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# Sensorless Control of Induction Motor using Simulink by Direct Synthesis Technique

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## Abstract

To analyze any motor or generator it is very much important to obtain the machine in terms of equivalent mathematical equations. Traditional per phase equivalent circuit has been widely used in steady state analysis and design of induction motor, but it is not appreciable to predict the dynamic performance of the motor. The dynamic model of the induction motor is derived by using a two-phase motor in direct and quadrature axes. This approach is desirable because of the conceptual simplicity obtained with two sets of windings. This paper describes a generalized model of the induction motor and its Simulink implementation of an induction motor model in a step-by-step approach. The stationary reference frame based model for induction motor is considered due to its simplicity, accurate and robustness to the parameter variation of induction motor. Also, the operation of speed controlled ac drives without mechanical speed or position sensors requires the estimation of internal state variables of the machine. The assessment is based exclusively on measured terminal voltages and currents. Continuing research has concentrated on the elimination of the speed sensor at the machine shaft without deteriorating the dynamic performance of drive control system. Speed estimation is an issue of particular interest with induction motor drives where the mechanical speed of the rotor is generally different from the speed of the revolving magnetic field. After the implementation of machine model, a sensorless control of induction motor using Direct Synthesis from State Equations have been carried out by using Matlab /Simulink for the evaluation of dynamic performance of induction motor.

**Keywords:** Induction motor, stator reference frame, direct synthesis, sensorless control, modeling, MATLAB/SIMULINK.

## Introduction

Usually, when an electrical machine is simulated in any *circuit simulators* like *PSpice* and *SABER* package, its steady state model is used. But for electrical drive studies, the transient behavior is very important. One advantage of *Simulink* over circuit simulators is the ease in modeling the transients of electrical machines and drives and to include drive controls in the simulation. As long as the equations are known, any drive or control algorithm can be modeled in *Simulink*. However, the equations by themselves are not always enough. Some experience with differential equation solving is also required.

Simulink based induction machine models are available in the literature [1], [3], [5], but they appear to be black-boxes with no internal details. Some of them have been recommended using S-functions, which are software source codes for Simulink blocks. This technique does not fully utilize the power and ease of Simulink because usage of S-function programming knowledge is requires to access the model variables. S-functions run faster than discrete Simulink blocks, but Simulink models can be made to run faster using “accelerator” functions or producing stand-alone Simulink models.

In this paper, a modular which is easy to understand Simulink induction motor is described. With the modular system, each block solves one of the model equations. Therefore unlike black-box models, all of the machine parameters are accessible for control and verification purpose.

The Sensorless vector control induction motor drive essentially means vector control without any speed sensor. An incremental shaft mounted speed encoder, usually an optical type is required for closed loop speed or position control in both vector control and scalar controlled drives. In this paper, it is also proposed to implement sensorless vector control of induction motor by direct synthesis of the state equations technique by using *SIMULINK.*

## Induction Motor Model

Before going to analyze any machine it is very much important to obtain the machine in terms of equivalent mathematical equations. The dynamic model of the induction motor is derived by using a two-phase motor in direct and quadrature axes. This approach is desirable because of the conceptual simplicity obtained with two sets of windings, one on the stator and the other in the rotor. The induction motor model can be developed from the fundamental electrical and mechanical equations. Assuming $d_s$-$q_s$ are oriented at θ angles, then the corresponding voltages $V_{ds}$ and $V_{qs}$ can be resolved in to as-bs-cs components and can be represented in matrix form with reference to stationary reference frame.

