



MATLAB-BASED SIMULATIONS OF A THREE-PHASE INDUCTION MOTOR FOR DYNAMIC STUDIES

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Abstract

The aim of this paper is to develop a generalized MATLAB program to study the dynamic behavior of a three-phase induction motor. The d-q axis transformation theory is applied in rotor reference frame to study the motor dynamics. A general-purpose MATLAB program is developed and used for the dynamic simulation of a 5HP, 460V, 60Hz, 4-poles induction motor. The developed program is used to study the effect of variation of Stator Resistance (R_s), Moment of Inertia (J), and Load Torque (T_L) at $t=0.7$ sec during transient state. The results obtained show that, the torque-speed characteristic curve and mechanical rotor speed-time characteristics of induction motor depend upon the rotor resistance and the moment of inertia. Also, during the simulation of the motor under loaded torque at $t=0.7$ sec, the results showed an increase in the initial starting torque and it reduces from 2000Nm – 0Nm as the operating time progressed. A sudden residual increase occurred in the torque from 0-1000Nm at the loaded time $t=0.7$ sec, and the mechanical rotor speed increased at starting time from 0-1800rpm with respect to operating time and suddenly experienced a drop from 1800rpm to about 1700rpm at the loaded time of $t=0.7$ sec. The developed program is particularly useful for machine designers in the manufacture of various types of induction machines.

Keywords: Induction Machine, D-Q Transformation, Modelling, Simulation, Machine Analysis, MATLAB.

1.0 INTRODUCTION

An asynchronous motor also known as induction motor is a commonly used AC motor. An electric machine is an energy conversion equipment that converts mechanical energy to electrical energy (Generator) or electrical energy to mechanical energy (motor). Three-phase induction motors are the most commonly used AC motors in the industry, this is because they have simple and rugged construction, low cost, high efficiency, good power factor, self-starting and low maintenance cost. About 90% of mechanical power in industry is delivered by three-phase induction motors [1].

Dynamic system modelling is used to described and predict the interactions over time between multiple components of a phenomenon that is viewed as a system. It focuses on the mechanism on how the components and the system changes over time [2, 3].

In induction motor modelling, the three phase quantities are converted or transformed to two phase quantities after the conversion, one phase is known as direct axis (d-axis) and the other phase is known as quadrature axis (q-axis). The dynamic model considers the instantaneous effects of varying voltage/currents, stator frequency and torque disturbances [3, 4].

Direct quadrature (d-q) transformation is a mathematical transformation used to simplify the analysis of three-phase circuits. In the case of balanced three-phase circuit application of d-q transformation reduces the three AC to two quantities.

During design and construction of electrical machines, design and constructional errors occur, limiting the operational expectancy of the machine performance. With dynamic modelling and simulation of electrical

machine, validation of design process of the system is assured, thereby eliminating such design and construction errors or mistakes and as well prevention of unscheduled downtimes of induction machine [4, 5].

1.1 MATLAB SOFTWARE

MATLAB is a computer software package for high performance computation and visualization. Its analysis capabilities, flexibility, reliability and powerful graphic makes MATLAB a high acceptable and utilized software package for engineers and scientists. MATLAB stands for Matrix Laboratory. It's a high-performance computer package with multiple accurate and reliable in-built mathematical functions. These functions provide solution to wide range of mathematical problems such as Matrix algebra, Complex arithmetic, Linear systems, Differential equations, Signal processing, Optimization, Non-linear systems and other scientific computations [15].

1.1.1 Direct Quadrature (D-Q) Transformation of Three-Phase Induction Motor

In balanced three-phase circuit, application of the d-q transformation reduces the three AC quantities to two DC quantities [6, 7, and 3]. The various stages applied to achieve d-q transformation are the Clarke's and the Park's transformation. The three phase voltages varying in time along the axis a, b, and c, can be algebraically transformed into two voltages varying in time along the axis, α and β according to Clark by the transformation matrix in equation (1), [6,7, 8].

Also, obtaining the three phase quantities from the two-phase quantities (inverse transformation) is

possible through the transformation matrix in equation (2).

