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SIMULATION MODEL FOR INDUCTION MOTOR DRIVE

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Abstract-Induction Motor Drives (IMD) have been widely used from last many years in various industrial as well as transportation systems i.e. hybrid /electric vehicles, and electric propulsion ships, where variable speed and constant torque with high performance requirements are demanding increasingly. This paper presents an introduction of indirect and direct ac/ac power conversion schemes, various topologies. It presents Comprehensive description of the model of induction motor drive in abc reference frame and then the motor model is derived in arbitrary reference frame using Park's transformation. The d-q model equations are presented and developed the model in MATLAB/ Simulink. Simulation results of induction motor drive is obtained when three phase balanced supply is applied to three phase induction motor and motor drive is simulated at no load as well as full load conditions. The steady state characteristics of drive under rated voltage and frequency are presented in terms of torque, stator current, input power, developed power and efficiency with respect to speed of the drive. The results demonstrate the versatility of the presented induction motor model.

Keywords: Induction Motor, d-q model, Scalar Control

1. INTRODUCTION

Variable speed drive systems are essential in many industrial applications [5]. In the past, DC motors were used extensively in areas where variable speed operation was required, since their flux and torque could be controlled easily by the field and armature current.

DC motors have certain disadvantages, which are due to the existence of the commutator and the brushes. That is, they require periodic maintenance; they cannot be used in explosive or corrosive environments and they have limited commutator capability under high speed, high voltage operational conditions. These problems can be overcome by the application of alternating current motors, which can have simple and rugged structure, high maintainability and economy; they are also robust and immune to heavy overloading [1]. These advantages have recently made induction machines widely used in industrial applications. However, the speed or torque control of induction motors is more difficult than DC motors due to their nonlinear and complex structure. The torque of the DC motors can be controlled by two independent orthogonal variables, stator current and rotor flux, where such a decoupling does not exist in induction motors [5].

Recent years have seen the evolution of a new control strategy for AC motors, called "vector control", which has made a fundamental change in this picture of AC motor drives in regard to dynamic performance. Vector control makes it possible to control an AC motor in a manner similar to the control of a separately excited DC motor, and achieve the same quality of dynamic performance [7]. As for DC machines, torque control in AC machines is achieved by controlling the motor currents. However, in contrast to a DC machine, in AC machine, both the phase angle and the modulus of the current has to be controlled, or in other words, the current vector has to be controlled. This is the reason for the terminology "vector control" [1].

The high quality of the dynamic performance of the seperately excited DC motor is a consequence of the fact that its armature circuit and the field circuit are magnetically decoupled. In a DC motor, the mmf produced by the field current and the mmf produced by the armature current are spatially in quadrature. Therefore there is no magnetic coupling between the field circuit and the armature circuit.

Because of the repetitive switching action of the commutator on the rotor coils as the rotor rotates, this decoupling continues to exist irrespective of the angular position and speed of the rotor. This makes it possible to effect fast current changes in the armature circuit, without being hampered in this by the large inductance of the field circuit. Since the armature current can change rapidly, the machine can develop torque and accelerate or decelerate very quickly when speed changes are called for, attain the demanded speed in the fastest manner possible. As in the DC motors, in AC motors also, the torque production is the result of the interaction of a current and a flux. But in the AC induction motor, in which the power is fed on the stator side only, the current responsible for the torque and the current responsible for producing flux are not easily seperable. The underlying principle of vector control is to separate out the component of the motor current responsible for producing the torque and the component responsible for producing the flux in such a way that they are magnetically decoupled, and then control each independently, in the same way as is done in a seperately excited DC motor [7]. One aspect of DC motor control simplicity is that the independent control of torque and flux in a DC drive is due to the basic design of the motor and, in practice, is not dependent on the parameters of any particular motor. This is not the case with an AC machine in which, torque and flux control is exercised using standard two axis machine concepts. For decoupling the torque and flux controlling components of current, motor parameters should be known. All inductance parameters are known to be nonlinear functions of the motor flux level and hence may change either intentionally, under field weakening region, or unintentionally, under detuning of the controller. Electrical parameters of the machine should be well known for field orientation. Parameters are also required for the design of the torque, flux and speed controllers and here the problem is common to both AC vector and DC drive systems. Generally, the settling response of the torque and field controllers is dependent on the stator and rotor time constants, respectively (for the DC machine these are dependent on armature and field time constant which are quite easy to measure). The settling response of the speed controller is, of course, load dependent and is thus normally catered for by variable PID controllers which can be adjusted at commissioning. The need to have a good knowledge of the induction motor parameters in addition to online identification of parameters is a significant disadvantage of vector controlled drives in comparison with the DC systems [7].

