ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 10, April 2014

An improved transient model of an Induction Motor including magnetizing and leakage inductances saturated effect

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Abstract*-Transient behavior of athree-phase squirrel cage induction motor (IM) starting directly from the power system may be causing a large drop on power system resulting in failing other connected loads. This behavior not found or not clearly in the most available models of an IM. To remedy these inconsistencies an improved equivalent circuit model is proposed that accounts not only the saturation effects in the stator and rotor, but also independently, for saturation in both the rotor and stator cores. The theory of reference frame has been effectively used as an efficient approach to analyze the performance of an IM. To increased accuracy of the dynamic model takes the saturation effect into account for both magnetizing and leakage inductances. The obtained a new Matlab-Simulink model is tested and compared with conventional model. The transient behavior results shows the difference between magnetizing and leakage inductances when varies as compare with the constant one (conventional mode). The proposed model demonstrates an improvement over other known models showing that detailed representations of saturation effects could be important in induction machine analysis.

Index Terms-**Induction motor, model, magnetic saturated, leakage inductances saturated and Matlab-Simulink.**

I. INTRODUCTION

Induction motors (IM) are popular due to their low-cost, high efficiency, rugged construction, good self-starting and low maintenance expenditure. However, induction motors have disadvantages such as nonlinear, complex, and multi-variable of mathematical model that providing variable speed operation [1]. In order to explore the problems such as starting current, voltage dips, and oscillatory harmonic in power system during transient operations and start up, the (*d*-*q*) axis model has been found to be well tested and proven [2]. The voltage and torque equations that depict the dynamic behavior of an IM are time-varying. It is effectively used to solve such differential equation and it may include some complication of these equations by eliminating all time-varying inductances, due to electric circuits in relative motion from the voltage equations of the motor. By this process, a poly-phase winding can be reduced to asset two phase windings (*d*-*q*) with their magnetic axes formed in quadrature [3,4]. In other words, the stator and rotor variables (currents, voltages, and flux linkages) of asynchronous motor are transferred to a reference frame, which may remain stationary or rotate at any angular velocity. During great transient operation like starting, short circuit, open circuit, etc., Torque oscillations and large current appear. High values of transient currents rise saturation of the leakage paths. Rotor current oscillations related to torque oscillations vary the saturation of the main flux path [5,6]. Upon a time, may attempt have been made to create a model of induction machine? In 1984 Thomas A. Lipo and et al proposed a model of induction machine that is a reference model for all new works [8]. This model not accurate in the motor transient behavior due to the proximity in saturation model and used oldest programs. Most researches from [1-4,10-14] presented a model for IM without saturation effect while the others [5-8,15,16] try to determine the saturation effect using Pspice or Matlab. This is a saturation model for only magnetizing circuit or only leakage reactance or do not compare the results with conventional model. The results for all above works do not cover the starting with and without load in addition to sudden change in load. The results then must compare with the conventional model of IM to get an agreement for all results. In this, paper a very fast approach using Matlab-Simulink to simulate a transient behavior of the IM uses state-space model along with considering the saturation of both the magnetizing and leakage inductances assuming that the main flux inductance, stator, and rotor leakage inductances vary with the current depending on Ref.[6-8]. The results show the deference between the conventional and saturated model for the IM and good transient behavior when start-up the motor with load in addition to sudden change in load.

II. AXES TRANSFORMATION

Consider a symmetrical 3-phase a synchronous motor with stationary (as, bs, cs) axes at ($\frac{2\pi}{3}$) angle apart, as shown in Fig. (1), purpose is to convert the 3-phase stationary reference frame (as ,bs , cs) variable into two-phase stationary reference frame $(d^s - q^s)$ variables and then convert these to synchronously rotating frame$(d^e - q^e)$, and vice versa. Assume that the $(d^s - q^s)$ axes are oriented at θ angle, as shown in Fig. (1). The voltage $v_{ds}{}^s$ and$v_{qs}{}^s$ can be determined into (as, bs, cs) component and can be represented in the matrix form as [4].

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ISO 9001:2008 Certified
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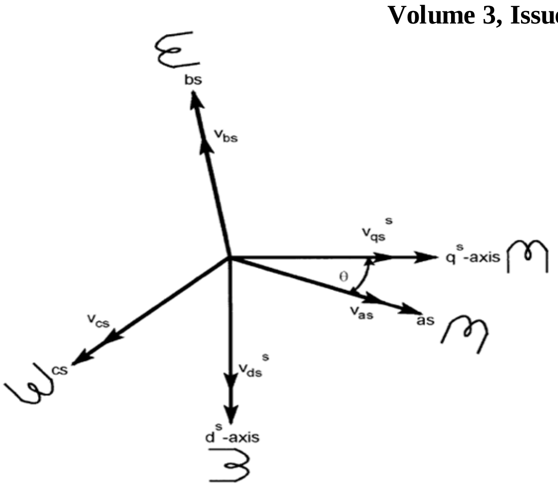

Fig. (1) Stationary frame a -b - c to *ds* - *qs* axes transformation

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-120^\circ) & \sin(\theta-120^\circ) & 1 \\ \cos(\theta+120^\circ) & \sin(\theta+120^\circ) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{os}^s \end{bmatrix} \quad \ldots(1)$$

The corresponding inverse relation is:

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{os}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta-120^\circ) & \cos(\theta+120^\circ) \\ \sin\theta & \sin(\theta-120^\circ) & \sin(\theta+120^\circ) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \ldots(2)$$

The component of zero sequence (v_{os}^s), which may or may not be present. It has been noticed that the accounted voltage is the variable. The flux linkages and current can be transformed by similar equations.

