CHAPTER 3

ANALYSIS OF SWITCHED MODE PWM INVERTER

3.1 INTRODUCTION

Fixed DC power can be converted into AC power at desired output voltage and frequency by using a power electronics circuit, called an inverter. Switched-mode DC-to-AC used in AC motor drives and uninterruptible AC power supplies where the objective is to produce a sinusoidal AC output whose magnitude and frequency can be controlled. Industrial applications of inverters are for adjustable-speed AC drives, HVDC transmission lines etc. DC power inputs that inverters can use are power supply network or rotating alternator through a rectifier, fuel cell, or photovoltaic array.

There are two common types of inverters, i) Voltage Source Inverters and ii) Current Source Inverters. When an inverter has a DC source with a small or negligible resistance, which means the inverter has a stiff DC voltage source at its input terminal, it is called a VSI or voltage fed inverter. When the input DC source has high resistance, which means the DC source is a stiff DC current source, the inverter is called a CSI or current fed inverter (Ned Mohan et al 2009).

3.2 CONCEPT OF PULSE WIDTH MODULATION

Higher order harmonics in the load current could be easily filtered out using a series Inductor. A selected range of lower order harmonics can be reduced or eliminated by choosing the number of pulses per half cycle. When
number of pulses increases then the order of harmonics is also increased and that can be easily eliminated by means of filters.

In this method, a fixed AC voltage is given to the converter and controlled DC output voltage is obtained by adjusting the ON and OFF periods of the pulses (Ned Mohan et al 2009). This is the most popular method of controlling the output voltage and this method is termed as pulse width modulation control.

3.3 ADVANTAGES OF PWM

The advantages possessed by PWM technique are as under:

- The output voltage control can be obtained without any additional components.

- Lower order harmonics can be eliminated or minimized along with its output voltage control. As higher order harmonics can be filtered easily, the filtering requirements are minimized.

3.4 DIFFERENT PWM TECHNIQUES

PWM techniques are characterized by constant amplitude pulses. The width of these pulses is, however, modulated to obtain output voltage control and to reduce its harmonic content. Different PWM techniques are as under.

- Single-pulse modulation
- Multiple-pulse modulation
- Sinusoidal-pulse modulation
3.4.1 Single-Pulse Width Modulation

In single pulse-width modulation control, there is only one pulse per half-cycle and the width of the pulse is varied to control the inverter output voltage.

![Figure 3.1 Single Pulse Width Modulation](image)

Figure 3.1 Single Pulse Width Modulation

Figure 3.1 shows the generation of gating signals. The gating signals are generated by comparing a rectangular reference signal of amplitude, \( A_r \), with a triangular carrier wave of amplitude; \( A_c \). The frequency of the reference signal determines the fundamental frequency of the output voltage. The ratio of \( A_r \) to \( A_c \) is the control variable and defined as the amplitude modulation index.
The amplitude modulation index or simply modulation index is

\[ M = \frac{A_r}{A_c} \]  

(3.1)

The RMS output voltage can be found from

\[ V_o = \sqrt{\frac{2}{\pi} \int_{(\pi-\delta)/2}^{(\pi+\delta)/2} V_s^2 d(\omega t)} = V_s \sqrt{\frac{\delta}{\pi}} \]  

(3.2)

### 3.4.2 Multiple-Pulse-Width Modulation

The harmonic content can be reduced using several pulses in each half-cycle of output voltage. The generation of gating signals for turning on and off of transistors is shown in figure 3.2 by comparing a reference signal with a triangular carrier wave. The frequency of reference signal sets the output frequency, \( f_o \), and the carrier frequency, \( f_c \), determines the number of pulses per half-cycle. The modulation index controls the output voltage. This type of modulation is also known as uniform pulse-width modulation (UPWM).

