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Speed Control of Induction Motor Using Vector Control Technique

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***Abstract*—Induction Motor (IM) control is a difficult and complex engineering problem due to multivariable, highly nonlinear, time-varying dynamics and unavailability of measurements. In this paper vector control for speed control of three-phase Squirrel Cage Induction Motor has been developed and analyzed. The present approach avoids use of flux and speed sensors which decreases the mechanical cost and robustness. Vector control has replaced traditional control method such as using the ratio of voltage and frequency as a constant, which improve greatly dynamic control efficiency of motor.**

Keywords— Field Oriented Control (FOC),PI, Squirrel Cage Induction Motor, Vector Control.

I. INTRODUCTION

Currently the use of three-phase induction machines has been increased tremendously in industrial applications due to several methods available to control the speed and torque of the motor. The control methods for induction motors can be divided into two parts: scalar control and vector control strategies. Scalar control is relatively simple method compared to vector control. The purpose of the scalar control technique is to control the magnitude of the chosen quantities. For the Induction Motor (IM) the technique is used as Volts/Hertz constant.

Vector control is more complex technique than scalar control, the evolution of which was inexorable, since scalar control technique cannot be applied for controlling systems with dynamic behavior. The vector control technique works with vector quantities, controlling the desired values by using space phasors. It is also known as field-oriented control because in the implementation the identification of the field flux of the motor is required.

In this paper an implementation of controller for speed control of an IM using vector control method has been developed and analyzed in detail. This paper is a complete mathematical model of Field Oriented Control of IM. Motor used in simulation is squirrel cage IM. An IM is asynchronous AC motor. The most widely used IM is squirrel cage motor because of its advantages such as mechanical robustness, simple construction and less maintenance. These applications include pumps and fans, paper and textile mills, subway and locomotive propulsions, electric and hybrid vehicles, home appliances, heat pumps and air conditioners, rolling mills, wind generation systems, robotics, etc. Thus IM have been used in industrial variable speed drive system with vector control technology. This method requires a speed sensor for speed control. But speed sensors cannot be mounted in some cases such as motor drives in high-speed drives and antagonistic environment [1]. It also becomes bulky and expensive. The performance at the high speed region is satisfactory but its performance at very low speed is poor. In most of the methods there is estimation of rotor flux angle and parameter tuning in FOC. In FOC, any controller is easily implemented and can approach desired system response [2].

However, if the controlled electrical drives require high performance, i.e., steady state and dynamic tracking ability to set point changes and the ability to recover from system variations. Then a conventional PI, fuzzy and neural controller for such drives lead to tracking and regulating performance simultaneously and then compared each other[3]. Thus now research is focused on sensor less vector control problem which reduces cost and increases reliability.

II. DYNAMIC MODEL OF INDUCTION MOTOR

Generally, an IM is described in arbitrary rotating frame, stationary reference frame or synchronously rotating frame. For transient studies of adjustable speed drives, usually it is more convenient to simulate an IM and its converter on a stationary reference frame. Moreover, calculations with stationary reference frame are less complex than rotating frame due to zero frame speed. For small signal stability analysis, a synchronously rotating frame which yields steady values of steady-state voltages and currents under balanced conditions is used [4].

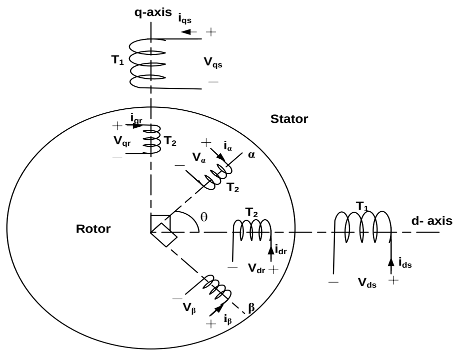


Fig. 1. Two-Phase Equivalent Diagram of Induction Motor

The two-phase equivalent diagram of three-phase induction motor with stator and rotor windings referred to d-q axes is shown in Fig.1. The windings are spaced by 90^o and rotor winding is at an angle θ_r from the stator d-axis. It is assumed that the d-axis is leading the q-axis in clockwise direction of rotation of the rotor. If the clockwise phase sequence is d-q, the rotating magnetic field will revolve at the angular speed of the supply frequency but counter to that of the phase sequence of the stator supply. Thus the rotor is pulled in the direction of the rotating magnetic field i.e. counter clockwise, in this case. The currents and voltages of the stator and rotor windings are marked in Fig.1. The number of turns per phase in the stator and rotor are T_1 and T_2 respectively.

