Speed Control of Induction Motor using Space Vector Modulation

K Srinivas
Assistant Professor, Department of EEE & JNTUH CEJ
Telangana, India

Abstract

Induction motors are the most widely used electrical motors due to their reliability, low cost and robustness. However, induction motors do not inherently have the capability of variable speed operation. Due to this reason, earlier dc motors were applied in most of the electrical drives. But the recent developments in speed control methods of the induction motor have led to their large scale use in almost all electrical drives. Out of the several methods of speed control of an induction such as pole changing, frequency variation, variable rotor resistance, variable stator voltage, constant V/f control, slip recovery method etc are conventional control methods. With advances in solid-state power electronic devices and microprocessors, various pulse-width-modulation (PWM) techniques have been developed for industrial applications to control the speed of the induction motor. This thesis discuss about the speed control of induction motor by using Space Vector Pulse Width Modulation (SVPWM) technique. In this thesis we vary the speed of the induction motor in two cases one is accelerating mode and another is decelerating mode. The simulation results show that the SVPWM technique has lower total harmonic distortion than the SPWM technique. The SVPWM technique in the under-modulation region can increase the fundamental output voltage by 15.5% over the SPWM technique.

Keywords— *Harmonics, DSTATCOM*

I. INTRODUCTION

Induction motors are the most widely used electrical motors due to their reliability, low cost and robustness. However, induction motors do not inherently have the capability of variable speed operation. Due to this reason, earlier dc motors were applied in most of the electrical drives. But the recent developments in speed control methods of the induction motor have led to their large scale use in almost all electrical drives [1]. Be it domestic application or industry, motion control is required everywhere. The conventional methods of speed control of an induction motor were either too expensive or too inefficient thus restricting their application to only constant speed drives [2].

Out of the several methods of speed control of an induction motor such as pole changing, frequency variation, variable rotor resistance, variable stator voltage, constant V/f control, slip recovery method etc. are the conventional methods. But these traditional per phase equivalent circuit analysis of an induction motor have the disadvantage that it is valid only if the system is a balanced one. Any imbalance in the system leads to erroneous analysis. Also the dynamic response of the motor cannot be obtained from the per phase equivalent circuit So the vector control method leads to a simpler analysis of an induction motor by use of rectifier and PWM inverter, we can vary the supply voltage as well as the supply frequency such that the ratio remains constant so that the flux remains constant too. So we can get different operating zone for various speeds and torques and also we can get different synchronous speed with almost same maximum torque. Thus the motor is completely utilized and also we have a good range of speed control.

II. CONTROL STRATEGIES

A. Pulse Width Modulation (PWM)

Pulse-width modulation (PWM) is a technique where the duty ratio of a pulsating waveform is controlled by another input waveform. The intersections between the reference voltage waveform and the carrier waveform give the opening and closing times of the switches. PWM is commonly used in applications like motor speed control, converters, audio amplifiers, etc. For example, it is used to reduce the total power delivered to a load without losses, which normally occurs when a power source is limited by a resistive element.

PWM is used to adjust the voltage applied to the motor. Changing the duty ratio of the switches changes the speed of the motor. The longer the pulse is closed compared to the opened periods, the higher the power supplied to the load is. The change of state between closing (ON) and opening (OFF) is rapid, so that the average power dissipation is very low compared to the power being delivered [3]. PWM amplifiers are more efficient and less bulky than linear power amplifiers. In addition, linear amplifiers that deliver energy continuously rather than through pulses have lower maximum power ratings than PWM amplifiers. There is no single PWM method that is the best suited for all applications and with advances in solid-state power electronic devices and microprocessors, various pulse-width modulations (PWM) techniques have been developed for industrial applications [4]. For these reasons, the PWM techniques have been the subject of intensive research since 1970s.