As the invention of power semiconductor devices started from 1950s, inventions of converter circuits, control and applications has enriched topology of converters. During last three decades, use of power electronics devices increases its applications in all major areas i.e. residential, commercial and industrial, machine drives, harmonic filtering, AC and DC power supplies etc. In near future, these devices influence the industrial productivity of nation and consumption of energy worldwide. As in the era of power electronics, Adjustable Speed Drive (ASD) plays a relevant role and now a day the market of adjustable speed drive is increasing worldwide at 10% per year approximately. Adjustable Speed Drive is an advanced technology, which is driven by numerous internal drivers i.e. advancement of power electronics components and other external drivers i.e. reliability, quality, price, applications, features and performance, efficiency, size and packaging, and product flexibility etc. As recently, there is increased interest in direct torque control of matrix converter fed induction motor drive. In this literature survey, different techniques based on the switching patterns for bidirectional switches of matrix converters and direct torque controlled matrix converter fed IM drive are presented.

In [4] which is a PhD thesis prepared by Erhan AKIN in 1994, principles of vector control and flux calculation methods are given in detail then experimental results of vector control algorithm using indirect field orientation are presented. In application bang-bang control are used in the inverter stage. Voltage model with an open integrator is used for flux estimation and hysteresis band current control is used in the inverter stage for vector control of induction machines. Cascaded filters are used as integrator to overcome the drift problem while taking integral in voltage model. Also space vector pulse with modulation, which gives better solution, is used instead of hysteresis band current control.

In [5] which is also a master thesis prepared by Ertan MURAT in 2002, parameter dependency of motor controllers are introduced. Theory of parameter estimation methods at standstill is explained in detail and also experimental results of these methods are presented. Finally a new online parameter estimation method is introduced and experimental results of online estimation for stator winding resistance is presented.

The theory of three- phase matrix converter is dealt with and mathematical equations for switching angles for all nine switches of matrix converter are presented by A. Zuckerberger, D. Weinstoc k, A. Alexand rovitz [10]. The operation of matrix converter operation is based upon calculated switching angles. Modeling and simulations of converter loaded with (induction motor) load are performed.

This paper discusses the induction motor modeling with v/f control method.

2. INDUCTION MOTOR MODEL

A three phase squirrel cage induction motor is schematically shown as in Fig. 2.1, where motor contains group of coupled circuits, which are linear in nature. Stator and rotor windings are distributed and magnetic axis of rotor and stator phases are shown as in Fig. 2.2. The stator is fed through three phase balanced supply and angular displacement θ_r between the stator and rotor phase axis varies with respect to time and is expressed as:

$$p\,\theta_r = \omega_r$$

Where ω_r is termed as rotor angular speed in radians per second.

The slip of induction motor is expressed as:

$$s = \left(\frac{\omega_e - \omega_r}{\omega_e} \right)$$

Where ω_e is termed as synchronous speed in radians per second.

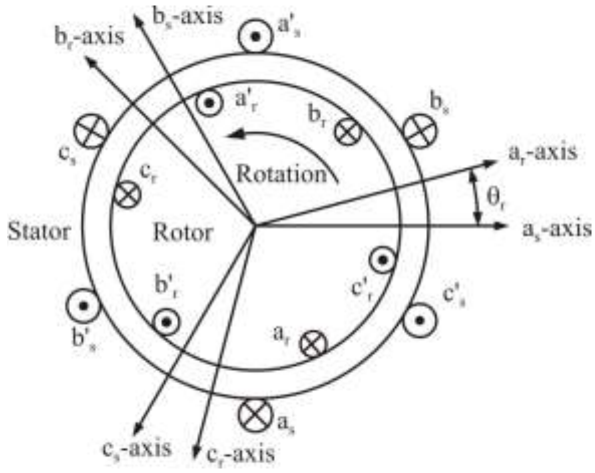

Fig. 2.1 Two Pole Three Phase Symmetrical Induction Motor

Following assumptions are taken to derive mathematical model of induction motor for sake of simplicity: Sinusoidal distribution of air gap flux, negligible hysteresis and eddy current losses, No magnetic saturation Uniform air gap and balanced rotor and stator windings with sinusoidal distributed MMF.