It is suitable to set $\theta = 0$, so that the q^s -axis is aligned with the as-axis. Neglecting the zero sequence component, the transformation relations can be simplified as [12,13].

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} \quad \ldots(3)$$

and inversely:

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \quad \ldots(4)$$

Fig. (2) Indicates the synchronously rotating ($d^e - q^e$)axes, which synchronous speed (ω_e) with respect to the ($d^s - q^s$) axes and the angle $\theta_e = \omega_e t$. The two-phase ($d^s - q^s$) winding are transformed into the presumptive winding mounted on the($d^e - q^e$) axes. The voltages on the($d^s - q^s$) axes can be converted into the ($d^e - q^e$) frame as follows:

$$\begin{bmatrix} v_{qs}^e \\ v_{ds}^e \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} \quad \ldots(5)$$

Again, resolving the rotating frame parameter into stationary frame, the relation is:

$$\begin{bmatrix} v_{qs}^s \\ v_{ds}^s \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} v_{qs}^e \\ v_{ds}^e \end{bmatrix} \quad \ldots(6)$$

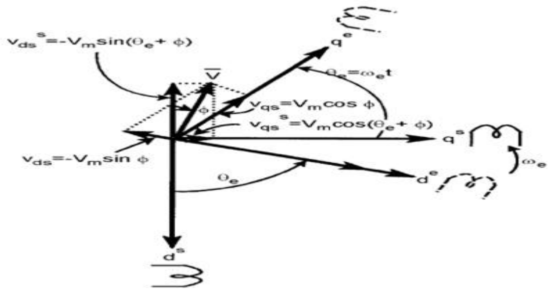

Fig. (2) Stationary frame d^s -$q^s$to synchronously rotating frame d^e -q^e transformation

Assume that the 3–phase stator voltages of an IM under a balanced condition can be expressed as:

$$v_{as} = Vm\sin(\omega_e t) \quad \ldots(7)$$

$$v_{bs} = Vm\sin\left(\omega_e t - \frac{2\pi}{3}\right) \quad \ldots(8)$$

$$v_{cs} = Vm\sin\left(\omega_e t + \frac{2\pi}{3}\right) \quad \ldots(9)$$

III. CONVENTIONAL IM MODEL DEVELOPMENT

In the development of the dynamic equations for the conventional motor model, the following assumptions are made:

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

The differential equations governing the transient performance of the IM can be described in several forms and they differ only in detail and in their suitability for use in a given application. The conventional motor model is developed using the traditional method of reducing the machine to a two-axes coi1 (*d*-*q*) axes model on both the stator and rotor as depicted by Ref.[9]. The dynamic axes model of the motor provides a convenient way of modeling the machine and it is appropriate for numerical solution. Fig.(3) shows the d-q equivalent circuits for a 3-phase, symmetrical squirrel- cage IM in arbitrary- frame with zero-sequence component neglected [10,11].

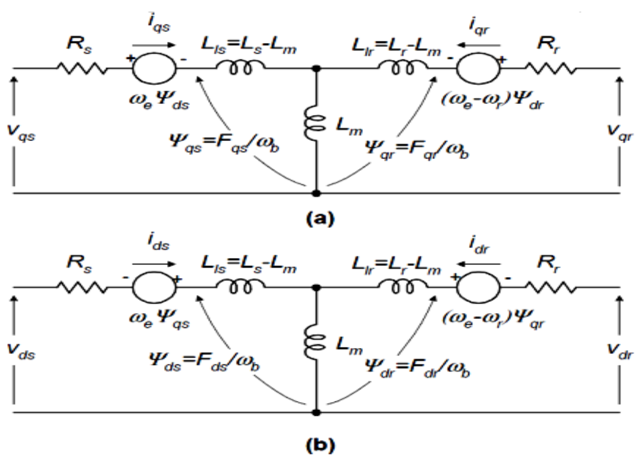

Fig. (3) Dynamic d^e-q^eequivalent circuits of the machine

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
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IV. DYNAMIC MODEL STATE – SPACE EQUATIONS

The dynamic machine model in state – space form is significant for transient analysis, especially for computer simulation study. The rotating and stationary frames can be used, but the rotating frame is generally preferred. The electrical variables in the model can be chosen as a flux, current or a mixture of both. In this paper, the state- space equations of the motor in rotating frame with flux linkage as the main variable is driven depending on Ref.[4,14]. Driving the model equations can be generated from the Fig. (3). The voltage equations associated with this circuit can be determined as given in the Appendix (A).

V. MODEL DEVELOPMENT WITH SATURATION EFFECT

The values of the inductances used in the development of the dynamic equations for the conventional model was assumed constant. By so doing the model fail to take into consideration the saturation affects of both the magnetizing inductance and the leakage inductances. It has been proved beyond doubts by several authors that the stability and dynamic conditions of induction machine are highly affected by saturation [8,9]. In this paper, the magnetizing and the leakage inductance vary with the exciting current. Therefore, the saturation curves of the tested motor must be determined [7-9].

