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Simulation of Indirect FOC Based 3-Phase Induction Motor Drive

Nithin S. Nair[1], Anoop.V.B.[2], Arun V.A.[3], Jishnu Chandran[4], SarathMenon C.S.[5]

Assistant Professor, Dept. of EEE, SNGCE, Kadayiruppu, Kerala, India [1]

UG Students [EEE], Dept. of EEE, SNGCE, Kadayiruppu, Kerala, India[2, 3, 4, 5]

ABSTRACT: This paper presents the need of Speed Control in Induction Motors. Among the various methods of controlling induction motors, field-oriented control has proven to be the most versatile. One of the basic requirements of this scheme is the PWM Inverter. This paper presents closed loop indirect field-oriented control (Vector control) of 3-phase Induction Motor. Based on the popular constant volts per hertz principle, two improved techniques are developed: keeping maximum torque constant or keeping magnetic flux constant.A squirrel-cage induction motor drive system that provides constant maximum torque or increased maximum torque and reduced slip speed at frequencies below the nominal frequency is simulated in MATLAB\SIMULINK platform.

KEYWORDS: Indirect Field Oriented Control, Induction motor, transformations.

NOMENCLATURE

R_s, R_r	Stator and Rotor Resistance
L_s, L_r	Stator and Rotor Self Inductance
L_{ls}, L_{lr}	Stator and Rotor Leakage Inductance
L_m	Mutual Inductance
V_{sa}, V_{sb}	Stator Voltages in 2 phase stator reference frame
V_{sd}, V_{sq}	Stator Voltages in Rotor flux reference frame
i_{sa}, i_{sb}	Stator Currents in 2 phase Stator reference frame
i_{sd}, i_{sq}	Stator Currents in Rotor Flux reference frame
T_e	Electromagnetic Torque Developed
T_L	Load Torque
ω_{elec}	Rotor Speed in electrical rad/sec
ω_{mech}	Rotor Speed in mechanical rad/sec
ω_{sl}	Slip Speed
P	Number of Pole Pairs
σ	Leakage Coefficient
σ_s	Stator Leakage coefficient
σ_r	Rotor Leakage Coefficient
Ψ	Flux
ρ	Rotor Flux Angle
J	Moment of Inertia
B	Viscous Friction Coefficient
G	Gain of Inverter

I.INTRODUCTION

Over the years induction motor (IM) has been utilized in the industry due to its easy construction and generally satisfactory efficiency. A.C. machines are preferred over D.C. machines due to their simple and most robust construction without any mechanical commutators. Induction motors are the most widely used motors for appliances like industrial control, and automation; hence, they are often called the workhorse of the motion industry [1]. However many applications need variable speed operation. The scalar V/f method is able to provide speed variation but does not handle transient condition control and is valid only during a steady state. The most efficient scheme of vector control:is the Indirect Field Oriented Control (IFOC), which is preferred in this work. Induction machine, with a speed/position sensor coupled to the shaft, acquires every advantage of a D.C. machine control structure, by achieving a very accurate steady state and transient control, but with higher dynamic performance.The well-developed vector control theory provides independent control between torque and flux where torque is controlled by the q-axis component of current if the flux is constant and oriented along the d-axis of the referred synchronous frame. The referred synchronous frame can be rotor flux, stator flux, or air-gap flux frame [2].

It is proved that rotor flux lies on d –axis when synchronous reference frame has been chosen. Compared to the D.C. motor, dynamic equations of the induction motor have been simplified. In a squirrel cage induction motor the stator phase current is a vector sum of the flux and torque producing current components. So, in order to achieve a dynamic performance similar to D.C. drive, a decoupling of the stator phase current into direct axis component (flux producing component) and quadrature axis component(torque producing component) is necessary. The decoupling of flux and torque control in an A.C. machine is popularly known has Field Oriented Control. This paper makes use of MATLAB/SIMULINK as simulation software. Using this software both steady state and dynamic performance can be studied.