The voltage equations for stator windings can be expressed as:

$$V_{as} = R_s\, i_{as} + p\,\psi_{as}\,,\quad V_{bs} = R_s\, i_{bs} + p\,\psi_{bs}\,,\quad V_{cs} = R_s\, i_{cs} + p\,\psi_{cs}$$

Similarly, the voltage equations for rotor windings are expressed as:

$$V_{ar} = R_r\, i_{ar} + p\,\psi_{ar}\,,\quad V_{br} = R_r\, i_{br} + p\,\psi_{br}\,,\quad V_{cr} = R_r\, i_{cr} + p\,\psi_{cr}$$

Where a, b and c represents the winding phases and r, s represents the rotor and stator respectively. Self inductances of stator and rotor phases, mutual inductances between stator phases, mutual inductances between rotor phases are constant due to smooth rotor construction, but the mutual inductance between stator phase and rotor phase depends upon position of rotor and the instantaneous values of these variables are proportional to cosine of the angle between stator and rotor axis at any instant.

The linking flux equations for stator and rotor windings are expressed as:

For stator winding:

$$\psi_{as} = L_{ss}\, i_{as} + L_{sm}(i_{bs}+i_{cs}) + L_{sr}\,[\,i_{ar}\cos\theta_r + i_{br}\cos(\theta_r+2\pi/3) + i_{cr}\cos(\theta_r-2\pi/3)]$$

$$\psi_{bs} = L_{ss}\, i_{bs} + L_{sm}(i_{as}+i_{cs}) + L_{sr}\,[\,i_{ar}\cos(\theta_r-2\pi/3) + i_{br}\cos\theta_r + i_{cr}\cos(\theta_r+2\pi/3)]$$

Similarly for rotor winding:

$$\psi_{ar} = L_{rr}\, i_{ar} + L_{rm}(i_{br}+i_{cr}) + L_{sr}\,[\,i_{as}\cos\theta_r + i_{bs}\cos(\theta_r-2\pi/3) + i_{cs}\cos(\theta_r+2\pi/3)]$$

$$\psi_{br} = L_{rr}\, i_{br} + L_{rm}(i_{ar}+i_{cr}) + L_{sr}\,[\,i_{as}\cos(\theta_r+2\pi/3) + i_{bs}\cos\theta_r + i_{cs}\cos(\theta_r-2\pi/3)]$$

$$\psi_{cr} = L_{rr}\, i_{cr} + L_{rm}(i_{ar}+i_{br}) + L_{sr}\,[\,i_{as}\cos(\theta_r-2\pi/3) + i_{bs}\cos(\theta_r+2\pi/3) + i_{cs}\cos\theta_r\,]$$

Where;

L_{ss}, L_{rr} are the self inductances of stator and rotor windings respectively.

L_{sm}, L_{rm} are the mutual inductances of stator and rotor windings respectively.

L_{sr} is the mutual inductance between stator and rotor windings.

The induction motor is fed through balanced supply system without neutral connections, so stator and rotor currents can be expressed as:

$$i_{as} + i_{bs} + i_{cs} = 0\,,\quad i_{ar} + i_{br} + i_{cr} = 0$$

$$i_{as} + i_{bs} = -i_{cs}\,,\quad i_{bs} + i_{cs} = -i_{as}\,,\quad i_{as} + i_{cs} = -i_{bs}$$

$$i_{ar} + i_{br} = -i_{cr}\,,\quad i_{br} + i_{cr} = -i_{ar}\,,\quad i_{ar} + i_{cr} = -i_{br}$$

