CONTROLLING OF THREE LEVEL DIODE CLAMPED MULTI LEVEL INVERTER FED INDUCTION MOTOR USING SPACE VECTOR PWM

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Abstract: In the current days, Multilevel Inverters (MLIs) are very popular in industrial applications. The main objective of this paper is to control the speed of an induction motor by changing the frequency using three level diode clamped multilevel inverter. To obtain high quality sinusoidal output voltage with reduced harmonics distortion, multicarrier SVPWM control scheme is proposed for three level diode clamped multilevel inverter. This method is implemented by changing the supply voltage and frequency applied to three phase induction motor at constant ratio. The proposed system is an effective replacement for the two level methods which produces high switching losses, results in poor drive performance. In this paper the voltage control model design and implementation has been done through MATLAB/SIMULINK software for speed control of induction motor and also parameters like stator current, rotor current ,torque and speed are expressed graphically.

Keywords— Multi Level Inverter (MLI), Diode Clamped Multilevel Inverter (DCMLI), Voltage Source Inverter (VSI), Pulse Width Modulation (PWM), Space Vector PWM (SVPWM)

1. INTRODUCTION

A multilevel (MLI) uses a sequence of semiconductor power converters (usually two or three) thus generating higher voltage. While an inverter would have to flip several switches. An inverter is a device which receives dc supply for its input and produces ac output. A multilevel inverter is a more powerful inverter, in higher and medium voltage grid it is trouble to connect only one semiconductor switch directly, As a result multilevel inverter was introduced. A multilevel inverter is a power electronic device that is widely used in industries for high voltage and high power applications, with output harmonic content is reduced by using multilevel inverter (MLI)) One important application of multilevel converters is focused on medium and high-power conversion.

2. DIODE CLAMPED MULTILEVEL INVERTER (DCMLI)

An inverter is commonly used in variable speed AC motor drives to produce a variable three-phase AC output voltage from a constant DC voltage source, which has two voltage level (+VDC, -VDC). The output waveform of inverters should be sinusoidal for efficient operation. But the output of conventional two level PWM inverters would be a square wave (or) quasi square wave. The square wave is rich in harmonic content. To minimize the output voltage distortion with improved fundamental voltage, the multilevel inverter concept has been implemented. The concept of utilizing multiple small voltage levels (multilevel) to perform power conversion was patented by an MIT researcher over twenty years ago. Advantages of this multilevel approach include good power quality, good electromagnetic compatibility (EMC), low switching losses, and high voltage capability. The main disadvantages of this technique are that a larger number of switching semiconductors are required for lower-voltage systems and the small voltage steps must be supplied on the DC side either by a capacitor bank or isolated voltage sources. The first topology introduced was the series H-bridge design (Baker 1975). This was followed by the diode clamped converter which utilized a bank of series capacitors. These designs can create higher power quality for a given number of semiconductor devices than the fundamental topologies alone due to a multiplying effect of the number of levels. These multilevel inverters are suitable for high voltage and high power application due to their ability to synthesize waveforms with better harmonic spectrum. Numerous topologies have been introduced and widely studied for utility and drive applications. Multilevel pulse width modulated(PWM) inverters are gaining importance due to the fact that the lower order harmonics in the output waveform can be eliminated without any increase in the higher order harmonics, unlike the regular two level PWM inverters .Multilevel inverters provide more than two voltage levels. As the number of levels reaches infinity, the output Total Harmonic Distortion (THD) approaches to zero. This inverter generates almost sinusoidal staircase voltage with only one time switching per line cycle. In this chapter the comparative performance of the three level, three phase diode clamped inverter with the conventional two level, three phase voltage source inverter was carried out for simulated results.

2.2 TWO LEVEL PULSE WIDTH MODULATED INVERTER:

The standard three-phase voltage source inverter is shown in Figure and the eight valid switch states. As in single-phase VSIs, the switches of any leg of the inverter (S1 and S4, S3 and S6, or S5 andS2) cannot be switched on simultaneously because this would result in a short circuit across the DC link voltage supply. Similarly in order to avoid undefined states in the VSI and thus undefined AC output line voltages of any leg of the inverter cannot be switched off simultaneously as this will result in voltages that will depend upon the respective line current polarity. Of the eight valid states, two of them produce zero AC line voltages. In this case, the AC line currents freewheel through either the upper or lower components. The remaining states produce non-zero AC output voltages. In order to generate a given voltage waveform, the inverter moves from one state to another. Thus the resulting AC output line voltages consist of discrete values of voltages that are Vi , 0, and ΔVi . The selection of the states in order to generate the given waveform is done by the modulating technique that should ensure the use of only the valid states (Muhammad H. Rashid 2004).

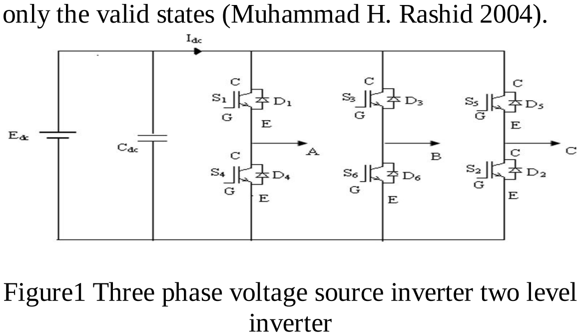

Figure1 Three phase voltage source inverter two level inverter

2.3 THREE LEVEL DIODE CLAMPED MULTI LEVEL INVERTER

Recently the “multilevel inverter” has drawn tremendous interest in the power industry (Peng and Lai 1996). The general structure of the multilevel inverter is to synthesize a sinusoidal voltage from several levels of DC voltage sources, typically obtained from DC-bus capacitor/voltage sources. A three-level inverter, also known as a neutral-clamped inverter, which consists of two capacitor voltages in series and uses the center tap as the neutral. Each phase leg of the three-level converter has two pairs of switching devices in series. The canter of each device pair is clamped to the neutral through clamping diodes. The waveform obtained from a three-level inverter is a quasi-square wave output.

