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Modeling and implementation of vector control for Induction motor Drive

K.Ramesh[1],Ch.Ravi Kumar[2],P.Bala Murali[3]

[1]P.G.Student,Dept of EEE,AITAM Engineering College,Andhra Pradesh

[2]Associate Professor ,Dept of EEE,AITAM Engineering College,Andhra Pradesh

[3]Associate Professor,Dept of EEE,AITAM Engineering College,Andhre Pradesh

ABSTRACT: This paper explains the performance of the induction motor drive by using vector control to overcome the coupling effect and inferior dynamic response of scalar control. The basic idea of the vector control is to decompose a stator current into a magnetic field-generating component (i_{ds}) and a torque generating component (i_{qs}) and both components can be separately controlled to make the performance of the AC machine similar to that of DC machine. This paper also gives the mathematical modeling explained with d-q reference frame. The control used in this paper controls the speed in four quadrants without any additional control elements. The effectiveness of the proposed control method is verified by using MATLAB/SIMULINK Software and results are presented to validate the effectiveness of topology.

KEY WORDS:

Mathematical model , induction motor(IM) drives, PWM inverter ,direct vector control, scalar control, MATLAB.

1. INTRODUCTION

Induction motor (IM) can be considered as the workhorse of the industry because of its special features such as low cost, high reliability, low inertia, simplicity and ruggedness. Even today IMs especially the squirrel cage type, are widely used for single speed applications rather than variable speed applications due to the complexity of controlling algorithm of IM variable speed drives. However, there is a great interest on variable speed operation of IM within the research community mainly because IMs can be considered as a major industrial load of a power system. It is well known fact that electric energy consumption of the appliances can be reduced by controlling the speed of the motor[1-2].

The methods which enjoyed wide acceptability in controlling in the speed and torque of the induction motor drive are termed as voltage control, frequency control, rotor resistance control, V/f control, flux control, slip control, slip power recovery control, etc. All these controls are termed as scalar control techniques of an IM in exhibits coupling effect and inferior dynamic response[3-7].

This paper explains the vector control to overcome the coupling effect and inferior dynamic response of scalar control techniques. Aim of vector control is decompose a stator current into magnetic field-generating component (i_{ds}) and a torque generating component (i_{qs}) and both components can be separately controlled to make the performance of IM similar to that of DC machine.This paper also explains the speed control of IM drive in four quadrants without using of any additional elements[8-16].

Vector control usually realized with PWM controller[17-20] in rotating(d-q) reference. In vector control stator current is controlled instantaneously which reduces the torque ripples and improves overall performance of machine[8-9]. In this paper vector control of IM is implemented and verified in MATLAB SIMULINK environment. It appears that eventually, vector control will oust scalar control, and will be accepted as the industry standard control for ac drives.

The paper is organized as follows: section 2 presents the modeling of IM. Section 3 develops the implementation of vector control. Section 4 provides the simulation results and analysis of vector control IM drive. Section 5 concludes the paper.

2. MATHEMATICAL MODELING

Mathematical modeling is required for simulation and analysis of drive system. IM equations are presented in d-q reference frame[8].

2.1 Axes Transformation

Consider a symmetrical three-phase induction machine with stationary as-bs-cs axis at 2π/3 angle apart. Our goal is transform the three-phase stationary reference frame (as-bs-cs) variables into two-phase stationary reference frame (d^s - q^s) variables[8-9]. Assume that d^s - q^s are oriented at θ angle as shown in Fig. 1.

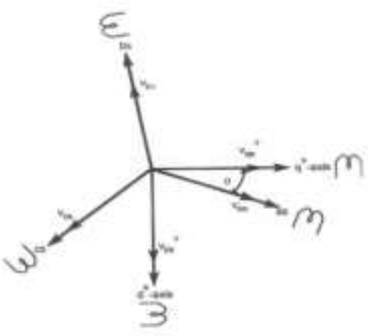

Fig. 1. 3-Φ to 2-Φ Transformation

The voltages v_{ds}^s and v_{qs}^s can be resolved into as-bs-cs components and can be represented in the matrix form as:

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 120^o) & \sin(\theta - 120^o) & 1 \\ \cos(\theta + 120^o) & \sin(\theta + 120^o) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} \qquad (1)$$

The corresponding inverse relation is:

