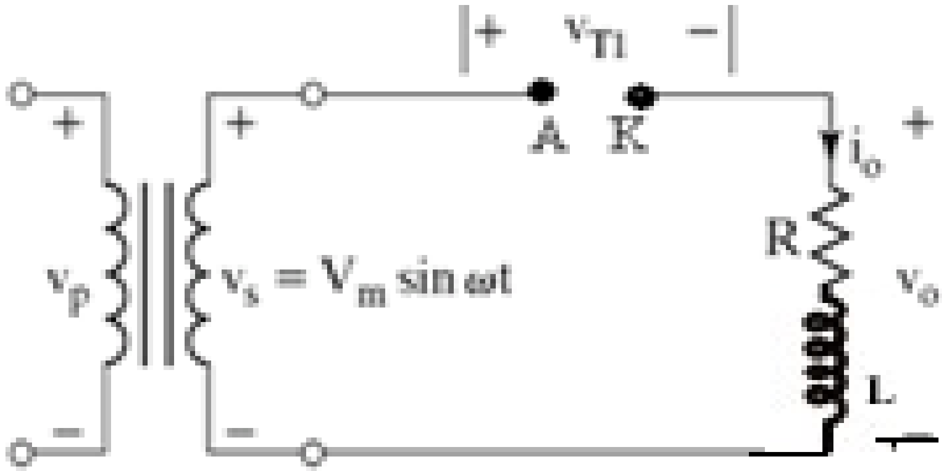
For $\alpha = 180^0$; $V_0 = 0$

Consequently, by altering the firing angle from 00 to 1800, the half wave converter's average output voltage is regulated from 0 to 0.

When α = 0, the highest average (dc) output voltage is achieved.

Converting half waves with RL-load

equivalent circuit in the event that T1 is not in use



The single-phase half wave rectifier with RL load is seen in the above figure.

• Motors are typically inductive loads, where L is the field coil's armature and R is its resistance.

• The SCR begins conduction at the firing angle "α" during the positive half cycle.

• Because of the modest and ignored drop across the SCR, the output voltage is identical to the supply voltage.

• The "RL" load causes a gradual rise in current through the SCR.

• When the load current reaches its maximum value at "π," the supply voltage is zero.

• The inductor stores energy and produces the voltage during the positive half cycle.

• The voltage across the inductor forward biases the SCR and keeps it conduction-free throughout the negative half-cycle.

• In essence, the inductance property resists changes in current.

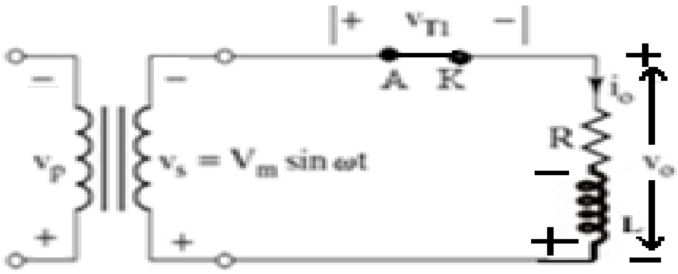
• Because the supply and output currents run in the same loop, io=is is constant.

• Following π, the inductor's energy is transferred to the mains, and "io" flows. As energy is used up by the circuit, current decreases as well.

• When the energy stored in the inductance reaches "β," "io" drops to zero and "T1" shuts off.

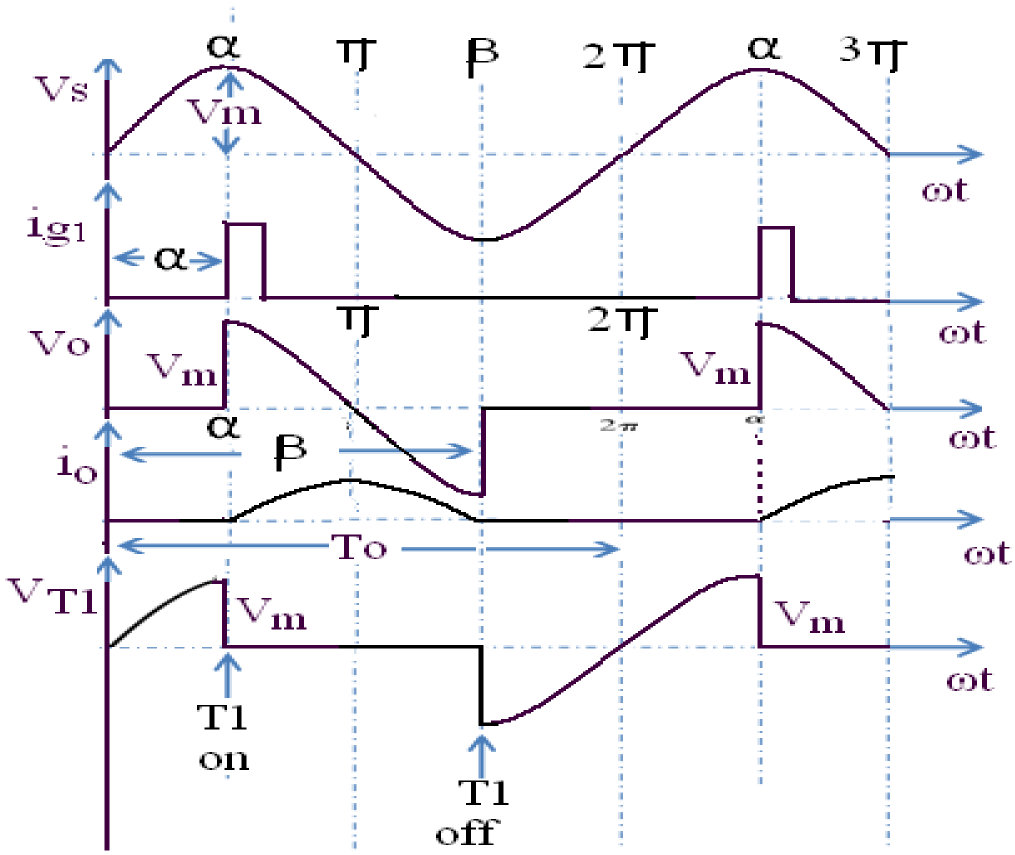
From "β" to "2π+α," "io" becomes 0, indicating discontinuous conduction.

equivalent circuit in the condition of T1 being on



Thyristor γ's conduction angle is equal to β-α.

Waveforms



The average output voltage $V_0 = \frac{1}{2\pi}\int_{\alpha}^{\beta} Vmsinwt\, d(wt) = \frac{Vm}{2\pi}(\cos\alpha - \cos\beta)$

$$I_0 = \frac{Vm}{2\pi R}(\cos\alpha - \cos\beta)$$

RMS load voltage $V_{0r} = \left\{\frac{1}{2\pi}\int_{\alpha}^{\beta} Vm^2 sin^2wt\, d(wt)\right\}^{1/2}$

$$= \frac{Vm}{2\sqrt{\pi}}\left[(\beta - \alpha) - \frac{1}{2}\{sin2\beta - sin2\alpha\}\right]^{1/2}$$

AVERAGE (DC) LOAD VOLTAGE EXPRESSION

As a result, α and β determine the average output voltage.

In the best scenario, β=π+α

Half wave rectifier control characteristics with RL-load

The value of V0 for α = 00 is

Regarding α = 900, V0 = 0.

Considering α = 1800, V0 = -

Consequently, by altering the firing angle from 00 to 1800, the average output voltage of a half wave converter with an RL load is regulated from to -.

When α = 0, the highest average (dc) output voltage is achieved.

FREE WHEELING DIODE EFFECTS

A freewheeling diode DFW coupled across a load is shown in Figure 27.3. Freewheeling diodes, commonly referred to as bypass diodes or commutating diodes, are used to enhance the power factor and load current waveshape. When the thyristor is blocked, the freewheeling diode DFW maintains the load current while allowing the energy stored in the load's inductance to be dissipated. The thyristor's conductivity will be limited to 180° when using a flywheel diode.