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{2}$$

While Park's transformation further transforms the two-axis orthogonal stationary reference frame quantities into rotating reference frame quantities. The referred parks transformation matrix is shown in equation (3).

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{3}$$

Transforming the quantities from two-phase rotating to two-phase stationary frame can be achieved using the below transformation matrix in equation (4) [6, 9, 8].

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} V_d \\ V_q \end{bmatrix} \tag{4}$$

1.1.2 Dynamic Model Equation of Three-Phase Induction Machine

The dynamic model equations of the induction motor can be obtained from the d-q equivalent circuit of the induction motor shown in figure 1 [9, 3, 4].

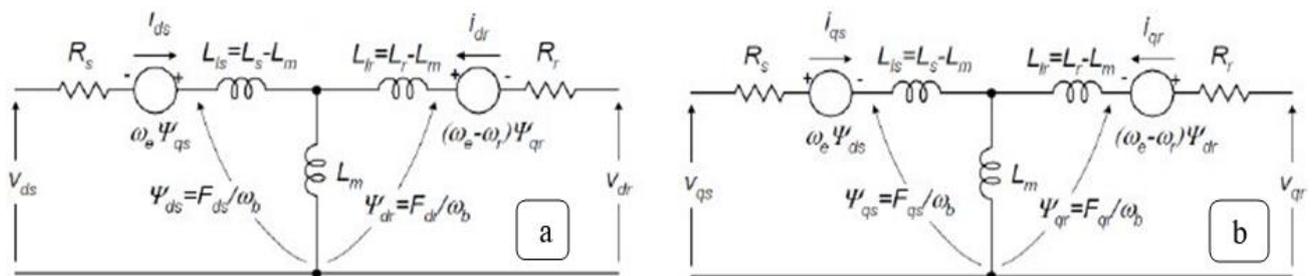


Figure 1: D- and Q-Axis Equivalent Circuit of an Induction motor [4]

Under balance condition, the three-phase stator voltage of an induction motor can be expressed as equation (5), (6), and (7).

$$V_a = \sqrt{2} V_{rms} \sin(\omega_t) \tag{5}$$

$$V_b = \sqrt{2} V_{rms} \sin\left(\omega_t - \frac{2\pi}{3}\right) \tag{6}$$

$$V_c = \sqrt{2} V_{rms} \sin\left(\omega_t + \frac{2\pi}{3}\right) \tag{7}$$

These three-phase voltages are transformed into two-phases synchronously rotating reference frame of d-q axis. This transformation is achieved through the

application of the following transformation matrix as shown in equation (8) [7, 11].

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (8)$$

Then, the d-q axis voltages are shown in equation (9):

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (9)$$

The instantaneous value of the stator and rotor currents of a three-phase induction motor are calculated by using the following matrix equations as shown in equation (10) and (11);

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (11)$$

The stator and rotor voltage equations of the direct and quadrature (d-q) axis of an induction motor are given in equations (12)-(15).

$$V_{qs} = R_s i_{qs} + \frac{d}{dt} \lambda_{qs} + \omega_e \lambda_{qr} \quad (12)$$

$$V_{ds} = R_s i_{ds} + \frac{d}{dt} \lambda_{qs} - \omega_e \lambda_{ds} \quad (13)$$

$$V_{qr} = R_r i_{qr} + \frac{d}{dt} \lambda_{qr} + (\omega_e - \omega_r) \lambda_{qr} \quad (14)$$

$$V_{dr} = R_r i_{dr} + \frac{d}{dt} \lambda_{dr} - (\omega_e - \omega_r) \lambda_{dr} \quad (15)$$

Where λ_{qr} , λ_{qs} , λ_{dr} , and λ_{ds} are the stator and rotor flux linkage of the d and q axis, these above equations show the synchronously rotating reference frame for the two-phase d-q-axis of the induction motor. For squirrel cage induction motor, the rotor voltages V_{qr} , V_{dr} are set to zero, since the rotor cage bars are shorted. Therefore, the flux linkage equations can be express as equations (16)-(22).

