MODULE-2

Phase Controlled Converter: Control techniques, Single phase half wave and full wave controlled rectifier with resistive and inductive loads, effect of freewheeling diode. **Choppers:** Chopper Classification, Basic Chopper operation: step-down, step-up and step-up/down choppers.

2.1 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.

2.2 CONTROL TECHNIQUES

Figure 2.1 shows the technique of controlled conversion from ac to dc for a half-wave circuit which uses 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.

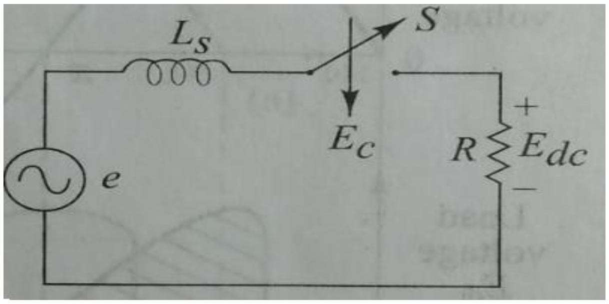


Fig. 2.1: Half wave controlled converter using unidirectional switch

2.2.1 Phase Angle-Control (Firing Angle Control)

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. Figure 2.2 shows various waveforms obtained using phase-angle control for half-wave-controlled converter circuit.

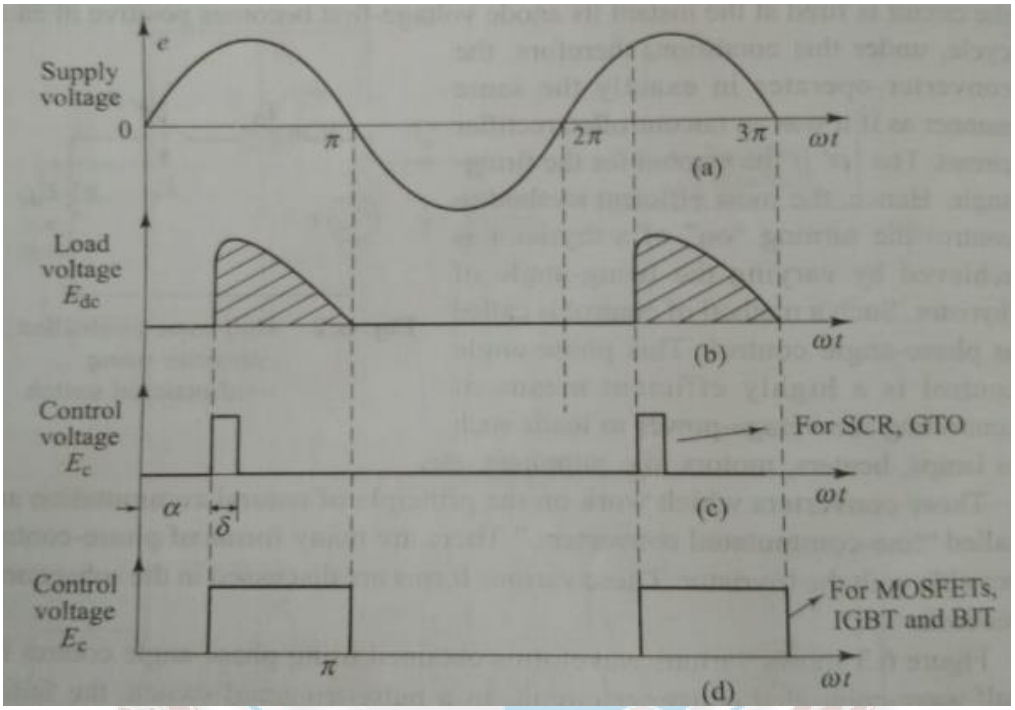


Fig. 2.2: Phase-angle control

2.2.2 Extinction Angle Control

Figure 2.3 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 (β). 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.

2.2.3 Pulse Width Modulation (PWM) Control

The output voltage waveform and control pulses using PWM control are shown in Fig. 2.4. As shown, the control pulse is symmetrically positioned with respect to the positive and negative peaks of the input voltage waveform. Pulse width & is the control parameter. Like extinction angle control, the control pulse consists of two short pulses in case of pulse-triggered switch.

