Chapter 6

Phase Controlled Converters

LEARNING OBJECTIVES:

- To examine the operation of naturally commutated converters.
- To understand the operation of converters in the rectifying and inverting modes.
- To understand the operation of single-phase and three-phase half controlled and fully controlled converters.
- To develop the general equations describing converter behaviour.
- To consider the function and operation of the freewheeling diode.
- To examine the effect of source inductance on commutation and to define overlap.
- To understand the various firing schemes for converters.
- To Understand the various techniques of improving power factor in phase controlled converters.

6.1 INTRODUCTION

Rectification is a process of converting an alternating current or voltage into a direct current or voltage. This conversion can be achieved by a variety of circuits based on and using switching devices. The widely used switching devices are diodes, thyristors, power-transistors, power MOS, etc. The rectifier circuits can be classified broadly into three classes: uncontrolled, fully-controlled and half-controlled. An uncontrolled rectifier uses only diodes and the d.c. output voltage is fixed in amplitude by the amplitude of the a.c. supply. The fully-controlled rectifier uses thyristors as the rectifying elements and the d.c. output voltage is a function of the amplitude of the a.c. supply voltage and the point-on-wave at which the thyristors are triggered (called firing-angle α). The half-controlled rectifier contains a mixture of diodes and thyristors, allowing a more limited control over the d.c. output voltage-level than the fully-controlled rectifier. The half-controlled rectifier is cheaper than a fully-controlled rectifier of the same ratings but has operational limitations.

Uncontrolled and half-controlled rectifiers will permit power to flow only from the a.c. system to the d.c. load and are, therefore, referred to as unidirectional converters. However, with a fully-controlled rectifier it is possible, by control of the point-on-wave at which switching takes place, to allow power to be transferred from the d.c. side of the rectifier back into the a.c. system. When this occurs, operation is said to be in the inverting mode. The fully controlled converter may therefore be referred to as a bidirectional converter.

Hence it is possible for the phase-controlled converters to provide either a one- quadrant, two-quadrant or four-quadrant operation at its d.c. terminals. Figure 6.1(a) shows the diagrammatic representation of one-quadrant converter which contains controlled and uncontrolled rectifiers in different circuit positions. With one-quadrant converters only one polarity of voltage and current at d.c. terminals is possible. Figure 6.1(b) shows the two-quadrant converter diagrammatic representation, which contains controlled rectifiers in all circuit positions. With two quadrant converters, the power can be made to flow either from the a.c. to the d.c. side of the converter or *vice versa*. Figure 6.1(c) shows the diagrammatic representation of four-quadrant converters which contains two 2- quadrant converters, connected back-to-back with one another, thus providing the facility for bidirectional current-flow through the load.

Rectifiers are often described by their pulse-number. This is the number of discrete switching operations involving load-transfer (commutation) between individual diodes, thyristors, etc., during one cycle of the a.c.-supply waveform. The pulse-number is, therefore, directly related to the repetition period of the d.c. voltage waveform and it is sometimes expressed in terms of the ripple-frequency of this waveform. For example, a six-pulse converter operating from a 50 Hz-supply produces a 300 Hz (6×50) ripple in the output d.c. voltage-waveform.

The converter type depends on the power to be handled and how much voltage ripple will be tolerated. For low-powers, below 20 kW, single-phase circuits are adequate but they themselves can take different forms. For high powers, above 20 kW, three-phase circuits are used.

This chapter presents the analysis of different configurations of phase controlled rectifiers. The output voltage in all the configurations is controlled by delaying the firing-angle of the thyristor.

6.2 CONTROL TECHNIQUES

Figure 6.2 shows the technique of controlled conversion from ac to dc for a half-wave circuit which uses a unidirectional switch. When this switch S is turned-on, it conducts current in the direction of the arrow. The output voltage waveform depends on the switch control waveform and the pulse-triggered switch, such as SCR, GTO and MCTs or level-triggered switch such as BJT, MOSFET and IGBTs. Current pulses are required for triggering SCRs and GTOs whereas voltage pulses are required for MCTs, MOSFETs and IGBTs. Usually the source has an inductance, such as the ac line inductance or leakage inductance of transformer. For analysis purpose we neglect this inductance.

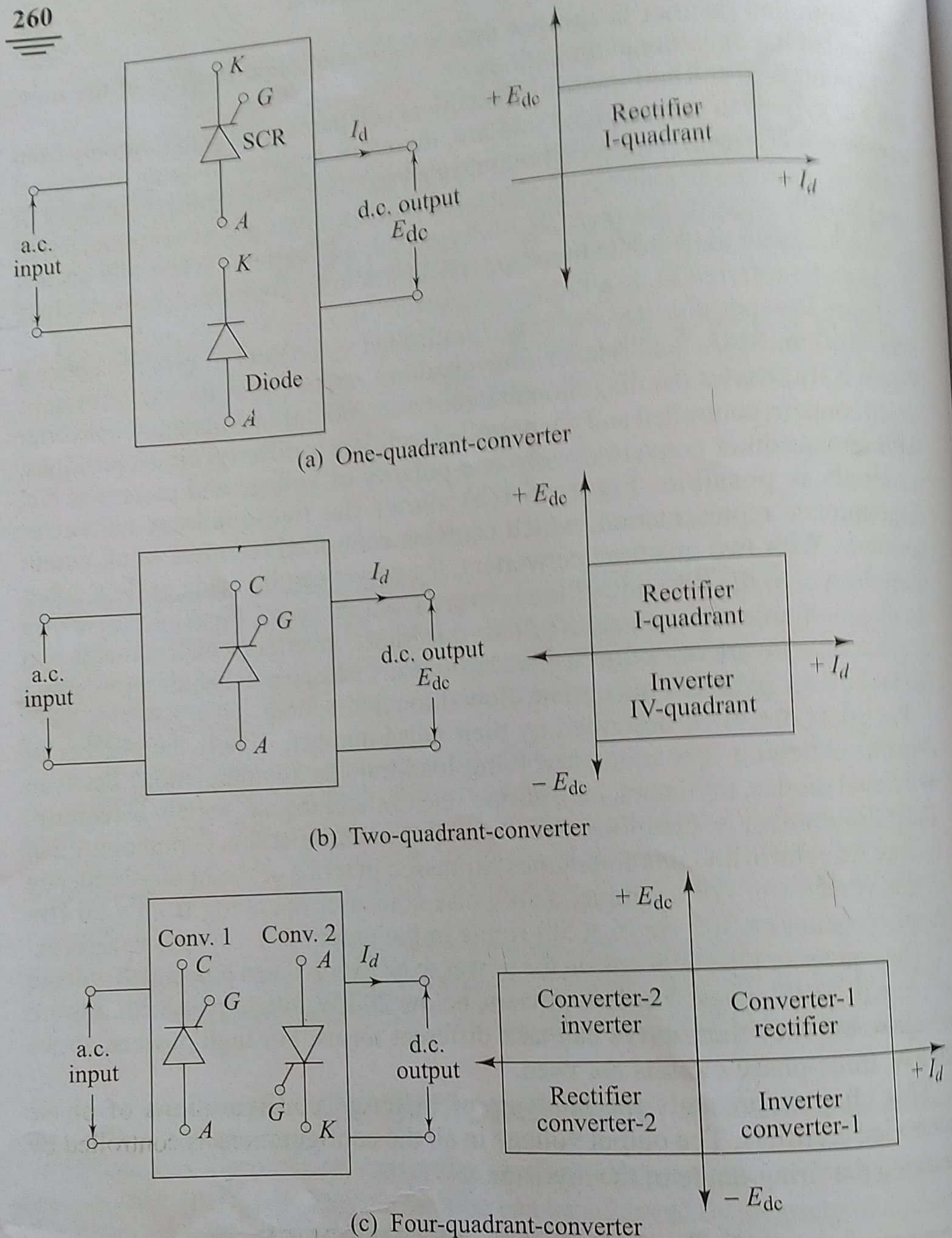

Fig. 6.1 *Types of phase-controlled converters*

6.2.1 Phase Angle-Control [Firing Angle Control]

In a.c. circuits, the SCR can be turned "on" by the gate at any angle, with respect to the applied voltage. This firing angle is measured with respect to a given reference, at which the firing pulses are applied to the thyristor gates. The reference point is the point at which the application of the gate pulses results in the maximum mean positive d.c.-terminal voltage of which the converter is capable. In other words, a firing-angle of 0° corresponds to the conditions when each thyristor in the circuit is fired at the instant its anode voltage-first becomes positive in each cycle, under this condition, therefore, the converter operates in exactly the same manner as if it was an uncontrolled rectifier circuit. The 'α' is the symbol for the firing-angle. Hence, the most efficient method to control the turning "on" of a thyristor is achieved by varying the firing-angle of thyristor. Such a method of control is called as phase-angle control. This phase-angle control is a highly efficient means of controlling the average-power to loads such as lamps, heaters, motors, d.c. suppliers, etc.

