Abstract—This paper proposes the implementation of a different SPACE VECTOR PWM technique applied to the indirect vector controlled induction motor (IM) drive involves decoupling of the stator current into torque and flux producing components of an induction motor. The drive control generally involves a fixed gain proportional-integral controller. Space vector pulse width modulation technique is widely used in inverter and rectifier controls. Compared to the sinusoidal PWM (SPWM), SVPWM is more suitable for digital implementation and can increase the obtainable maximum output voltage with maximum line voltage approaching 70.7% of the DC link voltage (compared to SPWM’s 61.2%) in the linear modulation range. Indirect vector controlled induction motor drive using different Space Vector PWM techniques are implemented in MATLAB-SIMULINK, the corresponding harmonic spectrum is calculated for various SVPWM techniques.

Keywords- Indirect Vector Control (IVC), Space Vector Pulse Width Modulation (SVPWM)

I. INTRODUCTION

The electrical machine that converts electrical energy into mechanical energy, and vice versa, is the workhorse in a drive system. Induction motors have been used for over a century because of their simplicity, ruggedness and efficiency[2]. The asynchronous or induction motor is the most widely used electrical drive. Separately excited dc drives are simpler in control because independent control of flux and torque can be brought about[9]. In contrast, induction motors involve a coordinated control of stator current magnitude and the phase, making it a complex control. The stator flux linkages can be resolved along any frame of reference. This requires the position of the flux linkages at every instant. Then the control of the ac machine is very similar to that of separately excited dc motor. Since this control involves field coordinates it is also called field oriented control (Vector Control)[4]. Depending on the method of measurement, the vector control is divided into two subcategories: direct and indirect vector control. In direct vector control, the flux measurement is done by using the flux sensing coils or the Hall devices. The most common method is indirect vector control. In this method, the flux angle is not measured directly, but is estimated from the equivalent circuit model and from measurements of the rotor speed, the stator current and the voltage [1]. The Main purpose of two level inverter topologies is to provide a three phase voltage source, where the amplitude, phase, and frequency of the voltages should always be controllable[9].

PWM methods, the carrier- based PWM is very popular due to its simplicity of implementation, known harmonic waveform characteristics, and low harmonic distortion[5]. Space vector pulse width modulation (SVPWM) technique is widely used in inverter and rectifier controls [6]. In a space-vector PWM inverter, which is widely used, the voltage utilization factor can be increased to 0.906, normalized to that of the six step operation [7]. The space-vector PWM can be obtained by properly adding a zero-sequence voltage to the original modulation waveform [8]. The motor-control issues are traditionally handled by fixed-gain proportional-integral (PI) and proportional-integral-derivative (PID) controllers.

II. INDUCTION MOTOR MODELLING:

The steady-state model and equivalent circuit are useful for studying the performance of machine in steady state. This implies that all electrical transients are neglected during load changes and stator frequency variations. The dynamic model of IM is derived by using a two-phase motor in direct and quadrature axes, where ds−qs correspond to stator direct and quadrature axes, and dr−qr correspond to rotor direct and quadrature axes[3]. The dynamic analysis and description of revolving field machines is supported by well established theories. An Induction Motor of uniform air gap, with sinusoidal distribution of mmf is considered. The saturation effect and parameter changes are neglected.

The stator and rotor voltage equations in synchronous reference frame as

\[
V_{qs} = R_s i_{qs} + \frac{d}{dt} \psi_{qs} + \omega_e \psi_{ds} \tag{1}
\]

\[
V_{ds} = R_s i_{ds} + \frac{d}{dt} \psi_{ds} - \omega_e \psi_{qs} \tag{2}
\]

\[
V_{qr} = R_r i_{qr} + \frac{d}{dt} \psi_{qr} + (\omega_e - \omega_r) \psi_{dr} \tag{3}
\]

\[
V_{dr} = R_r i_{dr} + \frac{d}{dt} \psi_{dr} - (\omega_e - \omega_r) \psi_{qr} \tag{4}
\]
Where vas, vbs and vcs are the three phase voltages and \( \psi_{d} \) and \( \psi_{q} \) are the q-d axes voltages. These equations are also applicable to the current and flux linkage transformation.