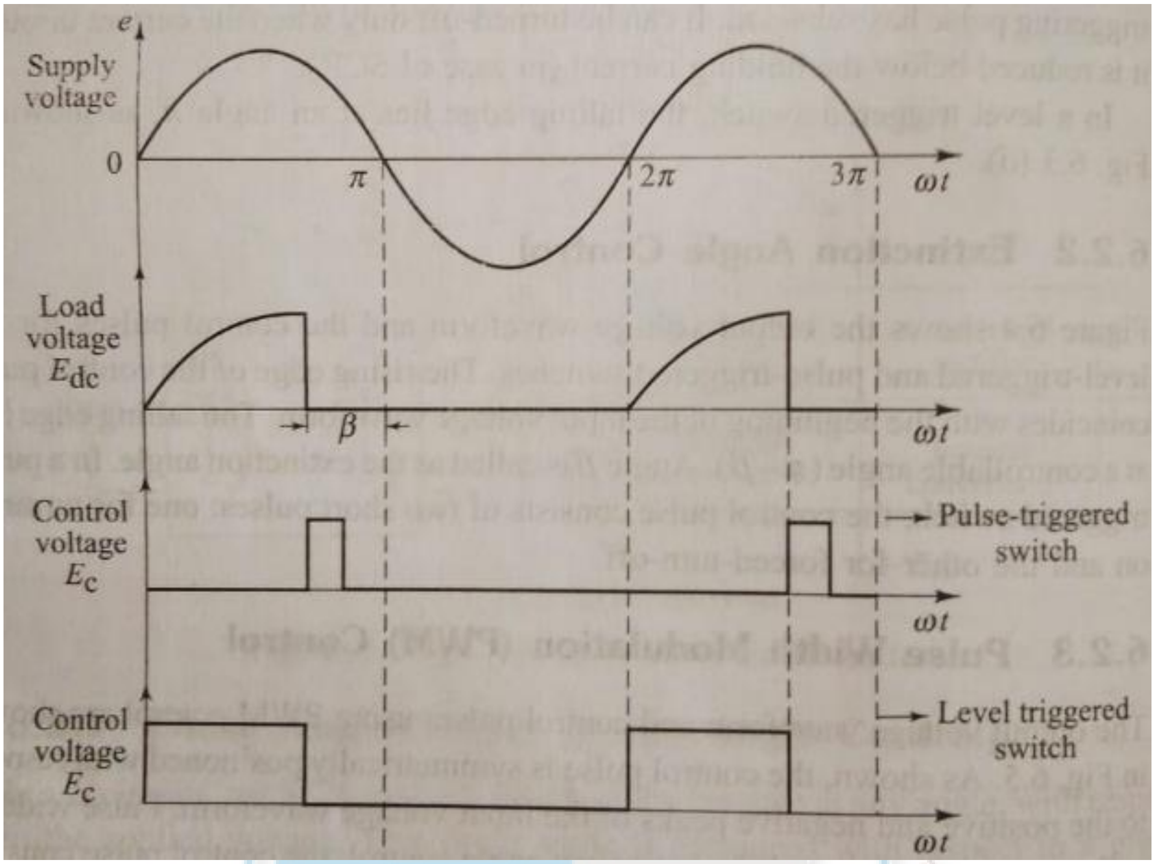


Fig. 2.3: Extinction angle control

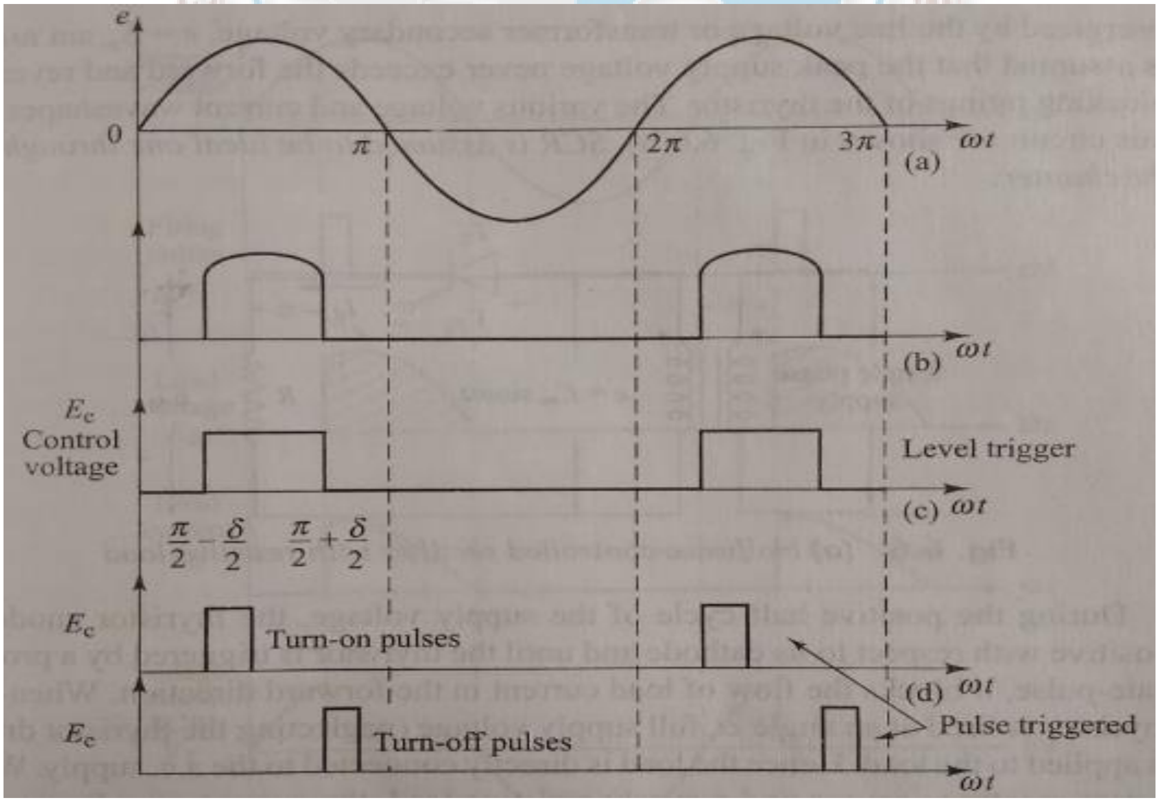


Fig. 2.4: PWM control

2.3 SINGLE PHASE HALF-WAVE CONTROLLED RECTIFIER

In half-wave single-phase controlled rectifier only one SCR is employed the circuit. The performance of the controlled rectifier depends upon parameters the output (load) circuit.

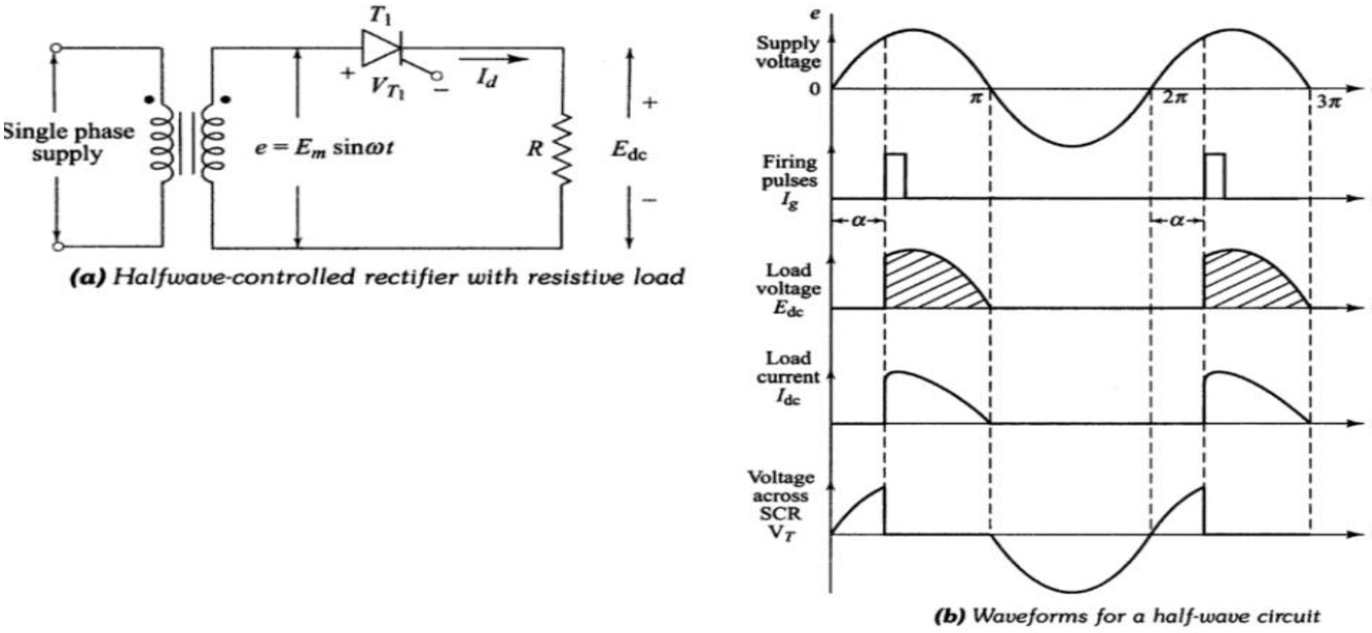
2.3.1 With Resistive Load

Figure 2.5(a) shows the circuit-diagram of a single-phase half-wave converter with resistive load. The circuit is energized by line voltage or transformer secondary voltage, $e=E_m \sin\omega t$. The various voltage and current wave shapes for this circuit are shown in Fig. 2.5(b).

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 is applied to the load. Hence the load is directly connected to the a.c. supply. With 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 of load resistance *R*.

As shown in Fig. 2.4(b), the load current will flow until it is commutated by reversal of supply voltage at ωt = π. The angle (π – α = β) during which the thyristor conducts is called the conduction angle. By varying the firing angle α, the output voltage can be controlled.

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.



(a) Halfwave-controlled rectifier with resistive load

(b) Waveforms for a half-wave circuit

Figure 2.5: (a) Circuit diagram (b) Waveforms

The voltage and current relations are derived as follows,

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

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

Where Em is the peak value of the a.c. input voltage

$$= \frac{1}{2\pi} E_m [-\cos\omega t]_{\alpha}^{\pi}$$

$$E_{\mathrm{dc}} = \frac{E_m}{2\pi}[1+\cos\alpha] \tag{2.1}$$

The maximum output voltage is obtained when α=0

$$\therefore \quad E_{\mathrm{dcmax}} = \frac{E_m}{\pi} \tag{2.2}$$

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

$$\therefore \quad I_d = \frac{E_m}{2\pi R}[1+\cos\alpha] \tag{2.3}$$

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

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

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

$$E_{\mathrm{rms}} = E_m\left[\frac{\pi-\alpha}{4\pi} + \frac{\sin 2\alpha}{8\pi}\right]^{1/2} \tag{2.4}$$

For firing angle α=0, $E_{\mathrm{rms}} = E_m / 2$ (2.5)

2.3.2 With Inductive Load

The single phase half-wave controlled rectifier with inductive-load is shown in Fig. 2.6(a). The wave shapes for voltage and current in case of an inductive load are given in Fig. 2.6(b). The load is assumed to be highly inductive.

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.

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 , current continuous to flow up to 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 average value of the load-voltage can be derived as:

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

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

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

$$E_{dc} = \frac{E_m}{\pi} \cos\alpha \qquad (2.6)$$

From equations (2.1) and (2.6), 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.

2.3.3 Effect of Free-Wheeling Diode

Many circuits, particularly those which are half or uncontrolled, include a diode across the load as shown in Fig.2.6. 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.

