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.

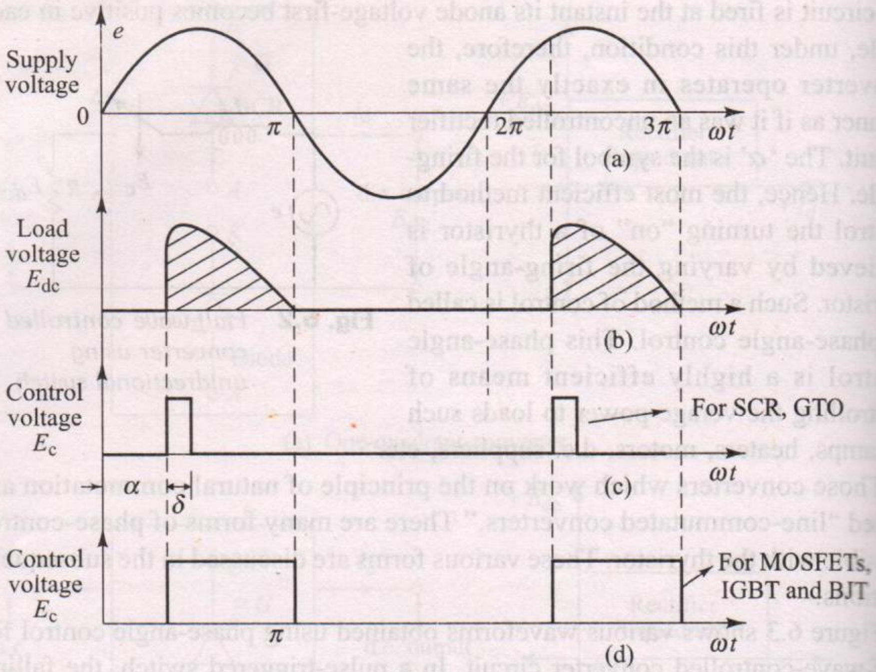

Fig. 6.3 *Phase-angle control*

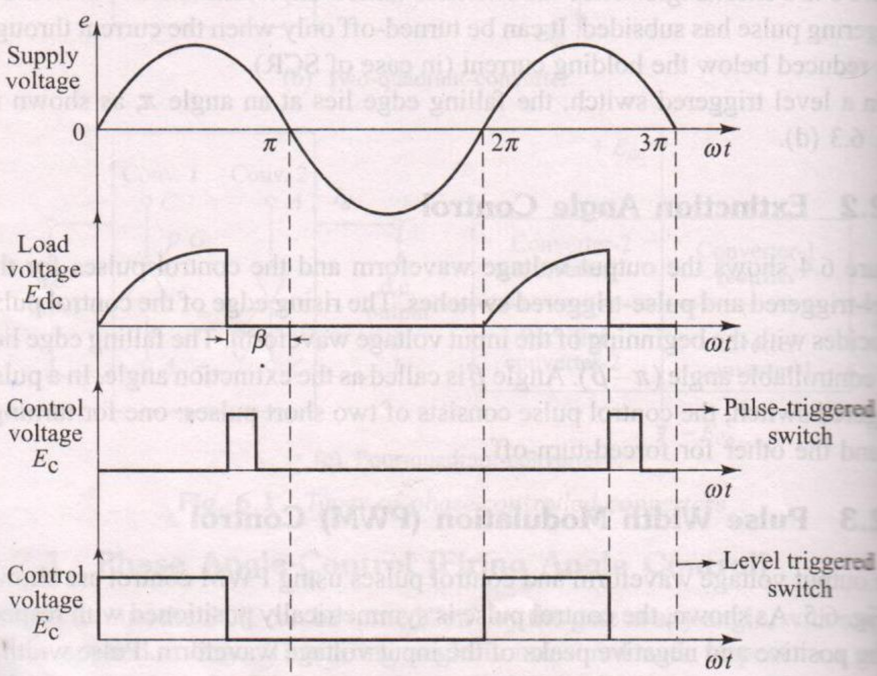

Fig. 6.4 *Extinction angle control*

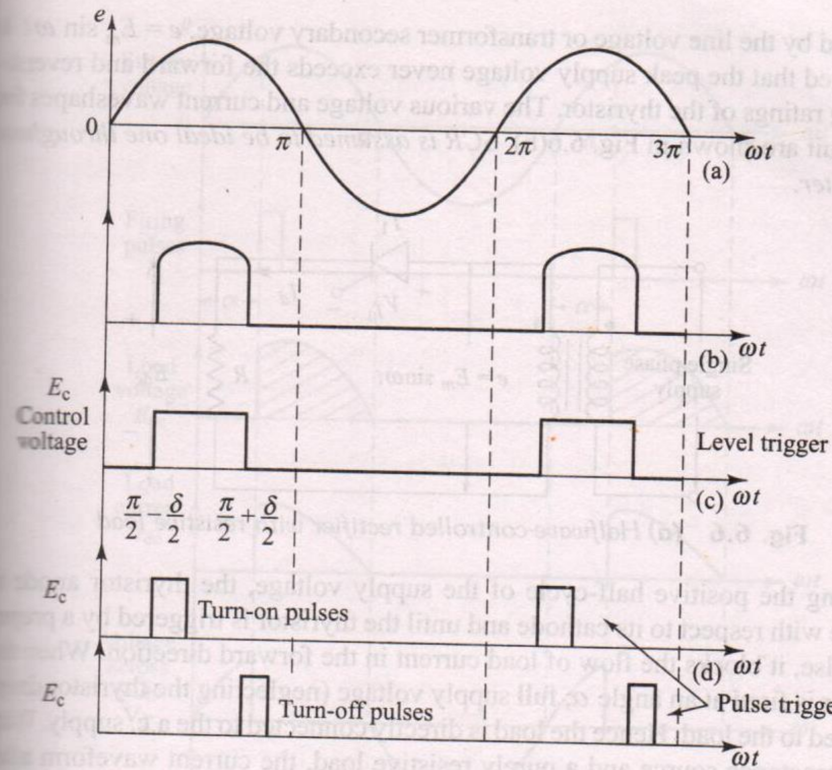

Fig. 6.5 *PWM control*

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 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*.