By substituting the values in the equations of stator flux linkage for phase a is expressed as:

$$\psi_{as} = L_{ss}\, i_{as} + L_{sm}(-i_{as}) + L_{sr}\,[\,i_{ar}\cos\theta_r + i_{br}\cos(\theta_r+2\pi/3) + i_{cr}\cos(\theta_r-2\pi/3)]$$

or

$$\psi_{as} = \left(L_{ss} - L_{sm}\right) i_{as} + L_{sr}\, i_{ar}\cos\theta_r + L_{sr}\, i_{br}\cos(\theta_r+2\pi/3) + L_{sr}\, i_{cr}\cos(\theta_r-2\pi/3)]$$

or

$$\psi_{as} = L_s\, i_{as} + L_1\, i_{ar} + L_3\, i_{br} + L_2\, i_{cr}$$

Where

$$L_s = L_{ss} - L_{sm},\ L_1 = L_{sr}\cos\theta_r,\ L_2 = L_{sr}\cos(\theta_r - 2\pi/3),\ L_3 = L_{sr}\cos(\theta_r + 2\pi/3)]$$

Similarly the expressions for ψ_{bs}, ψ_{cs}, ψ_{ar}, ψ_{br}, and ψ_{cr} are carried out and then the flux equations are expressed in matrix form as:

$$\begin{bmatrix} \psi_{as} \\ \psi_{bs} \\ \psi_{cs} \\ \psi_{ar} \\ \psi_{br} \\ \psi_{cr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & 0 & L_1 & L_3 & L_2 \\ 0 & L_s & 0 & L_2 & L_1 & L_3 \\ 0 & 0 & L_s & L_3 & L_2 & L_1 \\ L_1 & L_2 & L_3 & L_r & 0 & 0 \\ L_3 & L_1 & L_2 & 0 & L_r & 0 \\ L_2 & L_3 & L_1 & 0 & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_{ar} \\ i_{br} \\ i_{cr} \end{bmatrix}$$

The voltage equation for stator phase a can be obtained by substituting the value of stator flux linkage, as

$$V_{as} = R_s\, i_{as} + p\, L_s\, i_{as} + p\, L_1\, i_{ar} + p\, L_3\, i_{br} + p\, L_2\, i_{cr}$$

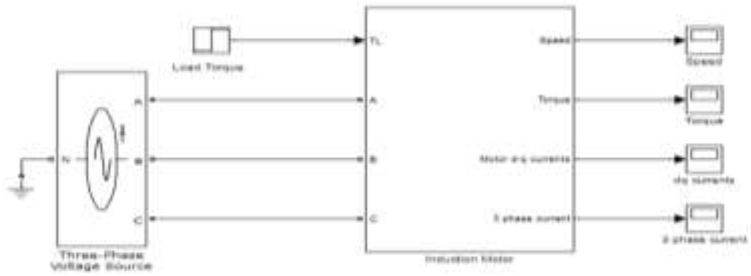

Fig. 2.2 Simulink Model of Induction Motor

Voltage equations for Vbs,Vcs, Var, Vbr and Vcr can be obtained in similar manner. After calculating all the required voltage equations, the mathematical model of induction motor in abc reference frame is expressed as:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \\ V_{ar} \\ V_{br} \\ V_{cr} \end{bmatrix} = \begin{bmatrix} R_s + p\,L_s & 0 & 0 & pL_1 & pL_3 & pL_2 \\ 0 & R_s + p\,L_s & 0 & pL_2 & pL_1 & pL_3 \\ 0 & 0 & R_s + p\,L_s & pL_3 & pL_2 & pL_1 \\ pL_1 & pL_2 & pL_3 & R_r + p\,L_r & 0 & 0 \\ pL_3 & pL_1 & pL_2 & 0 & R_r + p\,L_r & 0 \\ pL_2 & pL_3 & pL_1 & 0 & 0 & R_r + p\,L_r \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_{ar} \\ i_{br} \\ i_{cr} \end{bmatrix}$$

In this section, implementation of simulink model of induction motor is represented. In Fig. 2, three phase voltage source is applied as input of induction motor. The simulink implementation in d-q reference frame can be carried out using following equations, which are expanded form of rotor and stator dq voltage equations.

