Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 6 Issue 7, July - 2019

Modelling Of Six-Phase Induction Machine Including Saturation Effect

Akpama, E. J.
Department of Elect/Elect Engineering, Cross River University of Technology, Calabar/Nigeria
ekoakpama2004@yahoo.com

***Abstract*—The modelling of electrical machines takes a common unified treatment or generalized treatment of electrical machines. This generalized treatment models the machine as a two component dynamic system and the simplicity/complexity of the model depends on the expected details and parameters of interest of the modeller. Two models commonly identified; conventional model (CM) and non-linear effects model (NLEM). In this paper, a six phase induction machine is modelled using the DQ transformation and fixed to the rotor. Saturation is then included in the developed model, and with the help of MATLAB software, the developed models were simulated and results are compared. The parameters of interest are; the machine's phase currents, electromagnetic torque and the mechanical rotor speed. It is observed that, the conventional model presents acceptable results though, yet lacks salient details to describe the dynamic behaviour of the machine mostly when the machine driven to the non-linear region which is likely most time during specific applications. Hence, the saturation effect is considered and included in the induction machine model.**

Keywords—six-phase induction machine, modelling, non-linear effect, saturation effect, MATLAB

I. INTRODUCTION

Induction machines play a vital role in the industrial, commercial and domestic sectors. Due to demerits of the three phase system, the multiphase (>3) is conceived. Investigation shows that the six phase machine is more advantageous compared to the three phase counterpart. Six phase induction machine modelling as reported in [1,2] is seen as two three phase machines coupled together. The machine can also be modelled using the technique of vector space decomposition as demonstrated in [3], [4]-[6]. This method results in a model of the machine in single six-phase reference frame with three pairs of axes decoupled from one another. A less common modelling technique is the dual stator approach mentioned in [5],[6] and [7]. It considers the six-phase machine as two coupled three-phase machines, and uses three phase transformations.Some assumptions are usually made in the modelling of any engineering system depending on the interest of the modeller or the purpose of the modelling and the parameters of interest, and to ease computation time. Depending on the modeller, some technical details might be neglected without noticeable effect on the results. The conventional model though capable of predicting the performance of the system to some degree of accuracy based on the assumptions made, yet lacks merit in certain operational conditions. To study the performance of the induction machine or any electrical machine in the dynamic mode, accurate models must be developed that will account for non-linearity. The Machine designer is advised to accurately model the electrical machine in order to accurately set the limits. This is very important mostly when the modelling accounts for real life operating conditions. Also, considering the case of the association of a static converter to an electrical machine, the rational use of the whole process by a perfect control of the global dynamic behaviour, With PWM power supplies, the electrical machines have to work on a very large frequency range. From the above, a simplified model representation of this machine is not adequate, but only valid on a limited frequency range, and the result thereof is very unsatisfactory.

The inadequacy of the simplified model is more pronounced when the electrical machines have a massive structure (like asynchronous machines with cages, deep notches or massive rotor) characterized by skin effect (or frequency effect). Therefore, in order to model an electrical machine mostly for stability studies, it is very well in order to account for non-linear effects as much as possible.

II. INDUCTION MACHINE MODEL IN THE ROTOR REFERENCE FRAME

A. The speed of the rotor reference frame is

$\omega_k = \omega_r$ (1)

the angular position is, $\theta_k = \theta_r$ (2)

by substituting the speed in the impedance equation we have;

$[V^r]=[Z^r][i^r]$ (3)

The variables in equation (4.47) are defined below;

$[V^r] = [V_{qs1}^r \quad V_{ds1}^r \quad V_{qs2}^r \; V_{ds2}^r \; V_{qr}^r V_{dr}^r]^T$ (4)

$[i^r] = [i_{qs1}^r \quad i_{ds1}^r \quad i_{qs2}^r \; i_{ds2}^r \; i_{qr}^r i_{dr}^r]^T$ (5)

$$[Z^r] = \begin{bmatrix} r_1 + L_1P & \omega_r L_1 & L_2P & \omega_r L_2 & L_mP & \omega_r L_m \\ -\omega_r L_1 & r_1 + L_1P & -\omega_r L_2 & L_2P & -\omega_r L_m & L_mP \\ L_3P & \omega_r L_3 & r_2 + L_2P & \omega_r L_2 & L_mP & \omega_r L_m \\ -\omega_r L_3 & L_3P & -\omega_r L_2 & r_2 + L_2P & -\omega_r L_m & L_mP \\ L_mP & 0 & L_mP & 0 & r_r + L_rP & 0 \\ 0 & L_mP & 0 & L_mP & 0 & r_r + L_rP \end{bmatrix} \quad (6)$$

