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Speed Control of Three-Phase Induction Motor Drive Using V/f Control of Space Vector Modulation Inverter

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Abstract : **Induction motors are not inherently having the capability of variable speed operation but they are reliable, robustness and have cheaper cost. However the main field of research in induction motor speed controlling methods is intended for implementing electrical drives in large scale application. Most of the electrical drives used in industry the closed loop constant V/f speed control method. This paper discusses the complete scheme of applying V/f control by using the space vector modulation (SVM) fed to two-level inverter. In this paper, SVM inverters and induction motor drive have been modeled in Matlab environment. The developed industrial IM drive system MATLAB simulation of V/f speed control of SVM inverter fed 3-phase induction motor is successfully implement. The comparative analysis of IM drive torque is presented on the basis of applying various rotor speeds. It is observed that by using a proportional controller with closed-loop controlling scheme provided efficient way of induction motor speed control as well as maintaining a maximum torque in limit.**

Keywords — IM-Induction motor; SVM-Space Vector Modulation

I. INTRODUCTION

Mechanical energy is required in day to day life as well as in industrial drives. From the last few decades DC machines were used broadly in industrial due to advantageous operation such as high ease of control, starting torque, and efficient performance. However due to some drawbacks such as presence of mechanical commutator and brush in DC machine these drives have turn out to be obsolete today in industrial applications[1][2][3].

Now a day's induction motors mostly used in all industrial operations, because they have the cheaper cost, robustness, the better performance and the simplicity of maintenance make the induction motor advantageous in many industrial applications. There are two induction motors types that are the squirrel-cage design and wounded rotor both of them are in well-known use. The squirrel cage induction motors (SCIM) are more superior and widely used than all the rest of the electric motors. Without a proper control scheme induction motors are making more loss or we can say consuming large energies and having high operating costs. High frequency controlled by microcontrollers switching based power converters is the best efficient for industrial speed controlling of induction motor drive (IMD), the frequency, phase and magnitude are the main constraint of the input side of IM drive to change the motor speed and torque efficiently. Numerical electronics and power electronics makes it possible to deal with low power applications and variable speed of IM drive. [2][3][4]

The IM drive speed affected mainly by the applied frequency and the way of facilitating the speed control. The inverter is fed by using space vector Modulation (SVM) technique for efficient controlling desired V/f ratio. Mathematical dynamic models of SVM and IM drive are designed for better behavior understanding of drive system in both region transient and steady state. Mathematical dynamic modelling considered all characteristics equations such as the torque, inertia, speed versus time, currents, differential voltage, and flux linkages corresponding to stationary stator and moving rotor. The Mathematical dynamic model represents the three phase IM drive with a three phase to d-q axis transformations. [5][6][23].

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Figure 1. General classification of induction motor control methods

II. Dynamic Model of Induction Motor

The stator of IM drive having balanced three phase distributed windings separated 120 degrees in space. The rotating three phase magnetic field is created when current flowing in through the stator windings. The IM drive dynamic behavior is considered and managed by adjusting the speed of drive system with the help of power electronics converter.[8][9] A feedback loop is taken into account for this action of coupling effect of the rotor and stator windings, due to varying coupling coefficient along with rotor position [10][11]. Thus the set of differential equations with time varying coefficients is needed for correct representation of the IM drive model. [2][3]

A. Motor dynamic model in stationary frame

IM stationary frame equations are given by Stanley by substituting $\omega_e = 0$. The stator circuit equations (1 to 4) are written as:-

$$v_{qs}^{s} = R_s i_{qs}^{s} + \frac{d}{dt}\psi_{qs}^{s} \quad (1)$$

$$v_{ds}^{s} = R_s i_{ds}^{s} + \frac{d}{dt}\psi_{ds}^{s} \quad (2)$$

$$0 = R_r i_{qr}^{s} + \frac{d}{dt}\psi_{qr}^{s} - \omega_r \psi_{dr}^{s} \quad (3)$$

$$0 = R_r i_{dr}^{s} + \frac{d}{dt}\psi_{dr}^{s} + \omega_r \psi_{qr}^{s} \quad (4)$$