II. MODELINGOF 3 PHASE INDUCTION MOTOR

The dynamic model of the induction motor is derived by using a two phase motor in direct and quadrature axes as shown in Fig.1. This approach is desirable because of conceptual simplicity obtained with two sets of windings one on the stator and other on the rotor. The equivalence between the three phase and two phase models is derived from simple observation, and this approach is suitable for extending it to model an n – phase machine using a two phase machine [3]. The concept of power invariance is introduced which states that the power must be equal in the three phase machine and itsequivalent two phase model.

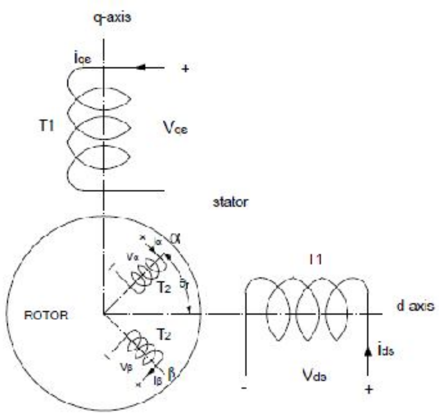

Fig. 1 Two Phase Model of 3 Phase Induction Motor

The following assumptions are made to derive the dynamic model:

1. Uniform air gap
2. Balanced stator and rotor windings, with sinusoidally distributed mmf
3. Inductance versus rotor position is sinusoidal
4. Saturation and parameter changes are neglected.

A two phase induction machine with stator and rotor windings is as shown in the figure, the winding are displaced in space by 90 electrical degrees, and the rotor winding, α, is at an angle θ_r from the stator d axis winding. The number of turns per phase in the stator and rotor respectively are T1 and T2. A pair of poles is assumed for this figure. $\theta_r$is the electrical rotor position at any instant, obtained by multiplying the mechanical rotor position by pair of electrical poles. The terminal voltages of the stator and the rotor windings can be expressed as the sum of voltage drops in resistances

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and rate of change of flux linkages which are the products of the currents and the inductances, given by equations (1) to (4).

Stator Equations

$$V_{sa} = R_s i_{sa} + L_s \frac{di_{sa}}{dt} + L_m \frac{di_{ra}}{dt} \quad (1)$$

$$V_{sb} = R_s i_{sb} + L_s \frac{di_{sb}}{dt} + L_m \frac{di_{rb}}{dt} \quad (2)$$

Rotor Equations

$$0 = R_r i_{ra} + L_r \frac{di_{ra}}{dt} + \omega L_r i_{rb} + L_m \frac{di_{sa}}{dt} + \omega L_m i_{sa} \quad (3)$$

$$0 = R_r i_{rb} + L_r \frac{di_{rb}}{dt} - \omega L_r i_{ra} + L_m \frac{di_{sb}}{dt} - \omega L_m i_{sa} \quad (4)$$

The dynamic model for the three phase induction machine can be derived from the two phase machine if the equivalence between three and two phases is established. The equivalence is based on the equality of the mmf produced in the two phase windings and equal current magnitudes [4]. Assuming that each of the three phase windings has T1 turns per phase and equal current magnitudes, the two phase windings will have (3/2)*T1 turns per phase for mmf equality. The d and q axes mmf's are formed by resolving the mmf's of the three phases along the d and q axes. It may be seen that the synchronous reference frame transforms the sinusoidal inputs into dc signals. This model is useful where the variables in steady state need to be dc quantities, as in the development of small – signal equations. Some high performance control schemes use this model to estimate the control input; this led to a major breakthrough in induction motor control by decoupling the torque and flux channels for control in a manner similar to that for separately excited dc motor drives.