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{0s}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 120^o) & \cos(\theta + 120^o) \\ \sin\theta & \sin(\theta - 120^o) & \sin(\theta + 120^o) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \qquad (2)$$

Here v_{0s}^s is zero- sequence component, convenient to set θ = 0, so that q^s - axis is aligned with as- axis. Therefore ignoring zero – sequence component[9], it can be simplified as

$$v_{qs}^s = \frac{2}{3} v_{as} - \frac{1}{3} v_{bs} - \frac{1}{3} v_{cs} \qquad (3)$$

$$v_{da}^s = \frac{-1}{\sqrt{3}} v_{bs} + \frac{1}{\sqrt{3}} v_{cs} \qquad (4)$$

Equation (3) and (4) consecutively called as clark transformation.

Fig .2 shows the synchronously rotating d^e - q^e axes, which rotate at synchronous speed w_e with respect to the d^s - q^s axes and the angle $\theta = w_e t$. The two-phase d^s - q^s windings are transformed into the hypothetical windings mounted on the d^e - q^e axes. The voltages on the d^s - q^s axes can be transformed into the d^e - q^e frame as follows:

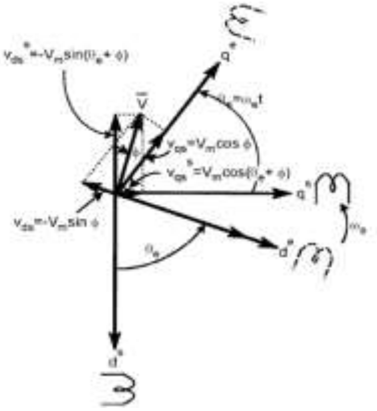

Fig .2. stationary frame d^s - q^s to synchronously rotating frame d^e - q^e transformation

$$v_{qs}^e = v_{qs}^s \cos\theta_e - v_{ds}^s \sin\theta_e \quad (5)$$

$$v_{ds}^e = v_{qs}^s \sin\theta_e + v_{ds}^s \cos\theta_e \quad (6)$$

Equation (5) and (6) consecutively called as park transformation.

Again, resolving the rotating frame parameters into a stationary frame, the relation are

$$v_{qs}^s = v_{qs}^e \cos\theta_e + v_{ds}^e \sin\theta_e \quad (7)$$

$$v_{ds}^s = -v_{qs}^e \sin\theta_e + v_{ds}^e \cos\theta_e \quad (8)$$

Equation (7) and (8) are known as inverse park transformation.

2.2 Induction motor Dynamic model

The following assumptions are made to derive the dynamic model

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

Fig. 3 shows the d-q equivalent circuits for a three phase symmetrical squirrel cage motor in synchronously rotating frame with zero sequence component neglected[8-9]. From the dynamic equivalent circuit, the induction motor parameters can be expressed in matrix equation (9), assuming that the rotor bars in squirrel cage induction motor are shorted out and the rotor voltages equal zero[8-9].

$$\begin{bmatrix} v_{qs}^e \\ v_{ds}^e \\ v_{qr}^e \\ v_{dr}^e \end{bmatrix} = \begin{bmatrix} R_S + PL_S & w_e L_s & L_m P & w_e L_m \\ -w_e L_s & R_s + L_s P & -w_e L_s & L_m P \\ L_m P & (w_e - w_r) L_m & R_r + PL_r & (w_e - w_r) \\ -(w_e - w_r) L_m & PL_m & -(w_e - w_r) L_r & R_r + PL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \qquad (9)$$

Where R_s , R_r are the stator and rotor resistance per phase respectively, L_s , L_r are the stator, and the rotor inductance per phase, respectively, $p= \frac{d}{dt}$ operator, w_e , w_r are synchronous and rotor speeds respectively.

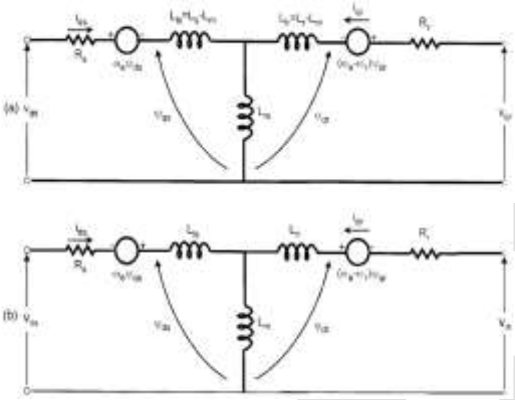

Fig. 3. Dynamic d^e-q^e equivalent circuits of machine (a) q^e-axis circuit, (b) d^e-axis circuit