Where

ψ_{qs}^{s}, ψ_{ds}^{s} = q-axis and d-axis stator flux linkages

ψ_{qr}^{s}, ψ_{qr}^{s} = q-axis and d-axis rotor flux linkages

R_s, R_r = stator and rotor resistances

ω_r = rotor speed and vdr = vqr = 0

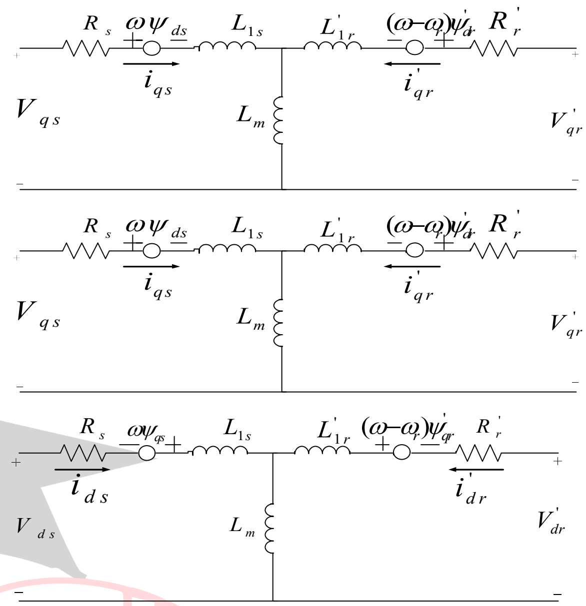

Figure 2. ds-qs equivalent circuits

Electromagnetic torque is generated by rotor mmf and air gap flux interaction which can be expressed in general vector form (5) as [4]

$$T_e = \frac{3}{2}\frac{P}{2}(\bar{\psi}_m) * (\bar{I}_r) \quad (5)$$

Stationary frame the torque equations (6 to 10) is written with corresponding variables as

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{dm}^{s} i_{qr}^{s} - \psi_{qm}^{s} i_{dr}^{s}) \quad (6)$$

$$= \frac{3}{2}\frac{P}{2}(\psi_{dm}^{s} i_{qs}^{s} - \psi_{qm}^{s} i_{ds}^{s}) \quad (7)$$

$$= \frac{3}{2}\frac{P}{2}(\psi_{ds}^{s} i_{qs}^{s} - \psi_{qs}^{s} i_{ds}^{s}) \quad (8)$$

$$= \frac{3}{2}\frac{P}{2}L_m(i_{dr}^{s} i_{qs}^{s} - i_{qr}^{s} i_{ds}^{s}) \quad (9)$$

$$= \frac{3}{2}\frac{P}{2}(\psi_{dr}^{s} i_{qr}^{s} - \psi_{qr}^{s} i_{dr}^{s}) \quad (10)$$

III. Space Vector Modulation

The PWM drives is advantageous for producing the switching pulses for power electronics converters and have higher efficiency, good power factor and relatively lesser regulation problems. It has the ability to operate with IM drive with nearly sinusoidal current. Now for the closed loop implementation of a controlling AC drive Space

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Vector PWM (SVM) is generally used [12-15] [22]. This paper discussing the modelling of SVM it generates voltage vector that produced a field synchronous with rotating voltage vector by different switching pattern of inverter. SVM have advantages over simple PWM method such as having better DC link voltage utilization and lower current ripple. The SVM has a 15% higher voltage utilization ratio comparison to SPWM.