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

The corresponding inverse relation is,

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{os} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-120) & \cos(\theta+120) \\ \sin\theta & \sin(\theta-120) & \sin(\theta+120) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \qquad (2)$$

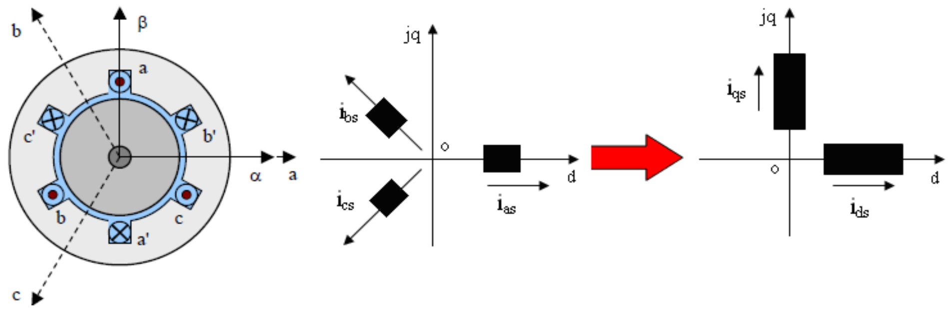


**Figure1:** Three-phase windings and Two-phase equivalent representation of induction motor.

From the above equivalent representation the terminal voltage equation (3) is obtained by assuming the machine is symmetrical with a linear air-gap and magnetic circuit, uniform air gap, sinusoidal distribution of mmf and negligible Saturation effect.

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + L_s\rho & 0 & L_m\rho & 0 \\ 0 & R_s + L_s\rho & 0 & L_m\rho \\ L_m\rho & -L_m\omega_r & R_r + L_r\rho & -L_r\omega_r \\ L_m\omega_r & L_m\rho & L_r\omega_r & R_r + L_r\rho \end{bmatrix}\begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \qquad (3)$$

Where $\rho = \frac{d}{dt}$, *differential operator*

The stator and rotor flux linkages in the stator reference frame are defined as,

$$\begin{aligned} \psi_{qs} &= L_s i_{qs} + L_m i_{qr} \\ \psi_{ds} &= L_s i_{ds} + L_m i_{dr} \\ \psi_{qr} &= L_r i_{qr} + L_m i_{qs} \\ \psi_{dr} &= L_r i_{dr} + L_m i_{ds} \end{aligned} \qquad (4)$$

$$\begin{aligned} \psi_{qm} &= L_m\left(i_{qs} + i_{qr}\right) \\ \psi_{dm} &= L_m\left(i_{ds} + i_{dr}\right) \end{aligned} \qquad (5)$$

From the terminal voltage and flux linkage equations, we get

$$\begin{aligned} V_{ds} &= R_s i_{ds} + \rho\psi_{ds} \\ V_{qs} &= R_s i_{qs} + \rho\psi_{qs} \\ V_{dr} &= R_r i_{dr} + \omega_r \psi_{qr} + \rho\psi_{dr} \\ V_{qr} &= R_r i_{qr} - \omega_r \psi_{dr} + \rho\psi_{qr} \end{aligned} \tag{6}$$

By solving the equations (4),(5) and (6), we have,

$$\psi_{ds} = \int (V_{ds} - R_s i_{ds})dt \tag{7}$$

$$\psi_{qs} = \int (V_{qs} - R_s i_{qs})dt \tag{8}$$

$$\psi_{dr} = \frac{-L_r \omega_r \psi_{qr} + L_m i_{ds} R_r}{R_r + sL_r} \tag{9}$$

$$\psi_{qr} = \frac{L_r \omega_r \psi_{dr} + L_m i_{qs} R_r}{R_r + sL_r} \tag{10}$$

$$i_{ds} = \frac{V_{ds}}{R_s + sL_s} - \left[\frac{\psi_{dr} sL_m}{L_r (R_s + sL_s)}\right] \tag{11}$$

$$i_{qs} = \frac{V_{qs}}{R_s + sL_s} - \left[\frac{\psi_{qr} sL_m}{L_r (R_s + sL_s)}\right] \tag{12}$$

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

$$T_e = \frac{3}{2}\frac{P}{2} L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr}\right) \tag{13}$$

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

$$T_e - T_L = \frac{2}{P} J \frac{d\omega_r}{dt} \tag{14}$$

Using above equations, the induction motor model will be developed in stator reference frame using *Simulink* by direct synthesis technique.

