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Space Vector Pulse Width Modulation Based Indirect Vector Control of Induction Motor Drive

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Abstract

This paper presents the implementation of a different SPACE VECTOR PWM techniques 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. This paper presents the 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 PWM techniques and the results are compared.

Keywords: Indirect vector control; Space vector pulse width modulation; DPWM; Induction motor

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 [1]. 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 [2]. 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) [1,2]. 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 [2].

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 [3]. PWM methods, the carrier-based PWM is very popular due to its simplicity of implementation, known harmonic waveform characteristics, and low harmonic distortion [3]. Space vector pulse width modulation (SVPWM) technique is widely used in inverter and rectifier controls [4,5]. 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 [6]. In the conventional Space Vector PWM technique complexity is involved due to sector identification and angle calculation. To reduce this complexity various discontinuous algorithms are proposed [5,6].

This paper presents the different Space Vector PWM techniques, which can be applied to the three phase VSI fed indirect vector controlled induction motor (IM) drive. The performance of the Induction Motor (IM) is analyzed in steady state and transient conditions.

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 [7].

The stator and rotor voltage equations in synchronous reference frame as:

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

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

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

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr} \tag{4}$$

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Where vas, vbs and vcs are the three phase voltages and v_{qs}^{s} v_{qs}^{s} v_{ds}^{s}, are the q-d axes voltages. These equations are also applicable to the current and flux linkage transformation.

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

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{dr} i_{qr} - \psi_{qr} i_{dr}) \tag{5}$$

Where Te, P, Ψdr, Ψqr 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

$$T_e = J\frac{d\omega_m}{dt} + T_L + B\omega_m \tag{6}$$

$$\omega_m = \int (T_e - T_L)\frac{P}{2J}dt \tag{7}$$

Where J, T_L, B, ω_m are the moment of inertia of motor and the load torque, the friction coefficient and the mechanical speed. The equations (1) to (7) form the mathematical model equations of a three phase induction motor.

Indirect Vector Control

In the indirect vector control the unit vector signals (Cos θ_ε and Sin θ_ε) are generated in feed forward manner, indirect vector control is very popular in industrial application. The $d^s - q^s$ axes are fixed on the stator, and $d^r - q^r$ axes are fixed on the rotor moves at speed ù $_r$ as shown in Figure 1.

Synchronously rotating axes $d^e - q^e$ is rotating ahead of the $d^r - q^r$ axes by the positive slip angle θ_{sl} corresponding to slip frequency ω_{sl}. Since the rotor pole is directed on the d_e axes and $\omega_e = \omega_r + \omega_{sl}$ we can write

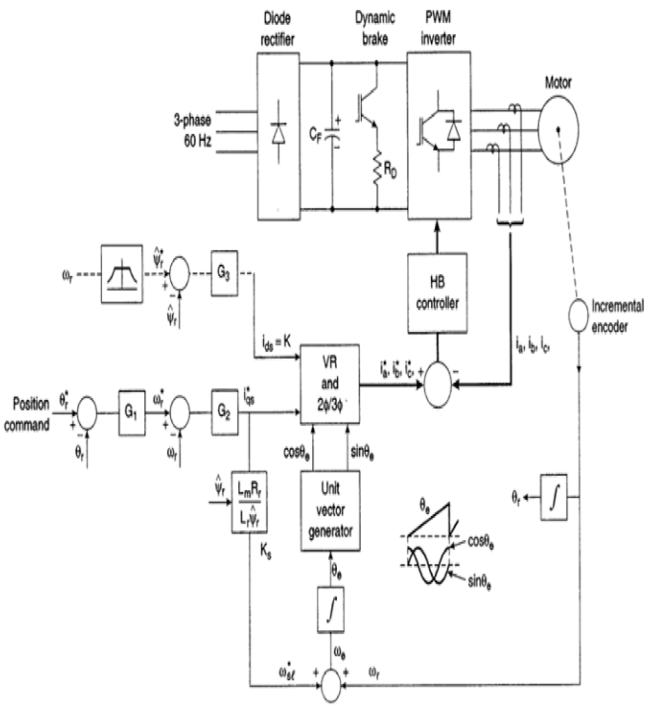

Figure 1: Block diagram of Indirect Vector controlled IM drive.