A. Saturation of stator and rotor leakage inductance

The total stator and rotor leakage inductances are separated into air-dependent and iron-dependent portions. The terms L_{lsi}andL_{lri} correspond to the sum of the iron dependent saturated leakage inductance which represents the leakage flux of slot, zig-zag, belt, and skew leakage for stator and rotor respectively. These different components of leakage flux are discussed in [8]. The term L_{lsa} and L_{lra} correspond to the air-dependent end winding leakage inductances and they are assumed to be constant [6,8].

B. Saturation of Magnetizing Inductance

The phenomenon of the saturation magnetizing inductances in inductions is a result of increases the magnetizing current beyond the certain limitation. By larger currents the specific permeability of the iron core is decreasing, this mean the magnetizing inductance decrease with increase magnetizing current [16]. The inductances (L_m, L_{lsi}, L_{lri}) become non-linear and the values of these inductances determined from their exciting currents [8].

VI. SATURATED FLUX MODELS

In order to simulate the dynamic operation of IM, the saturable flux leakage and magnetizing flux have to be modeled into some functional form. The flux saturation can be reasonably modeled by a normal magnetizing curve rather than the hysteresis loop. The function form used in this study for modeling the stator and rotor leakage flux saturation effects gives the following equation [6]:

$$\Psi = a_1 \arctan(a_2 i) + a_3 i \quad ...(10)$$

By using the actual data collected for (Ψ) and (i) the coefficients (a_1, a_2, and a_3) can be estimated, the incremental inductance is then:

$$L_{inc} = \frac{d\lambda}{dt} = \frac{a_1 * a_2}{1+a_2^2 i^2} + a_3 \quad ...(11)$$

The techniques to identify the constant in the equation (10) are based on nonlinear least squares estimation algorithm developed by Marquaredt [6,8], this can be done by Matlab-Apps curve fitting.

Similarly Ψ_m can be obtained as:

$$\Psi_m = a_1 \arctan(a_2 i) \quad ...(12)$$

By using the actual data collected for (Ψ_m) and (*i*) the coefficients a_1 and a_2 can be estimated the magnetizing inductance as given [6,15]

$$L_m = \frac{a_1 * a_2}{1+a_2^2 i^2} \quad ...(13)$$

VII. SIMULATION RESULTS

The proposed IM Model was test using a three-phase three-wire 230V, squirrel cage machine rated at 15hp, f= 60, R_s=0.4122, R_r=0.4976Ω, L_{lsa}=0.397, L_{lsi}=2.52mh, L_{lra}=0.397 mh, L_{lri}=2.52mh, L_m= 15.7 mh, and p=4, J=0.11Kg.m^2. Table (1B) and (2B) in Appendix (B) give the results for locked-rotor test and the no-load test respectively. The Ψ_{lsi} *and* Ψ_m are translated from (*Vs*) based on the given equation (14) and (15) [6,14].

$$\Psi_{lsi}, \Psi_{lri} = \frac{1}{\sqrt{6}} \frac{Vs}{\omega_b} \quad ...(14)$$

$$\Psi_m = \sqrt{\frac{2}{3} \frac{Vs}{\omega_b}} \quad ...(15)$$

In equation (14) Ψ_{lsi} *and* Ψ_{lri} are assumed equal, and ω_b is taken to be 377 rad/sec for both equations (14) and (15) [6]. The results of the leakage flux, incremental leakage inductance, magnetizing flux, and incremental magnetizing inductance are shown in Fig.s (4-7) respectively. Fig. (8) shown the proposed dynamic model of IM by Matlab-Simulink, Fig.s (9-17) shown the simulation results for the electromagnetic torque, stator current, and rotor angular electrical speed respectively, where (A) conventional model and (B) saturated model when the machine is accelerated at no-load, at15 N.m load, and suddenly loaded by 20 (N.m)in 1.2sec.

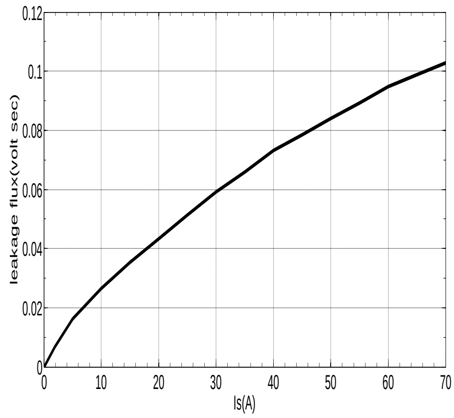

Fig. (4) Leakage flux Vs stator current

ISSN: 2277-3754
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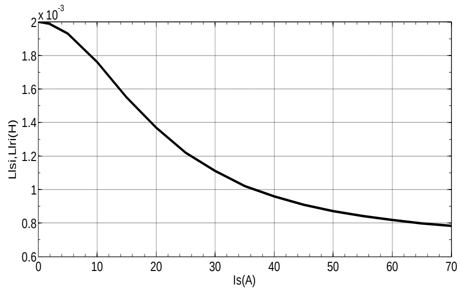