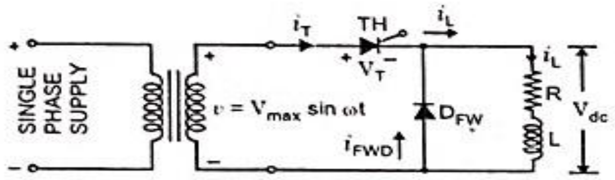


Fig. 27.3 *Half Wave Controlled Rectifier With a Freewheeling Diode*

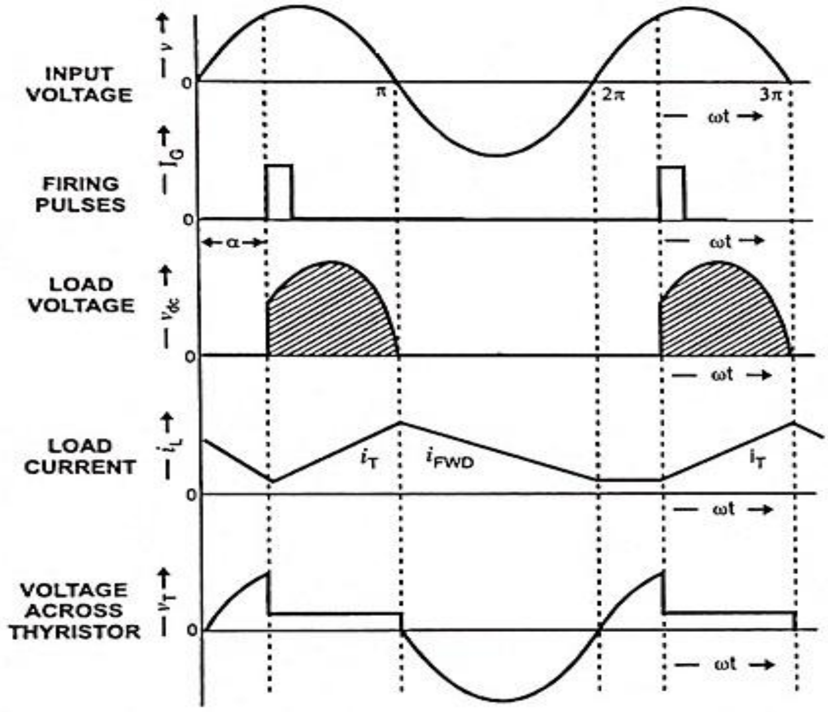


Fig. 27.4 *Waveforms For Half-Wave Controlled Rectifier With Inductive Load and Free Wheeling Diode*

The two primary purposes of the freewheeling diode are:

- With the exception of a little diode voltage drop, it stops the load voltage from reversing.
- When input voltage flips the cycle, it moves the load current away from the primary rectifier.

The waveforms of the load voltage and current are shown in Fig. 27.4.

The freewheeling diode DFW will begin conducting as soon as the induced voltage is large enough to allow the inductance to release its stored energy into the resistance. During the positive half cycle, the induced voltage in the inductance will change its polarity as the di/dt changes its sign.

The load current will thus freewheel via the diode after 180°, resulting in a reverse voltage across the thyristor. Only when the thyristor is conducting does electricity flow from the input. Without a freewheeling diode, the thyristor returns the energy stored in the load inductance to the supply mains during the supply voltage's negative half cycle. The freewheeling operation occurs with the freewheeling diode, and the supply source does not get any power back.

Therefore, for the phase-control circuit with a freewheeling diode, the ratio of the reactive power flow from the input to the total power used by the load is decreased. It indicates that using a freewheeling diode improves the input power factor.

Fill up

Thyristor conduction interval

- R-Load

From $\omega t=\alpha$ to $\omega t=\pi$

- RL-Load

From $\omega t=\alpha$ to $\omega t=\beta$

- RL-Load with FWD

From $\omega t=\alpha$ to $\omega t=\pi$

- RLE: Load

From $\omega t=\alpha$ to $\omega t=\beta$

Half wave phase controlled converter drawbacks

- Low dc output voltage is produced via a single phase half wave regulated rectifier.
- reduced efficiency and poor dc output power.
- increased ripple current and ripple voltage.
- increased factor of ripple.
- low factor of transformer usage.

- The transformer core may experience dc saturation as a consequence of the dc component in the input supply current waveform.

FULL WAVE SINGLE PHASE CONVERTER

- Compared to half-wave rectifiers, single phase full wave controlled rectifiers (also known as converters) have a higher effective dc voltage and less ripple since they employ both the positive and negative sides of the ac supply.

- Single Phase Full Wave Controlled Rectifiers come in two basic designs. They are divided into bridge converters and mid-point converters according to the configuration type that is used. Thyristors may either fully or partly replace the diodes used in full-wave rectifiers.

Bridge Converter in One Phase (B-2 Connection):

There are four thyristors required for a single phase bridge converter. Two quadrant operation results from this setup. This kind of converter is known as a completely regulated converter or two-quadrant converter. The bridge circuit is often altered by swapping out two thyristors for two diodes. One quadrant operation results from this arrangement (operation is confined to first quadrant). This kind of converter is known as a semiconverter or one-quadrant converter.

There are three types of loads that may be placed on the converter: solely resistive, inductive (R-L), or R-L-E. Resistance, inductance, and motor make up an R-L-E load (where E is the motor's back emf). In addition, the load could be powered by a battery (emf E) rather of a motor.

Considering Resistive Load:

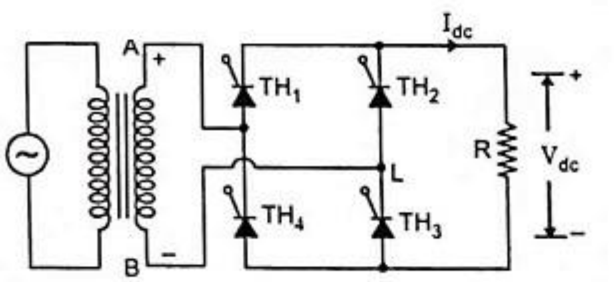


Fig. 27.13 *Single Phase Full-Wave Fully Controlled Rectifier (or Full Converter) With Resistive Load*

Fig. depicts a fully regulated full-wave bridge rectifier. 27.13. In theory, this circuit functions similarly to the two pulse mid-point circuit seen in Fig. 27. 7. Thyristors TH1–TH4 are the four devices utilized in the circuit to regulate the output power. Two thyristors that are diagonally opposed to one another are made to conduct and commutate concurrently in this circuit.

Thyristors TH1 and TH3 are forward biased during the first positive half cycle, and if they are activated simultaneously, current passes through the load via thyristor TH1--load-TH3-source. Thus, thyristors TH1 and TH3 are conducting during the positive half cycle.

Thyristors TH2 and TH4 are forward biased during the negative half cycle of the ac input, and if they are activated simultaneously, current passes through the load via thyristor TH2-load-TH4-source. In both the positive and negative half cycles of the supply voltage, thyristors TH1, TH3, and TH2 are activated at the same firing angle, α. The current likewise drops to zero when the source voltage does. Thus, natural commutation causes thyristors TH1, TH3, and TH2 to switch off in the positive half cycle and TH2 and TH4 in the negative half cycle. This circuit's associated voltage and current waveforms are shown.

