CHAPTER-6

INVERTERS USING IGBTS/MOSFETS

6.1 Introduction:

DC-to-AC converters are known as inverters. The function of an inverter is to change a dc input voltage to a symmetrical ac output voltage of desired magnitude and frequency. The output voltage could be fixed or variable at a fixed or variable frequency. A variable output voltage can be obtained by varying the input dc voltage and maintaining the gain of the inverter constant. On the other hand, if the dc input voltage is fixed and it is not controllable, a variable output voltage can be obtained by varying the gain of the inverter, which is normally accomplished by pulse-width-modulation (PWM) control within the inverter. The inverter gain may be defined as the ratio of the ac output voltage to dc input voltage.

The output voltage waveforms of ideal inverters should be sinusoidal. However, the waveforms of practical inverters are nonsinusoidal and contain certain harmonics. For low-and medium-power applications, square-wave or quasi-square-wave voltages may be acceptable; and for high-power applications, low distorted sinusoidal waveforms are required. With the availability of high-speed power semiconductor devices, the harmonic contents of output voltage can be minimized or reduced significantly by high frequency switching techniques.

6.2. Classification of Inverters:

Inverters can be broadly classified into two types: (1) Single-phase inverters, and (2) three-phase inverters. Each type can use controlled turn-on and turn-off devices **(e.g.BJTs, MOSFETs, IGBTs)**, or forced-commutated thyristors depending on their applications. These inverters generally use PWM control signals for producing an ac output voltage. An inverter is called a voltage-fed inverter (VFI or VSI) if the input voltage remains constant, a current-fed inverter (CFI or CSI) if the input current is maintained constant, and variable dc linked inverter if the input voltage is controllable.

The Voltage source inverters, are invariably used for low and medium power applications. The dc link current of the VSIs can be reversed almost instantaneously, and hence they are used in medium power reversible ac motor drives which require fast dynamic response. The current source inverters are used only for very high power ac motor drives.

The VSIs are further divided into (i) Square wave inverters and (ii) PWM inverters. In Square-wave inverters, 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 a waveform similar to a square wave and hence these inverters are called square wave inverters.

In Pulse width modulated inverters, the input dc voltage is essentially constant in magnitude. A diode bridge rectifier is used to obtain the dc input voltage to the inverter from the ac mains. Therefore the inverter must control both the magnitude and the frequency of the ac output voltage. This is achieved by Pulse Width Modulation (PWM) of the inverter switches and hence such inverters are called PWM inverters. There are various schemes to Pulse Width modulate the inverter switches in order to shape the output ac voltages to be as close to a sine wave as possible.

6.3 Single Phase Bridge inverter:

A single-phase bridge inverter is shown in Fig.6.1. It consists of four switching devices T_1, T_2, T_3, T_4 and the four inverse parallel diodes D_1, D_2, D_3, D_4. The diodes are essential to conduct the reactive current, and thereby to feed back the stored energy in the inductor to the dc source. These diodes are known as feed back diodes. The switching devices may be any one of the power switching devices discussed in Chapter 1.

6.4 Square Wave switching of Single-phase Bridge Inverter:

For square wave operation, the switches T_1, T_2 and T_3, T_4 are operated as two pairs with a duty cycle ratio of 0.5. Each of the switch is on for one half-cycle (180°) of the desired output frequency. This results in an output voltage waveform as shown in Fig.6.2. when T_1 and T_2 are switched load voltage is positive with terminal A at positive potential, and when T_3 and T_4 are switched the load voltage is negative with terminal B at positive potential with respect to the mid point 0.

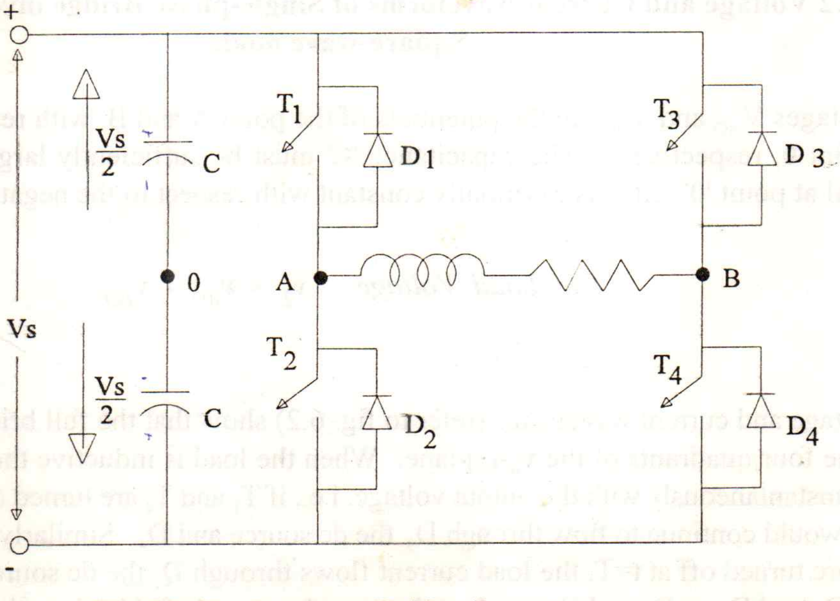

Fig.6.1 Single-phase Bridge Inverter.