3. VECTOR CONTROL

3.1 principal of Vector control

The fundamentals of vector control implementation can be explained with the help of Fig.4. Where the machine model is represented in synchronously rotating reference frame. The inverter has unity gain, that is, it generates the currents i_a , i_b , and i_c as dictated by corresponding command currents i_a^* , i_b^* , i_c^* from the controller. The machine terminal phase currents i_a , i_b and i_c are converted to i_{ds}^s and i_{qs}^s components by a 3-phase to 2-phase transformation. These are then converted to synchronously rotating frame by the unit vector control components $\cos\theta_e$ and $\sin\theta_e$ before applying them to the d^e - q^e machine model as shown. The controller makes two stages of inverse transformation, as shown, so that the control currents i_{ds}^* and i_{qs}^* correspond to the machine currents i_{ds} and i_{qs} , respectively. In addition the unit vector assures correct alignment of i_{ds} currents with flux vector $\hat{\Psi}_r$ and i_{qs} perpendicular to it as shown in Fig. 4[9].

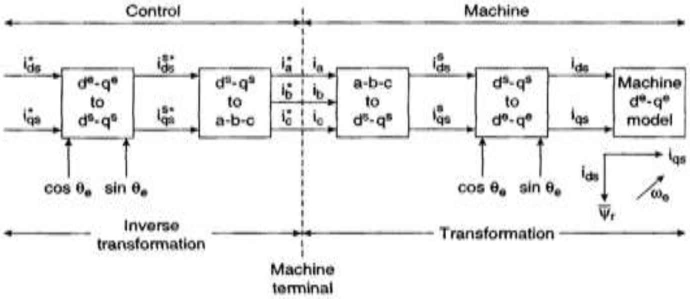

Fig4. vector control implementation principal with machine d^e – q^e model.

3.2 Direct or Feedback Vector control

The basic block diagram of the direct vector control method for a PWM voltage- fed inverter is shown in Fig. 5. We developed a strategy for rotor flux oriented direct vector control by manipulating equations derived from d^e-q^e equivalent circuit.

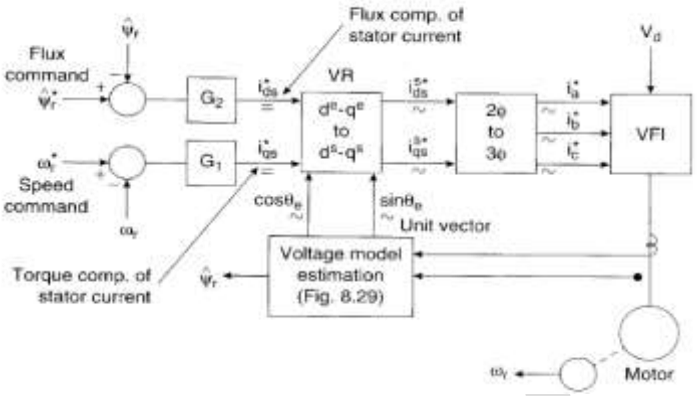

Fig. 5. Direct vector control block diagram.

The key estimation equation can be summarized as follows:

$$\Psi_{dr}^{s} = \hat{\Psi}_r \cos\theta_e \qquad (10)$$

$$\Psi_{qr}^{s} = \hat{\Psi}_r \sin\theta_e \qquad (11)$$

$$\cos\theta_e = \frac{\Psi_{dr}^{s}}{\Psi_r} \qquad (12)$$

$$\sin\theta_e = \frac{\Psi_{qr}^{s}}{\Psi_r} \qquad (13)$$

$$\Psi_r = \sqrt{\Psi_{dr}^{s^2} + \Psi_{dr}^{s^2}} \qquad (14)$$

Where vector $\overline{\Psi}_r$ is represented by magnitude $\hat{\Psi}_r$. Signals $\cos\theta_e$ and $\sin\theta_e$ have been plotted in correct phase position in Fig.6(b). These unit vector signals, when used for vector rotation in Fig. 5, give a ride of current i_{ds} on the d^e -axis(direction of $\overline{\Psi}_r$) and i_{qs} on the q^e -axis as shown. At this condition, $\Psi_{qr} = 0$ and $\Psi_{dr} = \overline{\Psi}_r$, as indicated in the figure. When the i_{qs} polarity is reversed by the speed loop, the i_{qs} position in Fig. 6(a) also reverse, giving negative torque. The generation of a unit vector signals from feedback flux vectors gives the name “direct vector control” [8-16]

