

Squirrel Cage of Induction Motors Simulation via Simulink

H. Arabaci and O. Bilgin

Abstract—This study presents Simulink implementation and mathematical model of squirrel cage induction motor. Induction motor models are generally available in form of d-q model in literature for Simulink simulations. But in this study the model include rotor bars and end-ring near the stator windings. So, the rotor bars and end-ring data (currents, voltages etc.) are accessible and can be investigated. And the rotor bars and end-ring parameters are verification and made optimization. In the solution the number of rotor bars determines the dimension of inductance matrix in the motor model. Because simulated motor has 18 rotor bars, dimension of this matrix is 22x22. Each component of the matrix changes according to motor position. Calculating of inverse of the matrix is necessary for every time period. This process is very difficult in Simulink by using function blocks. In the present study m-file block is used instead of function block. So, solution of mathematical model of squirrel-cage induction motor is implemented by Simulink. The simulation results are given with the model used in start-up condition. The results show that the proposed method is used simulation of the induction motor with squirrel-cage.

Index Terms—Simulink simulation, squirrel cage, mathematical model, induction motors.

I. INTRODUCTION

Simulation of the three-phase induction motor is well documented in the literature and digital computer solution can be performed using various methods, such as numeric programming, symbolic programming and the electromagnetic transient program. With the rapid development in computer hardware and software, new simulation packages which are much faster and more user friendly are now available. Traditionally, induction motors have been analyzed using the classical lumped parameter approach is practical and very useful for steady state analysis and design synthesis it does not allow transient conditions to be modeled and therefore cannot be used as part of a simulation procedure. One approach for modeling transient conditions is to use the d-q axis method [1]. Principally, the d-q axis model is only valid when the input voltage is sinusoidal so that any mmf can be resolved into the two axes current a.c machines drives however produce periodic but non-sinusoidal outputs. Since these voltages are not sinusoidal the d-q axis model cannot be used directly. In this contribution the original d-q axis model is adapted so that the cycloconverter model can be correctly applied. This is

achieved by utilizing separate d-q axis models [2]. But in present study the aimed model include rotor bars and end-ring together with the stator windings. So, the rotor bars and end-ring data (currents, voltages etc.) are accessible and can be investigated. And the rotor bars and end-ring parameters are verification and made optimization.

The facilities provided by the Simulink software of MATLAB are used to implement the block diagram which represents the governing squirrel cage induction motor mathematical model differential equations with cage model. The main advantage of the SIMULINK over other programming software is the simulation model is built up systematically by means of basic function blocks. A set of machine differential equations can thus be modeled by interconnection of appropriate function blocks, each of which performing a specific mathematical operation. The simulation model can be easily developed by addition of new sub-models to cater for various control functions. The following assumptions were made for the derivation of the appropriate mathematical model;

- The magnetic permeability of iron is considered to be infinite.
- The gap is very small compared to the radius of the rotor.
- Both surfaces of the stator and rotor are perfectly smooth.
- The resultant magnetic field produced in the gap is radial.
- The state of operation remains far below magnetic saturation.
- No skew bars were considered in the rotor cage.

II. MATHEMATICAL ANALYSIS OF SQUIRREL CAGE INDUCTION MOTOR

In order to study rotor values, a mathematical model was used, which also included a rotor equivalent circuit of the squirrel cage induction motor [3-7]. The rotor equivalent circuit of a three-phase induction motor with Nr number of rotor bars is shown in Fig. 1. The mathematical model was developed by using voltage equations developed on the basis of mesh currents.

$$\begin{aligned}
 V_a &= R_s i_a + \frac{d\Psi_a}{dt} \\
 V_b &= R_s i_b + \frac{d\Psi_b}{dt} \\
 V_c &= R_s i_c + \frac{d\Psi_c}{dt}
 \end{aligned} \tag{1}$$

Manuscript received April 8, 2012; revised May 15, 2012.

H. Arabaci is with the Electrical Engineering Department, Selcuk University, Konya, 42075 Turkey (e-mail: hayriarabaci@selcuk.edu.tr).

H. Bilgin is with the Electrical Engineering Department, Selcuk University, Konya, 42075 Turkey (e-mail: obilgin@selcuk.edu.tr).

Here, “ R_s ” refers to stator phase resistance and “ $\Psi_{a,b,c}$ ” to stator phase fluxes.