The State Space model of 3 phase squirrel cage induction motor with stator and rotor current components as state variables are given by the equations (5) to (8). Equations (5) to (10) are used for the modelling of the 3 phase squirrel cage induction motor.

$$\frac{di_{sa}}{dt} = \frac{1}{\sigma L_s}\left[V_{sa} - R_s i_{sa} + \frac{L_m R_r i_{ra}}{L_r} + \omega L_m i_{rb} + \frac{\omega L_m^2 i_{sb}}{L_r}\right] \quad (5)$$

$$\frac{di_{sb}}{dt} = \frac{1}{\sigma L_s}\left[V_{sb} - R_s i_{sb} + \frac{L_m R_r i_{rb}}{L_r} - \omega L_m i_{ra} - \frac{\omega L_m^2 i_{sa}}{L_r}\right] \quad (6)$$

$$\frac{di_{ra}}{dt} = \frac{1}{\sigma L_r}\left[-R_r i_{ra} - \frac{L_m V_{sa}}{L_s} - \omega L_m i_{sb} - \omega L_r i_{rb} + \frac{L_m R_s i_{sa}}{L_s}\right] \quad (7)$$

$$\frac{di_{rb}}{dt} = \frac{1}{\sigma L_r}\left[-R_r i_{rb} - \frac{L_m V_{sb}}{L_s} + \omega L_m i_{sa} + \omega L_r i_{ra} + \frac{L_m R_s i_{sb}}{L_s}\right] \quad (8)$$

Electromagnetic Torque developed by the motor is given by:

$$T_e = \frac{2}{3}\frac{P}{2} L_m [i_{sb} i_{ra} - i_{rb} i_{sa}] \quad (9)$$

Load dynamics is given by:

$$T_e = J\frac{d\omega_m}{dt} + B\omega_m + T_l \quad (10)$$

Transformation of Reference Frames

The idea behind vector control is to control the induction motors in the similar way for dc motor control. For a permanent-magnet (PM) excitation dc motor, torque control can be achieved by controlling its armature current. Since the torque results from the interaction of two perpendicular magnetic fields, which are the stator field generated by the PM excitation and armature field, created by the armature current. Once the flux level of stator field is kept constant, the torque can be controlled by armature current [5]. To apply this two-axis theory for dc motor control to induction motor control, it is required to transform the alternating current quantities to dc components, which can be achieved

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using a synchronous frame as the reference frame. The synchronous frame, which rotates with synchronous speed, can be fixed to the axis of rotor flux, stator flux, or air gap. In this paper synchronous frame is fixed to the axis of rotor flux.

3 Phase to 2 Phase Transformation.

Let i_{SA},i_{SB}, and i_{SC} are 3 Phase currents and i_{sa}, i_{sb} are 2 Phase currents in stationary(stator) reference frame. Voltage transformations are same as that of current. The transformation is given by equations (11) and (12). Inverse transformation are given by equation (13) to (15).

$$i_{sa} = \frac{3}{2} i_{SA} \quad (11)$$

$$i_{sb} = \frac{\sqrt{3}}{2} [i_{SB} - i_{SC}] \quad (12)$$

2 Phase to 3 Phase Transformation

$$i_{SA} = \frac{2}{3} [i_{sa}] \quad (13)$$

$$i_{SB} = -\frac{1}{3} i_{sa} + \frac{1}{\sqrt{3}} i_{sb} \quad (14)$$

$$i_{SC} = -\frac{1}{3} i_{sa} - \frac{1}{\sqrt{3}} i_{sb} \quad (15)$$

For an isolated neutral balanced system,

$$i_{SA} + i_{SB} + i_{SC} = 0 \quad (16)$$

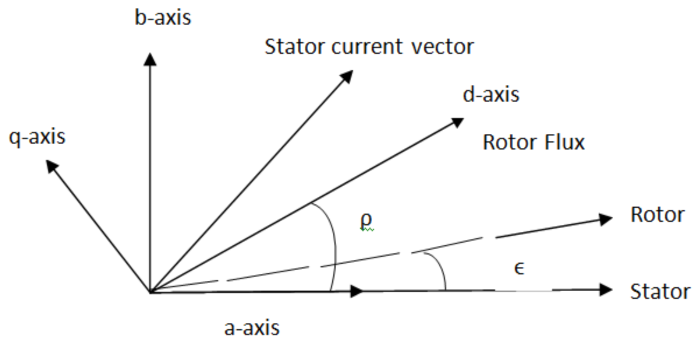

Fig.2 Orientation of Reference Frames

Stationary 2 Phase a-b (stator frame) to Rotating 2 Phase d-q (rotor flux frame) transformation is given by:

$$i_{sd} = i_{sa} \cos\rho + i_{sb} \sin\rho \quad (17)$$
$$i_{sq} = i_{sb} \cos\rho - i_{sa} \sin\rho$$