$$\frac{d\lambda_{qs}}{dt} = \omega_b \left[V_{qs} - \frac{\omega_e}{\omega_b} \lambda_{ds} + \frac{R_s}{X_{ls}} (\lambda_{mq} - \lambda_{qs}) \right] \quad (16)$$

$$\frac{d\lambda_{ds}}{dt} = \omega_b \left[V_{ds} + \frac{\omega_e}{\omega_b} \lambda_{qs} + \frac{R_s}{X_{ls}} (\lambda_{md} - \lambda_{ds}) \right] \quad (17)$$

$$\frac{d\lambda_{qr}}{dt} = \omega_b \left[V_{qs} - \left(\frac{\omega_e - \omega_r}{\omega_b} \right) \lambda_{qr} + \frac{R_r}{X_{lr}} (\lambda_{mq} - \lambda_{qr}) \right] \quad (18)$$

$$\frac{d\lambda_{qr}}{dt} = \omega_b \left[V_{qs} + \left(\frac{\omega_e - \omega_r}{\omega_b} \right) \lambda_{qr} + \frac{R_r}{X_{lr}} (\lambda_{mq} - \lambda_{qr}) \right] \quad (19)$$

Where;

$$\lambda_{mq} = X_{ml} \left[\frac{\lambda_{qs}}{X_{ls}} + \frac{\lambda_{qr}}{X_{lr}} \right] \quad (20)$$

$$\lambda_{md} = X_{ml} \left[\frac{\lambda_{qs}}{X_{ls}} + \frac{\lambda_{qr}}{X_{lr}} \right] \quad (21)$$

$$X_{ml} = \frac{1}{\left(\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X_{lr}} \right)} \quad (22)$$

To obtain the currents, we therefore substitute the value of flux linkages as shown in equations (23)-(26).

$$i_{qs} = \frac{1}{X_{ls}} (\lambda_{qs} - \lambda_{mq}) \quad (23)$$

$$i_{ds} = \frac{1}{X_{ls}} (\lambda_{ds} - \lambda_{md}) \quad (24)$$

$$i_{qr} = \frac{1}{X_{lr}} (\lambda_{qr} - \lambda_{mq}) \quad (25)$$

$$i_{dr} = \frac{1}{X_{lr}} (\lambda_{dr} - \lambda_{md}) \quad (26)$$

Based on the above equations, the torque and rotor speed can be determined as equations (27) and (28).

$$T_e = \frac{3}{2} \left(\frac{p}{2} \right) (\lambda_{qr} i_{dr} - \lambda_{dr} i_{qr}) \quad (27)$$

$$\omega_e = \int \frac{p}{2} (T_e - T_L) \quad (28)$$

2.0 METHODS

2.1 GENERALIZED MODEL IN ARBITRARY REFERENCE FRAME

The induction motor model equations in arbitrary reference frame are given by equation (29) [6, 12].

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + P L_s & \omega_e L_s & L_{mp} & 0 \\ -\omega_e L_s & R_s + L_{sp} & -\omega_e L_m & 0 \\ L_{mp} & (\omega_e - \omega_r) L_m & R_r + L_{rp} & 0 \\ -(\omega_e - \omega_r) L_m & L_{mp} & -(\omega_e - \omega_r) L_m & R_r + L_{rp} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (29)$$

2.2 STATIONARY REFERENCE FRAME MODEL

In stationary reference frame, the speed of the reference frame is zero, that is, $\omega_e = 0$. The equation in stationary reference frame is obtained by substituting $\omega_e = 0$ in equation (29) above. The resulting model becomes equation (30), [13, 14].

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + P L_s & 0 & L_m P & 0 \\ 0 & R_s + P L_s & 0 & L_m P \\ L_m P & -(\omega_r) L_m & R_r + L_r P & -(\omega_r) L_m \\ (\omega_r) L_m & L_m P & (\omega_r) L_m & R_r + L_r P \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (30)$$

If the stator voltage is unbalanced or discontinuous and the rotor voltages are balanced, the stationary reference frame is useful. Equation (30) can be represented in state space form for a digital computer simulation as shown in equation (31).

$$P[i] = [L^{-1}][[R] + \omega[G]][I] + L^{-1}[V] \quad (31)$$

where the inverse inductance matrix, d-q voltage matrix, stator and rotor current matrix, and other constants matrix found in equation (31), are expressed in equations (32)-(37) [7,10].

