A Novel Approach to Incorporate the Main Flux Saturation Effect in a Three-phase Induction Machine during Motoring and Plugging

K. S. Sandhu and Vivek Pahwa

***Abstract*—In this paper, a new model has been proposed for the transient study of a three phase induction motor, especially for motoring and plugging operation. The ensuing behavior of the machine is predicted by d-q axis based model using MATLAB/SIMULINK environment. Instantaneous value based saturation curve in place of conventional saturation curve has been used to account the saturation in the transient modeling of induction machine. Simulated results as obtained using proposed model are compared with experimental results on the two test machines. A close agreement between the simulated and experimental results proves the validity of proposed modeling.**

***Index Terms*—Modeling, Induction motor, Reference frames, Simulation, Transient analysis.**

I. Introduction

The three-phase induction machine may results in voltage dips, oscillatory torque and harmonics in the power system during starting period and other severe operations [1]. The estimation of induction motor performance traditionally based on constant parameter models has yielded good engineering results [2]. However it has been observed that some of the machine parameters may not be treated as constant due to saturation in magnetic circuit. Further, it is observed that highly saturated conditions may affect the static and dynamic performance of induction motor drives [3, 4]. For simulation study, different nonlinear models for saturated induction motors have been elaborated based on the equivalent electric circuit approach [5]. An analytical technique [6] has been suggested for predetermination of true saturation characteristic of transformers and reactors from the manufacturer data giving the conventional rms saturation characteristic. The method has some advantages over that suggested by [7]. [8] proposed a new model, in which saturation effects has been incorporated in the magnetizing inductance and the stator mutual inductances. A commercial software package, MATLAB, is used to simulate the dynamic behavior of induction machines with saturable inductances.

The computer results presented in [9] show the errors involved when the magnetizing, stator, and rotor leakage inductances are assumed constant as in the case of conventional machine model.

The approximate steady state analysis of braking performance of three phase induction motor was given in literature [10, 11]. [11] has also attempted to identify the transient patterns of torque and currents during plugging, but computed results were not supported by any standard mathematical model. The approach is found to be too approximate to provide proper correlation with experimental results. For transient analysis of three phase induction motor involving asymmetry and/or nonlinearity, the method of instantaneous symmetrical components along with operational equivalent circuits is given in [12-15]. Some of the researchers adopted the finite element modeling for transient study of such machines [16-19]. Same model i.e. finite element model may be adopted for transient study of these machines in plugging mode [20].

Therefore, in order to investigate effect of saturation during motoring and plugging mode in induction machine, the d, q axis model has been found to be well tested and proven to be reliable and accurate. [21, 22] also used the d-q axis based conventional model to investigate the transient behavior of three phase induction machine. [23-25] describes the basic concept of transient modeling of the machine. Matlab / Simulink is found to be very useful tool for modeling electrical machine and it may be used to predict the dynamic behavior of the machines. In this paper Matlab / Simulink based new model is proposed to study the dynamic behaviour of three phase induction machine during motoring and as well as in plugging operation.

II. Mathematical Modeling

Stationary reference frame model may be adopted to investigate the transient performance of a three-phase induction machine in motoring [25] and plugging. The applied voltages during motoring are:

$$\begin{aligned} V_{as} &= V_m \cos(\omega_s t + \lambda) \\ V_{bs} &= V_m \cos(\omega_s t + \lambda - 2\pi/3) \\ V_{cs} &= V_m \cos(\omega_s t + \lambda + 2\pi/3) \end{aligned} \tag{1}$$

And, during plugging operation stator voltages are:

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

According to qdo modeling

$$\lfloor V_{qdo} \rfloor = \lfloor T_{qdo} \rfloor \lfloor V_{abc} \rfloor \tag{3}$$

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where

$$\left[T_{qdo}\right] = 2/3\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (4)$$

The voltage balance equation for the q, d coils in stationary reference frame is as follows (Krishnan, 2007):

$$[V] = [Z]\,[i] \quad (5)$$

Where $[V]$ and $[i]$ represents '4x1' column matrices of voltage and current and are given as $\left[V_{qs}\ V_{ds}\ V_{qr}\ V_{dr}\right]^T$ and $\left[i_{qs}\ i_{ds}\ i_{qr}\ i_{dr}\right]^T$ respectively.