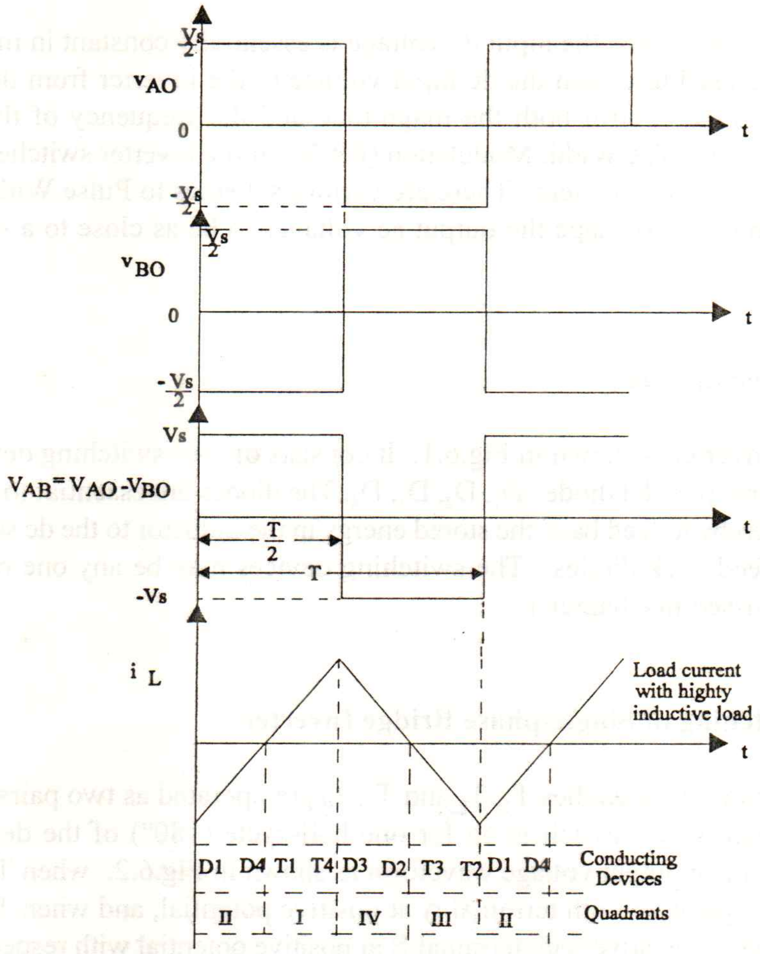

Fig.6.2 Voltage and Current waveforms of Single-phase Bridge inverter operating in Square-wave mode.

The voltages V_{AO} and V_{BO} are the potentials of the point A and B, with respect to the fictitious mid point 0, respectively. The capacitance 'C' must be sufficiently large to assume that the potential at point '0' remains essentially constant with respect to the negative dc bus N.

$$\text{The Load Voltage} \quad v_L = v_{AO} - v_{BO} \tag{1}$$

The voltage and current waveforms (refer to fig. 6.2) show that the full bridge inverter operates in all the four quadrants of the v_o-i_o plane. When the load is inductive the load current cannot change instantaneously with the output voltage. i.e., if T_1 and T_4 are turned off at t = T/2, the load current would continue to flow through D_3, the dc source and D_4. Similarly when the devices T_3 and T_4 are turned off at t=T, the load current flows through D_1 the dc source and D_2. When the diodes D_3 and D_4 or D_1 and D_2 conduct the stored energy is fed back to the dc source.

The rms value of the output voltage is given by

$$V_0 = \left[\frac{2}{T} \int_o^{\frac{T}{2}} V_s^2 \, dt \right]^{\frac{1}{2}} = V_s \qquad (2)$$

The Fourier series representation for the instantaneous output voltage $v_o(t)$ is

$$v_o(t) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4 \, V_s}{n \, \pi} \sin nwt \qquad (3)$$

note that n takes only odd values.

The rms value of the fundamental component (n=1) is

$$V_1 = \frac{4 \, V_s}{\sqrt{2} \, \pi} = 0.9 \, V_s \qquad (4)$$

The instantaneous load current with inductive load is

$$i_o(t) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4 \, V_s}{n\pi \sqrt{R^2 + (nwL)^2}} \, Sin \, (nwt - \phi_n) \qquad (5)$$

When $\phi_n = \tan^{-1}$ (nwL/R)
w - fundamental frequency (inverter frequency).
L - load inductance, R - Load resistance

For square wave operation the output voltage magnitude can be controlled by controlling the input dc voltage and output frequency is controlled by varying the switching frequency of the inverter switches.

The advantage of the square-wave operation is that each inverter switch changes its state only twice per cycle, which is important at very high power levels when the power switching devices have slower turn-on and turn-off speeds.

One of the serious disadvantages of square wave switching is that the inverter is not capable of regulating the output voltage magnitude. Therefore, the DC input voltage V_s to the inverter must be adjusted in order to control the magnitude of the inverter output voltage. Also as the output load voltage is square wave, it contains much of the harmonic components, which is undesirable for most of the applications.

6.5 Voltage control of single phase inverter

For many industrial applications the output ac voltage of the inverter must be sinusoidal in shape and the amplitudes and frequency must be controllable. This is achieved by PWM (Pulse width modulation) of the inverter switches. There are various schemes to pulse width modulate the inverter switches inorder to shape the output ac voltages to be as close to a sine wave as possible. The most commonly used techniques are.

i) Single pulse width modulation
ii) Multiple Pulse Width Modulation
iii) Sinusoidal Pulse width Modulation (SPWM)
iv) Trapezoidal Modulation
v) Staircase Modulation
vi) Stepped Modulation
vii) Hysteresis Current Control (delta Modulation)

Out of the various PWM techniques the sinusoidal pulse width modulation is most commonly used. This technique is discussed in detail in the following.

