MATLAB Simulation of Induction Machine with Saturable Leakage and Magnetizing Inductances

Dr.-Ing. O. I. Okoro

Department of Electrical Engineering
University of Nigeria, Nsukka
Enugu State, Nigeria.
Email: ogbonnayaokoro@hotmail.com

ABSTRACT

At high stator phase currents, the effect of saturation of the stator and rotor leakage inductances becomes noticeable to the extent that the conventional machine model fails to represent the dynamic performances of induction machines. In this paper, a commercial software package, MATLAB, is used to simulate the dynamic behavior of induction machines with saturable inductances. The computer results presented in this paper show the errors involved when the magnetizing, stator, and rotor leakage inductances are assumed constant as in the case of conventional machine model.

(Key words: rotor leakage, inductance, MATLAB, induction machine)

INTRODUCTION

The traditional method of modeling induction machines has been applied by several authors [1,2,3]. In this method of analysis, it is assumed that the effect of saturation due to either the magnetizing inductance or the leakage inductances is negligible.

Using this assumption, the values of the magnetizing inductance, stator leakage, and rotor leakage inductances are constant and thus do not vary with the magnetizing current. This method of analysis was reported by Smith [4] to meet only the demands of the steady-state behavior of the machine but is inadequate in applications involving variable speed drive. It has been proved beyond a doubt by several authors [5,6,7,8] that the stability and dynamic conditions of induction machines are highly affected by saturation.

Several methods have been developed for the modeling of saturation effects in induction machines [8,9,10,11,12]; each differing in areas of application and, of course, in the part of the machine that inductances are assumed to saturate. In [8,9] induction motors with saturable leakage reactance are modeled and simulated with the help of IGSPICE and an analog computer, respectively. In He [7] and Levi [11] the effect of considering the main flux saturation is investigated. It has been shown that the main magnetizing field contributes significantly to the disparity between the induction machines' computer simulation results and the experimentally derived values [7]. Therefore, to a very high level of accuracy, the effects of saturation in induction machines can be included through variation of the main flux inductance while assuming the leakage inductances to be constant. However, where the stator and rotor currents are expected to be very high values, inclusion of the leakage inductance saturation becomes imperative [13].

In this paper, MATLAB [14] is used to simulate the dynamic performances of an induction machine by assuming that the main flux inductance, stator, and rotor leakage inductances vary with the magnetizing current.

MATLAB, licensed by Mathworks, provides a powerful matrix analysis environment, the basis of state-space modeling of dynamic systems, for systems identification, engineering graphics, modeling and algorithm development. MATLAB has an open system environment, which provides access to algorithms and source code and allows the user to mix MATLAB with FORTRAN or C language, and generates code to be used in an existing program. This paper uses the d-q axis transformation technique to model induction machine parameters. Lastly, the computer results of the conventional method of analysis are compared with the results of the saturation model.

D-Q AXIS TRANSFORMATION THEORY

The substitutions which replace the variables (currents, voltages, and flux linkages) associated with the stator windings of a synchronous machine with variables related to fictitious windings rotating with the rotor was first investigated by Park [7]. This method was further extended by Keyhani [8] and Lipo [9] to the dynamic analysis of induction machines. By these methods, a polyphase winding can be reduced to a set of two phase-windings with their magnetic axes aligned in quadrature as shown in Figure 1.

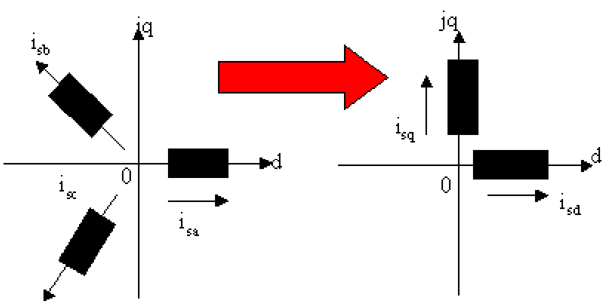


Figure 1: Polyphase winding and d-q equivalent.

The d-q axis transformation eliminates the mutual magnetic coupling of the phase-windings, thereby making the magnetic flux linkage of one winding independent of the current in the other winding. This system of transformation allows both polyphase windings in the stator and rotor of an induction machine to be viewed from a common reference frame, which may rotate at any angular speed or remain fixed to the stator. Generally, the reference frame can also be considered to be rotating at any arbitrary angular speed. The transformation from a three-phase system to a two-phase system and *vis versa* with the zero-sequence included is:

$$\begin{bmatrix} i_{sq} \\ i_{sd} \\ i_0 \end{bmatrix} = [C] \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = [C]^{-1} \begin{bmatrix} i_{sq} \\ i_{sd} \\ i_0 \end{bmatrix} \quad (2)$$

where,

$$[\mathbf{C}] = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{4\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (3)$$

$$[\mathbf{C}]^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta - \frac{4\pi}{3}\right) & \sin\left(\theta - \frac{4\pi}{3}\right) & 1 \end{bmatrix} \quad (4)$$

REFERENCE FRAMES VOLTAGES

Under balanced conditions, the stator voltages of a three-phase induction machine may be considered as sinusoidal and expressed as:

$$V_{as} = \sqrt{2}V\cos\omega_b t \quad (5)$$

$$V_{bs} = \sqrt{2}V\cos\left(\omega_b t - \frac{2\pi}{3}\right) \quad (6)$$

$$V_{cs} = \sqrt{2}V\cos\left(\omega_b t + \frac{2\pi}{3}\right) \quad (7)$$

These stator voltages are related to the d-q frame of reference by equation (1):

$$\begin{bmatrix} V_{sq} \\ V_{sd} \end{bmatrix} = [C_1] \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \quad (8)$$

where,

$$[C_1] = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ \sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \quad (9)$$

By applying trigonometric identities; equation (8) can be further simplified to yield:

$$V_{sq} = \sqrt{2}V\cos(\theta - \omega_b t) \quad (10)$$

$$V_{sd} = \sqrt{2}V\sin(\theta - \omega_b t) \quad (11)$$

Equations (10-11) can be applied in any reference frame by making a suitable choice for theta (θ).