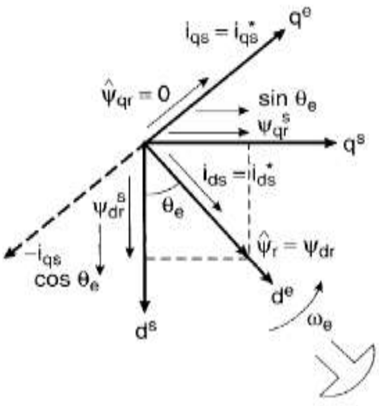

Fig 6(a)

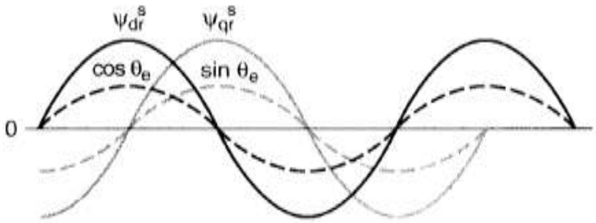

Fig 6(b)

Fig. 6: (a) d^s - q^s and d^e - q^e phasors showing correct rotor flux orientation, (b) plot of unit vector signals in correct phase position .

4. SIMULATION RESULTS AND ANALYSIS

Simulation is performed in MATLAB-SIMULINK to investigate the performance of vector controlled induction motor drive. In this section electromagnetic torque, speed, and stator currents of proposed motor drive has been studied and compared with scalar control.

Fig.7 shows the electromagnetic torque response of both vector controlled and scalar controlled IM drive. We can say that the torque response of the vector controlled IM drive has less transient ripples or less overshoot and it is smoothly following the load torque and it reaches the desired torque. The torque response of scalar controlled IM drive has spikes or transient ripples when the motor is in starting and suddenly loaded condition.

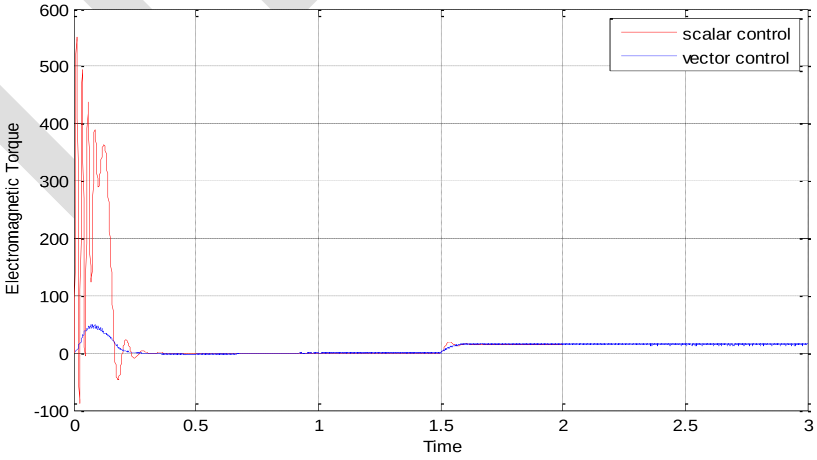

Fig.7. Torque response of both vector and scalar controlled IM drive.

The bad effect of that spiky transient torque is that the motor is forced to draw a higher current especially, when we have load torque which has to be applied for certain time and then switched off and so on and if the motor is over load even for short time the drive will effect dangerously.

Fig.8. shows the no-load speed response of both vector controlled and scalar controlled IM drive. We noticed that while using the vector control the overshoots obtained in speed response are very less as compared to the case when the scalar control is used. We can also noticed that the vector controlled IM drive reaches the desired speed in 0.5 seconds whereas scalar controlled IM drive takes 1 second to reach the desired speed.