\[
\begin{bmatrix}
 v_{qr}
 v_{dr}
 v_{qs}
\end{bmatrix} =
\begin{bmatrix}
 R + SL & \omega L_s & S L_e & \omega L_m & i_{qr}
 -\omega L_s & R + SL & -\omega L_m & S L_e & i_{dr}
 S L_e & (\omega - \omega) L_s & R + SL & (\omega - \omega) L_m & i_{qr}
\end{bmatrix}
\]

The electromagnetic torque obtained from machine flux linkages and currents is as:

\[
T_e = \frac{3P}{2} (\psi_{d} i_{q} - \psi_{q} i_{d})
\]

Where \( T_e \), \( P \), \( \psi_{d} \), \( \psi_{q} \) are the electromagnetic torque, number of poles, rotor d-q axes fluxes respectively. The electromagnetic dynamic equation describing the mechanical model of the induction motor is given by

\[
J \frac{d\omega_m}{dt} + T_L + B\omega_m = T_e - T_i
\]

Where \( J \), \( T_L \), \( B \), \( \omega_m \) are the moment of inertia of motor and the load torque, the friction coefficient and the mechanical speed. The equations (1) to (8) form the mathematical model equations of a three phase induction motor.

**III. INDIRECT VECTOR CONTROL:**

In the indirect vector control the unit vector signals (Cos \( \theta \) and Sin \( \theta \)) are generated in feed forward manner, indirect vector control is very popular in industrial application. The d-q axes are fixed on the stator, and d-q axes are fixed on the rotor moves at speed \( \omega_i \) as shown.

**Fig. 1. Block diagram of Indirect Vector controlled IM drive**
Synchronously rotating axes $\text{d}^e - \text{q}^e$ is rotating ahead of the $\text{d}^r - \text{q}^r$ axes by the positive slip angle $\theta_{\text{sl}}$ corresponding to slip frequency $\omega_{\text{sl}}$. Since the rotor pole is directed on the $\text{d}^e$ axes and $\omega_e = \omega_r + \omega_{\text{sl}}$ we can write

$$\theta_e = \int \omega_e dt = \int (\omega_r + \omega_{\text{sl}}) dt = \theta_r + \theta_{\text{sl}} \quad (9)$$

![Fig. 2. Phasor diagram explaining indirect vector control](image)

The field component of the stator current

$$i_{ds}^* = \frac{\psi_r^*}{L_m} \quad (10)$$

The torque component of the stator current

$$i_{qs}^* = \left( \frac{2}{3} \right) \left( \frac{2}{P} \right) \left( \frac{L_r}{L_m} \right) \left( \frac{T_e^*}{\psi_r^*} \right) \quad (11)$$

Where $\psi_r = \frac{L_m i_{ds}}{1 + \tau_r s}$

Therefore the slip speed

$$\omega_{\text{sl}} = \frac{L_m i_{\omega}}{\tau_r \psi_r} \quad (12)$$

IV. SPACE VECTOR PULSE WIDTH MODULATION

The SVPWM technique can increase the fundamental component by up to 27.39% that of SPWM. The fundamental voltage can be increased up to a square wave mode where a modulation index of unity is reached. SVPWM is a form of PWM proposed in the mid-1980s that is more efficient compared to natural and regularly sampled PWM. A three-phase mathematical system can be represented by a space vector. For example, given a set of three-phase voltages, a space vector can be defined by

$$V(t) = \frac{3}{2} \left[ V_a(t) e^{0} + V_b(t) e^{\frac{2\pi}{3}} + V_c(t) e^{\frac{4\pi}{3}} \right] \quad (13)$$

Where $V_a(t), V_b(t)$ and $V_c(t)$ are three sinusoidal voltages of the same amplitude and frequency but with $+120^\circ$ phase shifts.
In the space vector modulation, a three phase two level inverter can be driven to eight switching states where the inverter has six active states (1-6) and two zero states (0 and 7). The basic principle of SVPWM is based on the eight switch combinations of a three phase inverter. Each switching circuit generates three independent pole voltage $V_{a0}$, $V_{b0}$, and $V_{c0}$, which are the inverter output voltages with respect to the mid-terminal of the DC source marked as ‘O’ on the same figure.

