VOLTAGE CONTROL OF INVERTERS

An inverter may require voltage control to:

- cope with the variations in the input dc voltage
- compensate the voltage regulation of the inverter switches and transformer
- provide variable or adjustable voltage to the load.

Certain loads, such as variable frequency induction motor drive, require simultaneous control of frequency and voltage. Controlling the conduction intervals of the inverter switches can control frequency of the inverter output. Voltage control may be done by any of the following techniques:

1. Control of input dc voltage
2. External control of inverter ac output voltage
3. Internal control of inverter.

8.12.1 CONTROL OF INPUT DC VOLTAGE

The output voltage of an inverter may be controlled by controlling the input dc voltage supplied to the inverter. Figure 8.33 shows the various schemes used to control the input dc voltage. If the basic source is dc, variable dc voltage may be obtained using a chopper or a dc-to-dc converter, as shown in Fig. 8.33a. If the basic source is ac, variable dc voltage may be obtained using any of the schemes shown in Fig. 8.33b–d.

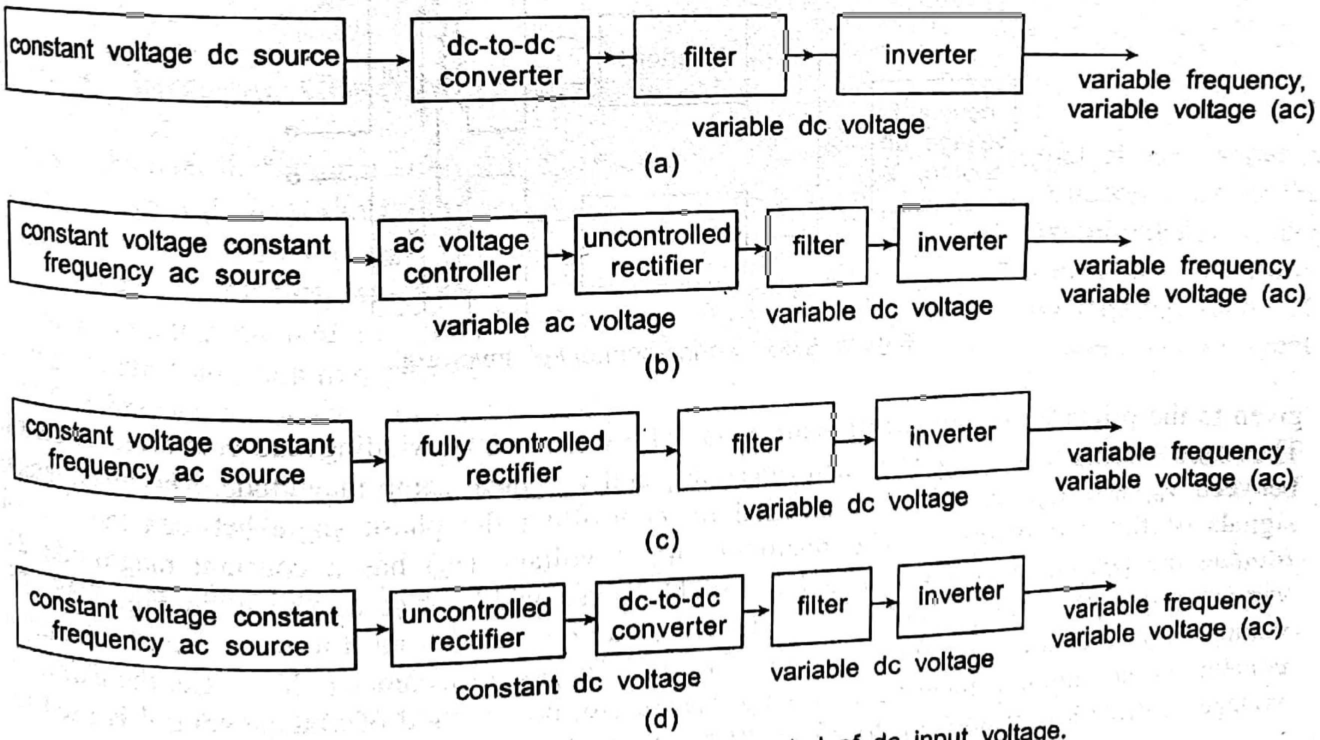

Figure 8.33 Inverter voltage control by control of dc input voltage.

