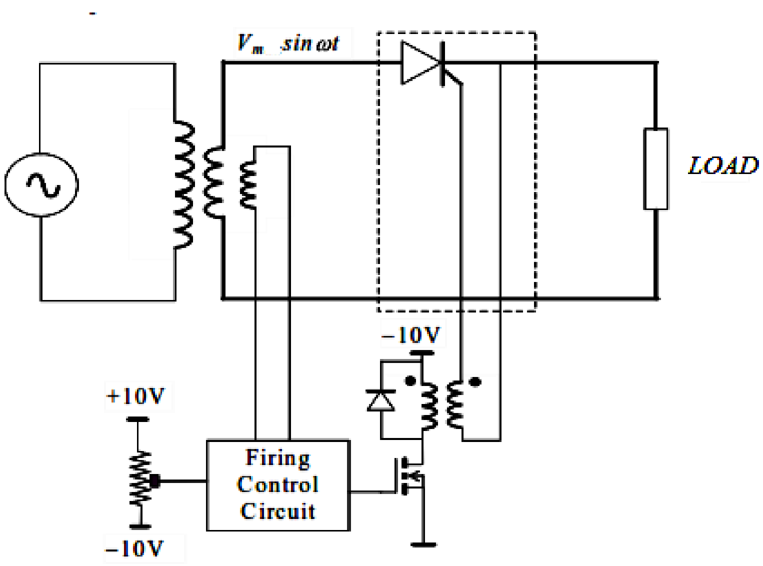
6. Controlled Rectifications

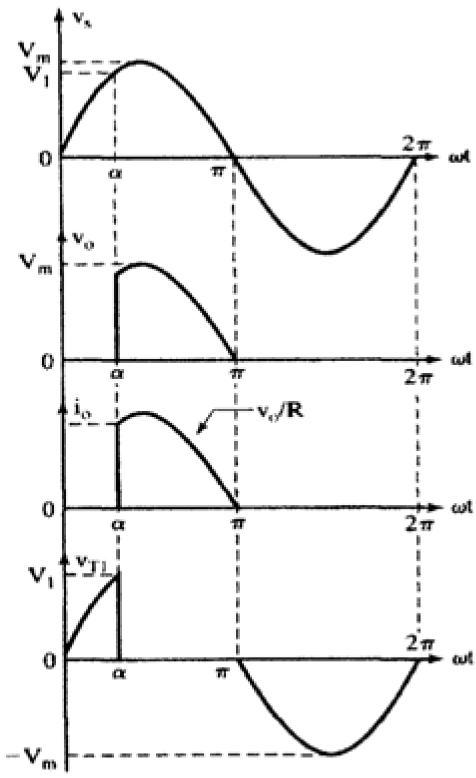
In this type, the generated DC power is controllable and variable. They usually use SCRs as their power switches. For fast switching operation, MOSFETs and IGBTs are used. The following subsections deal with the basic operation of some examples of controlled rectifiers single-phase half-wave controlled rectifier loaded with resistive load.

1. Single-phase, half-wave, controlled rectifier loaded with a resistive load

Fig. 6.1(a) shows the basic circuit for a single-phase, half-wave, controlled rectifier loaded with a resistive load. For this configuration, the thyristor will conducts when triggered using gate pulses provided that the supply voltage (v_S) is positive.The thyristor is fired at $\omega t=\alpha$ and the input voltage appears across the load. At $\omega t = \pi$, T_1 is reverse-biased by the negative supply voltage and is turned off. 'α' is termed as the delay or firing angle. The converter is said to operate in the first quadrant. This converter is not normally used in the industrial application because of its high ripple current and low ripple frequency. The waveforms for one total period of operation of this circuit are shown in Fig. 6.1(b).



(a) Circuit



(b) Waveforms

Fig.6.1 Single-phase half-wave controlled rectifier.