## Simulink implementation

The d-q model requires that all the three-phase variables have to be transformed in to the two-phase synchronously rotating frame. Consequently, the induction machine model will have blocks transforming the three-phase voltages to the d-q frame and the d-q frame back to three-phase.

The inputs of a squirrel cage induction machine are the three-phase voltages, their fundamental frequency, and the load torque. The outputs on the other hand are the three phase currents, rotor speed and the electrical torque.

**3-phase to 2-phase conversion**

For convenient the zero-sequence component, $V_{os}$ in equation (2) is set to $\theta = 0$ so that *qs-axis* is aligned with *as-axis*. Therefore ignoring zero-sequence component, d-q voltage equations can be simplified as,

$$V_{qs}^{s} = \frac{2}{3}V_{as} - \frac{1}{3}V_{bs} - \frac{1}{3}V_{cs} = V_{as}$$

$$V_{ds}^{s} = -\frac{1}{\sqrt{3}}V_{bs} + \frac{1}{\sqrt{3}}V_{cs}$$

Using these equations, 3-phase induction motor is equivalently converted to two phase induction motor as shown in figure 2. Inputs to this block are 3-φ voltages and outputs are equivalent 2-φ direct axis and quadrature axis voltages.

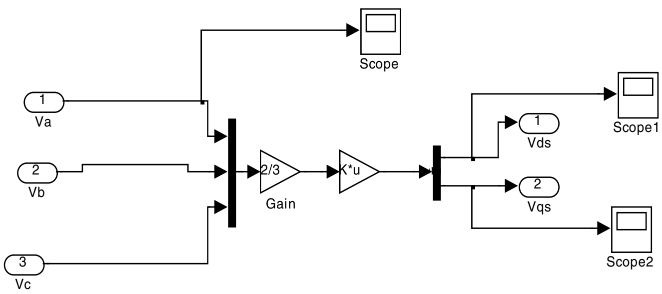


**Figure 2:** Simulink diagram of three-phase to two-phase conversion.

**2-phase to 3-Phase conversion**

The feedback quantities which are in rotating frame are transferred to stationary frame and then using SIMULINK it is transferred from 2-φ to 3-φ as shown in the figure 3.

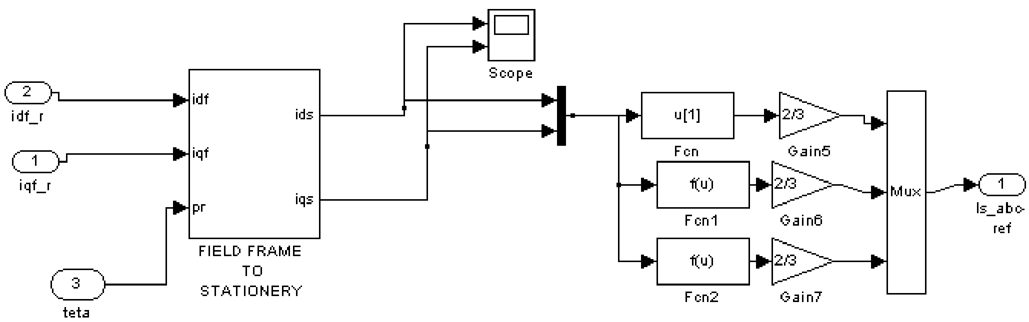


**Figure 3:** Simulink diagram of two-phase to three-phase conversion.

**Unit vector calculation BLOCK**

Unit vectors *cos* $\theta_e$ and *sin* $\theta_e$ are used in vector rotation blocks, "abc-syn conversion block" and "syn-abc conversion block". The angle, $\theta_e$ is calculated directly by integrating the frequency of the input three-phase voltages, $\omega_e$.

$$\theta_e = \int \omega_e dt$$

The unit vectors are obtained simply by taking the sine and cosine of $\theta_e$.

This block also were the initial rotor position can be inserted, if needed, by adding an initial condition to the simulink "integrator" block.

**Induction motor model**

The dynamic equations (7) to (14) were used to develop the simulink model of the induction motor model as shown in figure 4. The inputs to this block are direct and quadrature axes voltages and load torque. The outputs are direct axes stator and rotor fluxes, quadrature axes stator and rotor fluxes, direct and quadrature axes stator currents, developed electrical torque and rotor speed.

