Sensorless Control of Induction Motor Drive Using Direct Synthesis for Low Speed

P. Murali, P. Nagasekhar Reddy

Abstract*— This proposed paper proposes the controlling of Induction motor drives. The induction motor dynamics can be compared to that of a DC motor with fast transient response if the flux producing and torque producing components of the stator current can be controlled independently which means it is possible to control the amplitude and phase angle independently. For high performance, variable speed applications, the Induction Motors are used widely due to its low cost, low maintenance, requirement, robustness and reliability, thus replacing the DC motor drives. For wide range of speed applications and fast torque response, IMs perform satisfactory with the vector control strategy. Because of low maintenance and robustness, induction motors have many applications in industries. Speed control of induction motor is more important to achieve maximum torque and efficiency. Various control techniques such as scalar control, vector control, Sensor-less control are used. These Schemes suffers from parameter sensitivity and limited performance at low speed of operation. To make the system sensorless, we go for rotor speed estimation using direct synthesis of state equation, as the closed loop control requires the speed sensor. By using speed sensor, the IM becomes more costly and less reliable and increased maintenance cost. The different simulation results are observed and studied and the analysis of the different simulated results are presented.

***Index Terms*—sensorless,direct synthesis,drive,vectorcontrol.**

I. INTRODUCTION

Energy is the basis of any technical and industrial development. It must be developed and made available at the point of consumption in suitable form. For example chemical, thermal and mechanical are at acceptable price. For the control of any power electronic drive such as an induction motor drive, controllers are designed to control the system. This requires mathematical modeling of the drive, the reason being the higher order nonlinearity and multivariable nature of the systems [1]. By proper mathematical modeling of the plant, the design and development of the power electronics drive systems can be done. The induction motor modeling is mostly done by a three phase (a-b-c) to synchronously rotating (d-q) transformation neglecting saturation, with stator current and rotor flux linkages as the state variables. Electric drives are used in a wide power range, from a few watts to many thousands of kilowatts, in applications ranging from very precise, high-performance position controlled drives in robotics to variable-speed drives for adjusting flow rates in pumps. The basic function of a variable speed drive (VSD) is to control the flow of energy from the mains to the process [2]. Energy is supplied to the process through the motor shaft and the state of the shaft is described by torque and speed [3]. In practice, one of them is controlled and named either “torque control” or “speed control”. When the VSD operates in torque control mode, the load determines the speed. Likewise, when operated in speed control mode, the load determines the torque [4]. Vector controlled Induction motor drive gives robust performance against parameter variations, machine modeling inaccuracies, external disturbances. Irrespective of many advantages of sliding mode controller, it is associated with the chattering problem and needs the accurate knowledge of the system [5].

The volts/hertz (v/f) control and vector control are the most generally used control strategies of induction motor. In general v/f control method is used in fans, conveyors, centrifugal pumps, etc. where high performance and fast response is not needed [6]. The v/f principle adjusts a constant Volts-per-Hertz ratio of the stator voltage by feed forward control. It serves to maintain the magnetic flux in the machine at desired level. The absence of closed loop control and the restriction to low dynamic performance make v/f controlled drives very robust [7]. Scalar control is the technique in which the control action is obtained by the variation of only magnitude of control variables and disregards to control the coupling effect in the machine [8]. The voltage of the machine can be controlled to control the flux and frequency, or slip can be controlled to control the torque. The control is provided by frequency and voltage reference generator with constant volt per hertz ratio. Scalar control technique is somewhat simple to implement, but the inherent coupling effect results sluggish response and the system is easily prone to instability because of higher order system effect. The particular attraction of v/f-controlled drives is their extremely simple control structure, which favors an implementation by a few highly integrated electronic components [9]. There is no direct or indirect control of torque and flux. The status of the rotor is ignored, i.e. no speed or position signal is feedback. These costs-saving aspects are especially important for applications at low power below 5 kW. Even though, the cost advantage makes v/f control very attractive for low power applications their robustness favors its use at high power when a fast response is not required. Constant Volts-per-Hertz control ensures robustness at the expense of reduced dynamic performance, which is adequate for applications like pump and fan drives, and tolerable for other applications [10]. Although simple, this arrangement results in limited speed accuracy and poor torque response. The flux and torque responses are dictated by the response of the motor to the