6.6. Sinusoidal Pulse Width Modulation.

The switching sequence for the inverter switches in this case, is obtained by comparing a sinusoidal control signal, of adjustable amplitude and frequency with a fixed frequency triangular carrier. The frequency of the triangular carrier wave determines the switching frequency (f_s) of the inverter switches. The frequency (f_1) of the sinusoidal control signal decides the fundamental frequency of the inverter output voltage, and is also called the modulating frequency. The inverter output voltage will contain voltage components at harmonic frequencies of f_1. The amplitude modulation ratio m_a also called the modulation index is defined as

$$m_a = \frac{V_{control}}{\hat{V}_{tri}} \qquad (6)$$

Where $V_{control}$ is the amplitude of the control signal and V_{tri} is amplitude of the triangular carrier, which is generally kept constant.

The frequency modulation ratio is defined as

$$m_f = \frac{f_s}{f_1} \tag{7}$$

The sinusoidal pulse width modulation can be programmed to have either bipolar voltage switching or unipolar voltage switching. The unipolar voltage switching has the advantage of effectively doubling the switching frequency as compared to the bipolar voltage switching. This makes the lowest harmonics in the output voltage to appear as sidebands of twice the switching frequency, more over the voltage jumps in the output voltage at each switching are from 0-to V_s whereas in the case bipolar voltage switching it is from $-V_s$ to $+V_s$ and the magnitude of the voltage jumps is $2V_s$. For these reasons the unipolar voltage switching is most commonly used.

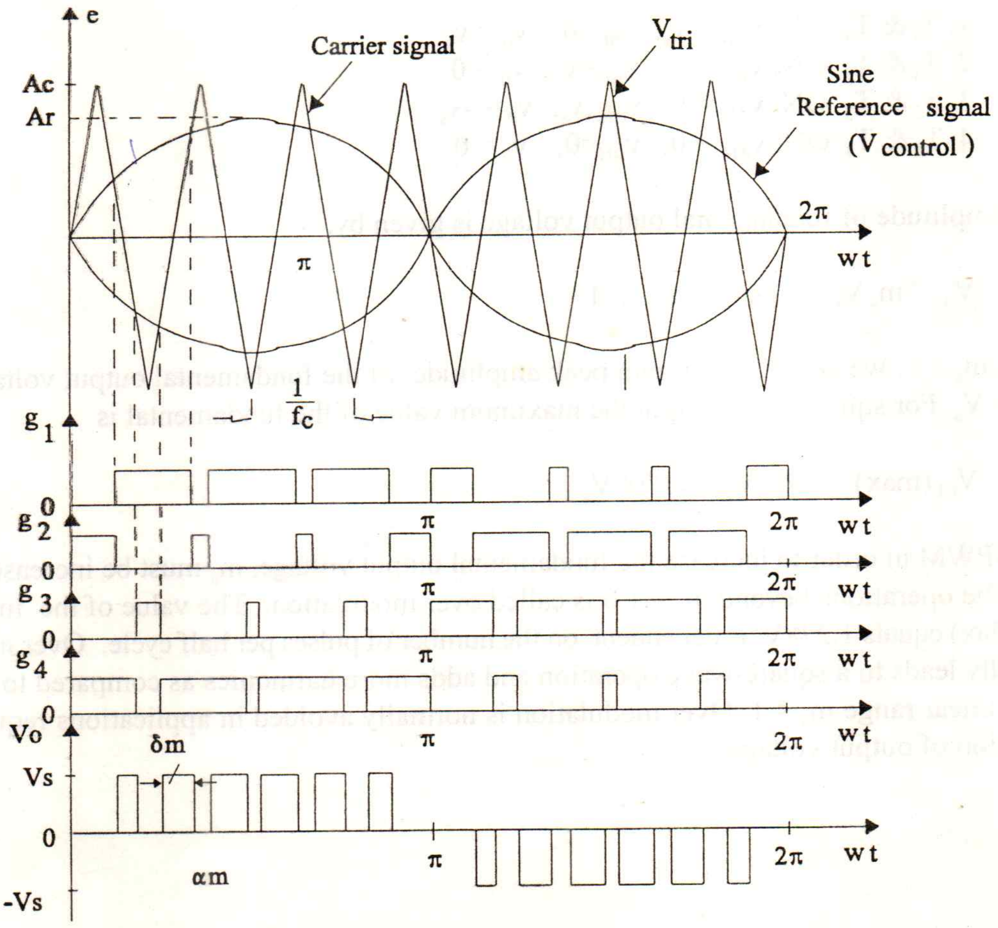

Fig.6.3. Sinusoidal Pulse-Width Modulation

6.7. Generation of SPWM Gating Signals with Unipolar Voltage Switching.

In PWM with unipolar voltage switching the switches in the two legs of the full bridge inverter of Fig 6.1 are independently controlled. The switching sequences are obtained by comparing the triangular carrier V_{tri} with $+V_{control}$ and $-V_{control}$ respectively. The logic signals are obtained as follows.

$v_{Control} > v_{tri}$ T_1 is ON and $V_{A0} = v_s$
$v_{control} < v_{tri}$ T_2 is ON and $V_{A0} = 0$. ----- (8)
$-v_{control} > v_{tri}$ T_3 is ON and $V_{B0} = v_s$
$-v_{control} < v_{tri}$ T_4 is ON and $V_{B0} = 0$

The generation of gating signals and the output voltage waveforms are shown in the fig. 6.3. Because of the feedback diodes in antiparallel with the switches the voltages given by equation (8) and (9) are independent of the direction of the output current i_l. The waveforms of fig 6.6 show that there are four combinations of switch on -states and the corresponding voltage levels as given below.

