TRANSIENT ANALYSIS OF THREE-PHASE INDUCTION MACHINE USING DIFFERENT REFERENCE FRAMES

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Abstract:
Three-phase induction machines are generally used as motors for many industrial applications and all this is due to its simple construction and other advantages in contrast to other machines. Popularity of these motors has resulted into a lot of research including the transient behaviour of the machine. Literature survey reveals that most of the researchers adopted only a single reference frame to estimate transient behaviour of the machine. In this work qd axis based modeling is proposed to analyze the transient performance of three-phase squirrel cage induction motor using stationary reference frame, rotor reference frame and synchronously rotating reference frame. Simulated results have been presented to buttress the functionality of these induction motor with the aid of MATLAB/SIMULINK.

Keywords: modeling, induction motor, reference frames, simulation, transient analysis.

I.Introduction

During start-up and under severe transient operations induction motor draws large currents, produces voltage dips, oscillatory torques and can even generate harmonics in the power systems. In order to investigate such problems, the *d, q axis* model has been found to be well tested and proven to be reliable.Numerous studies have been made on estimating the electrical parameters of the asynchronous machine given both skin effect, and the saturation level. For the electrical drives with three phase induction motors with deep rotor bars were developed mathematical models and command strategies for developing high performance systems. In electrical drives it is preferred the vector command in respect to the rotor flux, a flux that cannot be de-fined using one form for motor with deep rotor bars; as a result, in many cases it is used the air gap flux for the vector command. Using the pseudorotor-flux, it can be achieved similar performances as with the rotor flux orientation, in this case, the equivalent rotor parameters are used. The squirrel cage with deep rotor bars can be equivalent with a double cage, one of these cages having constant parameters. Based on the influence of the skin effect over electrical rotor parameters can be constructed a mathematical model for the asynchronous motor with deep rotor bars that allows simulation of different operating modes. The basic concept of transient modeling of the machine and thedynamic behaviour may be analyzed using any one of following reference frames: (a) Stationary reference frame, (b) Rotor reference frame and (c) Synchronous reference frame; specific tests to estimate the machine parameters that proceeds with transient modeling may be necessary[1-3].

Matlab/Simulink is a very useful tool for modeling electrical machine and it can be used to predict the dynamic behaviour of the machines. In this work Matlab/Simulink based modeling is proposed using all the three reference frames mentioned above. During simulations sufficient time span is included to predict the complete behaviour of the machine[4, 5].

II.Mathematical Modeling[6]

A three-phase induction motor can be modeled with *qd* axis theory. According to *qdo* axis modeling:

$$[F_{qdo}] = [T_{qdo}] * [F_{abc}] \tag{1}$$

where

$$[T_{qdo}] = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3 & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \tag{2}$$

The voltage balance equation for the *q*, *d* coils in arbitrary reference frames are as follows [2]:

$$[V^C] = [Z^C] * [i^C] \tag{3}$$

where

$[V^C]$ and $[i^C]$ represents '4x1' column matrices of voltage and current and are given as

$[V_{qs}^C V_{ds}^C V_{qr}^C V_{dr}^C]^T$ and $[i_{qs}^C i_{ds}^C i_{qr}^C i_{dr}^C]^T$ respectively; and, impedance matrices (4x4), $[Z^C]$ is given as,

$$[Z^C] = \begin{bmatrix} R_s + L_s p & \omega_c L_c & L_m p & \omega_c L_m \\ -\omega_c L_s & R_s + L_s p & -\omega_c L_m & L_m p \\ L_m p & (\omega - \omega_r) L_m & R_r + L_r p & (\omega_c - \omega_r) L_r \\ -(\omega - \omega_r) L_m & L_m p & -(\omega_c - \omega_r) L_r & R_r + L_r p \end{bmatrix}$$

III.Stationary Reference Frame Model [7, 8]

The speed of the reference frames is that of the stator, which is zero; hence,

$$\omega_c = 0 \tag{4}$$

Equation (4) is substituted into equation (3). The resulting model is

$$[V] = [Z] * [i] \tag{5}$$

where,

$[V]$ and $[i]$ represents '4x1' column matrices of voltage and current and are given as

$[V_{qs}, V_{ds}, V_{qr}, V_{dr}]^T$ and $[i_{qs}, i_{ds}, i_{qr}, i_{dr}]^T$ respectively.