$$\theta_e = \int \omega_e dt = \int (\omega_r + \omega_{s1})dt = \theta_r + \theta_{s1} \tag{8}$$

The field component of the stator current

$$\hat{\psi}_r = \frac{L_m i_{qs}^*}{(1+\tau_r s)} \quad i_{ds}^* = \frac{\hat{\psi}_r}{L_m} \tag{9}$$

The torque component of the stator current

$$i_{qs}^* = \left(\frac{2}{3}\right)\left(\frac{2}{P}\right)\left(\frac{L_r}{L_m}\right)\left(\frac{T_e^*}{\hat{\psi}_r}\right) \tag{10}$$

Where, $\hat{\psi}_r = \dfrac{L_m i_{qs}^*}{(1+\tau_r s)}$

Therefore the slip speed

$$\omega_{sl}^* = \left(\frac{L_m i_{qs}^*}{\tau_r \hat{\psi}_r}\right) \tag{11}$$

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 three-phase mathematical system can be represented by a space space vector. For example, given a set of three-phase voltages, space vector can defined by

$$V(t) = \frac{3}{2}\left[V_a(t)e^{j0} + V_b(t)e^{j\frac{2}{3}} + V_c(t)e^{j\frac{4}{3}}\right] \tag{12}$$

Where $V_a(t), V_b(t)$ and $V_c(t)$ are three sinusoidal voltages of the same amplitude and frequency but with +1200 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 2. 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 $V_{a0} = \frac{V_d}{2}$, $V_{b0} = -\frac{V_d}{2}$, and $V_{c0} = -\frac{V_d}{2}$. This state is denoted as (1,0,0) and, according to equation (12), 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 1 and Figure 3. In addition, the switches in one inverter branch are in controlled in a complementary fashion (1

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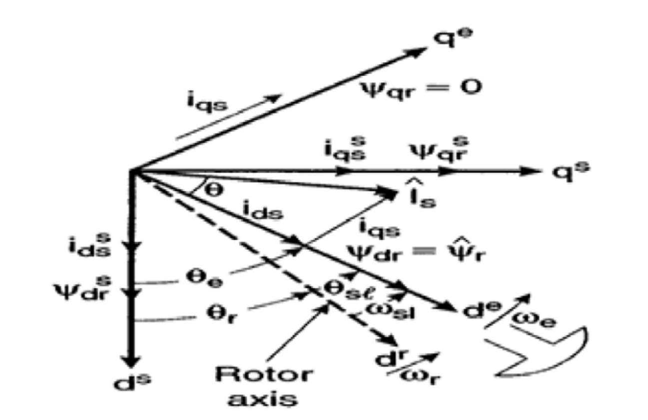

Figure 2: Phasor diagram explaining indirect vector control The field component of the stator current.