In the scheme of Fig. 8.33b, the input ac voltage is first converted into a variable ac voltage using an ac voltage controller and then it is converted into dc with the help of an uncontrolled rectifier. In this system, variable voltage, variable frequency ac is obtained after three conversion stages. Obviously, efficiency of the system is poor. Moreover, the input power factor becomes poor at low voltages.

Figure 8.33c shows an improved scheme. In this scheme, variable dc voltage is obtained using a controlled rectifier. As only two conversion stages are required, the efficiency of the system is better than that for the previous scheme. At low output voltages, the input power factor is poor. Another drawback of the scheme is that the output of the controlled rectifier contains appreciable amount of low-frequency harmonics. Therefore, large size filter components are required. This makes the system response sluggish.

Drawbacks of the system of Fig. 8.33c are removed in the system shown in Fig. 8.33d. This system converts the input voltage into dc using an uncontrolled rectifier. The constant dc voltage is then converted into a variable dc using a high-frequency (dc-to-dc converter). As the chopper operates at a high frequency, its output contains harmonics at very high frequencies. Thus the size of filter components is reduced. Moreover, the fundamental input power factor remains unity under all conditions of operation. However, losses in the system increase due to use of an additional converter.

8.12.2 EXTERNAL CONTROL OF AC OUTPUT VOLTAGE

The constant ac output voltage (rms) from an inverter may be controlled using an ac voltage regulator (ac phase control). This method introduces a large harmonic content in the output voltage. Moreover, the method can be used only for small power applications.

For high-power applications, two square-wave inverters may be connected in series to obtain variable ac voltage, as shown in Fig. 8.34. The output voltages of the inverter-I and inverter-II are given to the primaries of the two transformers, whose secondary windings are connected in series. The output voltages of the two transformers, v_{01} and v_{02}, have same magnitude. The phase angle between v_{01} and v_{02}, φ, can be controlled by controlling the phase angle between the control signals of the two inverters. The resultant output voltage (v_o) has a constant magnitude $2V$ (double the peak of v_{01} and v_{02}) and a variable pulse width, π-φ, as shown in Fig. 8.35. By varying φ from 0 to π, the width of output pulses may be varied from π to 0 and hence the output voltage may be controlled from $2V$ to zero. At low voltages, it becomes a thin pulse, the harmonic contents in the output voltage become large. Therefore, this method of voltage control is used for voltage control (lower side) up to 25 to 30 per cent of the rated voltage.

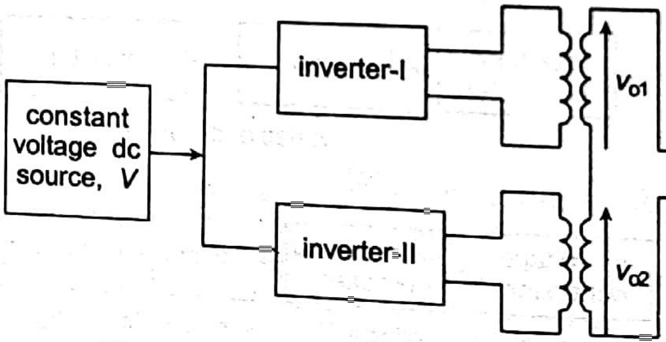

Figure 8.34 Series-connected inverters.