With advances in solid-state power electronic devices and microprocessors, various inverter control techniques employing pulse-width-modulation (PWM) techniques are becoming increasingly popular in AC motor drive applications [5]. These PWM-based drives are used to control both the frequency and the magnitude of the voltages applied to motors. Various PWM strategies, control schemes, and realization techniques have been developed in the past two decades. PWM strategy plays an important role in the minimization of harmonics and switching losses in converters, especially in three-phase applications. The first modulation techniques were developed in the mid-1960s by Kirnnich, Heinrick, and Bowes as reported in. The research in PWM schemes has intensified in the last few decades [6]. The main aim of any modulation technique is to obtain a variable output with a maximum fundamental component and minimum harmonics.

B. *Sinusoidal PWM (SPWM)*

The carrier-based PWM methods were developed first and were widely used in most applications. One of the earliest modulation signals for carrier-based PWM is sinusoidal PWM (SPWM) [7-8]. The SPWM technique is based on the comparison of a carrier signal and a pure sinusoidal modulation signal. It was introduced by Schonung and Stemmler in 1964. The utilization rate of the DC voltage for traditional sinusoidal PWM is only 78:5% of the DC bus voltage, which is far less than that of the six-step wave (100%).Improving the utilization rate of the DC bus voltage has been a research focus in power electronics.

C. *Space-vector PWM (SVPWM)*

Another method of increasing the output voltage is the space-vector PWM (SVPWM) technique. SVPWM was first introduced in the mid-1980s and was greatly advanced by Van Der Broeck in 1988. With the development of microprocessors, SVPWM has become one of the most important PWM methods for three-phase inverters. Many SVPWM schemes have been developed and extensively investigated in the literature. The goal in each modulation strategy is to lower the switching losses, maximize bus utilization, reduce harmonic content, and still achieve precise control.

The SVPWM technique utilizes the DC bus voltage more efficiently and generates less harmonic distortion when compared with the SPWM technique. The maximum peak fundamental magnitude of the SVPWM technique is about 90.6% of the inverter capacity. This represents a 15:5% increase in the maximum voltage compared with conventional sinusoidal modulation.

III.IMPLEMENTATION OF SPACE VECTOR PWM

The SVPWM scheme is more complicated than that of the conventional SPWM. It requires the determination of a sector, calculation of vector segments, and it involves region identification based on the modulation index and calculation of switching time durations.

Voltage vector	a	b	c	V_α	V_β	vector
V_0	0	0	0	0	0	0
V_1	1	0	0	$\frac{2V_{dc}}{3}$	0	V_{0^0}
V_2	1	1	0	$\frac{V_{dc}}{3}$	$\frac{V_{dc}}{\sqrt{3}}$	V_{60^0}
V_3	0	1	0	$-\frac{V_{dc}}{3}$	$\frac{V_{dc}}{\sqrt{3}}$	V_{120^0}
V_4	0	1	1	$\frac{2V_{dc}}{3}$	0	V_{180^0}
V_5	0	0	1	$-\frac{V_{dc}}{3}$	$-\frac{V_{dc}}{\sqrt{3}}$	V_{240^0}
V_6	1	0	1	$\frac{V_{dc}}{3}$	$-\frac{V_{dc}}{\sqrt{3}}$	V_{300^0}
V_7	1	1	1	0	0	V_{360^0}

Table 3.1 Voltage Vectors, Switching Vector α and β

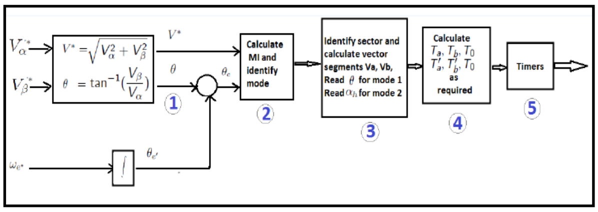

Fig 3.1 Flow Diagram for SVPWM Implementation

A simplified flow diagram for the implementation of the SVPWM algorithm is showing Figure 3.1. The procedure for implementing a two-level space vector PWM can be summarized as follows:

1. Calculate the angle θ and reference voltage vector based on the input voltage components.

2. Calculate the modulation index and determine if it is in the over-modulation region.
3. Find the sector in which lies, and the adjacent space vectors of and based on sector angle θ.
4. Find the time intervals and based on , and the angle θ.
5. Determine the modulation times for the different switching states.