The average value of the load voltage V_{dc} can be calculated as follows

$$V_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\pi} v_s(\omega t)\, d\omega t = \frac{1}{2\pi}\int_{\alpha}^{\pi} V_m \sin(\omega t)\, d\omega t$$

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

The average value of the load current I_{dc} is

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

Therefore, the average output voltage can vary from 0 to V_m/π and the average load current will vary from 0 to $V_m/\pi R$ when varying α from π to 0, respectively.

The rms value of the load voltage V_{rms} can be calculated as follows,

$$V_{rms} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi}\{v_s(\omega t)\}^2\, d\omega t} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi}\{V_m \sin(\omega t)\}^2\, d\omega t}$$

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

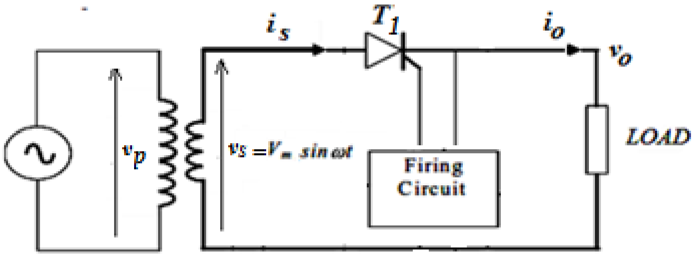
Therefore the rms value of the load current I_{rms} is

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

The PRV of the thyristor for this configuration is V_m .

Example -1 : A single- phase half - wave controlled rectifier shown in Fig.1, operates from an ideal sinusoidal source with v_s = 325 sinωt, at 50 Hz . If the load is purely resistive, and at a certain triggering α , the output d.c. voltage is V_{dc} = 95V, and the average value of the load current is 2.2 A. It is required to calculate the following:

(a) The triggering angle α
(b) Load resistance
(c) R.m.s load voltage
(d) R.m.s load current
(e) DC power
(f) The ripple factor



Solution

(a) For single-phase half-wave controlled rectifier with resistive load;

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

$$95 = \frac{325}{2\pi}(1+cos\alpha)$$

Hence α = 33.31° .

(b)

$$R = \frac{V_{dc}}{I_{dc}} = \frac{95}{2.2} = 43.18\Omega$$

(c) r.m.s load voltage

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

$$= \frac{325}{2}\sqrt{\frac{1}{\pi}(\pi-0.58+\frac{1}{2}sin66.62°)} = 159.34\,V$$

(d) R.m.s load current

$$I_{orms} = \frac{V_{orms}}{R} = \frac{}{43.18} = 3.7A$$

(e) The output DC power is given by:

$$P_{dc} = V_{dc}I_{dc} = \frac{V_{dc}^2}{R} = \frac{95^2}{43.18} = 209\,W$$

(f)

$$\text{Ripple factor} = \frac{\sqrt{V_{orms}^2 - V_{dc}^2}}{V_{dc}} = \frac{\sqrt{159.34^2 - 95^2}}{95} = 1.34$$

2. The Freewheeling Diode

The freewheeling diode is connected in the circuit in such away as to provide an alternative path for the decaying load current so that the thyriator current is al1owed to become zero and the thyristor is allowed to switch off.

Consider the half—wave rectifier of Fig 6.2 where FD is the freewheeling: diode. Then the supply voltage is positive, from α to π, FD is in reverse and passes no current,, so that source end load current are equal (is = i). During the negative half—cycle, the load current i flows through the low resistance path provided by FD rather than against the negative supply voltage, so that $i_{FD} = i$, and $i_s = 0$. Hence the thyristor.

This allowed to switch off. In this part of the half— cycle, the current is driven by the energy stored in L; it decays according to the time constant of the circuit (R, L, and FD); v is very small and negative, being equal to the voltage drop across FD.