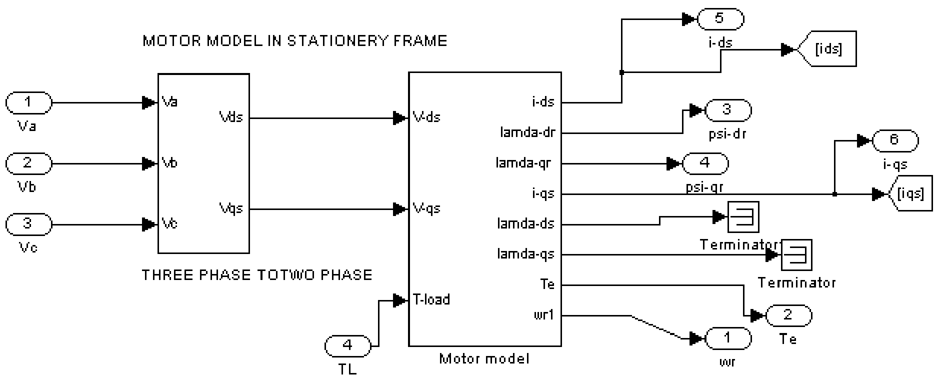


**Figure 4:** Simulink diagram of induction motor model.

## Parameters for Simulation

**Parameters for the induction motor**

| | |
|---|---|
| Stator circuit resistance | = 4.495 Ω |
| Rotor circuit resistance | = 5.365 Ω |
| Inductance of stator circuit | = 0.165 H |
| Inductance of rotor circuit | = 0.162 H |
| Mutual inductance | = 0.149 H |
| Moment of inertia | = 0.095 Kg.m$^2$ |

**Simulation parameters**

| | |
|---|---|
| DC link voltage | = 250 V |
| Step size | = 25 μs |

## Sensorless vector control

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. In high performance applications, the induction motor is controlled through field orientation techniques, which require knowledge of the rotor speed. Since speed sensors decrease the reliability of a drive system (and increase its cost), a common trend is to eliminate them and use various speed estimation techniques like slip calculation, direct synthesis from state equations, MRAS, speed adaptive flux observer, Extended kalman filter (EKF) and slot harmonics. In this paper, a direct synthesis from state equations technique were used to implement sensorless vector control using *SIMULINK*. 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.

The Simulink diagram of sensorless vector control of induction motor using direct synthesis of dynamic state equations is shown in figure 5.