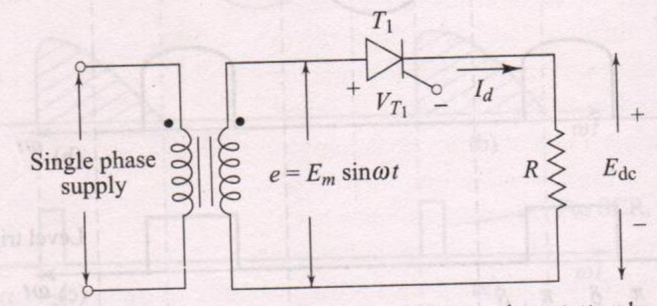

Fig. 6.6 ***(a)*** *Halfwave-controlled rectifier with resistive load*

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

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

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

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

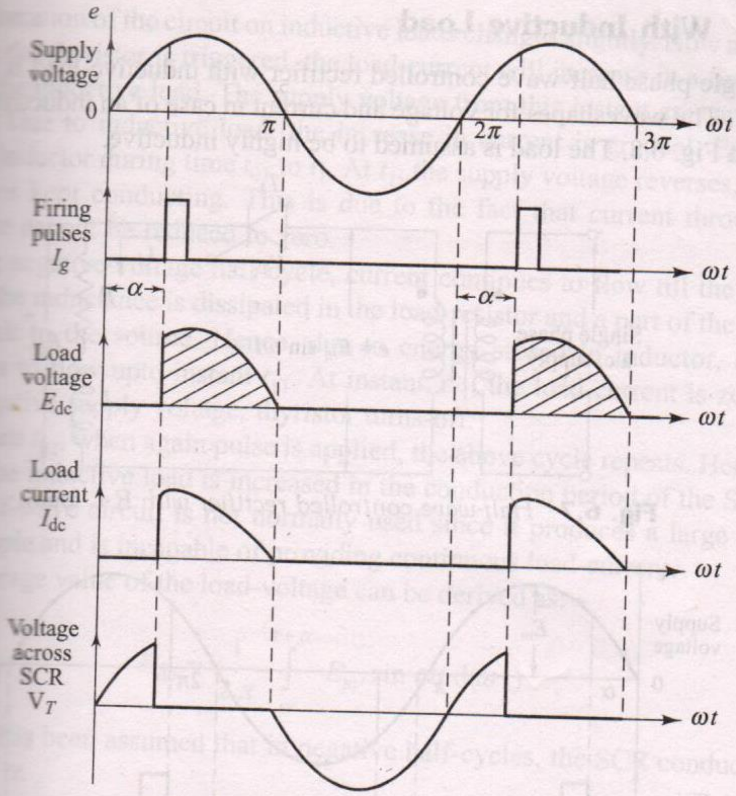

Fig. 6.6 ***(b)*** *Waveforms for a half-wave circuit*

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

$$I_d = \frac{E_m}{2\pi R}[1+\cos\alpha] \tag{6.3}$$