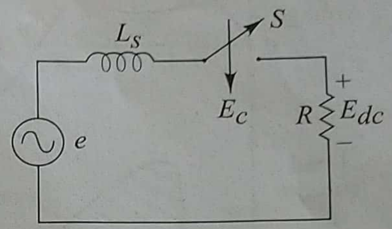

Fig. 6.2 *Half-wave controlled converter using unidrectional switch*

Those converters which work on the principle of natural commutation are called "line-commutated converters." There are many forms of phase-control possible with the thyristor. These various forms are discussed in the subsequent sections.

Figure 6.3 shows various waveforms obtained using phase-angle control for half-wave-controlled converter circuit. In a pulse-triggered switch, the falling edge of the control pulse (V_C) lies at an angle $\alpha + \delta$, as shown in Fig. 6.3 (c), where δ is a short angle. Once the switch is turned-on, it remains ON even if the triggering pulse has subsided. It can be turned-off only when the current through it is reduced below the holding current (in case of SCR).

In a level triggered switch, the falling edge lies at an angle π, as shown in Fig. 6.3 (d).

6.2.2 Extinction Angle Control

Figure 6.4 shows the output voltage waveform and the control pulses for the level-triggered and pulse-triggered switches. The rising edge of the control pulse coincides with the beginning of the input voltage waveform. The falling edge lies at a controllable angle ($\pi - \beta$). Angle β is called as the extinction angle. In a pulse triggered switch, the control pulse consists of two short pulses: one for turning-on and the other for forced-turn-off.

6.2.3 Pulse Width Modulation (PWM) Control

The output voltage waveform and control pulses using PWM control are shown in Fig. 6.5. As shown, the control pulse is symmetrically positioned with respect to the positive and negative peaks of the input voltage waveform. Pulse width δ is the control parameter. Like extinction angle control, the control pulse consists of two short pulses in case of pulse-triggered switch.

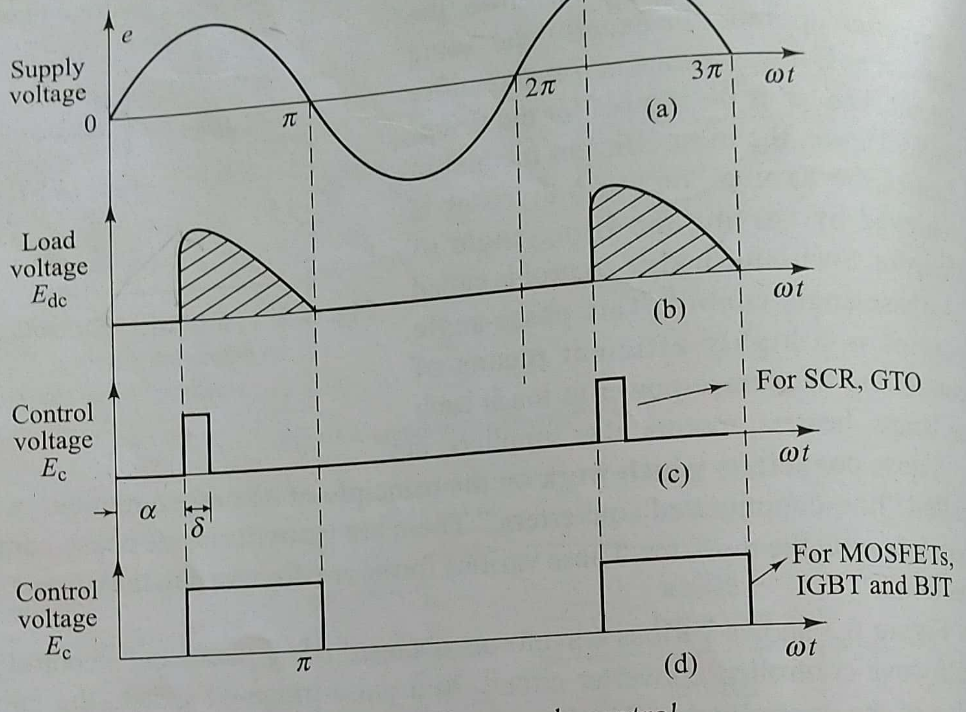

Fig. 6.3 *Phase-angle control*

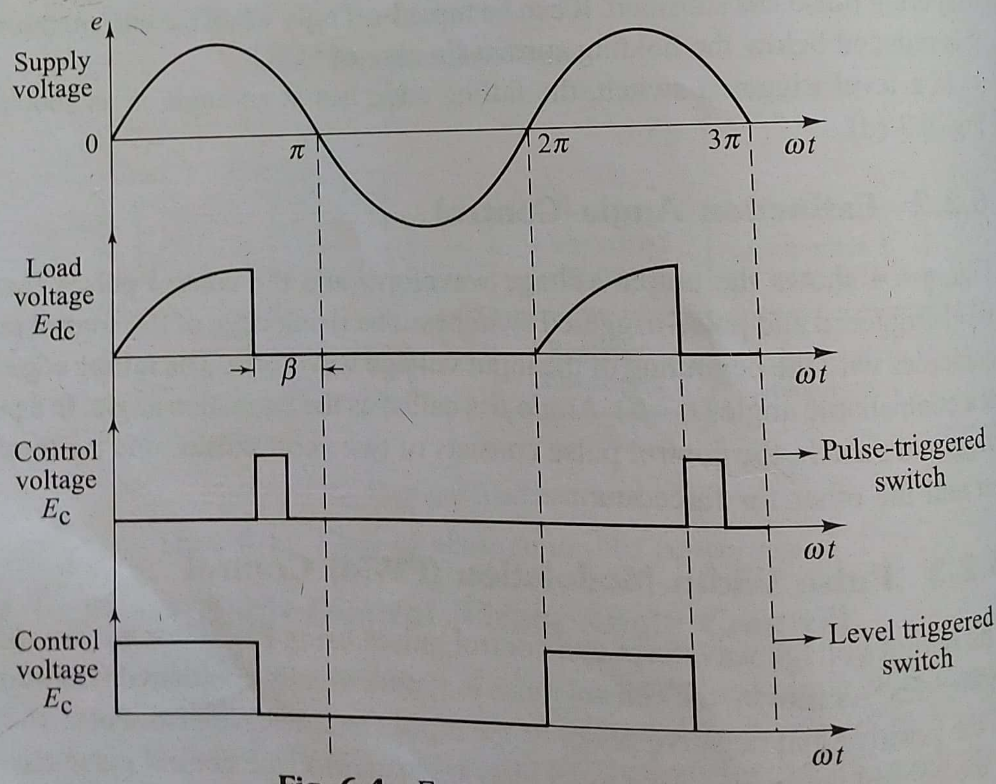

Fig. 6.4 *Extinction angle control*

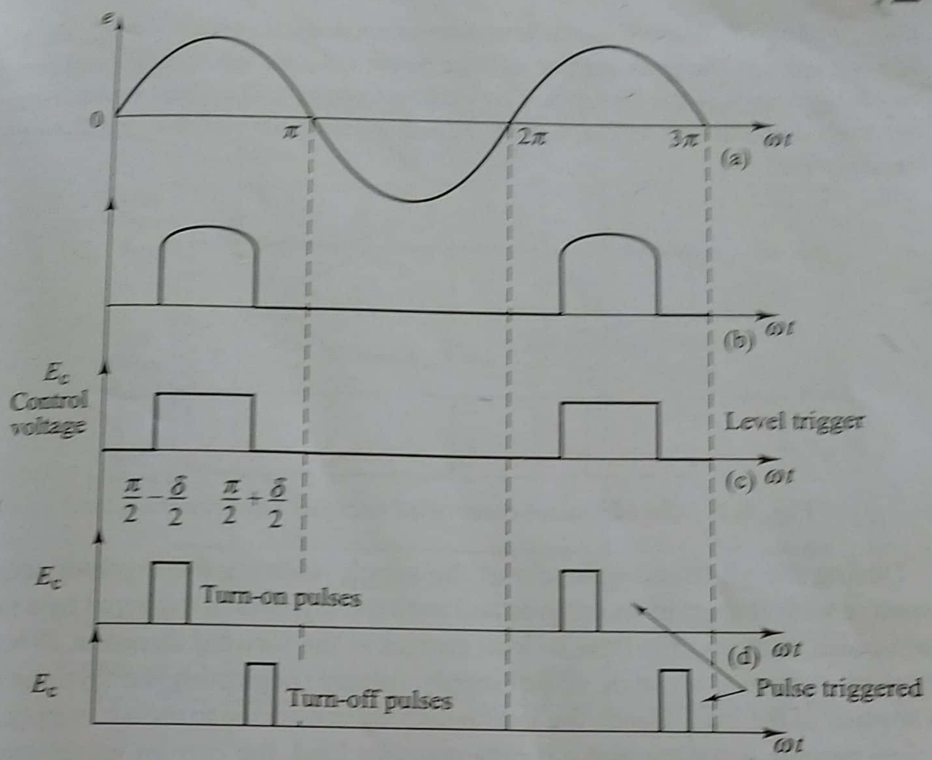

Fig. 6.5 *PWM control*

In multiple pulse width modulation (MPWM) control, control signals consists of p-pulses per half-period of the input voltage waveform. Both the pulse-width δ and the number of pulses p can be used as the control parameters. The two widely used methods are:

(a) Uniform multiple PWM [p-pulses of uniform pulse-width] and

(b) Sine-PWM [p-pulses with sinusoidal variation of pulse-width]

This type of control is suited for level triggered switches.