And the terminal voltage becomes;

For Set I (abc) winding

$V_{qs1}=V_m \cos(s\omega_s t+\lambda)$ (7)

$V_{ds1}=-V_m \sin(s\omega_s t+\lambda)$ (8)

For Set II (xyz) winding

$V_{qs2}=V_m \cos(s\omega_s t+\lambda)$ (9)

$V_{ds2}=-V_m \sin(s\omega_s t+\lambda)$ (10)

Observe that, the dq voltages are of slip frequency and the q-axis rotor current is the same as the phase a current. The torque equation is

$T_e = \frac{3}{2}\frac{P}{2} L_m\left(i_{qs}^r i_{dr}^r - i_{ds}^r i_{qr}^r\right)$(11)

The transformation matrix is given as

$$[T_{abc}^r] = \frac{2}{3}\begin{bmatrix} \cos\theta_r & \cos\left(\theta_r - {}^{2\pi}/_3\right) & \cos\left(\theta_r + {}^{2\pi}/_3\right) \\ \sin\theta_r & \sin\left(\theta_r - {}^{2\pi}/_3\right) & \sin\left(\theta_r + {}^{2\pi}/_3\right) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$$

(12)

III. SATURATION MODEL OF A SIX-PHASE INDUCTION MACHINE

A. Conventional Model

Most motors like induction motors are design to operate in the linear portion of the hysteresis curve, and therefore the machine working parameters are selected and the magnetic materials used are so determined. The continued operation of the electric motor without variable speed drives and other solid-state converters meant that a well-designed and run motor would rarely operate in electromagnetic saturation.

However, modern equipment used to control induction motor including those using standard voltage-frequency control technique, means that saturation zone is reached much more often, [8]. It is a practice in literature to present the induction machine model in conventional way. This conventional model of induction machine is developed based on the assumption that saturation effect is neglected. This assumption leads to erroneous results in certain operational conditions. Therefore, the conventional model though adequate does not present or predict the true performance of the induction machine performance in the dynamic mode. In most operation the machine is driven into the saturation region, as such the real model must take saturation effect into account. Therefore, this section presents the saturation effect modelling of six-phase induction machine to be included in the conventional model developed previously.

B. Saturation effect model

The conventional model of six-phase induction machine assumed constant inductances, [9-11]. So the result therefrom will definitely be different from the model of a saturated induction or any other electric machine. Saturation decreases the mutual inductances of the machine when the operating level of the machine into the non-linear region, this decrease becomes more pronounced when the machine id driven higher into saturation level. Therefore, including saturation effect in the induction machine model is very significant when adequate models to predict machine performance are needed. Different saturation models have been presented by many researchers [12]. In [13], saturation factors are used to account for saturation effect, while in [14-16], the FEA method was adopted for inclusion of saturation effect into the induction machine model. The application of the saturation curve is used in [17-20], to account for the effect of saturation effect. Among the three methods the last method is generally accepted because it takes into consideration the theory of the BH or hysteresis curve. The saturation curve will therefore be adopted in this work to account for the saturation effect in the sample machine.

According to [21-25], the magnetizing inductance L_m depends on the degree of saturation and is a non-linear function of the magnetizing current I_m, which can be obtained from the magnetization curve of the machine [26-27]. Thus, the magnetizing inductance is given by;

$$L_m = \lambda_m / I_m \qquad (13)$$

where λ_m and I_m are, the magnetizing flux linkage and magnetizing current space vectors. The cross-saturation coupling L_{dq}, is solely due to saturation and is given by,

$$L_{dq} = [i_{md} \, x i_{mq} / |i_m|] \, x \, [dL_m / d|i_m|] \qquad (14)$$

Where i_{md} and i_{mq} are the direct and quadrature axis components of the magnetizing current space vector. The d- and q-axis magnetizing inductances are

$$L_{md} = L_m + [\, i_{md} / i_{mq} \,] \, L_{dq} \qquad (15)$$

$$L_{md} = L_m + [\, i_{mq} / i_{md} \,] \, L_{dq} \qquad (16)$$

Under linear magnetic conditions

$$L_{dq} = 0, \;\; L_{md} = L_{mq} = L_m \qquad (17)$$

L_m is the steady state saturated magnetizing inductance given as

$$L_m = a_1 + a_2 i_m + a_3 i_m^2 + a_4 i_m^3 \qquad (18)$$

where a_1 , a_2, a_3, $a_4$and a_4 are constants.