If theta equals θ_r, then equations (10-11) lead to an expression for voltage in the rotor reference frame. Also, if θ is equal to zero, then equations (10-11) apply to a frame of reference rigidly fixed in the stator (i.e. stationary reference frame). Otherwise, for θ equal to ωt in equations (10-11), a synchronously rotating reference frame results.

CONVENTIONAL MACHINE MODEL DEVELOPMENT

In the development of transient equations for the conventional machine model, the following assumptions are made:

1. The machine is symmetrical with a linear air-gap and magnetic circuit
2. Saturation effect is neglected
3. Skin-effect and temperature effect are neglected
4. Harmonic content of the mmf wave is neglected
5. The stator voltages are balanced.

The differential equations governing the transient performance of the induction machine can be described in several ways; they only differ in minor detail and in their suitability for use in a given application. The conventional machine model is developed using the traditional method of reducing the machine to a two-axis coil (d-q axis) model on both the stator and the rotor as described by Krause and Thomas [1]. The d-q axis model of the motor provides a convenient way of modeling the machine and is most suitable for numerical solutions. This is preferable to the space-vector machine model that describes the machine in terms of complex variables [10]. Figure 2 shows the d-q equivalent circuits for a 3-phase, symmetrical squirrel-cage induction machine in arbitrary-frame with the zero-sequence component neglected.

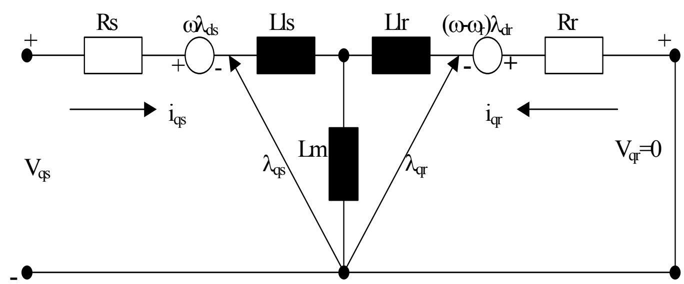


Figure 2a: Squirrel-Cage Induction machine models in d-q axis: (q-axis model).

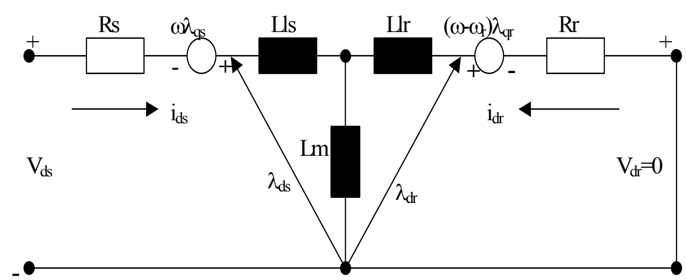


Figure 2b: Squirrel-Cage Induction machine models in d-q axis: (d-axis model).

ELECTRICAL MODEL OF THE MACHINE

The non-linear differential equations that describe the dynamic performance of an ideal symmetrical induction machine in an arbitrary reference frame could be derived from the d-q equivalent circuits as in (1).

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} (R_s + L_s p) & \omega L_s & L_m p & \omega L_m \\ -\omega L_s & (R_s + L_s p) & -\omega L_m & L_m p \\ L_m p & (\omega - \omega_r)L_m & (R_r + L_r p) & (\omega - \omega_r)L_r \\ -(\omega - \omega_r)L_m & L_m p & -(\omega - \omega_r)L_r & (R_r + L_r p) \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (12)$$

where,

$$L_s = L_{ls} + L_m \quad (13)$$

$$L_r = L_{lr} + L_m \quad (14)$$

$$p = \frac{d}{dt} \quad (15)$$

In the analysis of induction machines, it is always advisable to transform equation (12) to d-q axis fixed either on the stator [19], the rotor [20], or rotating in synchronism with the supply voltages [21]. In [19], equation (12) is modified by setting ω=0 and in [20] $\omega=\omega_r$ while in [21] $\omega=\omega_e$.

It is important to note that the choice of a reference frame will affect the waveforms of all d-q variables and also the simulation speed as well as the accuracy of the results. However, the following guidelines as suggested in [22] are in order:

1. Use the stationary reference frame if the stator voltages are either unbalanced or discontinuous and the rotor voltages are balanced (or zero)
2. Apply the rotor reference frame if the rotor voltages are either unbalanced or discontinuous and the stator voltages are balanced
3. Apply either the synchronous or stationary reference frames if all voltages are balanced and continuous.

Also, for analysis involving saturation and deep bar effect, a reference frame fixed to the rotor is recommended [20].