Manuscript Received on January 2015.
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applied frequency and voltages are not under the control of the drive [11]. In 1971, Blaschke proposed a scheme, which aims at the control of induction motor like a separately excited dc motor, called field oriented control or vector control. Vector control method of speed control of induction motor is generally used for high performance drives. Vector control method re-establishes one of the advantages of the dc drives through implementation of direct flux control. In this control the dynamics of the induction motor is viewed analogous to that of the dc motor by modeling the motor in an appropriate manner. This achieves the decoupling between torque and flux resulting in high accuracy and fast response equivalent to dc motor drive. This is achieved with accurate position information of the flux obtained with the help of sensors. As in dc motor, the torque and flux are controlled by controlling the torque current component and flux current component independently [12]. The main drawback of vector control method is Special arrangements are needed to mount sensors inside the motor, which will affect the ruggedness of drive and hence results in the poor reliability of the drive. Sensor less control of induction motor is nothing but vector control without any shaft or position encoder. The induction motor without speed sensor, extract information of the mechanical shaft speed from measured stator voltages and currents at the motor terminals. By using the speed estimation techniques, the information of speed can be estimated and this information is feedback to control of the induction motor drive. One of such a technique is MRAS, in which the information of speed can obtain by using the stator voltages and currents. The speed estimation by MRAS will give satisfactory operation at low speed also. But the speed estimation at very low speeds particularly at near zero speeds is a major challenge, because at very low speeds the estimation speed is not accurate [10-12].

In the V/Hz control, the speed of induction motor is controlled by the adjustable magnitude of stator voltages and frequency in such a way that the air gap flux is always maintained at the desired value at the steady-state.The large abrupt change in frequency leads to instability of the machine the devised output speed control cannot be maintained precisely because of open loop control. Scalar control enable to control the magnitude of the system only, and they require more complex systems to control [13]. Dynamic performance of the system will be varied depending on time. The field oriented control method controls the currents so it operates with fast responses. This method satisfies the requirements of dynamic drives, where fast response is necessary [14]. It is an excellent control method to handle transients. To overcome this kind unstable dynamic performance of the system vector control will be employed to Induction motor in this thesis. Sensorless vector control of the induction motor is performed in this paper to observe the performance of the drive system. To achieve sensorless operation, i.e. flux estimation and speed feedback without the use of an rotor speed sensor, an appropriate speed estimation has to be included in this paper. In vector control torque and flux are both controlled separately. In proposed paper, sensorless vector control which is used for low speed application by means of direct synthesis technique with the use of MATLAB/Simulink simulation package.

II. MATHEMATICAL MODELING OF INDUCTION MOTOR

The two-phase equivalent diagram of three-phase induction motor with stator and rotor windings referred to d – q axes are shown in Fig 3.1. The winding are spaced by 90o electrical and rotor winding at α , is at an angle θr from the stator d-axis. It is assumed that the d axis is leading the q axis for clockwise direction of rotation of the rotor. If the clockwise phase sequence is dq, the rotating magnetic field will be revolving at the angular speed of the supply frequency but counter to the phase sequence of the stator supply.