6.3 SINGLE PHASE HALF-WAVE CONTROLLED RECTIFIER

In its simplest form, phase control can be described by considering the half-wave thyristor circuit. In a half-wave single-phase controlled rectifier only one SCR is employed in the circuit. It is included in between the a.c. source and the load. The performance of the controlled rectifier very much depends upon the type and parameters of the output (load) circuit.

6.3.1 With Resistive Load

Figure 6.6(a) shows the circuit-diagram of a single-phase half-wave converter with resistive load. Triggering circuit is not shown in the figure. The circuit is energized by the line voltage or transformer secondary voltage, $e = E_m \sin \omega t$. It is assumed that the peak supply voltage never exceeds the forward and reverse-blocking ratings of the thyristor. The various voltage and current waveshapes for this circuit are shown in Fig. 6.6(b). *SCR is assumed to be ideal one throughout the chapter.*

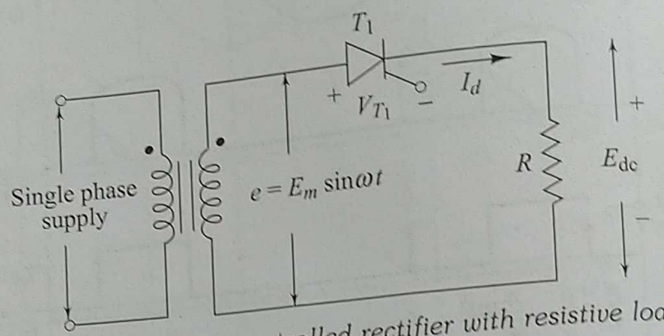

Fig. 6.6 **(a)** *Halfwave-controlled rectifier with resistive load*

During the positive half-cycle of the supply voltage, the thyristor anode is positive with respect to its cathode and until the thyristor is triggered by a proper gate-pulse, it blocks the flow of load current in the forward direction. When the thyristor is fired at an angle α, full supply voltage (neglecting the thyristor drop) is applied to the load. Hence the load is directly connected to the a.c. supply. With a zero reactance source and a purely resistive load, the current waveform after the thyristor is triggered will be identical to the applied voltage wave, and of a magnitude dependent on the amplitude of the voltage and the value of load resistance R. As shown in Fig. 6.6(b), the load current will flow until it is commutated by reversal of supply voltage at $\omega t = \pi$. The angle $(\pi - \alpha = \beta)$ during which the thyristor conducts is called the conduction angle. By varying the firing angle α, the output voltage can be controlled. During the period of conduction, voltage drop across the device is of the order of one volt.

During the negative half-cycle of the supply voltage, the thyristor blocks the flow of load current and no voltage is applied to the load R.

The voltage and current relations are derived as follows:

(a) ***Average Load Voltage*** The average value of the load-voltage can be derived as

$$E_{dc} = \frac{1}{2\pi}\int_{\alpha}^{\pi} E_m . \sin \omega t \, d(\omega t)$$

where E_m is the peak value of the a.c. input voltage

$$= \frac{1}{2\pi} E_m [-\cos \omega t]_{\alpha}^{\pi} \quad E_{dc} = \frac{E_m}{2\pi}[1 + \cos \alpha]. \tag{6.1}$$

The maximum output voltage is obtained when $\alpha = 0$.

$$\therefore \quad E_{dcmax} = \frac{E_m}{\pi} \tag{6.2}$$

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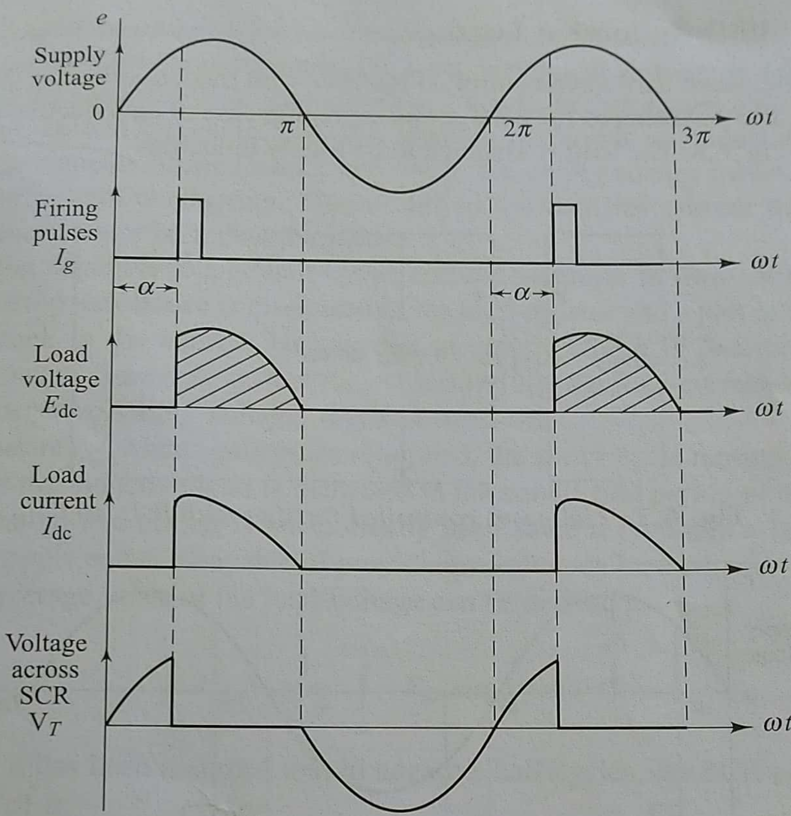

Fig. 6.6 ***(b)*** *Waveforms for a half-wave circuit*

(b) ***Average load current*** With resistive load, the average load current is directly proportional to the average load voltage divided by the load resistance:

$$\therefore \qquad I_d = \frac{E_m}{2\pi R}[1 + \cos\alpha] \qquad (6.3)$$

(c) ***RMS load voltage*** The RMS load voltage for a given firing angle α is given by

$$E_{rms} = \left[\frac{1}{2\pi}\int_{\alpha}^{\pi}(E_m \sin\omega t)^2 \, d(\omega t)\right]^{1/2} = \left[\frac{E_m^2}{2\pi}\int_{\alpha}^{\pi}\sin^2 \omega t \, d(\omega t)\right]^{1/2}$$

$$= E_m\left[\frac{1}{2\pi}\int_{\alpha}^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right) d(\omega t)\right]^{1/2} = E_m\left[\frac{1}{4\pi}\left(\omega t - \frac{\sin 2\omega t}{2}\right)_{\alpha}^{\pi}\right]^{1/2}$$

$$E_{rms} = E_m\left[\frac{\pi - \alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right]^{1/2} \qquad (6.4)$$

For firing angle $\alpha = 0$, $E_{rms} = \dfrac{E_m}{2}$ (6.5)

6.3.2 With Inductive Load

The single phase half-wave controlled rectifier with inductive-load is shown in Fig. 6.7. The waveshapes for voltage and current in case of an inductive load are given in Fig. 6.8. The load is assumed to be highly inductive.