Therefore, the electrical model of the squirrel-cage induction machine in the rotor reference frame becomes,

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} (R_s + L_s p) & \omega_r L_s & L_m p & \omega_r L_m \\ -\omega_r L_s & (R_s + L_s p) & -\omega_r L_m & L_m p \\ L_m p & 0 & (R_r + L_r p) & 0 \\ 0 & L_m p & 0 & (R_r + L_r p) \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (16)$$

For the purpose of digital simulation, equation (16) is represented in state variable form with currents as state variables.

$$p[\mathbf{i}] = -[\mathbf{L}]^{-1}([\mathbf{R}] + \omega_r [\mathbf{G}])[\mathbf{i}] + [\mathbf{L}]^{-1}[\mathbf{V}] \quad (17)$$

where,

$$[\mathbf{V}] = [V_{qs} \quad V_{ds} \quad 0 \quad 0]^t \quad (18)$$

$$[\mathbf{R}] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \quad (19)$$

$$[\mathbf{L}] = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \quad (20)$$

$$[\mathbf{G}] = \begin{bmatrix} 0 & L_s & 0 & L_m \\ -L_s & 0 & -L_m & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (21)$$

$$[\mathbf{i}] = [i_{qs} \quad i_{ds} \quad i_{qr} \quad i_{dr}]^t \quad (22)$$

The electromagnetic torque, Te is expressed as:

$$T_e = \frac{3}{2} P L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right) \quad (23)$$

where, P=Number of pole pairs.

MECHANICAL MODEL OF THE MACHINE WITHOUT COUPLING

The mechanical model of an induction motor is comprised of the equations of motion of the motor and driven load as shown in Figure 3 and is usually represented as a second-order differential equation [18].

$$J_m p^2 \theta_m = T_e - T_L \quad (24)$$

Decomposing equation (25) into two first-order differential equations gives,

$$p\theta_m = \omega_m \quad \text{(25)}$$

$$J_m\left(p\omega_m\right) = \left(T_e - T_L\right) \quad \text{(26)}$$

But,

$$\omega_r = \omega_m P \quad \text{(27)}$$

$$\theta_r = \theta_m P \quad \text{(28)}$$

where, ω_m, θ_m, θ_r, ω_r, J_m, and T_L represent angular velocity of the rotor, rotor angular position, electrical rotor angular position, electrical angular velocity, combined rotor and load inertia coefficient, and applied load torque respectively.

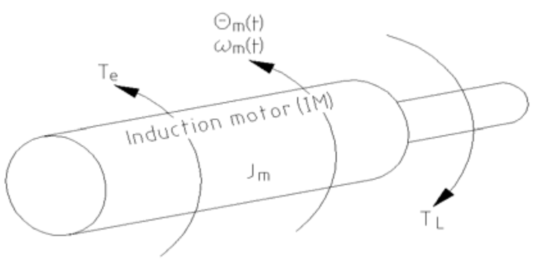


Figure 3: Motor mechanical model schematic without coupling.

The block diagram representing the mechanical model of the machine without coupling is shown in Figure 4.

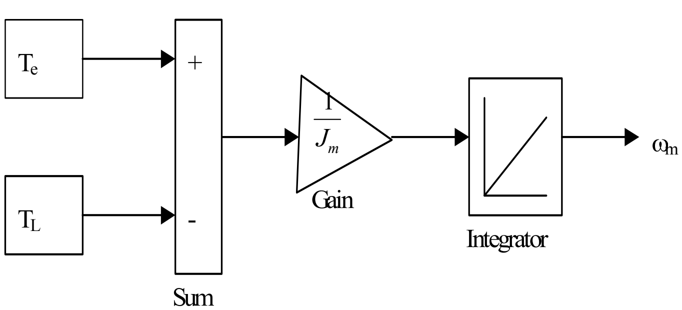


Figure 3: Block diagram of the mechanical model without coupling.

MECHANICAL MODEL OF THE MACHINE WITH COUPLING

Figure 5 represents the motor mechanical model schematic for the motor-load connection. In this paper, the coupled load is a 36KW, IEC 132, Class F, D.C. motor with a rated current of 53.8A.

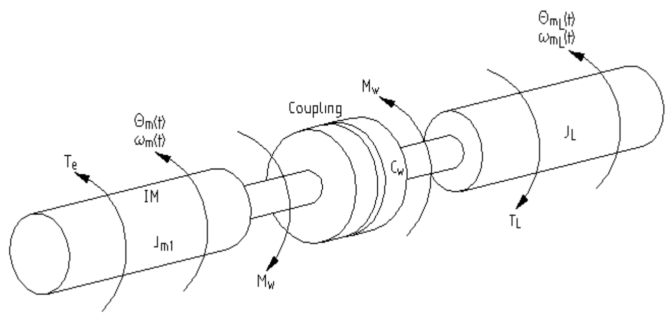


Figure 5: Motor mechanical model schematic with coupling.