1. T_1 & T_4 ON; $v_{AN} = v_s$; $v_{BN}=0$; $v_0 = v_s$
2. T_1 & T_3 ON; $v_{AN} = v_s$; $v_{BN}=v_s$; $v_0 = 0$
3. T_2 & T_3 ON; $v_{AN} = 0$ $v_{BN}=v_s$; $v_0 = -v_s$
4. T_2 & T_4 ON; $v_{AN} = 0$; $v_{BN}=0$; $v_0 = 0$ ----- (9)

The Amplitude of fundamental output voltage is given by.

$$V_{01} = m_a V_s \quad \text{for} \quad m_a \leq 1 \qquad \text{----- (10)}$$

When $m_a = 1$, we get the maximum peak amplitude of the fundamental output voltage as V_{01} max = V_s. For square wave output the maximum value of the fundamental is

$$V_{01}(\text{max}) = 4/\pi\, V_s = 1.278\, V_s \qquad \text{--- (11)}$$

with SPWM in order to increase the fundamental output voltage, m_a must be increased beyond 1.0. The operations beyond $m_a = 1.0$ is called over modulation. The value of the m_a at which V_{01} (Max) equals $1.278V_s$ is dependent on the number of pulses per half cycle. Over modulation basically leads to a square-wave operation and adds more harmonics as compared to operation in the linear range $m_a < 1$. Over modulation is normally avoided in applications requiring low distortion of output voltage.

6.8. Other Modulation Techniques

The SPWM which is most commonly used PWM technique, suffers from the drawback that the fundamental voltage obtained is low. The other techniques are aimed at improving the fundamental output voltage by selectively eliminating the harmonics. Such PWM techniques are

i. Trapezoidal modulation
ii. Single pulse width modulation
iii. Multiple pulse width modulation
iv. Staircase modulation
v. Stepped Modulation
vi. Hysteresis Current Controlled PWM (Delta Modulation).

The first two techniques are discussed in the following.

6.8 .1. Trapezoidal Modulation.

In this case the gating signals are generated by comparing a triangular carrier wave with a modulating trapezoidal wave as shown in fig 6.4. The trapezoidal wave can be obtained from a triangular wave by limiting its magnitude to ± Ar which is related to the peak value Ar(max) by

$$A_r = \sigma\, A_r(\max) \tag{6.12}$$

Where σ is called the triangular factor, because the waveform becomes a triangular wave when σ=1

The modulation index m_a is defined as

$$m_a = \frac{A_r}{A_c} = \frac{\sigma\, A_r(\max)}{\hat{V}_m} = 0 \le m_a \le t \tag{6.13}$$

The angle of the flat portion of the trapezoidal wave is given by.

$$2\phi = (1 - 0)\,\pi \tag{6.14}$$

For fixed values of Ar(max) and Ac, m_a that varies with the output voltage can be varied by changing the triangular factor, σ. This type of modulation increases the peak fundamental output voltage upto 1.05 v_s but the output contains lower order harmonics.

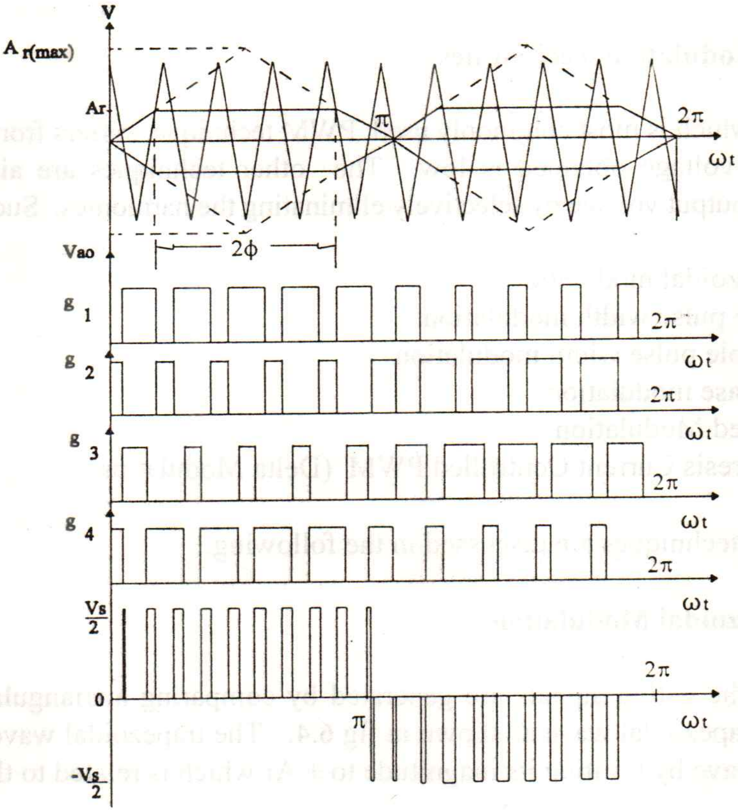

Fig.6.4. Generation of Gating Signals - Trapezoidal PWM

6.8.2. 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 (6.5) shows the generation of gating signals and output voltage of single-phase full-bridge inverters. The gating signals are generated by comparing a rectangular reference signal of amplitude, Ar, with a triangular carrier wave of amplitude Ac. The frequency of the reference signal determines the fundamental frequency of output voltage. By varying Ar from 0 to Ac, the pulse width δ can be varied from 0° to 180°. The ratio of Ar to Ac is the control variable and defined as the amplified modulation index.