From the above Fig.1, the terminal voltages calculated are as follows,

$$V_{qs} = R_q i_{qs} + p(L_{qq} i_{qs}) + p(L_{qd} i_{ds}) + p(L_{q\alpha} i_\alpha) + p(L_{qb} i_\beta) \quad (1)$$

$$V_{ds} = p(L_{dq} i_{qs}) + R_d i_{ds} + p(L_{dd} i_{ds}) + p(L_{d\alpha} i_\alpha) + p(L_{qb} i_\beta) \quad (2)$$

$$V_\alpha = p(L_{\alpha q} i_{qs}) + p(L_{\alpha d} i_{ds}) + R_\alpha i_\alpha + p(L_{\alpha\alpha} i_\alpha) + p(L_{\alpha\beta} i_\beta) \quad (3)$$

$$V_\beta = p(L_{\beta q} i_{qs}) + p(L_\beta i_{ds}) + p(L_{\beta\alpha} i_\alpha) + R_\beta i_\beta + p(L_{\beta\beta} i_\beta) \quad (4)$$

The following are the assumptions made in order to simplify the (1) to (4).

- Uniform air-gap
- Balanced rotor and stator windings with sinusoidal distribution of magneto motive forces (mmf)
- Inductance in rotor position is sinusoidal and
- Saturation and parameter changes are neglected

From the above assumptions the (1) to (4) of terminal voltages are modified as

$$V_{qs} = (R_s + L_s p) i_{qs} + L_{sr} p(i_\alpha \sin\theta_{qr}) - L_{sr} p(i_\beta \cos\theta_r) \quad (5)$$

$$V_{ds} = (R_s + L_s p) i_{ds} + L_{sr} p(i_\alpha \cos\theta_r) + L_{sr} p(i_\beta \sin\theta_r) \quad (6)$$

$$V_\alpha = L_{sr} p(i_{qs} \sin\theta_r) + L_{sr} p(i_{ds} \cos\theta_r) + (R_{rr} + L_{rr} p) i_\alpha \quad (7)$$

$$V_\beta = -L_{sr} p(i_{qs} \cos\theta_r) + L_{sr} p(i_{ds} \sin\theta_r) + (R_{rr+L_{rr}} p) i_\beta \quad (8)$$

Where,

$R_s = R_q = R_d$, $R_{rr} = R_\alpha = R_\beta$

By applying Transformation to the α and β rotor winding currents and voltages the (5) to (8) will be written as

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qrr} \\ V_{drr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & L_{sr} p & 0 \\ 0 & R_s + L_s p & 0 & L_{sr} p \\ L_{sr} p & -L_{sr}\theta^o{}_r & R_{rr} + L_{rr} p & -L_{rr}\theta^o{}_r \\ L_{sr}\theta^o{}_r & L_{sr} p & L_{rr}\theta^o{}_r & R_{rr} + L_{rr} p \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qrr} \\ i_{drr} \end{bmatrix} \quad (9)$$

The rotor equations in above (9) are refereed to stator side. From this, the physical isolation between stator and rotor d-q axis is eliminated.

$\overset{o}{\theta}_r$ is derivative of θ_r,

a = transformer ratio = (stator turns)/(rotor turns),

$$\left.\begin{aligned} & L_r = a^2 L_{rr} , \quad R_r = a^2 R_{rr} \\ & i_{qr} = \frac{i_{qrr}}{a} , \quad i_{dr} = \frac{i_{drr}}{a} \\ & V_{qr} = aV_{qrr} , \quad V_{dr} = aV_{drr} \end{aligned}\right\} \quad (10)$$