The equation of motion of the motor and the coupling is given by:

$$T_e - M_w = J_{m1}\frac{d^2\theta_m}{dt^2} \quad \text{(29)}$$

From equation (25),

$$\frac{d\omega_m}{dt} = \frac{d^2\theta_m}{dt^2} \quad \text{(30)}$$

Inputting equation (30) into equation (29), we have:

$$T_e - M_w = J_{m1}\frac{d\omega_m}{dt} \quad \text{(31)}$$

Similarly, the equation of motion between the coupling and the driven load is related by:

$$M_w - T_L = J_L\frac{d\omega_{mL}}{dt} \quad \text{(32)}$$

Where,

$$\omega_{mL} = \frac{d\theta_{mL}}{dt} \quad \text{(33)}$$

By definition [23],

$$M_w = c_w(\theta_m - \theta_{mL}) \quad \text{(34)}$$

Taking the first derivative of equation (34), equation (35) results, as follows:

$$\frac{dM_w}{dt} = c_w\left(\frac{d\theta_m}{dt} - \frac{d\theta_{mL}}{dt}\right) \quad \text{(35)}$$

Substituting equations (25) and (33) into equation (35) we have,

$$\frac{dM_w}{dt} = c_w(\omega_m - \omega_{mL}) \quad \text{(36)}$$

Therefore, the general equation of the coupled system, with damping factor (d_w) neglected, can be expressed in matrix form as:

$$\begin{bmatrix} \dot{\omega}_m \\ \dot{\omega}_{mL} \\ \dot{M}_w \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{J_{m1}} \\ 0 & 0 & \frac{1}{J_L} \\ c_w & -c_w & 0 \end{bmatrix} \begin{bmatrix} \omega_m \\ \omega_{mL} \\ M_w \end{bmatrix} + \begin{bmatrix} \frac{T_e}{J_{m1}} \\ -\frac{T_L}{J_L} \\ 0 \end{bmatrix} \quad \text{(37)}$$

where, J_{m1}, M_w, J_L, c_w and ω_{mL} represent the moment of inertia of the induction motor, shaft torque, moment of inertia of the D.C. motor, stiffness constant of the shaft system, and mechanical speed of the D.C. motor, respectively. The block diagram of equation (37) is shown in Figure 6.

DETERMINATION OF THE SHAFT SYSTEM STIFFNESS CONSTANT

Since it is difficult to experimentally measure the electromagnetic torque developed by induction machines unlike the shaft torque, it therefore becomes necessary to compute the shaft torque.

To do this, the stiffness constant, c_w in equation (36), which defines the time function of the shaft torque, needs to be determined.

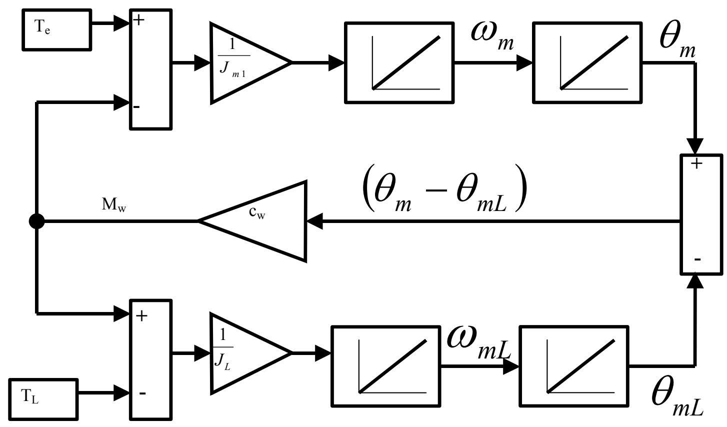


Figure 6: Block diagram of motor mechanical model with coupling.

Holzweißig and Dresig [23] give the relationship between the shaft's undamped natural frequency (ω_d) and the shaft stiffness constant (c_w) as:

$$\omega^2_d = c_w \frac{(J_{m1} + J_L)}{(J_{m1} J_L)} \quad \text{(38)}$$

From equation (38), equation (39) results in:

$$c_w = \frac{\omega^2_d (J_{m1} J_L)}{(J_{m1} + J_L)} \quad \text{(39)}$$

Figure 7 shows the measured shaft system oscillation, from which the undamped natural frequency of the shaft system is estimated to be 80Hz(502.65rad/s).

By substituting the experimental values of the moment of inertia of the motor (J_{m1}) and the load (J_L) together with the shaft undamped natural frequency in equation (39), the shaft stiffness constant, c_w becomes 14320Nm/rad.

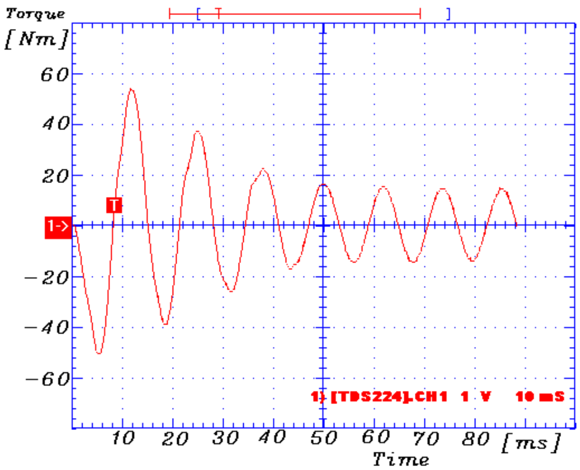


Figure 7: Measured shaft system oscillation waveform.

MODEL DEVELOPMENT WITH SATURATION EFFECT

The values of the inductances used in the development of the dynamic equations for the conventional induction machine model were assumed to be constant. By so doing, the models fail to take into consideration the saturation effects of both the magnetizing inductance and the leakage inductances. In this paper, it is assumed that the magnetizing inductance, stator, and rotor leakage inductances saturate. This implies that the magnetizing inductance and the leakage inductances vary with the magnetizing current. Therefore, the saturation curves of the test machine have to be determined.