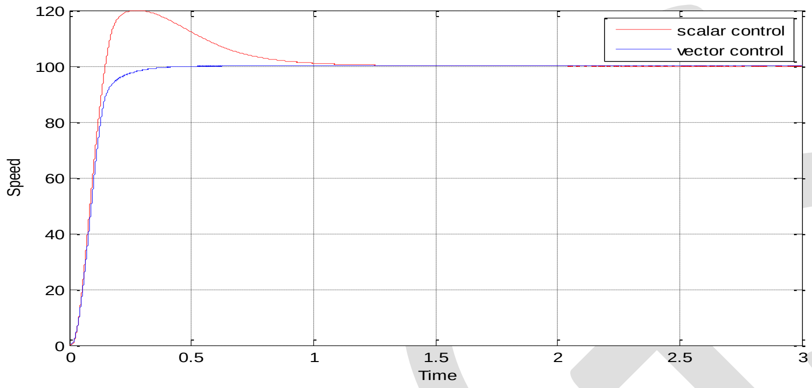

Fig.8. Speed response of both vector and scalar controlled IM drive on no-load.

Fig .9 shows the response of the IM drive at loaded condition. The IM drive speed set as 100 rad/sec and the load of 15 Nm is applied at 1.5 seconds. The scalar control drive response shows decrease in speed of the induction motor during loaded condition. The vector controlled drive has a very low speed drop in speed response compared to the scalar controlled drive. And also we noticed that the vector controlled drive gives slight decrease in steady state speed response.

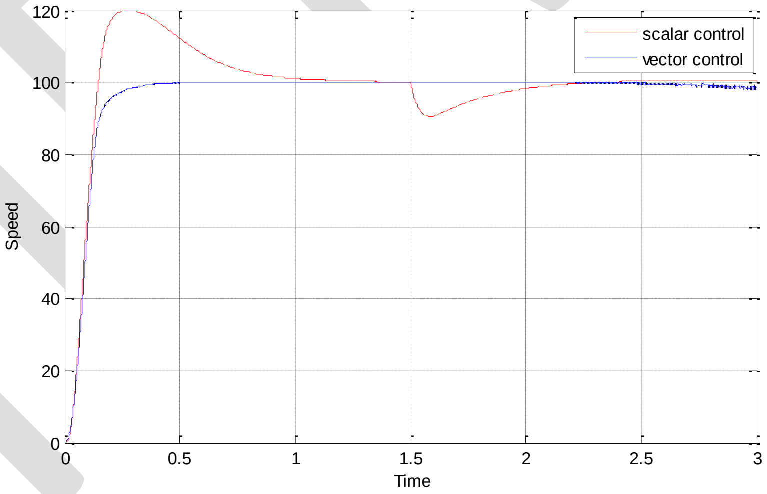

Fig.9. Speed response of both vector and scalar controlled IM drive on load.

Fig .10 shows the speed repose of vector controlled IM drive which is accurately trace the reference speed command value irrespective of load, machine parameter and any external environment change. Fig.11 shows the speed response of scalar controlled IM drive which is not accurately trace the reference speed command value.

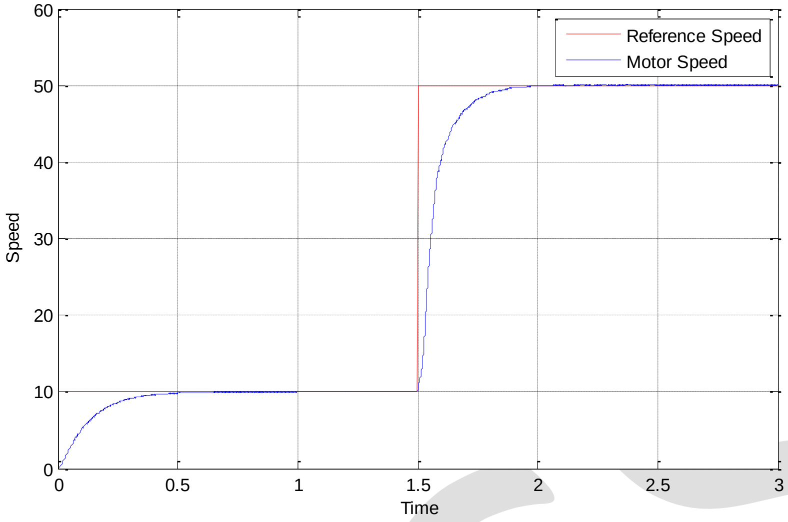

Fig.10. Speed response of vector controlled IM drive.