A. Angle and Reference Voltage Vector

In the Space Vector PWM, the three-phase output voltage vector is represented by a reference vector that rotates at an angular speed of $\omega = 2\pi f$. The Space Vector PWM uses the combinations of switching states to approximate the reference vector $\overrightarrow{V_{ref}}$ .A reference voltage vector $\overrightarrow{V_{ref}}$ that rotates with angular speed ω in the $\alpha\beta$ plane represents three sinusoidal waveforms with angular frequency ω in the abc system. Each output voltage combination in Table 5.1 corresponds to a different voltage space vector. Three sinusoidal and balanced voltages are given by the relations

$$V_a(t) = V_{ref}\cos(\omega t) \quad \ldots\ldots\ldots\ldots\ldots\ldots 5.1$$

$$V_b(t) = V_{ref}\cos\left(\omega t - \frac{2\pi}{3}\right) \quad \ldots\ldots\ldots\ 5.2$$

$$V_c(t) = V_{ref}\cos\left(\omega t + \frac{2\pi}{3}\right) \quad \ldots\ldots\ldots\ldots 5.3$$

For any three-phase system with three wires and equal load impedances, we have

$$V_a + V_b + V_c = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.4$$

The space vector with magnitude $\overrightarrow{V_{ref}}$ rotates in a circular direction at an angular velocity of ω where the direction of rotation depends on the phase sequence of the voltages. If it has a positive phase sequence, then it rotates in the counter clockwise direction. Otherwise, it rotates in the clockwise direction with a negative phase sequence. The three-phase voltages could be described with only two components, α and β, in a Two-dimensional plane. The magnitude of each active vector is $\frac{2V_{dc}}{3}$. The active vectors are 60^0 apart and describe a hexagon boundary. The locus of the circle projected by the space reference vector $\vec{V}_{ref}$ depends on $\overrightarrow{V_0}, \overrightarrow{V_1}, \overrightarrow{V_2}, \overrightarrow{V_3}, \overrightarrow{V_4}, \overrightarrow{V_5}, \overrightarrow{V_6}, \overrightarrow{V_7}$

$$\overrightarrow{V_{ref}} = \frac{2}{3}(V_a + aV_b + a^2V_c) \quad \ldots\ldots\ldots\ldots\ldots\ldots 5.5$$

Where $a = e^{j\frac{2\pi}{3}}$.

The magnitude of the reference vector is:

$$\left|\overrightarrow{V_{ref}}\right| = \sqrt{V_\alpha^2 + V_\beta^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.6$$

The phase angle is evaluated from

$$\theta = \tan^{-1}\left(\frac{V_\beta}{V_\alpha}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.7$$

Where $\theta \in [0, 2\pi]$

B. Determination of the Switching Times for Each Transistor Switch (S1 - S6)

It is necessary to arrange the switching sequence so that the switching frequency of each inverter leg is minimized. There are many switching patterns that can be used to implement SVPWM. To minimize the switching losses, only two adjacent active vectors and two zero vectors are used. To meet this optimal condition, each switching period starts with one zero vector and end with another zero vector during the sampling time T_s . This rule applies normally to three-phase inverters as a switching sequence. Therefore, the switching cycle of the output voltage is double the sampling time, and the two output voltage waveforms become symmetrical during T_s . Table 3.2 presents a symmetric switching sequence. Referring to this table, the binary representations of two adjacent basic vectors differ in only one bit, so that only one of the upper transistors switches is closed when the switching pattern moves from one vector to an adjacent one. The two vectors are time-weighted in a sample period Ts to produce the desired output voltage.

C. *Types of Different Schemes*

There are two modes of operation available for the PWM waveform: symmetric and asymmetric PWM. The pulse of an asymmetric edge aligned signal always has the same side aligned with one end of each PWM period. On the other hand, the pulse of symmetric signals is always symmetric with respect to the centre of each PWM period. The symmetrical PWM signal is often preferred because it has been shown to have the lowest total harmonic distortion (THD). Output patterns for each sector are based on a symmetrical sequence. There are different schemes in space vector PWM and they are based on their repeating duty distribution. The seven-segment technique is studied in this thesis and will be referred to as the symmetric technique. Based on the equations for T_a , T_b , T_0 , T_7 , and according to the principle of symmetrical PWM, the switching sequence in Table 5.5 is shown for the upper and lower switches.