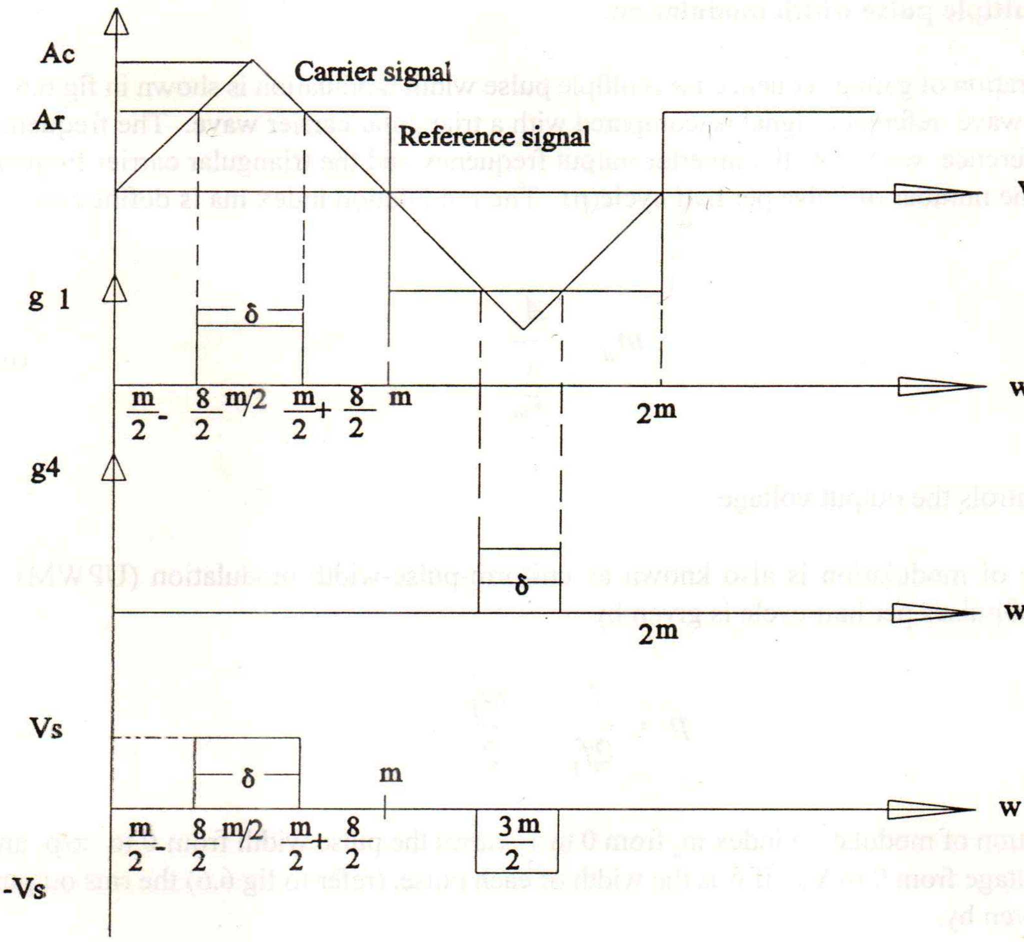

Fig. 6.5. Single Pulse Width Modulation

The amplified modulation index $M = A_r / A_c$

The r.m.s. output voltage,

$$V_0 = \left[\frac{2}{2\pi} \int_{(\pi-\delta)/2}^{(\pi+\delta)/2} V_s^2 \, d\,(\omega t) \right]^{1/2}$$

$$= V_s \sqrt{\frac{\delta}{\pi}}$$

6.8.3 Multiple pulse width modulation.

The generation of gating sequence for multiple pulse width modulation is shown in fig.6.6., Here a square wave reference signal is compared with a triangular carrier wave. The frequency (f_1) of the reference wave sets the inverter output frequency and the triangular carrier frequency f_c decides the number of pulse per half cycle(p). The modulation index ma is defined as

$$m_a = \frac{A_r}{\substack{A\\ V_{tri}}} \qquad (6.15)$$

and it 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 given by.

$$p = \frac{f_c}{2f_1} = \frac{m_f}{2} \qquad (6.16)$$

The variation of modulation index m_a from 0 to 1, varies the pulse width from 0 to π/p and the output voltage from 0 to Vs. If δ is the width of each pulse, (refer to fig 6.6) the rms output voltage is given by.

$$V_0 = V_s \frac{\sqrt{p\delta}}{\pi} \qquad (6.17)$$

The multiple-pulse-width-modulation gives more fundamental output voltage than the SPWM, but the output will have lower order harmonics