And, impedance matrices (4x4), $[Z]$ is given as

$$[Z]=\begin{bmatrix} R_s+L_s p & 0 & L_m p & 0 \\ 0 & R_s+L_s p & 0 & L_m p \\ L_m p & -\omega_r L_m & R_r+L_r p & -\omega_r L_r \\ \omega_r L_m & L_m p & \omega_r L_r & R_r+L_r p \end{bmatrix}$$

The torque equation is

$$T_e=\frac{3}{2}\frac{P}{2}L_m(i_{qs}i_{dr}-i_{ds}i_{qr}) \tag{6}$$

In case bus bar voltages are

$$\begin{aligned} V_{as} &= V_m*\cos(\omega_s t+\lambda) \\ V_{bs} &= V_m*\cos(\omega_s t+\lambda-2\pi/3) \\ V_{cs} &= V_m*\cos(\omega_s t+\lambda+2\pi/3) \end{aligned} \tag{7}$$

And the motor terminals are connected directly to the bus, then using the transformation of equation (2),

$$\begin{aligned} V_{qs} &= V_m*\cos(\omega_s t+\lambda) \\ V_{ds} &= -V_m*\sin(\omega_s t+\lambda) \end{aligned} \tag{8}$$

IV.Rotor Reference Frames Model [9, 10]

The speed of the rotor reference frames is

$$\omega_c=\omega_r \tag{9}$$

and the angular position is

$$\theta_c=\theta_r \tag{10}$$

Substituting in the upper subscript *r* for rotor reference frames and equation (4) in the equation (3), the induction-motor model in rotor reference frames is obtained. The equations are given by

$$[V^r]=[Z^r]*[i^r] \tag{11}$$

$[V^r]$ and $[i^r]$ represents '4x1' column matrices of voltage and current and are given as

$[V^r_{qs},V^r_{ds},V^r_{qr},V^r_{dr}]^T$ and $[i^r_{qs},i^r_{ds},i^r_{qr},i^r_{dr}]^T$ respectively; and, impedance matrices (4x4), $[Z^r]$ is given as

$$[Z^r] = \begin{bmatrix} R_s + L_s p & \omega_r L_s & L_m p & \omega_r L_m \\ -\omega_r L_s & R_s + L_s p & -\omega_r L_s p & L_m p \\ L_m p & 0 & R_r + L_r p & -0 \\ -0 & L_m p & -0 & R_r + L_r p \end{bmatrix}$$

and the electromagnetic torque is

$$T_e = \frac{3}{2}\frac{P}{2} L_m (i_{qs}^r \ i_{dr}^r \ - i_{ds}^r \ i_{qr}^r \ ) \tag{12}$$

The transformation from *abc* to *qdo* variables is obtained by substituting (10) into $[T_{abc}]$ defined in (2) as

$$[T_{abc}^r] = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos(\theta_r - 2\pi/3) & \cos(\theta_r + 2\pi/3) \\ \sin\theta_r & \sin(\theta_r - 2\pi/3) & \sin(\theta_r + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \tag{13}$$

The terminal voltage equation (7) becomes

$$\begin{aligned} V_{qs} &= V_m * \cos(s\omega_s t + \lambda) \\ V_{qs} &= -V_m * \sin(s\omega_s t + \lambda) \end{aligned} \tag{14}$$

The *q*, *d* voltages are therefore of slip frequency and the *q- axis* rotor current behaves exactly as the phase a rotor current does.

V.Synchronously Rotating Reference Frame Model [11]

The speed of the reference frame is

$$\omega_c = \omega_s \tag{15}$$

Stator supply angular frequency (rad /sec) and the instantaneous angular position is

$$\theta_c = \theta_s = \omega_s t \tag{16}$$

By substituting (15) into (3), the induction motor model in the synchronous reference frames is obtained. By using the superscript e to denote this electrical synchronous reference frame, the model is obtained as

$$[V^e] = [Z^e] * [i^e] \tag{17}$$

where,

$\left[V^e\right]$ and $\left[i^e\right]$ represents '4x1' column matrices of voltage and current and are given as $\left[V_{qs}^e, V_{ds}^e, V_{qr}^e, V_{dr}^e\right]^T$ and $\left[i_{qs}^e, i_{ds}^e, i_{qr}^e, i_{dr}^e\right]^T$ respectively, and, impedance matrices (4x4), $\left[Z^e\right]$ can be given as,

$$\left[Z^e\right] = \begin{bmatrix} R_s + L_s p & \omega_s L_s & L_m p & \omega_w L_m \\ -\omega_s L_s & R_s + L_s & -\omega_s L_m & L_m p \\ L_m p & (\omega_s - \omega_r) L_m & R_r + L_r p & (\omega_s - \omega_r) L_r \\ -(\omega_s - \omega_r) L_m & L_m p & -(\omega_s - \omega_r) L_r & R_r + L_r p \end{bmatrix}$$