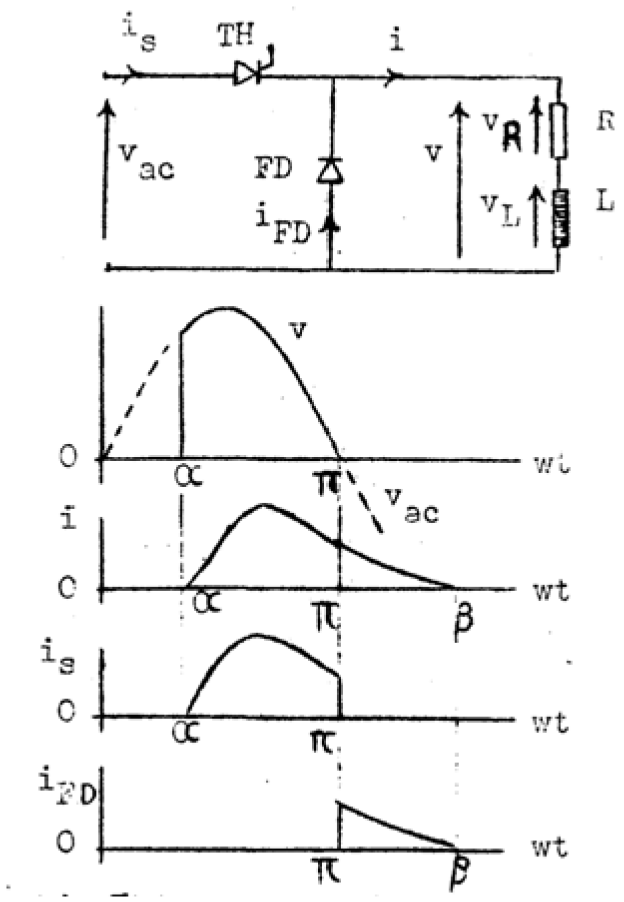


Fig.6.2

3. Single-phase controlled converter circuits

3.1 Single-phase, fully-controlled bridge rectifier (p = 2)

Single-phase, fully-controlled full- wave rectifier bridge is shown in Fig.6.3.In this this circuit, two thyristors must triggered simultaneously to permit current to flow. For example, with the instantaneous polarity indicated in Fig.6.3, T1 and T4 must be triggered, while in reverse, T3 and T2 must triggered at the same time. The output voltage waveform is shown in Fig.6.4 for the case of resistive load.