Magnetizing and control inductances are

$$L_m \propto T_1^2 , \quad L_{sr} \propto T_1 T_2 \quad (11)$$

Magnetizing inductance of the stator is

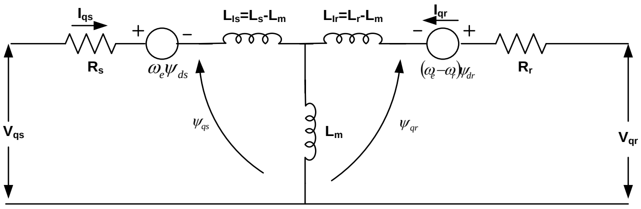
$$L_m = aL_{sr} \quad (12)$$

From equations (10), (11) and (12), the (1) to (4) are modified as

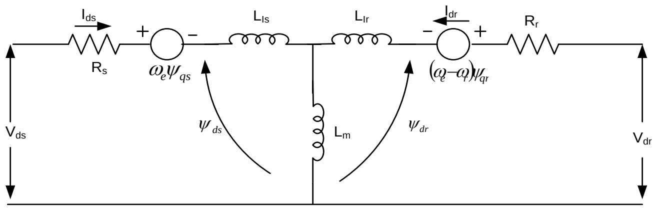
$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & L_m p & 0 \\ 0 & R_s + L_s p & 0 & L_m p \\ L_m p & -L_m\theta^o{}_r & R_r + L_r p & -L_r\theta^o{}_r \\ L_m\theta^o{}_r & L_m p & L_r\theta^o{}_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}$$

Where, $\theta^o{}_r = \omega_r = d\theta/dt$ and p= d/dt

Fig.2 shows the d^e-q^e dynamic model. This is the equivalent circuit of induction motor under synchronous rotating reference frame. If $V_{qr} = V_{dr} = 0$ and $\omega_e = 0$ then it becomes stationary reference frame dynamic model.



(a)



(b)

Fig. 2. Dynamic d^e-q^e Equivalent Circuits of Machine (a) q^e-axis circuit, (b) d^e-axis circuit

The dynamic equations of the induction motor in any reference frame can be represented with the help of flux linkages as variables so as to reduce the number of variables in the dynamic equations. The flux linkages are continuous even if the voltages and currents are discontinuous. In the stator reference frame the stator and rotor flux linkages are defined as follows,

$$\psi_{ds} = \int (v_{ds} - R_s i_{ds})dt \qquad 13)$$

$$\psi_{qs} = \int (v_{qs} - R_s i_{qs})dt \qquad (14)$$

$$\psi_{dr} = \frac{-L_r \omega_r \psi_{qr} + L_m i_{ds} R_r}{R_r + sL_r} \qquad (15)$$

$$\psi_{qr} = \frac{L_r \omega_r \psi_{dr} + L_m R_r i_{qs}}{R_r + sL_r} \qquad (16)$$

$$i_{ds} = \frac{v_{ds}}{R_s + sL_s} - \left[\frac{\psi_{dr}.sL_m}{L_r.(R_s + sL_s)}\right] \qquad (17)$$

$$i_{qs} = \frac{v_{qs}}{R_s + sL_s} - \left[\frac{\psi_{qr}.sL_m}{L_r.(R_s + sL_s)}\right] \qquad (18)$$

The electromagnetic torque of the induction motor in stator reference frame from fig.2 is given by following equations

$$T_e = \frac{3}{2}\frac{p}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \qquad (19)$$

OR

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}(i_{qs}\psi_{dr} - i_{ds}\lambda_{qr}) \qquad (20)$$

III. PRINCIPLE OF VECTOR CONTROL

The fundamental concept of vector control can be explained with the help of Fig.3, in which the machine model is represented in a synchronous rotating reference frame. Assume that the inverter has the unity current gain, i.e. it generates currents i_a, i_b and i_c as ordered by the corresponding command currents i_a^*, i_b^* and i_c^* from the controller. A machine model with internal conversions is shown on the right hand side of the fig. 3. The machine terminal phase currents i_a, i_b and i_c are converted to i_{ds}^s and i_{qs}^s components by 3ϕ-2ϕ transformation. Before applying them to the d^e- q^e machine model these are converted to synchronously rotating frame with the help of unit vector components $\cos\theta_e$ and $\sin\theta_e$.