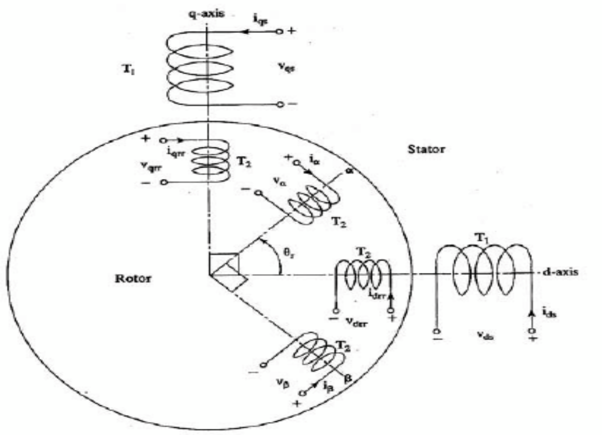

Fig. 1 Two-phase equivalent diagram of induction motor

Therefore 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 figure 1. 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. But it is applicable with slight modification for any number of pairs of poles if it is drawn in terms of electrical degrees. Note that θr is the electrical rotor position at any instant, obtained by multiplying the mechanical rotor position by pairs of electrical poles. The terminal voltages of the stator and rotor windings can be expressed as the sum of the voltage drops in resistances, and rate of change of flux linkages, which are the products of currents and inductances.

From the above figure the terminal voltages are as follows

$$\left.\begin{aligned} V_{qs} &= R_q i_{qs} + p(L_{qq} i_{qs}) + p(L_{qd} i_{ds}) + p(L_{q\alpha} i_\alpha) + p(L_{q\beta} i_\beta) \\ V_{ds} &= p(L_{dq} i_{qs}) + R_d i_{ds} + p(L_{dd} i_{ds}) + p(L_{d\alpha} i_\alpha) + p(L_{d\beta} i_\beta) \\ V_\alpha &= p(L_{\alpha q} i_{qs}) + p(L_{\alpha d} i_{ds}) + R_\alpha i_\alpha + p(L_{\alpha\alpha} i_\alpha) + p(L_{\alpha\beta} i_\beta) \\ V_\beta &= p(L_{\beta q} i_{qs}) + p(L_{\beta d} i_{ds}) + p(L_{\beta\alpha} i_\alpha) + R_\beta i_\beta + p(L_{\beta\beta} i_\beta) \end{aligned}\right\} \quad (1)$$

Where *p* is the differential operator *d/dt*, and V_{qs}, V_{ds} are the terminal voltages of the stator *q* axis and *d* axis. V_α, V_β are the voltages of rotor α and β windings, respectively. iqs and ids are the stator *q* axis and *d* axis currents, respectively. i_α and i_β are the rotor α and β windings currents, respectively. L_{qq}, L_{dd}, $L_{\alpha\alpha}$ and $L_{\beta\beta}$ are the stator q and d axis winding and rotor α and β winding self-inductances, respectively.

$$\left.\begin{aligned} V_{qs} &= (R_s + L_s p) i_{qs} + L_{sr} p(i_\alpha \sin\theta_r) - L_{sr} p(i_\beta \cos\theta_r) \\ V_{ds} &= (R_s + L_s p) i_{ds} + L_{sr} p(i_\alpha \cos\theta_r) + L_{sr} p(i_\beta \sin\theta_r) \\ V_\alpha &= L_{sr} p(i_{qs} \sin\theta_r) + L_{sr} p(i_{ds} \cos\theta_r) + (R_{rr} + L_{rr} p) i_\alpha \\ V_\beta &= -L_{sr} p(i_{qs} \cos\theta_r) + L_{sr} p(i_{ds} \sin\theta_r) + (R_{rr} + L_{rr} p) i_\beta \end{aligned}\right\} (2)$$

where

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

$$\begin{bmatrix} i_{drr} \\ i_{qrr} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ \sin\theta_r & -\cos\theta_r \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

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By applying Transformation to the α and β rotor winding currents and voltages the equation 3.6 will be written as

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qrr} \\ V_{drr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 & L_{sr}p & 0 \\ 0 & R_s + L_s p & 0 & L_{sr}p \\ L_{sr}p & -L_{sr}\theta_r^{\circ} & R_{rr} + L_{rr}p & -L_{rr}\theta_r^{\circ} \\ L_{sr}\theta_r^{\circ} & L_{sr}p & L_{rr}\theta_r^{\circ} & R_{rr} + L_{rr}p \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qrr} \\ i_{drr} \end{bmatrix} \quad (4)$$

The rotor equations in above equation 4 refereed to stator side as in the case of transformer equivalent circuit. From this, the physical isolation between stator and rotor d-q axis use eliminated.