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

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

Incorporation of instantaneous value based saturation curve

The non-linear relation between magnetizing reactance, ' X_m ' and magnetizing current, ' I_m' of two machines (Appendix-I),using conventional modeling may be represented as;

$X_m = -1.225I^3_m + 22.293I^2_m - 128.027\, I_m + 294.936\ \Omega$

$X_m = 0.3372\, I^3_m - 1.8650\, I^2_m + 9.1425\, I_m + 114.2482\ \Omega$ (6)

Saturation curve as defined below may be modified (Appendix-I) and represented respectively as:

$x_m = 0.755i^3_m - 7.703i^2_m - 4.8319i_m + 196.78\ \Omega$

$x_m = 0.1205\, i^3_m - 0.7154\, i^2_m + 8.6888\, i_m + 114.4563\ \Omega$ (7)

The above modified relationships may be adopted to account the saturation effect during the transient study of a three-phase induction machine.

The magnetizing current, i_m is defined as:

$$i_m = \sqrt{i_{dt}^2 + i_{qt}^2} \quad (8)$$

and

$$i_{dt} = i_{ds}^r + i_{dr}^r \quad (9)$$

$$i_{qt} = i_{qs}^r + i_{qr}^r \quad (10)$$

Equation of Motion

Expression for electromagnetic torque using d-q axis model is given as,

$$T_e = \frac{3}{2}\frac{P}{2} L_m (i^r{}_{qs} i^r{}_{dr} - i^r{}_{ds} i^r{}_{qr}) \quad \text{(N.m)} \quad (11)$$

Whereas, the equation of motion may be defined as,

$$T_e - T_L = -2H(P\,\omega_r/\omega_b) - T_{damp} \quad (12)$$

Where inertia constant 'H', is defined as the ratio of the kinetic energy at base speed to the rated power and T_{damp}, is damping torque.

III. Results And Discussions

Figure 1-2 shows the comparison of simulated results (using conventional and proposed model) with experimental results on two test machines 1&2 [Appendix-II]. The machines under consideration initially run at no-load in motoring mode. After one second operation is changed to plugging mode by reversing the phase sequence of the supply system. Figure 1 shows the variation of stator phase currents with time. Analysis of figure1 and figure2 gives the following observations;

i. Simulated results as obtained using proposed model are close to experimental results. This proves the effectiveness of proposed modeling in contrast to conventional modeling and hence the same may be used to investigate the transient performance of induction machines.
ii. Inrush current drawn from the supply system becomes even greater than motoring mode during the change of operation from motoring to plugging mode. This necessitates a strong need to control this current during change over period.
iii. For the same machines settling time for plugging operation is found to be more as compared to its operation in motoring mode.

Simulated results of voltage, instantaneous value of current, torque, rotor speed and magnetizing current of machine-2, have been shown in figures3, 4 and figures 5, 6 without and with moment of inertia of the system attached respectively. Analysis of these figures gives the following observations;

i. Proposed transient modeling results into a large value of magnetizing current in contrast to conventional transient modeling for three phase induction machine. Hence in the absence of any starting arrangement, there is a possibility of saturation in magnetic circuit of the machine.
ii. There is hardly any appreciable change in the variation of torque and speed with time.

Figure 7 and 8 shows the variation of instantaneous torque of the machine with conventional and proposed modeling.

i. The rotor speed overshoots and the torque speed curve shows decayed oscillations about the final operating point during motoring and plugging mode (refer figure7).
ii. Figure 8 shows the effects of an increase in moment of inertia. It is found that transients appear initially during motoring and plugging, the rotor speed is highly damped and the final operating point is attained without oscillations. The large transient mechanical stresses on the motor shaft can be seen very high during plugging mode instead of motoring mode.
iii. Another noticeable point, in the torque speed characteristics incorporating conventional and proposed model, is that the simulated value of torque during changeover process is more with conventional model i.e. with conventional saturation curve.