The diode clamp method can be applied to higher-level inverters. As the number of levels increases, the synthesized output waveform adds more steps, producing a staircase wave which approaches the sinusoidal wave with minimum harmonic distortion. Ultimately, a zero harmonic distortion of the output wave can be obtained by an infinite number of levels (Jih-Sheng Lai and Fang Zheng Peng 1996).In three level inverters, the switching of the upper and lower devices in a half-bridge inverter generates a $a0$ V wave with positive and negative levels ($\Delta 0.5Vd$ and Δ $0.5Vd$), respectively. If the fundamental output voltage and corresponding power level of the PWM inverter are to be increased to a high value, the DC link voltage Vd must be increased and the devices must be connected in series. By using matched devices in series, static voltage sharing may be somewhat easy, but dynamic voltage sharing during switching is always difficult. The problem may be solved by using a multilevel, Neutral clamped inverter (Fang Zheng Peng 2001). The diode-clamped inverter provides multiple voltage levels through connection of the phases to a series bank of capacitors. According to the original invention, the concept can be extended to any number of levels by increasing the number of capacitors. Early descriptions of this topology were limited to three-levels (Fracchia et al 2000), where two capacitors are connected across the DC bus resulting in one additional level. The additional level was the neutral point of the dc bus, so the terminology neutral point clamped (NPC) inverter was introduced. However, with an even number of voltage levels, the neutral point is not accessible, and the term multiple point clamped (MPC) is sometimes applied (Fracchia et al 2000). Due to capacitor voltage balancing issues, the diode-clamped inverter implementation has been mostly limited to the three-level. Because of industrial developments over the past several years, the three-level inverter is now used extensively in industry applications (Yamanaka et al 2000). Although most applications are medium voltage, a three-level inverter for 480V is on the market.

The basic configuration of a three-level three-phase diode clamped inverter is shown in Figure. In this configuration the DC link capacitor C has been split to create the neutral point 0. Since the operation of all the phase groups is essentially identical, consider only the operation of the half-bridge or phase a. A pair of devices with bypass diodes is connected in series with an additional diode connected between the neutral point and the center of the pair as shown in Figure. The devices Q1 and Q4 function as main devices (like a two-level inverter), and Q2 and Q3 function as auxiliary devices which help to clamp the output potential to the neutral point with the help of clamping diodes D1 and D2 (Nikola Celanovic and Dushan Boroyevich2000).

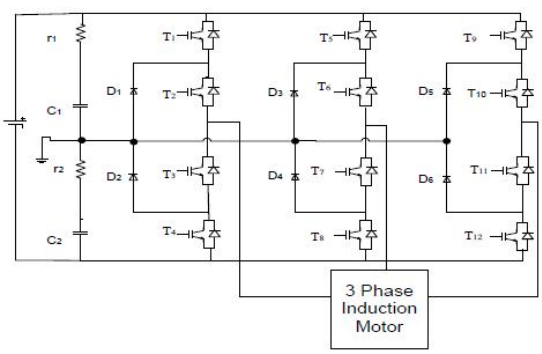

Figure2: Diagram of 3 Level Diode clamped multilevel inverter

The phase voltage Va0 waveform with three angles and the corresponding gate voltage switching waves as shown in Figure . The main devices (Q1 and Q4) generate the Va0 wave, whereas the auxiliary devices (Q3 and Q2) are driven complementary to the respective main devices, with such control, each output potential is clamped to the neutral potential in the off periods of the PWM control, as indicated in the Figure 8.10. Evidently, positive phase current +ia will be carried by devicesQ1 and Q2 when Va0 is positive, by devices D3 and D4 when Va0 is negative, and by devices D1 and Q2 at the neutral clamping condition. On the other hand, negative phase current- ia will be carried by D1 and D2 when Va0 is positive, by Q3 and Q4, when Va0 is negative, and by Q3 and D2 at the neutral clamping condition. This operation mode gives three voltage levels (+ 0.5Vd, 0, - 0.5Vd) at the Va0 wave, compared to two levels (+0.5Vd an- 0.5Vd) in a conventional two level inverter. The levels of line voltage wave Vab are +Vd, - Vd, +0.5Vd, - 0.5Vd and 0 compared to levels +Vd, -Vd and 0 ina two-level inverter. Therefore, the three-phase inverter has 33 = 27 switching states but there are only eight states are available for a two level inverter. The Line-Line voltage waveform is shown in Figure (Fang Zheng Peng2001).