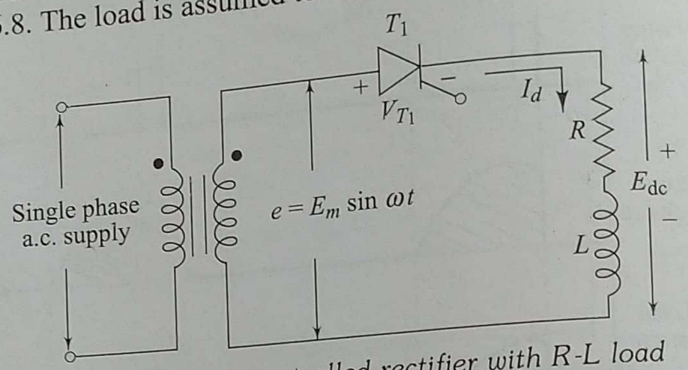

Fig. 6.7 *Half-wave controlled rectifier with R-L load*

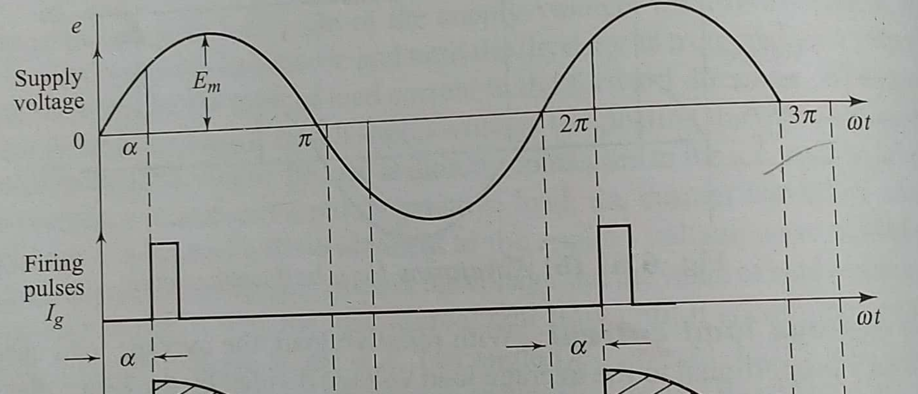

Fig. 6.8 *Waveforms for a half-wave controlled rectifier with RL load*

The operation of the circuit on inductive loads changes slightly. Now at instant t_{01}, when the thyristor is triggered, the load-current will increase in a finite-time through the inductive load. The supply voltage from this instant appears across the load. Due to inductive load, the increase in current is gradual. Energy is stored in inductor during time t_{01} to t_1. At t_1, the supply voltage reverses, but the thyristor is kept conducting. This is due to the fact that current through the inductance cannot be reduced to zero.

During negative-voltage half-cycle, current continues to flow till the energy stored in the inductance is dissipated in the load-resistor and a part of the energy is fed-back to the source. Hence, due to energy stored in inductor, current continuous to flow upto instant t_{11}. At instant, t_{11}, the load-current is zero and due to negative supply voltage, thyristor turns-off.

At instant t_{02}, when again pulse is applied, the above cycle repeats. Hence the effect of the inductive load is increased in the conduction period of the SCR.

The half-wave circuit is not normally used since it produces a large output voltage ripple and is incapable of providing continuous load-current.

The average value of the load-voltage can be derived as:

$$E_{dc} = \frac{1}{2\pi} \int_{\alpha}^{\pi+\alpha} E_m . \sin \omega t \, d(\omega t)$$

Here, it has been assumed that in negative half-cycles, the SCR conducts for a period of α.

$$\therefore \quad E_{dc} = \frac{E_m}{2\pi} [-\cos \omega t]_{\alpha}^{\pi+\alpha} \quad \text{Or,} \quad E_{dc} = \frac{E_m}{\pi} \cos \alpha \qquad (6.6)$$

From Eqs (6.1) and (6.6), it is clear that the average load-voltage is reduced in case of inductive load. This is due to the conduction of SCR in negative cycle.

6.3.3 Effect of Freewheeling Diode

Many circuits, particularly those which are half or uncontrolled, include a diode across the load as shown in Fig. 6.9. This diode is variously described as a commutating diode, flywheel diode or by-pass diode. This diode is commonly described as a commutating diode as its function is to commutate or transfer load current away from the rectifier whenever the load-voltage goes into a reverse-state.

This diode serves two main functions:

(i) It prevents reversal of load voltage except for small diode voltage-drop.

(ii) It transfers the load current away from the main rectifier, thereby allowing all of its thyristors to regain their blocking states.

Figure 6.10 shows a half-wave controlled rectifier with a freewheeling diode D_f connected across R–L load. The load-voltage and current waveforms are also shown in Fig. 6.11.

With diode D_f, thyristor will not be able to conduct beyond 180°.

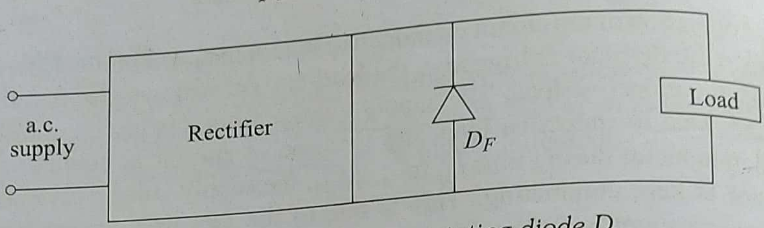

Fig. 6.9 *Position of commutating diode D_F*

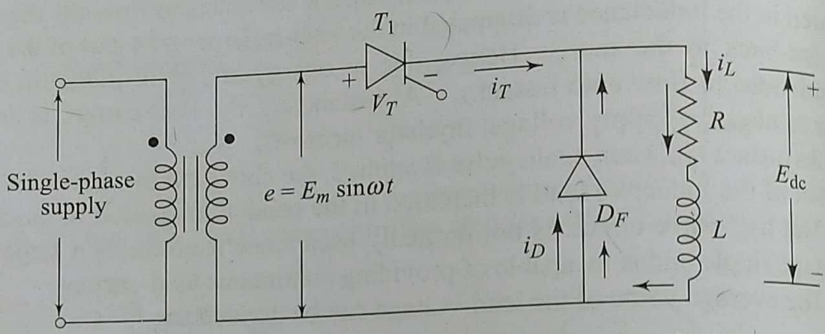

Fig. 6.10 *Half-wave rectifier with a freewheeling diode*

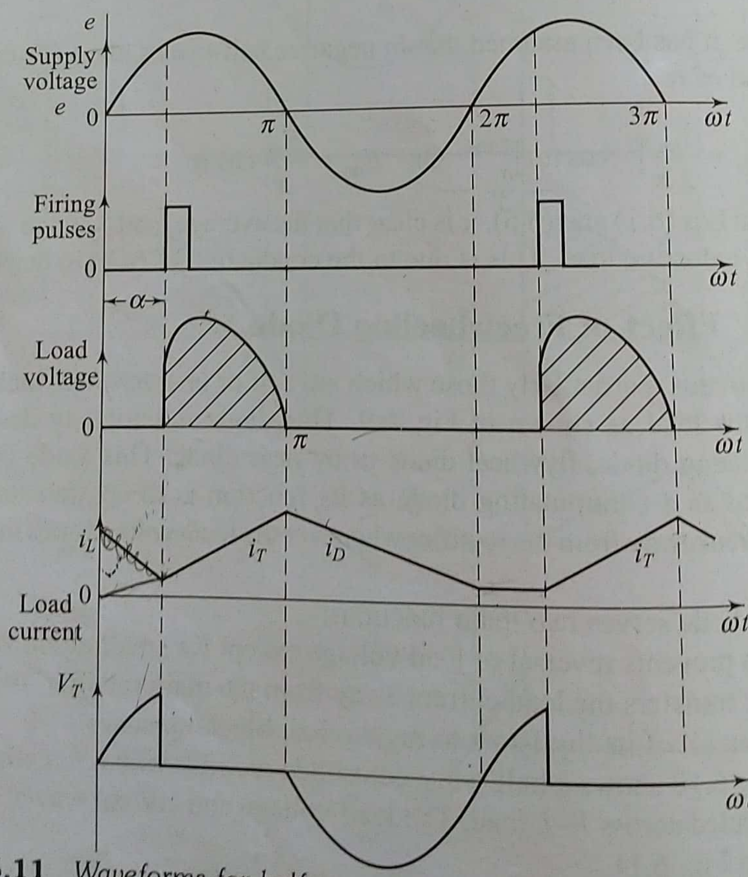

Fig. 6.11 *Waveforms for half-wave controlled-rectifier with inductive load and freewheeling diode*

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Hence it is clear th
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Example 6.1 If
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Solution:

(a) Rectification e

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We know that during the positive half-cycle, voltage is induced in the inductance. Now, this induced voltage in inductance will change its polarity as the di/dt changes its sign and diode D_f will start conducting as soon as the induced voltage is of sufficient magnitude, thereby enabling the inductance to discharge its stored energy into the resistance.

Hence, after 180°, the load current will freewheel through the diode and a reverse-voltage will appear across the thyristor. The power flow from the input takes place only when the thyristor is conducting. If there is no freewheeling diode, during the negative portion of the supply voltage, thyristor returns the energy stored in the load inductance to the supply line. With diode D_f, the freewheeling action takes place and no power will be returned to the source. Hence, the ratio of the reactive power flow from the input to the total power consumed in the load is less for the phase-control circuit with a freewheeling diode. In other words, the freewheeling diode improves the input power-factor.