Figure 5.6 shows the switching patterns of all six sectors in the circle. As shown in the same figure, the space vector for a three-phase voltage source inverter is divided into six sectors based on six fundamental vectors. Any voltage vector in this vector space can be synthesized using two adjacent vectors. One switching period is depicted in the same figure. In sector 1, for example, switching is achieved by applying a zero state vector followed by two adjacent active state vectors in a half switching period. The next half of the switching period is the mirror image of the first half. In order to reduce the switching loss of the power components of the inverter, it is required that at each time only one bridge arm is switched. After re-organizing the switching sequences, a scheme with center - aligned pulses is obtained as shown in Figure 5.5. The switching pulse patterns of six different sectors in Figure 5.7 are shown for the upper and lower switches of a three-phase inverter. It is obvious that in the odd sector the active state sequence is in ascending-descending order; whereas, it is in a descending- ascending order in an even sector. For example:

1. In an odd sector 1, the state sequence of space vectors is in the order

$$\overrightarrow{V_0} - \overrightarrow{V_1} - \overrightarrow{V_2} - \overrightarrow{V_7} - \overrightarrow{V_7} - \overrightarrow{V_2} - \overrightarrow{V_1} - \overrightarrow{V_0}$$

2. In an even sector 2, the state sequence of space vectors is:

$$\overrightarrow{V_0} - \overrightarrow{V_3} - \overrightarrow{V_2} - \overrightarrow{V_7} - \overrightarrow{V_7} - \overrightarrow{V_2} - \overrightarrow{V_3} - \overrightarrow{V_0}$$

Following the same procedure, we have the switching sequence summarized in

sector	Switching Segment						
	1	2	3	4	5	6	7
1	$\overrightarrow{V_0}$,[000]	$\overrightarrow{V_1}$,[100]	$\overrightarrow{V_2}$,[110]	$\overrightarrow{V_7}$,[111]	$\overrightarrow{V_2}$,[110]	$\overrightarrow{V_1}$,[100]	$\overrightarrow{V_0}$,[000]
2	$\overrightarrow{V_0}$,[000]	$\overrightarrow{V_3}$,[010]	$\overrightarrow{V_2}$,[110]	$\overrightarrow{V_7}$,[111]	$\overrightarrow{V_2}$,[110]	$\overrightarrow{V_3}$,[010]	$\overrightarrow{V_0}$,[000]
3	$\overrightarrow{V_0}$,[000]	$\overrightarrow{V_3}$,[010]	$\overrightarrow{V_4}$,[011]	$\overrightarrow{V_7}$,[111]	$\overrightarrow{V_4}$,[011]	$\overrightarrow{V_3}$,[010]	$\overrightarrow{V_0}$,[000]
4	$\overrightarrow{V_0}$,[000]	$\overrightarrow{V_5}$,[001]	$\overrightarrow{V_4}$,[011]	$\overrightarrow{V_7}$,[111]	$\overrightarrow{V_4}$,[011]	$\overrightarrow{V_5}$,[001]	$\overrightarrow{V_0}$,[000]
5	$\overrightarrow{V_0}$,[000]	$\overrightarrow{V_5}$,[001]	$\overrightarrow{V_6}$,[101]	$\overrightarrow{V_7}$,[111]	$\overrightarrow{V_6}$,[101]	$\overrightarrow{V_5}$,[001]	$\overrightarrow{V_0}$,[000]
6	$\overrightarrow{V_0}$,[000]	$\overrightarrow{V_1}$,[100]	$\overrightarrow{V_6}$,[101]	$\overrightarrow{V_7}$,[111]	$\overrightarrow{V_6}$,[101]	$\overrightarrow{V_1}$,[100]	$\overrightarrow{V_0}$,[000]

Table 3.2 for All Six Sectors

IV. SIMULATION RESULTS

Here we are observing the speed variation of Induction motor in two cases one is accelerating case and another is deceleration case. The resulting speed, torque, stator voltages, stator currents are shown in below figures.

