CONTROL OF INDUCTION MOTOR DRIVE USING SPACE VECTOR PWM

1SYED MAHAMOOD ALI, 2 DR. MOHAMMAD HASEEB KHAN, 3 DR. ARSHIA AZAM
1Student, Electrical Engineering Department, Muffakham Jah College of Engineering and Technology, Telangana State, INDIA, mahamood1248@gmail.com
2Professor, Electrical Engineering Department, Muffakham Jah College of Engineering and Technology, Telangana State, INDIA, haseeb_md@yahoo.com
3Associate Professor in ECE dept., Polytechnic, Maulana Azad National Urdu University, Hyderabad, Telangana, India.

ABSTRACT

In this paper speed of induction motor is controlled which is fed from three phase bridge inverter. In this paper the speed of an induction motor can be varied by varying input Voltage or frequency or both. Variable voltage and variable frequency for Adjustable Speed Drives (ASD) is invariably obtained from a three-phase Voltage Source Inverter (VSI). Voltage and frequency of inverter can be easily controlled by using PWM techniques, which is a very important aspect in the application of ASDs. A number of PWM techniques are there to obtain variable voltage and variable frequency supply such as PWM, SPWM, SVPWM to name a few, among the various modulation strategies SVPWM is one of the most efficient techniques as it has better performance and output voltage is similar to sinusoidal. In SVPWM the modulation index in linear region will also be high when compared to other Modulation techniques, and DC link voltage utilization in space Vector PWM technique is 15% more compared to Sinusoidal PWM.

Index Terms: Adjustable Speed Drive (ASD); Voltage source inverter (VSI), Sinusoidal PWM (SPWM), Space Vector PWM (SVPWM).

1. INTRODUCTION

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).

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).

If a squirrel cage induction motor is fed from a fixed frequency, fixed magnitude voltage utility grid, the motor provides a specific fixed torque-speed characteristic. To obtain controllable speed and torque from the same induction motor, it has to be driven from a variable voltage variable frequency supply. Adjustable Speed Drives (ASDs) provide this function. The first stage is the AC to DC conversion stage that obtains DC voltage from the AC utility grid. The second stage involves DC to AC conversion and such a device is called an inverter. In an ASD, this converter is utilized to obtain variable voltage and frequency at the output of the ASD so that the motor speed, torque, etc. can be controlled with high performance.

2. PULSE WIDTH MODULATION (PWM)

2.1 INTRODUCTION

Variable voltage and frequency supply for Adjustable Speed Drives (ASD) is invariably obtained from a three-phase VSI. In electronic power converters and motors, PWM is used extensively as a means of powering alternating current (AC) devices with an available direct current (DC) source or for advanced DC/AC conversion. Variation of duty cycle in the PWM signal to provide a DC voltage across the load in a specific pattern will appear to the load as an AC signal, or can control the speed of motors that would otherwise run only at full speed or off. The pattern at which the duty cycle of a PWM signal
varies can be created through simple analog components, a digital microcontroller, or specific PWM integrated circuits.

**Figure 2: PWM Technique and Block diagram**

Figure-2 shows the input reference waveform (square wave) and a carrier wave (triangular wave) is passed into a comparator to achieve the PWM waveform. The triangular wave is simple to create, utilizing an op-amp driver. The triggering pulses are generated at the instants of the carrier signal magnitude is greater than the reference signal magnitude. The firing pulses are generated to turn-on the IGBT switches so that the output voltage is available during the interval triangular voltage wave exceeds the square modulating wave.

The advantages possessed by PWM technique are,

(i) The output voltage control with this method can be obtained without any additional components.

(ii) With this method, 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.

The main disadvantage of this method is that the inverter switches are expensive as they must possess low turn-off and turn-on times.

**2.2 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)

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

ii. 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.

iii. Selected harmonic elimination PWM:

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

\[ v(t) = \sum_{n=1}^{\infty} (a_n \cos nt + b_n \sin nt) \]  

Where;

\[ a_n = \frac{2}{\pi} \int_{0}^{\pi} v(t) \cos nt \, dt \]

\[ b_n = \frac{2}{\pi} \int_{0}^{\pi} v(t) \sin nt \, dt \]

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

Therefore, \( a_n = 0 \)

\[ v(t) = \sum_{n=1}^{\infty} b_n \sin nt \]  

Where,

\[ b_n = \frac{4}{\pi} \int_{0}^{\pi/2} v(t) \sin nt \, dt \]

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

\[ v(t) = \frac{4}{\pi} \left[ 1 + \sum_{n=2}^{\infty} (-1)^{n+1} \left( \frac{1}{n^2} \right) \right] \]

iv. 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.

v. 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 3: Phase Voltage Wave for SHEPWM**

**Figure 4: 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.

\[
\text{Modulation index (Ma)} = \frac{\text{amplitude of sinusoidal signal}}{\text{amplitude of triangular signal}}
\]

(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 space vector PWM (SVM) method is an advanced, computation-intensive PWM method and is possibly the best method among all PWM techniques for variable-frequency drive application. Because of its superior performance characteristics, it has been finding wide spread application in recent years.