RMS load voltage The RMS load voltage for a given firing angle α is given by

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

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

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

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.

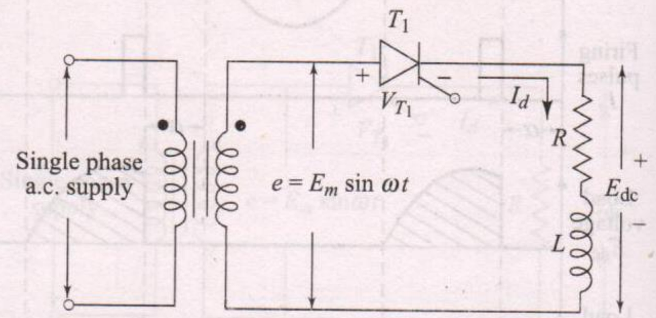

Fig. 6.7 *Half-wave controlled rectifier with R-L load*

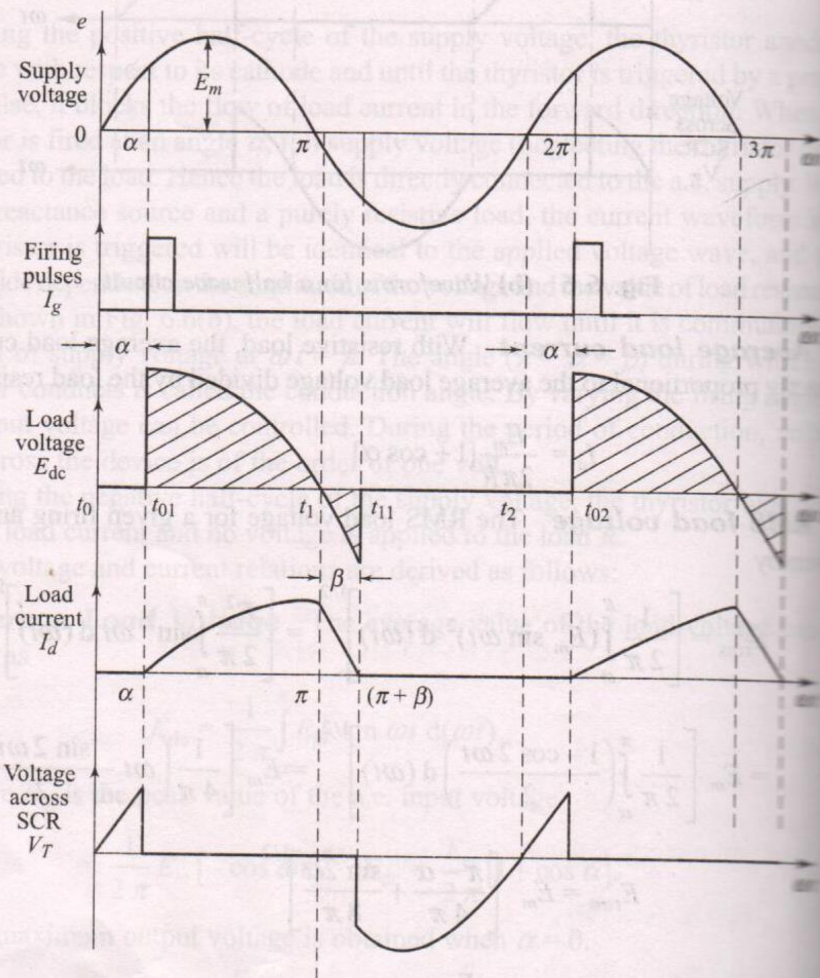

Fig. 6.8 *Waveforms for a half-wave controlled rectifier with RL load*

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.