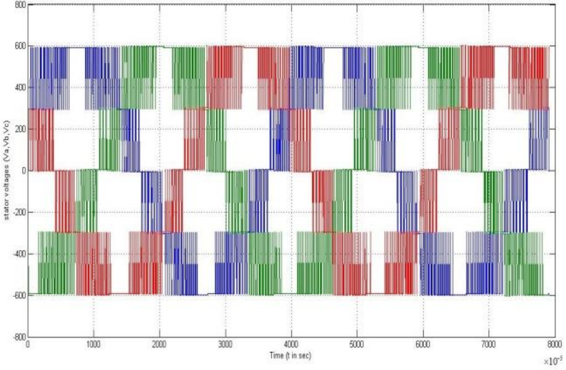

Fig 4.1 Stator Voltages (Va,Vb,Vc)

A. *Deceleration*

In figure 4.2 and 4.3 shown deceleration mode of induction motor, Fig.4.2 shows speed drops instantly when load on the motor increases, with respect load changes torque also changes with same time period shown in fig.4.3.

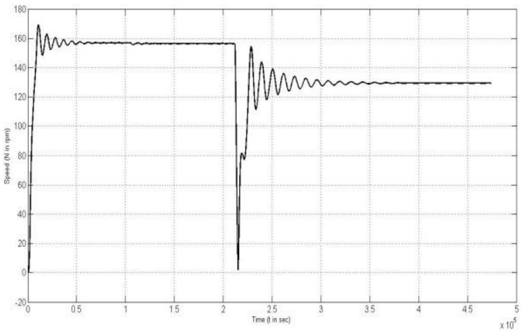

Fig 4.2 Speed Variation with Time in Deceleration Case

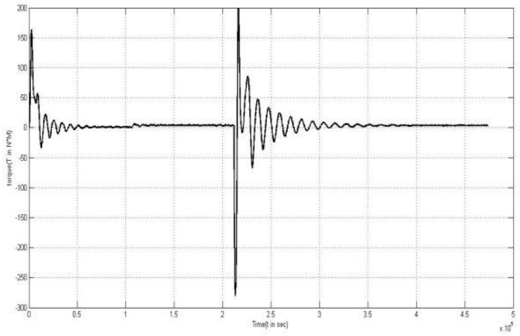

Fig 4.3 Torque Variation with Time in Deceleration Case

B. *Acceleration*

When load on the motor drops suddenly, speed of the motor increases shown in fig.4.4 and torque changes shown in fig.4.5

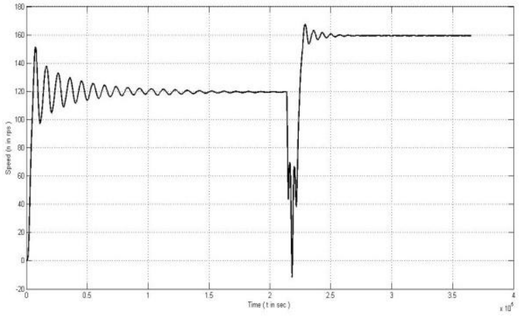

Fig 4.4 Speed Variation with Time in Acceleration Case

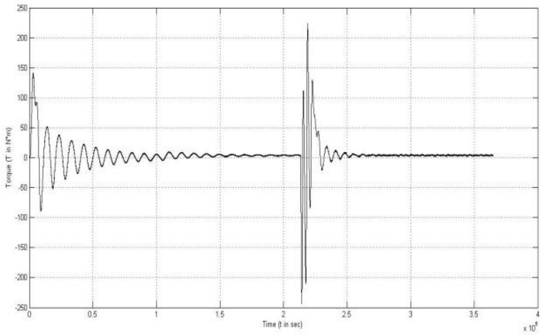

Fig 4.5 Torque Variation with Time in Acceleration Case

When load changes instantaneously three phase currents from the stator side also changes shown in fig. 4.6-4.9