These voltages are also called pole voltages. The pole voltages that can be produced are either $\frac{V_{dc}}{2}$ or $-\frac{V_{dc}}{2}$. For example, when switches $S_1$, $S_6$, $S_2$ are closed, corresponding pole voltages are $V_{a0} = \frac{V_{dc}}{2}$, $V_{b0} = -\frac{V_{dc}}{2}$, and $V_{c0} = -\frac{V_{dc}}{2}$. This state is denoted as (1,0,0) and, according to equation (3.1), may be depicted as the space vector $V(t) = \frac{3}{2} [V_{dc} \, e^{j0}]$. Repeating the same procedure, we can find the remaining active non-active states.

The three-phase inverter is therefore controlled by six switches and eight inverter configurations. The eight inverter states can transformed into eight corresponding space vectors. In each configuration, the vector identification uses a ‘O’ to represent the negative phase voltage level and a ‘1’ to represent the positive phase voltage level.

The relationship between the space vector and the corresponding switches states is given in Table 3.1 and figure 3.7. In addition, the switches in one inverter branch are in controlled in a complementary fashion (1 if the switch is on and 0 if it is off). Therefore,

\begin{align*}
S_1+S_4 &= 1 \\
S_3+S_6 &= 1 \\
S_5+S_2 &= 1
\end{align*}

We use orthogonal coordinates to represent the three-phase two-level inverter in the phase diagram. There are eight possible inverter states that can generate eight space vectors. These are given by the complex vector expressions

\begin{equation}
V_k = \begin{cases} 
\frac{2}{3} V_{dc} e^{j(k-1)\pi/3} & \text{if } k = 1,2,3,4,5,6 \\
0 & \text{if } k = 0,7.
\end{cases}
\end{equation} 

(14)

Fig.3. Space Vectors of 3-phase bridge inverter
**A. MODULATION INDEX**

From a Fourier analysis, the fundamental voltage magnitude is given by

$$V_{\text{max-sixstep}} = \frac{2V_{dc}}{\pi}$$  \hspace{1cm} (15)

The ratio between the reference vector $V_{\text{ref}}$ and the fundamental peak value of the square phase voltage wave ($2V_{dc}/\pi$) is called the modulation index. The mode of operation is determined by the modulation index `MI`. In this linear region, the MI can be expressed as

$$MI = \frac{V_{\text{ref}}}{V_{\text{max-sixstep}}}$$  \hspace{1cm} (16)

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. 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 4.4 is shown for the upper and lower switches.

| Sector | Upper Switches: S1,S3,S5 | Lower Switches S4,S6,S2 |
|--------|--------------------------|-------------------------|
| 1      | $S_1 = T_a + T_b + \frac{T_0}{2}$, $S_1 = T_a + \frac{T_0}{2}$ | $S_4 = \frac{T_0}{2}$, $S_6 = T_a + \frac{T_0}{2}$, $S_2 = T_a + T_5 + \frac{T_0}{2}$ |
| 2      | $S_1 = T_a + \frac{T_0}{2}$, $S_4 = T_a + T_5 + \frac{T_0}{2}$, $S_6 = T_a + \frac{T_0}{2}$, $S_2 = T_a + T_5 + \frac{T_0}{2}$ |
| 3      | $S_1 = T_a + \frac{T_0}{2}$, $S_4 = T_a + T_5 + \frac{T_0}{2}$, $S_6 = T_a + \frac{T_0}{2}$, $S_2 = T_a + T_5 + \frac{T_0}{2}$ |
| 4      | $S_1 = T_a + \frac{T_0}{2}$, $S_4 = T_a + T_5 + \frac{T_0}{2}$, $S_6 = T_a + \frac{T_0}{2}$, $S_2 = T_a + T_5 + \frac{T_0}{2}$ |
| 5      | $S_1 = T_a + \frac{T_0}{2}$, $S_4 = T_a + T_5 + \frac{T_0}{2}$, $S_6 = T_a + \frac{T_0}{2}$, $S_2 = T_a + T_5 + \frac{T_0}{2}$ |
| 6      | $S_1 = T_a + \frac{T_0}{2}$, $S_4 = T_a + T_5 + \frac{T_0}{2}$, $S_6 = T_a + \frac{T_0}{2}$, $S_2 = T_a + T_5 + \frac{T_0}{2}$ |