Figures 8, 9, and 10, show the dependency of the magnetizing inductance and leakage inductances with the magnetizing current as reported by Okoro [13]. In order to find an analytical expression for the saturation characteristic curves of figures (8-10), a curve-fitting method for the algorithm of Marquardt [24] is employed. In Figure 8, the estimated function becomes,

$$L_m = 1.2e-14 i_m^{\,7} - 8.4e-12 i_m^{\,6} + 2.1e-9 i_m^{\,5} - 2e-7 i_m^{\,4}$$
$$+ 6.2e-6 i_m^{\,3} - 1.7e-4 i_m^{\,2} + 2.9e-4 i_m + 8.3 \text{ [mH]} \quad (40)$$

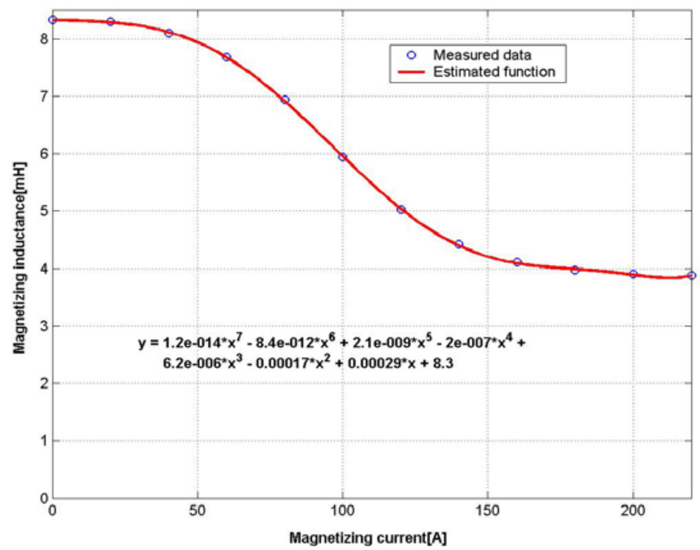


Figure 8: Measured shaft system oscillation waveform.

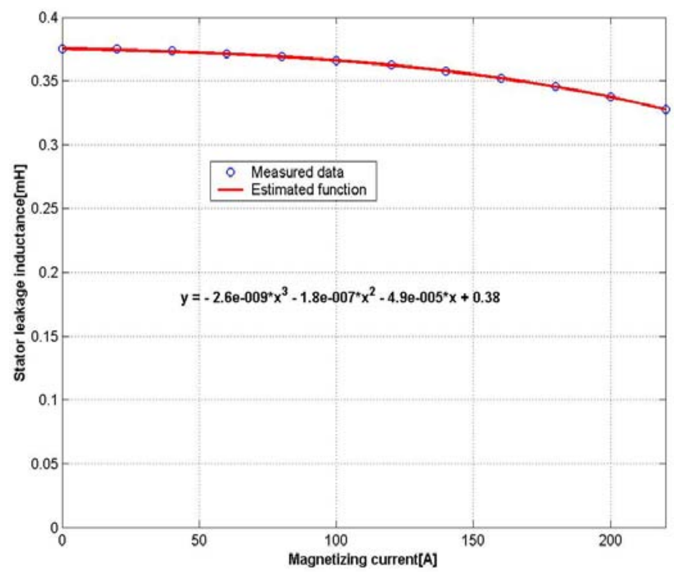


Figure 9: Graph of stator leakage inductance against magnetizing current.

and in figure 9 and figure 10, we have:

$$L_{1\sigma} = -2.6e-9 i_m^{\,3} - 1.8e-7 i_m^{\,2}$$
$$-4.9e-5 i_m + 0.38 \text{ [mH]} \quad (41)$$

$$L_{2\sigma} = -8.7e-10 i_m^{\,3} - 5.1e-8 i_m^{\,2}$$
$$-1.6e-5 i_m + 0.12 \text{ [mH]} \quad (42)$$

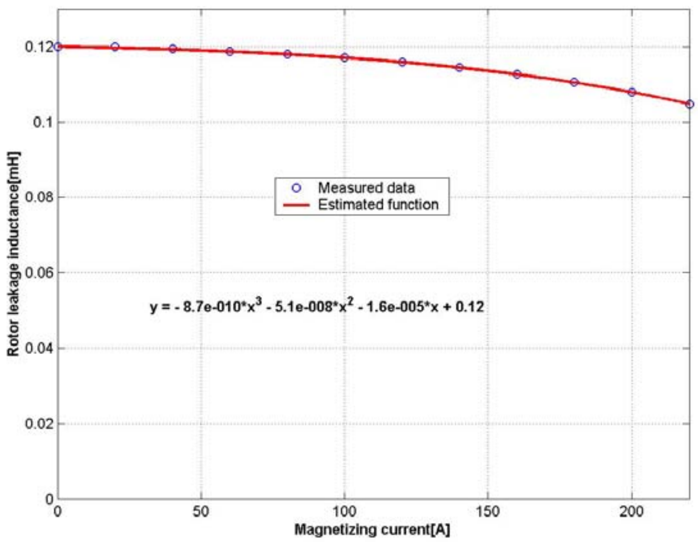


Figure 10: Graph of rotor leakage inductance against magnetizing current.