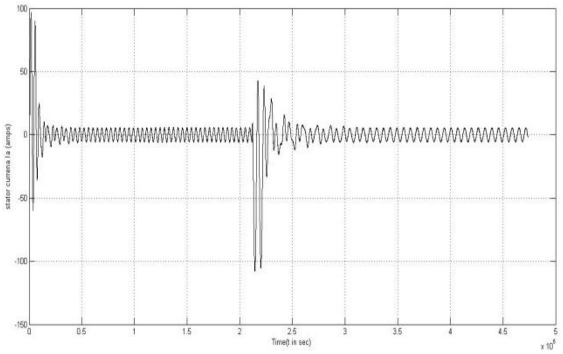

Fig 4.6: Stator Current Phase A (I_A)

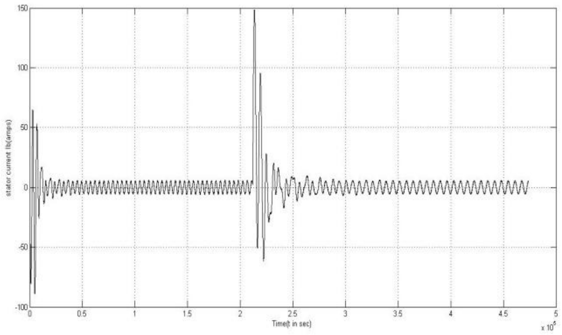

Fig 4.7: Stator Current Phase B (I_B)

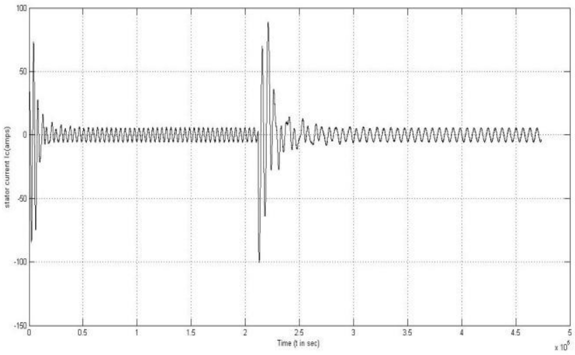

Fig 4.8: Stator Current Phase C (I_C)

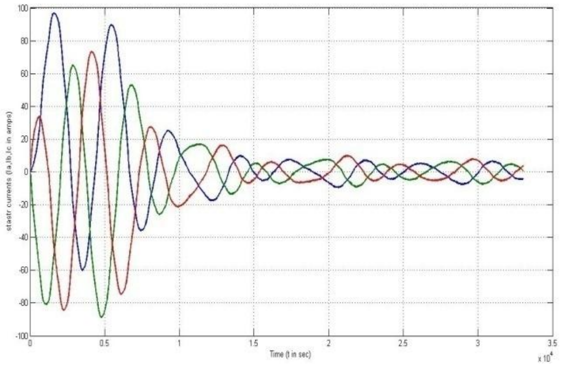

Fig 4.9 Stator Currents Phases A,B,C (I_A, I_B, I_C)

V. CONCLUSION

In this thesis we explained about the speed control of the induction motor in two cases one is accelerating mode and another is decelerating mode by using SVPWM (in the linear modulation region) technique. The contributions of the thesis are as follows:

- The thesis has provided a thorough review of the operation of SVPWM in the under-modulation.
- In this thesis, Simulink models for all this technique has been developed and tested in the MATLAB/Simulink environment.

As seen from the simulation results, The SVPWM technique is more suitable for a three-phase inverter and it increases the overall system efficiency. The SVPWM is used for controlling the switching of the machine side converter.

Advantages of this method include

- The Modulation Index is higher for SVPWM as compared to SPWM.
- The output voltage is about 15.5% more in case of SVPWM as compared to SPWM.
- The current and torque harmonics produced are much less in case of SVPWM and also lower switching losses, and less harmonic distortion compared to SPWM.

So the Space Vector Pulse Width Modulation (SVPWM) research has been widespread in recent years making it one of the most popular methods for three-phase inverters.

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