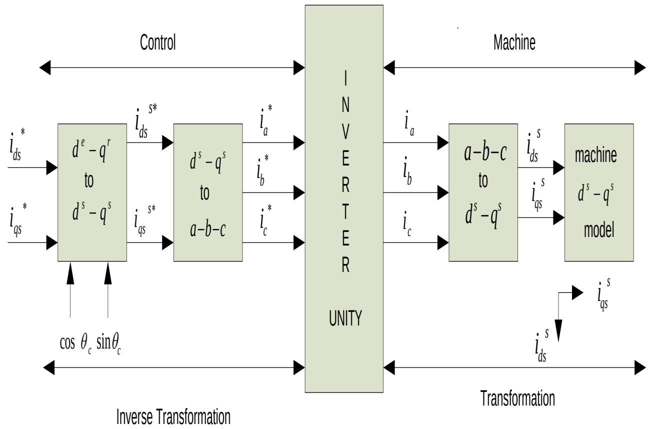


Fig. 3 Basic Vector Control Block Diagram

Vector control implementation principle with machine d^s-q^s model is as shown in above Fig. 3. The controller makes two stages of inverse transformation, so as to 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} current with the flux vector $\hat{\Psi}_r$ and i_{qs} perpendicular to it. Note that the transformation and inverse transformation including the inverter ideally do not incorporate any dynamics. Therefore, the response to i_{ds} and i_{qs} is instantaneous (neglecting computational and sampling delays).

IV. AXES TRANFORMATION

We know that per phase equivalent circuit of the induction motor is valid only in steady state condition. But, it is not that much effective with the transient response of the motor. In transient response condition three phase voltages and currents are not in balance condition. Thus it becomes too much difficult to study the machine performance by analyzing the three phases. In order to reduce this complexity, transformation of axes from 3 – Φ to 2 – Φ is necessary. Another reason for transformation is to analyze any machine of 'n' number of phases. Thus, an equivalent model of 3 – Φ to 2 – Φ is adopted universally, i.e. 'd – q model'.

Consider a symmetrical three-phase IM with stationary axis a_s-b_s-c_s at 2π/3 angle apart. Our aim is to transform the three-phase stationary reference frame (a_s-b_s-c_s) variables into two-phase stationary reference frame (d^s-q^s) variables. Assume that d^s- q^s are oriented at θ angle as shown in Fig. 4

The voltages $V_{ds}{}^s$ and $V_{qs}{}^s$ can be resolved into a_s-b_s-c_s components and can be represented in matrix from as given below,

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

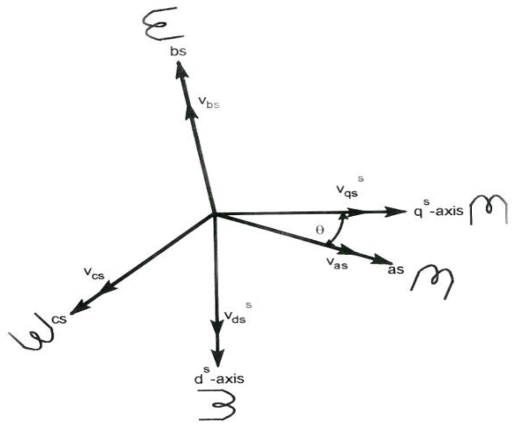


Fig. 4. Three-Phase to Two-Phase Transformation

The corresponding inverse relation is

$$\begin{bmatrix} V_{qs}{}^s \\ V_{ds}{}^s \\ V_{os}{}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} Cos\theta & Cos(\theta-120^o) & Cos(\theta+120^o) \\ Sin\theta & Sin(\theta+120^o) & Sin(\theta+120^o) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix}$$

Here $V_{as}{}^s$ is zero-sequence component, convenient to set θ=0 so that q^s axis is aligned with a_s-axis. Therefore ignoring zero-sequence component, it can be simplified as follows-

$$V_{qs}{}^s = \frac{2}{3}v_{as} - \frac{1}{3}v_{bs} - \frac{1}{3}v_{cs} = v_{as} \quad (21)$$

$$V_{ds}{}^s = \frac{-1}{\sqrt{3}}v_{bs} + \frac{1}{\sqrt{3}}v_{cs} \quad (22)$$

Equation (21) and (22) are called as Clark Transformation.

Fig.5 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 $\theta_y = \omega_e * t$. 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 axis resolved into the d^e-q^e frame as follows,

$$v_{qs} = v_{qs}^s \cos\theta_e - v_{ds}^s \sin\theta_e \quad (23)$$

$$v_{ds} = v_{qs}^s \sin\theta_e + v_{ds}^s \cos\theta_e \quad (24)$$

Constitutively (21) and (22) are known as Park Transformation.