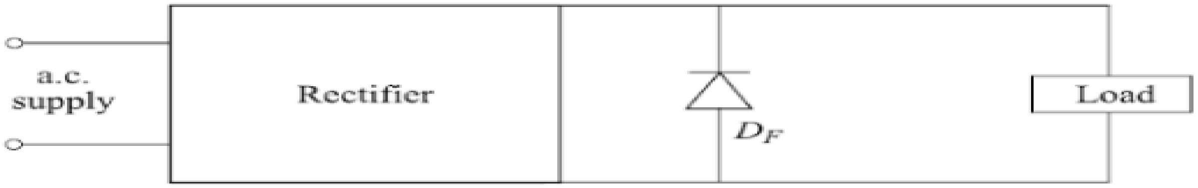


Fig.2.6: *Position of commutating diode* D_F

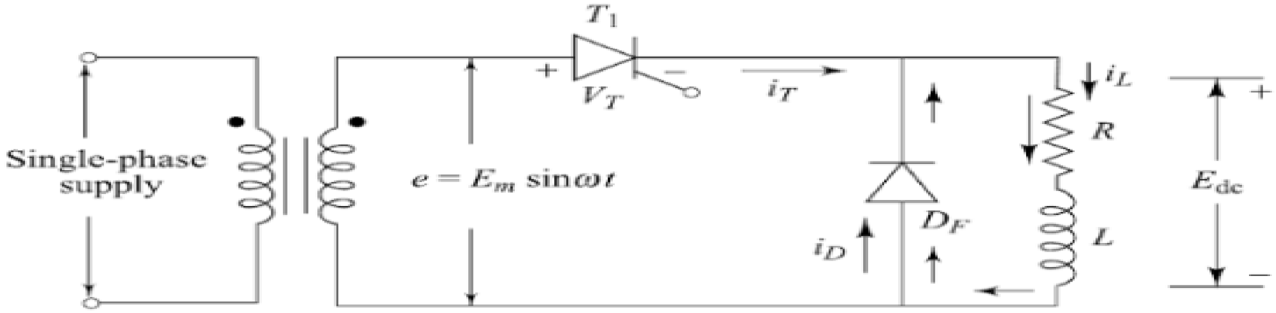


Fig.2.7: *Half-wave rectifier with a freewheeling diode*

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 2.7 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.2.8. With diode D_f thyristor will not be able to conduct beyond 180°.

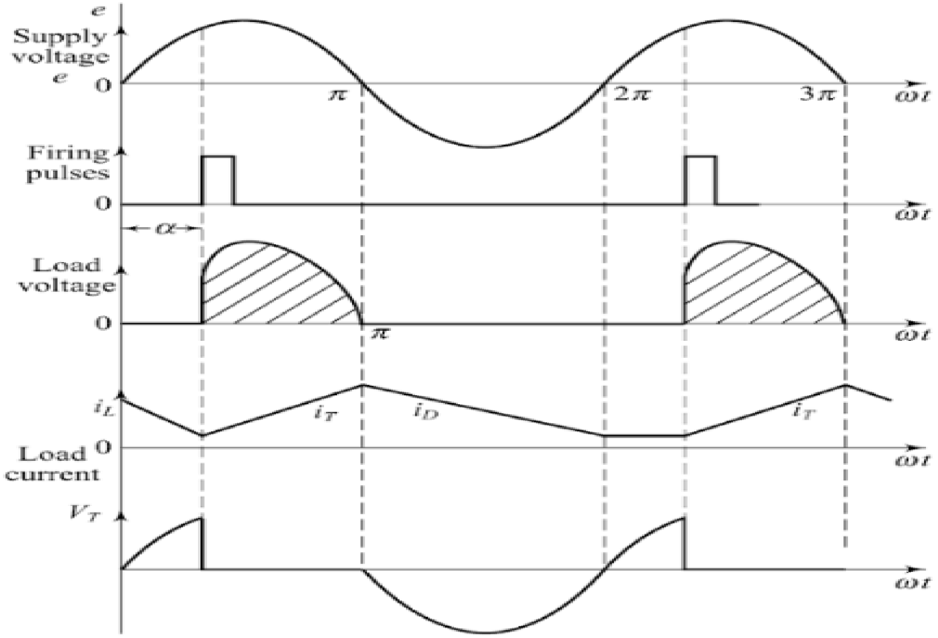


Fig.2.8: *Waveforms for half-wave controlled-rectifier with inductive load and freewheeling diode*

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, 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 free- wheeling 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.

2.4 SINGLE PHASE HALF-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.

2.4.1 Mid-point Converters (M-2 Connection)

In a single phase full-wave controlled-rectifier circuit with mid-point configuration two SCR's (M-2) and a single-phase-transformer with centre-tapped secondary windings are employed. Single phase full-wave circuit with transformer mid-point configuration are generally used for rectifiers of low ratings.

1. With Resistive Load

Figure 2.9 illustrates a 2-pulse mid-point converter circuit with resistive-load. This type of full-wave rectifier circuit uses two SCR's connected to the centre-tapped secondary of a transformer, as shown in Fig. 2.10. The input signal is coupled through the transformer to the centre tapped secondary.

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. This current path is also shown in Fig. 2.9. 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.

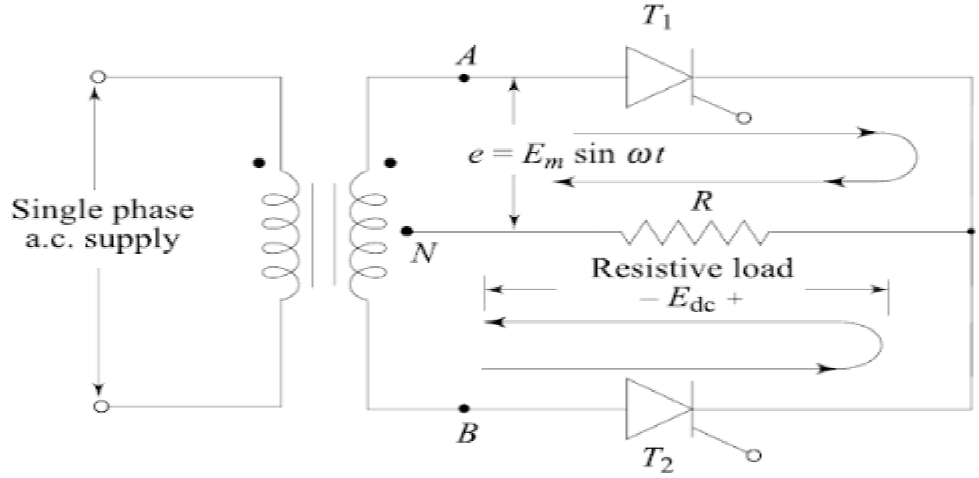


Fig. 2.9: *Full-wave mid-point circuit with resistive load*

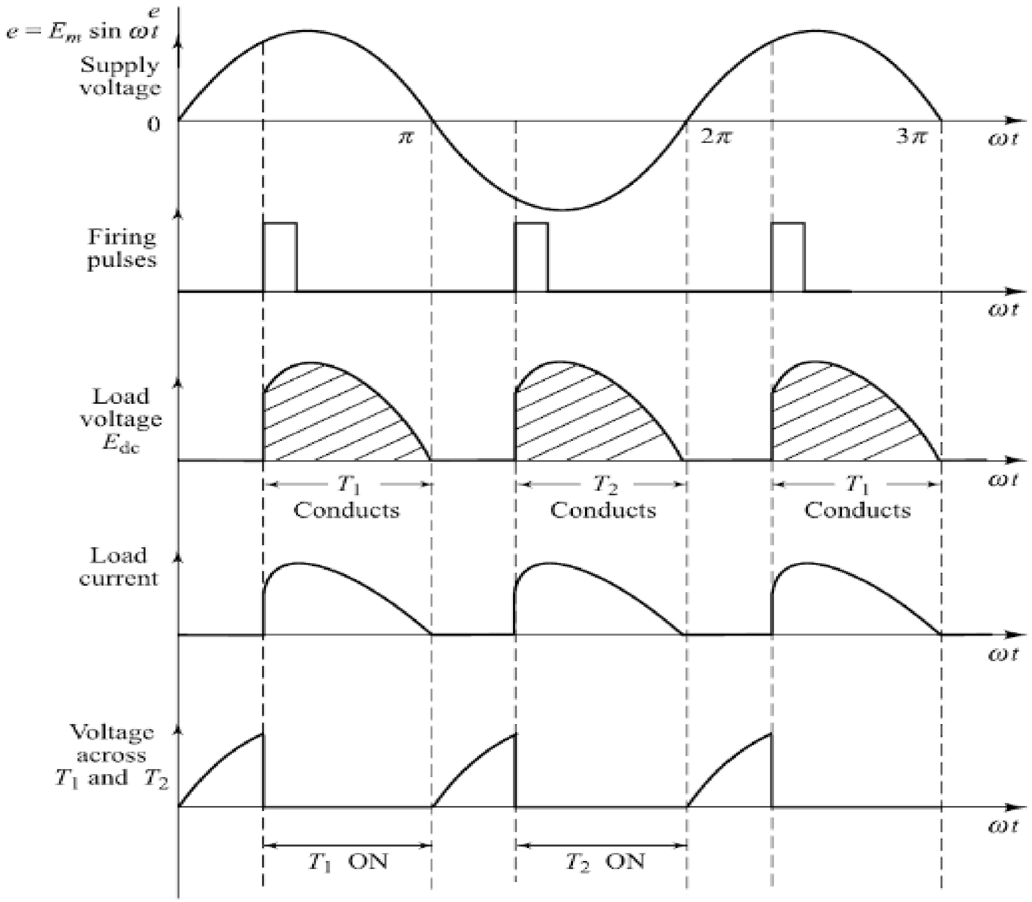


Fig. 2.10: *Waveforms for M-2 configuration with resistive-load*

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 (π+α), 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.