Fig. (5) Leakage inductance Vs stator current

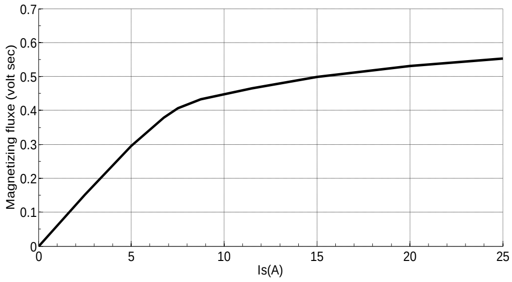


Fig. (6) Magnetizing flux Vs stator current

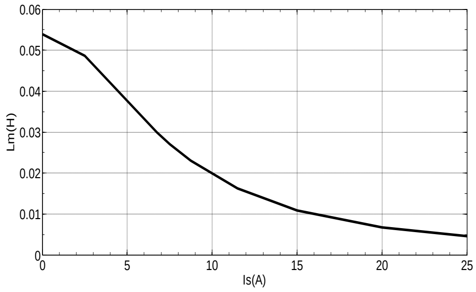


Fig. (7) Magnetizing inductance Vs stator current

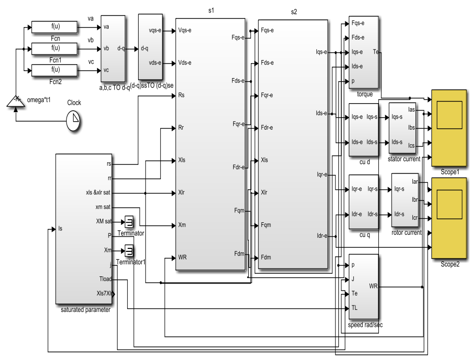
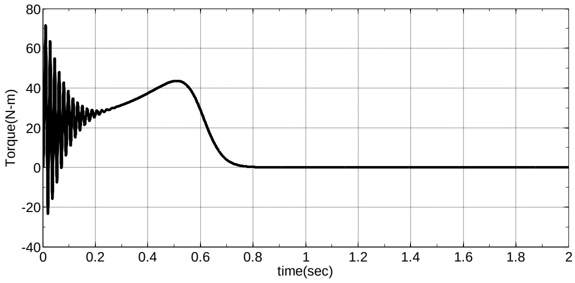
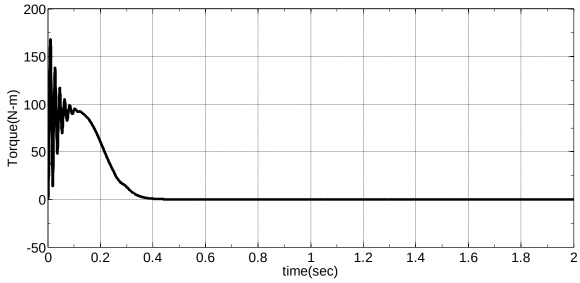


Fig. (8) The proposed Matlab-Simulink IM dynamic model

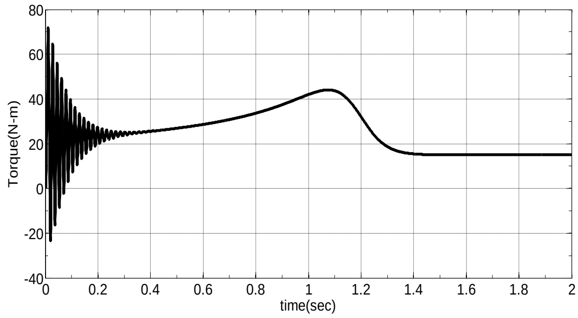


(A) Conventional model

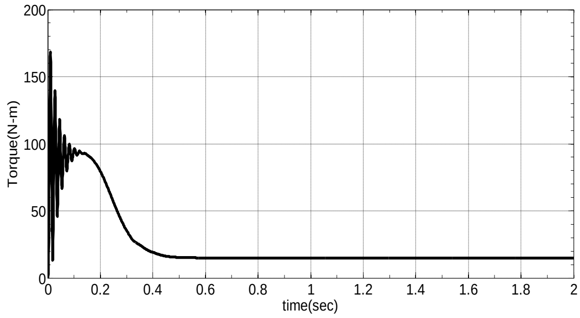


(B) Saturated model

Fig. (9) Electromagnetic torque at no-load for (A) conventional model and (B) saturated model

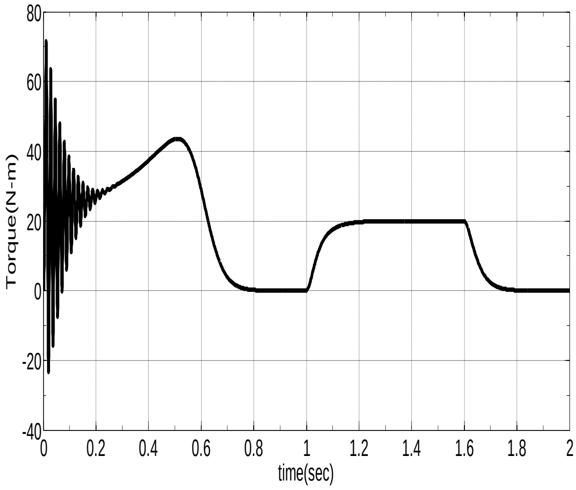


(A) Conventional model



(B) Saturated model

Fig. (10) Electromagnetic torque at load for (A) conventional model and (B) saturated model.