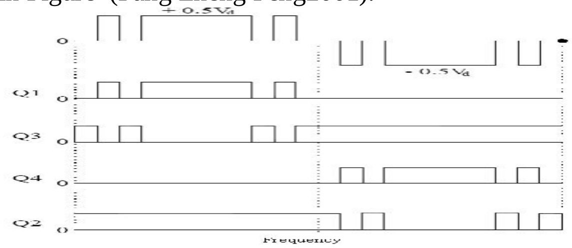

Figure 3: PWM signals for switching devices

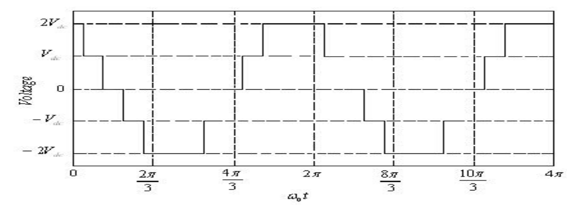

Figure 4: Line – line voltage waveform

2.4 COMPARISON OF TWO LEVEL AND THREE LEVEL DIODE CLAMPED INVERTER:

In multilevel inverters the power switches of lower voltage can be used to obtain desired voltages. These are faster and smaller than the power switches of high voltage, which is used in two level inverters. Multilevel inverters offer better sinusoidal voltage waveform than two voltage levels. This cause the Total Harmonic Distortion (THD) to be lower. Switching losses are reduced because switching frequency can be lower than that of two level inverter and also the switching speed is faster. Conduction losses are also lower because of low forward-voltage drop. When several voltage levels are used, the dv/dt of the output voltage is smaller thus the stress in cables and motors is smaller. The energy per cycle is more in the three level inverter when compared to two level inverter. In the determination of inverter configuration, usually the cost comparison of different configuration has to be executed. The cost of the inverter is affected mainly by the DC-link capacitor, IGBT and the filtering components, while rests of the electronic component have quite insignificant affects. The good estimation of inverter costs can be done by comparing the cost of IGBT and Capacitor. In general, the two-level configuration is 30% cheaper than the three-level configuration. The difference is mostly due to the cost of clamping diodes, which are not needed in two-level configuration. The cost comparison is not taking account the effect of the volume to the unit prices.

The effect of volume will decrease the unit price, which can affect to the relation between total costs.

2.5 APPLICATIONS, OF DIODE CLAMPED MULTI LEVEL INVERTER:

Keeping in mind the popularity graph of this topology and the number of times it has been proposed by different researchers, I can confidently say that it has many applications. Few of its major uses have been mentioned.

- It can be used with high power motors which have relatively medium speed as a variable drive.
- It can be used very conveniently and efficiently at the interface of high power DC power line and high power AC power line.
- It is also used in static VAR compensation.

2.5i) ADVANTAGES

- High efficiency for switching at fundamental frequency.
- Pre charging of capacitors is done in groups.
- In three phase inverter, all three phases use a common DC bus which reduces the requirement of capacitance.
- Efficient for back to back high power connections.
- Low cost.
- Lesser number of components.

2.5ii) DISADVANTAGES

- Quadratic relation between number of diodes and number of levels is difficult to calculate, especially when number of levels get higher it becomes stressful and you would surely want to avoid it.
- Difficulty in real power flow.
- Maintaining certain charging and discharging is difficult.
- Charge balance gets disturbed for more than three level

3. VOLTAGE SOURCE INVERTER (VSI)

An adjustable speed drive (ASD) is a device used to provide continuous range process speed control. An ASD is capable of adjusting both speed and torque from an induction or synchronous motor. An electric ASD is an electrical system used to control motor speed. ASDs may be referred to by a variety of names, such as variable speed drives, adjustable frequency drives or variable frequency inverters. The two terms adjustable frequency drives or variable frequency inverters will only be used to refer to certain AC systems, as is often the practice, although some DC drives are also based on the principle of adjustable frequency (Switching frequency of chopper switch).

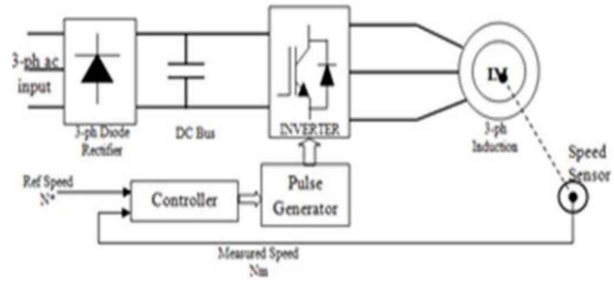

Figure 5: ASD Block Diagram

Adjustable speed drives are the most efficient (98% at full load) types of drives. They are used to control the speeds of both AC and DC motors. They include variable frequency/voltage AC motor controllers for squirrel-cage motors, DC motor controllers for DC motors, eddy current clutches for AC motors (less efficient), wound-rotor motor controllers for wound-rotor AC motors (less efficient) and cycloconverters (less efficient).

A squirrel cage induction motor with constant frequency, constant magnitude voltage supply is supplied, the motor provides constant torque and speed characteristic. To regulate the speed and torque for same induction motor, the motor has to run at variable voltage and frequency. The variable voltage and variable frequency can be obtain from (ASD) adjustable speed drives. AC to DC converter is the first step by which we get DC voltage from AC utility grid. This step is called rectification it occur by diodes connected in bridge form. The second step is DC to AC by operating in inversion operation mode is called inverter device.

4. PULSE WIDTH MODULATION (PWM)

Variable voltage and frequency supply for Adjustable Speed Drives (ASD) is invariably obtained from a three-phase VSI. In power electronics, converters and motors, the PWM technique is mostly used to supply AC current to the load by converting the DC current and it appears as a AC signal at load or can control the speed of motors that run at high speed or low. The duty cycle of a PWM signal varies through analog components, a digital microcontroller or PWM integrated circuit

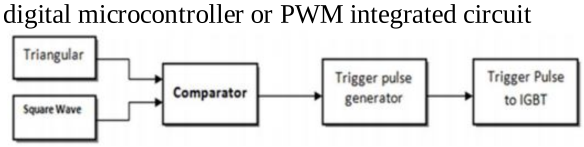

Figure 6: shows the comparator gets the inputs as reference waveform (square wave) and a carrier wave (triangular wave) is supply to the comparator to obtained PWM waveform. Triangular wave is formed by op-amp driver. Triggering pulses are produced at the instant of the carrier signal magnitude is greater then the reference signal magnitude. To turn-on the IGBT switches, firing pulses are produced, the output voltage during the interval triangular voltage wave stipulated the square modulating wave.