The voltage and current waveforms of this configuration is shown in Fig.210. It is clear from Fig.2.10 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

$$E_{\mathrm{dc}} = \frac{1}{\pi}\int_{\alpha}^{\pi} E_m \cdot \sin\omega t \cdot \mathrm{d}(\omega t) = \frac{E_m}{\pi}\left[-\cos\omega t\right]_{\alpha}^{\pi} = \frac{E_m}{\pi}\left[1+\cos\alpha\right] \tag{2.7}$$

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

$$I_{\mathrm{dc}} = \frac{E_m}{\pi \cdot R}\left[1+\cos\alpha\right] \tag{2.8}$$

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

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

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

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

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

$$E_{\mathrm{rms}} = E_m \cdot \left[\frac{\pi-\alpha}{2\pi} + \frac{\sin 2\alpha}{4\pi}\right]^{\frac{1}{2}} \tag{2.9}$$

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.2.11. The various voltage and current waveforms are shown in Fig.2.12.

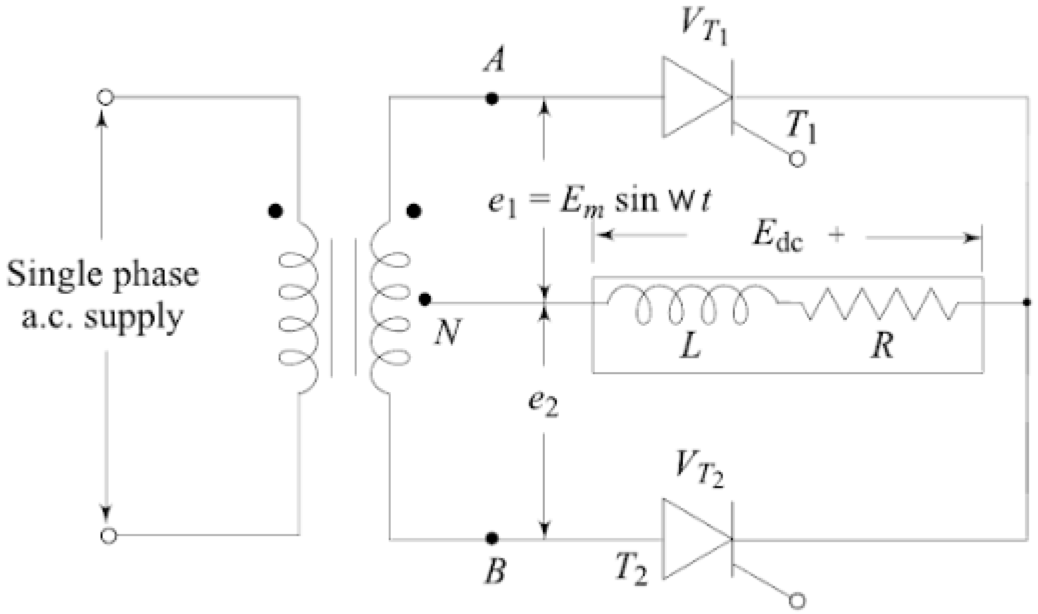


Fig.2.11: *Bi-phase half-wave circuit*

With reference to Fig. 2.11, 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, 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 to thyristor T_2. The thyristor voltage, V_T waveform in Fig.2.12 shows that it can be fired into conduction at any time when V_T is positive. The peak reverse (and forward) voltage that appears across the thyristor is $2E_m$ that is, the maximum value of the complete transformer secondary voltage.

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.2.12 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.

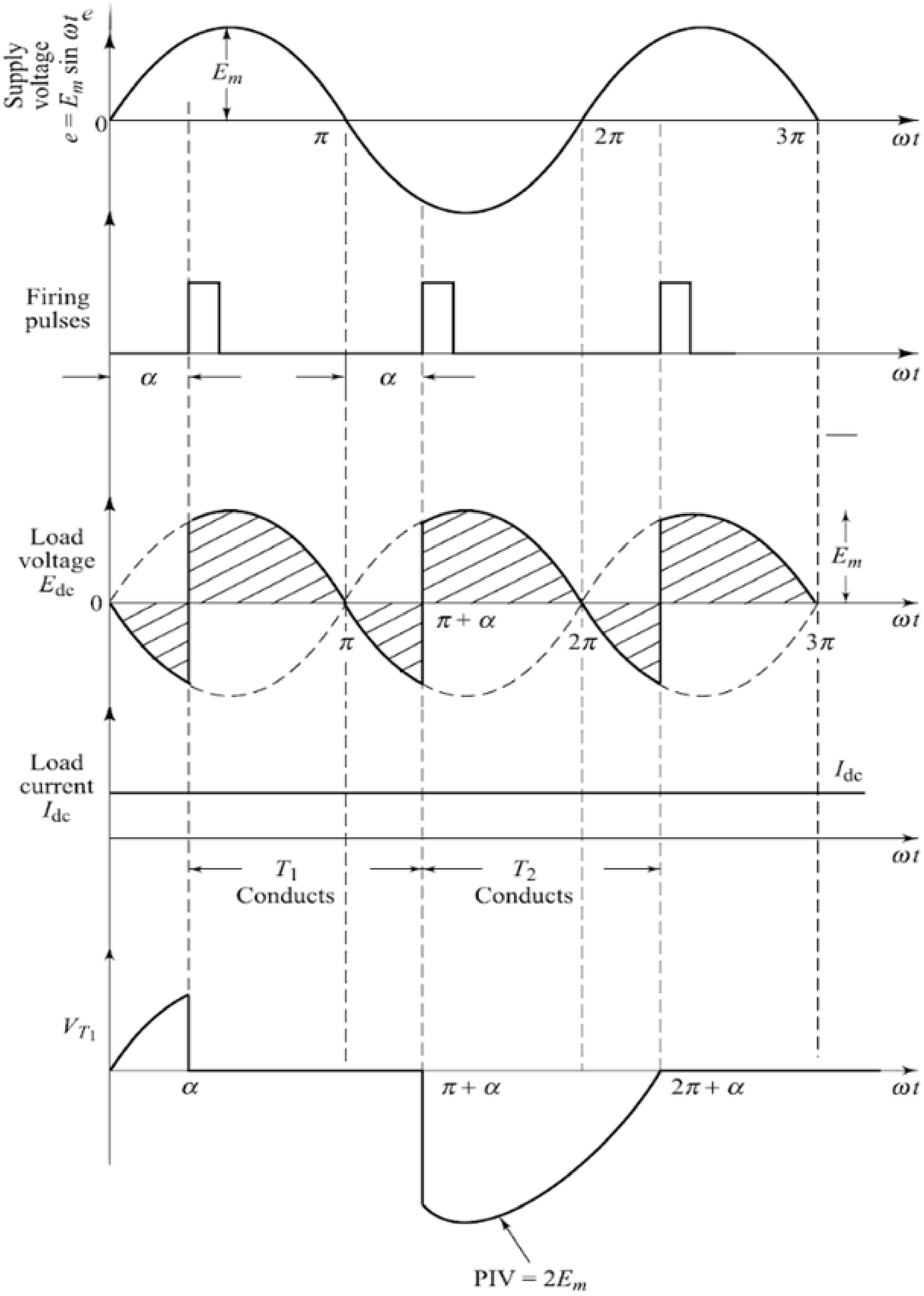


Fig.2.12: *Waveforms for M-2 connection with R-L load*

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

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

$$E_{\mathrm{dc}} = \frac{2E_m}{\pi}\cos\alpha \qquad (2.10)$$

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. $\alpha=0^\circ$.
2. This voltage is zero when $\alpha=90^\circ$. i.e., the load voltage will contain equal positive and negative areas, giving zero output voltage.
3. This voltage is negative maximum when $\alpha=180^\circ$.