Sector	Upper Switches: S1,S3,S5	Lower Switches S4,S6,S2
1	$S_1 = T_a + T_b + \frac{T_0}{2}$ $S_3 = T_b + \frac{T_0}{2}$ $S_5 = \frac{T_0}{2}$	$S_4 = \frac{T_0}{2}$ $S_6 = T_a + \frac{T_0}{2}$ $S_2 = T_a + T_b + \frac{T_0}{2}$
2	$S_1 = T_a + \frac{T_0}{2}$ $S_3 = T_a + T_b + \frac{T_0}{2}$ $S_5 = \frac{T_0}{2}$	$S_4 = T_b + \frac{T_0}{2}$ $S_6 = \frac{T_0}{2}$ $S_2 = T_a + T_b + \frac{T_0}{2}$
3	$S_1 = \frac{T_0}{2}$ $S_3 = T_a + T_b + \frac{T_0}{2}$ $S_5 = T_b + \frac{T_0}{2}$	$S_4 = T_a + T_b + \frac{T_0}{2}$ $S_6 = \frac{T_0}{2}$ $S_2 = T_a + \frac{T_0}{2}$
4	$S_1 = \frac{T_0}{2}$ $S_3 = T_a + \frac{T_0}{2}$ $S_5 = T_a + T_b + \frac{T_0}{2}$	$S_4 = T_a + T_b + \frac{T_0}{2}$ $S_6 = T_b + \frac{T_0}{2}$ $S_2 = \frac{T_0}{2}$
5	$S_1 = T_b + \frac{T_0}{2}$ $S_3 = \frac{T_0}{2}$ $S_5 = T_a + T_b + \frac{T_0}{2}$	$S_4 = T_a + \frac{T_0}{2}$ $S_6 = T_a + T_b + \frac{T_0}{2}$ $S_2 = \frac{T_0}{2}$
6	$S_1 = T_a + T_b + \frac{T_0}{2}$ $S_3 = \frac{T_0}{2}$ $S_5 = T_a + \frac{T_0}{2}$	$S_4 = \frac{T_0}{2}$ $S_6 = T_a + T_b + \frac{T_0}{2}$ $S_2 = T_b + \frac{T_0}{2}$

Table 1: Comparision of %THD of different PWM sequences.

if the switch is on and 0 if it is off). Therefore,

$$S_1 + S_4 = 1$$
$$S_3 + S_6 = 1$$
$$S_5 + S_2 = 1$$

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 as

$$V_k = \{2/3V_{dr}e(k-1)\frac{\pi}{3} \quad \text{if k=1,2,3,4}$$
$$= 0 \quad \text{if k=0,7}$$

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 1 is shown for the upper and lower switches.

Proposed Discontinuous SVPWM Technique

Continuous PWM (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. It uses the concept of imaginary switching times. The imaginary switching time periods are proportional to the instantaneous values of the reference phase voltages are defined as

$$T_a = \left(\frac{T_s}{V_d}\right)V_a \tag{14}$$

$$T_b = \left(\frac{T_s}{V_d}\right)V_b \tag{15}$$

$$T_c = \left(\frac{T_s}{V_d}\right)V_c \tag{16}$$

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

$$T_2 = T_x - T_{\min} \tag{17}$$

$$T_2 = T_x - T_{\min} \tag{18}$$

Where $T_x \in (T_{as}, T_{bs}, T_{cs})$ 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

$$T_{eff} = T_1 + T_2 \tag{19}$$

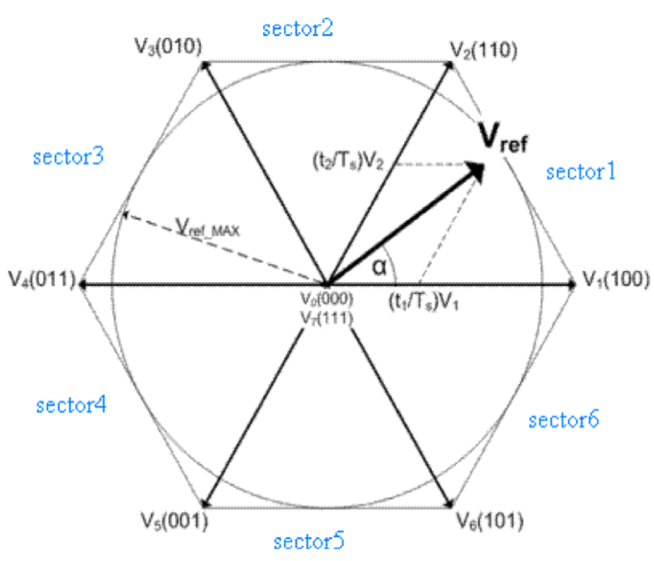

Figure 3: Space Vectors of 3-phase bridge inverter.