Advantages of PWM technique:

• Output voltage can be controlled without other components.

• Output voltage can be controlled, lower order harmonics can be eliminated and filtering out higher order harmonics by this filter requirements is minimized.

Disadvantages of PWM technique:

• The inverter switches are costly as they must have low turn off and turn on times.

Types of PWM techniques:

A number of PWM techniques are there to obtain variable voltage and frequency supply such as, (i) Single-pulse modulation
(ii) Multiple-pulse modulation
(iii) Selected harmonic elimination PWM
(iv) Minimum ripple current PWM
(v) Sinusoidal-pulse PWM (SPWM)
(vi) Space vector-pulse PWM (SVPWM)

Single Pulse Modulation:

The output voltage waveform of single pulse full-bridge inverter is modulated, it contains pulse of width located symmetrically about ʌ/2 and another pulse located symmetrically about 3ʌ/2. The range of pulse width 2d varies from 0 to ʌ; i.e.0<2d<ʌ. The output voltage is controlled by varying the pulse width 2d. This shape of the output voltage wave is called quasi-square wave.

Multiple-pulse modulation:

This method of pulse modulation is an extension of single-pulse modulation. In this method, several equidistant pulses per half cycle are used.

Selected harmonic elimination PWM:

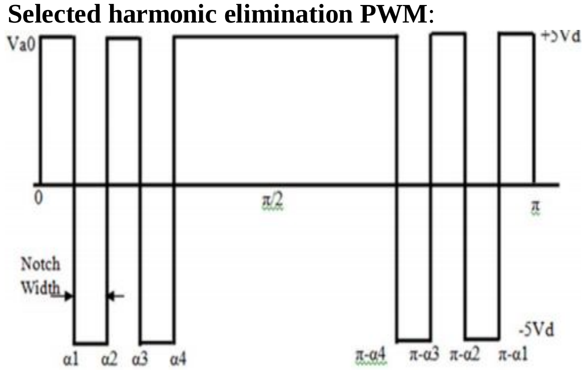

Figure 7: Phase Voltage Wave for SHEPWM

The undesirable lower order harmonics of a square wave can be eliminated and the fundamental voltage can be controlled as well by what is known as selected harmonic elimination (SHE) PWM. A large no. of harmonics can be eliminated if the waveform can accommodate additional notch angles.

The general Fourier series of the wave can be given as

$$v(t) = \sum_{n=1}^{\infty}(a_n \cos n\omega t + b_n \cos n\omega t) \quad (1)$$

Where;

$$a_n = \frac{1}{\pi}\int_0^{2\pi} v(t)\cos n\omega t \, d\omega t \, ; b_n = \frac{1}{\pi}\int_0^{2\pi} v(t)\sin n\omega t \, d\omega t$$

For a waveform with quarter-cycle symmetry only the odd harmonics with sine components will be present.

Therefore, an=0

$$v(t) = \sum_{n=1}^{\infty}(b_n \cos n\omega t) \quad (2)$$

Where ,

$$b_n = \frac{1}{\pi}\int_0^{2\pi} v(t)\sin n\omega t \, d\omega t$$

Assuming that the wave has unit amplitude that is v(t)=+1, bn can be expanded and after solving we can get,

$$v(t) = \frac{4}{n\pi}\left[1 + 2\sum_{k=1}^{k}(-1)^k(\sin n\alpha_k)\right] \quad (3)$$

Minimum ripple current PWM:

One disadvantage of the SHE PWM method is that the elimination of lower order harmonics considerably boosts the next higher level of harmonics. Since the harmonic loss in a machine is dictated by the RMS ripple current, it is the parameter that should be minimized instead of emphasizing the individual harmonics.

Sinusoidal-pulse PWM (SPWM):

Sinusoidal PWM is a modulation technique in which a sinusoidal signal is compared with the triangular signal, in which the frequency of triangular signal (ftri) is equals to the desired sinusoidal output and the frequency of triangular signal gives the switching frequency of the switches.

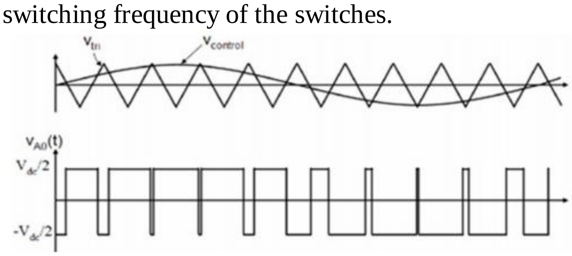

Figure 8: Output Voltage Waveform with Sinusoidal Pulse Modulation

The magnitude of o/p voltage depends on modulation index which is defined as, “the ratio Vtri/VC is called Modulation Index (Ma)” and it controls the harmonic content of the output voltage waveform.

$$modulation\ index\ (Ma) = \frac{amplitude\ of\ sinusiodal\ signal}{amplitude\ of\ triangular\ signal} \quad (4)$$

Advantages

• Controlled inverter output voltage
• Reduction of harmonics

Disadvantages

• Increase of switching losses due to high PWM frequency
• Reduction of available voltage
• EMI problems due to high-order harmonics

Space vector-pulse PWM (SVPWM):

The advance method in PWM techniques is space vector PWM method. It computation intensive PWM method and is excellent method among all the PWM techniques for variable frequency drive application. Its characteristic's is superior to other methods so it is wide spread application in recent years.