(A) Conventional model

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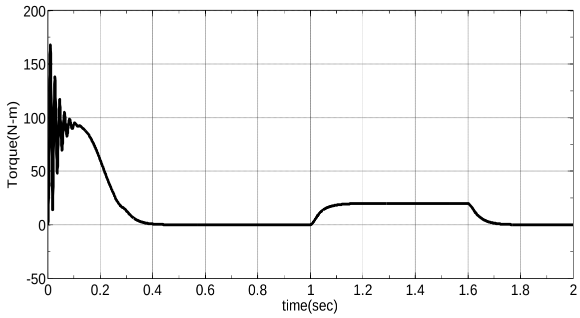
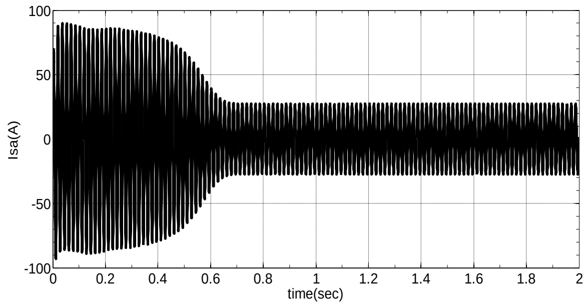
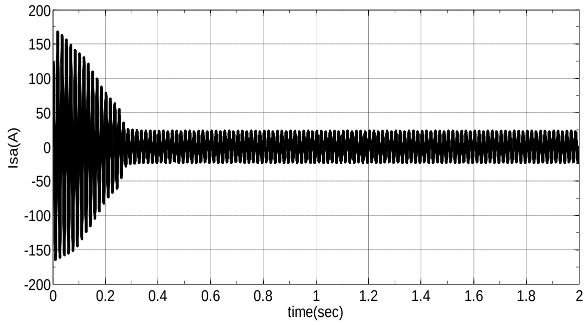


(B) Saturated model

Fig. (11) Electromagnetic torque at sudden load for (A) conventional model and (B) saturated model

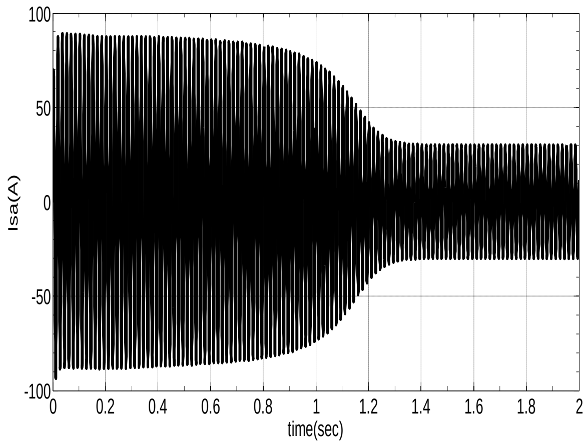


(A) Conventional model

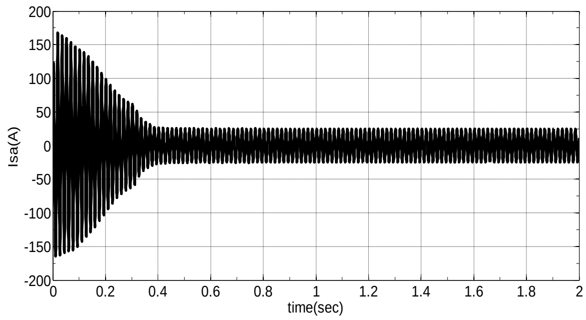


(B) Saturated model

Fig. (12) Stator current at no-load for (A) conventional model and (B) saturated model.

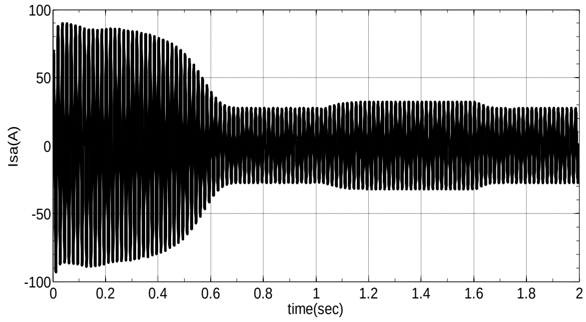


(A) Conventional model

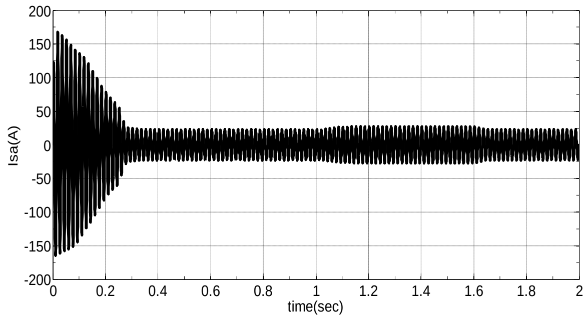


(B) Saturated model

Fig. (13) stator current at the load for (A) conventional model and (B) saturated model

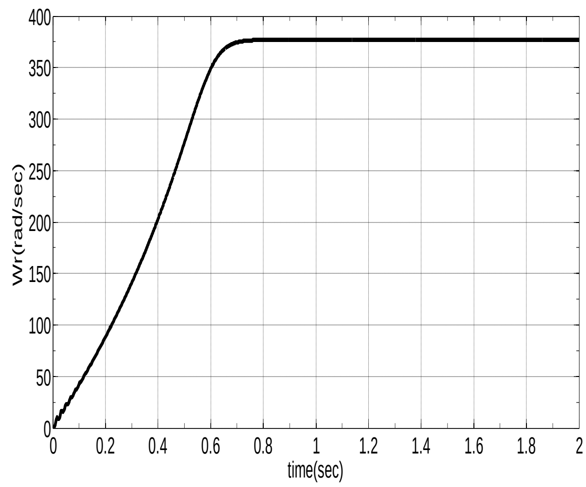


(A) Conventional model



(B) Saturated model

Fig. (14) Stator current at sudden load for (A) conventional model and (B) saturated model