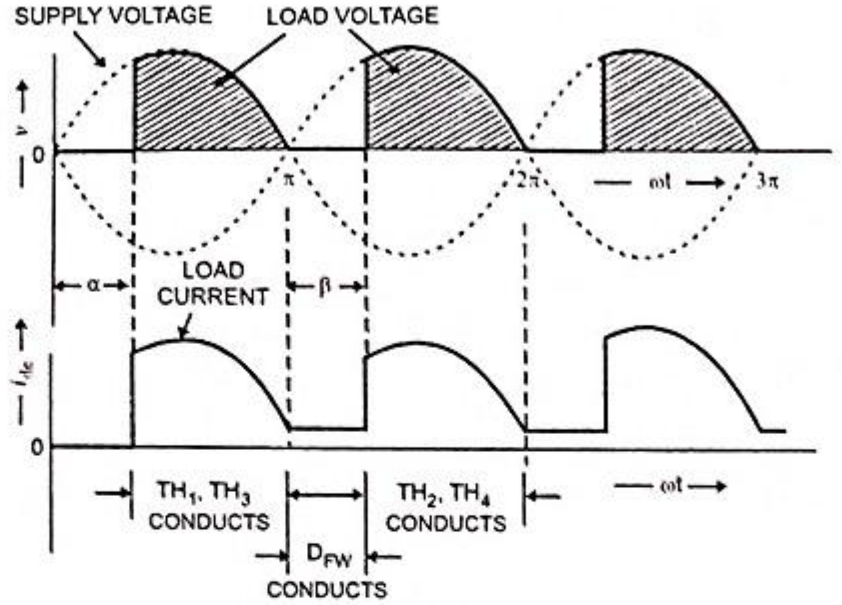


Fig. 27.14 *Waveforms For Full-Wave Converter With Resistive Load*

The dc voltage output across the resistive load is determined by

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_{max} \sin \omega t \, d(\omega t) = \frac{V_{max}}{\pi}(1 + \cos \alpha) \qquad ...(27.12)$$

The average load current is provided by

$$I_{dc} = \frac{V_{dc}}{R} = \frac{V_{max}}{\pi R}(1 + \cos\alpha) \qquad ...(27.13)$$

For a certain firing angle α, the formula for the load

$$\begin{aligned} V_{L\,rms} &= \sqrt{\frac{1}{\pi}\int_0^{\pi} V_{max} \sin^2 \omega t \, d(\omega t)} \\ &= \frac{V_{max}}{\sqrt{2\pi}}\left(\pi - \alpha + \frac{1}{2}\sin 2\alpha\right)^{1/2} \\ &= V_{max}\left(\frac{\pi - \alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right)^{1/2} \qquad ...(27.14) \end{aligned}$$

voltage's rms value is

The load current's RMS value is provided by

$$I_{L\,rms} = \frac{V_{L\,rms}}{R} = \frac{V_{max}}{R}\left(\frac{\pi - \alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right)^{1/2} \qquad ...(27.15)$$

Using RL Load:

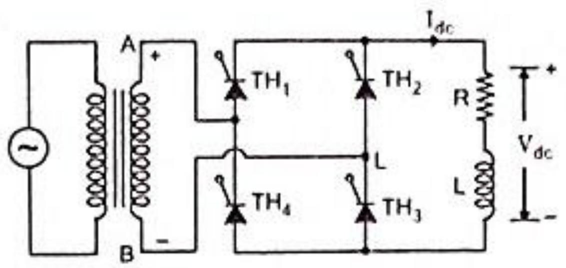
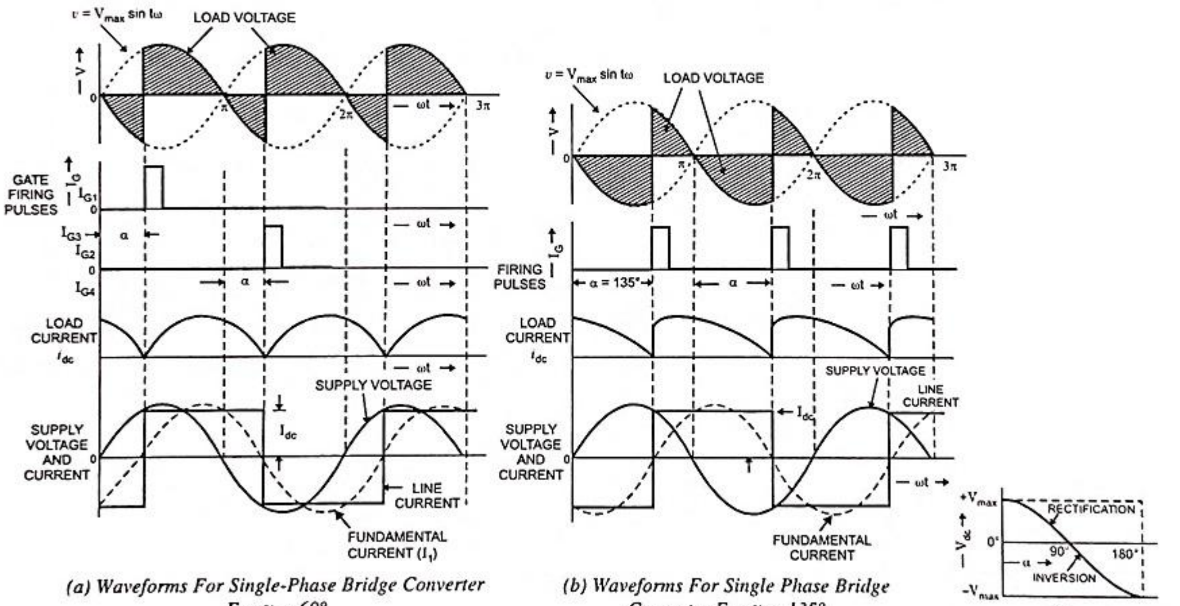


Fig. 27.15 *Single Phase Full-Wave Converter With Inductive (R-L) Load*

A single phase fully regulated bridge rectifier (also known as a complete converter) with R-L load is seen in Figure 27.15. Like a mid-point full-wave converter, the fully regulated bridge rectifier produces two pulses every cycle. This circuit's waveforms and working principle are comparable to those of a mid-point full-wave converter. It is assumed that the firing angles of the two thyristor pairs are equivalent. A high value of L will cause the load to have a constant, continuous current. For large firing angles, a small value of L will result in a discontinuous load current. Fig. shows the waveforms with two distinct firing angles. 27.16.

With a fundamental frequency double that of the ac supply, the voltage waveform at the dc terminals consists of a constant dc component overlaid with an ac ripple component.



(a) Waveforms For Single-Phase Bridge Converter For α = 60°

(b) Waveforms For Single Phase Bridge Converter For α = 135°

(c)

Fig. 27.16

as seen in Fig. 27.16 (a) triggers thyristors TH1 and TH3 at a firing angle $\alpha = 60°$. The current is forced through the load by the supply voltage that is visible across the output terminals at this moment. It is assumed that the load current Idc remains constant. As seen in Fig., this current also passes through the supply and travels from line to neutral, which is interpreted as positive. 27.16 (a) in addition to the voltage that was applied.

The supply voltage flips at moment π, but the current continues to flow in the same direction at constant magnitude Idc due to the extremely high inductance L. As a result, the output terminals display a negative supply voltage because the thyristors TH1 and TH3 continue to operate in a conducting condition. The thyristors TH2 and TH4 are activated at an angle $\pi + \alpha$. In order to commutate thyristors TH1 and TH3, the negative supply voltage reverse biases thyristor TH1 via thyristor TH2 and thyristor TH3 through thyristor TH4.

Every half cycle, the current keeps flowing, and the output voltage is as shown in the figure. As shown, when TH1 and TH3 are conducting, the current is positive; when TH2 and TH4 are conducting, the current is negative.

The average dc voltage output is provided by

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_{max} \sin \omega t \, d(\omega t) = \frac{2V_{max}}{\pi} \cos \alpha \qquad \text{...(27.20)}$$

Assuming constant current flow at the dc terminals, the firing angle α may be constantly changed from positive maximum to negative maximum to change the average value of the output dc voltage. The power flow in the convener may be either way because the average dc voltage is reversible even if the load's current flow is unidirectional. As a result, the complete converter offers two operating modes.