If i_{dt} and i_{qt} is given as

$$i_{dt} = i_{d1} + i_{d2} + i_{dr} \qquad (19)$$

$$i_{qt} = i_{q1} + i_{q2} + i_{qr} \qquad (20)$$

then i_m is given as

$$i_m = \sqrt{[(i_{dt}^2 + i_{qt}^2)]} \qquad (21)$$

Two approaches to the modelling of the main flux saturation exist. The first utilizes the current as state space variables, while the other relies on d-q axis flux components as state space variables. The latter approach is adopted here to incorporate the saturation effect in the analytical model. Although the flux state space model is simpler to use, but has an advantage in the sense that it concede the effect of cross saturation, which is however, accounted for. In fact the current state space model contains explicit terms that describe the cross-saturation effect and, therefore, a better physical insight into the overall behaviour of the saturated induction machine is achieved. More so, it should be noted that the corresponding flux state space model of a saturated induction machine may be utilized instead without any loss of information or accuracy in the simulation result. From the best fit equation, a_1=1.4, a_2=2.914, a_3=0.94 a_4=2.4and a constant of 230.

Similarly, the model equation to predict the performance of the machine accounting for saturation is simulated and the plots presented in figures 1 to 6 below. The results are compared between the conventional model and the saturation model, these shows that, there exists a difference between the two models. So to completely predict the performance of the machines the right model must be developed depending on the parameters of interest.

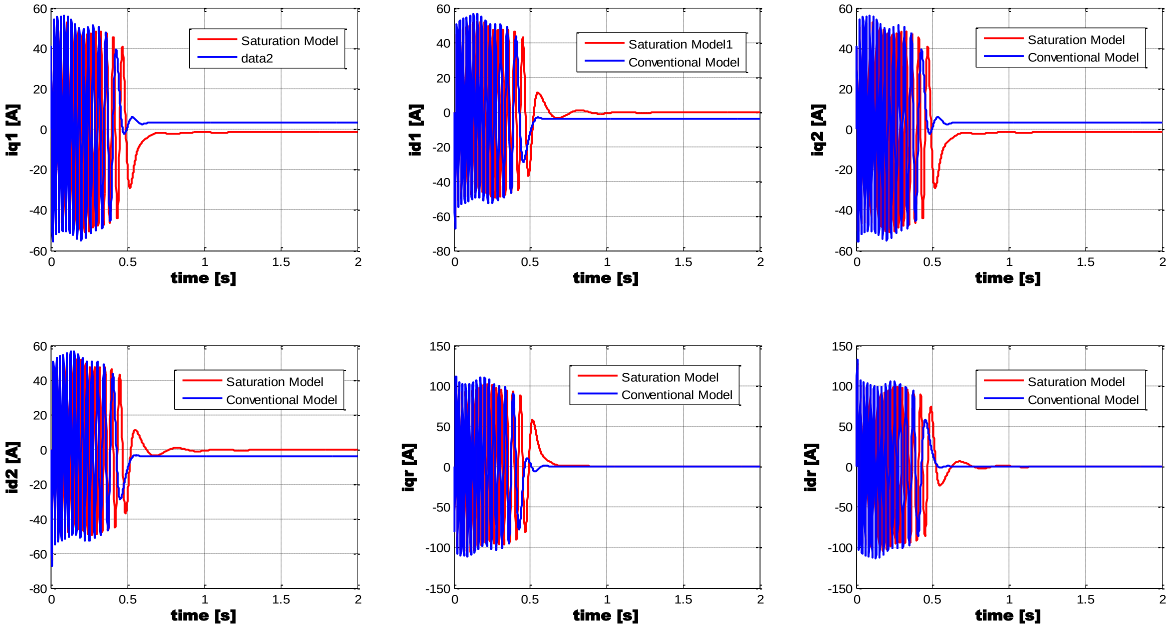
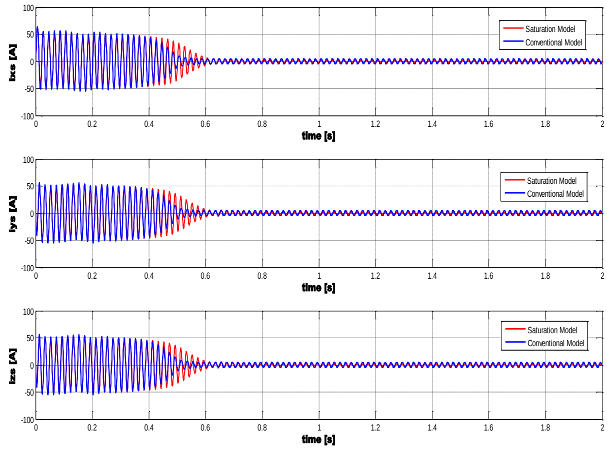