The following assumptions were made in modeling solutions:

- Rotor bars and short circuit ring do not contact the rotor core.
- Leakage fluxes in rotor and stator are ignored.

Stator phase equations are given in Equation (1) [7]-[9].

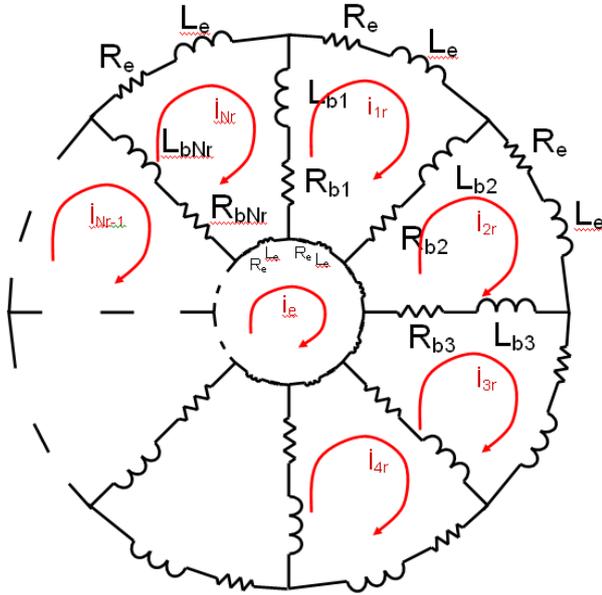


Fig. 1. Rotor mesh currents and rotor cage.

The k . rotor mesh equation is given in Equation (2).

$$0 = 2 \left(R_b + \frac{R_e}{N_r} \right) i_{kr} + \frac{d\Psi_{kr}}{dt} - R \left(i_{(k-1)r} + i_{(k+1)r} \right) \quad (2)$$

Here, “ R_b ” refers to rotor bar resistance, “ R_e ” to resistance of end ring, “ N_r ” to total nr of rotor bars and “ Ψ_{kr} ” to rotor bar fluxes.

The mesh equation for one short-circuited ring is given in Equation (3).

$$0 = R_e i_e + L_e \frac{di_e}{dt} - \sum_1^{N_r} \left(\frac{R_e}{N_r} i_{kr} + L_e \frac{di_{kr}}{dt} \right) \quad (3)$$

The most important part of the model is the mutual inductance matrix. Mutual inductances between the stator and the rotor are $L_{akr}, L_{bkr}, L_{ckr}$, which are given in Equation (4).

$$\begin{aligned} L_{akr}(\theta_r) &= L_{sr} \cos[\theta_{er} + (k_r - 1)\alpha] \\ L_{bkr}(\theta_r) &= L_{sr} \cos \left[\theta_{er} + (k_r - 1)\alpha - \frac{2\pi}{3} \right] \\ L_{ckr}(\theta_r) &= L_{sr} \cos \left[\theta_{er} + (k_r - 1)\alpha + \frac{2\pi}{3} \right] \end{aligned} \quad (4)$$

Here, “ $\alpha = p_1 2\pi / N_r$, $\theta_{er} = p_1 \theta_r$, p_1 ” refers to dipole nr, “ L_{sr} ” to mutual inductance between the stator and the rotor bars.

The matrix form of the equations can be written as Equation (5):

$$[V] = [R][i] + [L'(\theta_{er})] \left[\frac{di}{dt} \right] + \left[\frac{d[L'(\theta_{er})]}{dt} \right] [i] \quad (5)$$

Here, resistance and flux matrices are as follows:

$$\begin{aligned} [V] &= [V_a, V_b, V_c, 0, 0, \dots, 0]^T \\ [I] &= [i_a, i_b, i_c, i_{1r}, i_{2r}, \dots, i_{N_r}, i_e]^T \end{aligned} \quad (6)$$

When the fluxes in Equation (5) are solved, Equation (7) is obtained:

$$[I] = \int \left([L'(\theta_{er})]^{-1} [V] - [L'(\theta_{er})]^{-1} \left[R + \frac{d[L'(\theta_{er})]}{dt} \right] [I] \right) dt \quad (7)$$

As seen in Equation (4), mutual inductances change depending on the electrical angle of the rotor (θ_{er}) and the angle between the bars (α). In case the rotor bar is broken, angle “ α ” will be doubled in the broken area, and the value of the mutual inductance matrix and of some matrix elements will change. In this case, motor currents -particularly the stator currents- will be affected.