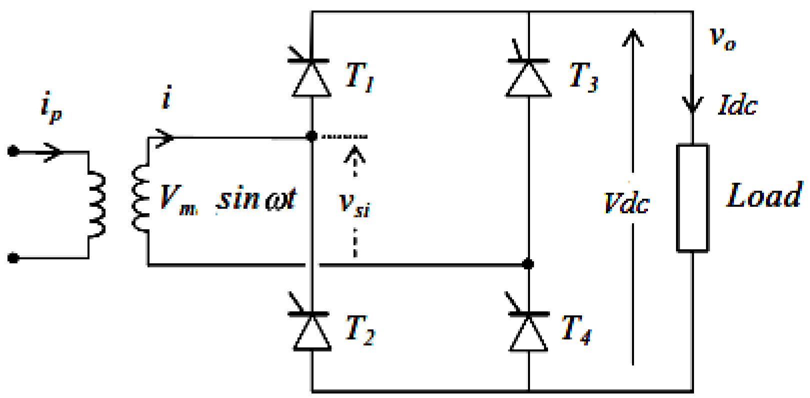


Fig. 6.3 Single-phase fully-controlled full- wave Rectifier Bridge

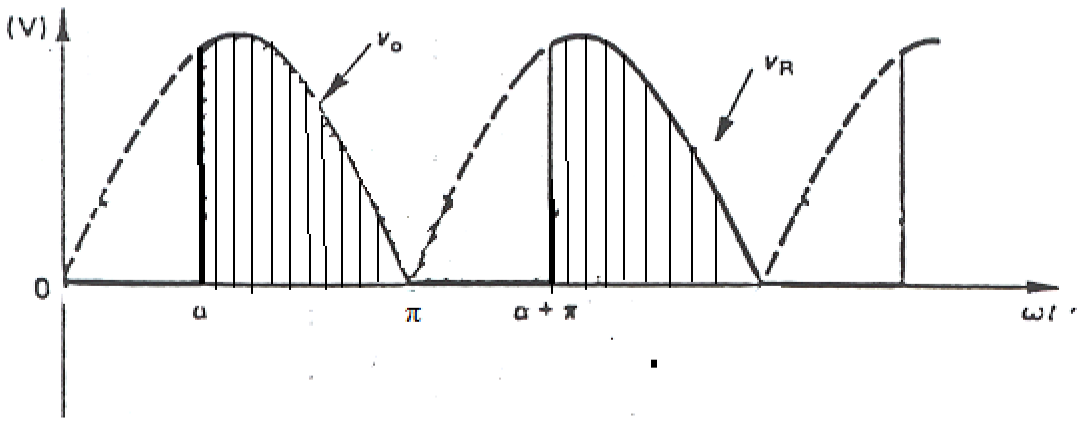


Fig.6.4 Output voltage waveform

- **Operation of the converter with Resistive load**

The dc output voltage of the converter with resistive load is given by

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi} V_m \sin\omega t \, d\omega t$$

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

$$\text{RMS output voltage} = V_{rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}(V_m \sin\omega t)^2 d\omega t}$$

$$= V_m \sqrt{\frac{\pi - \alpha + \frac{1}{2}\sin 2\alpha}{2\pi}}$$

- **Operation of the converter with R – L load**

(i) Case of R - L load with small L / R ratio : <u>Discontinuous load current</u> .

In this case the current will be discontinuous as shown in Fig.6.5.

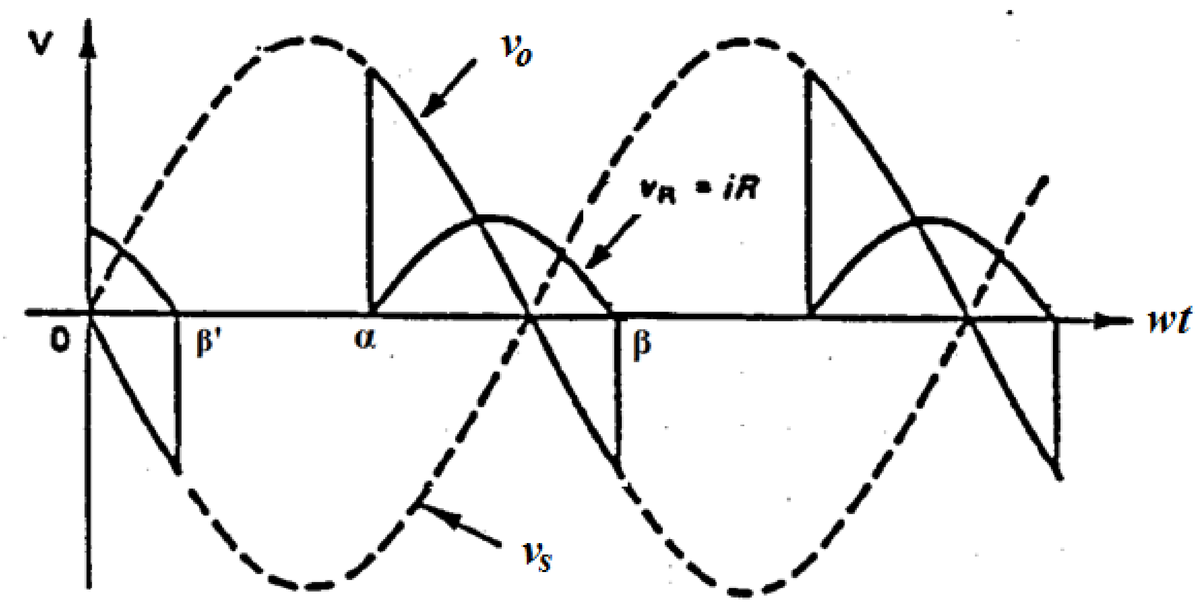


Fig.6.5 Discontinuous current operation.