Figure 1: A graph of dq currents comparison



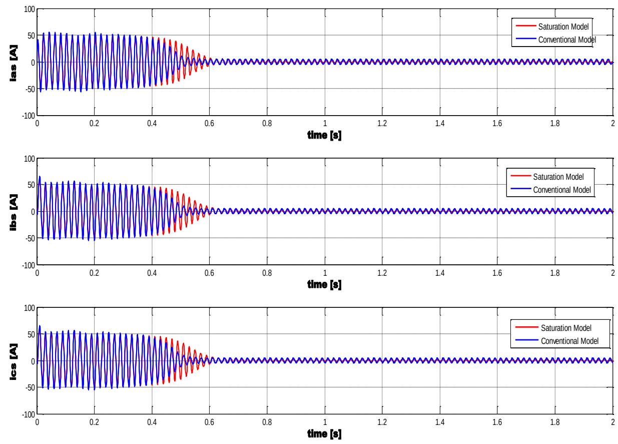
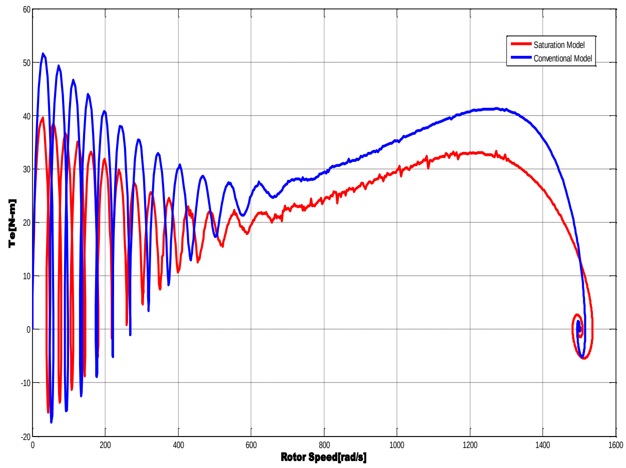