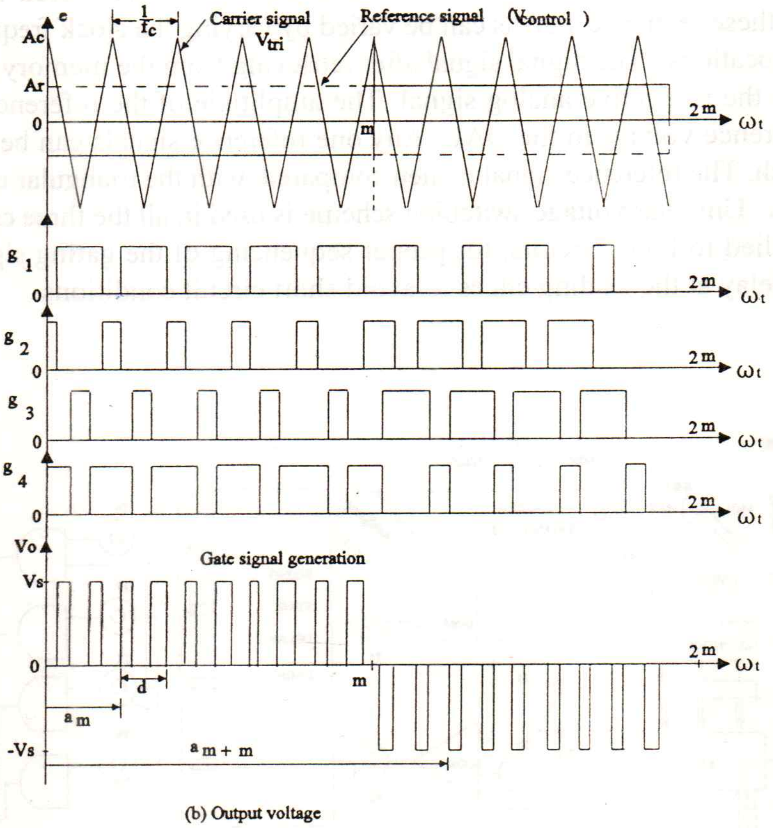

Fig.6.6. Multiple Pulse Width Modulation

6.9. Block Schematic of the Generation of Gating Sequences.

The block schematic of the generation of gating sequences is shown in fig 2.4. The reference sinusoidal waveform, trapezoid and the square waveforms are stored in an EPROM. The frequency of these reference signals can be varied by varying the clock frequency used to address the memory locations. The digital signal after retrieving from the memory is applied to a DAC, which gives the respective analog signal. The amplitude of the reference signal is varied by varying reference voltage to the DAC. Any one reference signals can be selected through the selector switch. The reference signal is then compared with the triangular carrier to generate the gating signals. Unipolar voltage switching scheme is used in all the three cases. The comparator output is applied to logic circuits, for proper sequencing of the gating signals and to produce appropriate delay at the leading edges to avoid short circuit conditions.

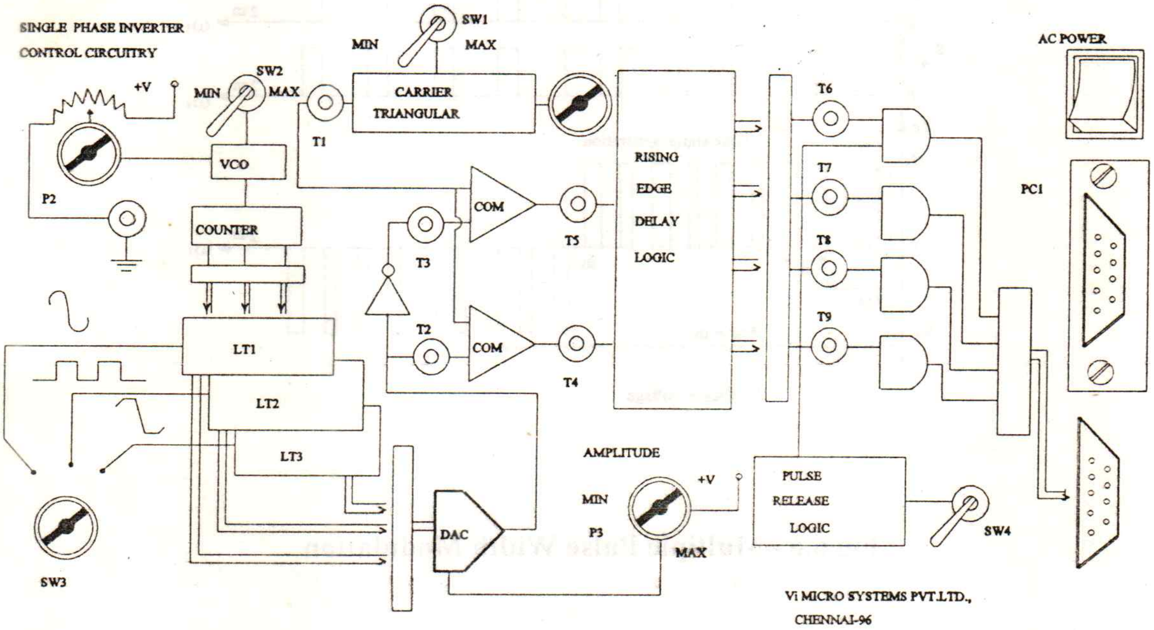

Figure. 6.7. Block Schematic of the Generation of Gating Sequences

EXPERIMENT E-1:

AIM:

To study the operation of single phase bridge inverter with single pulse width modulation.

EQUIPMENTS REQUIRED:

1. MOSFET/IGBT Module
2. Single Phase Single Pulse Inverter Control Module (PEC16 M4#2)
3. CRO
4. R-L Load

PRECAUTION:

1. Ensure all switches are in the OFF position while doing connection.
2. Ensure pulse release ON/OFF switch is in OFF position, whenever power is switched ON to the Inverter power circuit module.