In Matrix form ab-dq and dq-ab transformations are given by:

$$\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = \begin{bmatrix} \cos\rho & \sin\rho \\ -\sin\rho & \cos\rho \end{bmatrix} * \begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix} \quad (18)$$

$$\begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix} = \begin{bmatrix} \cos\rho & -\sin\rho \\ \sin\rho & \cos\rho \end{bmatrix} * \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \quad (19)$$

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III. MODELING OF INDIRECT VECTOR CONTROLLER

Figure 3 shows the block diagram of an IFOC, in which a closed loop controller compares the torque command against the demanded torque. The demanded torque is the reference input provided by an outer speed control loop. This loop determines the necessary to make the torque component equal to the demanded torque [6]. In the similar way there is a control loop for field control. This loop compares the computed value of the field component against the field reference. As in the case of a D.C. motor, the field reference has a constant value at all speeds below the base speed.

The field control loop compares the computed value of the actual field component against the reference. This loop determines the change, if any, necessary to make the actual field component equal to the commanded value. In this manner the torque control loop determines the required change in the torque component and the field control loop determines the change required in the field component. These two individual values of the required changes are added to get the total change required in the output current of the inverter. The inverter switching times are appropriately modified to implement the required total change [7]. Thus a reference waveform is provided to the inverter and the switching control circuit of the inverter suitably varies the inverter switching instants to make the inverter output current conforms to the reference waveform.

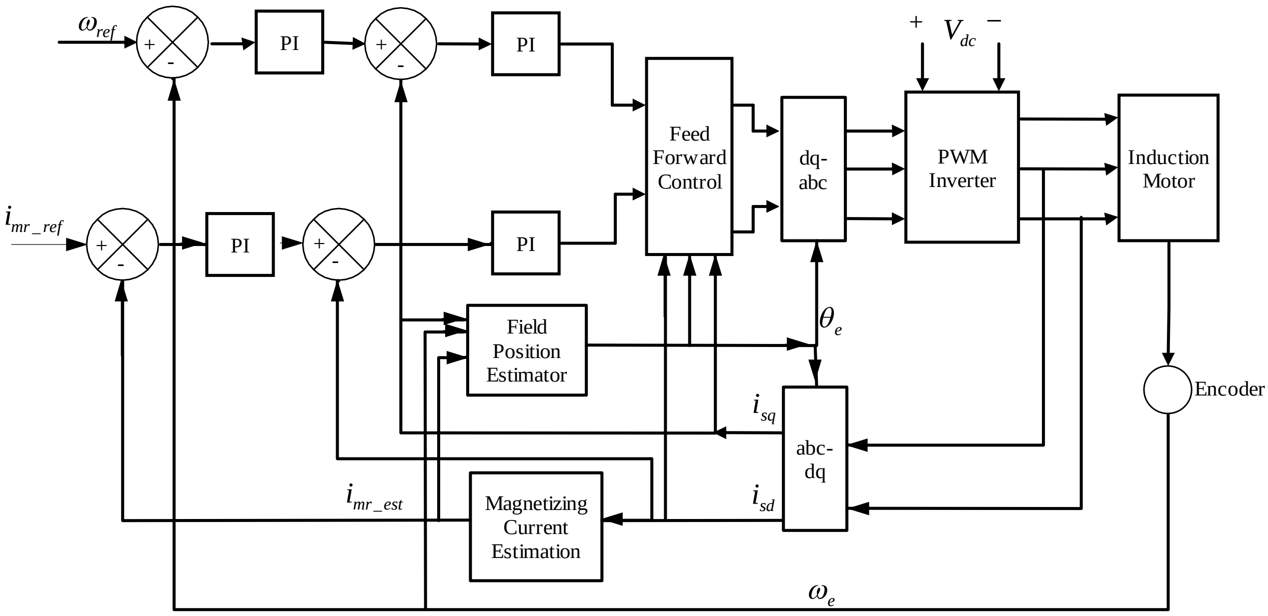

Fig. 3Block diagram of vector controlled IM drive.