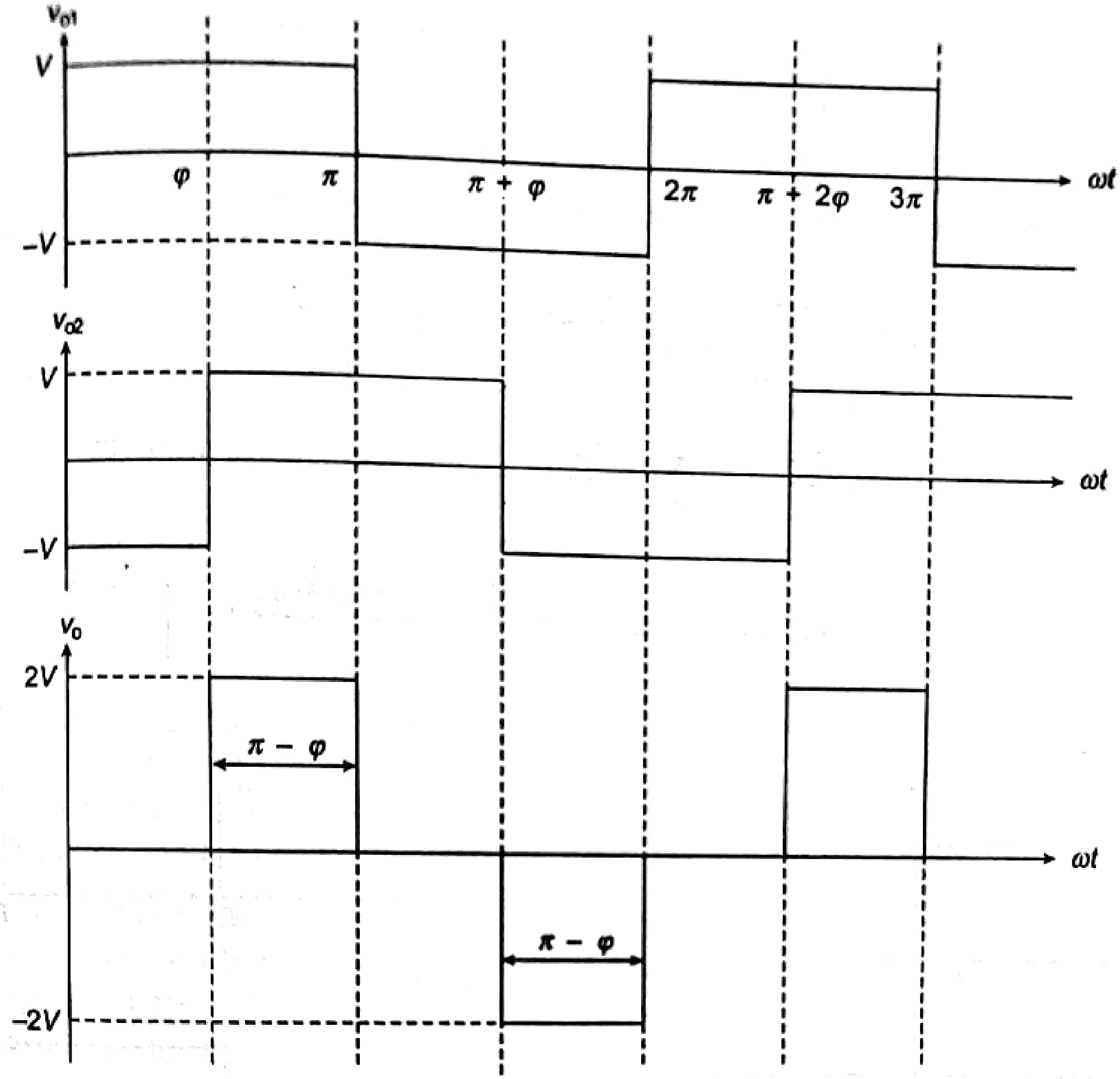

Figure 8.35 Waveforms of series-connected inverters.

8.12.3 INTERNAL CONTROL OF INVERTERS

In this technique, the voltage control is obtained within the inverter. The output of the inverter is in the form of a pulse width modulated wave. Controlling the width of output pulses, controls the output voltage. This method not only provides variable output voltage but also eliminates certain low frequency harmonics, which are responsible for poor performance. This method is therefore, the most popular method of voltage control of inverter. Depending on the required range of voltage control and required performance, a suitable PWM technique may be used. The different PWM techniques are discussed in next pages

Internal

CONTROL OF INVERTER OUTPUT VOLTAGE

The output voltage of a single-phase inverter suffers from two major limitations: the amplitude of the output voltage is fixed and approximately equal to the supply voltage; the output voltage contains appreciable harmonics (low frequency range) and a high value of THD. However, in many industrial applications it is necessary to control the output voltage of the inverter due to the following reasons.

1. To compensate the variations of the input voltage.
2. To compensate for the voltage regulation of the inverters.
3. To supply a constant voltage/frequency control requirement.

There are various techniques to control this output voltage, *viz.,* controlling the dc input voltage; controlling the ac output voltage; pulse width modulation.