(a) Mode of Rectification:

The circuit rectifies the input ac supply when the firing angle α is less than 90°. As seen in Fig., the average voltage at the dc terminals is positive within the 0° to 90° range. 27.16 (c). Power is moved from the source to the load in this mode.

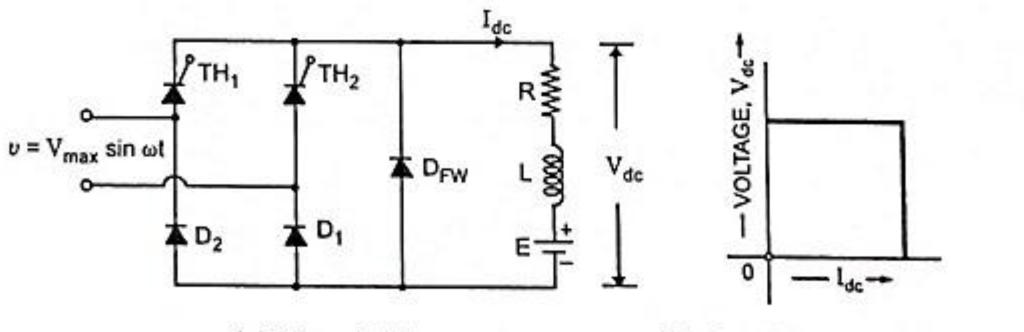
(b) Mode of Inversion:

The load voltage is negative for firing angles between 90° and 180°, indicating that power is coming from the load to the source. Fig. displays waveforms at α = 135°. 27.16 (b). This kind of operation is used in high voltage direct current (HVDC) transmission and the regenerative braking mode of DC drives.

Semi-converter or single-phase half-controlled bridge rectifier:

Half-controlled bridge rectifiers, also known as semi converters, are created when one pair of thyristors in a single phase fully controlled bridge circuit is swapped out for diodes. The mean dc voltage can be continuously controlled using this kind of circuit, from its maximum to almost zero, however the mean output voltage cannot be reversed. Therefore, this circuit can only provide a one-quadrant action.

Fig. displays an R-L-E load that is powered by single phase ac supply mains via a semi-controlled rectifier. 27.18 (a). The circuit has two diodes, D1 and D2, as well as two thyristors, TH1 and TH2. When the thyristor is not conducting, the freewheeling diode DFW aids in current conduction.

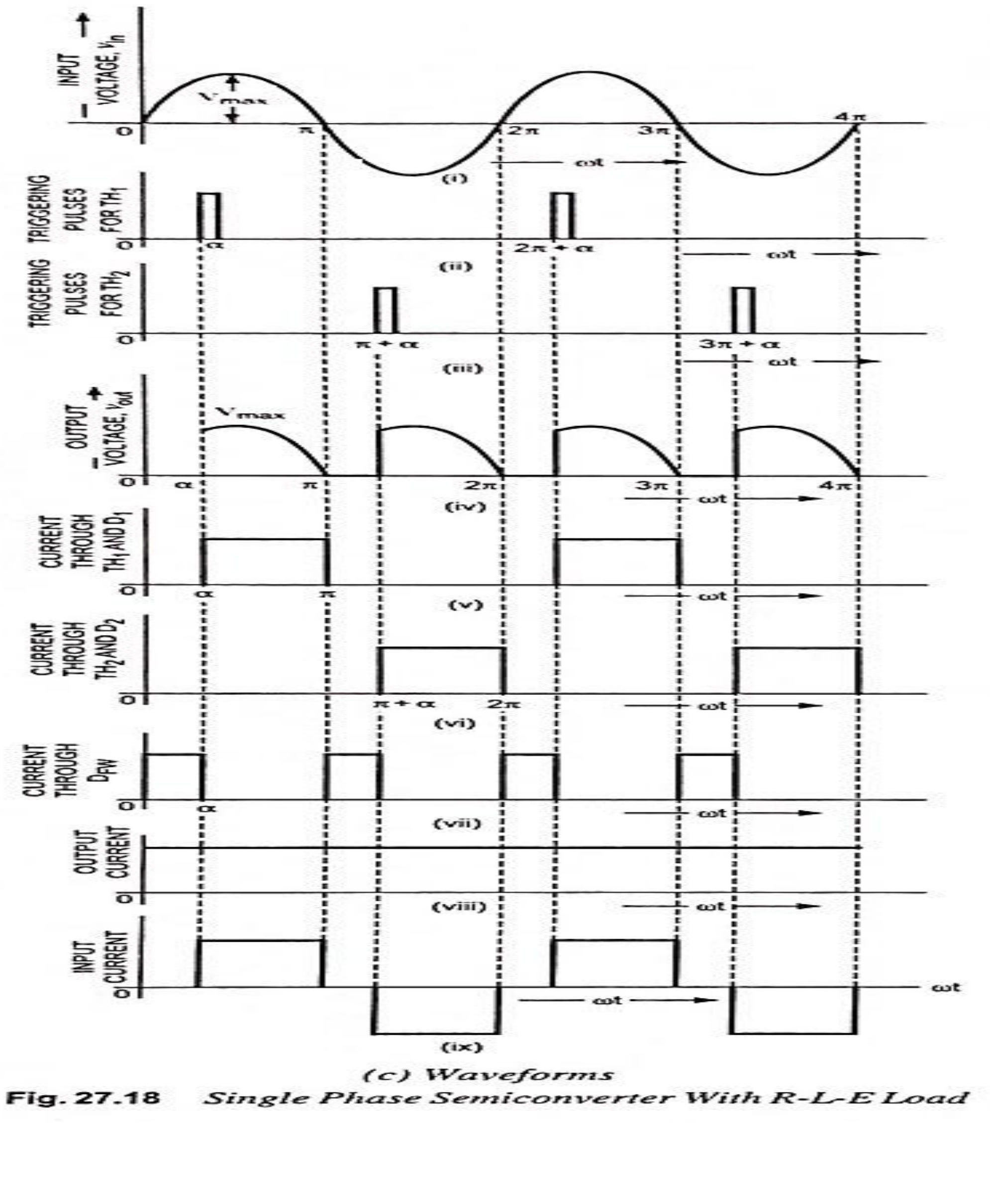


(a) Circuit Diagram *(b) Quadrant of Operation*

Fig. 27.18

Thyristor TH1 is activated at ωt = α and begins conducting throughout the positive half cycle. It is important that the value of α be such that Vmax sin α > E.From ωt = α to ωt = π, the current passes via TH1, the motor, and diode D1. The input voltage drops and the freewheeling diode DFW gets forward biased at ωt = π. As a result, current moves to DFW at ωt = π when the thyristor TH1 and diode D1 cease to conduct.

The thyristor TH2 is forward biased during the negative half cycle. It is activated at ωt = π + α, which causes the freewheeling diode DFW to cease conducting and transfer current to the TH2, D2 combination. From ωt = π + α to ωt = 2π, TH2 and D2 conduct. Thyristor TH2 and diode D2 are cut off at ωt = 2π, and current flows freely through DFW from ωt = 2π to ωt = 2π + α. The circuit operates as follows: DFW conducts for 0 ≤ ωt ≤ α; TH1 and D1 conduct for α ≤ ωt ≤π; DFW conducts for π ≤ ωt ≤ π + α; and TH2 and D2 conduct for π + α ≤ ωt ≤ 2π. This occurs when ωt = 2π + α triggers the thyristor TH1 once again, initiating the subsequent cycle of operation.



(c) Waveforms

Fig. 27.18 *Single Phase Semiconverter With R-L-E Load*

Figs. display the waveshapes and the operating quadrant. The corresponding values are 27.18 (b) and 27.18 (c).