*Discontinuous SVPWM:*  
CPWM suffers from the drawbacks like computational burden and inferior performance at high modulation indices. Moreover, continuous PWM (CPWM) method the switching losses of the inverter are also high. Hence to reduce the switching losses and to improve the performance in high modulation region several discontinuous PWM (DPWM) methods have been reported.
\[
T_{as} = \left( \frac{T_s}{V_{dc}} \right) V_a
\]

(17)

\[
T_{bs} = \left( \frac{T_s}{V_{dc}} \right) V_b
\]

(18)

\[
T_{cs} = \left( \frac{T_s}{V_{dc}} \right) V_c
\]

(19)

Where \( T_s \) is the sampling period and \( V_{dc} \) is the dc link voltage. \( V_a, V_b, V_c \) are the phase voltages. The active vector switching times \( T_1 \) and \( T_2 \) may be expressed as

\[
T_1 = T_{max} - T_s
\]

(20)

\[
T_2 = T_s - T_{min}
\]

(21)

Where \( T_s \in (T_{as}, T_{bs}, T_{cs}) \) and is neither maximum nor minimum switching time. The effective time is the duration in which the reference voltage vector lies in the corresponding active states, and is the difference between the maximum and minimum switching times as given

\[
T_{eff} = T_1 + T_2
\]

(22)

\[
T_0 = T_s - T_{eff}
\]

(23)

In the proposed method the zero state time will be divided between two zero states as \( T_0 \mu \) for \( V_0 \) and \( T_0 (1-\mu) \) for \( V_7 \) respectively, where \( \mu \) lies between 0 and 1. The \( \mu \) can be defined as

\[
\mu = 1 - 0.5(1 + \text{sgn} (\cos(\omega t + \delta)))
\]

where \( \omega \) is the angular frequency of the reference voltage, \( \text{sgn}(y) \) is the sign function, \( \text{sgn}(y) \) is 1, 0, and -1 when \( y \) is positive, zero and negative respectively. The modulation phase angle is represented by \( \delta \). When \( \mu = 1 \) any one of the phases is clamped to the positive bus for 120 degrees and when \( \mu = 0 \) any one of the phases is clamped to the negative bus for 120 degrees. When \( \mu = 0 \) and \( \mu = 1 \), DPWMMAX and DPWMMIN are obtained respectively and \( \mu = 0.5 \) results CPWM.

V. SIMULATION RESULTS:

Indirect Vector controlled IM drive is implemented in MATLAB SIMULINK. It consists of Induction motor, Indirect vector Control and SVPWM blocks. Induction motor is supplied from the Variable Voltage and Variable Frequency 3-phase Voltage Source Inverter. Inverter switching Pattern is done with the help Space Vector Pulse Width Modulation Technique. Induction Motor Output Rotor Speed is taken as a Feedback signal and given to indirect vector control. Indirect Vector Control generates the 3-phase voltages to the Space Vector PWM. SVPWM generates Pulses to the Inverter.
Fig. 4. Current Response for PI (t=0.7)

Fig shows the performance characteristic of a 1.5KW, 400 V, 4 poles, 50 Hz Induction Motor, operating with a PI speed controller. Steady state region reaches at 0.07sec, currents are 2Amp. Load is applied at 0.7 sec corresponding stator currents are shown in fig 5.4.

Fig. 5. Speed Response for PI (t=0.7)

The machine is initially at stand still at no load. The reference speed is linearly increased from zero to 157.5 rps. Simulation were carried out on PI controller on the indirect vector control of induction motor. Load is applied at 0.7 sec. so that, the motor speed is decreases to 147.5 rps.