$\dot{\theta}_r$ Derivative of θ_r ,a=transformer ratio=(stator turns)/(rotor turns)

$$\left.\begin{aligned} R_r = a^2 R_{rr}; \quad L_r = a^2 L_{rr} \\ i_{qr} = \frac{i_{qrr}}{a}; \quad i_{dr} = \frac{i_{drr}}{a} \\ V_{qr} = a v_{qrr}; \quad V_{dr} = a v_{drr} \end{aligned}\right\} \quad (5)$$

magnetizing and control inductances are

$$L_m \propto T_1^2 \qquad L_{sr} \propto T_1 T_2 \quad (6)$$

magnetizing inductance of the stator is

$$L_m = aL_{sr} \quad (7)$$

from equations, the equation (4) is modified as,

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

(8)

Where θ_r° = ωr = dθ/dt and p= d/dt

The dynamic equations of the induction motor in any reference frame can be represented by using flux linkages as variables. This involves the reduction of a number of variables in the dynamic equations. Even when the voltages and currents are discontinuous the flux linkages are continuous. The stator and rotor flux linkages in the stator reference frame are defined as

$$\left.\begin{aligned} \Psi_{qs} = L_s i_{qs} + L_m i_{qr} \\ \Psi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \Psi_{qr} = L_r i_{qr} + L_m i_{qs} \\ \Psi_{dr} = L_r i_{dr} + L_m i_{ds} \end{aligned}\right\} \quad (9)$$

$$\left.\begin{aligned} \Psi_{qm} = L_m(i_{qs} + i_{qr}) \\ \Psi_{dm} = L_s(i_{ds} + i_{dr}) \end{aligned}\right\} \quad (9a)$$

From (8) and (9) we get

$$\left.\begin{aligned} v_{ds} = R_s i_{ds} + p\Psi_{ds} \\ v_{qs} = R_s i_{qs} + p\Psi_{qs} \\ v_{dr} = R_r i_{dr} + \omega_r \Psi_{qr} + p\Psi_{dr} \\ v_{qr} = R_r i_{qr} - \omega_r \Psi_{dr} + p\Psi_{qr} \end{aligned}\right\} \quad (10)$$

since the rotor windings are short circuited, the rotor voltages are zero. therefore

$$\left.\begin{aligned} R_r i_{dr} + \omega_r \Psi_{qr} + p\Psi_{dr} = 0 \\ R_r i_{qr} + \omega_r \Psi_{dr} + p\Psi_{qr} = 0 \end{aligned}\right\} \quad (11)$$

The electromagnetic torque of the induction motor in stator reference frame is given by,

$$T_e = \frac{3}{2}\frac{p}{2} L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (12)$$

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}(i_{qs}\Psi_{dr} - i_{ds}\lambda_{qr}) \quad (13)$$

The electro-mechanical equation of the induction motor drive is given by,

$$T_e - T_L = \frac{2}{p} J \frac{d\omega_r}{dt} \quad (14)$$

by using the above equations, the induction motor model is developed in stator reference frame.

III. PRINCIPLE OF VECTOR CONTROL

The fundamentals of vector control can be explained with the help of figure 2, where the machine model is represented in a synchronously reference frame. The inverter is omitted from the figure, assuming that it has units current gain, that is, if generates currents i_a,i_b, and i_c as dictated 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. The machine terminal phase currents i_a,i_b,i_c are converted to i_{ds}^s and i_{qs}^s Components by 3φ-2φ transformation. These are then converted to stationary rotating frame by the unit vector components cos θ_e and sin θ_e before applying them to the de- qe machine model. 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 ids and i_{qs}, respectively. In addition, the unit rector assures correct alignment of i_{ds} current with the flux vector Ψ_r and i_{qs} perpendicular to it, as shown. It can be noted that the transformation and inverse transformation. Including ideally does not incorporate any dynamics, and therefore, the response to. i_{ds} and i_{qs} is instantaneous (neglecting computational and sampling delays).