(A) Conventional model

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
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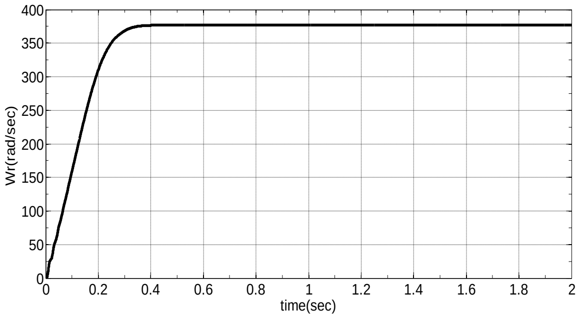
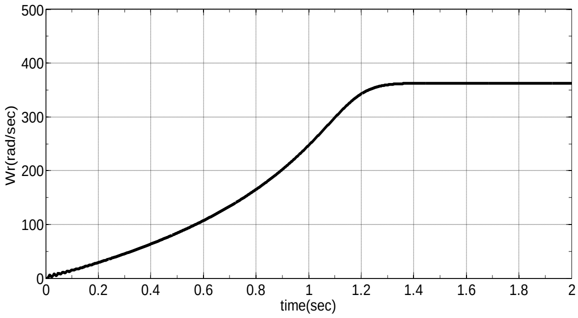
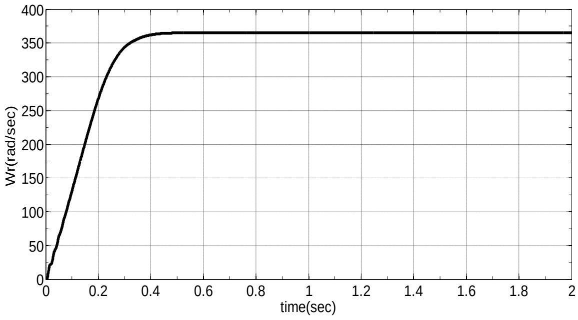


(B) Saturated model

Fig. (15) Rotor angular electrical speed at no-load for (A) conventional model and (B) saturated model

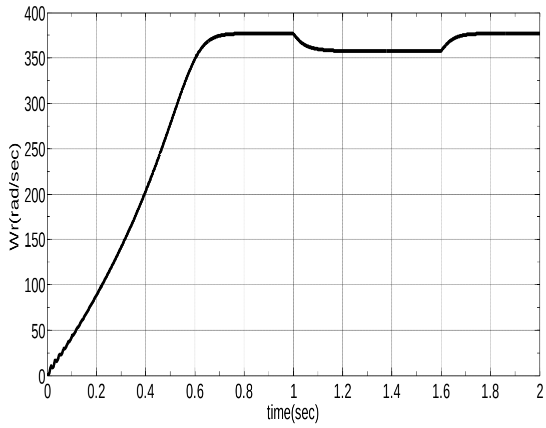


(A) Conventional model

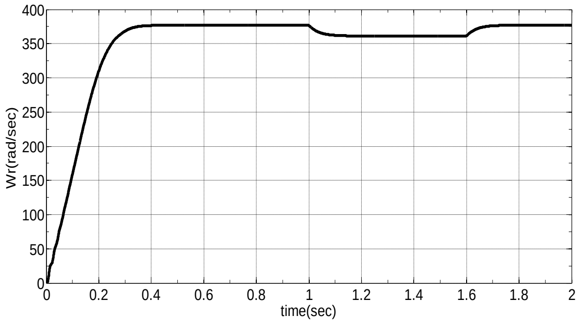


(B) Saturated model

Fig. (16) Rotor angular electrical speed at load for (A) conventional model and (B) saturated model



(A) Conventional model



(B) Saturated model

Fig. (17) Rotor angular electrical speed at sudden load for (A) conventional model and (B) saturated model.

VIII. CONCLUSION

This paper presents a new MATLAB-Simulink IM dynamic model. The simulated transient results show differences between the conventional IM model and saturation model. The results indicate that the unsaturated model by using Matlab-Simulink give a sub-station error when compared with the tests. So the saturation effect during the acceleration period can't be neglected and a recognize that the model's parameters are time varying and they are a function of excitation current, is very important to get an accurate simulation results that compatible with the practical actual dynamic beavers of IM.

APPENDIX (A)

The voltage equations associated with an IM circuit of Fig. (3) Can be determined as follows: [1-4]

$$v_{qs}^{e} = R_s i_{qs}^{e} + \frac{d}{dt}\Psi_{qs}^{e} + \omega_e \Psi_{ds}^{e} \quad \ldots (1A)$$

$$v_{ds}^{e} = R_s i_{ds}^{e} + \frac{d}{dt}\Psi_{ds}^{e} - \omega_e \Psi_{qs}^{e} \quad \ldots (2A)$$

$$v_{qr}^{e} = R_r i_{qr}^{e} + \frac{d}{dt}\Psi_{qr}^{e} + (\omega_e - \omega_r)\Psi_{dr}^{e} \quad \ldots (3A)$$

$$v_{dr}^{e} = R_r i_{dr}^{e} + \frac{d}{dt}\Psi_{dr}^{e} - (\omega_e - \omega_r)\Psi_{qr}^{e} \quad \ldots (4A)$$

Let's define the flux linkage variables as follows:

$$F_{qs}^{e} = \omega_b \Psi_{qs}^{e} \quad \ldots (5A)$$

$$F_{qr}^{e} = \omega_b \Psi_{qr}^{e} \quad \ldots (6A)$$

$$F_{ds}^{e} = \omega_b \Psi_{ds}^{e} \quad \ldots (7A)$$

$$F_{dr}^{e} = \omega_b \Psi_{dr}^{e} \quad \ldots (8A)$$

Where ω_b= base frequency of the machine.