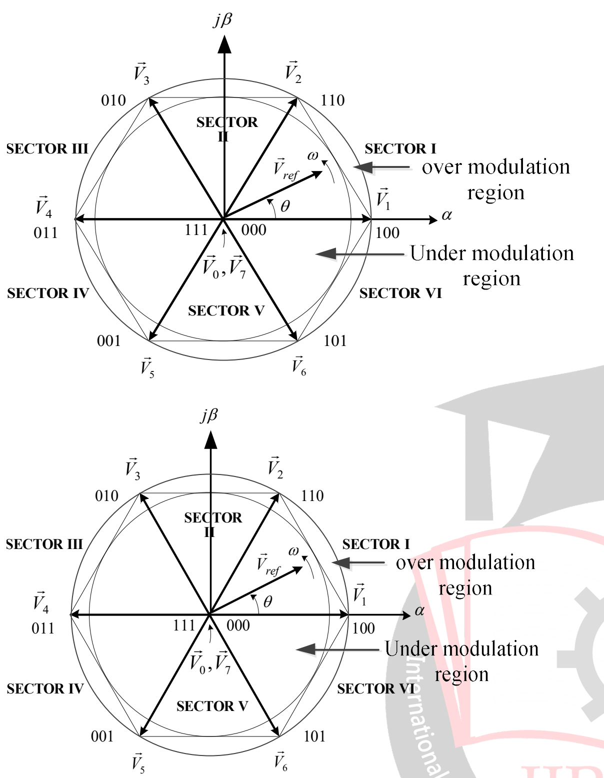

Figure 3. Space voltage vectors in different sectors

A three-phase system can be described by mathematical equations as for a space vector, given a set of three-phase voltages; a space vector can be defined by (11)

$$\vec{V}(\mathrm{t}) = \frac{2}{3}[V_a(\mathrm{t})\mathrm{e}^{j0} + V_b(\mathrm{t})\mathrm{e}^{j\frac{2\Pi}{3}} + V_c(\mathrm{t})\mathrm{e}^{j\frac{4\Pi}{3}}] \tag{11}$$

With Clark's transformation vector magnitude and angle can be calculated.

$$\vec{V}_{ref} = V_\alpha + jV_\beta = \frac{2}{3}\left(V_a + aV_b + a^2V_c\right) \tag{12}$$

Where

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

The reference vector voltage magnitude and its angle are:

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

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

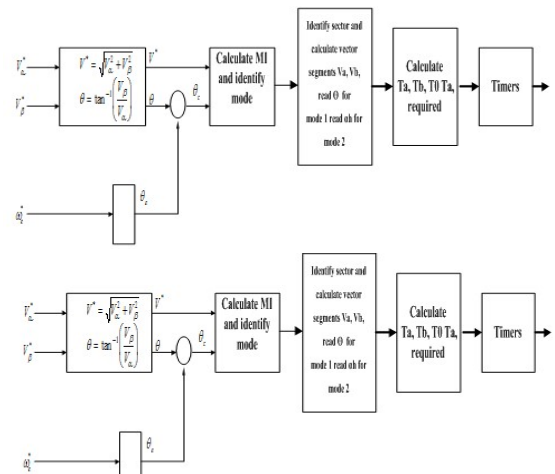

Figure 4. Flow diagram of SVM implementation

The modulation index is the Phase voltage wave (2Vdc/π) that describes the mode of operation. In this linear region, the MI is shown as:

$$MI = \frac{\vec{V}_{ref}}{V_{\max - sixstep}} \tag{13}$$

The maximum value of the MI is obtained when Vref equals the radius of the inscribed circle

$$\vec{V}_{ref\,(\max)} = \frac{2}{3}V_{dc}\cos\left(\frac{\pi}{6}\right) \tag{14}$$

$$MI_{\max} = \frac{\frac{2}{3}V_{dc}\cos(\pi/6)}{\frac{2V_{dc}}{\pi}} = 0.907 \tag{15}$$

$$\int_0^{\frac{T_s}{2}} \vec{V}_{ref}\,dt = \int_0^{\frac{T_0}{4}} \vec{V}_0\,dt + \int_{\frac{T_0}{4}}^{\frac{T_0}{4}+T_a} \vec{V}_k\,dt + \int_{\frac{T_0}{4}+T_a}^{\frac{T_0}{4}+T_a+T_b} \vec{V}_{k+1}\,dt + \int_{\frac{T_0}{4}+T_a+T_b}^{\frac{T_s}{2}} \vec{V}_7\,dt \tag{16}$$