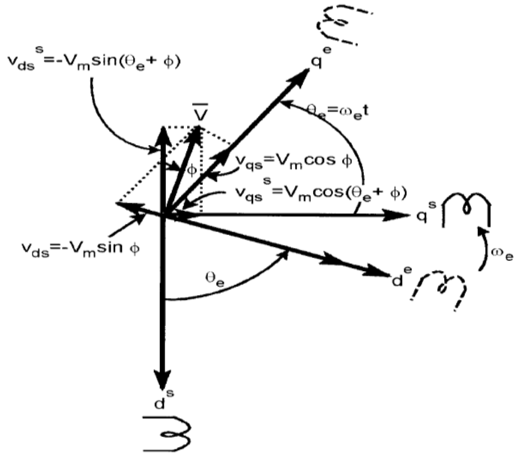


Fig. 5. d^s-q^s Stationary Frame to d^e-q^e Synchronously Rotating Frame Transformation

For simplifications, now onwards the superscript 'e' has been dropped from the synchronous rotating frame parameters. Again, resolving the rotating frame parameters into a stationary frame, the relations are

$$v_{qs}^s = v_{qs}\cos\theta_e + v_{ds}\sin\theta_e \quad (25)$$

$$v_{ds}^s = -v_{qs}\sin\theta_e + v_{ds}\cos\theta_e \quad (26)$$

Constitutively (25) and (26) are known as Inverse Park Transformation [6].

V. INVERTER

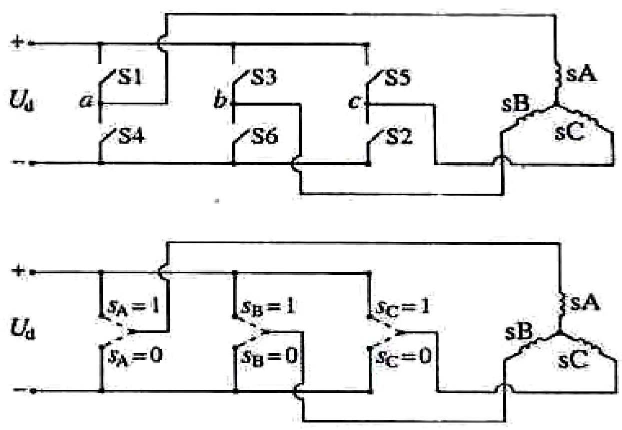


Fig. 6. Schematic diagram of voltage source inverter

Schematic diagram of the voltage source inverter is as shown in fig.6.Switching logic handles the torque status output and flux status output. The function of the optimal switching logic is to select the appropriate stator voltage vector that will satisfy both the torque status and flux status output. Table I shows the possible switching states for S_A, S_B and S_C

VI. VECTOR CONTROL OF INDUCTION MOTOR

The Vector Control or FOC of induction motor is simulated on Matlab/Simulink to study the various aspects of the controller. The actual system can be modeled with a high degree of accuracy in this package. It provides a user interactive platform and a wide variety of numerical algorithms. In this section we will discuss the realization of vector control of induction motor using Simulink blocks [5]. Fig.7 shows the simulink diagram of Vector controlled IM block for simulation. This system consists Induction Motor Model, Three Phase to Two phase transformation block, Two phase to Three phase block, Flux estimator block and Inverter block all together.