The electrical moment statement is given in Equation (8).

$$T_e = p_1 [I]^T \frac{\partial [L(\theta_{er})]}{\partial \theta_{er}} [I] \quad (8)$$

By assigning a specific value to the initial value of the rotor angle, the moment statement given in Equation (8) can be solved by solving the currents in Equation (7). Since rotor failures will change mutual inductance matrices, the value of matrix elements and, in turn, currents, the results obtained from Equation (8) will be directly affected. Rotation equations are given in Equation (9) and Equation (10).

$$\frac{d\omega_r}{dt} = \frac{p_1}{J} (T_e - T_{load}) \quad (9)$$

$$\omega_r = \frac{d\theta_{er}}{dt} \quad (10)$$

Here, “ J ” refers to moment of rotor inertia. Calculation of current and electrical moment values will give rotor speed value. Rotor failures will affect electromagnetic moment and, in turn, rotor speed. However, the moment of rotor inertia will mitigate these effects proportional to its value.

III. SIMULATION AND RESULTS

The model was simulated in Simulink. In first

initializations were made so that all the motor parameters were known. So, all the parameters were formed an initialization file. This file assigns values to the machine parameter variables in the Simulink. Motor output data are investigated via changing the values before running simulation. The simulated motor initial values are given in Table I. Simulation was made by applying 380V three-phase AC voltage at 50 Hz with just an inertia load. Fig. 2 shows the Simulink implementation and the inside of these blocks where each equation from the mathematical model of induction motor which was included squirrel cage structure. The marked region in Fig. 2 was zoomed and shown in Fig. 3. The important points were marked and described in Fig. 3.

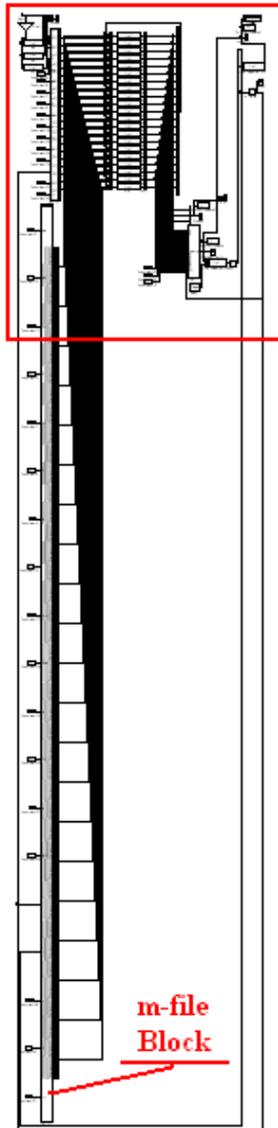


Fig. 2. The complete Simulink model of squirrel cage induction motor.

The number of rotor bars is 18. So, dimensions of $[I]$ and $[V]$ matrices in Equation (6), they are necessary for solution, will be 22×1 . Therefore, dimension of $[L(\theta)]$ matrix in Equation (7) will be 22×22 . In the solution based on time stepping all of the equations in the section II are solved for each time period which is determined to be suitable according to transient analyze resolution. For this reason, inverse of $[L(\theta)]$ is calculated for each time period. When its dimension and each component which consist of equations (for exp. Equation (4)) are taken into consideration, it will be

very difficult that the inverse operation is made by using Simulink blocks. So, in this study m-file block is used instead of formulation block. The used m-file block is shown Fig. 2.

TABLE I
FLUCTUATION RATE OF STATOR CURRENTS

Symbol	Value	Unit
Vmax	380	V
p	1	
Nr	18	
α	$2 \cdot \pi / 18$	rad
J	0.54	Kgm ²
Tload	30	Nm
Rs	$2.08e-1$	ohm
Rb	$8.89e-7$	ohm
Lsr	$6.94e-4$	H
Re	$1.21e-8$	ohm
Le	$7.12e-7$	H