The semiconverter's average output voltage is provided as

$$V_{out} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_{max} \sin \omega t \, d(\omega t)$$

$$= \frac{V_{max}}{\pi}\left[-\cos \omega t\right]_{\alpha}^{\pi} = \frac{V_{max}}{\pi}(1 + \cos \alpha) \qquad ...(27.22)$$

The average load current is

$$I_{out} = \frac{V_{out}}{R} = \frac{V_{max}}{\pi R}(1 + \cos \alpha) \qquad ...(27.23)$$

The semiconverter's RMS load (or output) voltage value is provided as

$$V_{out\,(rms)} = \sqrt{\left[\frac{V_{max}^2}{\pi}\int_{\alpha}^{\pi} \sin^2 \omega t \, d(\omega t)\right]}$$

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

$$= \frac{V_{max}}{\sqrt{2\pi}}\sqrt{\left[\omega t - \frac{\sin 2\omega t}{2}\right]_{0}^{\pi}}$$

$$= V_{max}\left[\frac{\pi - \alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]^{1/2} \qquad ...(27.24)$$

RMS load current value,

$$I_{out\,(rms)} = \frac{V_{out\,(rms)}}{R} = \frac{V_{max}}{R}\left[\frac{\pi - \alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]^{1/2} \qquad ...(27.25)$$

power output,

$$P_{out} = V_{out}\, I_{out} = \frac{V_{max}}{\pi}(1 + \cos \alpha)\, I_{out} \qquad ...(27.26)$$

Considering that the output current Iout is the input current's ripple-free RMS value,

$$I_{out\,(rms)} = \sqrt{\frac{\pi - \alpha}{\pi}}\, I_{out} \qquad \text{...(27.27)}$$

$$\text{Input power factor} = \frac{P_{out}}{\text{Input VA}}$$

$$= \frac{V_{out}\, I_{out}}{V_{out\,(rms)} \times I_{out\,(rms)}}$$

$$= \frac{\dfrac{V_{max}}{\pi}(1 + \cos\alpha) \times I_{out}}{\dfrac{V_{max}}{\sqrt{2}} \times \sqrt{\dfrac{\pi - \alpha}{\pi}}\, I_{out}}$$

$$= \left(\frac{2}{\pi(\pi - \alpha)}\right)^{1/2} (1 + \cos\alpha) \qquad \text{...(27.28)}$$

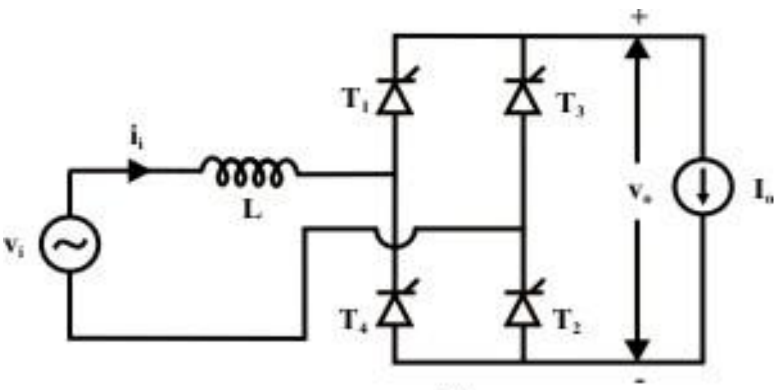
When the output voltage is below the maximum, or when the tiresome angle α is significant, phase-controlled converters have a low power factor. Although the difference is slight, semiconverters provide a higher power factor than complete converters.

Single-phase bridge converters provide the following advantages over single-phase mid-point converters:

- In a fully regulated bridge converter, thyristors are exposed to a PIV of Emax, and in a mid-point converter, 2Emax. Therefore, the power handled by the bridge arrangement is about double that handled by the mid-point configuration for the identical thyristor voltage and current ratings.

- Every transformer secondary should be able to provide the whole load in a mid-point arrangement. Therefore, in a mid-point layout, the transformer rating is twice that of the load. But with the bridge setup, this isn't the case.

SOURCE INDUCTANCE'S IMPACT



(a)

WAVE FORMS OUTPUT

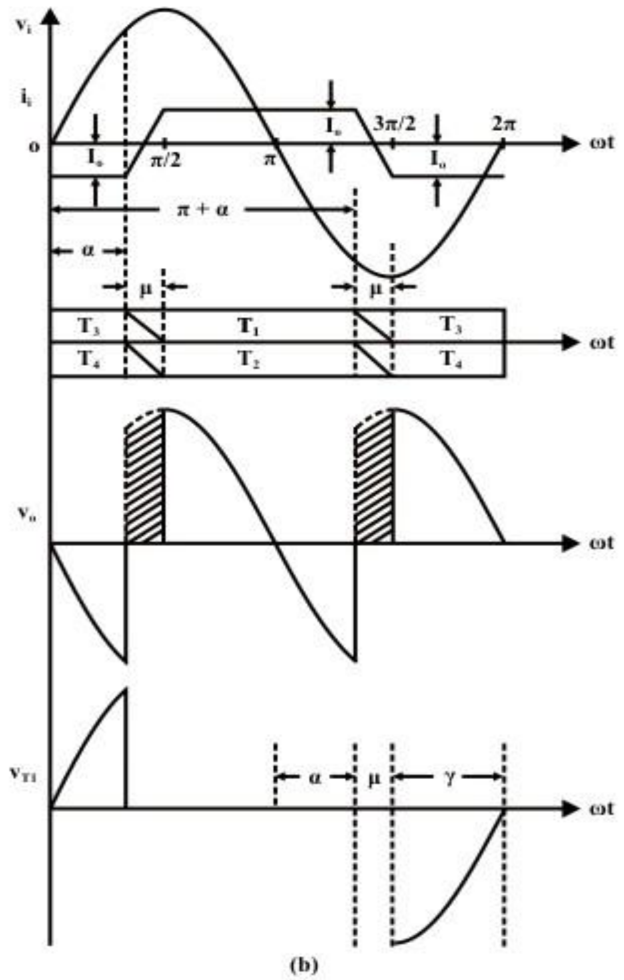
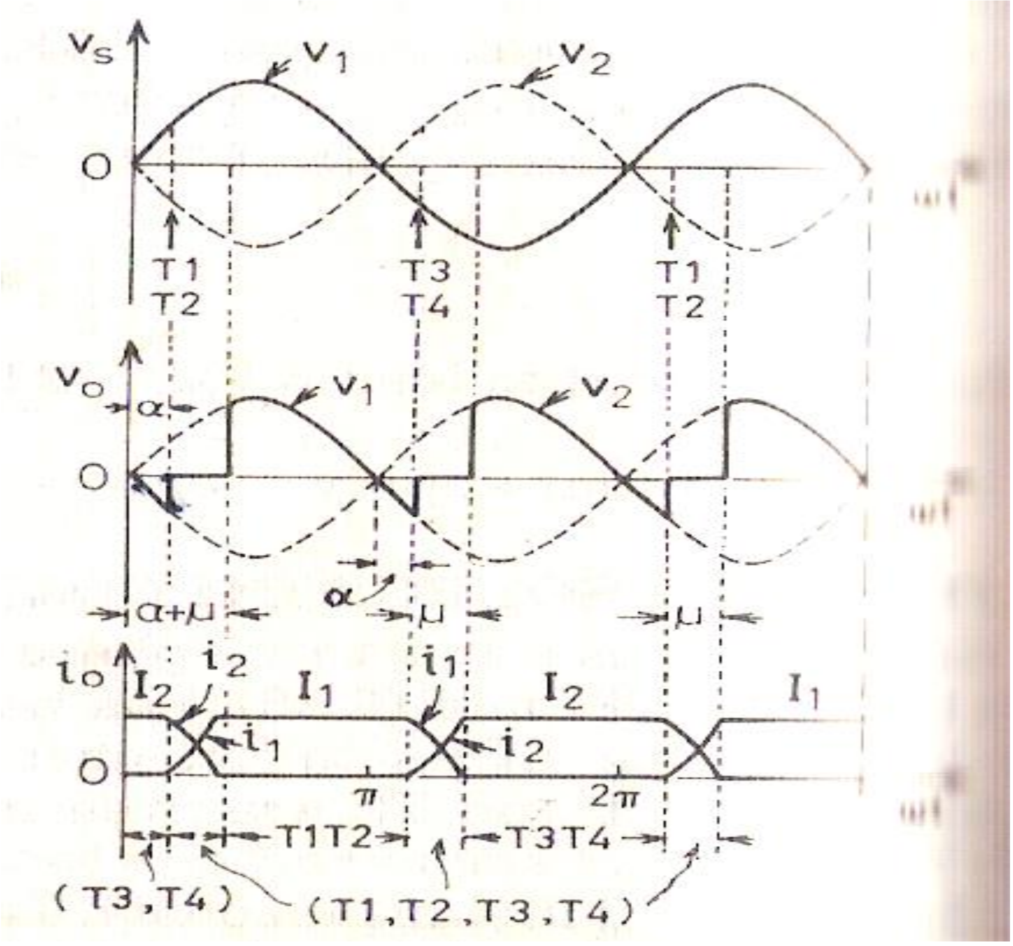
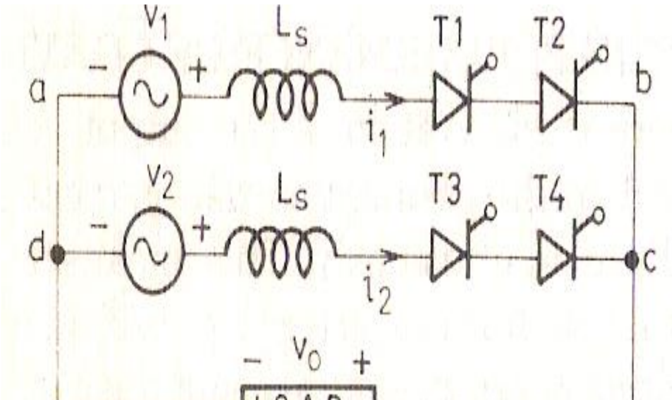