For $\alpha \le \omega t \le \beta$, the circuit equation is given by :-

$$\text{Average output voltage} = V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\beta} V_m \sin\omega t \, d\omega t$$

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

(ii) Case of R - L load with large L / R ratio: <u>Continuous load current</u> .

Under these conditions, a thyristor is still conducting when another is forward-biased and is turned on. The first device is instantaneously reverse-biased by the second device which has been turned on. The first device is commutated and load current is instantaneously transferred on the incoming device . In this case the current is continuous as shown in Fig.6.6.

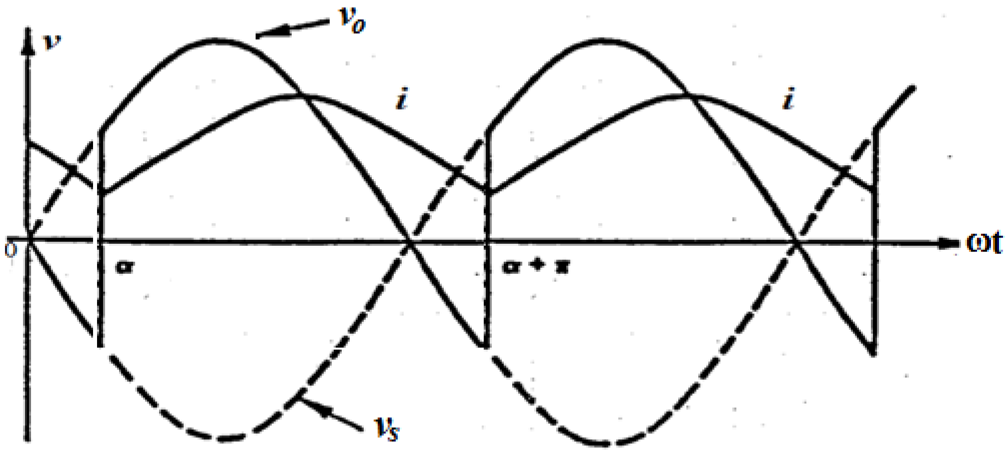


Fig. 6.6

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

Under all delay angle condition, the average current is given by:

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

From the above voltage equation, if the firing angle is greater than 90°, the average voltage can be negative .Thus if the firing angle is suddenly increased to 170° , a large negative voltage will be applied to the load and the power is fed back to the supply. This process is known as 'INVERSION'.
The graph shown in Fig. 6.7 gives the relation between the firing angle and the output voltage in p.u. for the two modes of operation (continuous and discontinuous) for full-wave single- phase rectifier.

Rule – of- thumb: To find roughly the current is continuous or discontinuous:

If $\pi + \alpha < \beta$ The current is continuous
If $\pi + \alpha > \beta$ The current is discontinuous