$$[V] = [V_{qs} \quad V_{ds} \quad 0 \quad 0]^t \quad (32)$$

$$[I] = [i_{qs} \quad i_{ds} \quad i_{qr} \quad i_{dr}]^t \quad (33)$$

$$[R] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \quad (34)$$

$$[L] = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \quad (35)$$

$$[G] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -L_m & 0 & -L_r \\ L_m & 0 & L_r & 0 \end{bmatrix} \quad (36)$$

$$[F] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ -L_s & -L_m & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad (37)$$

3.0 RESULTS AND DISCUSSION

In this research, MATLAB SOFTWARE is extensively used to implement the adopted analysis method. A 50HP, 460V, 60Hz, induction motor was used for dynamic simulation, the motor parameters are stated in table 1, and the simulation parameters are stated in table 2.

3.1 SIMULATION RESULTS FOR CONVENTIONAL ASYNCHRONOUS MOTOR UNDER NO-LOAD CONDITION.

Figure 2, shows that at initial starting period, the motor developed an inherent torque, but at an interval when the motor attained some level of stability, the torque reduces to zero, showing the no load condition of the motor. Figure 3, shows an increase in the torque of the motor which give rise to a decrease in the speed of the motor at no load operating condition. And as the torque keep reducing the motor accelerates progressively in speed.

Figure 4, shows a build-up acceleration in the mechanical rotor speed at an initial starting of the

motor. The accelerating mechanical rotor speed attained stability at 1800 rpm, at 0.2sec.

Figure 5, shows an initial starting current which build up to about 1015 A, as the motor operation continuous, the current attained steady state period at zero at an interval of 0.2sec, showing an unloaded stator current behavior of the motor at Phase A.