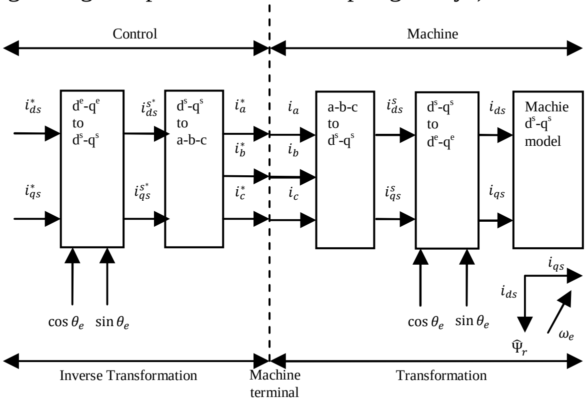

Fig. 2 Vector control implementation principle with machine ds-qs model.

In the direct vector control method, as discussed above, it is necessary to estimate the rotor flux components Ψ_{dr}^S and Ψ_{qr}^S so that the unit vector and rotor flux can be calculated. In this method, the machine terminal voltages and currents are sensed and the fluxes are computed from the stationary frame (d_s-q_s) equivalent circuit shown in figure 2.

These equations are:

$$i_{qs}^s = \frac{2}{3} i_a - \frac{1}{3} i_b - \frac{1}{3} i_c = i_a \quad (15)$$

$$i_{ds}^s = -\frac{1}{\sqrt{3}} i_b - \frac{1}{\sqrt{3}} i_c \quad (16)$$

$$= -\frac{1}{\sqrt{3}}(i_a + 2i_b) \quad (17)$$

Since i_c=-(i_a+i_b) for isolated neutral load

$$v_{qs}^s = \frac{2}{3} v_a - \frac{1}{3} v_b - \frac{1}{3} v_c \quad (18)$$

$$= \frac{1}{3}(v_{ab} + v_{ac})$$

$$v_{ds}^s = -\frac{1}{\sqrt{3}} v_b + \frac{1}{\sqrt{3}} v_c$$

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$$= -\frac{1}{\sqrt{3}} v_{bc} \quad (19)$$

$$\Psi_{ds}^{s} = \int (v_{ds}^{s} - R_s i_{ds}^{s}) dt \quad (20)$$

$$\Psi_{qs}^{s} = \int (v_{qs}^{s} - R_s i_{qs}^{s}) dt \quad (21)$$

$$\Psi_r = \sqrt{\Psi_{ds}^{s\ 2} + \Psi_{qs}^{s\ 2}} \quad (22)$$

$$\Psi_{dm}^{s} = \Psi_{ds}^{s} - L_{ls} i_{ds}^{s} = L_m (i_{ds}^{s} + i_{dr}^{s}) \quad (23)$$

$$\Psi_{qm}^{s} = \Psi_{qs}^{s} - L_{ls} i_{qs}^{s} = L_m (i_{qs}^{s} + i_{qr}^{s}) \quad (24)$$

$$\Psi_{dr}^{s} = L_m i_{ds}^{s} + L_r i_{dr}^{s} \quad (25)$$

$$\Psi_{qr}^{s} = L_m i_{qs}^{s} + L_r i_{qr}^{s} \quad (26)$$

Eliminating i_{dr}^{s} and i_{qr}^{s} we get the following equations.

$$\Psi_{dr}^{s} = \frac{L_r}{L_m} \Psi_{dm}^{s} - L_{lr} i_{ds}^{s} \quad (27)$$

$$\Psi_{qr}^{s} = \frac{L_r}{L_m} \Psi_{qm}^{s} - L_{lr} i_{qs}^{s} \quad (28)$$

$$\Psi_{dr}^{s} = \frac{L_r}{L_m} (\Psi_{ds}^{s} - \sigma L_s i_{ds}^{s}) \quad (29)$$

$$\Psi_{qr}^{s} = \frac{L_r}{L_m} (\Psi_{qs}^{s} - \sigma L_s i_{qs}^{s}) \quad (30)$$

where

$$\sigma = 1 - \frac{L_m^2}{L_r L_s}$$

the torque equation in stationary frame is given by,

$$T_e = \frac{3}{2} \left(\frac{P}{2}\right) \frac{L_m}{L_r} (\Psi_{dr}^{s} i_{qs}^{s} - \Psi_{qr}^{s} i_{ds}^{s}) \quad (31)$$