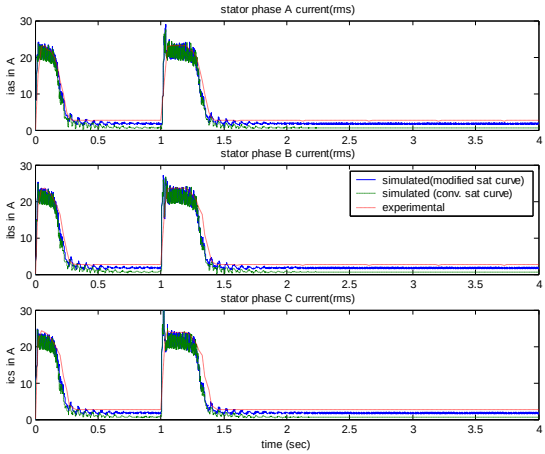

Fig.1: Transient phase currents for machine-1, J = 0.23kgm$^{2.}$

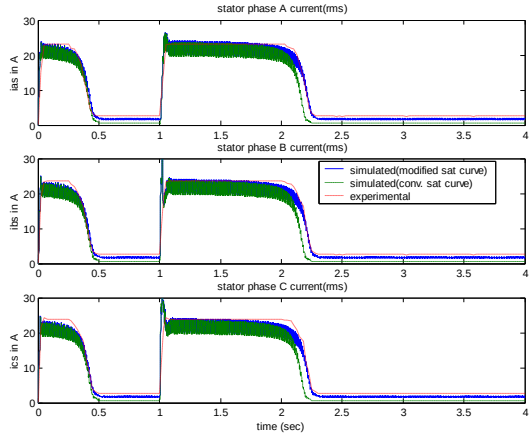

Fig.2: Transient phase currents for machine-2, J =0.913kgm^2.

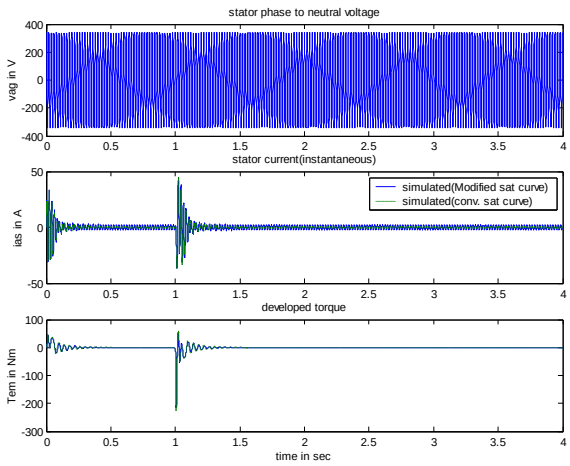

Fig.3: Simulated transient results for voltage, current and torque for machine-2, J = 0.113 kgm^2.

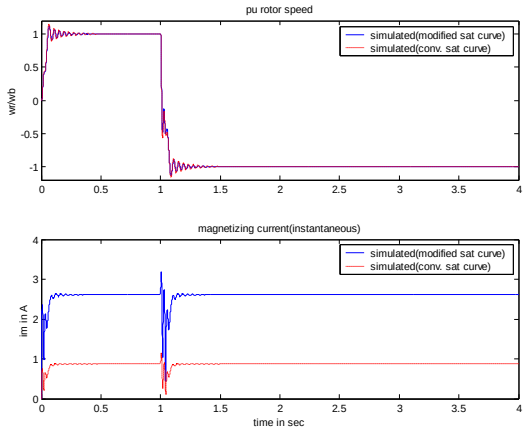

Fig.4: Simulated transient results for rotor speed and magnetizing current for machine-2, J = 0.113 kgm^2.

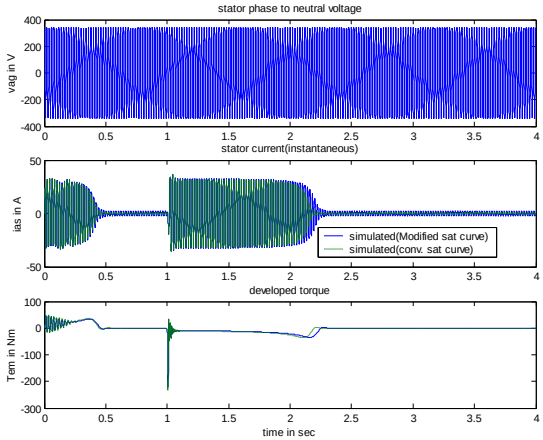

Fig.5: Simulated transient results for voltage, current and torque for machine-2, J = 0.913 kgm^2.