The magnetizing current, i_m is defined as:

$$i_m = \sqrt{i_{dt}^2 + i_{qt}^2} \qquad (43)$$

and

$$i_{dt} = i_{ds} + i_{dr} \qquad (44)$$

$$i_{qt} = i_{qs} + i_{qr} \qquad (45)$$

By storing the analytical expressions of equations (40-42) in the computer, the values of the magnetizing inductance and leakage inductances in the conventional machine model can be updated at each integration step.

INDUCTION MACHINE MODEL COMPUTER SIMULATION

In order to simulate the induction motor transient model, the differential equation (17), together with equations (40-42), equation (23) and equation (37), which gives the mechanical behaviour of the motor, are solved by developing MATLAB [27] m-files which incorporate an in-built numerical algorithm, ODE45; a program that uses the Runge-Kutta numerical method. The simulations have been carried out using the motor data obtained from the No-load, Blocked-rotor, D.C. measurement and Retardation tests of the motor under study (See Appendix A).

By assuming that the magnetizing and leakage inductances are constant, the conventional machine model is simulated and equations (40-42) are omitted. Figure 11 shows the comparison between the conventional model transient behaviours and the model with saturation effect for the electromagnetic torque, shaft torque, and mechanical speed as a function of time.

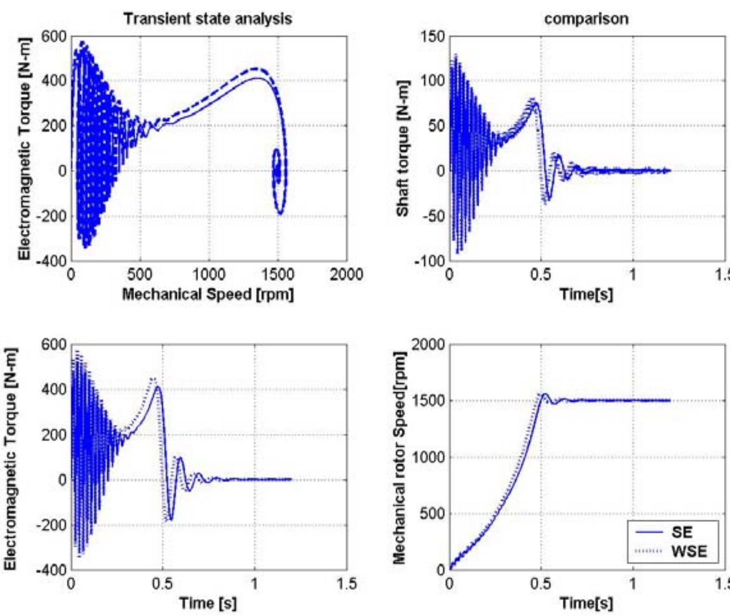
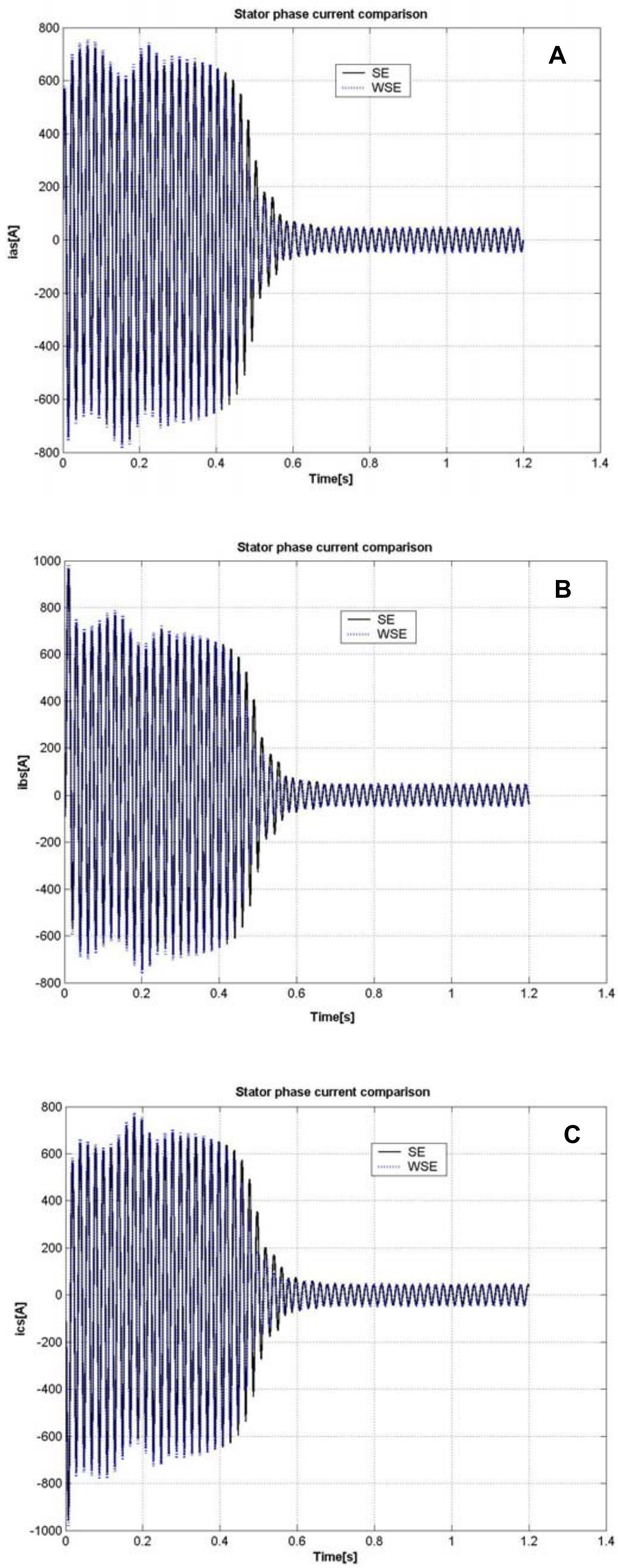