$$\vec{V}_{ref} = V_\alpha + jV_\beta,\ \vec{V}_{ref} = V_\alpha + jV_\beta,$$

$$\begin{bmatrix} T_a \\ T_b \end{bmatrix} = \frac{\sqrt{3}T_s\left|\vec{V}_{ref}\right|}{2V_{dc}} \begin{bmatrix} \sin\frac{k\pi}{3} & -\cos\frac{k\pi}{3} \\ -\sin\frac{(\mathrm{k}-1)\pi}{3} & \cos\frac{(k-1)\pi}{3} \end{bmatrix} \begin{bmatrix} \mathrm{cosn}\,\omega T_s \\ \mathrm{sinn}\,\omega T_s \end{bmatrix} \tag{17}$$

Since the sum of 2Ta and 2Tb should be less than or equal to Ts, the inverter has to stay in a zero state for the rest of the period [4]. The duration of the null vectors is the remaining time in the switching period. Since

$$T_s = T_0 + 2(\mathrm{T}_a + \mathrm{T}_b) \tag{18}$$

Then the time interval for the zero voltage vectors is

$$T_0 = T_s - 2(\mathrm{T}_a + \mathrm{T}_b) \tag{19}$$

The calculated values of Ta and Tb in term of Ts/Vdc for all six sectors, the time durations of two adjacent nonzero vectors in each sector are calculated. [6][22]

A. Speed Control of Induction Motor

The speed of IM drive frequently needs to vary according operation speed of load. Electric motors and

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coupling combinations are implemented for varying the speed as either a “Torque Source” or "Speed Source". The load is driven at a constant speed free from the load torque known as a speed source. While the torque source is the one where the constant torque is provided to a driven load and thus speed changes to the point of equalization of torque delivered and driven load torque of the motor. A feedback loop is applied to closed loop controllers employ for converting the torque source into a speed source controller. Various speed control techniques implemented by modern age VFD are mainly classified in the following three categories

Scalar Control Method (V/f Control)

Vector control Method (indirect torque control)

Direct torque control Method (DTC)

B. Scalar control (V/f) of an induction motor

In this Method, field orientation is not considered as the voltage and frequency are the two main controlling variables which are applied to stator windings.[16][17][18] The ignored rotor status means that there is no speed and position signal is feeding back. The drive is therefore regarded as an open-loop drive [20].

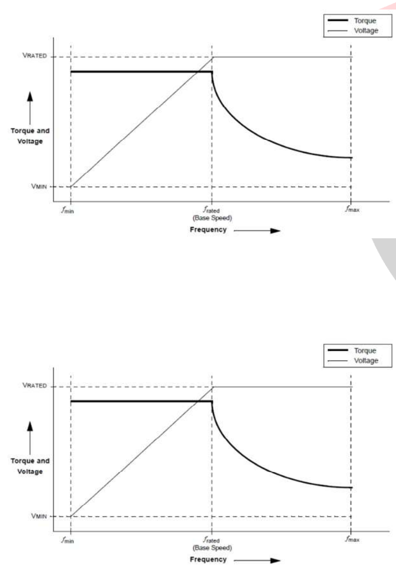

Figure 5. V/f characteristics of induction motor

As from the figure 5, the speed-torque characteristics of IM drive gives the rated torque and draws the rated current at the rated speed. Whenever the load is increases higher than the rated load value running at rated speed, this will increases the slip and hence speed drops. The IM drive can go up to 2.5 times the rated torque with 20% drop in speed. Stalling of the motor occurs if further increment of shaft load [19]. The developed torque of the IM drive is directly proportional to the stator produced magnetic field. So, the stator applied voltage is directly proportional to the angular velocity and stator flux product. This makes the stator produced flux proportional to the ratio of supply frequency and voltage applied. By varying the frequency, the speed of the motor can be varied [21] Therefore, by varying frequency and the voltage for having the same ratio as for constant flux the torque is constant throughout the operational speed range.