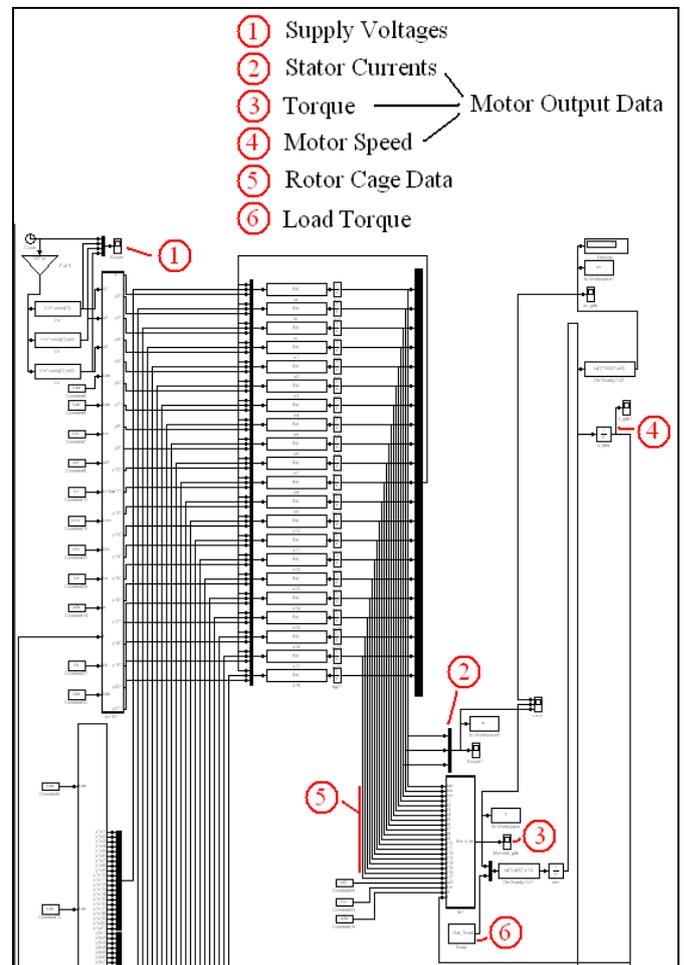


Fig. 3. The zoomed region of Simulink model of squirrel cage induction motor.

The Simulation results about three phase currents, torque and motor speed are shown Fig. 4, Fig. 5 and Fig. 6 for three phase the squirrel cage induction motor which specifications are 50 Hz, 2 poles, 18 rotor bars. The motor becomes starting, accelerates and reaches to steady state at 4.1 s under no-load. at the 6th second load was increased to 30 Nm. The motor accelerates and reaches to steady state at 7.35 s under this load. In these significant times, transient changes at the

current, torque and speed are shown and investigated via the simulation results.

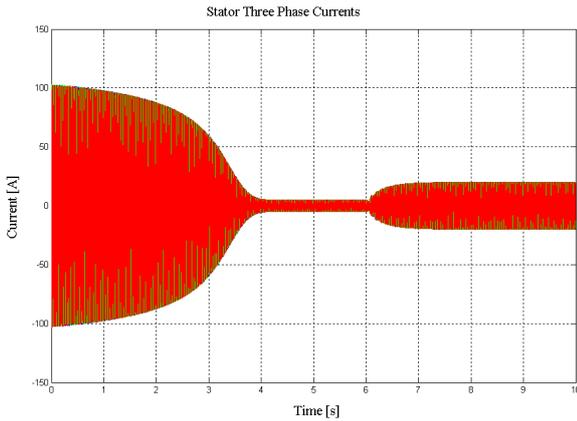


Fig. 4. The Simulation results about three phase currents.

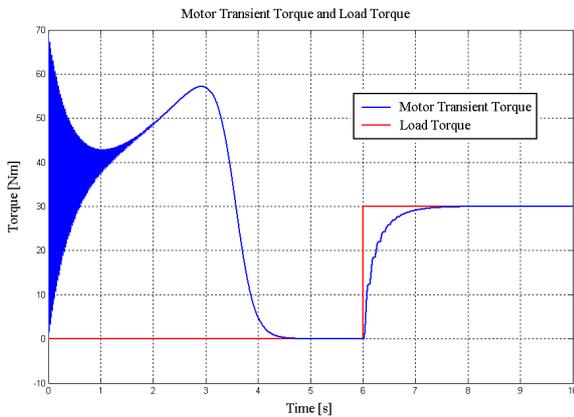


Fig. 5. The Simulation results about torque.