Mathematically:

$$\frac{EI\sin\phi}{EI} = \text{less} \quad \therefore \sin\phi = \text{less} \tag{6.7}$$

Since, ϕ = less $\therefore$ Power-factor $\cos\phi$ = more (6.8)

Hence it is clear that the freewheeling diode helps in improvement of power-factor of the system.

SOLVED EXAMPLES

Example 6.1 If the half-wave controlled rectifier has a purely resistive load of R and the delay angle is $\alpha = \pi/3$. Determine:

(a) Rectification efficiency (b) Form factor (c) Ripple factor
(d) Transformer utilization factor (e) Peak inverse voltage for SCR T_1

Solution:

(a) Rectification efficiency $\eta = \dfrac{p_{dc}}{p_{ac}}$ where, p_{dc} = dc load power = E_{dc}^2/R and

p_{ac} = rms load power = $\dfrac{E_{rms}^2}{k}$. We have the relation, from Eq. (6.1),

$$E_{dc} = \frac{E_m}{2\pi}(1+\cos\alpha), \text{ Since, } \alpha = \pi/3 \quad \therefore E_{dc} = 0.239\, E_m$$

Also, from equation (6.4), we have

$$E_{rms} = E_m\left[\frac{\pi-\alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right]^{1/2}$$

For firing angle $\alpha = \pi/3$, $E_{rms} = 0.485\, E_m$

$$\because \quad \text{Rectification efficiency } \eta = \frac{(0.239\,E_m)^2}{(0.485\,E_m)^2} \quad \therefore \quad \eta = 24.28\%$$

(c) Supply power factor $= \dfrac{I_{\text{rms}}^2 \cdot R + I_d \cdot E_b}{E_{\text{rms}} \cdot I_{\text{rms}}}$

$$= \frac{1096.68 + 1194}{230 \times 14.81} = 0.672 \text{ lagging.}$$

6.4 SINGLE-PHASE FULL-WAVE CONTROLLED RECTIFIER (TWO-QUADRANT CONVERTERS)

There are two basic configurations of full wave controlled rectifiers. Their classification is based on the type of SCR configuration employed. They are—

(1) Mid-point converters. (2) Bridge converters.

6.4.1 Mid-point Converters (M-2 Connection)

In a single phase full-wave controlled-rectifier circuit with mid-point configuration two SCRs (M-2) and a single-phase-transformer with centre-tapped secondary windings are employed. These converters are also referred to as two pulse converters as two triggering pulses or two sets of triggering pulses are to be generated during every cycle of the supply to trigger the various SCRs. Single-phase full-wave circuit with transformer mid-point configuration are generally used for rectifiers of low ratings.

1. With Resistive Load Figure 6.12 illustrates a 2-pulse mid-point converter circuit with resistive-load. This type of full-wave rectifier circuit uses two SCRs connected to the centre-tapped secondary of a transformer, as shown in Fig. 6.12. The input signal is coupled through the transformer to the centre-tapped secondary.

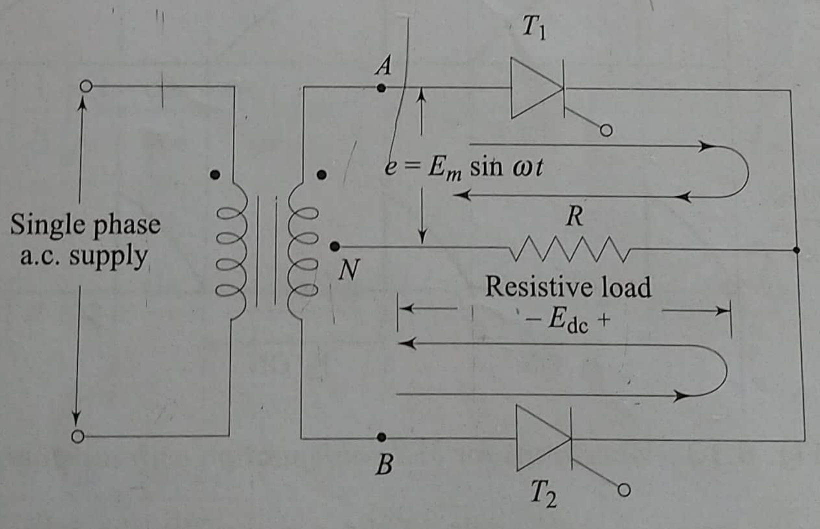

Fig. 6.12 *Full-wave mid-point circuit with resistive load*

During the positive half-cycle of the a.c. supply, i.e. when terminal A of the transformer is positive with respect to terminal B, or the secondary-winding terminal A is positive with respect to N, SCR_1 (T_1) is forward-biased and SCR_2

(T_2) is reverse-biased. Since no triggering pulses are given to the gates of the SCRs, initially they are in off-state. When SCR_1 is triggered at a firing-angle α, current would flow from terminal A through SCR_1, the resistive load R and back to the centre-tap of the transformer (i.e. terminal N). This current path is also shown in Fig. 6.12. This current continuous to flow up to angle π when the line voltage reverses its polarity and SCR_1 is turned-off. Depending upon the value of α and the load circuit parameters, the conduction angle of SCR_1 may be any value between 0 and π.

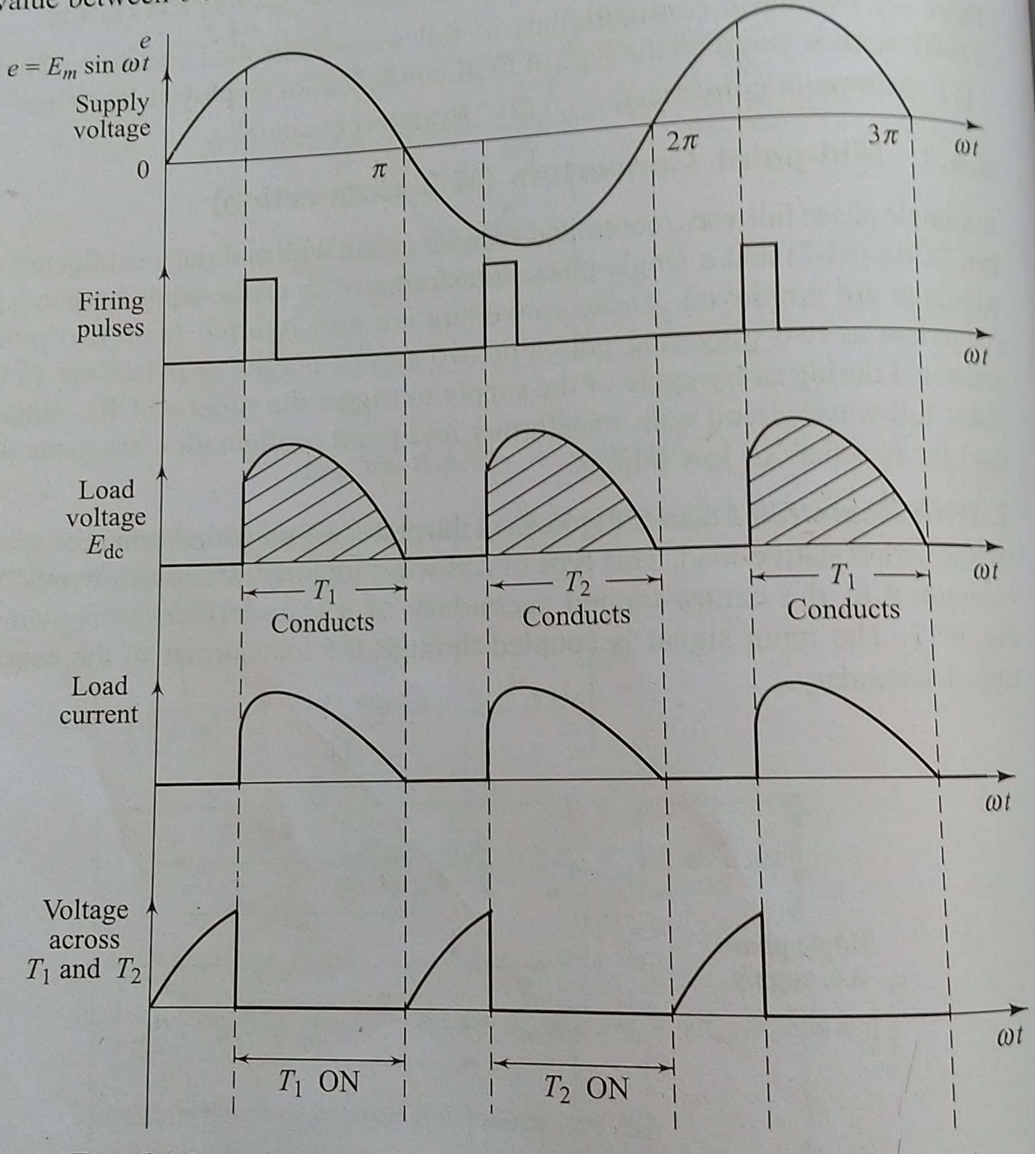

Fig. 6.13 *Waveforms for M-2 configuration with resistive-load*

During the negative half-cycle of the a.c. supply, the terminal B of the transformer is positive with respect to N. SCR_2 is forward-biased. When SCR_2 is triggered at an angle $(\pi + \alpha)$, current would flow from terminal B, through SCR_2, the resistive load and back to centre-tap of the transformer. This current continues till angle 2π, then SCR_2 is turned off. Here it is assumed that both thyristors are triggered with the same firing angle, hence they share the load current equally.