The decoupled stator voltage equations in rotor flux reference frame are given by equations (20) and (21)

$$V_{sd} = R_s i_{sd} + \sigma L_s \frac{di_{sd}}{dt} - \omega_{mr} i_{sq} \sigma L_s + (1-\sigma) L_s \frac{di_{mr}}{dt} \qquad (20)$$

$$V_{sq} = R_s i_{sq} + \sigma L_s \frac{di_{sq}}{dt} + \omega_{mr} i_{sd} \sigma L_s + (1-\sigma) L_s i_{mr} \omega_{mr} \qquad (21)$$

The decoupled Flux channel and Torque channel equations are given by equations (22) and (23) respectively.

$$T_r \frac{di_{mr}}{dt} + i_{mr} = i_{sd} \qquad (22)$$

$$T_e = \frac{2}{3}\frac{P}{2}\frac{L_m}{1+\sigma_r} i_{mr} i_{sq} \qquad (23)$$

The instantaneous angular speed of rotor flux is given by

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$$\omega_{mr}(t) = \frac{i_{sq}}{i_{mr}T_r} + \omega_e = \frac{d\rho}{dt} \quad (24)$$

Where slip speed is given by

$$\omega_{sl} = \frac{i_{sq}}{i_{mr}T_r} \quad (25)$$

On integrating equation (24) Field angle (position) ρ and thereby unit vector signals $\cos\rho$ and $\sin\rho$ can be estimated [8].The eqn. (22) of flux channel includes only flux component of stator current. So rotor flux can be controlled by varying i_{sd} without affecting i_{sq}. The variation in i_{sd} cause variation in i_{mr} and there by flux Ψ_r. i_{sd} is analogous to field current in a D.C. motor. Torque channel equation (23) shows that torque can be controlled by varying both i_{sq} and i_{mr}. Since the time constant associated with flux channel T_r is large, torque is controlled by varying i_{sq} by keeping i_{mr} constant at its rated value in order to obtain fast dynamic response. Current i_{sq} is analogous to armature current in a D.C. motor [9].

IV.SIMULATION RESULTS AND DISCUSSION

From the fig. 4, it can be seen that motor has a high starting current and after few seconds it attains normal full load current of 15.3 amperes.

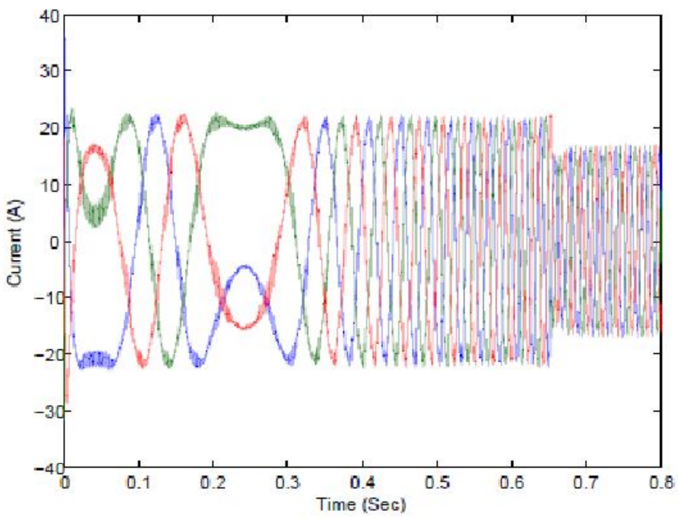

Fig. 4Motor Line Current (Full Load Condition 15.3 Amp)

Fig. 5 and Fig. 6 showing the currents in rotor flux reference frame, i.e., in d-q reference frame. It can be seen that they appear as D.C. values in steady state so control variables are steady state D.C. values.