$$T_0 = T_s - T_{eff} \tag{20}$$

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-μ) for V_7 respectively, where μ lies between 0 and 1. The μ can be defined as μ = 1-0.5(1 + sg n (cos3(ωt + δ)) where ω is the angular frequency of the reference voltage, sgn(y) is the sign function, sgn(y) is 1, 0.0 and -1 when y is positive, zero and negative respectively. The modulation phase angle is represented by δ. When μ = 1 any one of the phases is clamped to the positive bus for 120 degrees and when and μ = 0 any one of the phases is clamped to the negative bus for 120 degrees. When μ=0 and μ=1, DPWMMAX and DPWMMIN are obtained respectively and μ=0.5 results CPWM.

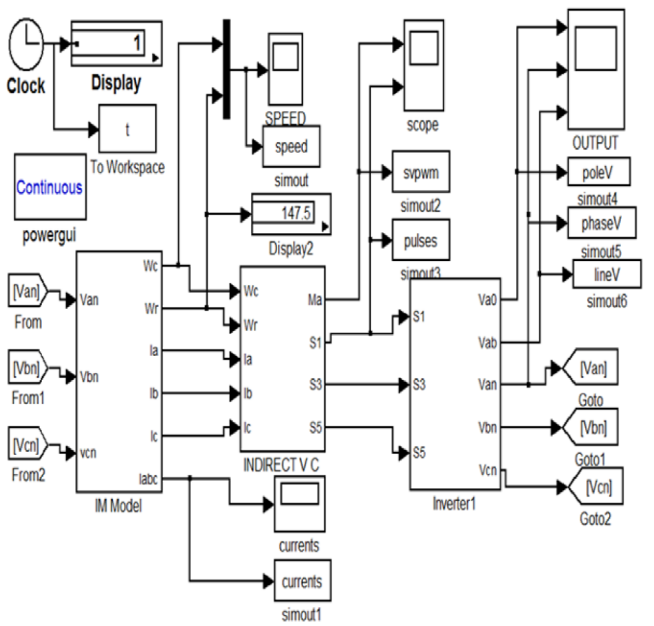

Figure 4: Simulation block diagramof indirect vector controlled IM drive.

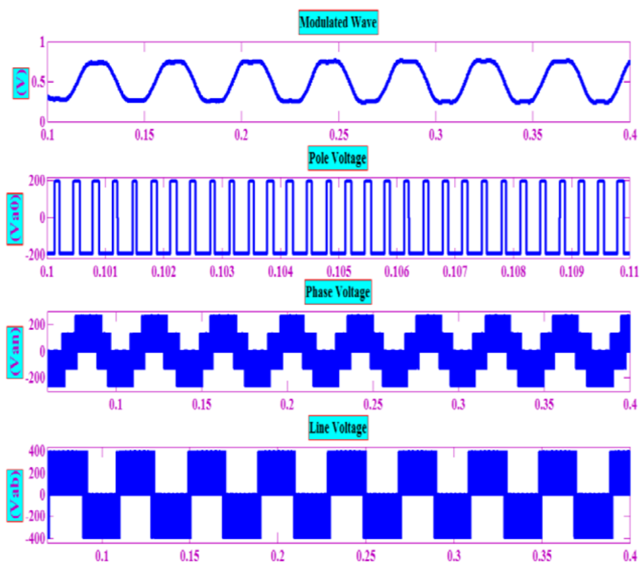

Figure 5: Modulated wave andf Pole and Phase and Line Voltages of an Inverter using CSVPWM.