Each half of the input-wave is applied across the load. Thus, across the load, there are two pulses of current in the same direction. Hence the ripple frequency across the load is twice that of the input supply frequency. The voltage and current waveforms of this configuration is shown in Fig. 6.13. It is clear from Fig. 6.13 that with purely resistive load, the load current is always discontinuous.

The voltage and current relations are derived as follows:

(a) Average d.c. Output Voltage The output d.c. voltage, E_{dc}, across the resistive load is given by

$$E_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi} E_m . \sin \omega t \, d(\omega t) = \frac{E_m}{\pi}[-\cos \omega t]_{\alpha}^{\pi} = \frac{E_m}{\pi}[1+\cos\alpha] \tag{6.9}$$

(b) Average-load Current The average-load current is given by

$$I_{dc} = \frac{E_m}{\pi \cdot R}[1+\cos\alpha] \tag{6.10}$$

(c) RMS Load-voltage The RMS load-voltage for a given firing angle α is given by

$$E_{rms} = \left[\frac{1}{\pi}\int_{\alpha}^{\pi} E_m^2 \sin^2 \omega t \, d\,\omega t\right]^{\frac{1}{2}} = E_m \cdot \left[\frac{1}{\pi}\int_{\alpha}^{\pi} \sin^2 \omega t \, d\,\omega t\right]^{\frac{1}{2}}$$

$$= E_m \cdot \left[\frac{1}{\pi}\int_{\alpha}^{\pi}\left(\frac{1-\cos 2\omega t}{2}\right) d\,\omega t\right]^{\frac{1}{2}} = E_m \cdot \left[\frac{1}{2\pi}\left(\omega t - \frac{\sin 2\omega t}{2}\right)_{\alpha}^{\pi}\right]^{\frac{1}{2}}$$

$$= E_m \cdot \left[\frac{1}{2\pi}\left(\pi - \alpha + \frac{\sin 2\alpha - \sin 2\pi}{2}\right)\right]^{\frac{1}{2}} = E_m \cdot \left[\frac{1}{2\pi}\left(\pi - \alpha + \frac{\sin 2\alpha}{2} - 0\right)\right]^{\frac{1}{2}}$$

$$E_{rms} = E_m \cdot \left[\frac{\pi - \alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]^{\frac{1}{2}} \tag{6.11}$$

2. *With inductive Load* The circuit diagram of the single-phase full wave, or bi-phase half-wave controlled rectifier with R_L load is shown in Fig. 6.14. The various voltage and current waveforms are shown in Fig. 6.15.

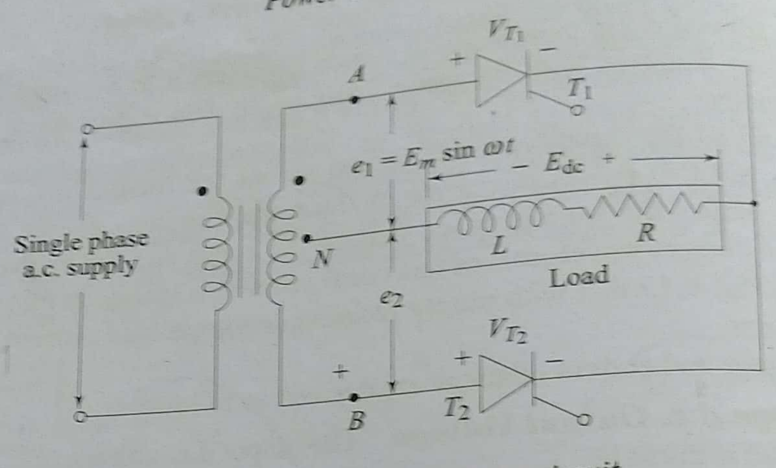

Fig. 6.14 *Bi-phase half-wave circuit*

With reference to Fig. 6.14, thyristor T_1 can be fired into the on-state at any time after e_1 goes positive. Once thyristor T_1 is turned-on, current builds up in the inductive load, maintaining thyristor T_1 in the on-state up to the period when e_1 goes negative. However, once e_1 goes negative, e_2 becomes positive, and the firing of thyristor T_2 immediately turns on thyristor T_2 which takes up the load current, placing a reverse voltage on thyristor T_1, its current being commutated (transferred) to thyristor T_2. The thyristor voltage, V_T, waveform in Fig. 6.15 shows that it can be fired into conduction at anytime when V_T is positive. The peak reverse (and forward) voltage that appears across the thyristor is 2 E_m, that is, the maximum value of the complete transformer secondary voltage.

The load-current may be continuous or discontinuous, depending on the inductance value. The load current is continuous if inductance value is greater than its critical value. It is discontinuous if inductance value is less than its critical value. The analysis given here assumes that the inductance is sufficiently large, so that each thyristor conducts for a period of 180° (conduction of current is continuous). Also, both thyristors are triggered with the same delay angle, hence they share the load current equally. As shown in Fig. 6.15, due to large inductance in the circuit and continuous current conduction, the thyristors continue to conduct even when their anode voltages are negative with respect to the cathode. The load current is shown to be constant d.c.

Now, the output d.c. voltage E_{dc} can be obtained as

$$E_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi+\alpha} E_m . \sin \omega t \, d(\omega t) = \frac{E_m}{\pi}\left[\cos \alpha - \cos(\pi + \alpha)\right]$$