Figure 11: Transient-state models comparison: {Saturation effect (SE), Without saturation effect (WSE)}

The comparison of the simulated transient behaviours of the test machine stator phase currents as a function of time for the conventional model and saturation effect model are shown in Figures 12 a, b, and c.

The predicted time function of the magnetizing current is shown in Figure 13. Figure 14 shows the time function of the magnetizing inductance, stator, and rotor self-inductances.



Figures 12 a, b, and c: Simulated stator phase currents comparison: {Saturation effect (SE), Without saturation effect (WSE)}

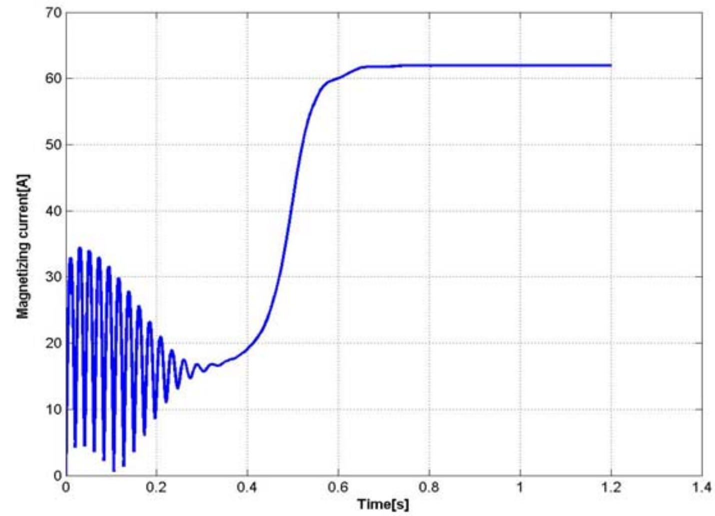


Figure 13: Graph of magnetizing current against time.

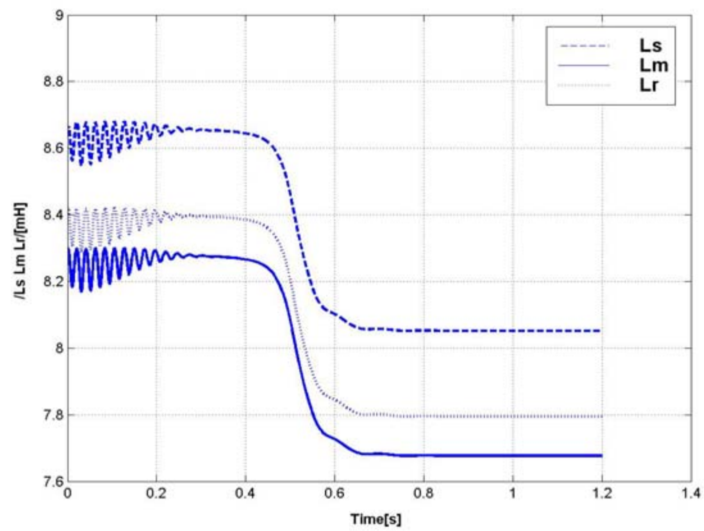


Figure 14: Graph of Ls, Lm and Lr against time.

CONCLUSION

This paper demonstrates that it is possible to use MATLAB to model and simulate the dynamic behaviours of induction machines with saturable leakage and magnetizing inductances. The simulated transient results show that there exists a difference between the conventional machine model and the model with saturation. It can be seen in Figure 11, that the conventional machine model has a higher starting torque than the model with saturation effect. Also in Figure 11, the time function of the mechanical rotor speed graph shows that the model with saturation effect rises faster to synchronous speed than the conventional model. However, little difference was observed for the stator phase currents of the two models. The fact that the effect is not noticeable may be due to the level of saturation considered. These simulation results clearly show the errors that are involved when the conventional model is used to predict the dynamic behaviours of induction machines without the inclusion of a saturation effect. Therefore, for accurate modelling and simulation of induction machines in dynamic states, the effect of saturation must be taken into consideration.

ACKNOWLEDGEMENT

The author wishes to express his thanks to DAAD for their financial support and to Prof. Dr.-Ing. B. Weidemann of the University of Kassel, Germany for his assistance in producing this paper.

REFERENCES

[1.] Krause, P.C. and Thomas, C.H.; Simulation of symmetrical induction machinery. *Transactions IEEE*, PAS-84, Vol. 11, PP.1038-1053, 1965.

[2.] Jordan, H.E.: Digital computer analysis of induction machines in dynamic systems. *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-86, No.6, PP. 722-728, June 1967.

[3.] Chattopadhyay, A.K.: Digital computer simulation of an adjustable-speed induction motor drive with a cycloconverter-type thyristor-commutator in the rotor. *IEEE Transactions on Industrial Electronics and Control Instrumentation*. PP.86-92, Feb; 1976.