5. SPACE VECTOR-PULSE PWM (SVPWM)

It is an algorithm for the control of pulse width modulation (PWM). SVPWM is used for producing of alternating current (AC) waveforms. It is frequently used to drive 3-phase AC powered motors at variable speed from DC power. Various variations of SVPWM that result in different quality and computational requirements. The development is in the reduction of total harmonic distortion (THD) created by the rapid switching inherent to these algorithms.

Space vector modulation is a PWM regulator algorithm for multi-phase AC generation. The reference signal is sampled frequently, after each sample, non-zero active switching vectors adjacent to the reference vector and one or more of the zero switching vectors are preferred for the suitable fraction of the sampling period in order to integrate the reference signal as the average of the used vectors.

Principle of Space Vector PWM:

The circuit model of a typical three-phase voltage source PWM inverter is shown in Fig. 5, S1 to S6 are the six power switches that shape the output, which are controlled by the switching variables a, aĄ , b, bĄ , c and cĄ . When an upper IGBT is switched on, i.e., when a, b or c is 1, the corresponding lower IGBT is switched off, i.e., the corresponding aĄ , bĄ or cĄ is 0.

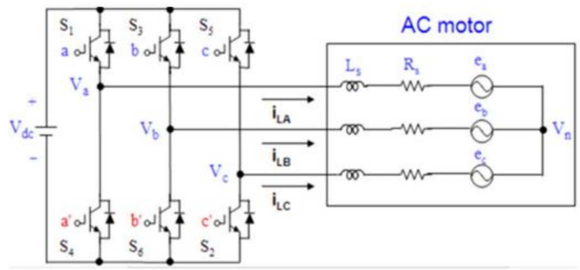

Figure 9: Three-phase voltage source PWM Inverter

Therefore, the ON and OFF states of the upper IGBTs S1, S3 and S5 can be used to determine the output voltage. The relationship between the switching variable vector and the line-to-line voltage vector is given by in the following:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & 1 & 0 \\ 0 & -1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (5)$$

The relationship between the switching variable vector [a,b,c]^t and the phase voltage vector [Vab Vbc Vca]^t is given by in the following:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = V_{dc} \begin{bmatrix} 2 & 1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (6)$$

As illustrated in Figure-5, there are eight possible combinations of ON and OFF patterns for the three upper power switches. The on and off states of the lower power devices are opposite to the upper one and so are easily determined once the states of the upper power IGBTs are determined. According to equations (5) and (6), the eight switching vectors, output line to neutral voltage (phase voltage), and output line-to-line voltages in terms of DC link Vdc, are given in Table 1, and Fig. 5 shows the eight inverter voltage vectors (V0 to V7). The major advantage of SVPWM method is from the fact that there is a degree of freedom of space vector placement in a switching cycle. This improves the harmonic performance of this method.

Voltage vectors	Switching vectors			Line to neutral voltage			Line to line voltage		
	A	B	C	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_0
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

Table 1
Switching vectors, phase voltages and output line to line voltages

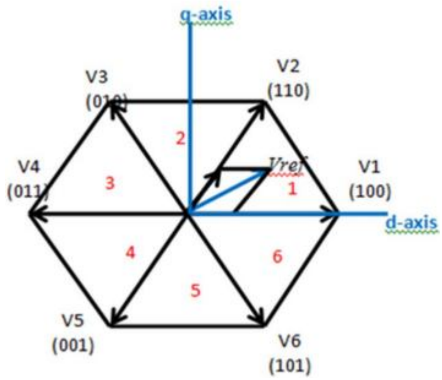

Figure 10: Basic Sector and Vector diagram.

To implement the space vector PWM, the voltage equations in the abc reference frame can be transformed into the stationary dq reference frame that consists of the horizontal (d) and vertical (q) axes.

The relation between these two reference frames is below,

$$f_{dqo} = K_s f_{abc} \quad (7)$$

$$K_s = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (8)$$

$$f_{dqo} = [f_d \quad f_q \quad f_o]^T;\ f_{abc} = [f_a \quad f_b \quad f_c]^T \quad (9)$$

And f denotes either a voltage or a current variable. As described in Fig. 7, this transformation is equivalent to an orthogonal projection of [a,b,c]t onto the two-dimensional perpendicular to the vector [1,1,1] t (the equivalent d-q plane) in a three-dimensional coordinate system. As a result, six nonzero vectors and two zero vectors are possible. Six nonzero vectors (V1 - V6) shape the axes of a hexagonal as depicted in Fig. 7, and feed electric power to the load. The angle between any adjacent two nonzero vectors is 60 degrees. Meanwhile, two zero vectors (V0 and V7) are at the origin and apply zero voltage to the load. The eight vectors are called the basic space vectors and are denoted by V0, V1, V2, V3, V4, V5, V6, and V7.

Steps for implementation of Space vector PWM:

Step 1: Determine Vd, Vq, Vref and angle (Ị)

Step 2: Determine time duration T1, T2, T0

Step 3: Determine the switching time of each IGBT (S1 to S6)

Step 1: Determine Vd, Vq, Vref, and angle (Ị):

From Fig. 5.5, the Vd, Vq, Vref,and angle (Ị) can be determined as follows:

$$V_d = v_{an} - \frac{1}{2}v_{bn} - \frac{1}{2}v_{cn} \quad (10)$$

$$V_q = v_{an} - \frac{\sqrt{3}}{2}v_{bn} - \frac{\sqrt{3}}{2}v_{cn} \quad (11)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} \quad (12)$$

$$|\overline{v_{ref}}| = \sqrt{v_d^2 + v_q^2}\ ;\ \alpha = \tan^{-1}\left(\frac{V_q}{V_d}\right) = \omega t = 2\pi f t \quad (13)$$