$$E_{dc} = \frac{2E_m}{\pi} \cos \alpha. \qquad (6.12)$$

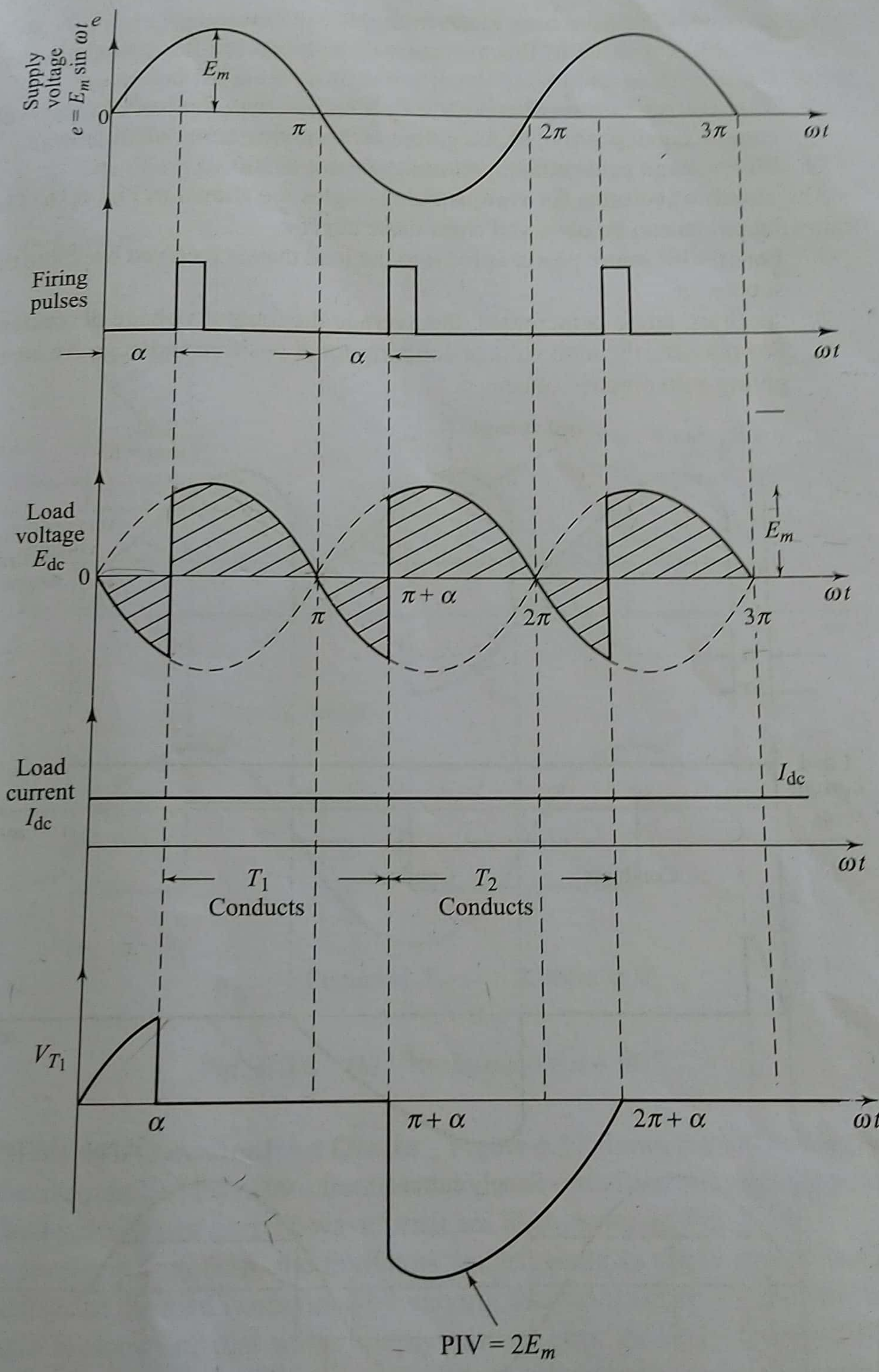

Fig. 6.15 *Waveforms for M-2 connection with R-L load*

Some conclusions have been made from this equation—

1. The highest value of this voltage will be when the firing angle is zero i.e. $\alpha = 0°$.
2. This voltage is zero when $\alpha = 90°$. Meaning that, the load voltage will contain equal positive and negative areas, giving zero output voltage.
3. This voltage is negative maximum when $\alpha = 180°$.

The circuit waveforms for various firing-angles are shown in Fig. 6.16. The following points can be observed from these curves:

1. For $\alpha = 30°$, more power is fed into the load than is received back into the supply.
2. As firing-angle α increases, the average d.c. output voltage decreases. For $\alpha = 90°$, the load voltage contains equal positive and negative areas, giving zero output-voltage.

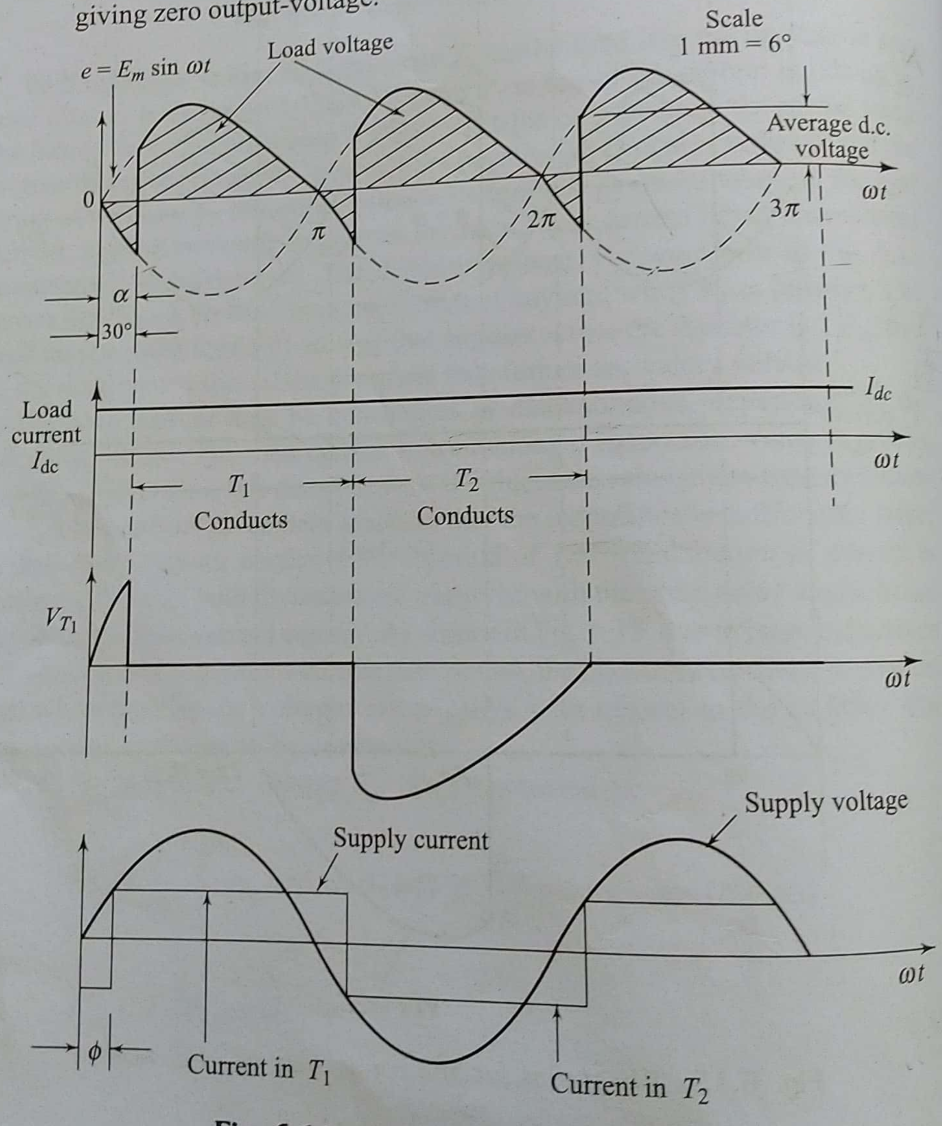

Fig. 6.16 *(a) Waveforms for $\alpha = 30°$*

3. For firing-angle $\alpha > 90°$, the d.c. voltage goes negative. At $\alpha = 180°$, the negative d.c. voltage is maximum.
4. The period for which a thyristor is reverse-biased reduces as the firing angle increases to 180°. To turn OFF a thyristor, it must be reverse-biased for greater than its turn-off time.

Therefore, the maximum firing-angle must always be less than 180°.

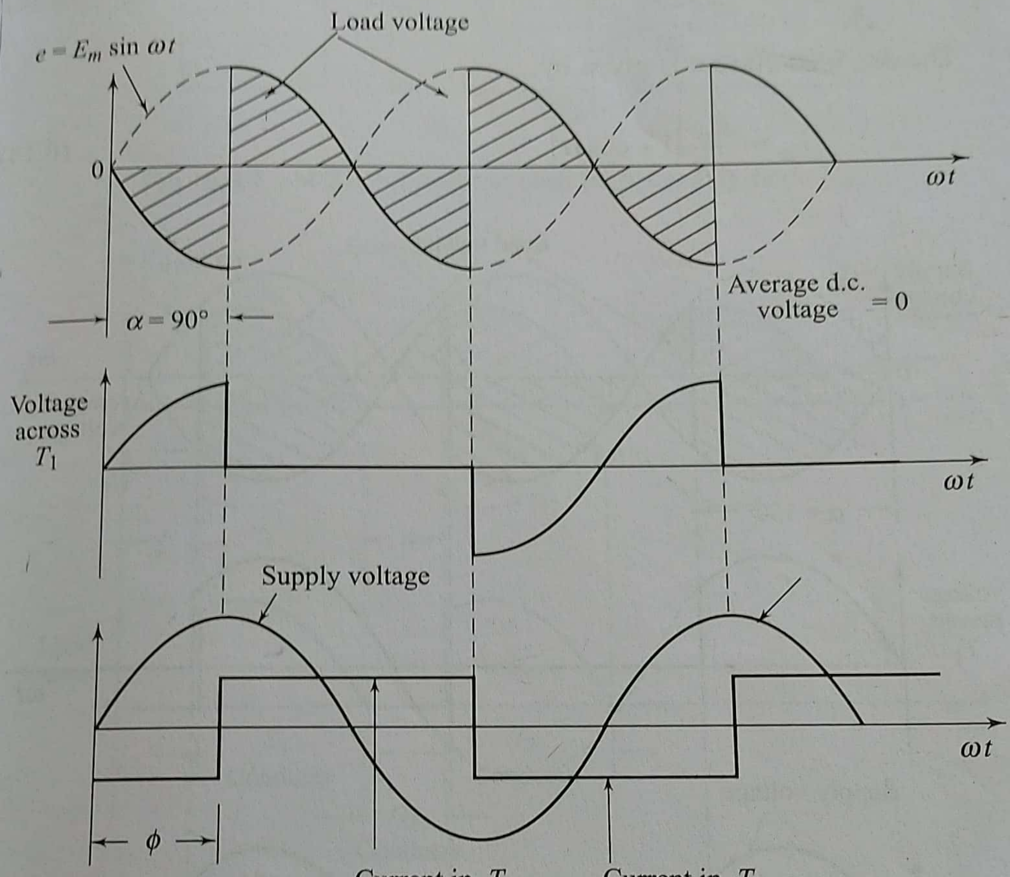

Fig. 6.16 ***(b)*** *Waveforms for $\alpha = 90°$*

3. Effect of Freewheeling Diode Figure 6.17 shows the full-wave centre tap phase-controlled thyristor-circuit with inductive load and freewheeling diode. The load voltage and current-waveforms are also shown in Fig. 6.18.