The electromagnetic torque is,

$$T_e = \frac{3}{2}\frac{P}{2} L_m (i_{qs}^e i_{dr}^e - i_{ds}^e i_{qr}^e) \text{ N-m} \qquad (18)$$

The transformation from *abc* to *dqo* variables is found by substituting (16) into equation (2) and is given as

$$\left[T_{abc}^e\right] = \frac{2}{3}\begin{bmatrix} \cos\theta_s & \cos(\theta_s - 2\pi/3) & \cos(\theta_s + 2\pi/3) \\ \sin\theta_s & \sin(\theta_s - 2\pi/3) & \sin(\theta_s + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \qquad (19)$$

The terminal voltage in equation (7) become

$$\begin{aligned} V_{qs} &= V_m * \cos\lambda \\ V_{ds} &= V_m * \sin\lambda \end{aligned} \qquad (20)$$

This means the stator d, q voltages are dc quantities. The mechanical motion described by

$$p\omega_r = (T_e - T_L)/J \qquad (21)$$

VI. Matlab/Simulink model

Figure 1shows a Matlab/Simulink model which is a high level technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numerical computation. Matlab can also be used as computational back-end for a variety of specialized tasks. It can be extended by modules, so called toolboxes. There exist toolboxes for various applications as for machine learning, for different kind of statistics or for creating user interfaces. Simulink is such a toolbox. It provides a graphical environment for designing, modeling and simulating dynamic systems. Simulink can be used to model a wide variety of complex systems as for example motor control, access systems or computer vision algorithms. Simulink itself can further be expanded with other toolboxes to add domain specific functionality, as for example special tools for modeling real-time systems. A very important aspect about Simulink models is that they can be used to automatically generate code for various embedded platforms.

Simulink models are created by using a graphical user interface. It can model continuous as well as discrete systems. Complex models are built of a small number of elementary building blocks which are connected with each other. Before a system can be simulated the model of the system has to be compiled. During this process Simulink compiles the model into an equation system that is then solved by Matlab. Simulink provides a number of solvers and parameters for this process so models can be simulated as required by a project.

VII.Simulation

Asynchronous motor is essentially the stator resistance and leakage reactance inseries with the rotor resistance and leakage reactance. Consequently with the rated applied voltage, the starting current is large, in some cases in the order of 10 times the rated value. This is observed in Figure 2 stator phase voltage at full-load.Figure3is stator phase current at transient and steady state, Figure 4 is torque speed of induction motor; while Figure 5is electromagnetic produced during transient condition. It is recommended that reduced voltage starting methods such as star/delta, autotransformer and soft start methods be employed to reduce the excess starting current. The rotor accelerates from stall with zero mechanical load torque and since friction and windage losses are not taken into account, the machine accelerates to synchronous speed[12 -14].

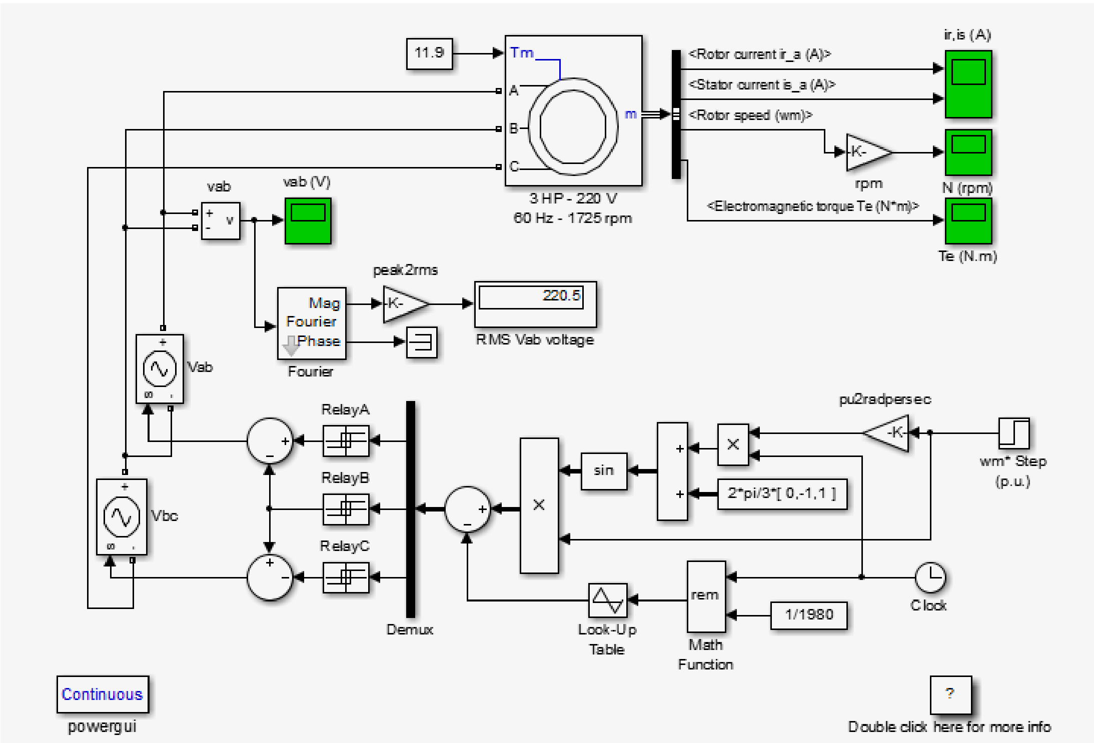
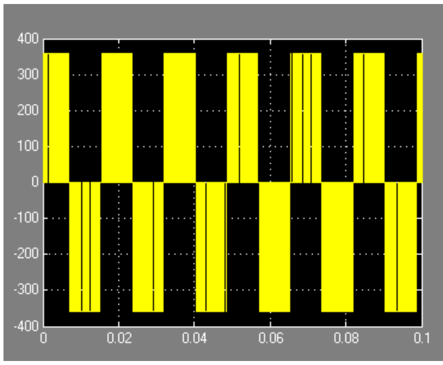