The number of pulses per half-cycle is found from

\[ p = \frac{f_c}{2f_o} = \frac{mf}{2} \]  

(3.3)

where \( m_f = f_0/f_c \) is defined as the frequency modulation ratio.
If $\delta$ is the width of each pulse, the RMS output voltage can be found from

$$V_o = \left[ \frac{2p}{2\pi} \left( \int_{\alpha_m}^{\alpha_m+\pi} V_s^2 \cos^2(\omega t) \, dt \right) \right]^{1/2} = V_s \sqrt{\frac{p\delta}{\pi}}$$

(3.4)

### 3.4.3 Sinusoidal Pulse Width Modulation

Instead of maintaining the width of all pulses the same as in the case of multiple-pulse modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the centre of the same pulse. The distortion factor and lower-order harmonics are reduced significantly. The gating signals as shown in figure 3.3 are generated by comparing a sinusoidal reference signal with a triangular carrier wave of
frequency, \( f_c \). This type of modulation is commonly used in industrial applications and abbreviated as SPWM. The frequency of the reference signal, \( f_r \), determines the output frequency \( f_o \), and its peak amplitude, \( A_r \), controls the modulation index \( m \), and then in turn the RMS output voltage, \( V_o \). The number of pulses per half cycle depends on the carrier frequency.

The RMS output voltage can be varied by varying the modulation index \( m \). If \( \delta_m \) is the width of the pulse, the RMS output voltage can be found from

\[
V_o = V_s \left( \frac{1}{\pi} \sum_{m=1}^{p} \frac{\delta_m}{\pi} \right)^{1/2} \tag{3.5}
\]

Figure 3.3 Sinusoidal Pulse Width Modulation
The three PWM techniques listed above differ from each other in the harmonic content in their respective output voltages. Thus the choice of a particular PWM technique depends upon the permissible harmonic content in the converter output voltage. The devices are switched on and off several times within each half cycle to control the output voltage which has low harmonic content.

3.5 **VOLTAGE SOURCE INVERTERS**

Voltage source inverters are used in high power AC motor drives. It is further classified into three general categories:

- Pulse width modulated inverter
- Square wave PWM inverter
- Single phase inverter with voltage cancellation

### 3.5.1 Pulse Width Modulated Inverter

In these inverters, the input DC voltage is essentially constant in magnitude, such as in the circuit of figure 3.4, where a diode rectifier is used to rectify the line voltage. Therefore, the inverter must control the magnitude and the frequency of the AC output voltages. This is achieved by PWM of the inverter switches and hence such inverters are called switched mode PWM inverters. These types of inverters are most widely used in industry (Ned Mohan et al 2009).
3.5.2 Square Wave PWM Inverter

In this inverter, the input DC voltage is controlled in order to control the magnitude of the output AC voltage, and therefore, the inverter has to control only the frequency of the output voltage. The output AC voltage has waveform similar to a square wave, and hence, called as a square wave inverter.

3.5.3 Single Phase Inverter with Voltage Cancellation

In the case of inverter with single phase output, it is possible to control the magnitude and the frequency of the inverter output voltage, even though the input to the inverter is a constant DC voltage and the inverter switches are not pulse-width modulated (and hence the output voltage is like a square wave). Therefore, these inverters combine the characteristics of the Pulse Width Modulated Inverter and Square Wave PWM Inverter. It should be noted that the voltage cancellation technique works only in single phase inverters and not in three phase inverter.
3.6 THREE-PHASE VSI PWM INVERTER

Three phase inverter is used to provide adjustable frequency power for industrial applications. Three phase inverter is more common than single phase inverters. DC supply for three phase inverters is taken from a battery or usually from a rectifier.

In industrial application, VSI is mostly used, because a wide range of speed control is possible. Three phase VSI is operated at two modes i) 180 degree mode operation and ii) 120 degree mode operation. In 180 degree mode of operation three switches conduct at one cycle, each IGBT is operated at 60 degree delay angle. In this mode of operation, one can easily get the pure sine wave using a filter. So it is otherwise called as a quasi square wave mode or switched mode (Ned Mohan et al 2009). In 120 degree mode operation is pair of switch conduct at 120 degree delay angle. In this mode a shoot through fault occurs.