If the dc input voltage to the inverter is supplied from a controlled rectifier, by varying the firing angle, the input voltage of the inverter can be controlled, thereby controlling the output ac voltage of the inverter. This technique affects the commutation ability of the inverter if the input dc voltage is utilized to charge the commutation capacitor; in addition it also requires large value filters.

Control at the ac output voltage of the inverter can be carried out either by using an ac voltage controller or a series-inverter controller. Hence, these two techniques require extra peripheral components, which increase the cost of the system. However, the last technique, pulse width modulation (PWM) requires no extra peripheral component and controls the ac voltage within the inverter itself in an efficient and economical way. In this technique, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by varying the on and off periods of the inverter components [3]. These inverters are capable of producing ac voltages of variable magnitude as well as variable frequency. PWM inverters are quite popular in industrial applications, such as adjustable speed ac motor drive loads where one needs to feed the motor with a variable voltage, variable frequency supply. PWM inverters can be single phase as well as three phase. Their principle of operation remains similar. They are characterized by the generation of constant amplitude pulses with the pulse duration modulated to obtain a specific waveform. The commonly used modulation techniques are:

- Single-pulse width modulation
- Multiple-pulse width modulation
- Sinusoidal-pulse width modulation

The main emphasis of all these techniques is to generate a good quality, sinusoidal output voltage with the desired fundamental frequency and magnitude. To judge the quality, a detailed harmonic analysis of the voltage waveform needs to be carried out. A typical analog circuit diagram of the above stated PWM techniques is shown in Figure 7.16. The only difference between them is in the harmonic content of their respective output voltages. It is a bridge configuration with four MOSFETs that are switched on and off several times in each half-cycle to control the output voltage. MOSFETs can be replaced by power BJTs, IGBTs, HEXFETs and ETOs as per the application [4, 8]. Some more advanced PWM techniques are easily realized by using digital processors like microprocessors, microcontrollers, digital signal processors and/or personnel computers.

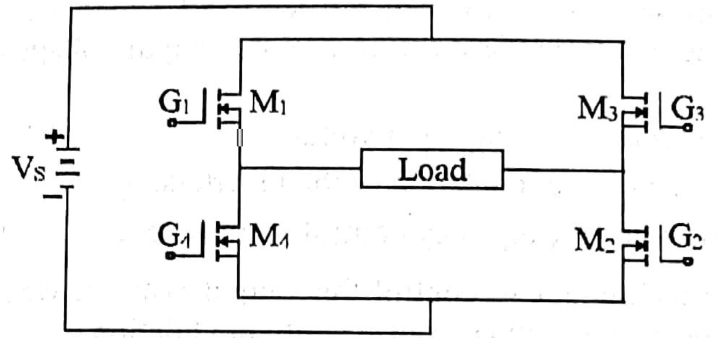

Figure 7.16: Single-phase bridge inverter

7.6.1 Single-pulse Width Modulation

In single-pulse width modulation only one pulse is obtained in each half-cycle and the output voltage is varied by controlling the width of the pulse. Figure 7.17 shows the output voltage of a single-phase bridge inverter with gate signal generation. These gating signals are obtained by comparing a reference rectangular signal of amplitude A_r with a triangular carrier wave of amplitude A_c. The frequencies of these two signals are the same and determine the fundamental frequency of the output voltage. The width d of the output pulse depends upon the amplitude of the reference signal, which can be varied from 0 to π. By varying the ratio of A_r to A_c the width of the output pulse can be varied and is called the *modulation index M*.

$$M = \frac{A_r}{A_c} \tag{7.37}$$

The rms output voltage is

$$V_{rms} = \left[\frac{2}{2\pi}\int_{(\pi-d)/2}^{(\pi+d)/2} V_s^2 \, d\theta\right]^{1/2} = V_s\sqrt{\frac{d}{\pi}} \tag{7.38}$$

The Fourier coefficient b_n of the output voltage is

$$b_n = \frac{2}{\pi}\int_{(\pi-d)/2}^{(\pi+d)/2} V_s \sin n\theta \, d\theta = \frac{4V_s}{n\pi}\left[\sin\frac{n\pi}{2}\sin nd\right] \tag{7.39}$$