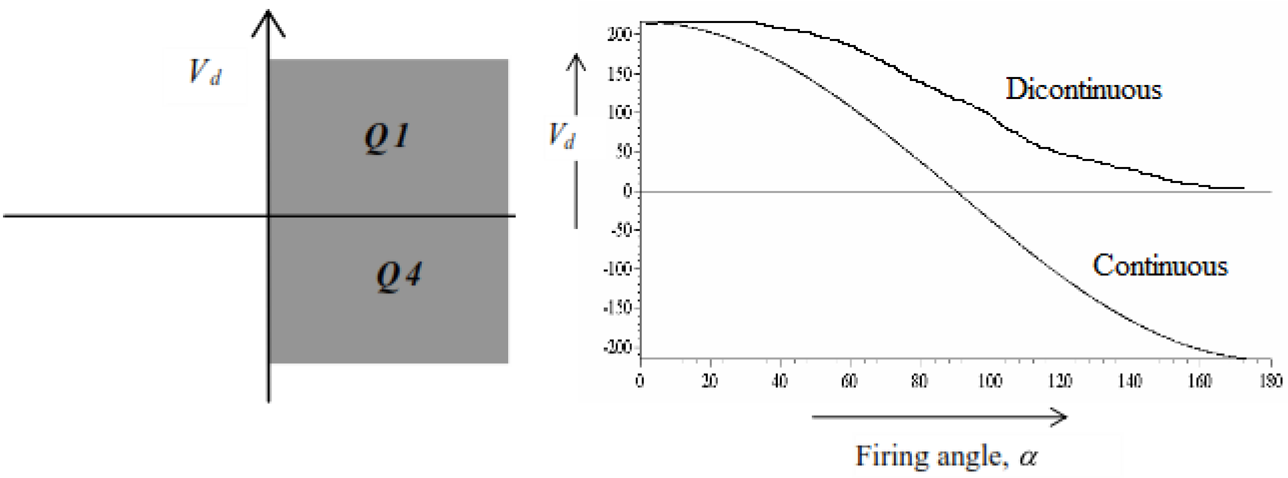


Fig. 6.7

Example: A single-phase fully controlled full-wave rectifier shown in Fig.8 has a source of 220 V r.m.s at 50 Hz, and is feeding a load R = 15 Ω and L = 20 mH. The firing angle $\alpha = 30°$ and the current extinction angle β =225.

(a) Specify whether the current is continuous or discontinuous.
(b) Sketch the appropriate load voltage and load current waveforms
(c) Determine the average load voltage and current.
(d) Determine the r.m.s load voltage and current.
(e) Determine the a.c and d.c powers absorbed by the load.
(f) If thyristor T_3 fails to open circuit, what will be the average output voltage?