A six step bridge is used for three phase inverter by using six switches, with two switches for each phase. Each step is defined as a change in the time of operation for each IGBT to the next IGBT in proper sequence. For one cycle of $360^\circ$, each step would be of $60^\circ$ intervals for a six step inverter. Figure 3.5 shows the power circuit diagram of a three phase bridge inverter using six IGBTs. The source voltage $V_s$ fed from three phase uncontrolled rectifier. Large capacitors ($C_1=V_s/2$ and $C_2=V_s/2$) are connected at the input terminal to make the DC input constant and also to suppress the harmonics fed back to the source (Bimal Bose 2002). T1, T2, T3, T4, T5 and T6 are the IGBTs switch. In figure 3.5 shows a, b, and c are the output terminals of the switched mode PWM inverter. This output terminals fed by three phase induction motor, where n is three phase induction motor neutral terminal.
There are two patterns of gating the transistors. In one pattern, each transistor conducts for 180 degree and in the other, each transistor conducts for 120 degree. But in both the patterns gating signals are applied and removed at 60 degree intervals of the output voltage waveform. Both modes require a six step bridge inverter.

3.6.1 Three-Phase 180 Degree Mode VSI

By referring to figure 3.5, three switch conducts for 180 degree mode of operation. The conduction sequence can be written as follows T6T1T2, T1T2T3, T2T3T4, T3T4T5, T4T5T6, and T5T6T1. For consider one switching sequence T1T2T3, T1T3 are upper group and T2 is lower group. T1 operated delay at $\omega t = 0^0$, T3 operated delay at $\omega t = 120^0$, and T2 operated delay at $\omega t = 60^0$. Transistors in the upper group i.e. T1, T3, and T5 conduct at an interval of 120°. It implies that if T1 is operated delay at $\omega t = 0^0$, 

Figure 3.5 Power Circuit Diagram of a Three Phase Bridge Inverter using Six IGBTs
then T3 must be operated delay at $\omega t = 120^0$ and T5 delay at $\omega t = 240^0$, the same thing for lower group of transistors. Table 3.1 shows the switching states for six switches and also phase to phase $V_{ab}$, $V_{bc}$ and $V_{ca}$ voltages are obtained.

**Table 3.1 Switching States for Three-Phase Voltage Source Inverter for 180 Degree Conduction**

<table>
<thead>
<tr>
<th>Sl No.</th>
<th>Switching states</th>
<th>$V_{ab}$</th>
<th>$V_{bc}$</th>
<th>$V_{ca}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>On On Off Off Off On</td>
<td>$V_S$</td>
<td>0</td>
<td>$-V_S$</td>
</tr>
<tr>
<td>2</td>
<td>On On On Off Off Off</td>
<td>0</td>
<td>$V_S$</td>
<td>$-V_S$</td>
</tr>
<tr>
<td>3</td>
<td>Off On On On Off Off</td>
<td>$-V_S$</td>
<td>$V_S$</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Off Off On On On Off</td>
<td>$-V_S$</td>
<td>0</td>
<td>$V_S$</td>
</tr>
<tr>
<td>5</td>
<td>Off Off Off On On On</td>
<td>0</td>
<td>$-V_S$</td>
<td>$V_S$</td>
</tr>
<tr>
<td>6</td>
<td>On Off Off Off On On</td>
<td>$V_S$</td>
<td>$-V_S$</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>On Off On Off On Off</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>Off On Off On Off On</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### 3.6.2 Three-Phase 120 Degree Mode VSI

The power circuit diagram of this inverter is the same as shown in Figure 3.5. The 120 degree mode VSI, each transistor conducts for 120 degree of a cycle. Like 180 Degree mode, 120 Degree mode inverter also requires six steps, each of 60 Degree duration, for completing one cycle of the output AC voltage.