Since the positive and negative half-cycles of the output voltage v_o are symmetrical and identical, the value of the coefficient $a_n = 0$. Thus, the Fourier series of the output voltage is

$$v_o = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_s}{n\pi} \sin\frac{nd}{2} \sin n\theta \qquad (7.40)$$

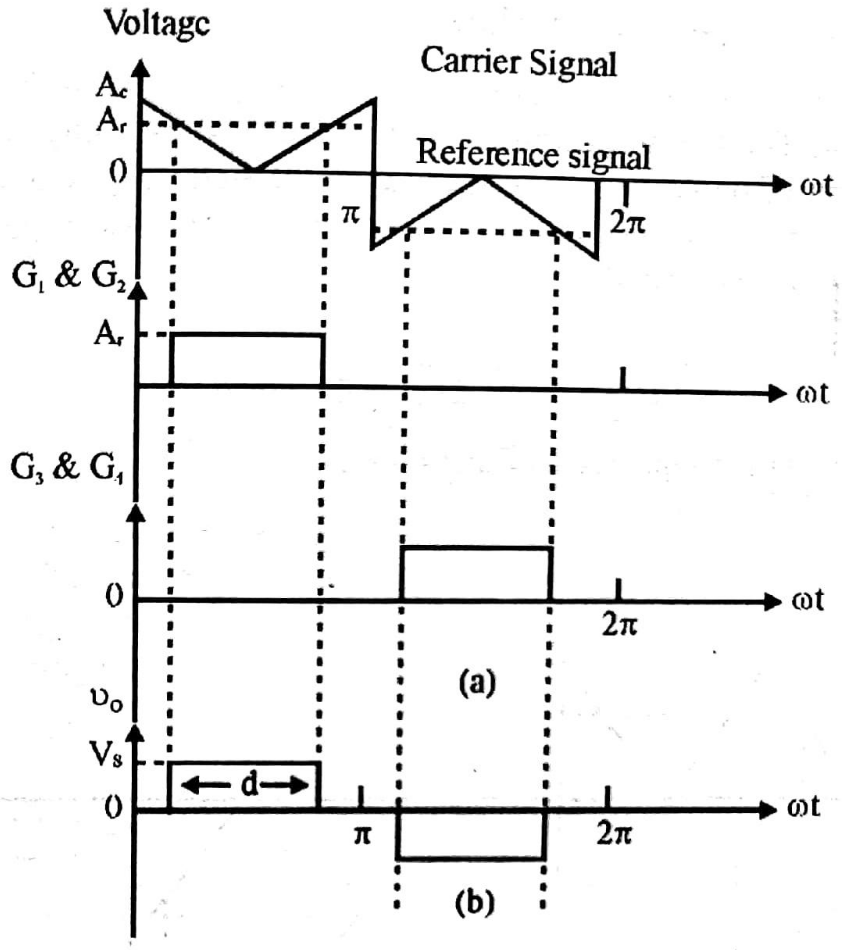

Figure 7.17: Waveforms of single-pulse width modulation (a) gate signal generation; (b) output voltage

where $\theta = \omega t$

To eliminate the n^{th} harmonic,

$$\sin\frac{nd}{2} = 0$$

$$\frac{nd}{2} = k\pi$$

where k is an interger.

For example, the third harmonic can be eliminated if the pulse width $d = (360/3) = 120°$. Similarly, for the 5^{th} harmonic $d = (360/5) = 72°$.

The main limitation of this modulation is that the harmonic content is greater at a lower pulse width and the maximum rms value of the fundamental component is only 90.4% of the dc supply voltage. At a modulation index of 3%, the amplitude of the third harmonic is equal to the amplitude of the fundamental frequency; hence, the dominant harmonic is the third harmonic.

7.6.2 Multiple-pulse Width Modulation

This technique of modulation is an extension of single-pulse width modulation, having less harmonic content. The harmonic content can be reduced by using several pulses in each half-cycle. The number of output pulses depends upon the frequency ratio of the carrier wave f_c and the frequency of the reference wave f_r. The number of pulses in each half-cycle can be obtained from the following expression:

$$p = \frac{f_c}{2f_r} = \frac{mf}{2} \tag{7.41}$$

where $mf = f_c/f_r$ is called the frequency modulation ratio.