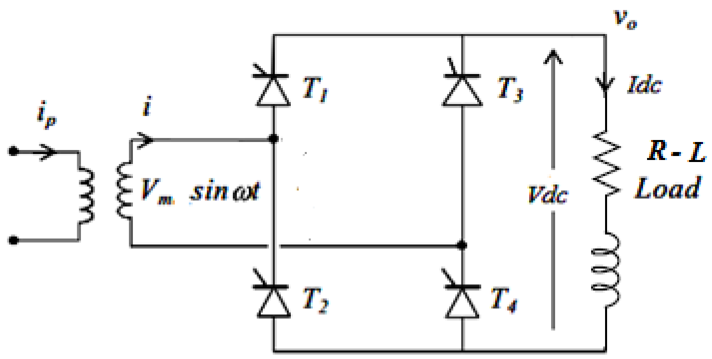


Fig.8

Solution

(a) Since

$\pi + \propto = 180° + 30° = 210° < \beta$ then the current is continous

(b) The load voltage v_o and load current i waveforms are as in figure 6.9

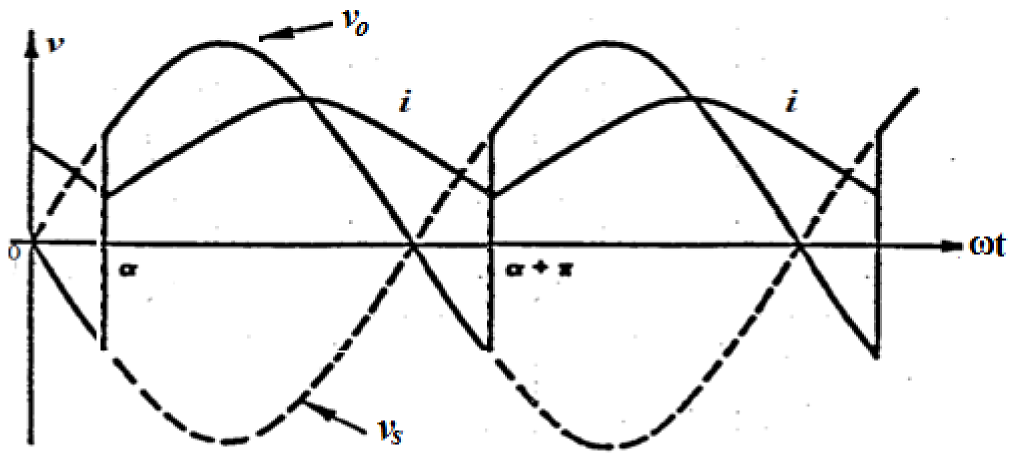


Fig.6.9 Same as Fig.6.6.

(c)

$$V_m = 220 \times \sqrt{2} = 311.08 \text{ V}$$

$$V_{dc} = \frac{1}{\pi} \int_{\propto}^{\propto + \pi} V_m sin\omega t \ d\omega t = \frac{2 \ V_m}{\pi} cos\alpha$$

$$= \frac{2 \times 311.08}{\pi} \cos 30 = 171.12 \ V$$

$$I_{dc} = \frac{V_{dc}}{R} = \frac{171.12}{15} = 11.44 \ A$$

(e) The rms values of the output voltage and current:

$$V_{orms} = \frac{V_m}{\sqrt{2}}\sqrt{\frac{1}{\pi}(\pi - \alpha + \frac{1}{2}sin2\alpha)} = \frac{220x\sqrt{2}}{\sqrt{2}}\sqrt{\frac{1}{\pi}(\pi - \frac{\pi}{6} + \frac{1}{2}sin60°)}$$
$$= 216.788 \text{ V}$$

$$I_{orms} = \frac{V_{rms}}{Z_L} = \frac{V_{rms}}{\sqrt{R^2 + (\omega L)^2}} = \frac{216.88}{15^2 + (2\pi x50x20x10^{-3})^2} = 13.29 \text{ A}$$

(f) The dc and ac powers are,

$$P_{dc} = V_{dc}\, I_{dc} = 171.12 \times 11.44 = 856.73 \text{ W}$$

$$P_{ac} = V_{rms}\, I_{rms} = 216.788 \times 13.29 = 2881.78 \text{ W}$$

(g) If thyristor T_3 fails to open circuit, then the cct will act as half-wave controlled rectifier

$$V_{dc} = \frac{V_m}{2\pi}(1 + cos\alpha) = 311.08 \times \frac{1}{2\pi}(1 + cos30) = 92.43V$$

(iii) Case of highly inductive load. (L > > R)

Fig. 6.8 (a) shows the circuit connection for a single-phase, full-wave, controlled rectifier loaded with a highly inductive load. For one total period of operation of this circuit, the corresponding waveforms are shown in Fig. 6,8(c) . The average value of the load voltage V_{dc} can be calculated as follows,

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} v_s(\omega t)\, d\omega t = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} V_m \sin(\omega t)\, d\omega t\, d\omega t$$

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

Since the load is a highly inductive load. Then, the load current is considered constant (ripple free current) and equal to the average value of the load current I_{dc} as follows,