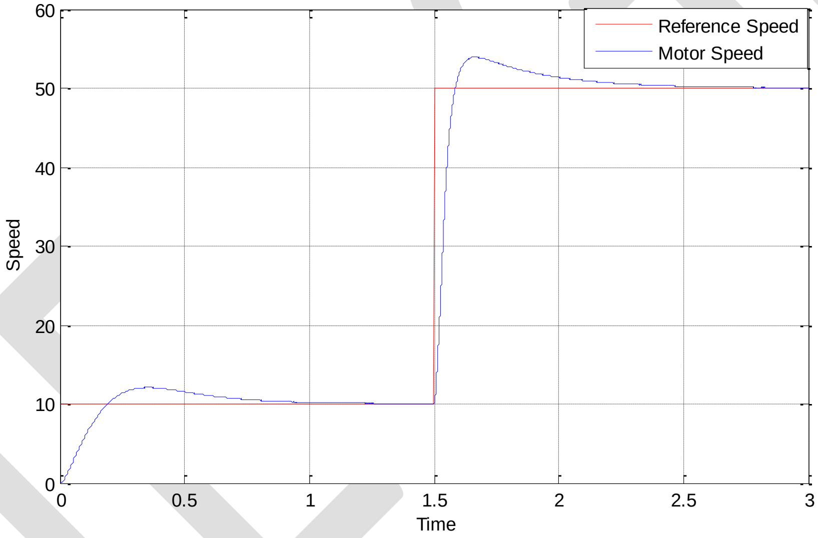

Fig.11. Speed response of scalar controlled IM drive.

Fig .12 shows the stator currents of both vector controlled and scalar controlled IM drive. We can notice that scalar controlled drive maintain high stator current, due to the effect of spiky torque at starting position of the drive. This higher magnitude of current will give dangerous effect to drive. This bad effect is overcome by vector control.

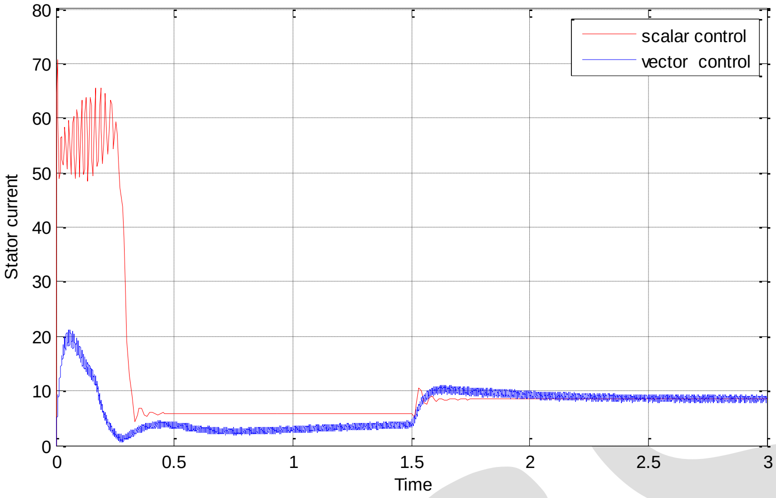

Fig.12. Stator current response of both vector and scalar controlled IM drive.

Fig .13 Three phase currents of vector controlled IM drive fed three phase space vector pulse width modulated inverter at step change in 0-15Nm.

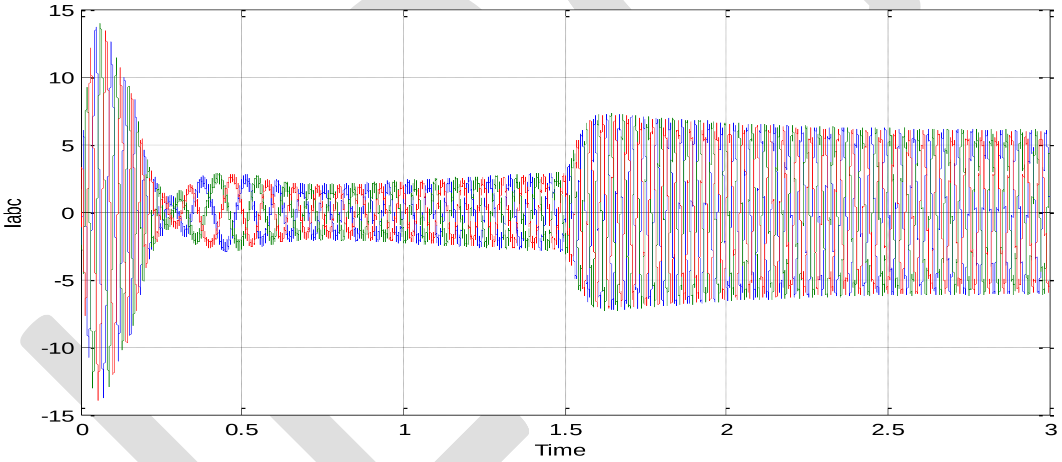

Fig .13 Three-phase currents of vector controlled IM drive at step change in 0-15Nm.