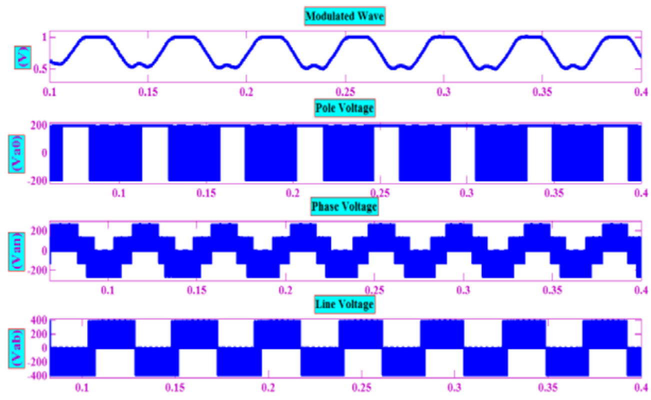

Figure 6: Modulated wave and Pole and Phase and Line Voltages of an Inverter using DPWMMAX.

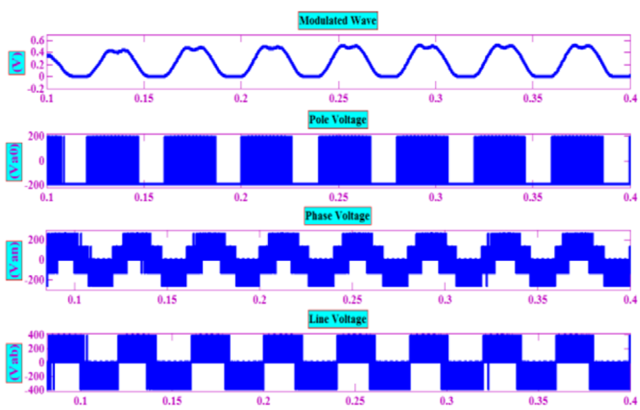

Figure 7: Modulated wave and Pole and Phase and Line Voltages of an Inverter using DPWMMIN.

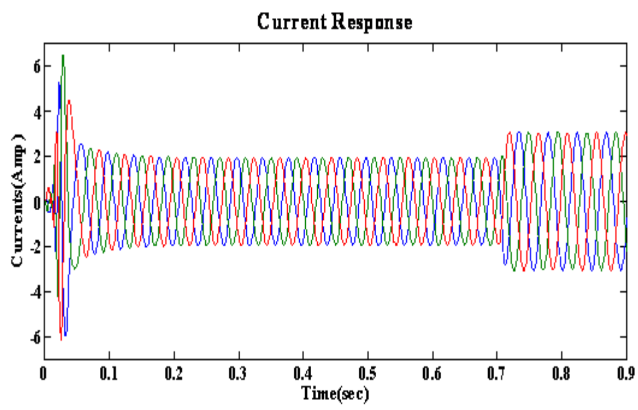

Figure 8: Stator current response of an induction motor under loaded conditions.

Simulation Results

To validate Space Vector Based indirect vector controlled induction motor drive. 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.

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)	175.2	13.83	27.90

Table 2: Switching sequence.

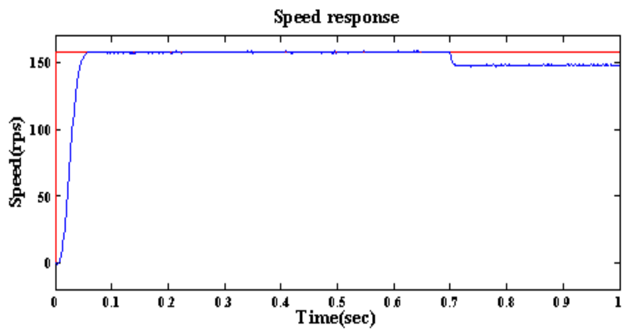

Figure 9: Speed response of an induction motor under loaded conditions.