$$I_{dc} = I_a = \frac{V_{dc}}{R} = \frac{2V_m}{\pi R}\cos(\alpha)$$

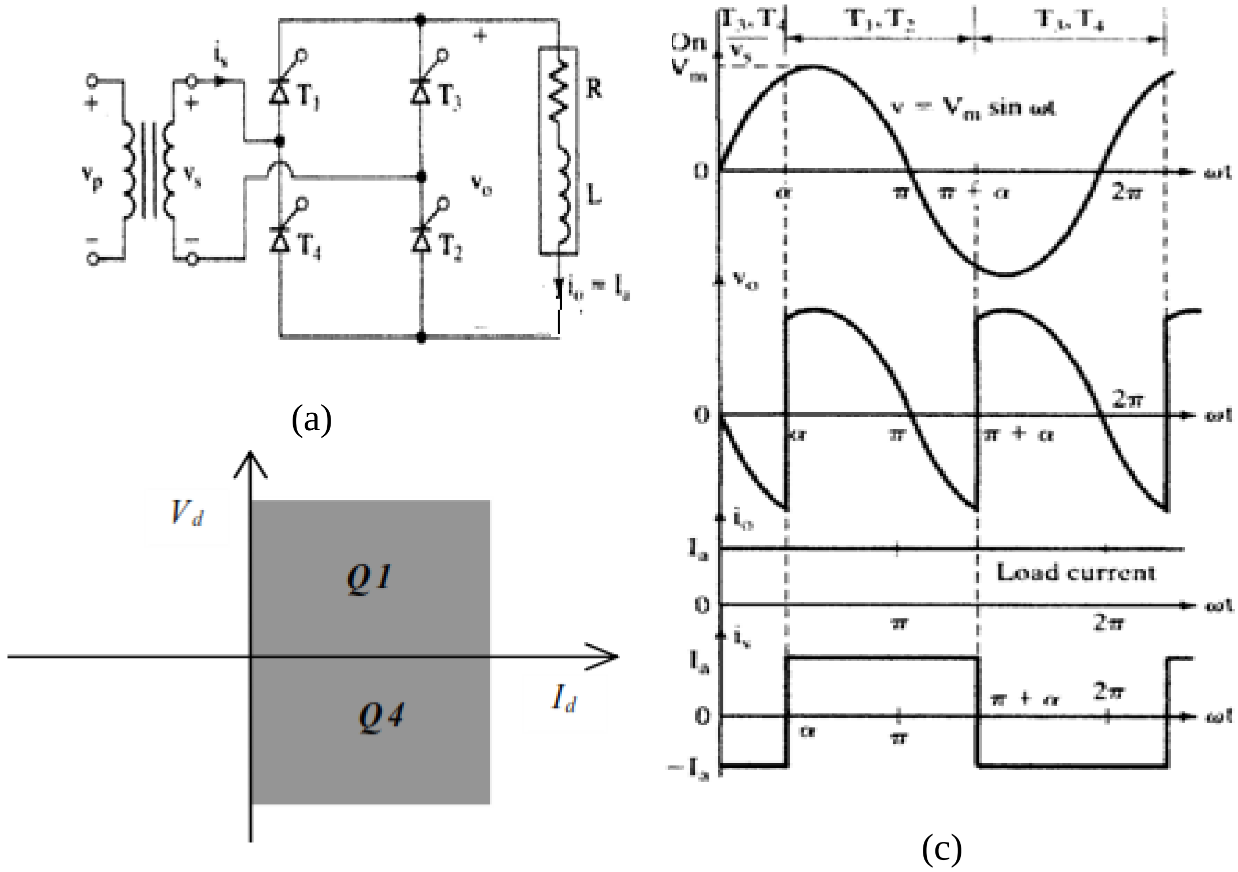


Fig. 6.8 Single phase full-wave rectifier loaded with highly inductive load

Therefore, the average output voltage can vary from $+2V_m/\pi$ to $-2V_m/\pi$ when varying α from π to 0, respectively. Moreover, since the load voltage for this configuration can be positive or negative while the load current is always positive because the thyristors prevents a reverse current flow. Therefore, this converter operates in the first and the fourth quadrants as shown in Fig. 6.8(b).
The rms value of the load voltage V_{rms} can be calculated as follows,

$$V_{rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha}\{v_s(\omega t)\}^2\, d\omega t} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi+\alpha}\{V_m \sin(\omega t)\}^2\, d\omega t} = \frac{V_m}{\sqrt{2}}$$

Since the load current is constant over the studied period, therefore the rms value of the load current I_{rms} is :

$$I_{rms} = I_{dc} = I_a$$

The PRV for any thyristor in this configuration is (V_m).