Substituting the above relation in equations (1-4) the result will be:

$$v_{qs}^{e} = R_s i_{qs}^{e} + \frac{1}{\omega_b}\frac{dF_{qs}^{e}}{dt} + \frac{\omega_e}{\omega_b}F_{ds}^{e} \quad \ldots (9A)$$

$$v_{ds}^{e} = R_s i_{ds}^{e} + \frac{1}{\omega_b}\frac{dF_{ds}^{e}}{dt} - \frac{\omega_e}{\omega_b}F_{qs}^{e} \quad \ldots (10A)$$

$$v_{qr}^{e} = R_r i_{qr}^{e} + \frac{1}{\omega_b}\frac{dF_{qr}^{e}}{dt} + \frac{(\omega_e - \omega_r)}{\omega_b}F_{dr}^{e} \quad \ldots (11A)$$

$$v_{dr}^{e} = R_r i_{dr}^{e} + \frac{1}{\omega_b}\frac{dF_{dr}^{e}}{dt} - \frac{(\omega_e - \omega_r)}{\omega_b}F_{qr}^{e} \quad \ldots (12A)$$

Where it is assumed that $v_{qr}^{e} = v_{dr}^{e} = 0$.

From Fig. (3) it can be found the flux linkage expressions as follows:

$$\Psi_{qs}^{e} = L_{ls} i_{qs}^{e} + L_m(i_{qs}^{e} + i_{qr}^{e}) \quad \ldots (13A)$$

$$\Psi_{ds}^{e} = L_{ls} i_{ds}^{e} + L_m(i_{ds}^{e} + i_{dr}^{e}) \quad \ldots (14A)$$

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
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$$\Psi_{qr}{}^{e} = L_{lr} i_{qr}{}^{e} + L_m\left(i_{qs}{}^{e} + i_{qr}{}^{e}\right) \quad ...(15A)$$
$$\Psi_{dr}{}^{e} = L_{lr} i_{dr}{}^{e} + L_m\left(i_{ds}{}^{e} + i_{dr}{}^{e}\right) \quad ...(16A)$$
$$\Psi_{qm}{}^{e} = L_m\left(i_{qs}{}^{e} + i_{qr}{}^{e}\right) \quad ...(17A)$$
$$\Psi_{dm}{}^{e} = L_m\left(i_{ds}{}^{e} + i_{dr}{}^{e}\right) \quad ...(18A)$$

Resulting in the equations of ($F_{qs}{}^{e}$,$F_{ds}{}^{e}$,$F_{qr}{}^{e}$,$F_{ds}{}^{e}$) by multiplying equations (13-18) by (ω_b).

$$F_{qs}{}^{e} = x_{ls} i_{qs}{}^{e} + F_{qm}{}^{e} \quad ...(19A)$$
$$F_{ds}{}^{e} = x_{ls} i_{ds}{}^{e} + F_{dm}{}^{e} \quad ...(20A)$$
$$F_{qr}{}^{e} = x_{lr} i_{qr}{}^{e} + F_{qm}{}^{e} \quad ...(21A)$$
$$F_{dr}{}^{e} = x_{lr} i_{dr}{}^{e} + F_{dm}{}^{e} \quad ...(22A)$$

From above equations, the currents can be expressed in terms of the flux linkage as given in the following equations:

$$i_{qs}{}^{e} = \frac{F_{qs}{}^{e} - F_{qm}{}^{e}}{x_{ls}} \quad ...(23A)$$
$$i_{qr}{}^{e} = \frac{F_{qr}{}^{e} - F_{qm}{}^{e}}{x_{lr}} \quad ...(24A)$$
$$i_{ds}{}^{e} = \frac{F_{ds}{}^{e} - F_{dm}{}^{e}}{x_{ls}} \quad ...(25A)$$
$$i_{dr}{}^{e} = \frac{F_{dr}{}^{e} - F_{dm}{}^{e}}{x_{lr}} \quad ...(26A)$$

Substituting equations (23A and 24A) in (19A and 21A), respectively the (F_{qm}) expression is given as:-

$$F_{qm}{}^{e} = \frac{x_{ml}}{x_{ls}} F_{qs}{}^{e} + \frac{x_{ml}}{x_{lr}} F_{qr}{}^{e} \quad ...(27A)$$
$$x_{ml} = \frac{1}{\left(\frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x_{lr}}\right)} \quad ...(28A)$$

Similar derivations can be made for ($F_{dm}{}^{e}$) as follows:

$$F_{dm}{}^{e} = \frac{x_{ml}}{x_{ls}} F_{ds}{}^{e} + \frac{x_{ml}}{x_{lr}} F_{dr}{}^{e} \quad ...(29A)$$