Figure 2: ABC phase currents comparison

Figure 3: XYZ phase currents comparison



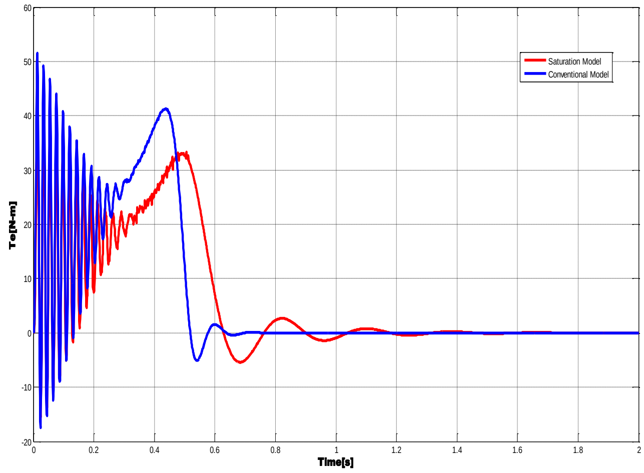


Figure 4: Torque against time

Figure 5: Torque against Rotor Speed

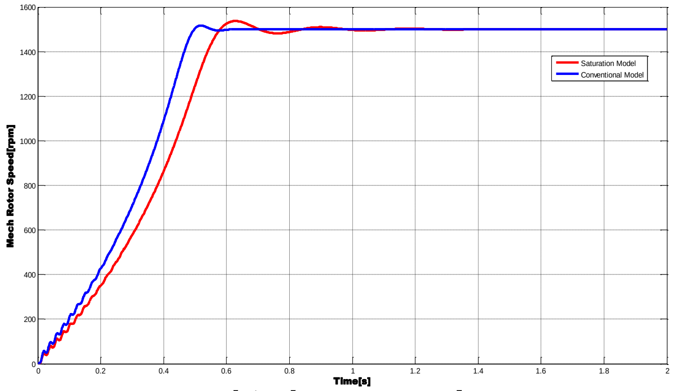


Figure 6: Mech'cal Rotor Speed against time

IV. DISCUSSION OF RESULTS

The test machine, six phase split wound induction machine is described by a system of differential equations. The number of equations predicting the performance of the machine is equal to the number of phase winding sets in the stator and rotor circuits.In the non-linear region, temperature, saturation and skin effect are incorporated into the conventional model and the simulation results presented. The saturation effect model also show a comparative difference from the conventional, for instance, the stator phase currents reaches steady state in 0.5secs in the conventional model compared the 0.6secs in the saturation effect model. While the electromagnetic torque of the conventional model synchronises in 0.7secs and,that of the saturation model is in13secs.

CONCLUSION

A six phase induction machine is modelled and simulated using the dq transformation in the rotor reference frame. The six phase machine has two sets of three phase winding in the stator. The results has shown that, to study the performance of the six phase induction machine the conventional model is enough to adequately predict the behaviour, hence, the model must include nonlinear effects like, saturation effect, skin effect, temperature variation, etc. the complete model will inform the designer regarding setting limits.

References

[1] Akpama, E. J. and Okoro, O. I. 'Modelling Multi-phase Induction Machine for Torque improvement' Umudike Journal of Engineering and Technology, Volume 1, Number 1, June, 2015, pg. 73-78

[2] Akpama, E. J., Linus Anih, and Ogbonnaya Okoro, 'Transient Analysis and Modelling of Six phase Asynchronous Machine' American Journal of Electrical Power and Energy Systems 2015; 4(6): 77-83, Oct. 31, 2015

[3] Y. Zhao and T.A. Lipo, "Space vector PWM control of dual three-phase inductionmachine using space vector decomposition," *IEEE Trans. Ind. Appl.*, vol. 31, pp.1100-1109, Sept./Oct. 1995.

[4] E. Levi, R. Bojoi, F. Profumo, H.A. Toliyat and S. Williamson, "Multiphase inductionmotor drives - a technology status review," *Elec. Power Appl., IET*, vol. 1, no. 4,pp.489-516, Jul. 2007.

[5] G.K. Singh, K. Nam and S.K. Lim, "A Simple Indirect Field-Oriented Control Schemefor Multiphase Induction Machine," *IEEE Trans. Ind. Electron.*, vol. 52, no. 4, pp. 1177- 1184, Aug. 2005.

[6] K. E. Hallenius, P. Vas. and J. E. Brown, "The Analysis of a Saturated Self-Excited Asynchronous Generator," IEEE Trans. Energy Conversion, vol. 6, pp. 336-345, 1991.

[7] R. Bojoi, E. Levi, F. Farina, A. Tenconi, F. Profumo and, "Dual three-phase inductionmotor drive with digital current control in the stationary reference frame," *IEE Proc.Elec. Power Appl*, vol.153, no.1, pp. 129- 139, Jan. 2006.

[8] R. Bojoi, F. Farina, M. Lazzari, F. Profumo and A. Tenconi, "Analysis of theasymmetrical operation of dual three-phase induction machines," *IEEE IEMDC'03*,vol.1, pp. 429- 435, Jun. 2003.

[9]D. Hadiouche, H. Razik, A. Rezzoug, "On the modelling and design of dual-stator windings to minimize circulating harmonic currents for VSI fed ac machines", IEEE Trans. Ind. Appl. 40 (2), pp. 506–515, 2004.