Fig.14(a) shows the simulation results for the vector controlled IM drive speed 100 rad/sec and 0 rad/sec under constant load torque 15 N.m like dc machine, speed control is possible in four quadrants without any additional control element. In motor braking condition, the torque T_e is negative, the drive initially goes into regenerative braking mode as shown in Fig.14(b) .

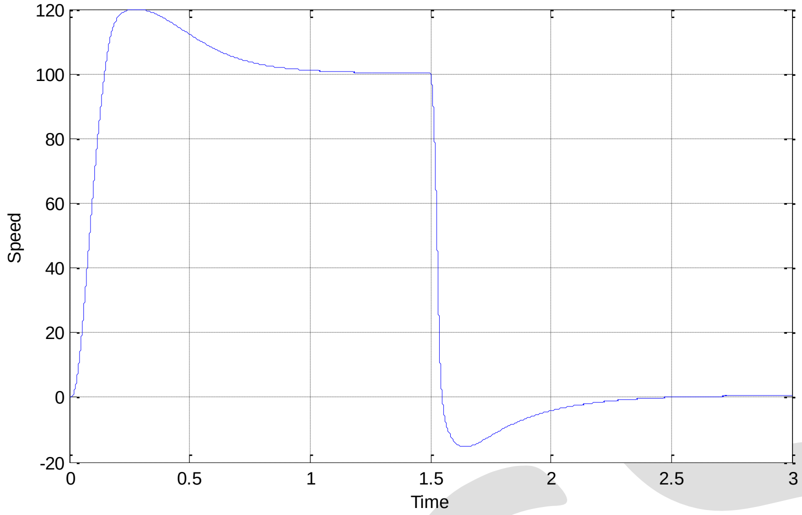

Fig.14(a) Speed response of vector controlled IM drive.

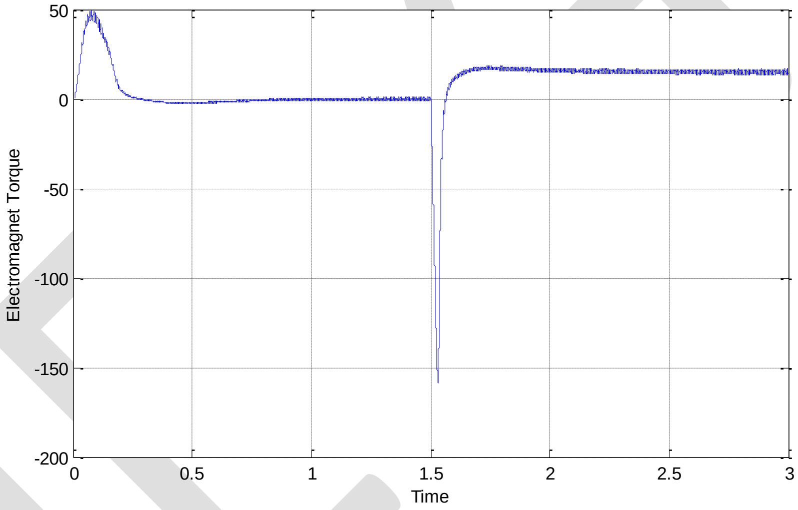

Fig.14(b) Torque response of vector controlled IM drive when speed is zero.

As mentioned before and based on the simulation results the vector controlled IM drive having good dynamic response. Speed and torque of a vector controlled IM drive are controlled separately like the dc machine which is not possible with scalar control.

5. CONCULUSION

This paper demonstrates a direct vector control in an induction motor drive system. The proposed control method assures:

- Torque generating component and magnetic field – generating component have been controlled independently and gives good dynamic response

- The transient response will be fast and dc machine like because torque control by i_{qs} does not affect the flux.

- Like a dc machine, speed control is possible in four quadrants without any additional control elements.

- Good stabilization of load torque for wide range speed control.

The effectiveness of the proposed control method is verified by simulation in MATLAB SIMULINK environment.

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