PROCEDURE:

1. Using the inverter module and referring to the mimic diagram of Fig.2.2. Connect the circuit diagram of fig E.6.1.

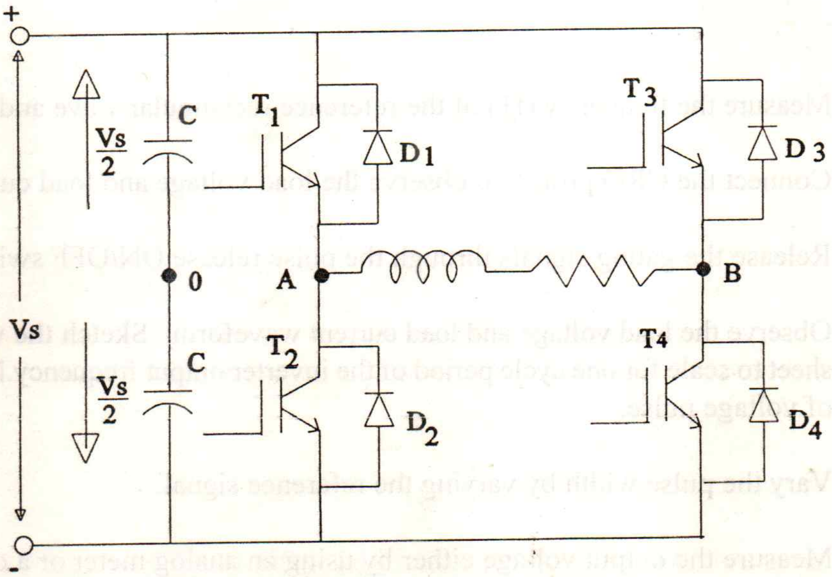

Fig E.6.1 Single Phase Bridge inverter circuit.

- i) Connect B11 to V+1 using patch cords
- ii) Connect B12 to B21 using patch cords
- iii) Connect B23 to V-1 using patch cords
- iv) Connect V+2 to B31 using patch cords
- v) Connect B32 to B41 using patch cords
- vi) Connect V-2 to B43 using patch cords

2. Connect R-L Load between B_{13} and B_{33}.

3. Connect the gating signals from the single pulse inverter control module to the inverter module through signal cable provided.

4. Connect the power cables for both modules and CRO.

5. Keep the pulse release ON/OFF switch SW_4 in the control module in the OFF position. Switch ON ac mains to CRO control module and the inverter module.

6. Observe the reference rectangular waveform and the triangular carrier waveforms on the CRO.

7. Measure the amplitude of the rectangular wave and the triangular carrier wave and calculate the modulation index

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

8. Measure the frequency (f1) of the reference rectangular wave and the triangular carrier.

9. Connect the CRO probes to observe the load voltage and load current waveforms.

10. Release the gating signals through the pulse release ON/OFF switch.

11. Observe the load voltage and load current waveform. Sketch the waveforms on a graph sheet to scale for one cycle period of the inverter output frequency.Measure the amplitude of voltage pulse.

12. Vary the pulse width by varying the reference signal.

13. Measure the output voltage either by using an analog meter or a digital multimeter.

14. Calculate the rms output voltage

$$V_0 = V_s \sqrt{\frac{\delta}{\pi}}$$

15. Repeat steps 7-15 for various amplitude of the reference wave and tabulate the readings as in Table-III. Plot the characteristics-Modulation index versus output voltage.

TABLE NO.1

Sl.NO	V_{tri} (A_C) (Volts)	$V_{(rect)}$ (A_r) (Volts)	Pulse width measured (δ)	M	V_o measured (Volts)	V_o(calculated) (Volts)

Experiment E-2:

Aim: To study the operation of single-phase bridge inverter with sinusoidal pulse width modulation.

Equipments required:

1. MOSFET/IGBT Module
2. Inverter Control Module(PEC 16M4)
3. CRO
4. R-L Load

PRECAUTION:

1. Ensure all switches are in the OFF position while doing connection.

2. Ensure pulse release ON/OFF switch is in OFF position, whenever power is switched ON to the inverter circuit module.

PROCEDURE:

1. Using the inverter module and referring to the mimic diagram of Fig 2.1 connect the circuit diagram of fig E 6.1

   i. Connect B_{11} to V_{+1} using patch cords
   ii. Connect B_{12} to B_{21} using patch cords
   iii. Connect B_{23} to V_{-1} using patch cords
   iv. Connect V_{+2} to B_{31} using patch cords
   v. Connect B_{32} to B_{41} using patch cords
   vi. Connect V_{-2} to B_{43} using patch cords

2. Connect R-L Load between B13 and B33.

3. Connect the gating signals from the inverter control module to the inverter module through signal cable provided.

4. Connect the power cables for both modules and CRO

5. Select sinusoidal pulse-width modulation by setting the selector switch SW3 at Position I

6. Keeping the pulse release ON/OFF switch SW4 in the control module in the OFF position switch on ac mains to CRO, control module and the inverter module.

7. Observe the reference sine waveform and the triangular carrier waveforms on the CRO.

8. Measure the amplitude of the sine wave and the triangular carrier and calculate the modulation index.

9. Measure the frequency (f_1) of the reference sine wave and the triangular carrier (f_c). Adjust the sine wave frequency to about 50Hz.

10. Connect the CRO probes to observe the load voltage and load current waveforms.

11. Release the gating signals through the pulse release ON/OFF switch SW_4.

12. Observe the load voltage and load current waveforms. Sketch the waveforms on a graph sheet to scale for one cycle period of the inverter output frequency. Measure the amplitude of the voltage pulses.

13. Measure the output voltage either by using an analog meter or a digital multimeter.

14. Calculate the rms output voltage.

15. Repeat steps 7-14 for various amplitude of the reference sine wave and tabulate the readings as in Table-1. Plot the characteristics-modulation Index versus output voltage. It will be as shown in fig E 6.1.2.

Table - 2

S.No.	V_{tri} (Volts)	V_{sine} (Volts)	m_a	V_0 measured (volts)	V_0 calculate volts

EXPERIMENT E-3.