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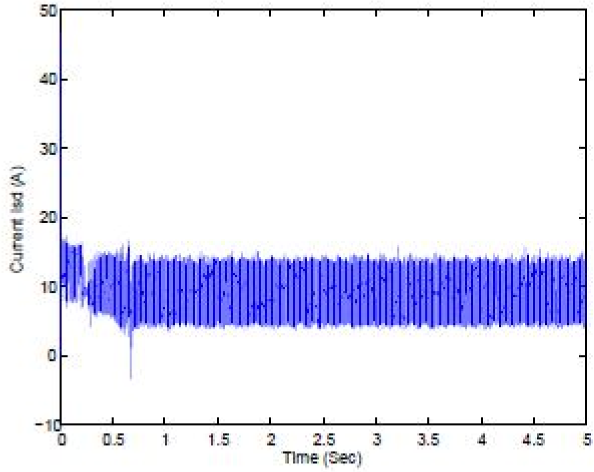

Fig. 5Flux Component of Stator Current

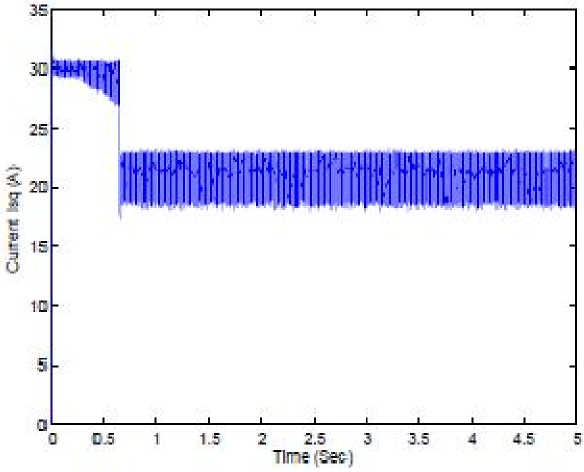

Fig. 6Torque Component of Stator Current

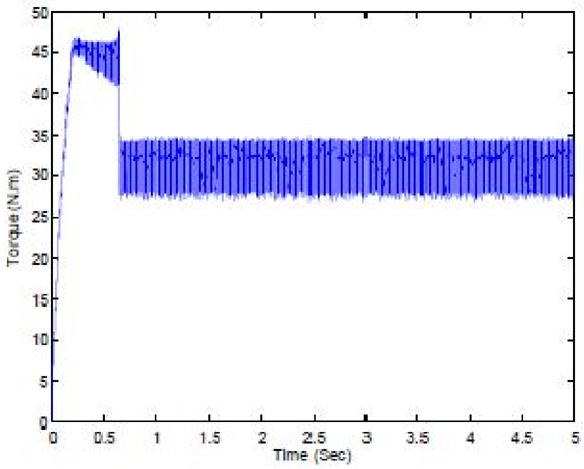

Fig. 7Torque Response of Drive at full load (32 N.m.)

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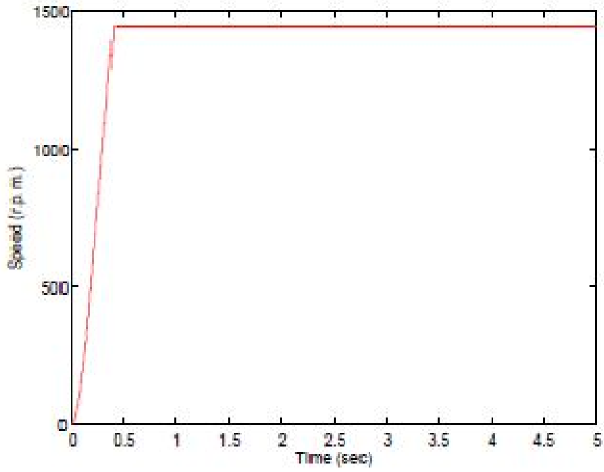

Fig. 8Speed Response of Drive at full load (reference speed = 1440 r.p.m.)

Fig. 7 and Fig. 8 showing the torque response and speed response of the drive at full load and reference speed of 1440 r.p.m. It can be seen that the motor attains the rated torque of 32 N.m. after the transient oscillations. Also the speed settles to the reference value of 1440 r.p.m.