### 3. SPACE VECTOR-PULSE PWM (SVPWM)

SVM is an algorithm for the control of pulse width modulation (PWM). It is used for the creation of alternating current (AC) waveforms; most commonly to drive 3 phase AC powered motors at varying speeds from DC using multiple class-D amplifiers. There are various variations of SVM that result in different quality and computational requirements. One active area of 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 control algorithm for multi-phase AC generation, in which the reference signal is sampled regularly, after each sample, non-zero active switching vectors adjacent to the reference vector and one or more of the zero switching vectors are selected for the appropriate fraction of the sampling period in order to synthesize the reference signal as the average of the used vectors.

#### 3.1 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, a’, b, b’, c and c’. 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 a’, b’ or c’ is 0.

The relationship between the switching variable vector \([a,b,c]^\top\) and the phase voltage vector \([V_{ab} V_{bc} V_{ca}]^\top\) is given by in the following:

\[
\begin{bmatrix}
V_{ab} \\
V_{bc} \\
V_{ca}
\end{bmatrix}
= V_{dc} \begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1 \\
-1 & 0 & 1
\end{bmatrix} \begin{bmatrix}
a \\
b \\
c
\end{bmatrix}
\]

(5)

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.

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

<table>
<thead>
<tr>
<th>Voltage vectors</th>
<th>Switching vectors</th>
<th>Line to neutral voltage</th>
<th>Line to line voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>V0</td>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
</tr>
<tr>
<td>V1</td>
<td>1 0 0</td>
<td>2/3 -1/3 -1/3</td>
<td>1 0 -1</td>
</tr>
<tr>
<td>V2</td>
<td>1 1 0</td>
<td>1/3 1/3 -2/3</td>
<td>0 1 -1</td>
</tr>
<tr>
<td>V3</td>
<td>0 1 0</td>
<td>-1/3 2/3 -1/3</td>
<td>-1 1 0</td>
</tr>
<tr>
<td>V4</td>
<td>0 1 1</td>
<td>-2/3 1/3 1/3</td>
<td>0 1 0</td>
</tr>
<tr>
<td>V5</td>
<td>0 0 1</td>
<td>-1/3 1/3 2/3</td>
<td>0 -1 1</td>
</tr>
<tr>
<td>V6</td>
<td>1 0 1</td>
<td>1/3 -2/3 1/3</td>
<td>1 -1 0</td>
</tr>
<tr>
<td>V7</td>
<td>1 1 1</td>
<td>0 0 0</td>
<td>0 0 0</td>
</tr>
</tbody>
</table>
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,

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = K_d \begin{bmatrix} 1 & -1/2 & -1/2 \\ -1/2 & 1/2 & 1/2 \\ 1/2 & -1/2 & 1/2 \end{bmatrix} \begin{bmatrix} d \\ q \end{bmatrix} = K_d \begin{bmatrix} 2d \\ \sqrt{3}q \\ \sqrt{3}d \end{bmatrix} \begin{bmatrix} d \\ q \end{bmatrix} = K_d \begin{bmatrix} 2d \\ 3q \\ 2d \end{bmatrix}$$

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 non-zero 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 non-zero 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:

1. **Step 1:** Determine V_d, V_q, V_ref, and angle (α)
2. **Step 2:** Determine time duration T_1, T_2, T_0
3. **Step 3:** Determine the switching time of each IGBT (S1 to S6)

**Step 1: Determine V_d, V_q, V_ref, and angle (α):**

From Fig. 5.5, the V_d, V_q, V_ref, and angle (α) can be determined as follows:

$$V_d = V_{sn} - \frac{1}{2}V_{in} - \frac{1}{2}V_{in}$$

**Step 2: Determine time duration T_1, T_2, T_0:**

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

$$T_1 = \frac{\theta_1}{\alpha}$$

$$T_2 = \frac{\theta_2}{2\alpha}$$

$$T_0 = \frac{\theta_0}{3\alpha}$$

Where, \( \alpha = \tan^{-1}\left(\frac{V_{ref}}{V_{in}}\right) = \omega t = 2\pi f t \)
Where \( n = 1 \) to 6, \( 0 \leq \alpha \leq 60 \)

**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 8: Switching pulse pattern for the three phases in Sector 1.](image)