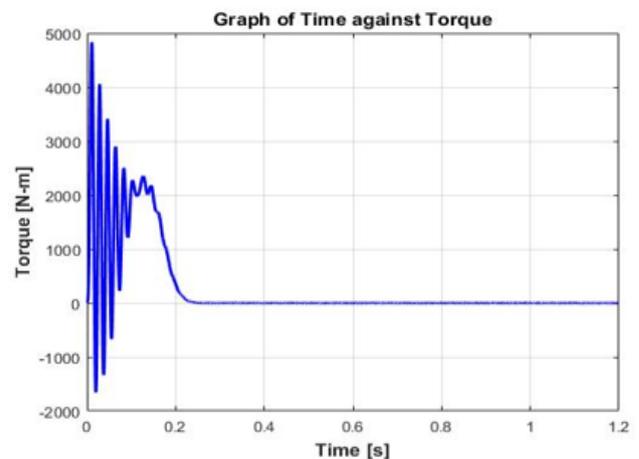


Figure 2: A graph of torque against time

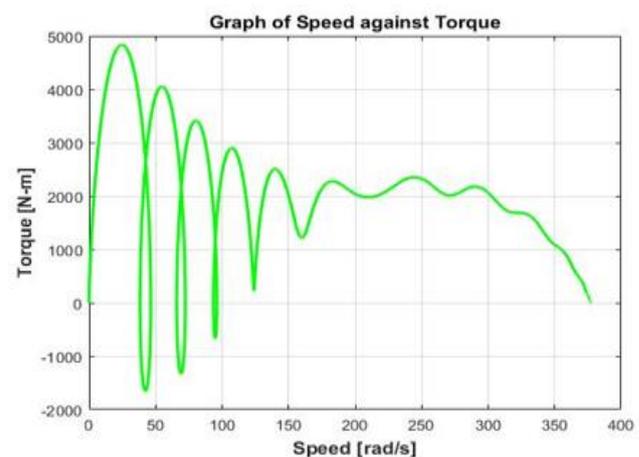


Figure 3: A graph of torque against rotor speed

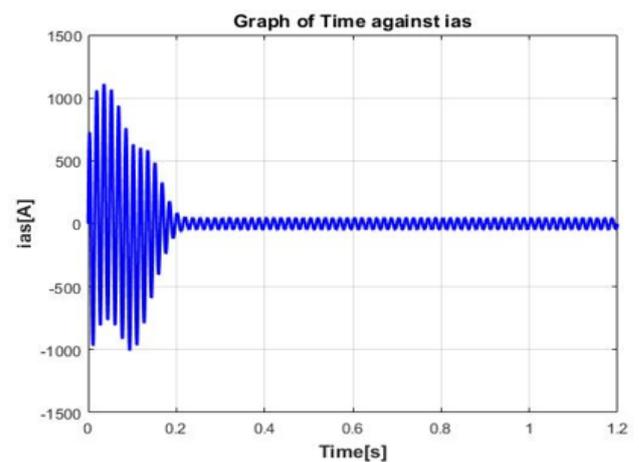


Figure 4: A graph of time against ias

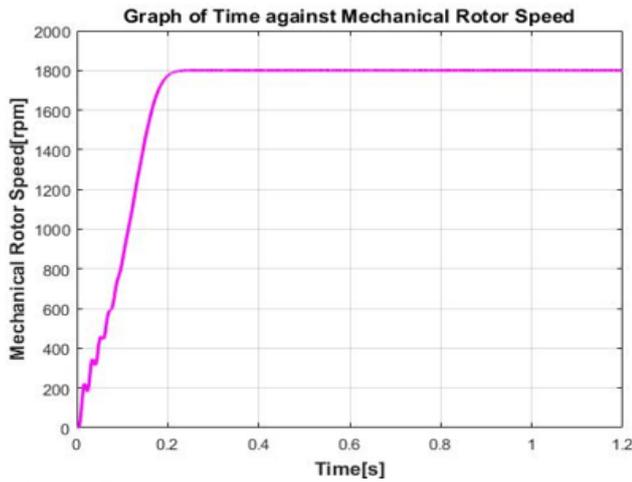


Figure 5: A graph of time against mechanical rotor speed

3.2 SIMULATION OF ASYNCHRONOUS MOTOR UNDER STATOR RESISTANCE VARIATION RESULTS

Figure 6, shows effect of stator resistance variation on the load torque of the motor at various interval in time. A percentage variation in the stator resistance results to high starting torque of the motor. The motor then experienced a transient stability when the torque drops to zero at 0.2 sec.

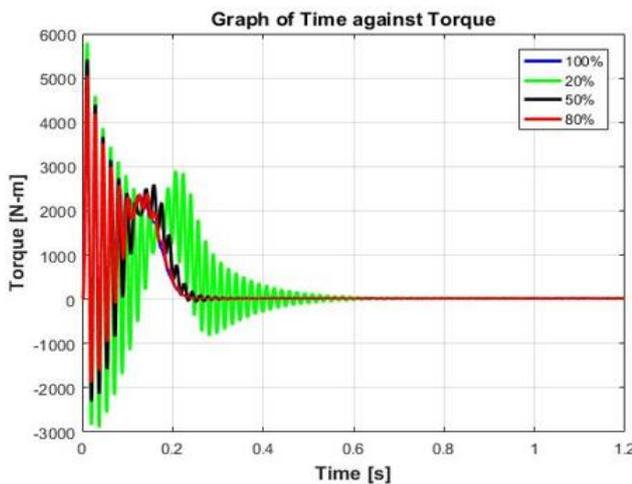


Figure 6: A graph of torque against time

Figure 7, shows the mechanical rotor speed reduces when rotor resistance is introduced at various variations of the stator resistance. At 0.2 sec and about 1800 rpm, the mechanical rotor speed come to stability. Figure 8, shows the effect of resistance on the stator current at different variations in the stator resistance. The current reduces when resistance is introduced, as the motor continue in operation and the

various effect of resistance comes to stability under various dynamic operation.