IV. SENSORLESS CONTROL OF INDUCTION MOTOR DRIVE

The schematic diagram of control strategy of induction motor with sensorless control is shown in Fig 3. Sensor less control induction motor drive essentially means vector control without any speed sensor. The inherent coupling of motor is eliminated by controlling the motor by vector control, like in the case of as a separately excited motor. The inverter provides switching pulses for the control of the motor. The flux and speed estimators are used to estimate the flux and speed respectively. These signals then compared with reference values and controlled by using the PI controller.

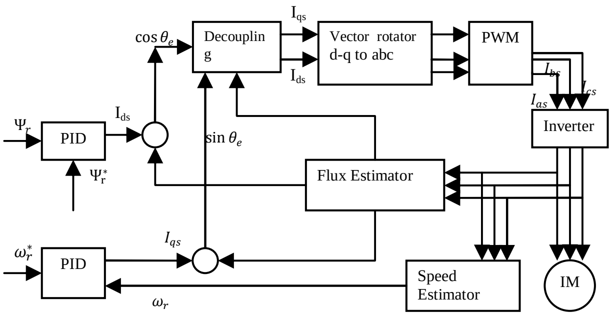

Fig. 3 Block Diagram of Sensorless Control of Induction Motor drive

The dynamic d_s-q_s frame state equations of a machine can be manipulated to compute the speed signal directly. The stator voltage equation for v_{ds} in a d_s-q_s equivalent circuit can be written as

$$v_{ds}^{s} = i_{ds}^{s} R_s + L_{ls} \frac{d(i_{ds}^{s})}{dt} + \frac{d(\Psi_{dm}^{s})}{dt} \quad (32)$$

$$v_{ds}^{s} = \frac{L_m}{L_r} \frac{d(\Psi_{dr}^{s})}{dt} + (R_s + \sigma L_s S) i_{ds}^{s} \quad (33)$$

where

$$\sigma = 1 - \frac{L_m^2}{L_r L_s}$$

$$\frac{d\Psi_{dr}^{s}}{dt} = \frac{L_r}{L_m} v_{ds}^{s} - \frac{L_r}{L_m} (R_s + \sigma L_s S) i_{ds}^{s} \quad (34)$$

Similarly Ψ_{qr} expression can be given as

$$\frac{d\Psi_{qr}^{s}}{dt} = \frac{L_r}{L_m} v_{qs}^{s} - \frac{L_r}{L_m} (R_s + \sigma L_s S) i_{qs}^{s} \quad (35)$$

The above voltage model equations have used to rotor fluxes. The Sensor less control of induction motor using direct synthesis from state equations is simulated on MATLAB/SIMULINK - platform to study the various aspects of the controller. The actual system can be modeled with a high degree of accuracy in this from state equations package. It provides a user interactive platform and a wide variety of numerical algorithms. This chapter discusses the realization of Sensorless control of induction motor using direct synthesis from state equations for Simulink blocks.

V. RESULTS

The parameters for 1.5 hp, 2-pole, 50 Hz induction motor are given below: Stator circuit resistance = 0.277 ohms, Rotor circuit resistance = 0.183 ohms, Inductance of stator circuit = 0.00533H, Inductance of rotor circuit = 0.056H, Mutual inductance = 0.0538H, Moment of inertia = 0.0165 $Kg.m^2$

Case-1: No-Load Condition

The reference speed of 100 rad/sec is considered for the drive system and the same speed is estimated by the drive. Fig.4. shows that the actual speed of induction motor and estimated speed using MRAS are same.