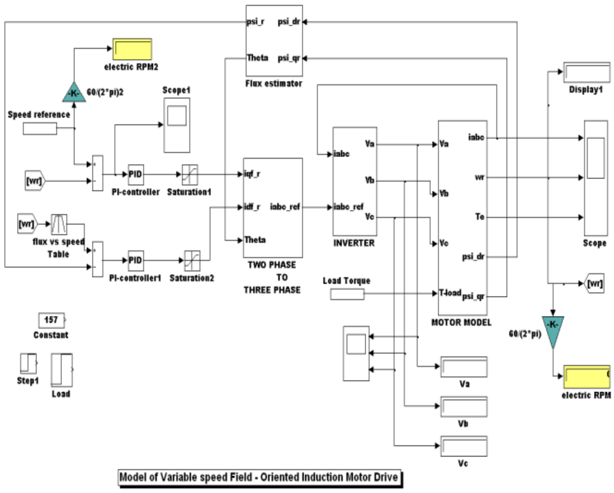


Fig. 7. Simulink Model of Vector Controlled Induction Motor

TABLE I. POSSIBLE SWITCHING STATES FOR S_A, S_B AND S_C

Switching States	S_A	S_B	S_C	**Machine phase voltages**			**d and q axes voltages**	
				v_{as}	v_{bs}	v_{cs}	v_{qs}	v_{ds}
1	1	0	0	(2/3) v_{dc}	(-1/3) V_{dc}	(-1/3) V_{dc}	(2/3) V_{dc}	0
2	1	1	0	(1/3) V_{dc}	(1/3) V_{dc}	(-2/3) V_{dc}	(1/3) V_{dc}	(-1/√3)V_{dc}
3	0	1	0	(-1/3) V_{dc}	(2/3) V_{dc}	(-1/3) V_{dc}	(-1/3) V_{dc}	(-1/√3)V_{dc}
4	0	1	1	(-2/3) V_{dc}	(1/3) V_{dc}	(1/3) V_{dc}	(-2/3) V_{dc}	0
5	0	0	1	(-1/3) V_{dc}	(-1/3) V_{dc}	(2/3) V_{dc}	(-1/3) V_{dc}	(1/√3 V_{dc}
6	1	0	1	(1/3) V_{dc}	(-2/3) V_{dc}	(1/3) V_{dc}	(1/3) V_{dc}	(1/√3)V_{dc}
7	0	0	0	0	0	0	0	0
8	1	1	1	0	0	0	0	0

Fig.8 shows the Simulink block diagram for Induction Motor model. Direct and quadrature axes voltages and load torque are the inputs to this block. And direct and quadrate axis rotor fluxes, direct and quadrature axes stator currents, electrical torque developed and rotor speed are the outputs.

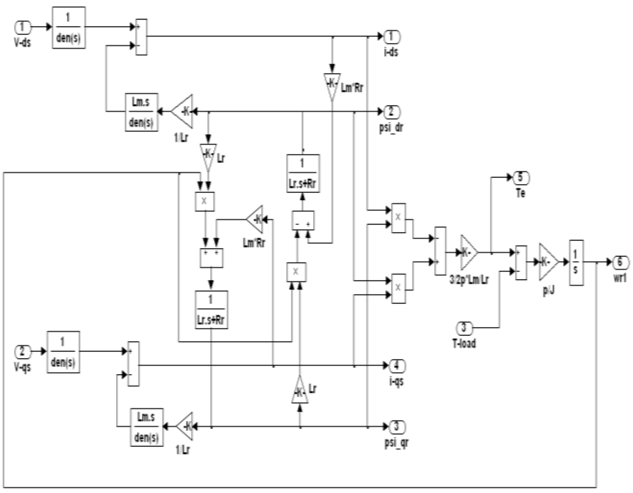


Fig. 8. Simulink Block Diagram of Induction Motor Model

VII. SIMULATION RESULTS

The Simulation of Vector Control of Induction Motor is done by using MATLAB/SIMULINK. The results for different cases are given below.

A. Case 1: No Load Condition

Fig.9 shows the no load line currents, speed and torque waveforms. From the figures it is clear that at starting the values of currents and torque will be high. The motor reaches to its final steady state position with in less time. Rise time is 0.15sec. So we can say that it has fast dynamic response.

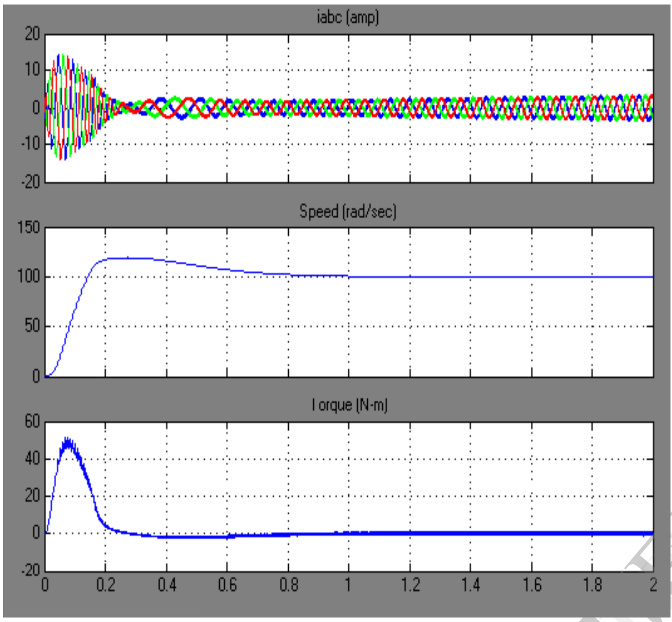


Fig. 9. Simulation results of3-ϕ currents, Speed, and Torque for no-load reference speed of 100 rad/sec.