Substituting the current equation (23A-26A) in the voltage equations the voltage equation is given as:

$$v_{qs}{}^{e} = \frac{R_s}{x_{ls}}\left(F_{qs}{}^{e} - F_{qm}{}^{e}\right) + \frac{1}{\omega_b}\left(\frac{dF_{qs}{}^{e}}{dt}\right) + \frac{\omega_e}{\omega_b} F_{ds}{}^{e} \quad ...(30A)$$
$$v_{ds}{}^{e} = \frac{R_s}{x_{ls}}\left(F_{ds}{}^{e} - F_{dm}{}^{e}\right) + \frac{1}{\omega_b}\left(\frac{dF_{ds}{}^{e}}{dt}\right) - \frac{\omega_e}{\omega_b} F_{qs}{}^{e} \quad ...(31A)$$
$$0 = \frac{R_r}{x_{lr}}\left(F_{qr}{}^{e} - F_{qm}{}^{e}\right) + \frac{1}{\omega_b}\left(\frac{dF_{qr}{}^{e}}{dt}\right) + \frac{(\omega_e - \omega_r)}{\omega_b} F_{dr}{}^{e} \quad ...(32A)$$
$$0 = \frac{R_r}{x_{lr}}\left(F_{dr}{}^{e} - F_{dm}{}^{e}\right) + \frac{1}{\omega_b}\left(\frac{dF_{dr}{}^{e}}{dt}\right) - \frac{(\omega_e - \omega_r)}{\omega_b} F_{qr}{}^{e} \quad ...(33A)$$

Thatcan be expressed in state –space forms.

$$\frac{dF_{qs}{}^{e}}{dt} = \omega_b[v_{qs}{}^{e} - \frac{\omega_e}{\omega_b} F_{ds}{}^{e} + \frac{R_s}{x_{ls}}\left(F_{qm}{}^{e} + F_{qs}{}^{e}\right) \quad ...(34A)$$
$$\frac{dF_{ds}{}^{e}}{dt} = \omega_b[v_{ds}{}^{e} + \frac{\omega_e}{\omega_b} F_{qs}{}^{e} + \frac{R_s}{x_{ls}}\left(F_{dm}{}^{e} + F_{ds}{}^{e}\right) \quad ...(35A)$$
$$\frac{dF_{qr}{}^{e}}{dt} = \omega_b[v_{qr}{}^{e} - \frac{(\omega_e - \omega_r)}{\omega_b} F_{dr}{}^{e} + \frac{R_r}{x_{lr}}\left(F_{qm}{}^{e} - F_{qr}{}^{e}\right) \quad ...(36A)$$
$$\frac{dF_{dr}{}^{e}}{dt} = \omega_b[v_{dr}{}^{e} + \frac{(\omega_e - \omega_r)}{\omega_b} F_{qr}{}^{e} + \frac{R_r}{x_{lr}}\left(F_{dm}{}^{e} - F_{dr}{}^{e}\right) \quad ...(37A)$$

Finally, the motor torque and rotor speed equations can be determined as follows [1, 2, 4].

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{1}{\omega_b}\left(F_{ds}{}^{e} i_{qs}{}^{e} - F_{qs}{}^{e} i_{ds}{}^{e}\right) \quad ...(38A)$$
$$\omega_r = \int \frac{p}{2J}\left(T_e - T_l\right) \quad ...(39A)$$

Where

d: direct axis,
q: quadrature axis,
s: stator variable,
r: rotor variable,
$F_i$is the flux linkage (*i*=*q* or *d* and j=*s* or *r*),
v_{qs},v_{ds}: *q* and *d* axis stator voltages,
v_{qr},v_{dr} : *q* and *d* axis rotor voltages,
F_{qm},F_{dm}: *q* and *d* axis magnetizing flux linkages,
R_r: rotor resistance,
R_s: stator resistance,
x_{ls}: stator leakage reactance ($\omega_e L_{ls}$),
x_{lr}: rotor leakage reactance ($\omega_e L_{lr}$),
i_{qs}, i_{ds}: *q* and *d*-axis stator currents,
i_{qr}, i_{dr} : *q* and *d*-axis rotor currents,
p: number of poles,
J: moment of inertia,
T_e: electrical output torque,
T_l: load torque,
ω_e: stator angular electrical frequency.
□$_r$: rotor angular electrical speed.

APPENDIX (B)

The locked-rotor test and the no-load test for the sample IM are shown in the following tables.

Table (1B) IM locked rotor test

Measured Vs in Volt (RMS)	Calculated $\Psi_{lsi} = \Psi_{lri}$	Measured Is in Amper(RMS)
0.00	0.00000	0.00
6.25	0.00677	1.88
15.00	0.01625	5.00
24.5	0.02653	10.00
32.50	0.03520	15.00
40.00	0.04332	20.00
47.50	0.05144	25.00
54.50	0.05902	30.00
60.75	0.06579	35.00
67.50	0.07310	40.00
72.50	0.07852	45.00
77.50	0.08393	50.00
82.50	0.08935	55.00
87.50	0.09476	60.00
91.25	0.09882	65.00
95.00	0.10289	70.00

Table (2B) IM no-load test

Measured Vs in Volt (RMS)	Calculated Ψ_m	Measured Is in Amper (RMS)
0.00	0.00000	0.00
70.00	0.15162	2.50
136.25	0.29512	5.00
175.00	0.37905	6.75
187.50	0.40613	7.50
200.00	0.43320	8.75
215.00	0.46569	11.50
230.00	0.49818	15.00
245.00	0.53067	20.00
255.00	0.55233	25.00

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ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
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