Figure 1: Matlab/Simulink model of the three-phase induction motor



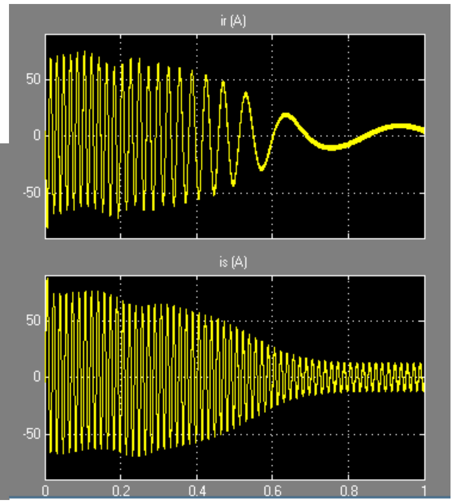
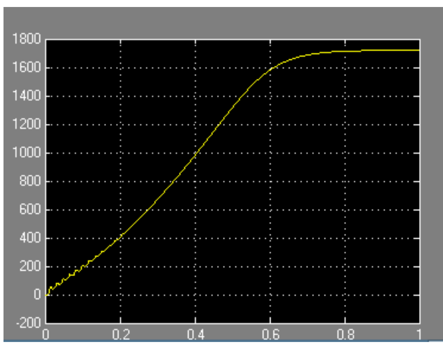


Figure 2: Stator phase Voltage at full-load

Figure 3: Stator phase current at transient and steady state



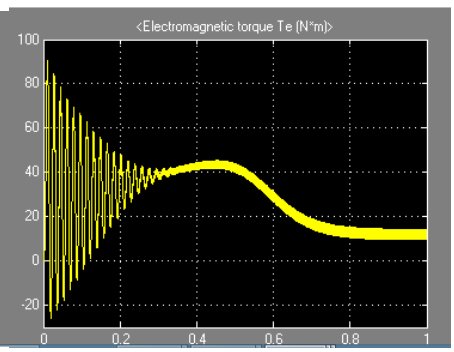


Figure 4: Torque speed of Induction motor

Figure 5: Electromagnetic produced during transient condition.

VII.Conclusion

For the analysis of dynamic behaviour of the asynchronous machine, study of reference frames are essential. This paper has demonstrated the elegance of MATLAB/SIMULINK in the dynamic modeling and simulation of asynchronous motor driving a mechanical load. The results obtained clearly show the elegance of *d-q axis* transformation theory in machine modeling, the inherent limitations of asynchronous motors and effect of mechanical loading on various motor output variables. The transient process for the stator currents has a longer variation due to the rotor parameters variation with the changing speed. The transient behaviour has two steps: the first step is when the rotor parameters vary in respect to the pulsating currents from the rotor circuit, this variation is maintained almost till the operating speed; the second step takes place for the constant rotor parameters and transient behaviour, which are carried out similar to inductive circuits. For the first step the transient behaviour is not changed significantly since the rotor parameters vary continuously and in tight limits.In simulation of dynamic (transient) behaviour of the induction motor, equations have been used; exhibits nonlinear form due to both their structure and frequency variation of the rotor parameters.

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