Aim :

To study the operation of the single phase bridge inverter using multiple pulse width modulation.

EQUIPMENTS REQUIRED.

1. MOSFET/IGBT Module
2. Inverter Control Module (PEC 16 M4)
3. CRO
4. R-L Load

PRECAUTION:

1. Ensure all switches are in the OFF position while doing connection.
2. Ensure pulse release ON/OFF switch is in OFF position, whenever power is switched ON to the Inverter power circuit module.

PROCEDURE

1. Using the inverter module and referring to the mimic diagram of Fig 2.1 connect the circuit diagram of fig E 6.1

   i. Connect B_{11} to V_{+1} using patch cords
   ii. Connect B_{12} to V_{21} using patch cords
   iii. Connect B_{23} to V_{-1} using patch cords
   iv. Connect V_{+2} to B_{31} using patch cords
   v. Connect B_{32} to B_{41} using patch cords
   vi. Connect V_{-2} to B_{43} using patch cords

2. Connect R-L Load between B_{13} and B_{23}.

3. Connect the gating signals from the inverter control module to the inverter module through signals cable provided.

4. Connect the power cables for both modules and CRO

5. Select the multiple pulse width modulation by setting the selector switch SW3 at position II.

6. Keeping the pulse release ON/OFF switch SW_4 in the control module at the OFF position switch on ac mains to CRO, control module and the inverter module.

7. Observe the reference square wave and the triangular carrier waveforms on the CRO.

8. Measure the amplitude of the square waveforms and calculate the modulation index.

$$m_a = \frac{A_r}{\hat{V}_{tri}} = \frac{\text{Amplitude of the square wave}}{\text{Amplitude of the Triangular carrier}}$$

9. Measure the frequency (f_1) of the reference square wave and the triangular carrier (f_c). Adjust the square wave frequency to about 50Hz.

10. Connect the CRO probes to observe the load voltage and load current waveforms.

11. Release the gating signals through the pulse release ON/OFF switch SW_4

    Calculate the number of pulses per half cycle as

$$p = \frac{f_c}{2f_1}$$

12. Observe the load voltage and load current waveforms sketch the waveforms on a graph sheet to scale for one cycle period of the inverter output frequency. Measure the amplitude of the voltage pulses.

13. Measure output voltage either by using an analog meter or a digital multimeter.

14. Calculate the RMS output voltage

$$V_0 = V_s \sqrt{p\sigma/\pi}$$

15. Repeat steps 7-14 for various amplitude of the reference square wave and tabulate the reading as in Table-2. Plot the characteristics-modulation index versus output voltage. It will be as shown in fig E 6.1.2.

16. Compare the fundamental output voltage obtained with SPWM.

Table - 3 MULTIPLE PULSE WIDTH MODULATION.

S.No.	Λ V_{tri}	V_{cont} square (volts)	m_a	no. of pulses (p)	V_0 measured (volts)	V_0 calculated (volts)

EXPERIMENT E-4.

Aim:

To study the operation of the single phase bridge inverter using trapezoidal pulse width modulation.

EQUIPMENTS REQUIRED.

1. MOSFET/IGBT Module
2. Inverter Control Module
3. CRO
4. R-L Load

PRECAUTION:

1. Ensure all switches are in the OFF position while doing connection.
2. Ensure pulse release ON/OFF switch is in OFF position, whenever power is switched ON to the Inverter power circuit module.

PROCEDURE

1. Using the inverter module and referring to the mimic diagram of Fig 2.1 connect the circuit diagram of fig E 6.1

   i. Connect B_{11} to V_{+1} using patch cords
   ii. Connect B_{12} to V_{21} using patch cords
   iii. Connect B_{23} to V_{-1} using patch cords
   iv. Connect V_{+2} to B_{31} using patch cords
   v. Connect B_{32} to B_{41} using patch cords
   vi. Connect V_{-2} to B_{43} using patch cords

2. Connect R-L Load between B_{13} and B_{23}.

3. Connect the gating signals from the inverter control module to the inverter module through signals cable provided.

4. Connect the power cables for both modules and CRO

5. Select the trapezoidal pulse width modulation by setting the selector switch SW3 at position II.

6. Keeping the pulse release ON/OFF switch SW_4 in the control module at the OFF position switch on ac mains to CRO, control module and the inverter module.

7. Observe the triangular wave form and trapezoidal waveform on the CRO.

8. Measure the peak value $Ar_{(max)}$. Then calculate $A_r = \sigma A_r(max)$.

9. Measure the amplitude of the triangular waveforms and calculate the modulation index.

$$m_a = \frac{A_r}{A_c} = \frac{\sigma A_r \text{ (max)}}{\hat{V}_{tr}}$$

10. Measure the frequency of the triangular wave and the frequency of the trapezoidal wave.

11. Connect the CRO probes to observe the load voltage and load current waveforms.

12. Release the gating signals through the pulse release ON/OFF switch SW_4

13. Observe the load voltage and load current waveforms sketch the waveforms on a graph sheet to scale for one cycle period of the inverter output frequency. Measure the amplitude of the voltage pulses.

14. Measure output voltage either by using an analog meter or a digital multimeter.

15. Calculate the RMS output voltage

16. Repeat steps 7-14 for various amplitude of the trapezoidal waveform and tabulate the reading as in Table-2. Plot the characteristics-modulation index versus output voltage. It will be as shown in fig E 6.1.2.

Table - 4 TRAPEZOIDAL PULSE WIDTH MODULATION.

S.No.	A_r	σ	A_c	m_a	V_0 measured (volts)	V_0 calculated (volts)