In variable voltage variable frequency, operation of an IM drive system of the machine has lower slip characteristics but having higher efficiency. So thus the IM drive inherently having the lower the starting torque at the rated frequency operation, IM drive must be started at the maximum value of the IM torque. For removing the stress on IM drive and improving its life high in-rush starting current should be taken care of by employing suitable protection strategy [20].

$$T_m = \frac{3V_s^2}{2\omega\left[r_s + r_s^2 + X_{sc}^2\right]} Nw - m \tag{20}$$

Where

$$X_{sc} = x_s + x_r' \quad \omega_s = \frac{2\pi n_s}{60} \quad \text{and} \quad X_{sc} = x_s + x_r'$$

At higher frequencies $r_s < X_{sc}$ and, therefore, neglecting r_s,

$$T_m = \frac{3V_s^2}{2\omega_s\left[X_{sc}\right]} Nw - m \tag{21}$$

$$X_{sc} \alpha f \quad \text{Since} \quad \omega_s \alpha f \quad \text{and} \quad X_{sc} \alpha f$$

$$T_m \alpha \frac{V_s^2}{f^2} \tag{22}$$

The maximum torques is remains constant if the speed is maintain by changing the supply frequency with the constant Vs/f ratio. The leakage equivalent reactance Xsc value is lesser at small frequency operation of IM drive. Hence, therefore for maintain the value of maximum torque and the overload torque of IM drive; the voltage should be less than the corresponding frequency range.

IV. SIMULINK MODEL AND RESULT ANALYSIS

This section summarizes the result of the work done on the proposed algorithms. The work demonstrates the speed control of the V/f control induction motor in latest Matlab/Simulink R2013a [7]. Computer modelling and simulation is widely used to study the behavior of complex system. With proper simulation techniques, a significant amount of experimental cost could be saved in the prototype development. The main principal behind this control scheme of speed control of IM drive is to vary the

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frequency and variable magnitude of the IM drive. The following block diagram shows the closed loop V/f control using a VSI.

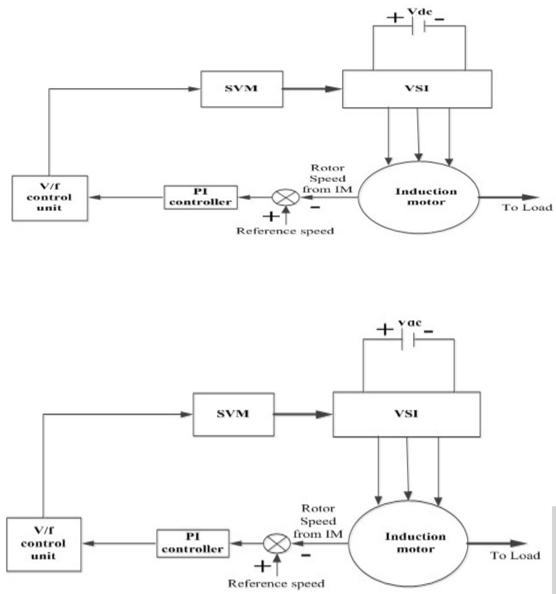

Figure 6. Block diagram for closed loop V/f control on a three phase IM

A. Matlab simulation model for closed loop V/f control method of IM

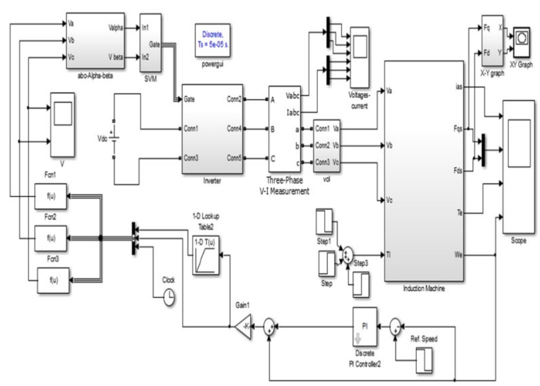

Figure 7. Matlab simulation for V/f closed loop control of IM

B. Results and analysis of closed loop V/f control of IM

In this section describe the results for different load and speed condition as well as step change of speed and load condition, and induction motor stator current, stator flux, rotor speed, and electromagnetic torque.