Where, f = fundamental frequency

Step 2: Determine time duration T1, T2, T0:

From Fig. 5.6, the switching time duration can be calculated as follows:

Switching time duration at Sector 1:

$$\int_0^{T_z} \bar{V}_{ref} = \int_0^{T_z} \bar{V}_1\,dt + \int_{T_1}^{T_1+T_2} \bar{V}_2\,dt + \int_{T_1-T_2}^{T_z} \bar{V}_0\,dt$$

$$\therefore T_z.\bar{V}_{ref} = T_1.\bar{V}_1 + T_2.\bar{V}_2 \quad (14)$$

$$=> T_z.|\overline{v_{ref}}|.\begin{bmatrix}\cos\alpha \\ \sin\alpha\end{bmatrix} = T_1.\frac{2}{3}V_{DC}.\begin{bmatrix}1 \\ 0\end{bmatrix} + T_1.\frac{2}{3}V_{DC}.\begin{bmatrix}\cos(\pi/3) \\ \sin(\pi/3)\end{bmatrix} \quad (15)$$

Where ,$(0 \le \alpha \le 60)$

$$\therefore T_1 = T_z.\alpha.\frac{\sin\left(\frac{\pi}{3}-\alpha\right)}{\sin\left(\frac{\pi}{3}\right)} \quad (16)$$

$$\therefore T_2 = T_z.\alpha.\frac{\sin(\alpha)}{\sin\left(\frac{\pi}{3}\right)} \quad (17)$$

$$\therefore T_0 = T_z - (T_1 + T_2) \quad (18)$$

$$\left\{ where\ , T_z = \frac{1}{f}\ and\ a = \frac{|\overline{v_{ref}}|}{\frac{2}{3}V_{dc}} \right\}$$

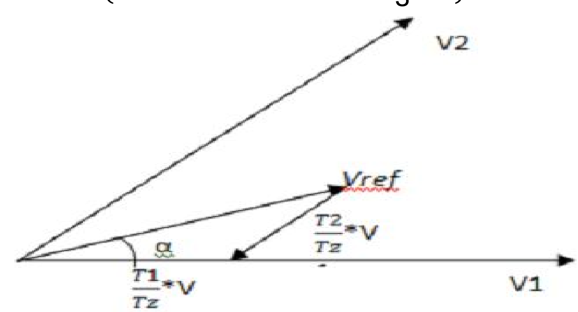

Figure 11: Reference vector as a combination of adjacent vectors at sector 1.

Switching time duration at any Sector:

$$\therefore T_1 = \frac{\sqrt{3}.T_z.|\overline{v_{ref}}|}{V_{dc}}\left(\sin\left(\frac{\pi}{3} - \alpha + \frac{n-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}.T_z.|\overline{v_{ref}}|}{V_{dc}}\left(\sin\left(\frac{n\pi}{3} - \alpha\right)\right) \quad (19)$$

$$\therefore T_2 = \frac{\sqrt{3}.T_z.|\overline{v_{ref}}|}{V_{dc}}\left(\sin\left(\alpha - \frac{n-1}{3}\pi\right)\right)$$

$$= \frac{\sqrt{3}.T_z.|\overline{v_{ref}}|}{V_{dc}}\left(-\cos\alpha.\sin\left(\frac{n-1}{3}\pi\right) + \sin\alpha.\cos\left(\frac{n-1}{3}\pi\right)\right)$$

(20)

$$\therefore T_0 = T_z - (T_1 +)T_2$$

Where n=1 trough $6, 0 \le \alpha \le 60$

Step 3: Determine the switching time of each IGBT (S1 to S6):

Following figure gives the switching times of each IGBT switches. Here Fig. 8 gives the brief idea about the switching timing pattern of inverter IGBT switches under different sectors to generate three phase voltage waveform.

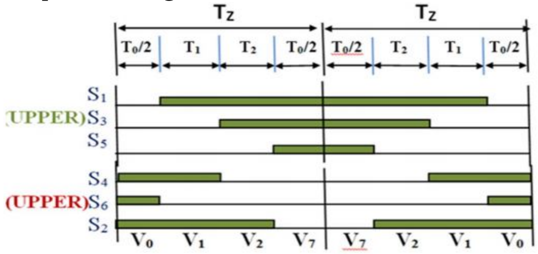

Figure 12: Switching pulse pattern for the three phases in Sector 1.

Based on above figure, the switching time at each sector is summarized in Table (2), and it will be built in Simulink model to implement SVPWM.

Table 2
Switching time calculation at each sector

Sector	Upper Switches (S1,S3,S5)	Lower Switches (S4,S6,S2)
1	S1=T1+T2+T0/2; S3=T2+T0/2; S5=T0/2	S1=T0/2; S3=T1+T0/2; S5=T1+T2+T0/2
2	S1=T1+ T0/2; S3=T1+T2+T0/2; S5=T0/2	S1=T2+T0/2; S3=T0/2; S5=T1+T2+T0/2
3	S1= T0/2; S3=T1+T2+T0/2; S5=T2+T0/2	S1=T1+T2+T0/2; S3=T0/2; S5=T1+T0/2
4	S1= T0/2; S3=T1+ T0/2; S5=T1+T2+T0/2	S1=T1+T2+T0/2; S3=T2+T0/2; S5=T0/2
5	S1= T2+T0/2; S3= T0/2; S5=T1+T2+T0/2	S1=T1+T0/2; S3=T1+T2+T0/2; S5=T0/2
6	S1=T1+T2+T0/2; S3= T0/2; S5= T1+T0/2	S1=T0/2; S3=T1+T2+T0/2; S5=T2+T0/2