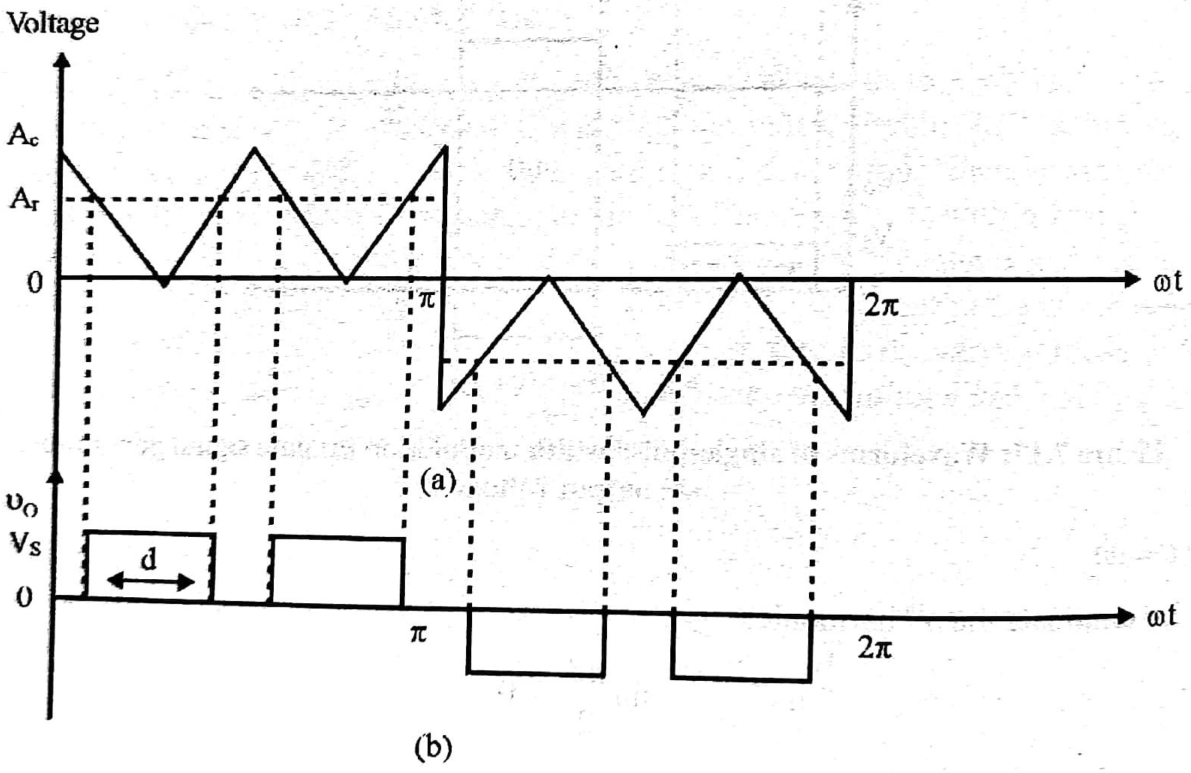

Figure 7.18: Multiple-pulse width modulation (a) gate signal generation; (b) output voltage

The rms output voltage is

$$V_{rms} = \left[\frac{2p}{2\pi} \int_{(\frac{\pi}{p}-d)/2}^{(\frac{\pi}{p}+d)/2} V_s^2 \, d\theta \right]^{1/2} = V_s \sqrt{\frac{pd}{\pi}} \tag{7.42}$$

Figure 7.18 shows the waveforms for a frequency ratio of three. Since the widths of the pulses are equal and symmetrical, it is also called a *uniform pulse width modulation or symmetrical pulse width modulation*. The pulse width d can be varied by varying the amplitude A_r of the reference signal, and its value lies between 0 and π/p.

In this method, low-order harmonics are reduced for large values of p. However, fast on-off switching increases the switching losses.

7.6.3 Sinusoidal-pulse Width Modulation

In this technique several pulses are produced in each half-cycle but the width of the pulses is not the same as in the case of multiple-pulse width modulation, however the width of each pulse is varied in accordance with the amplitude of the sine wave reference voltage. The width of the pulse at the centre of the half-cycle is maximum and decreases on either side. Figure 7.19 shows the generation of the output signal by comparing a sinusoidal reference signal f_r with a triangular carrier wave of frequency f_c. The carrier and reference waves are compared by a comparator and when the sinusoidal wave has a higher magnitude than the triangular wave the comparator output is high, otherwise it is low. This output of the comparator is used to turn on the MOSFETs in the bridge configuration of Figure 7.16, which generates the output voltage.