MODULATED WAVE & POLE & PHASE AND LINE VOLTAGES OF AN INVERTER USING CSVPWM:

Fig. 6. Modulated wave & Pole & Phase and Line Voltages of an Inverter using CSVPWM

Inverter DC input Voltage Vd is 390V, pulses to the 2-level inverter are applied using continuous SVPWM technique, so that the pole voltage (Va0) is (Vd/2) = 195V; Phase Voltages (Van) are (Vd/3) & (2Vd/3) the values are 130V & 260V; Line Voltage (Vab) is (Vd) = 390V;

Total Harmonic Distortion:
Total harmonic distortion of Induction motor stator currents are calculated for a indirect vector controlled Induction Motor drive fed from the CSVPWM based inverter. The Fundamental frequency is 33.33Hz and total harmonic distortion is 19.15%.

**Modulated wave & Pole & Phase and Line Voltages of an Inverter using DPWMMAX**

Inverter DC input Voltage Vd is 390V, pulses to the 2-level inverter are applied using discontinuous maximum clamping SVPWM technique, so that one of the phases is clamped to the positive bus for 120 degrees and the Pole Voltage (Va0) is \( \frac{Vd}{2} = 195V \); Phase Voltages (Van) are \( \frac{Vd}{3} \) & \( \frac{2Vd}{3} \) the values are 130V & 260V; Line Voltage (Vab) is \( Vd = 390V \);

| SVPWM Technique                  | Fundamental Voltage (V) | Current THD’s (%) | Voltage THD’s (%) |
|----------------------------------|-------------------------|-------------------|-------------------|
| Continuous                       | 191                     | 19.15             | 34.92             |
| Discontinuous (max clamping)     | 176.33                  | 13.62             | 28.93             |
| Discontinuous (min clamping)     | 172.2                   | 13.58             | 26.90             |

Total harmonic distortion of an induction motor stator currents are calculated for a indirect vector controlled Induction Motor drive fed from the DPWMMAX based inverter. The Fundamental frequency is 33.33Hz and total harmonic distortion is 13.62%.

**Modulated wave & Pole & Phase and Line Voltages of an Inverter using DPWMMIN.**

**Fig.7. THD of Currents for CSVPWM**

**Fig.8. Modulated wave & Pole & Phase and Line Voltages of an Inverter using DPWMMAX**

**Fig.9. THD of Currents for DPWMMAX.**
Inverter DC input Voltage Vd is 390V, pulses to the 2-level inverter are applied using discontinuous minimum clamping SVPWM technique, so that one of the phases is clamped to the negative bus for 120 degrees and the Pole Voltage (Va0) is (Vd/2) = 195V; Phase Voltages (Van) are (Vd/3) & (2Vd/3) the values are 130V & 260V; Line Voltage (Vab) is (Vd) = 390V;

**Total Harmonic Distortion**

![THD of Currents for DPWMMIN](image)

Total harmonic distortion of an induction motor stator currents are calculated for a indirect vector controlled Induction Motor drive fed from the DPWMMIN based inverter. The Fundamental frequency is 33.33Hz and total harmonic distortion is 13.58%.

**Comparison of THD’s for different techniques:**

In above table THD values of the currents and output phase voltages are observed and compared for continuous and discontinuous techniques of SVPWM. From these results, it is proved that the better performance can be obtained by using DSVPWM than the CSVPWM.

**V. Conclusion and Future Scope**

In this work, indirect vector controlled induction motor drive fed from two-level 3-phase Space Vector PWM is implemented. Estimating the rotor flux and the magnetizing current in a synchronously rotating reference frame. SVPWM Technique has been described and applied to the two-level 3-phase voltage source inverter, fed indirect vector controlled induction motor drive. SVPWM uses the dc bus voltage than SPWM. In CPWM technique the switching losses of the inverter are high, compare to the DPWM technique. In DPWMMAX technique 120° interval in the positive half cycle of the output voltage, DPWMMIN technique 120° interval in the negative half cycle of the output voltage. In this proposed work, Indirect vector controlled induction motor drive using different Space Vector PWM techniques are implemented in MATLAB simulink, and the corresponding harmonic spectrum is calculated for various SVPWM techniques.

In this work Indirect Vector Controlled IM drive fed with 2-level SVPWM inverter is implemented. The same work can be extended to multilevel inverters using for different hybrid PWM techniques using dspace kit.

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