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**

<table>
<thead>
<tr>
<th>Sector</th>
<th>Upper Switches (S1, S3, S5)</th>
<th>Lower Switches (S4, S6, S2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T1 = T2 + T3 + T4</td>
<td>T2 = T1 + T3 + T4</td>
</tr>
<tr>
<td>2</td>
<td>T1 = T2 + T3 + T4</td>
<td>T2 = T1 + T3 + T4</td>
</tr>
<tr>
<td>3</td>
<td>T1 = T2 + T3 + T4</td>
<td>T2 = T1 + T3 + T4</td>
</tr>
<tr>
<td>4</td>
<td>T1 = T2 + T3 + T4</td>
<td>T2 = T1 + T3 + T4</td>
</tr>
<tr>
<td>5</td>
<td>T1 = T2 + T3 + T4</td>
<td>T2 = T1 + T3 + T4</td>
</tr>
<tr>
<td>6</td>
<td>T1 = T2 + T3 + T4</td>
<td>T2 = T1 + T3 + T4</td>
</tr>
</tbody>
</table>

**4. SIMULATION AND RESULTS**

**4.1 SIMULATION OF SINUSOIDAL PWM BASED MODEL**

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. Frequency in conventional SPWM output waves owing to their fixed switching frequencies.

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. Here the controlling of inverter is done by PWM method i.e. sinusoidal PWM.

The speed and electromagnetic responses of induction motor with the different load torques at different instants are as shown in Fig. 11. From this figure it is observed that when load is applied on the motor the speed of motor gets reduced.

![Figure 10: Inverter o/p line voltages](image)

**4.2 SIMULATION OF SPACE VECTOR PWM BASED MODEL**

i) Open Loop Model

SVPWM based pulse generator simulation diagram is as shown in Fig. 14. The switching times of switches T1, T3 and T5 are determines in the block MATLAB function.

![Figure 9: SPWM Pulses](image)

![Figure 11: Motor Speed and Electromagnetic torque.](image)
block to which some parameters are given such as sector number, angle (α), 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. And T4, T6 and T2 are the inverted switching times of T1, T3 and T5 respectively.

T1 to T6 pulse signals are as shown in Fig. 12. These pulsed are given to the six IGBT switches of bridge inverter.

![Figure 12: SVPWM output gate pulses](image)

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 command is converted into frequency command and given to SVPWM block. The SVPWM block generates gate pulses with respect to speed command so as to run motor at reference speed.

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

![Figure 13: Open Loop Drive Speed response with TL=0](image)

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. In open loop model, variation of speed with the load is as shown in table (3)
Table (4): Open Loop Model Variation of motor speed with Load torque

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Load Torque (N-m)</th>
<th>Speed (rpm) SVPWM</th>
<th>Load Current (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>0</td>
<td>1390</td>
<td>1.4</td>
</tr>
<tr>
<td>2.</td>
<td>5</td>
<td>1375</td>
<td>1.9</td>
</tr>
<tr>
<td>3.</td>
<td>9</td>
<td>1362</td>
<td>5.2</td>
</tr>
<tr>
<td>4.</td>
<td>11</td>
<td>1354</td>
<td>6.4</td>
</tr>
</tbody>
</table>

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.

5. CONCLUSION

The simulation of “Control of Induction Motor Drive Using Space Vector PWM” is carried out in MATLAB/Simulink. The simulation has been done for open loop as well as closed control. The appropriate output results are obtained.

The variation of speed of induction motor has been observed by varying the load torque in open loop control and results are noted down in the table. Also 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.

REFERENCES


BIOGRAPHIES

Mr. Syed Mahamood Ali is a PG student [Power Electronic & Systems] of Electrical Engineering department, from Muffakham Jah College Of Engineering & Technology, Affiliated to Osmania University Hyderabad, Telangana, India. Received his B.Tech degree in Electrical & Electronics Engineering from Jaya Prakash Narayan College Of Engineering & Technology, Affiliated to Jawaharlal Nehru Technological University Hyderabad, Telangana, India in 2013. His research interests include Power Electronic Systems, Electric Drives and Industrial Electronic Systems.

Dr. Mohammad Haseeb Khan received his B.Tech. (EEE) from Kakatiya University in the year 1999, M.Tech (PE) and Ph.D. (EEE) in the years 2003 and 2012 respectively from Jawaharlal Nehru Technological University. He has 15 years of teaching experience. Currently he is working as Professor in EED, Muffakham Jah College Of Engineering & Technology, Hyderabad. His research areas include Power Electronics, Electric drives, intelligent systems.

Dr. Arshia Azam received her B.E. (ECE) from Osmania University in the year 1999, M.Tech (ICS) and Ph.D. (ECE) in the years 2004 and 2011 respectively from Jawaharlal Nehru Technological University. She has 15 years of teaching experience. Currently she is working as Associate Professor in ECE dept., Polyttechnic, Maulana Azad National Urdu University, Hyderabad, Telangana, India. Her research areas include Intelligent systems, reduced rule fuzzy logic controllers, Power electronics and mobile computing.