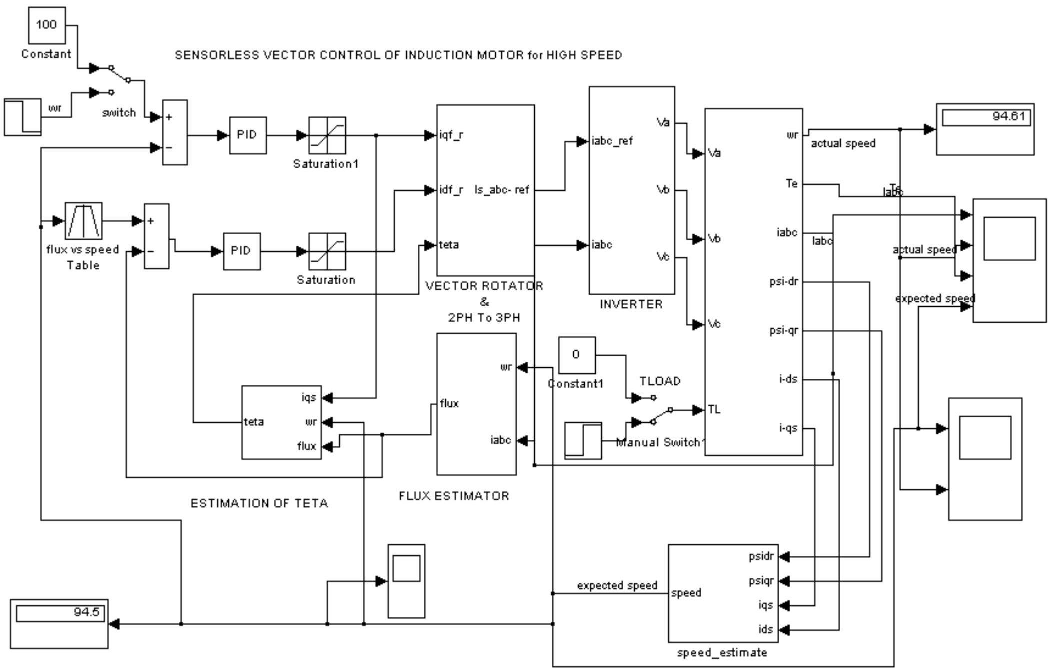


**Figure 5:** Simulink diagram of sensorless vector control.

## Simulation results

The induction motor modeling and Sensorless control of induction motor is done by using *SIMULINK*. The results of direct and quadrature axes voltages & currents, drive for starting, steady state, step change in load and speed reversals were presented.