$$\mathrm{V}_{qs} = R_s\, i_{qs} + \frac{d}{dt}\psi_{qs} + \omega\,\psi_{ds} \qquad \mathrm{V}_{ds} = R_s\, i_{ds} + \frac{d}{dt}\psi_{ds} - \omega\,\psi_{qs}$$

$$\mathrm{V}_{qr} = R_r\, i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega - \omega_r)\,\psi_{dr} \qquad \mathrm{V}_{dr} = R_r\, i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega - \omega_r)\,\psi_{qr}$$

Above equation represents stator q and d axis voltages. The torque of motor is expressed as:

$$T_e = 1.5\, p\ (\psi_{ds}\, i_{qs} - \psi_{qs}\, i_{ds})$$

$$\psi_{qs} = L_s\, i_{qs} + L_m\, i_{qr}$$

$$\psi_{ds} = L_s\, i_{ds} + L_m\, i_{dr}$$

$$\psi'_{qr} = L_r\, i_{qr} + L_m\, i_{qs}$$

$$\psi'_{dr} = L_r\, i_{dr} + L_m\, i_{ds}$$

$$L_s = L_{ls} + L_m$$

$$L_r = L_{lr} + L_m$$

Where;

The first order differential equation for angular velocity of motor can be expressed as:

$$\frac{d}{dt}\omega_m = \frac{1}{2H}(T_e - F\,\omega_m - T_m)$$

Where

$$\frac{d}{dt}\theta_m = \omega_m$$

3. SIMULATION RESULTS

The Simulink results and the characteristics for three phase induction motor is obtained when balanced supply is applied to induction motor. The model of motor is simulated at no load as well as full load conditions.

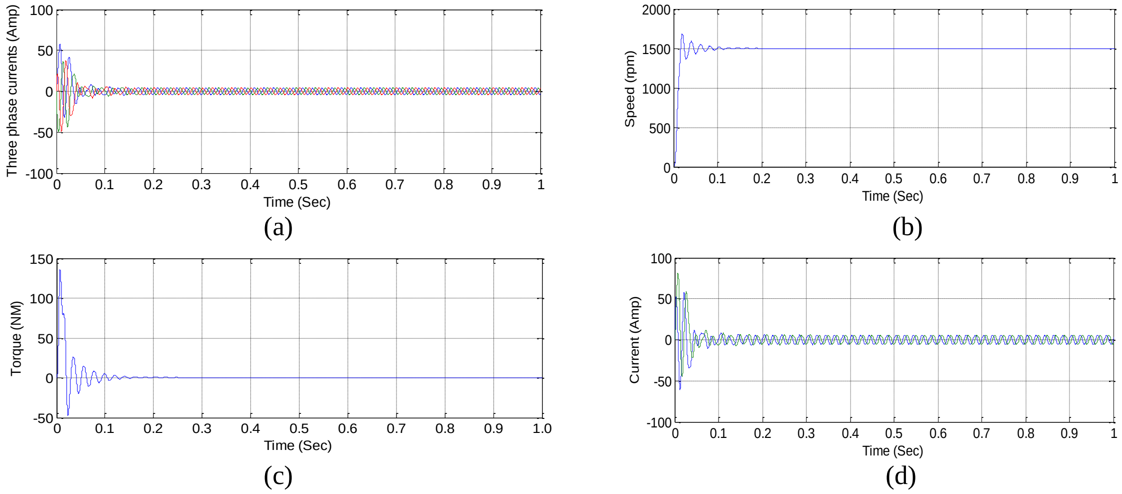

Fig. 3.1 Induction Motor Characteristics at No Load with Respect to Time (a) Three Phase Currents (b) Speed (c) Torque (d) dq Current

The three phase induction motor behaves as short circuited transformer at standstill conditions, when it is fed through full supply voltages and draws very high currents. Fig. 3.1 (a) shows that motor draws large amount of currents when it is accelerated from standstill conditions. During starting conditions, motor basically draws inrush currents i.e. generally four times as compared to its rated full load value for the production of torque, which is generally greater than full load torque. During starting, motor accelerates and reaches at maximum speed and at that time current level is high during starting and it settles at low value at steady state condition as motor attains rated speed. The speed characteristics at no load conditions are shown as in Fig. 3.1(b). Fig. 3.1 (c) shows the electromagnetic torque of motor, which has very high during starting conditions and as soon as motor attains its steady state conditions, electromagnetic torque sets at zero. Fig. 3.1 (d) shows the d-q currents for three phase induction motor.