Fig. 15.1: Operation of single phase fully controlled converter with source inductance
(a) circuit diagram,
(b) waveforms.

OUTPUT WAVEFORMS:





$$v_1 - L_s \cdot \frac{di_1}{dt} = v_2 - L_s \frac{di_2}{dt}$$

$$v_1 - v_2 = L_s \left(\frac{di_1}{dt} - \frac{di_2}{dt} \right)$$

It is seen from Fig. 6.32 (c) that if $v_1 = V_m \sin \omega t$, then $v_2 = - V_m \sin \omega t$.

$$\therefore \qquad L_s \left(\frac{di_1}{dt} - \frac{di_2}{dt} \right) = 2\, V_m \sin \omega t$$

As the load current is assumed constant throughout $i_1 + i_2 = I_0$

$$\frac{di_1}{dt} + \frac{di_2}{dt} = 0$$

From Eq. (6.40),

$$\frac{di_1}{dt} - \frac{di_2}{dt} = \frac{2V_m}{L_s} \sin \omega t$$

Addition of Eqs. (6.41) and (6.42) gives

$$\frac{di_1}{dt} = \frac{V_m}{L_s} \sin \omega t$$

$$V_0 = \frac{V_m}{\pi} \int_{(\alpha + \mu)}^{(\alpha + \pi)} \sin \omega t \cdot d(\omega t) = \frac{V_m}{\pi} [\cos (\alpha + \mu) - \cos (\alpha + \pi)]$$

$$= \frac{V_m}{\pi} [\cos \alpha + \cos (\alpha + \mu)]$$

$$\cos (\alpha + \mu) = \cos \alpha - \frac{\omega L_s}{V_m} I_0$$

$$V_0 = \frac{2\, V_m}{\pi} \cos \alpha - \frac{\omega L_s}{\pi} I_0$$

$$\cos\alpha = \frac{\omega L_s}{V_m} I_0 + \cos(\alpha + \mu).\ \text{Su}$$

$$V_0 = \frac{2\,V_m}{\pi}\cos(\alpha + \mu) + \frac{\omega L_s}{\pi} I_0$$

Three-phase half-wave rectifier operation with R and RL loads

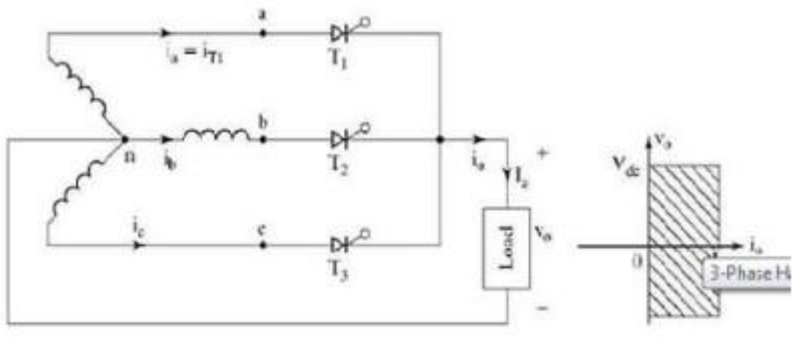


Figure: 2.16 circuit diagram three phase half wave rectifier

Three single phase half wave controlled rectifiers are combined into a single circuit and fed a common load by the three-phase half wave converter. Series with one of the supply phase windings 'a-n', the thyristor T1 functions as a one-half wave regulated rectifier.

The second half wave controlled rectifier is the second thyristor T2, connected in series with the supply phase winding 'b-n'. The third half wave regulated rectifier is the third thyristor T3 connected in series with the supply phase winding.

As shown in the image, the three-phase input supply is applied via the supply transformer that is linked to the star. One end of the load is linked to the supply's common neutral point, while the other end is connected to the common cathode point. The thyristor T1 conducts when $\omega t=(\prod/6 + \alpha)=(30° + \alpha)$ is activated, causing the phase voltage Van to emerge across the load.

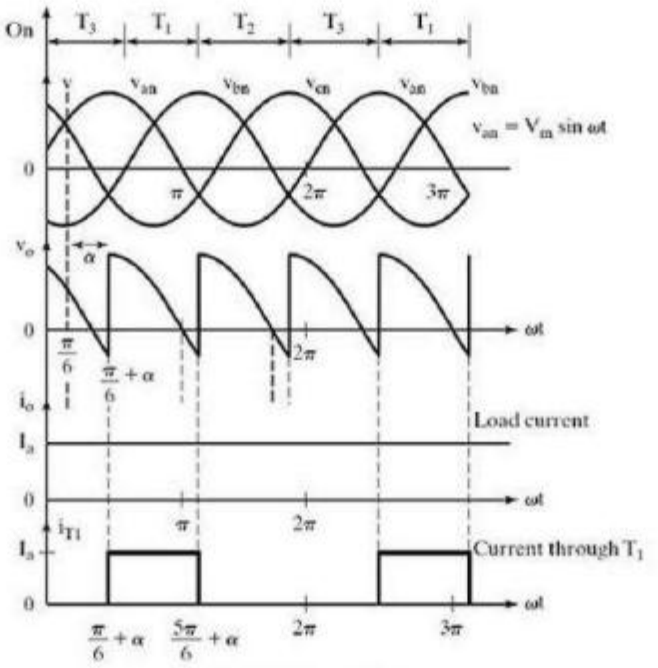


Figure: 2.17 input and output waveforms of three phase half wave rectifier

Equations for three-phase supply voltage

We define three line neutral voltages (3 phase voltages) as follows

$V_{RN} = V_{an} = V_m$ sinwt where V_m is the maximum voltage

$V_{YN} = V_{bn} = V_m \sin (wt-\frac{2\pi}{3})$

$V_{BN} = V_{cn} = V_m \sin (wt-\frac{4\pi}{3})$

The load current passes via thyristor T1 as long as it conducts and through supply phase winding 'an'. Thyristor T1 gets reverse biased and shuts off when thyristor T2 is activated at $\omega t=(5\prod/6\alpha)$. The supply phase windings 'b-n' and the thyristor both receive the load current.