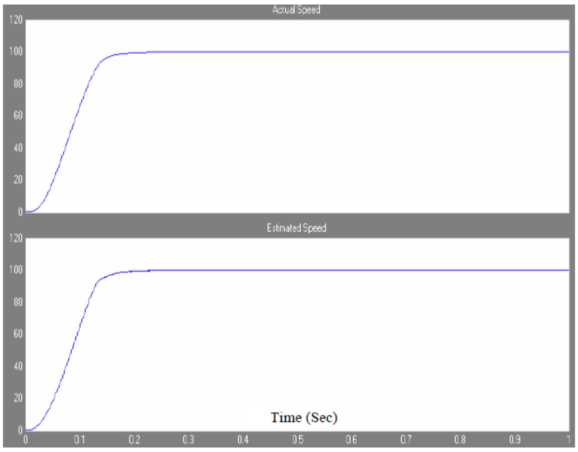


**Figure 6:** Actual speed and estimated speed using direct synthesis of state equations in rad/sec.

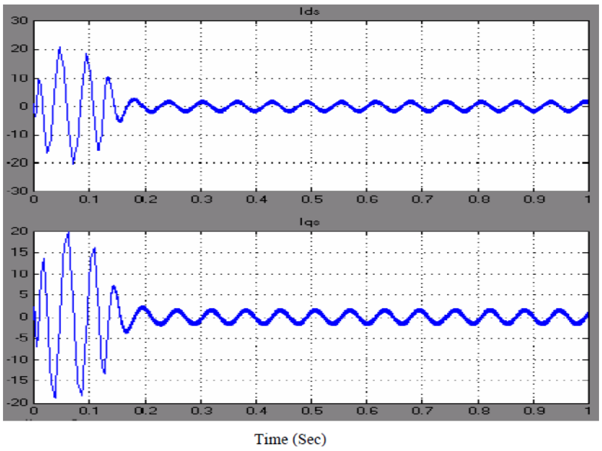


**Figure 7:** direct and quadrature axes currents.

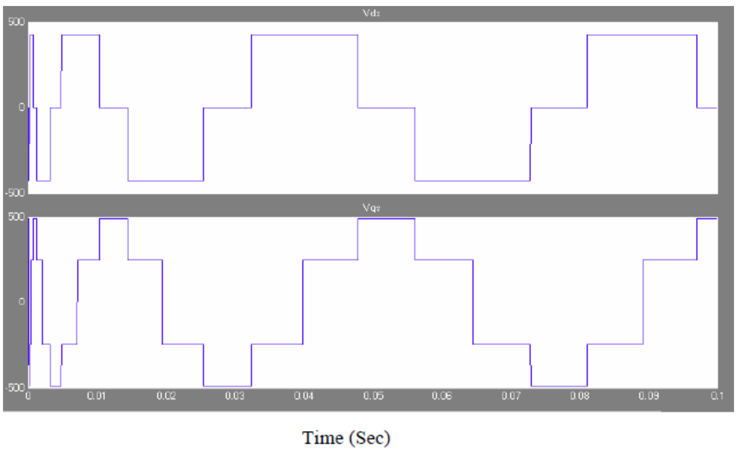


**Figure 8:** direct and quadrature axes voltages.

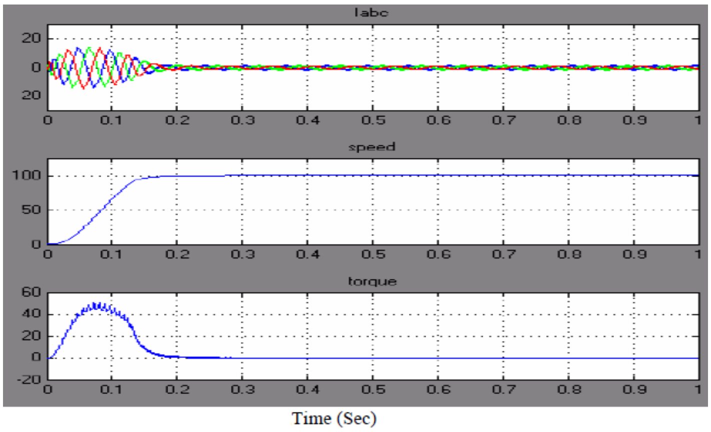


**Figure 9:** simulation results of a drive during starting and steady state.

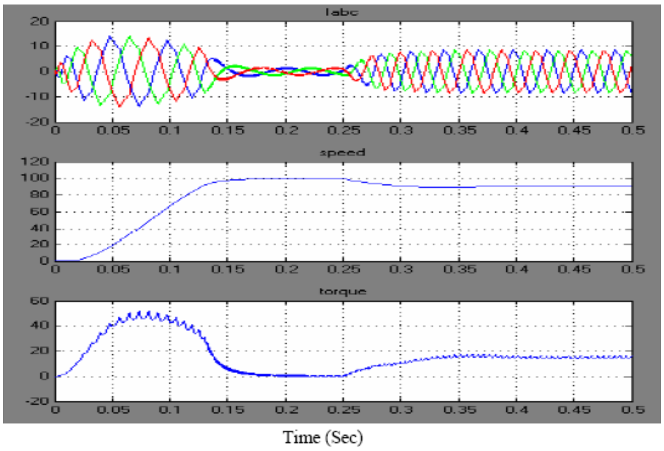


**Figure 10:** simulation results of a drive on step change in load; a 15 N-m is applied at time t=0.25 sec.

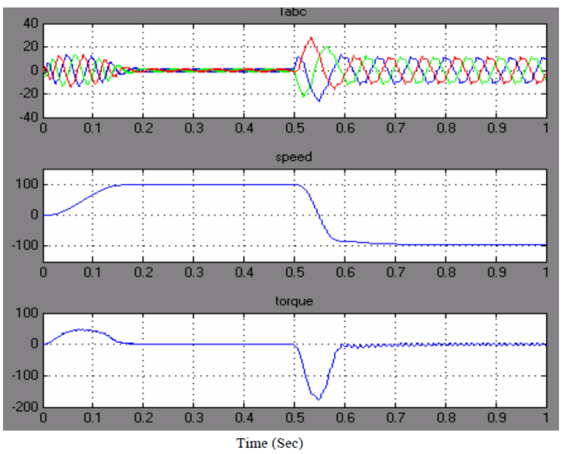


**Figure 11:** transient response of a drive during speed reversal of a drive; speed is changed from +100 rad/sec to -100 rad/sec.

## Conclusion

The simulink simulation model presented in this paper is effective for transient analysis of the induction motor using direct synthesis. Using direct synthesis of Simulink software, each block of the model can be connected and be modified easily. Finally, sensorless control of induction motor using direct synthesis from the state equations have been presented for starting, steady state, transient and speed reversal without using any shaft encoder as in the case of vector control. The developed simulink model increases the ruggedness as well as it provides fast response.

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