Similarly full load torque of 28.78 Nm (as calculated from parameters of the machine) is applied to simulink model of three phase induction motor at 0.5 sec.

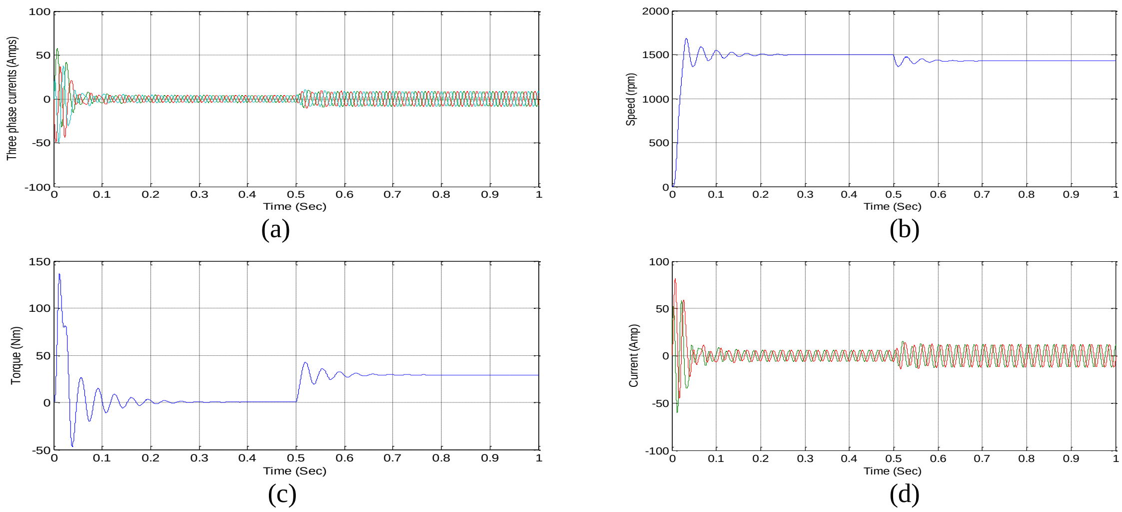

Fig. 3.2 Induction Motor Characteristics at Full Load with Respect to Time (a) Three Phase Currents (b) Speed (c) Torque (d) dq Current

Fig. 3.2 (a) shows the three phase currents for motor, which is similar to no load conditions, as full load torque of 28.78 Nm is applied at 0.5 sec the current increases and attains its rated value after a short interval of time approx. 0.02 sec. The speed characteristic at full load conditions is shown as in Fig. 3.2 (b). It can be observed from Fig. 3.2 (b) that during starting motor speed increases rapidly and attains rated speed at 0.2 sec and when full load torque is applied at 0.5 sec, speed decreases due to application of load torque. After 0.02 sec, motor again attains rated speed at full load conditions. When machine attains rated speed at full load (1430 rpm), all machine variables attains their steady state values. Fig. 3.2 (c) shows the electromagnetic torque of motor whereas Fig. 3.2 (d) shows the d-q currents for three phase induction motor at full load torque conditions.

From the simulation results at no load as well as full load conditions, it is verified that the simulation model is accurately developed and can be used for further investigations.

CONCLUSION

This paper presents an introduction of indirect and direct ac/ac power conversion schemes, various topologies. It presents Comprehensive description of the model of induction motor drive in abc reference frame and then the motor model is derived in arbitrary reference frame using Park's transformation. Simulation results obtained when three phase balanced supply is applied to three phase induction motor and motor drive is simulated at no load as well as full load conditions. The steady state characteristics of drive under rated voltage and frequency are presented in terms of torque, stator current, input power, developed power and efficiency with respect to speed of the drive. The results demonstrate the versatility of the presented induction motor model.

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