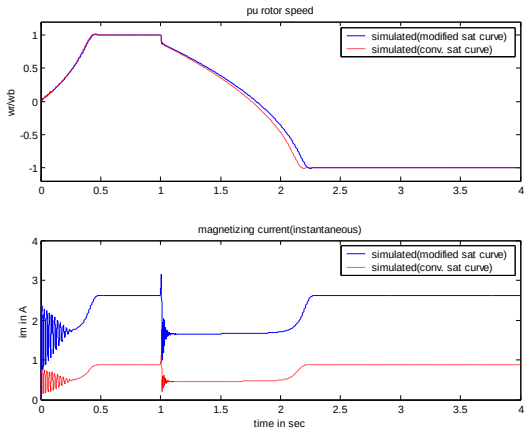

Fig.6: Simulated transient results for speed and magnetizing current for machine-2, J = 0.913 kgm^2

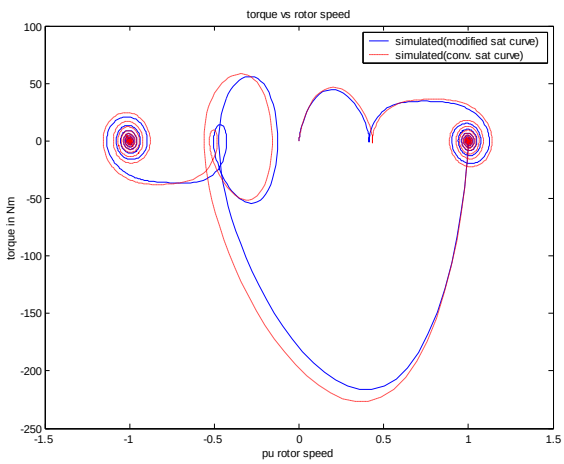

Fig.7: Simulated transient results of torque- speed characteristics for machine-2, J = 0.113 kgm^2.

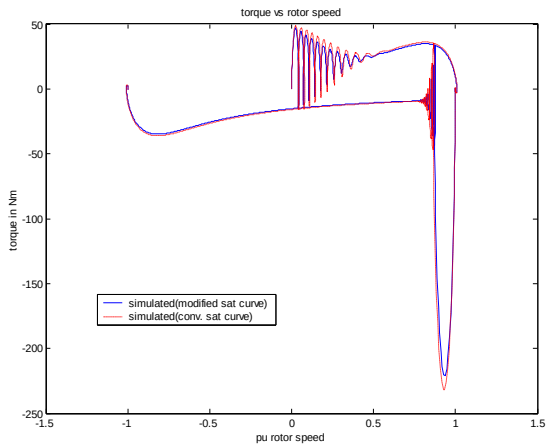

Fig.8: Simulated transient results of torque- speed characteristics for machine-2, J = 0.913 kgm^2

IV. Conclusion

In this paper, an attempt is made to analyze the dynamic behaviour of three phase induction machine using a new proposed model, which incorporates the saturation effect in a different manner in contrast to conventional models. A close comparison of simulated results using proposed modeling on two test machines with experimental data, confirms the validity and superiority of proposed model. Simulated results as obtained are further used to describe the dynamic behaviour of three phase induction machine in motoring and plugging operation.

Appendix

Appendix-I

The 3-phase induction motor under consideration is driven at rated synchronous speed with prime mover, after ensuring that the two machines run in the same direction if fed individually. Input current, power is recorded for different values of applied voltage. As shown in figure 9 and figure 10, observations as obtained may be used to plot the r.m.s. value based saturation curve of induction machine. The data as obtained may be further used to develop the instantaneous value based saturation curve and it is shown in figure 11 and figure 12:

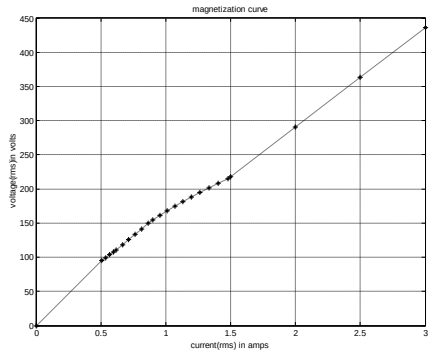

Fig.9: Saturation curve of machine1.