[4.] Smith, J.R.: *Response Analysis of A.C. Electrical Machines-Computer Models and Simulation*. John Wiley and Sons, New-York, 1990.

[5.] Melkebeek,J.A.A.: Magnetizing-field saturation and dynamic behavior of induction machines. Part 1: Improved calculation method for induction-machine dynamics. I*EE Proc.* Vol. 130, Pt. B, No.1, PP. 1-9, January 1983.

[6.] De Mello, F.P. and Walsh, G. W.: Reclosing Transients in induction motors with terminal capacitors. *AIEE Transactions,* PP. 1206-1213, Feb; 1961.

[7.] He, Yi-Kang and Lipo, T.A.: Computer simulation of an induction machine with spatially dependent saturation. *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-103, No.4, PP.707-714, April 1984.

[8.] Keyhani, A. and Tsai, H.: IGSPICE simulation of induction machines with saturable inductances. *IEEE Transactions on Energy Conversion*, Vol. 4, No.1, PP.118-125, March 1989.

[9.] Lipo, T.A. and Consoli, A.: Modeling and simulation of induction motors with saturable leakage reactances. *IEEE Transactions on Industry Applications*, Vol. IA-20, No.1, PP. 180-189, Jan/Feb, 1984.

[10.] Boldea, I. and Nasar, S.A.: A general Equivalent Circuit (GEC) of Electric machines including Cross-coupling saturation and frequency effects. IEEE Transactions on Energy Conversion, Vol.3, PP. 689-695, September 1988.

[11.] Levi, E.: A unified approach to main flux saturation modeling in D-Q axis models of induction machines. *IEEE Transactions on Energy Conversion,* Vol. 10, No.3, PP. 455-460, September 1995.

[12.] Slemon,G.R.: Modeling of induction machines for electric drives. *IEEE Transactions on Industry Applications*, Vol.25, No.6, PP. 1126-1131, Nov.-Dec. 1989.

[13.] Okoro, O.I.: Dynamic and thermal modelling of induction machine with non-linear effects. Dissertation, University of Kassel, Germany, September 2002.

[14.] "The MATLAB Compiler user's guide", in *Mathworks Handbook*. Mathworks, April 1997.

[15.] Park, R.H.: Two-reaction theory of synchronous machines. *AIEE Transactions,* Vol.57, PP.717-727, 1929.

[16.] Stanley, H.C.: An analysis of the induction machine. *AIEE Transactions*, Vol. 57, PP. 751-757, 1938.

[17.] Kron, G.: *A Short Course in Tensor Analysis for Electrical Engineers.* John Wiley and Sons, New York, 1942.

[18.] Vas, Peter: *Electrical Machines and Drives-A Space –Vector Theory Approach.* Oxford, Clarendon Press, 1992.

[19.] Lipo, T. A.: The analysis of induction motors with voltage control by symmetrically triggered thyristors. *IEEE Transactions on Power Apparatus and Systems,* Vol. PAS-90, No. 2, PP. 515-525, March/April 1971.

[20.] Levy, W. et al: Improved models for the simulation of deep bar induction motors. *IEEE Transactions on Energy Conversion*, Vol. 5, No.2, PP. 393-400, June 1990.

[21.] Cornell, E.P. and Lipo, T.A.: Modeling and design of controlled current induction motor drive systems. *IEEE Transactions on Industry Applications*, Vol. IA-13, No.4, PP.321-330, July/August 1977.

[22.] Krause, P.C.: *Analysis of Electric Machinery,* New York, Mcgraw-Hill, 1986.

[23.] Holzweißig, F. and Dresig, H.: *Lehrbuch der Maschinendynamik: Maschien-dynamische probleme und ihre parktische Lösung.* Zweite Auflage, Springer-Verlag, Wien, 1982.

[24.] Marquardt, D. W.: An Algorithm for least-square estimation of non-linear parameters. *J. Soc. Ind. Appl. Math*, Vol. 11, No.2, PP. 431-441, June 1963.

APPENDIX: MACHINE DATA

Output Power	36KW
Rated voltage	192V
Winding connection	Delta
Number of Poles	4
Rated speed	1465rpm
Rated frequency	50Hz
Stator resistance	26.37mΩ
Stator self inductance	7.31mH
Rotor resistance	14.14mΩ
Rotor self inductance	7.06mH
Magnetizing inductance	6.94mH
Mechanical shaft torque	235N.m
Estimated rotor inertia moment	0.541Kgm^2
Rated current	48.3A
Moment of inertia of the DC motor	0.1096Kgm^2
Shaft stiffness constant	14320Nm/rad

ABOUT THE AUTHOR

Dr.–Ing. O.I. Okoro holds a Ph.D. in Electrical Machines from the University of Kassel, Germany where he conducted his research under a DAAD Scholarship. He currently lectures in the Department of Electrical Engineering at the University of Nigeria, Nsukka. His research interests are in the areas of dynamic simulation and control of induction machines as well as in the thermal and dynamic analysis of AC machines. He is a member of the IEEE.

SUGGESTED CITATION

Okoro, O.I. 2004. MATLAB Simulation of Induction Machine with Saturable Leakage and Magnetizing Inductances. *Pacific Journal of Science and Technology*. 5(1):5-15.

Pacific Journal of Science and Technology