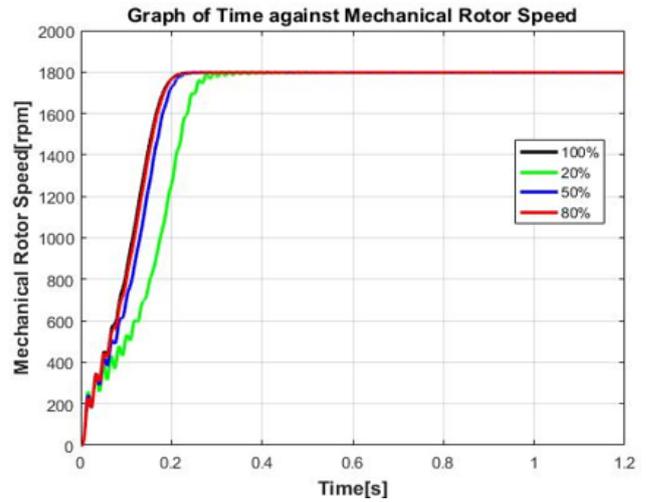


Figure 7: A graph of rotor speed against time

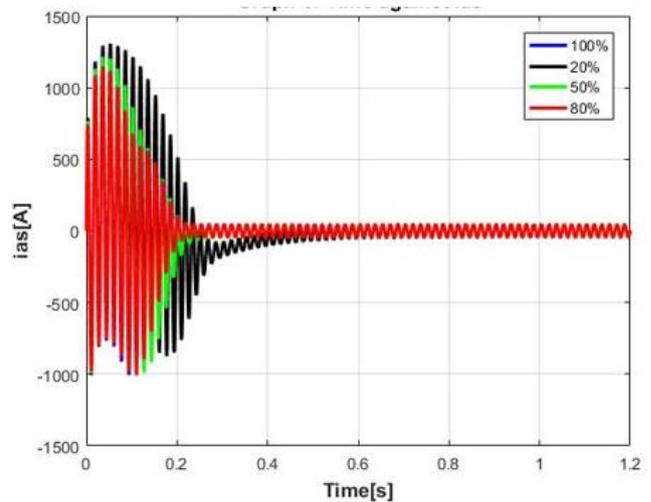


Figure 8: A graph of i_{as} against time

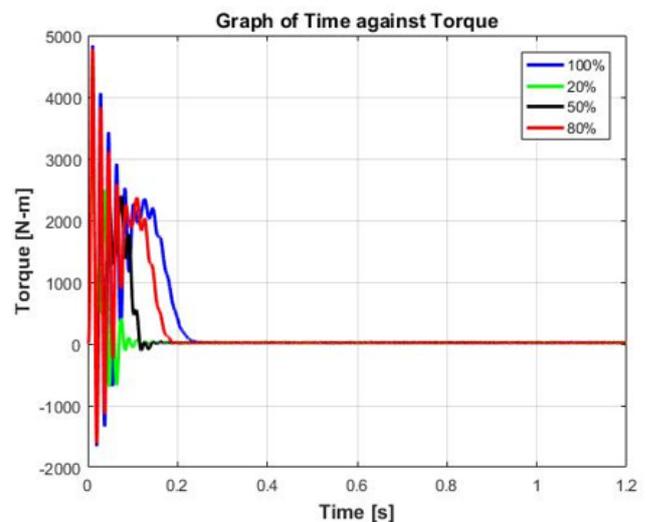


Figure 9: A graph of torque against time

3.3 SIMULATION OF ASYNCHRONOUS MOTOR UNDER MOMENT OF INERTIA (J) VARIATIONS

Figure 9, shows an increased in load torque at initial starting of the motor, as the motor operational time increases, the load torque reduces at every variation in the moment of inertial. Thus, a transient in load was observed. Figure 10, shows a rise in mechanical rotor speed during the initial start of the motor, as the operating time increases the mechanical rotor speed comes to stability at about 1800rpm.