B. Case 2: Step change in Load

Fig.10 shows the line currents, speed and torque wave forms under loading condition. Motor starts under no load condition. At t = 1.5 sec a load of 15 N-m is applied. It can be seen that at 1.5 sec, the values of currents & torque will increase to meet the load demand and at the same time speed of motor falls relatively and later reaches to the reference speed. Since speed is inversely proportional to the load, and as we increase the load on the motor, motor speed decreases and load torque increases to balance the increased load.

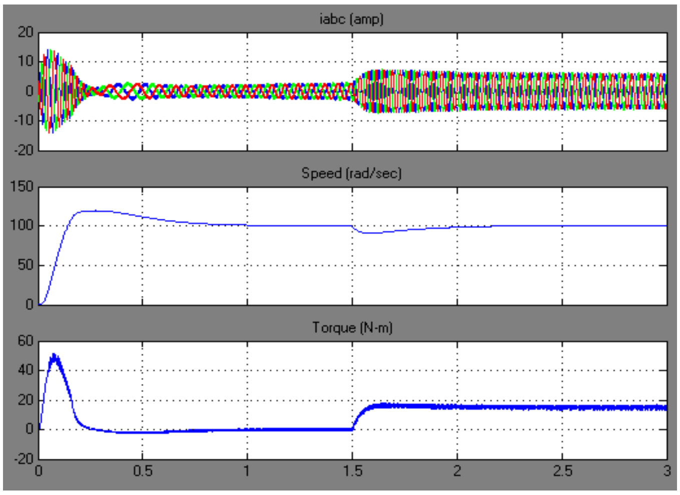


Fig. 10. Simulation results of3-ϕ currents, Speed, and Torque for load torque of 15N-m at t=1.5sec with reference speed of 100 rad/sec.

C. Case 3: Reversal of speed

Speed reversal command is applied at t = 1.5 sec for 100 rad/sec to –100 rad/sec.

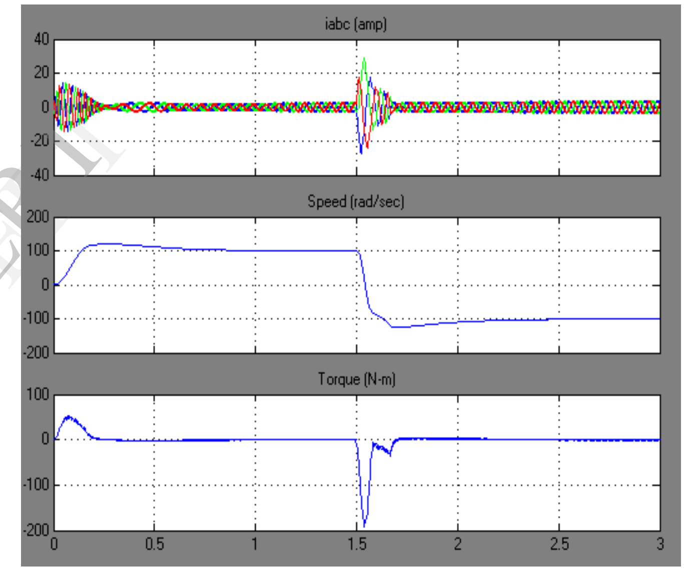


Fig. 11. Simulation results of3-ϕ currents, Speed, and Torque for reversal of speed from 100 to -100 rad/sec

Fig.11 shows the motor is started under no load condition and speed reversal command is applied at t=1.5 sec. at 1.5 sec the motor speed decays from 100 rad/sec and within 0.25 sec it reached its final steady state in the opposite direction. At 1.5 sec torque will increase negatively and reaches to steady state position corresponds to steady state speed value. Speed changes from 100 rad/sec to -100 rad/sec.

VIII. CONCLUSION

In this paper, we have developed the sensor less control of an IM using vector control approach. In this paper indirect vector control is given in details. Simulation results of vector control of an Induction Motor (IM) are obtained using MATLAB/SIMULINK and shown. From the analysis of simulation results the transient and steady state performance of the drive have been presented. Following observations are made from the obtained simulation results.

1) Dynamic response of the drive is fast.
2) Using vector control, we are estimating the speed which is same as that of the actual speed of an IM.

Thus we can also increase the robustness of the motor as well as response of motor to transient condition/ dynamic loading is achieved.

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