(A) Dynamic performance under reference speed constant (speed=1400 rpm, TL=0 N.m)

Table 1

Motor parameters for simulation			
Rotor Type	Squirrel Cage	Stator Inductance	0.005839 H
Ref. Frame	Stationary	Rotor Resistance	1.395 ohm
Capacity	4KW/5.4 HP	Rotor Inductance	0.005839 H
Speed	1430 Rpm	No. of Pole	4
Voltage	400V	Mutual inductance	0.1722 H
Frequency	50Hz	Inertia (J)	0.0131 Kg*m^2
Stator Resistance	1.405 ohm	Simulation time	1sec

The performance of induction motor with SVM is studied with reference speed constant at no load

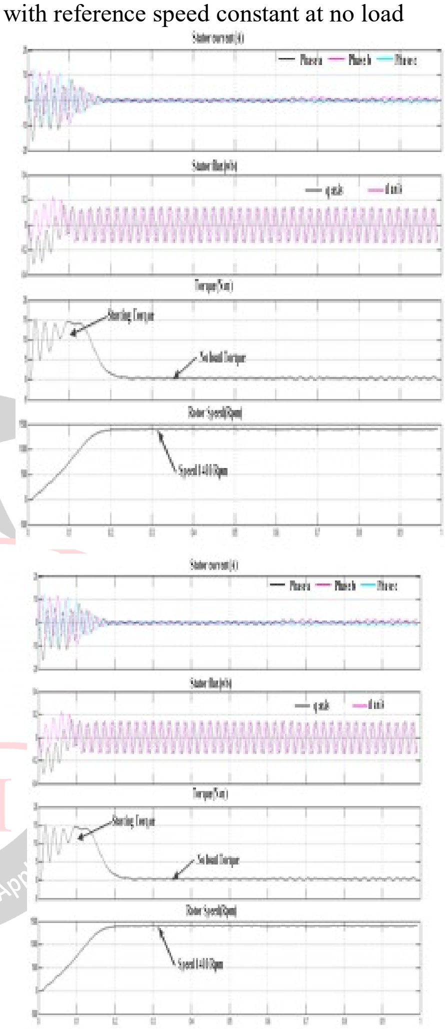

Figure 8. Stator current, stator flux, torque, and speed of IM

As shown Figure 8 speed and electromagnetic torque of induction motor are constant respectively 1400 Rpm and 0 Nm.

(B) Dynamic performance under reference speed and torque constant (Speed=1400 rpm, TL=4 N.m)

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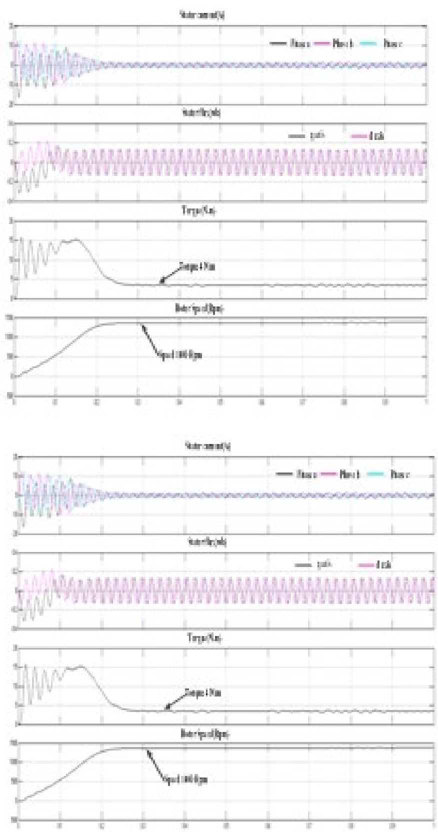