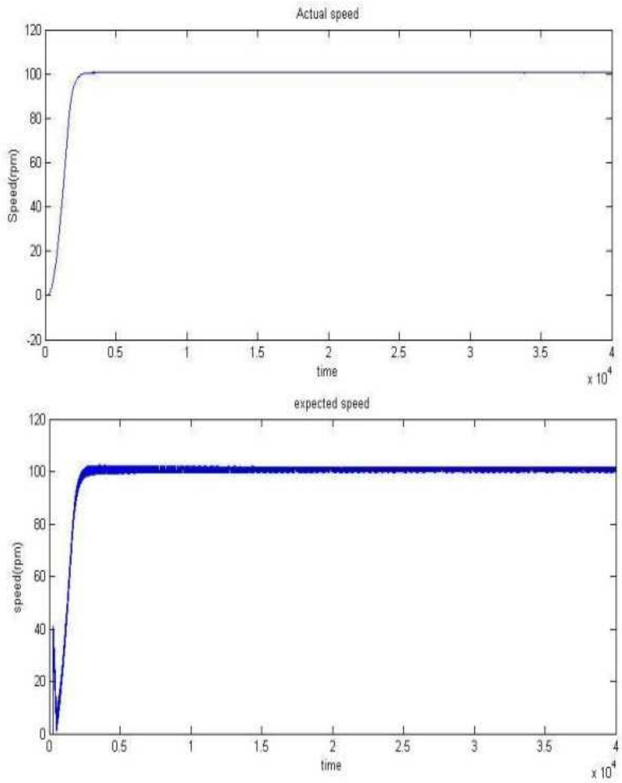

Fig. 4 Actual Speed and Estimated speed Using direct synthesis from state equations in rad/sec

Fig 5 shows the no load line currents, speed and torque wave forms. It can be seen that at starting the values of currents and torque will be high. The motor reaches to its final steady state position within 0.2 sec. Hence it has fast dynamic response.

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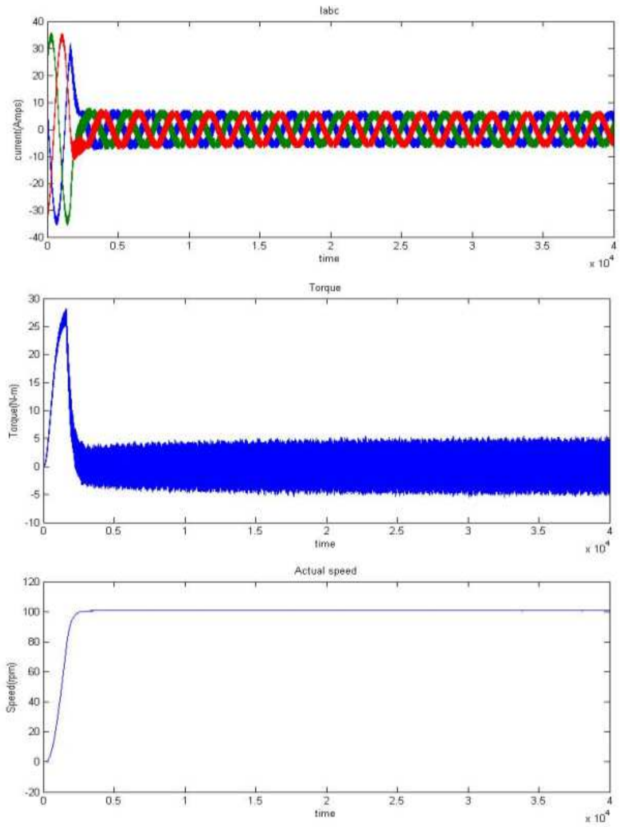

Fig. 5 (a) Line currents in Amps (b) Speed in rad/sec (c) Torque in N-m on no load

Case-2: Step Change in Load

Reference speed = 100 rad/sec; Load torque of 15 N-m is applied at t = 0.5 sec.