3. Effect of Free-Wheeling Diode

Figure 2.13 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.2.14.

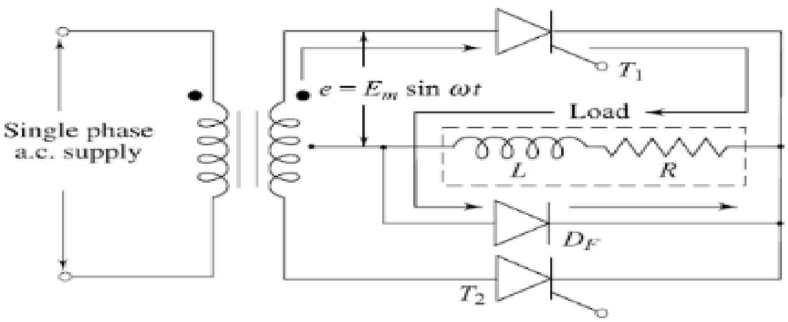


Fig.2.14: *M-2 configuration with freewheeling diode D_f*

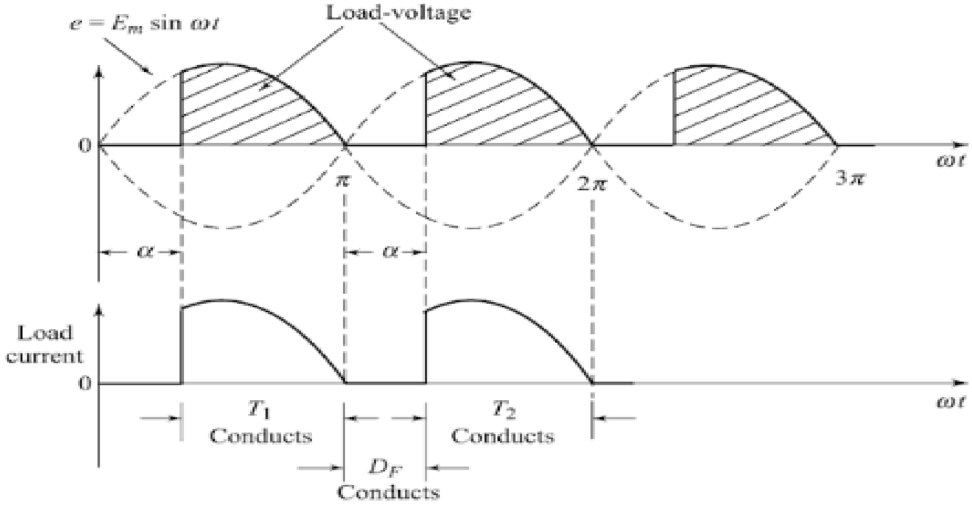


Fig.2.15: *Waveforms*

As shown in Fig.2.15, 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. 2.15. The stored-energy in the inductive load circulates current through the feedback-diode in the direction shown in Fig.2.14.

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

$$E_{\mathrm{dc}} = \frac{1}{\pi}\int_{\alpha}^{\pi} E_m \cdot \sin\omega t \cdot \mathrm{d}(\omega t) = \frac{E_m}{\pi}[1+\cos\alpha] \tag{2.11}$$

The load current is given by

$$I_{\mathrm{dc}} = \frac{E_m}{\pi R}[1+\cos\alpha] \tag{2.12}$$

It is also observed from Fig. 2, that the freewheeling diode Df, 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

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

$$ID_f = \frac{E_m}{\pi^2 R}(\alpha + \alpha' \cos\alpha) \tag{2.13}$$

2.4.2 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.2.16. The operation of this circuit is in principle similar to that of the two -pulse midpoint circuit. In the bridge circuit, diagonally opposite pair of thyristors are made to conduct, and are commutated, simultaneously.

During the first positive half-cycle, SCRs T_1 and T_2 are forward biased and if they are triggered simultaneously, then current flows through the path L-T_1-R-T_2-A. Hence, in the positive half cycle, thyristors T_1 and T_2 are conducting.

During the negative half-cycle of the a.c. input, SCRs T_3 and T_4 and biased and if they are triggered simultaneously, then current flows through the path A-T_3-R-T_4-L are forward biased and. Thyristors T_1, T_2 and T_3, T_4 are triggered at the same firing angle α in each positive and negative half-cycles of the supply voltage, respectively.

When the supply voltage falls to zero, the current also goes to zero. Hence thyristors T_1, T_2 in positive half-cycle and T_3, T_4 in negative half cycle turn-off by natural commutation. The related voltage and current waveforms for this circuit are shown in Fig.2.16. The relations for E_{dc}, I_{dc} and E_{rms} for this bridge configuration is similar to the equations in mid-point configuration.

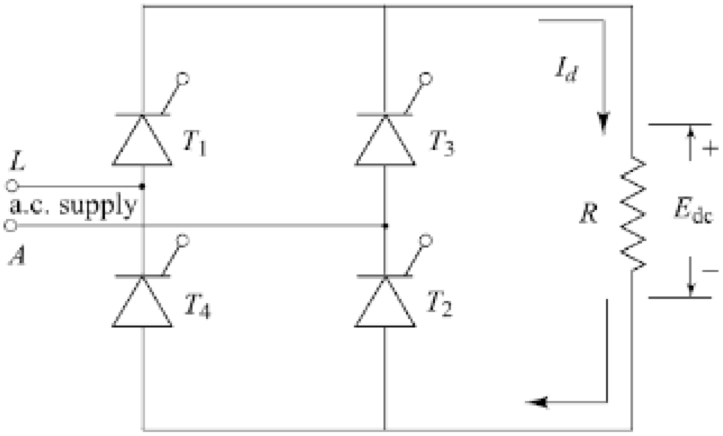


Fig.2.16: *Fully-controlled bridge-circuit with resistive-load*

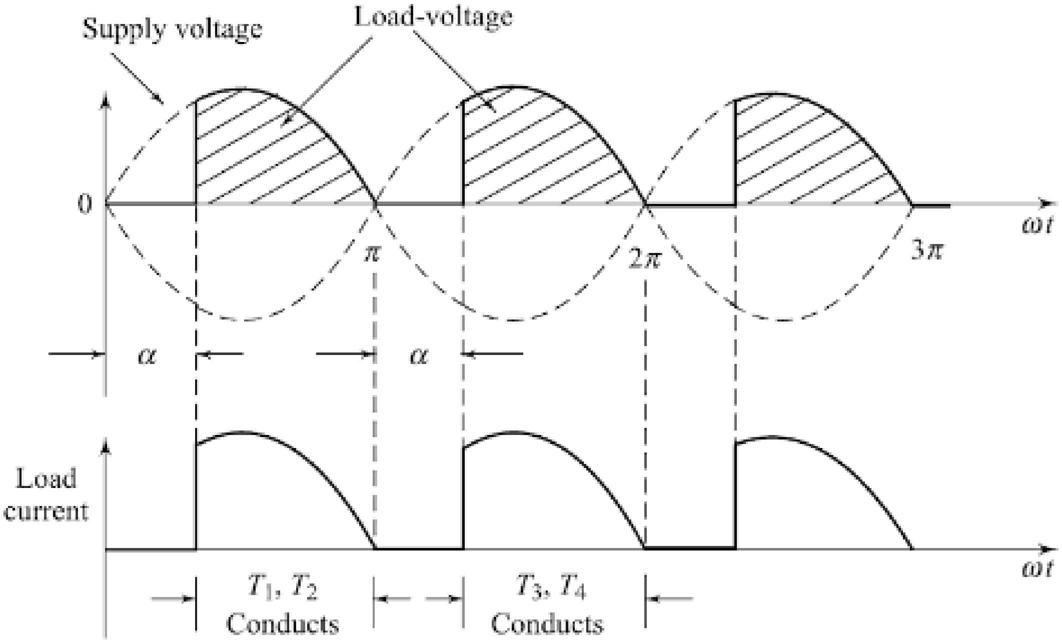


Fig.2.17: *Waveforms for fully-controlled bridge with resistive-load*

1. Fully Controlled Bridge Circuit With Inductive Load (R-L Load)

The single phase fully controlled bridge circuit with RL load is shown in Fig. 2.18. Conduction does not takes place until the thyristors are fired and, in order for current to flow, thyristors T_1 and T_2 must be fired together, as must thyristors T_3 and T_4 in the next half-cycle. Both thyristors T_1 and T_2 are fired from the same firing circuit. Inductance L is used in the circuit to reduce the ripple. A large value of L will result in a continuous steady current in the load. The waveforms with two different firing-angles are shown in Fig.2.19.