The reference signal frequency f_r determines the output frequency f_o of the inverter, and its peak amplitude A_r, controls the modulation index M, and thereby the rms output voltage v_o. Thus, the output voltage is controlled by varying the amplitude of the sine wave within the range from zero to V_p, where V_p is the peak of the triangular wave. The number of pulses in each half-cycle depends on the carrier frequency f_c. If the ratio of these two signals (reference and carrier) is equal to m, then the number of pulses in each half-cycle is $(m - 1)$.

From Figure 7.19, it is clear that the widths of the pulses do not change significantly with variation in the modulation index at the middle of the half-cycle. This is because of the characteristics of the reference sine wave. If the carrier wave is applied during the first and last $\pi/3$ interval in each half-cycle, *i.e.*, at 0 to $\pi/3$ and $2\pi/3$ to π, then the widths of the pulses can be changed significantly. This type of modulation is shown in Figure 7.20, and is known as *modified sinusoidal pulse-width modulation*. Due to this modification the fundamental component is increased, the harmonic characteristics are improved and the switching losses are reduced.

For a three-phase voltage control inverter, a three-phase inverter circuit is required in which each phase output is displaced by 120°.

There are some other modulation techniques, which are commonly used in advance circuits to improve the performance, such as: trapezoidal modulation, staircase modulation, stepped modulation, Sine+3rd harmonic modulated PWM, space vector based PWM, current controlled PWM and delta modulation or hysteresis modulation. For a deeper study the readers are advised to go through the books given in the references.