SIMULATIONS AND RESULTS

Simulation of sinusoidal PWM based model:

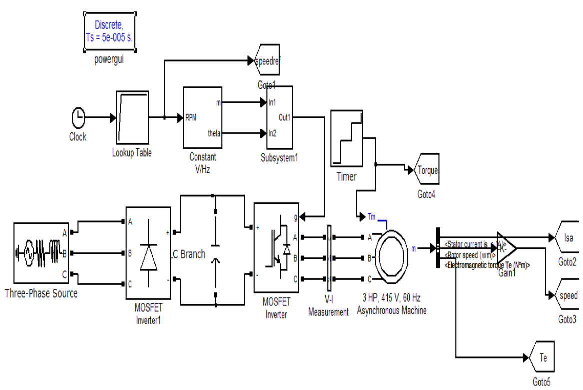

Figure :13 simulation block diagram of the sinusoidal pwm

In Sinusoidal PWM three phase reference modulating signals are compared against a common triangular carrier to generate the PWM signals for the three phases. It is simple and linear between 0% and 78.5% of six step voltage values, which results in poor voltage utilization.

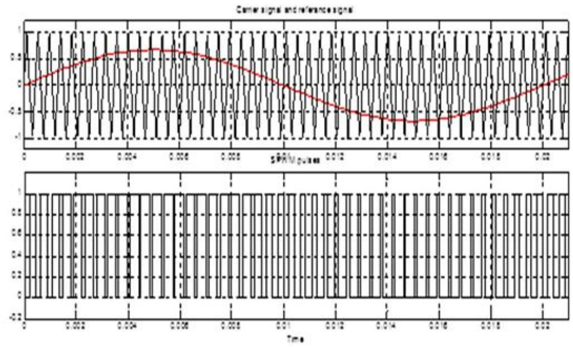

Figure 14: SPWM Pulses

The simulation circuit connection of a three phase inverter based induction motor drive with Sinusoidal PWM (SPWM) is as shown in above figure. Here the three-phase 415V, 50Hz ac supply is converted into dc and then this DC voltage is converted into 3-phase variable frequency ac.

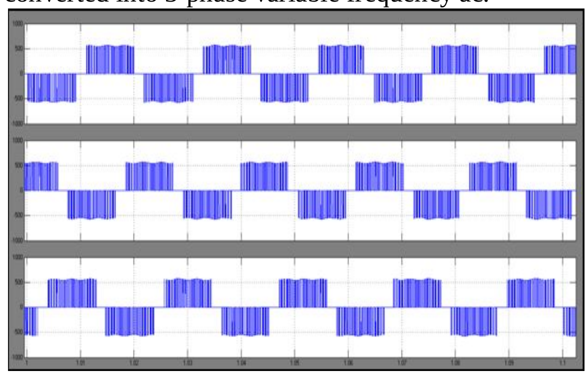

Figure 11: Inverter o/p line voltages

The speed and electromagnetic responses of induction motor with the different load torques at different instants are as shown in Fig. 12

Figure 15: Motor Speed and Electromagnetic torque.

Simulation of Space Vector PWM based model:

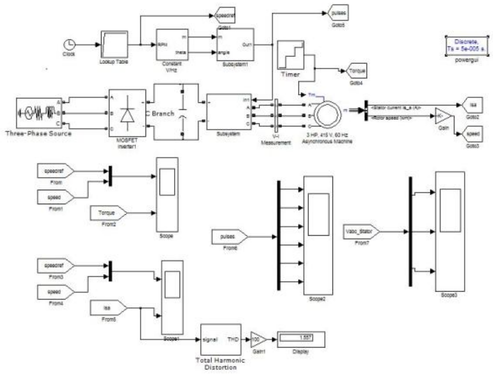

Figure16: simulation block diagram of the three level svpwm

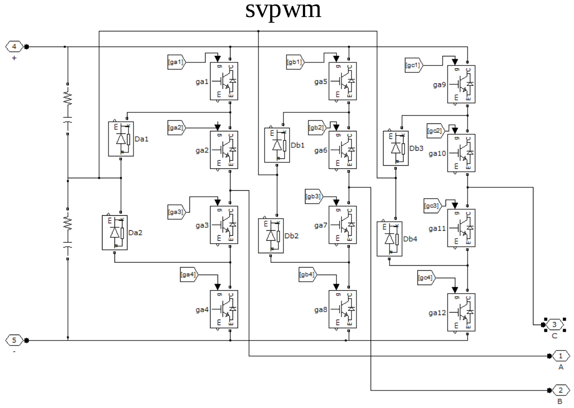

Figure 18: simulation diagram of the three level inverter

i) Open Loop Model:

SVPWM based pulse generator simulation diagram is as shown in Fig. 15. The switching times of switches T1, T3 and T5 are determines in the block MATLAB function block to which some parameters are given such as sector number, angle (Į), Vref and sampling time. The switching times T1, T3 and T5 are calculated in 6 sectors individually by changing the sector. The output of the block is T1, T3 and T5 which is again compared with the high frequency carrier wave so as to reduce the harmonics in the output of inverter.