Until the thyristor T3 is activated, the phase voltage vbn is visible across the load while T2 conducts. T2 is reverse biased and switches off when the thyristor T3 is activated at $\omega t=(3\prod/2 + \alpha)=(270°+\alpha)$. When T3 conducts, the phase voltage Van is visible throughout the load. Since the thyristor T3 is inherently reverse biased, it shuts off when T1 is activated once again at the start of the subsequent input cycle.

Assuming a constant and ripple-free load current for a highly inductive load, the figure displays the three-phase input supply voltages, the output voltage that appears across the load, and the current flowing through the thyristor T1. When the polarity of the corresponding phase supply voltage flips, each thyristor naturally commutates, and the load current appears as a discontinuous load current for a fully resistive load with the load inductance "L = 0" and the trigger angle α >(∏/6).

For a three-phase half wave converter, the output 76 | P a g e ripple frequency is fs, where fs is the input supply frequency. 3 Due to the drawback that the supply current waveforms include dc components (i.e., the supply current waveforms have an average or dc value), the 3-phase half wave converter is not often used in practical converter systems.

The reference phase voltage is vRN=van=Vmsinωt, which may be used to calculate the average output voltage of a three-phase half wave converter with continuous load current. The cross-over locations of the 3-phase supply voltage waveforms are used to calculate the trigger angle.

The first cross-over point occurs at ωt=(∏/6)radians 30° when the phase supply voltage Van starts its positive half cycle at ωt=0. The cross over point at is used to calculate the trigger angle α for the thyristor T1. During the ωt=30° to 150° interval, when the phase supply voltage van has a greater amplitude than the other phase supply voltages, the thyristor T1 is forward biased. T1 may thus be activated between 30° and 150°. The equation is used to get the average or dc output voltage for continuous load current when the thyristor T1 is actuated at a trigger angle α.

$$V_{avg} = \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} \text{Vmsinwt}\, d(wt)$$

$$= \frac{3Vm}{2\pi}\left[(-\cos\alpha)_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha}\right]$$

$$= \frac{3\sqrt{3}Vm}{2\pi}\cos\alpha$$

$$= \frac{3Vml}{2\pi}\cos\alpha$$

Using R and RL loads to operate a three-phase half-controlled bridge rectifier

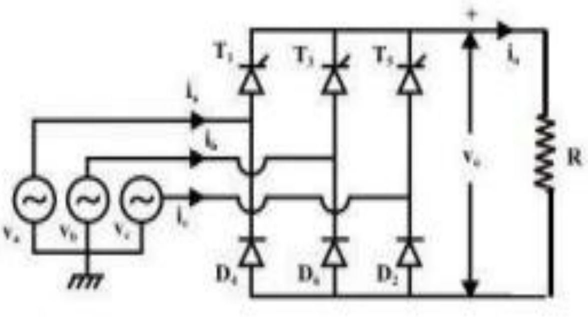


Figure: 2.18 circuit diagram three phase half controlled rectifier

Waveforms of the output voltage of a three-phase half wave regulated rectifier for various trigger angles with R load

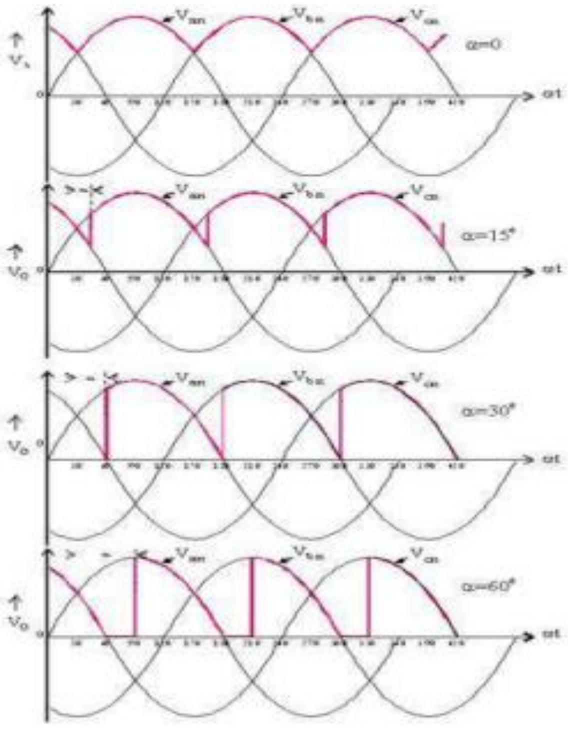


Figure: 2.19 input and output waveforms of three phase half controlled rectifier with R load

It is possible to create a three phase half wave converter by connecting three single phase half wave converters. Similar to this, a three-phase semi-converter utilizes three SCRs (T1, T3, and T5) and three diodes (D2, D4, and D6). In the circuit above, line voltage is delivered across the load whenever any device conducts. In order to draw the phase shift between two line voltages, which is 60 degrees, and between two phase voltages, which is 120 degrees, line voltages are required. Each phase and line voltage is a sine wave with a frequency of 50 Hz. In relation to "N," the phase voltages are R, Y, and B.

The thyristor T1 is activated at ωt=(30°+α) in a three-phase half wave regulated rectifier with a resistive load, and it conducts until ωt=180°=&pron; radians. The load current drops to zero and the thyristor T1 shuts off when the phase supply voltage drops to zero. The conductivity of T1 is therefore from ωt=(30° + α) to (180°). 78 | P a g e Therefore, the equation is used to get the average dc output voltage for a 3-pulse converter (3-phase half wave controlled rectifier).

The average output voltage $V_{avg} = \frac{3}{2\pi}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}} \text{Vmlsinwt}\, d(wt) + \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}+\alpha} \text{Vmlsinwt}\, d(wt)$

$$= \frac{3Vml}{2\pi}\,(1 + cos\alpha)$$

operation of a three-phase completely controlled rectifier with R and RL loads Three-phase full converters use six thyristors coupled in a full wave bridge arrangement to operate as fully controlled bridge controlled rectifiers. The six thyristors are all controlled switches that are activated when the proper gate trigger signals are applied.

When two quadrant operations are needed, the three phase complete converter is widely employed in industrial power applications up to an output power level of about 120kW. A three-phase complete converter with a highly inductive load is seen in the image. This circuit is often referred to as a six pulse converter or a three phase full wave bridge. Thirty degrees, or (∏/3) radians, separate the thyristors' activation points. Compared to three phase semi and half wave converters, the filtering need is lower and the output ripple voltage frequency is 6 fs.

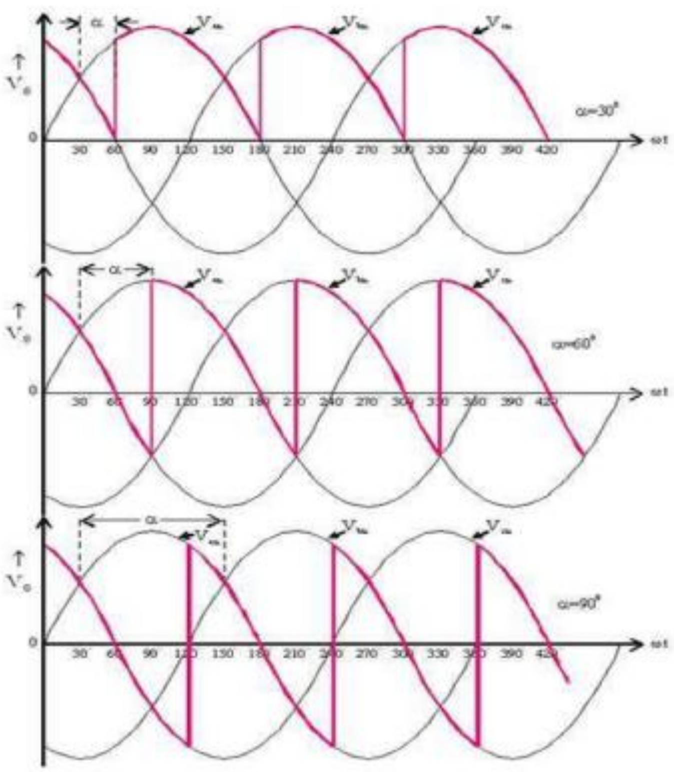


Figure: 2.19 Input and output waveforms of three phase half controlled rectifier with RL load

When the gating signal is sent to the gate of the thyristor, it is already conducting at ωt=(∏/6 +α).