As shown in Fig. 6.18, the thyristors are triggered at angle α. The variable d.c. voltage at the load is obtained by varying this firing angle α. From the same figure, it is also clear that as the supply voltage goes through zero at 180°, the load voltage cannot be negative since the freewheeling diode, D_f, starts conducting and clamps the load voltage to zero volts. A constant load current is maintained by freewheeling current through the diode. The conduction period of thyristors and diode is also shown in Fig. 6.18. The stored-energy in the inductive load circulates current through the feedback-diode in the direction shown in Fig. 6.17. The rate of decay of this current depends upon the time-constant of the load.

The average d.c. output voltage can be calculated as

$$E_{\text{dc}} = \frac{1}{\pi}\int_{\alpha}^{\pi} E_m \cdot \sin \omega t \, d(\omega t) = \frac{E_m}{\pi}[1 + \cos \alpha] \tag{6.13}$$

The d.c. load-current is given by

$$I_{\text{dc}} = \frac{E_m}{\pi R}[1 + \cos \alpha] \tag{6.14}$$

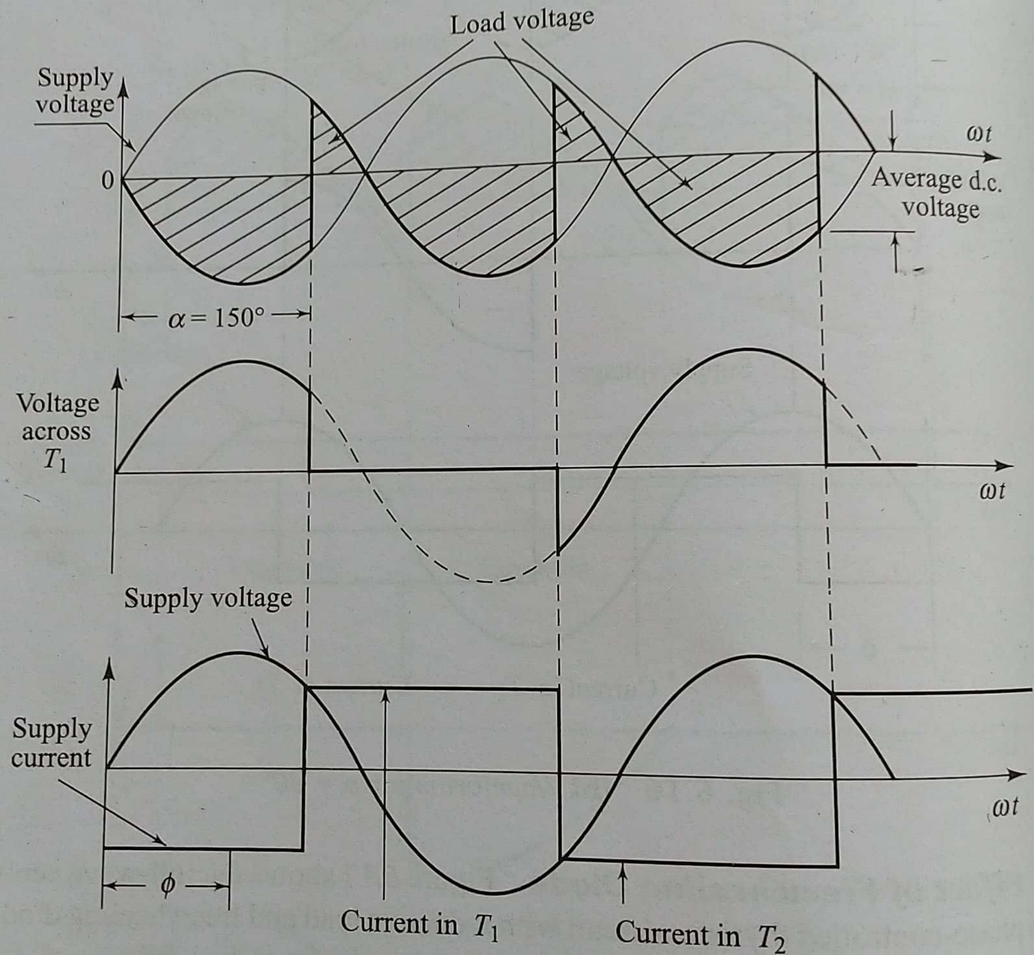

Fig. 6.16 ***(c)*** *Waveforms for $\alpha = 150°$*

It is also observed from Fig. 6.18, that the freewheeling diode, D_F, carries the load-current during the firing-angle α when the thyristors are not conducting. Hence, the current through the diode D_F is given by

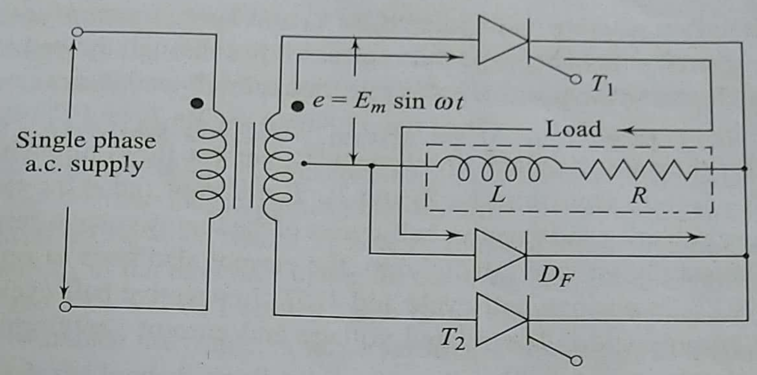

Fig. 6.17 *M-2 configuration with freewheeling diode* D_f

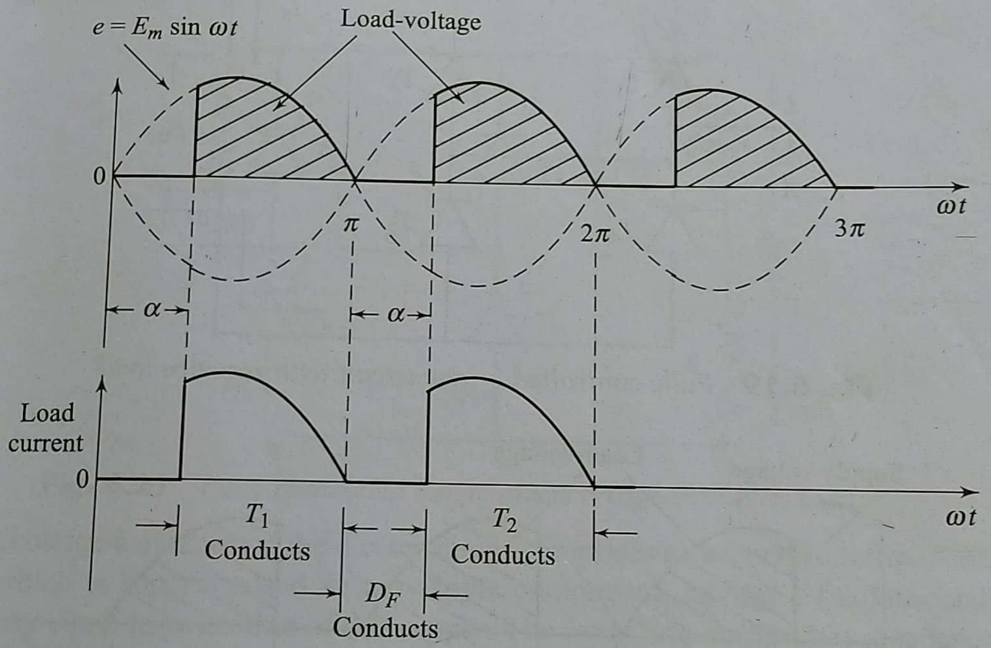

Fig. 6.18 *Waveforms*

$$ID_f = I_{dc}\,\frac{\alpha}{\pi} = \frac{E_m}{\pi R}(1+\cos\alpha)\,\frac{\alpha}{\pi}$$

$$ID_f = \frac{E_m}{\pi^2 R}(\alpha + \alpha'\cos\alpha) \qquad (6.15)$$

6.4.2 Bridge-Configurations (B-2 Connection)

An alternative-circuit arrangement of a two-quadrant converter, operating from a single-phase supply, is a fully controlled bridge-circuit as shown in Fig. 6.19. The operation of this circuit is in principle similar to that of the 2-pulse midpoint circuit of Fig. 6.12. In the bridge circuit, diagonally opposite pair of thyristors are made to conduct, and are commutated, simultaneously.