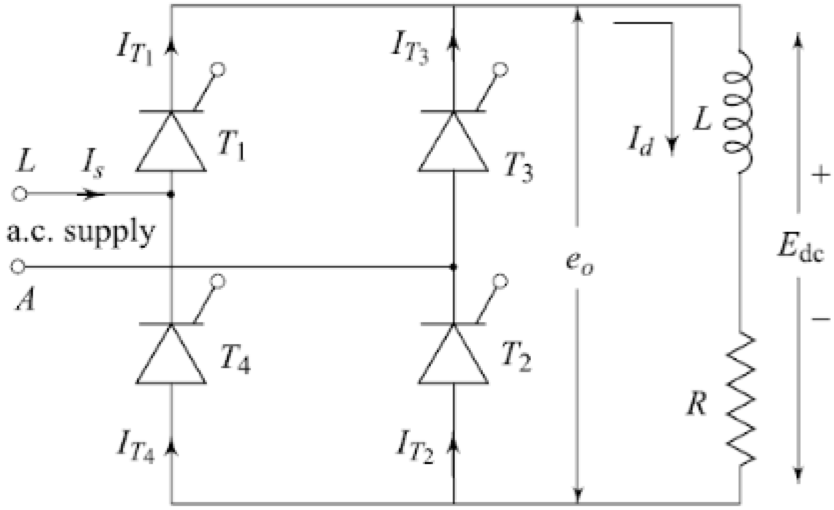


Fig. 2.18: *Fully controlled single-phase bridge with R–L load*

The voltage waveform at the d.c. terminals comprises a steady d.c. component on to which is superimposed an a.c. ripple component, having a fundamental frequency equal to twice that of a.c. supply. The input line-current has a square waveform of amplitude I_d the fundamental component of this waveform is in phase with the input-voltage.

As shown in Fig. 2.19, at firing angle $\alpha=60^{\circ}$, thyristors T_1 and T_2 are triggered. Current flows through the path L-T_1-A-L-R-B-T_2-N. Supply voltage from this instant appears across output terminal and forces the current through load. This load-current, I_d, is assumed to be constant. This current also flows through the supply and the direction is from line to neutral, which is taken positive, as shown in Fig. 2.19, along with the applied voltage. Now, at instant π, voltage reverses. However, because of very large inductance L, the current is maintained in the same direction at constant magnitude I_d which keeps the thyristors T_1 and T_2 in conducting state and hence, the negative supply voltage appears across output terminals.

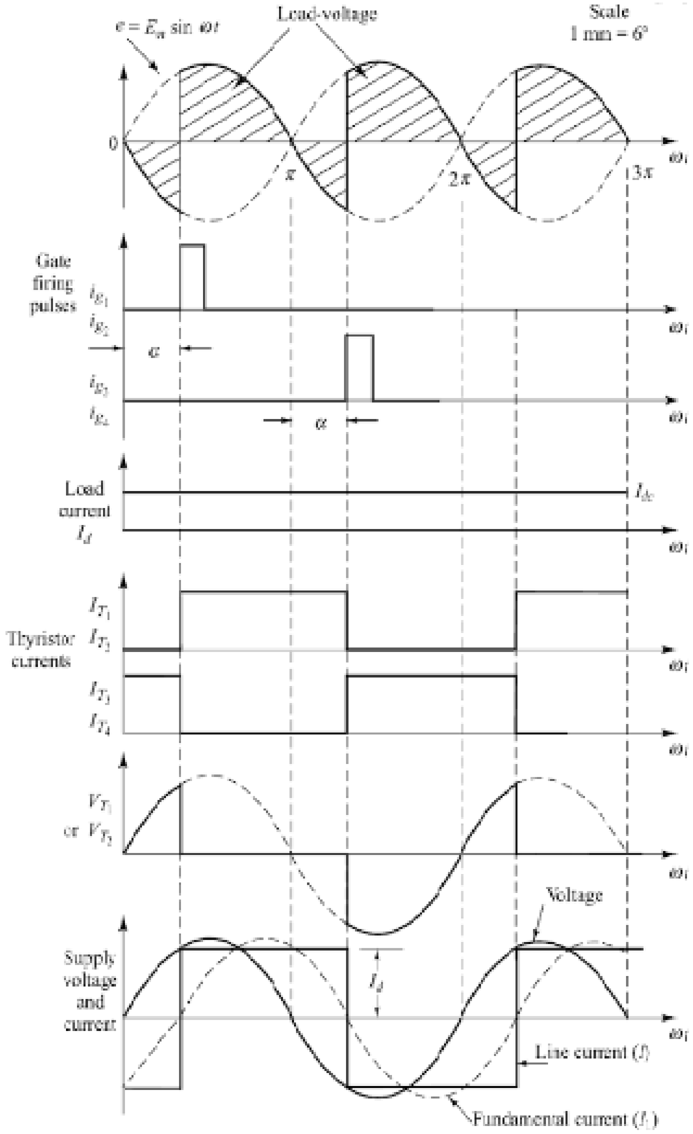


Fig. 2.19: *(a) Waveforms for α = 60°*

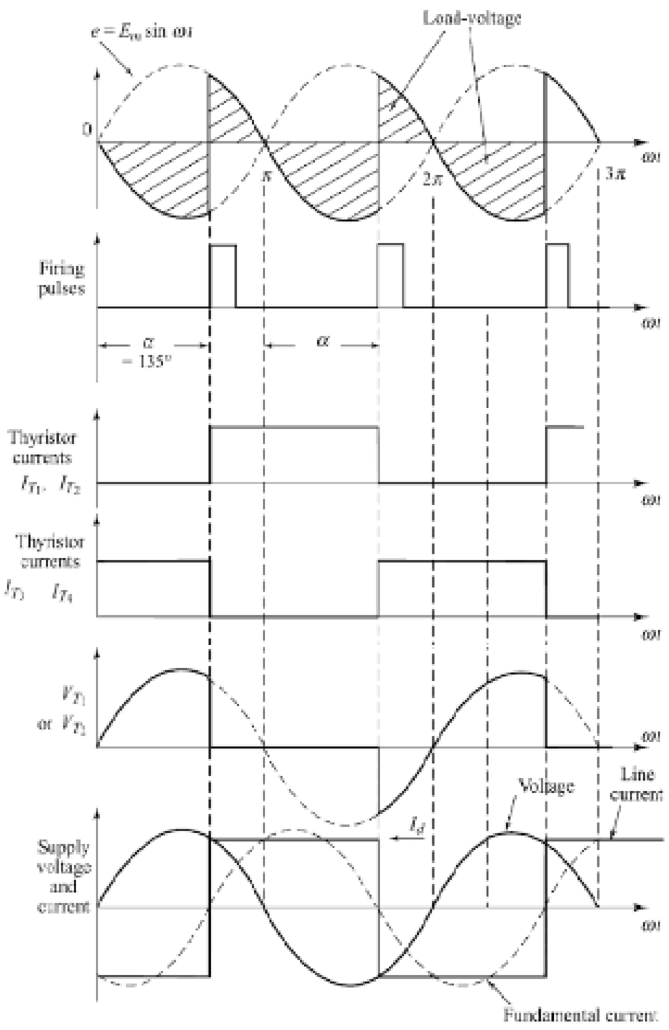


Fig. 2.19: *(b) Waveforms for α = 135°*

At an angle π+α, thyristors T_3 and T_4 are fired. With this, the negative line voltage reverse biases thyristors T_1 through T_3, and T_2 through T_4 of commutating thyristors T_1 and T_2. The current flows through the path N-T_3-A-L-R-B-T_4-L. This continues in every half cycle and we get the output voltage as shown in the figure. As shown, the line current is positive when T_1, T_2 conducting and negative when T_3T_4 are conducting.