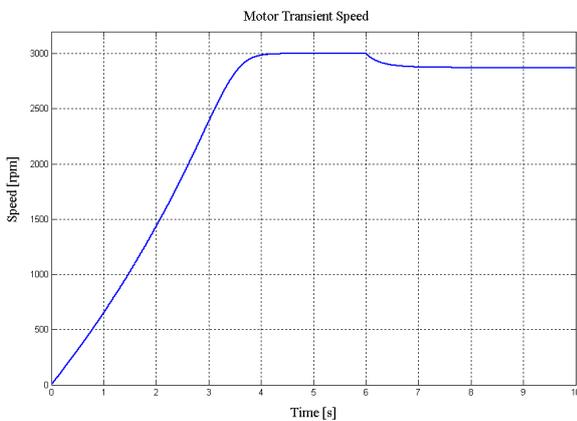


Fig. 6. The Simulation results about motor speed.

IV. CONCLUSION

In this paper, implementation of Simulink simulation for squirrel cage induction motor mathematical model has been

introduced. Unlike most other induction motor d-q model implementations, with this model, the user has access to rotor bar and end-ring variables and data. Any squirrel cage induction motor can be simulated in the Simulink with this model. In the future works, if need be, when the estimators are developed, the estimators can be verified achieved the output signals.

REFERENCES

- [1] K. L. Shi, T. F. Chan, and Y. K. Wong, "Modelling of the three-phase Induction Motor using SIMULINK," *IEEE International Electric Machines and Drives Conference Record*, 1997.
- [2] A. A. M Shaban, "Modelling and Simulation Of Variable Frequency Fed Induction Motors," Universities Power Engineering Conference, UPEC2008, pp. 1-5, 2008.
- [3] X. Ying, "Characteristic Performance Analysis of Squirrel Cage Induction Motor with Broken Bars," *IEEE Transactions on Magnetics*, vol. 45, no. 2, pp. 759-766, 2009.
- [4] J. F. Bangura and N. A. Demerdash, "Diagnosis and Characterization of Effects of Broken Bars and Connectors in Squirrel-Cage Induction Motors by a Time-Stepping Coupled Finite Element-State Space Modeling Approach," *IEEE Transactions on Energy Conversion*, vol. 14, no. 4, pp. 1167-1176, 1999.
- [5] H. A. Toliyat and T. A. Lipo, "Transient Analysis of Cage Induction Machines Under Stator, Rotor Bar and End Ring Faults," *IEEE Transactions on Energy Conversion*, vol. 10, no. 2, pp. 241-247, 1995.
- [6] ST. J. Manolas and J. A. Tegopu Oulos, "Analysis of Squirrel Cage Induction Motors with Broken Bars and Rings," *IEEE Transactions on Energy Conversion*, vol. 14, no. 4, pp.1300-1305, 1999.
- [7] X. Luo, Y. Liao, H. A. Toliyat, A. El-Antably, and T. A. Lipo, "Multiple couple circuit modelling of induction machines," *IEEE Transactions on Industry Applications*, vol. 31, no. 4, pp. 311-318, 1995.
- [8] R. J. Vidmar. (1992, August). On the use of atmospheric plasmas as electromagnetic reflectors. *IEEE Trans. Plasma Sci.* [Online]. 21(3). pp. 876-880. Available: <http://www.halcyon.com/pub/journals/21ps03-vidmar>
- [9] A. Menacer, S. Moreau, G. Champenois, M. S. N. Said, and A. Benakcha, "Experimental Detection of Rotor Failures of Induction Machines by Stator Current Spectrum Analysis in Function of the Broken Rotor Bars Position and the Load," EUROCON 2007 The International Conference on "Computer as a Tool," Warsaw, pp. 1752-1758, 2007.



H. Arabaci was born in Konya, Turkey, in 1977. He received the B.S., M.S. and Ph.D. degrees in electrical and electronics engineering from Selcuk University, Konya, Turkey, in 2001, 2005 and 2011, respectively. He is currently pursuing as a Research Assistant in Electric-Electronics Department of Selcuk University, Konya. His research interests include performance analysis and fault detection of electric motors.

O. Bilgin was born in Hatay, Turkey, in 1966. He received the B.S. degree Electrical Engineering from Yıldız Technical University, İstanbul, Turkey, 1990. He received M.S. and Ph.D. degrees in electrical and electronics engineering from Selcuk University, Konya, Turkey, in 1995 and 2002, respectively.