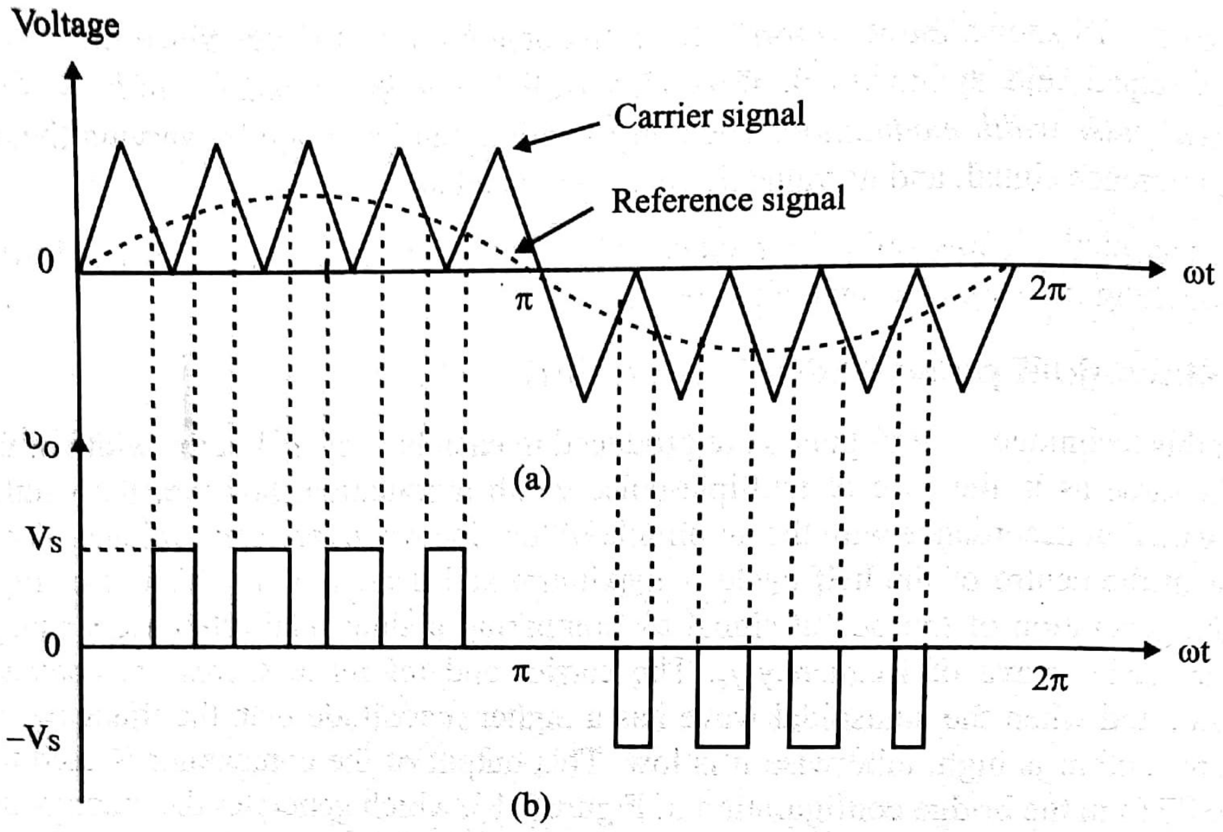

Figure 7.19: Sinusoidal pulse width modulation (a) gate signal voltage; (b) output voltage

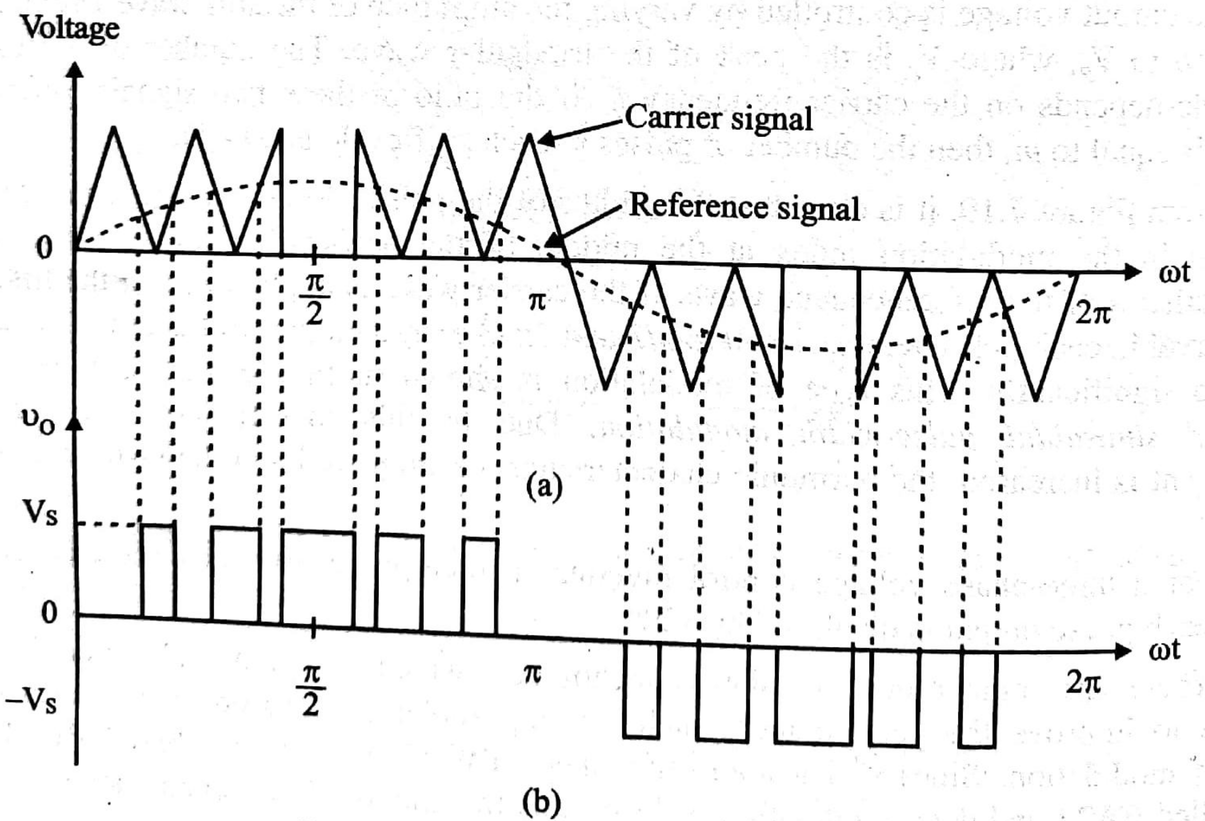

Figure 7.20: Modified sinusoidal PWM