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

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

$$= \frac{E_m}{\pi}[\cos\alpha - \cos(\pi+\alpha)]E_{dc} = \frac{2E_m}{\pi}\cos\alpha \tag{2.14}$$

By controlling the phase-angle of firing pulses, applied to the gates of the thyristors in the range $0_\circ-180_\circ$, the average-value of the d.c. voltage can be continuous current flow at the d.c. terminals. Because the average d.c. voltage is reversible even though the current flow in the d.c. terminals is unidirectional, the power-flow in the converter can be in either direction. Hence two modes of operation are possible with fully controlled single-phase bridge circuit.

Mode 1 Rectifying Mode: During the interval α to π, both supply- voltage E_s and supply-current I_s are positive; power, therefore, flows from a.c. source to load. During the interval (π to $\pi+\alpha$), E_s is negative but I_s is positive, the load therefore returns some of its energy to the supply system. But the net power flow is from a.c. source to d.c. load because $(\pi-\alpha)>\alpha$.

Also Eq.2.14 shows that if $\alpha<90_\circ$, the voltage at the d.c. terminals is positive, therefore, the power flows from a.c. side to d.c. side and the converter operates as a rectifier.

Mode 2 Inverting Mode: In Fig.2.19 (b) the firing pulses are retarded by an angle of 135°. The d.c. terminal voltage waveforms now contains a mean negative component, and the fundamental component of the a.c. line-current waveforms lags the voltage by an angle of 135°. Since the mean d.c. terminal voltage is negative, the d.c. power, and hence also the mean a.c. power, must also be negative. In other words is now being delivered from the d.c. side of the converter to the a.c. side, and the converter is operating as a "line- commutated inverter."

2.5 Choppers

The DC Choppers convert the input DC voltage into fixed or variable DC output. Hence DC chopper is also called as dc to dc converter. The output V_0 can be greater or lesser than the input. Hence the chopper can be step-down or step-up type.

2.5.1 Classification of Chopper:

DC Choppers can be classified as:

(A) According to the Input /Output Voltage Levels

(i) Step-down chopper: The output voltage is less than the input

(ii) Step-up chopper: The output voltage is greater than the input voltage.

(B) According to the Directions of Output Voltage and Current

(i) Class A (type A) chopper

(ii) Class B (type B) chopper

(iii) Class C (type C) chopper

(iv) Class D (type D) chopper

(v) Class E (type E) chopper

(C) According to Circuit Operation

(i) First-quadrant chopper: The output voltage and both must be positive (Type A).

(ii) Two-quadrant chopper: The output voltage is positive and current can be positive or negative (class-C) or the output current is positive and the voltage can be positive or negative (class-D).

(iii) Four-quadrant chopper: The output voltage and current both can be positive or negative (class-E).

(D) According to Commutation Method

(i) Voltage-commutated choppers

(ii) Current-commutated choppers

(iii) Load-commutated choppers

(iv) Impulse-commutated choppers

2.6 Basic Chopper Operation

2.6.1 Principle of Step-Down Chopper (Buck-Converter)

In general, d.c. chopper consists of power semiconductor devices (SCR, BJT, power MOSFET, IGBT, GTO, MCT, etc., which works as a switch), input d.c. power supply, elements (R, L, C etc.) and output load. (Fig. 2.20) The average output voltage across the load is controlled by varying on-period and off-period (or duty cycle) of the switch.

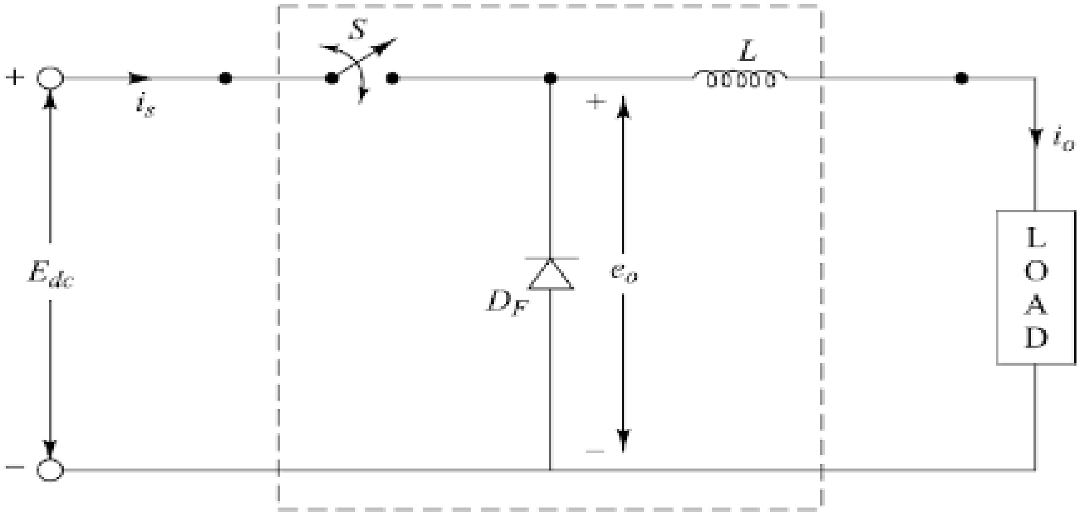


Fig. 2.20: *Basic chopper circuit*

A commutation circuitry is required for SCR based chopper circuit. Therefore, in general, gate-commutation devices based choppers have replaced the SCR-based choppers. However, for high voltage and high-current applications, SCR based choppers are used. The variations in on- and off periods of the switch provides an output voltage with an adjustable average value. The power-diode D_f operates in freewheeling mode to provide a path to load-current when switch (S) is OFF. The smoothing inductor filters out the ripples in the load current. Switch *S* is kept conducting for period T_{on} and is blocked for period T_{off}. The chopped load voltage waveform is shown in Fig.2.21.

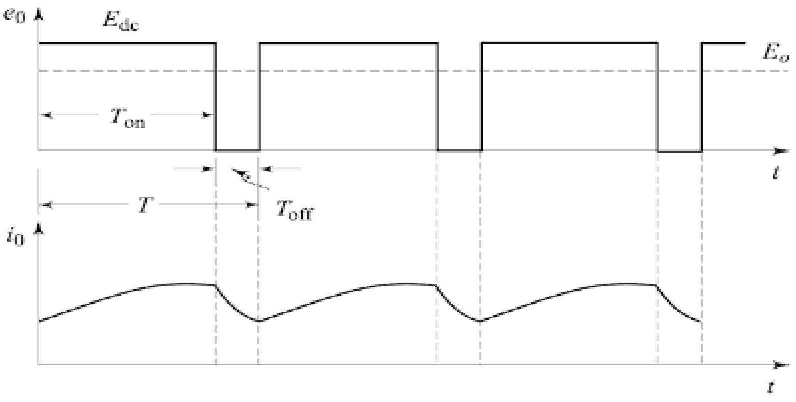


Fig. 2.21: *Output voltage and current waveforms*

During the period T_{on}, when the chopper is on, the supply terminals are connected to the load, terminals. During the interval T_{off}, when the chopper is off, load current flows through the freewheeling diode D_f. As a result, load terminals are short circuited by D_f and load voltage is therefore, zero during T_{off}. In this manner, a chopped d.c. voltage is produced at the load terminals. From Fig. 2.21, the average load-voltage E_0 is given by

$$E_0 = E_{dc}\frac{T_{on}}{T_{on+off}} \tag{2.15}$$

where,

T_{on} = on-time of the chopper,

T_{off} = off-time of the chopper

$T = T_{on} + T_{off}$ = chopping period

If $\alpha = T_{on} / T$, be the duty cycle, then above equation becomes,

$$E_0 = E_{dc} \cdot \frac{T_{on}}{T} \quad \text{or} \quad E_0 = E_{dc} \cdot \alpha \tag{2.16}$$

Thus, the load voltage can be controlled by varying the duty cycle of the chopper.

Also,

$$E_0 = \frac{T_{\text{on}}}{T} E_{\text{dc}} = T_{\text{on}} \cdot f \cdot E_{\text{dc}} \tag{2.17}$$

From Eq. 2.16, it is obvious that the output voltage varies linearly with the duty cycle. It is therefore possible to control the output voltage in the range zero to E_{dc}.

If the switch *S* is a transistor, the base-current will control the ON and OFF period of the transistor switch. If the switch is GTO thyristor, a positive gate pulse will turn-it ON and a negative gate pulse will turn it OFF. If the switch is an SCR, a commutation circuit is required to turn it OFF.