Thyristors conduct together and the line-to-line supply voltage occurs across the load throughout the time interval ωt=(∏/6 +α) to (∏/2 +α). When ωt=(∏/2 + α), the thyristor T2 is activated, T6 is instantly reverse biased, and T6 shuts off as a result of natural commutation.

Thyristors T1 and T2 conduct together throughout the interval ωt=(∏/ +α) to (5∏/6 +α), and the line-to-line supply voltage is visible across the load. In the circuit schematic, the thyristors are numbered according to the sequence in which they are activated. The thyristors' trigger sequence, also known as their firing sequence, is 12, 23, 34, 45, 56, 61, 12, 23, and so on. The three-phase input supply voltage waveforms, output voltage, thyristor current via T1 and T4, and supply current through line "a" are all shown in the figure. VRN = Van = Vm sinwt, where Vm is the maximum voltage, is how we construct three line neutral voltages (3 phase voltages).

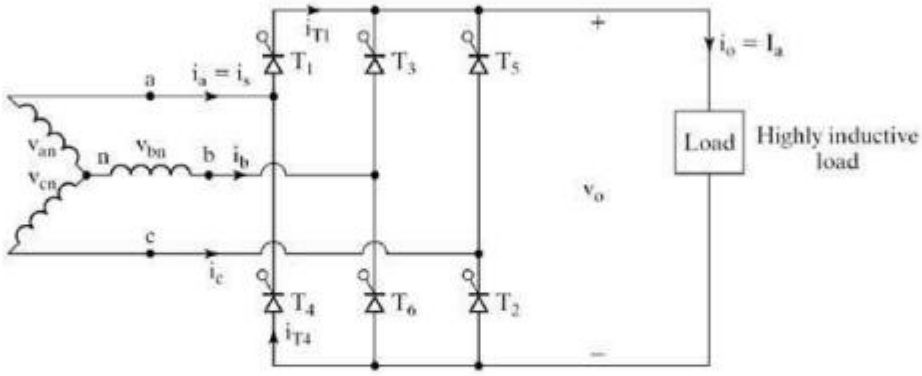


Figure: 2.20 circuit diagram three phase fully controlled rectifier with R and RL load

$V_{RN} = V_{an} = V_m$ sinwt where V_m is the maximum voltage

$V_{YN} = V_{bn} = V_m \sin\left(wt - \frac{2\pi}{3}\right)$

$V_{BN} = V_{cn} = V_m \sin\left(wt - \frac{4\pi}{3}\right)$

The corresponding line to line voltages are

$V_{RY} = V_{ab} = V_{an} - V_{bn} = \sqrt{3}\,Vm \sin\left(wt + \frac{\pi}{6}\right)$

$V_{YB} = V_{bc} = V_{bn} - V_{cn} = \sqrt{3}\,Vm \sin\left(wt - \frac{\pi}{2}\right)$

$V_{BR} = V_{ca} = V_{cn} - V_{an} = \sqrt{3}\,Vm \sin\left(wt + \frac{\pi}{2}\right)$

An equation for the average output voltage of a three-phase full converter with a strongly inductive load, assuming continuous and constant load current, is derived as follows: The output load voltage is composed of six voltage pulses over a 2-radian time.

$$V_{avg} = \frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vod(wt)$$

$$V_o = V_{ab} = \sqrt{3}\,Vm \sin\left(wt + \frac{\pi}{6}\right)$$

$$V_{avg} = \frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} \sqrt{3}\,Vm \sin\left(wt + \frac{\pi}{6}\right) d(wt)$$

$$= \frac{3\sqrt{3}Vm}{\pi}\cos\alpha$$

$$= \frac{3Vml}{\pi}\cos\alpha$$

The output voltage's RMS value is determined from

$$V_{orms} = \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vo^2\,d(wt)\right]^{1/2}$$

$$= \left[\frac{6}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} Vab^2\,d(wt)\right]^{1/2}$$

$$= \left[\frac{3}{\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{\pi}{2}+\alpha} 3\ Vm^2 \sin^2\left(wt+\frac{\pi}{6}\right) d(wt)\right]^{1/2}$$

$$= \sqrt{3}Vm\left(\frac{1}{2}+\frac{3\sqrt{3}}{4\pi}cos2\alpha\right)^{1/2}$$

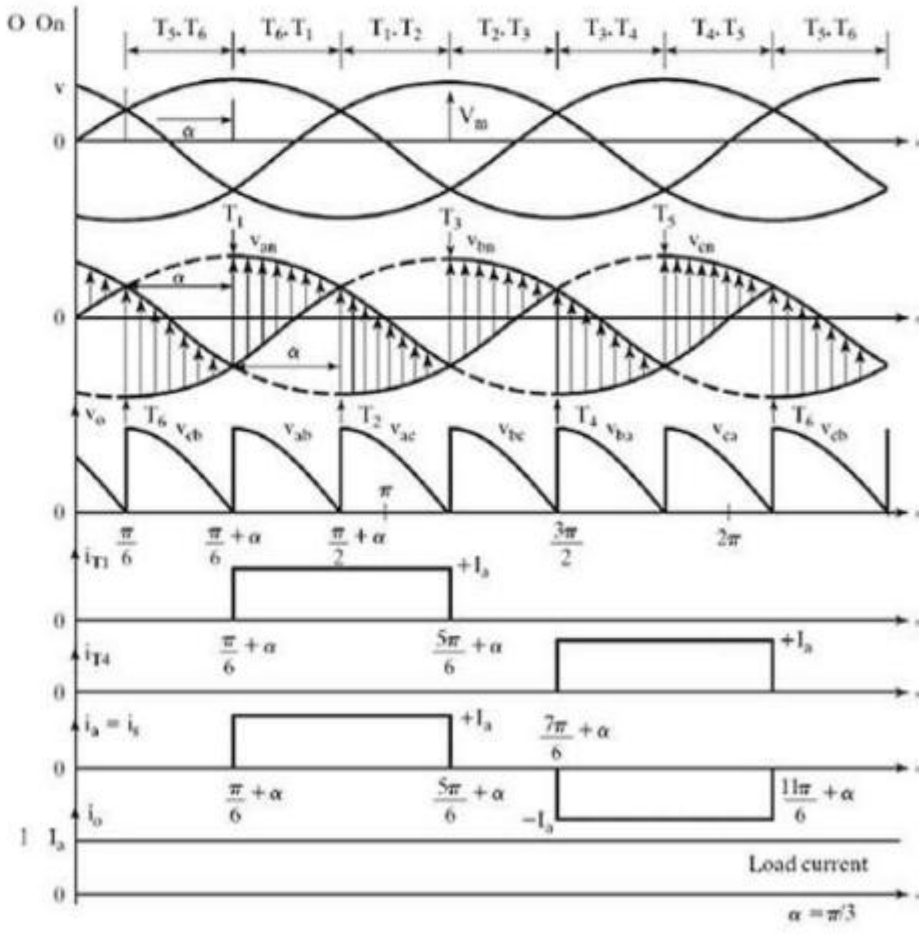


Figure: 2.21 Input and output waveforms of three phase fully controlled rectifier