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

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°.

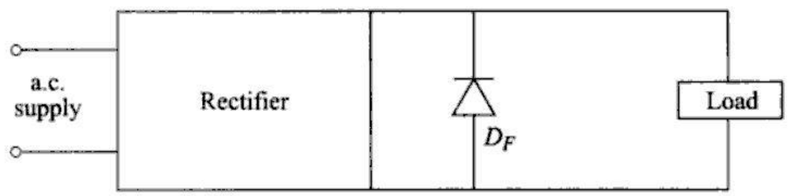

Fig. 6.9 *Position of commutating diode D_F*

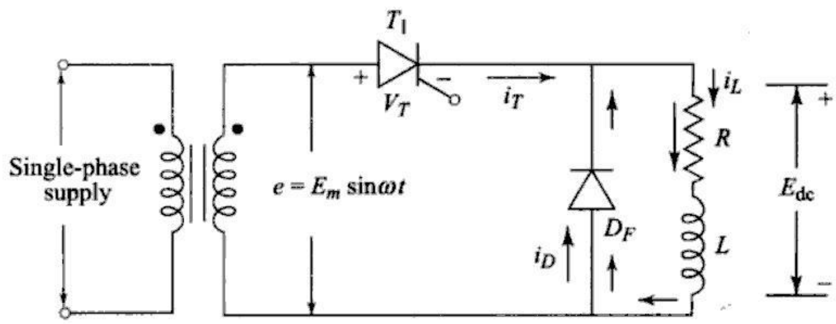

Fig. 6.10 *Half-wave rectifier with a freewheeling diode*

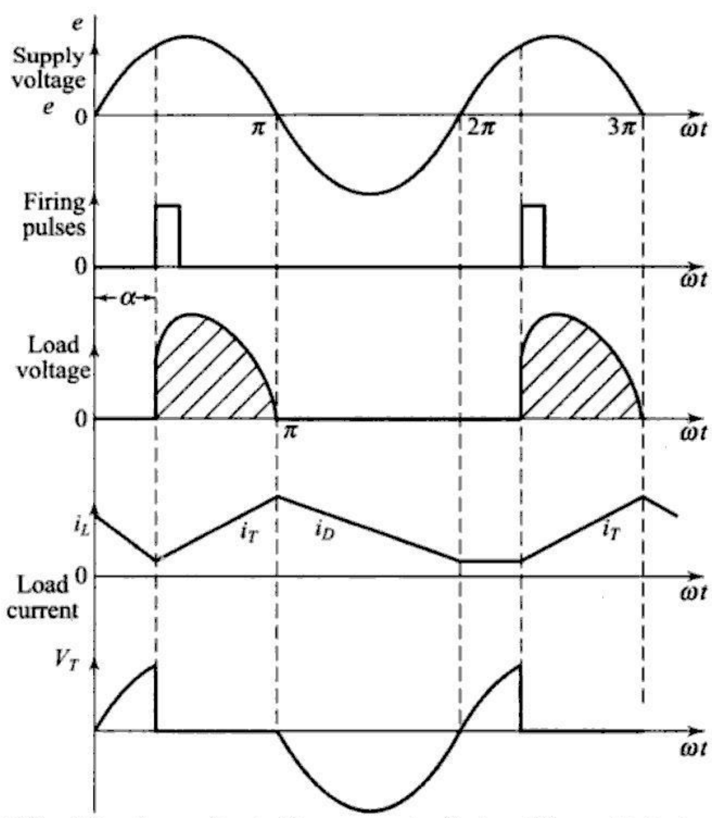

Fig. 6.11 *Waveforms for half-wave controlled-rectifier with inductive load and freewheeling diode*

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 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.

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

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