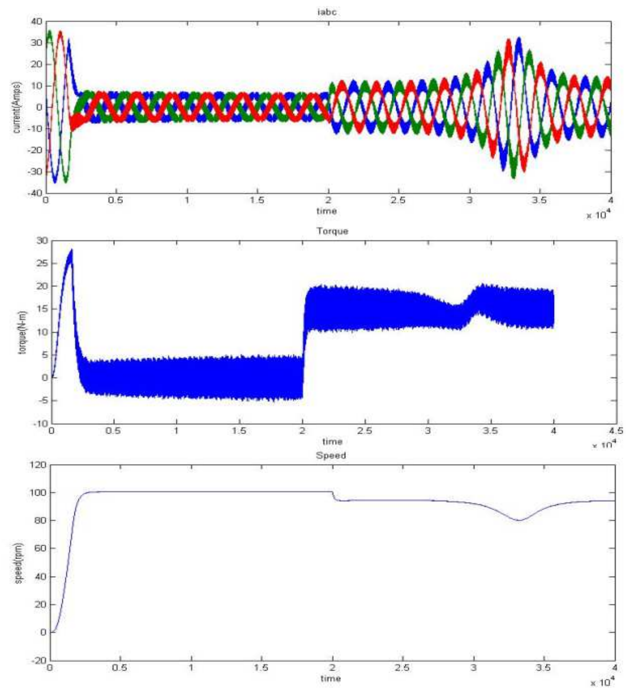

Fig. 6 (a) Line currents in Amps (b) Speed in rad/sec (c) Torque in N-m on step change in load. Fig.6 shows the line currents, speed and torque wave forms under load condition. First the motor is started under no load and at t = 0.25 sec a load of 15 N-m is applied. It can seen that at 0.25 sec, the values of currents & torque will increase to meet the load demand and at the same time speed of motor is slightly falls.

Case-3: Speed Reversal Command

Reference speed = 100 rad/sec; speed reversal command is applied at t = 0.5 sec.

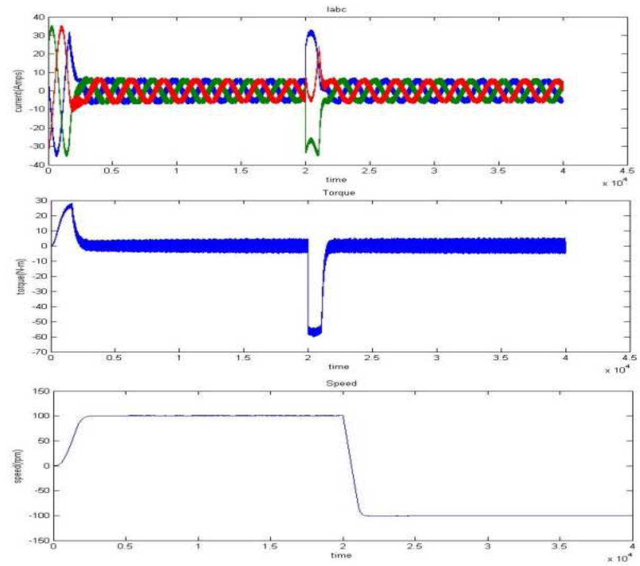

Fig. 7 (a) Line currents in Amps (b) Speed in rad/sec (c) Torque in N-m on no load, speed reversal

The motor is started under no load condition and speed reversal command is applied at t = 0.5 sec. At 0.5 sec the motor speed decays from 100 rad/sec and within 0.1 sec it reached its final steady state in the opposite direction. At 0.5 sec torque will increase negatively and reaches to steady state position corresponds to steady state speed value. Speed change from 100 rad/sec to 40 rad/sec.

VI. CONCLUSIONS

In this paper, Sensorless control of induction motor drive using direct synthesis from state equation has been proposed. Sensor less control gives the benefits of Vector control without using any shaft encoder. The mathematical model of the drive system has been developed and results have been simulated. Simulation results of sensor less control of induction motor using direct synthesis from state equation were carried out by using Matlab/Simulink and from the analysis of the simulation results, the transient and steady state performance of the drive have been presented and analyzed.

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