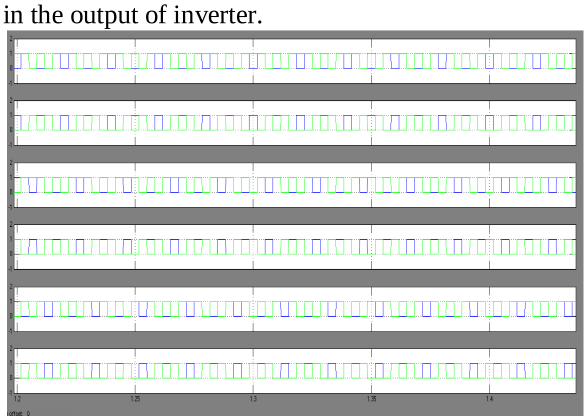

Figure 19: voltage source inverter svpwm output gate pulses

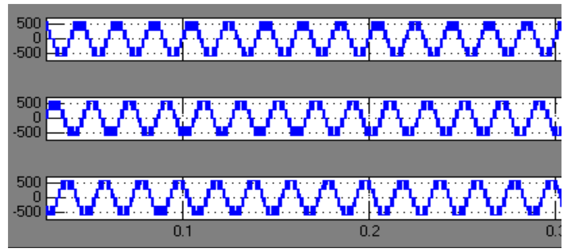

Figure20: Diode clamped inverter svpwm output gate pulses

When SVPWM pulse generator is connected to 3-phase bridge inverter with the induction motor load form a open loop drive. The motor will run at a reference speed.

The reference speed and motor speed graph with time and load torque=0 are as shown in below figure.

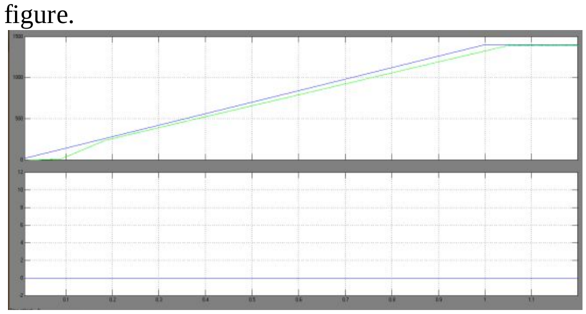

Figure 21:Open Loop Drive Speed response with TL=0

Speed response of Induction motor with different load torque is as shown in below Fig. For 1400rpm of constant input speed command and different load torque at different instant has been applied therefore the speed of motor will falls as load increases.

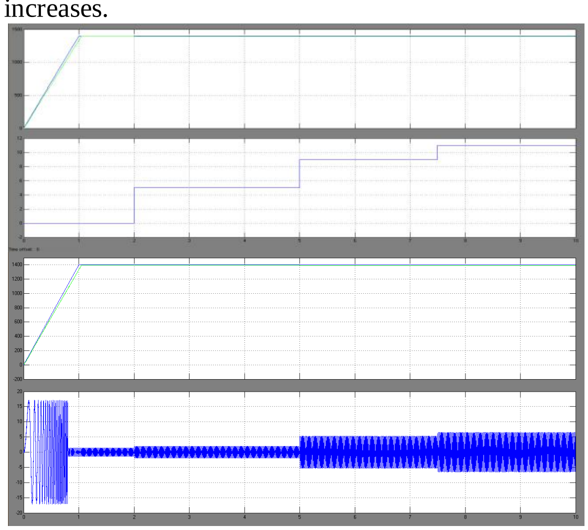

Figure 22: Open Loop Drive Speed response with different TL

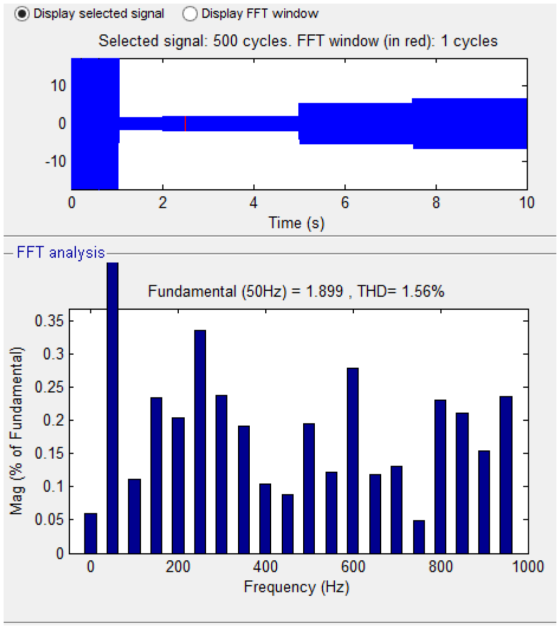

Figure 23: SVPWM based open loop drive Load Current THD

Table 3, variation of motor speed and load current response in gives the open loop model with different load torque. Also table 4, shows closed loop response with different load torques.

S. No.	Load Torque TL (N-m)	Speed (rpm) SVPWM	Load Current (Amps)
1.	0	1391	1.5
2.	5	1374	2.1
3.	9	1359	5.3
4.	11	1352	6.4

Table(3):Open Loop Model Variation of motor speed with Load torque

S. No.	Load Torque (N-m)	Speed (rpm) SVPWM	Load Current (Amps)
1.	0	1390	1.4
2.	5	1375	1.9
3.	9	1362	5.2
4.	11	1354	6.4

Table(4):Closed Loop Model Variation of motor speed with Load torque

ii)**Closed Loop Model:**

To maintain the motor speed at a reference speed value, it needs a feedback loop of motor speed and a speed controller. The drive requires a speed sensor, and the output of the speed sensor will be in terms of rpm. This speed will be processed in the speed controller as explained in the above session.

CONCLUSION

According to the concept of "Control of Induction Motor Drive Using Space Vector PWM" which is implemented in the MATLAB/Simulink. Here the simulation has been done for both open and closed loop. There are appropriate outputs results are see in the paper. Therefore the results of variation of speed of Induction Motor have been observed by varying the load torque in open loop control is mention in the table. And it is observed that for the change in input speed commands the motor speed is settled down to its final value within 0.1sec in closed loop model.

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