Figure 9. Stator current, stator flux, torque, and speed of IM (speed=1400, TL=4)

In this case performance of induction motor with SVM is studied with 1400 Rpm reference speed at 4 N.m load. As shown Figure 9 speed and electromagnetic torque of induction motor are constant respectively 1400 Rpm and 4 N.m. and also stator current and flux increase due to load increase

(C) *Effect of a step change in reference speed.*

Change in load torque at a reference speed of 1000 Rpm By change the load torque from 0 N.m-10 N.m-0N.m, show the change in electromagnetic toque and rotor speed in Figure 10 due to change in torque at reference speed 1000 Rpm

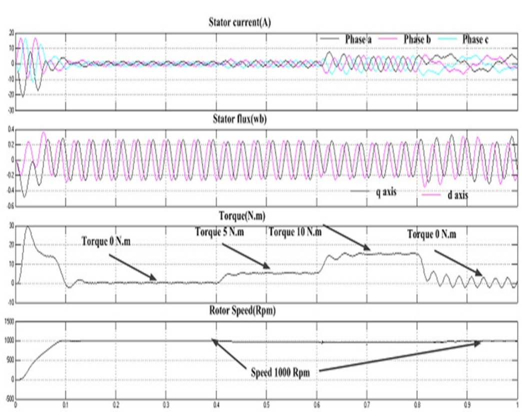

Figure 10. Stator current, stator flux, torque, and speed of IM (speed=1000, TL=0-5-10-0)

(D) *Dynamic performance under load torque change*

The speed reference is changed from 1000 Rpm to 1300 Rpm at load torque 5 N.m the effect on electromagnetic torque produced by motor and the effect on motor speed is shown in Figure 11.A sudden jerk is noticed on the torque at the change the reference speed here also show electromagnetic torque is constant. So no change in torque.

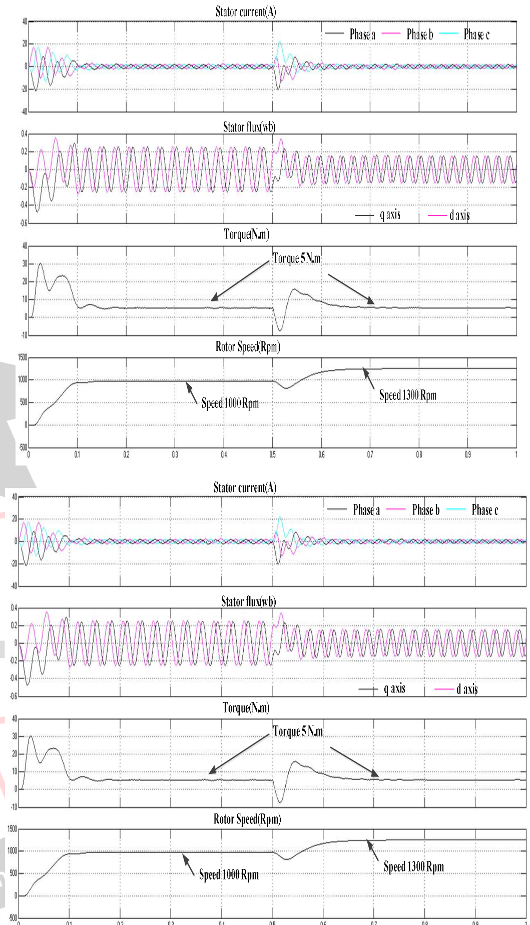

Figure 11. Stator current, stator flux, torque, and speed of IM (speed=1000 to 1300, TL=0 to 10)

V. CONCLUSION

For any induction motor drives, closed loop V/f scalar control method is one of the widely used methods in industry for speed control. It allows decoupled control of motor speed and electromagnetic torque. From the analysis is it proved that this strategy of induction motor control is simpler to implement than other control methods as it does not require pulse width modulation technique. But SVPWM introduces minimized torque and current ripple purpose. This method also cost efficient methods of speed control of three phase induction motor.

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