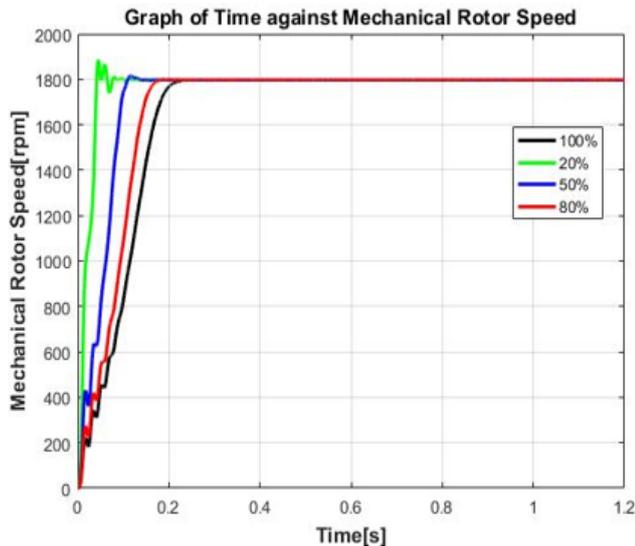


Figure 10: A graph of rotor speed against time

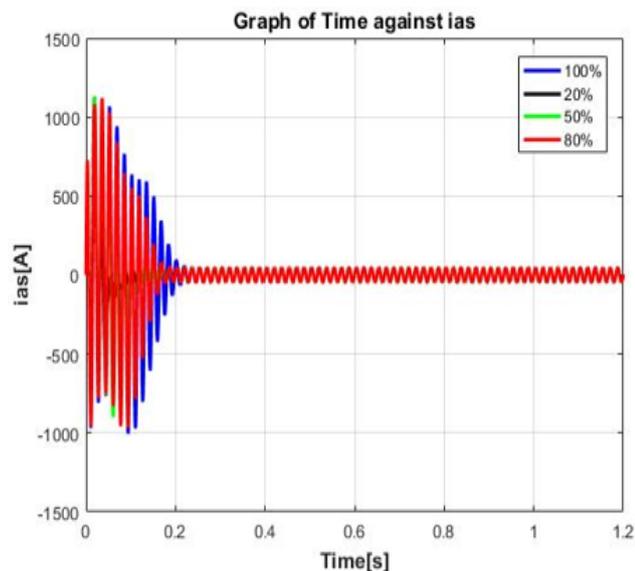


Figure 11: A graph of i_{as} against time

Figure 11, shows the effect of variation in moment of inertial on the stator current, the current drops sharply at the loaded time of 0.7 Sec, as the motor continue in operation the various effect of moment of inertial comes to stability under various dynamic operation.