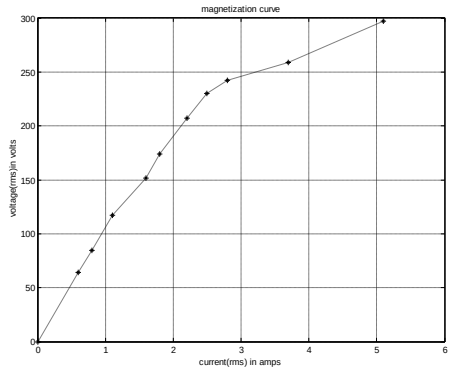

Fig.10: Saturation curve of machine2.

Modeling as given below may be used to convert conventional saturation curve into modified saturation curve. For a sinusoidal input voltage of frequency, ω, the corresponding flux linkage is given by

$$\Psi_k = \sqrt{2}V_k \quad , k = 0, 1, \text{----------}, n \qquad \text{(A1)}$$

Instantaneous value of current is obtained as

$$i_k = \sum_{j=1}^{k} K_j (\Psi_j - \Psi_{j-1}) \quad , k = 0, 1, \text{------- ---}, n \qquad \text{(A2)}$$

Where; K_j is the inverse of slope of line joining two points j & $(j\text{-}1)$ on the curve and 'n' is total number of points on the curve under consideration & in this paper its value is fifteen.

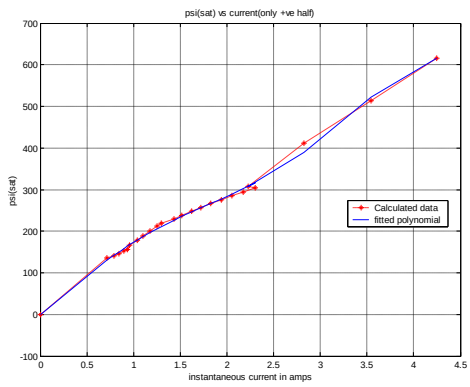

Fig.11: Modified saturation curve of machine1.

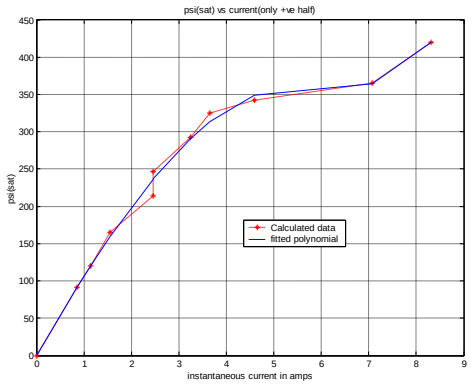

Fig.12: Modified saturation curve of machine2.

Appendix-II

Machine-1

3-hp, 3-phase, 50 Hz, 415 volts Induction Motor;
Stator Resistance, R_s = 4.44 ohms
Rotor Resistance, R_r = 0.9512 ohms
Stator & Rotor Inductance, $L_s = L_r = 14.97$ mH
Moment of Inertia of test machine set up
Without coupling, J = 0.113 kgm^2
Moment of Inertia of test machine set up
With coupling, J = 0.23 kgm^2

Machine-2

3-hp, 3-phase, 50 Hz, 220 volts Induction Motor;
Stator Resistance, R_s = 3.35 ohms
Rotor Resistance, R_r = 1.7 ohms
Stator & Rotor Inductance, $L_s = L_r = 15.44$ mH
Moment of Inertia of test machine set up
Without coupling, J = 0.113 kgm^2
Moment of Inertia of test machine set up
With coupling, J = 0.913 kgm^2

NOMENCLATURE

V_{as}, V_{bs}, V_{cs} = Bus bar voltages for phase A, B and C respectively

V_m = Maximum Voltage

$Vqds$ = Stator q and d axes voltages in stationary reference frame

$Vqdr$ = Rotor q and d axes voltages in stationary reference frame

$iqds$ = Stator q and d axes currents in stationary reference frame

$iqdr$ = Stator q and d axes voltages in stationary reference frame

R_s = Stator Phase Resistance/phase

L_s = Stator Self inductance/phase

L_m = Mutual inductance/phase

R_r = Rotor Phase Resistance/phase

L_r = Rotor self inductance/phase

ω_s = Angular speed (radian/sec.) in synchronously rotating reference frame

J = Inertia of Motor

T_e = Electrical Torque

T_L = Load Torque

p = Operator for differentiation

λ = Initial angle in degrees

Subscripts:

q = Quadrature axis
d = Direct axis
0 = Zero axis
s = Stator quantities
r = Rotor quantities

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