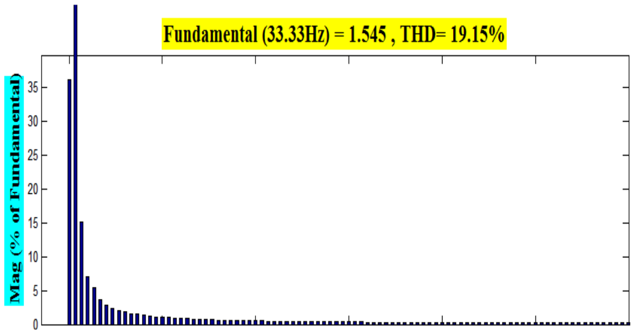

Figure 10: Stator current THD using CSVPWM Technique.

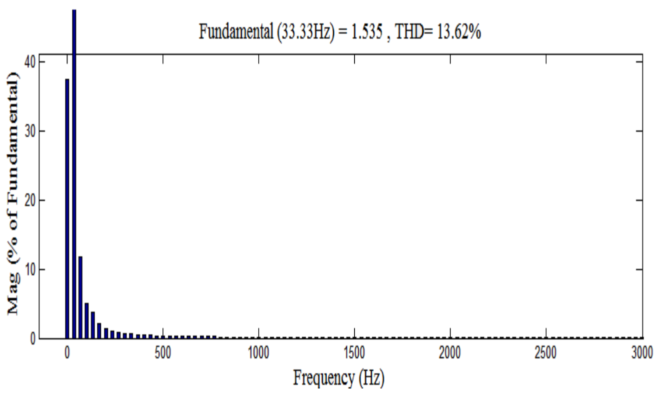

Figure 11: Stator current THD using DPWMAX Technique.

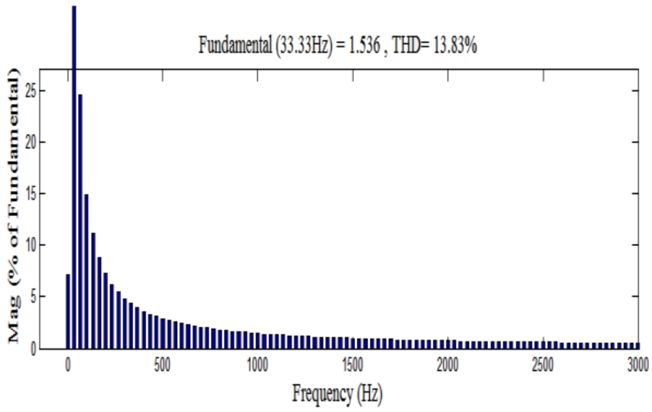

Figure 12: Stator current THD using DPWMIN Technique.

The induction motor used in this case study is a 4 KW, 1440 rpm, 4-pole, 3-phase and the corresponding modula-ting, pole voltage, phase and line voltages are shown in Figures 4-8.

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

The figure shows that the stator current response of an IM, it reaches the Steady state reaches at 0.07 sec, currents are 2 Amp and the load torque of 2.5 N-M applied at 0.7 sec.

From the speed response the IM attains steady state at 0.07 sec and the speed is nearly at its rated speed i.e. 150 rad/sec.

Until load is applied at 0.7 sec (Figures 9-12).

Conclusion

In This work, indirect vector controlled induction motor drive fed from two-level 3-phase Space Vector PWM inverter is implemented. SVPWM uses the dc bus voltage than SPWM. In Continuous PWM (CPWM) technique the switching losses of the inverter are high. To reduce the switching loss and complexity in CPWM technique DPWM techniques are implemented. The modulating waveforms of different DPWM sequences are obtained based on their clamping sequences. In DPWMMAX method, the clamping of 120° takes place at the middle of 0°-180° for every 360° of fundamental voltage. In DPWMMAX method the clamping of 120° takes place at the middle of 180°–360° for every 360° of fundamental voltage. The corresponding harmonic spectrum is calculated and tabulated for various PWM techniques. Therefore, switching losses of the inverter are reduced greatly using DPWM techniques over CPWM.

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