[10] A. de Andrade Darizon, A. A. de Freites Marcos, Luciano M. Nito, Helder de Paula and Jose L. Domingos, "Effect of Magnetic Saturation on Induction Machine driven by static converters", Revista controle & Automacao, vol.15 No 2, April Maio e Junho 2004.

[11] I. O. Okoro; "Matlab Simulation of Induction Machine with Saturable Leakage and

Magnetizing Inductances", Botswana Journal of Technology, pp. 20 – 28, April 2004.
[12] J. E. Brown, K. P. Kovacs, and P. Vas, "A method of including the effects of main flux path saturation in the generalized equations of a.c machines," IEEE Trans. Power Appar. Syst. Vol., PAS-102, no. 1, pp. 96-103, Jan. 1983.
[13] P. Vas, K. E. Hallenious, and J. E. Brown, "Cross-saturation in smooth-air-gap electrical machines," IEEE Trans. Energy Conversion, vol. EC-1, no. 1, pp. 103-109, Mar. 1986.
[14] R. J. Kerkman, "Steady-state and transient analysis of an induction machine with saturation of the magnetizing branch," IEEE Trans. Ind. Appicat., vol !A-21, no. 1, pp. 226-234, Jan-Feb. 1985.
[15] J. Robert, "A simplified method for the study of saturation in A.C machines,' in modelling and simulation of Electrical Machines and power systems," J. Roberts and D. K. Trans, eds. North-Holland: Elsevier science Publishers B. V., pp. 129-136, 1988.
[16] M. S. Garrido, L. Pierrat, and E. Dejaeger, "The matrix analysis of saturated electrical machines," in modelling and simulation of Electrical Machines and power systems, J. Roberts and D. K. Trans, eds. North-Holland: Elsevier science Publishers B. V., pp. 137-144, 1988.
[17] R. D. Lorenz, and D. W. Novotny, "Saturation effects in field-oriented induction machine," IEEE Trans. Ind. App., vol. 26, no. 2, pp. 283-9, 1990.
[18] F. M. H. Khater, R. D. Lorenz, D. W. Novotny, and K. Tang, "Saturation effects in field-oriented induction machine," IEEE Trans. Ind. App., vol. 1A-23, no. 2, pp. 276-82, 1987.
[19] C. R. Sullivan and S. R. Sanders, "Models for induction machines with magnetic saturation of the main flux path," IEEE Trans. Ind. App. Soc, Annu. Meeting, vol. 1, pp. 123-131, 1992.
[20] C. R. Sullivan and S. R. Sanders, "Models for induction machines with magnetic saturation of the main flux path," IEEE Trans. Ind. App., vol. 31, no. 4, 1995.
[21] H. F. Ouadi. Giri, and L. Dugard. "Modelling saturated induction motors". IEEE Conference on Control Applications (CCA'04), Taipei, Taiwan. Vol.1, pp. 75 – 80, 2004.
[22] M. Akbaba, and S. Q. Fakhro, "Saturation Effect in Three-phase - Induction Motors," I Electric Machines and Power Systems. V01.12, pp.179- 193, 1987.
[23] M. Akbaba, "Modelling of the Saturated Leakage Reactance of Induction Motors as a Time Varying Parameter for Transient Computations", ibid, Vol. 18.
[24] J. E. Brown, K. P. Kovacs, and P. Vas, "A Method of Including the Effects of Main Flux Path Saturation in the Generalized Equations of a.c. Machines", IEEE Trans.,
[25] E. Levi, "A Unified Approach to main Flux Saturation Modelling in d-q Axis Models of Induction Machines", ibid., Vol.EC-10(3), pp.455-461, 1995.
[26] K. E. Hallenius, P. Vas, and J. E. Brown, "The Analysis of A Saturated Self-Excited Asynchronous Generator", ibid., Vol.EC-6, No.2, June 1991, pp. 336-345.
[27] T. W. Nehl, F. A. Fouad, and N. A. Demerdash, "Determination of saturated values of rotating machinery incremental and apparent inductances by an energy perturbation method," *IEEE Trans. Power App. Syst.*, vol. 101, no. 12, pp. 4441–4451, Dec. 1982.