During the first 120 degree, T1 conducts with T6 for 60 degree, and then conducts with T2 for another 60 degree. The T3 will conduct for 120 degree (from $120^0$ to $240^0$) for 60$^0$ (from $120^0$ to $180^0$) with T2 and then
conduct another \(60^\circ\) (from \(180^\circ\) to \(240^\circ\)) with T4. The T5 will conduct \(120^\circ\) (from \(240^\circ\) to \(360^\circ\)) with T4 for \(60^\circ\) (from \(240^\circ\) to \(300^\circ\)) and then conducts for another \(60^\circ\) (from \(300^\circ\) to \(360^\circ\)) with T6. The conduction sequence can be written as follows: T6T1, T1T2, T2T3, T3T4, T4T5, T5T6, and T6T1. The disadvantage of \(120^\circ\) mode VSI is shoot through fault will occur during the conduction period.

### 3.7 PWM SWITCHING FREQUENCY EFFECTS

The VSI output voltage has PWM voltage pulses, which causes PWM ripple in the output current. The current ripple decreases with increasing output inductance. When the AC motor is directly connected to the VSI output, since the leakage inductance of the motor acts as a low-pass filter, it partially suppresses the PWM current ripple and the motor current is nearly sinusoidal. However, when the switching frequency is low or inverter output inductance is small, the ripple current becomes high, which results in higher losses, thermal stresses, and acoustic noise in the motor. Also when the ripple current is high, inverter current reaches high peak values, which increases current stresses on the inverter switches. Thus, in such cases additional filters are needed to reduce the PWM ripple.

### 3.8 EFFECTS RELATED TO SWITCH TURN-ON AND TURN-OFF TRANSIENTS

The inverter output current ripple and the associated problems can be overcome by increasing the PWM switching frequency. This also reduces the filter size and cost, and increases control bandwidth. Increasing the switching frequency requires fast turn-on and turn-off switches to minimize the switching losses. The turn-on and turn-off times of modern IGBTs approach several hundred nanoseconds or less, which correspond to switching transients with frequencies of MHz range. At these frequencies, the parasitic
capacitive elements of the motor drive become effective. For AC motor drives fed by the standard utility grid, the DC bus voltage is approximately 550V and for switching times of hundreds of nanoseconds, the rate of change (dv/dt) of the inverter output voltage is as high as 5kV/μs. Interaction between these voltage pulses and the parasitic capacitances of the motor drive cause undesired effects in the motor drive.

One of the important undesired effects of high dv/dt is voltage overshoot at the motor terminals which is caused by the rectangular shaped differential mode (line-to-line) voltages of the inverter. If the motor is at a long distance from the inverter, the long cable connecting the motor to the inverter acts like a transmission line due to the parasitic capacitances and inductances of the cable which become effective at dv/dt related frequencies (Jin Meng et al. 2006). Due to the voltage reflection, excessive overvoltage (higher than two times the DC bus voltage) may appear across the motor terminals (across the closest motor windings to the cable output terminals). These overvoltages can be as high as 3-4 times the DC bus voltage when there are instantaneous polarity reversals on the inverter output differential mode voltages. Motor terminal overvoltage may cause breakdown in the motor winding insulation and lead to motor failure.

3.9 ADVANTAGES OF PWM INVERTER

- Wide range of speed control.
- Lower order harmonics are eliminated.

3.10 APPLICATIONS OF INVERTER

This assumes that the inverter has the proper power output for the given load. Everyday appliances such as micro-Ovens, power tools, TVs and VCRs, lights, audio/visual equipment, battery chargers and computers are
common loads. An inverter, designed sized for loads with heavy inrush current can be used to power air compressors, water pumps, heaters, ventilation fans, and air conditioners. Nova Electric’s Pure Sine Wave inverters are ideal for running sensitive test equipment such as communications equipment, oscilloscopes, scales, high end stereos and video equipment, communications equipment, etc.

3.11 SUMMARY

The vital role of voltage source inverters for the high power AC motor drives has been described. The concept of pulse width modulation and different PWM Techniques has been emphasized. The proposed switched mode PWM inverter has been discussed in detail, which is one among the various types of VSI’s. Since quasi square wave model VSI is widely used in industrial applications, its modes of operation, switching states of the power circuit switches and switching sequence were presented in detail. The concept of PWM current ripples in the output current, its variation due to change in high frequency clearly shows that the use of filters becomes mandatory in order to reduce it.