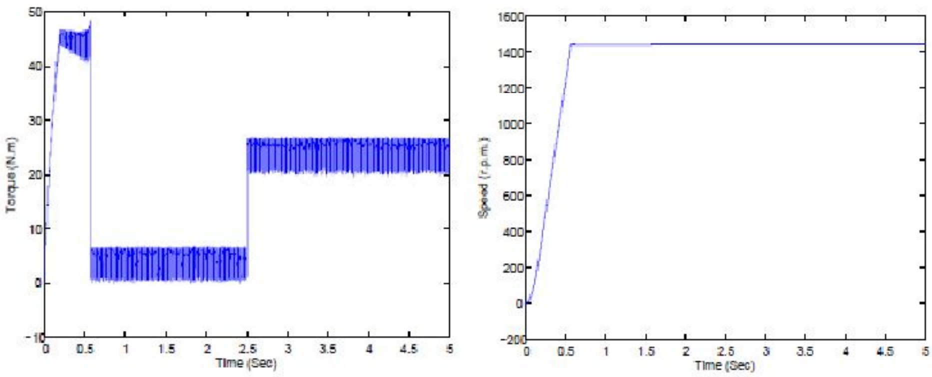

Fig. 9Torque and Speed Response for a step change in Load Torque (5-25 Nm) at 2.5 sec

Figure 9 shows the torque and speed response of the drive for a step change in load torque of (5-25 Nm) at 2.5 sec. with speed command remains unchanged. The main advantage of vector control is shown in this graph i.e. speed of the machine remains constant for change in load torque or any load disturbances. Also it can be seen that the dynamic torque response is very fast for the step change in load torque.

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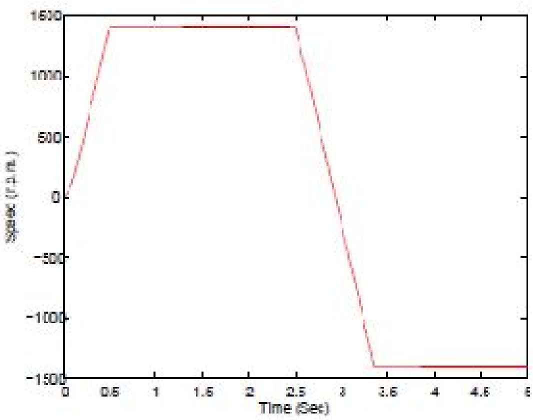

Fig.10Speed Response for a Speed Reversal (1400 to -1400 rpm) at 2.5 sec.

Figure 10 shows the speed response of the drive for a speed reversal command of (1400 to -1400 rpm) at 2.5 sec. it can be seen that response is very fast with a minimum lag determined by the inertia of the rotating system.

V.CONCLUSION

This paper presented the Indirect Field Oriented Controlled Three Phase Induction Motor Drive. The drive is simulated in MATLAB/SIMULINK and the results are analysed. The results demonstrate the efficiency of the vector control as compared to scalar control techniques. It is proved that rotor flux lies on d –axis when synchronous reference frame has been chosen. Compared to the D.C. motor, dynamic equations of the Induction Motor have been simplified. In a squirrel cage induction motor the stator phase current is a vector sum of the flux and torque producing the current components. So, in order to achieve a dynamic performance similar to D.C. drive, a decoupling of the stator phase current into direct axis component (flux producing component) and quadrature axis component(torque producing component) is necessary. The decoupling of flux and torque control in an A.C. machine is achieved in this project. This paper makes use of MATLAB/SIMULINK as simulation software. Using thissoftware both steady state and dynamic performance were studied.

APPENDIX

INDUCTION MOTOR DATA USED FOR SIMULATION

Machine Parameter	Value
Rated Power	10 HP
Rated Voltage	400 V (L-L)
Rated Current	15.5 Amp
Rated Speed	1440 rpm
Rated Torque	32 Nm
Frequency	50 Hz
Number of Pole Pairs	2
Stator Resistance and Leakage Inductance	0.7384 , 0.003045H
Rotor Resistance and Leakage Inductance	0.7402, 0.003045H
Mutual Inductance	0.1241H
Moment of Inertia	0.0343 kg m^2
Viscous Friction Coefficient	0.000503 $\frac{\text{Nm}}{\text{rad/sec}}$

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