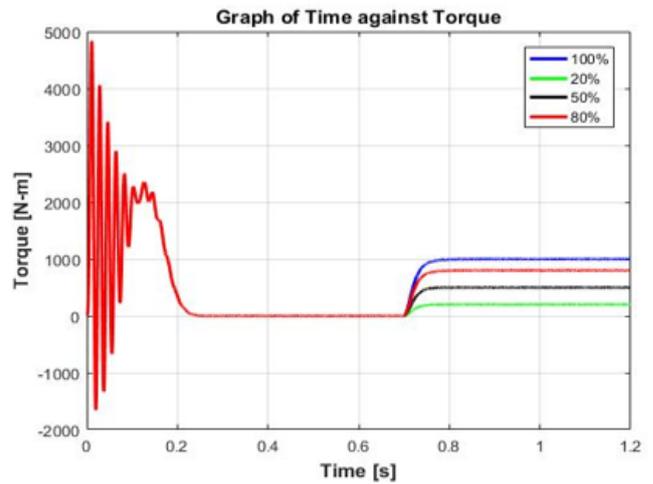


Figure 12: A graph of torque against time

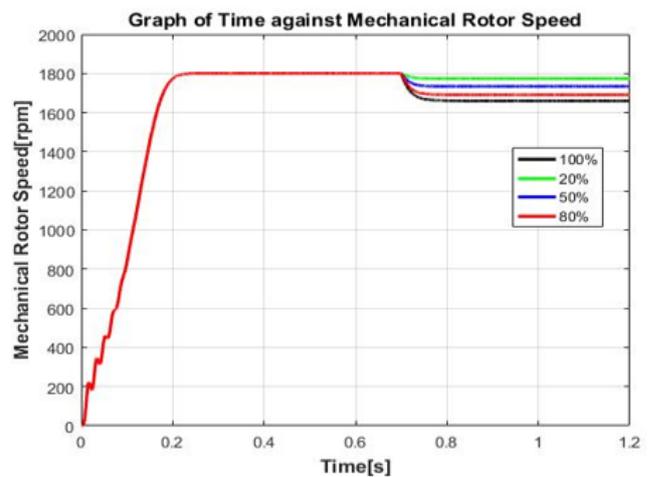


Figure 13: A graph of rotor speed against time

3.4 SIMULATION OF ASYNCHRONOUS MOTOR UNDER LOADED CONDITION AT T=0.7SEC

Figure 12, shows that at initial starting period, the torque rises and sudden transient is observed as the operating time of the motor increases from 0-0.2sec, thereafter, the motor-maintained stability within 0.2sec to 0.7sec. From 0.7sec time interval, the motor experienced short circuit error and during this period, the torque increases considerably from 0 Nm to 1000 Nm maximum increased variation. Figure 13, shows that the motor mechanical speed rises to a peak value and then comes to stability at 1800 rpm within 0.2sec to 0.7sec. At 0.7sec, the motor experienced short circuit error and at 0.7sec, the motor mechanical speed drop from 1800 rpm to about 1600rpm at variation in the load torque. Figure 14, shows that at the initial starting of the motor, the current rises to its peak value to about 1000A, within 0.2 Sec to 0.7sec stability was observed. During 0.7sec short circuit occur and the current experience a risen edge and the amplitude of the current increases little at 0.7 to 1.2 sec.

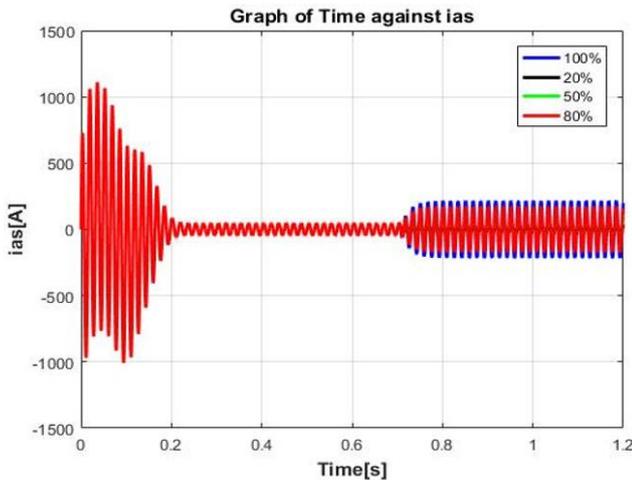


Figure 14: A graph of i_{as} against time

Table 1: Rated Machine Parameters

| Parameters | Rating |
|-----------------------------|-------------------------|
| Power Rating | 50 HP |
| Rated Phase Voltage | 460 V |
| Rated Frequency | 60 Hz |
| Winding Connection | Star |
| Stator Resistance | 0.087 Ω |
| Rotor Resistance | 0.0228 Ω |
| Number of Poles | 4 |
| Magnetizing Inductance | 34.7X10 ⁻³ H |
| Rotor Self-Inductance | 0.8X10 ⁻³ H |
| Stator Self-Inductance | 0.8X10 ⁻³ H |
| Moment of Inertial | 1.660 kgm ² |
| Load Torque | 20 Nm |
| Loading torque at T=0.7sec. | 1000Nm |

Table 2: Simulation Parameters

| Parameters | Rating |
|------------------------------------|---------------|
| Starting Time (t0) | 0 Second |
| Final or Stopping Time (tf) | 1.2 Seconds |
| Loading Time (T) | 0.7 Second |
| TimeInterval (tinterval) | 0.0001 Second |
| No of the Initial State Vector (n) | 5 |

4.0 CONCLUSION

Asynchronous motor is a very essential machine in various industrial applications. To mitigate design and constructional errors and its resulting impact which limit operational expectancies, the dynamic behavior of the motor needs to be properly analyzed and understood for prompt solutions. A Generalized MATLAB program for the dynamic simulation of induction motor is presented here. The variables of interest are; stator resistance (R_s), the torque (TL), and moment of inertial (J). These were observed in the dynamic mode from the responses during the motor performance. This research work subjected a selected

induction motor to loading condition at varied load torque. The effect of loading is observed on the motor speed, torque-speed characteristics and also on the various phase stator currents (Phases A, B, and C). The MATLAB program results proved that MATLAB is a sophisticated tool for the study of dynamic performance of induction motor under various transient and steady state conditions, which will help to mitigate sudden down time and other production inconveniences in its industrial applications.

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