The average value of the load current is given by

$$I_0 = \frac{E_o}{R} = \frac{\alpha \cdot E_{\text{dc}}}{R} \tag{2.18}$$

The effective (RMS) value of the output voltage is given by

$$E_{o(\text{RMS})} = \sqrt{\frac{E_{\text{dc}}^2 \cdot T_{\text{on}}}{T}} = E_{\text{dc}} \cdot \sqrt{\frac{T_{\text{on}}}{T}} = E_{\text{dc}}\sqrt{\alpha} \tag{2.19}$$

2.6.2 Principle of Step-up Choppers

The chopper which is used to produce higher voltages at the load than the input voltage (i.e. $E_0 < E_{dc}$) is called step up chopper, which is shown in Fig. 2.22.

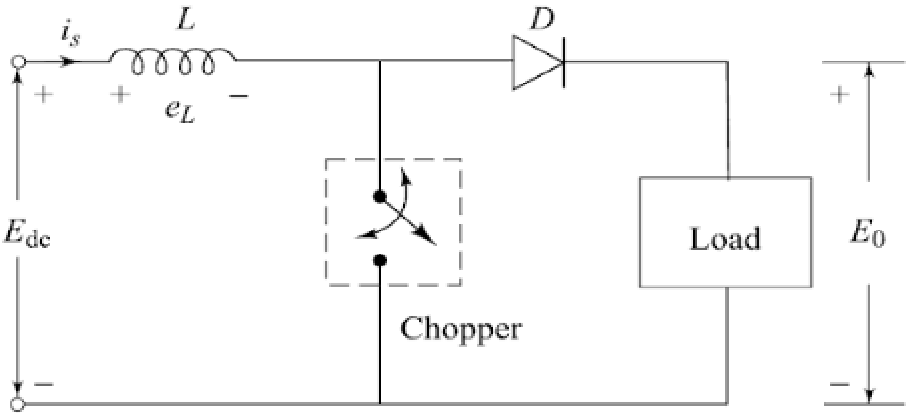


Fig. 2.22: *Step-up chopper or boost choppers*

When the chopper is OFF, the inductor current is forced to flow through the diode and load for a period T_{off}. As the current tends to decrease, polarity of the emf induced in inductor L is reversed to that of shown in Fig. 2.22 and as a result voltage across the load E_0 becomes

$$E_0 = E_{\mathrm{dc}} + L\frac{\mathrm{d}i_s}{\mathrm{d}t}$$

that is, the inductor voltage adds to the source voltage to force the inductor current into the load. In this manner, the energy stored in the inductor is released to the load. Here, higher value of inductance L is preferred for getting lesser ripple in the output.

During the time T_{on}, when the chopper is ON, the energy input to the inductor from the source is given by

$$W_i = E_{dc}\, I_s\, T_{on} \tag{2.20}$$

Equation 2.20 is based on the assumption that the source current is free from ripples. Now, during the time T_{off} when chopper is OFF, energy released by the inductor to the load is given by

$$W_o = (\, E_o - E_{dc}\,)\, I_s\, T_{off} \tag{2.21}$$

Considering the system to be lossless, and, in the steady-state, these two energies will be equal.

$$\therefore \quad E_{\mathrm{dc}} \cdot I_s T_{\mathrm{on}} = (E_0 - E_{\mathrm{dc}})\, I_s T_{\mathrm{off}}$$

or

$$E_0 = E_{\mathrm{dc}} \frac{T_{\mathrm{on}} + T_{\mathrm{off}}}{T_{\mathrm{off}}}$$

or

$$E_0 = E_{\mathrm{dc}} \frac{T}{T - T_{\mathrm{on}}}$$

or

$$E_0 = E_{\mathrm{dc}} \frac{1}{T/T - T_{\mathrm{on}}/T}, \quad But, \ \frac{T_{\mathrm{on}}}{T} = \alpha$$

$$\therefore \quad E_0 = \frac{E_{\mathrm{dc}}}{1-\alpha}$$

For $\alpha = 0, E_0 = E_{\mathrm{dc}}; \quad and \quad \alpha = 1, E_0 = \infty$

Hence, for variation of a duty cycle $\alpha\alpha$ in the range $0<\alpha<10<\alpha<1$, the output voltage E_0 will vary in the range $E_{dc} < E_0 < \infty$.

2.6.3 Basic principle of Step Up/ Step Down Chopper

A chopper can also be used both in step-up and step-down modes by continuously varying its duty cycle. The principle of operation is illustrated in Fig. 2.23. As shown, the output, polarity is opposite to that of input voltage E_{dc}.

When the chopper is ON, the supply current flows through the path E_{dc+} − CH – L − E_{dc-}. Edc+−CH−L−Edc−. Hence, inductor *L* stores the energy during the T_{on} period.

When the chopper CHCH is OFF, the inductor current tends to decrease and as a result, the polarity of the emf induced in *L* is reversed as shown in above figure. Thus, the inductance energy discharges in the load through the path, L_+ − Load – D – L_-.

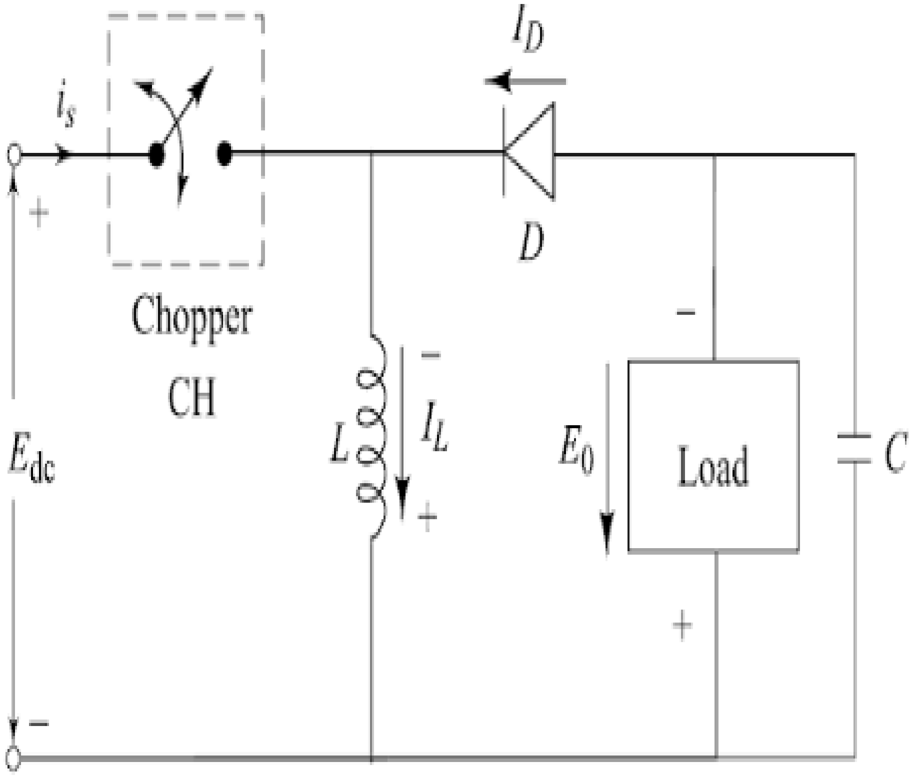


Fig. 2.23: Step-up/down chopper

During T_{on}, the energy stored in the inductance is given by

$W_i = E_{dc} I_s T_{on}$

During T_{off}, the energy fed to the load is

$W_o = E_0 I_s T_{off}$

For a lossless system, in steady-state: Input energy, Wi= output energy, Wo.

$$\therefore \quad E_{dc} \cdot I_s \cdot I_{on} = E_0 I_s T_{off}, \; or \; E_0 = E_{dc} \cdot \frac{T_{on}}{T_{off}}$$

or

$$E_0 = E_{dc} \cdot \frac{T_{on}}{T - T_{on}} = E_{dc} \cdot \frac{1}{T/T_{on} - T_{on}/T_{on}}$$

Substituting

$$\frac{T_{on}}{T} = \alpha, \; we \; get, \; E_0 = E_{dc} \cdot \frac{1}{1/\alpha - 1}$$

or

$$E_0 = E_{dc} \frac{\alpha}{1 - \alpha}$$

For 0<α<0.5, the step-down chopper operation is achieved and for 0.5<α<1, step-up chopper operation is obtained.