

## Dynamics and Performance Characteristics of a 5hp Induction Machine

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### ABSTRACT

Regulation and controllability have been an important aspect of the industrial motor drives. The three-phase induction machine has been the motor of choice in industrial settings for about the past decade due to its easy speed and torque controllability. Its ruggedness and low cost cum other inherent features thus necessitated the quest to study its operating behavior. This work highlighted the mathematical modeling of an induction motor specifically in the stationary reference frame. The induction motor parameters and the generated equations were used to form the embedded MATLAB function which in turn was used to generate graphs that illustrate the performance of a 5HP motor. The torque –speed response among other characteristics were fully simulated thus resulting to a sound study of the performance characteristics of a three phase 5HP induction motor using MATLAB/Simulink.

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### 1.0 INTRODUCTION

Induction machines are the most widely used AC machines. They are known to be superior to their DC counterparts based on ruggedness, reliability, cost, size and output power per weight. Like other electrical machines, the asynchronous machine is reversible, i.e. it can operate as both a generator and a motor with the mode of operation of the machine being determined by the speed of the rotating field in addition to the rotor. In most cases, the induction machine operates as a motor [1]. Induction machines are commonly used in industrial motion control systems and main powered home appliances [2]. This has motivated the study of induction motor performance in various drives and thus a constant effort is continuously being made for the performance improvement of induction motors. There is the need therefore to study the motor's performance. Herein, the parameters of the given motor were used for simulation so as to study the performance characteristics of a 5HP motor. In [3] a modular, easy to understand Simulink model is described. In this system, each block solves one of the model equations thus unlike black box models, each machine parameter is accessible for control and verification purposes. Here two methods of control were shown, the open-loop V/F operation and the indirect vector control operation. The former gives results where the response of the drive to the changes in the speed command and load disturbances can be observed while the latter gives excellent response to the speed tracking and torque disturbances. Sunil Sehra, K. K. Gautam and Vijay Bhuria in [4] made an analysis on the performance characteristics of induction machines using MATLAB by carrying out tests with the induction machine on no-load and in blocked rotor tests. In their tests, it was observed that these tests gave the correct information regarding the induction machine with various parameter results in form of improved efficiency, better result of various torque and decrease in slip with increase in efficiency. These simulation models are developed to support and enhance electric machinery. In [5], Shi K. L, (et al) described a dynamic model of a three-phase

induction motor using Simulink. They performed a simulation study of direct-on-line starting to illustrate the transient operation of the induction motor. The results are similar to those obtained using the traditional simulation method involving differential equations. Although it is noticed that when the supply cable has a large resistance, the torque oscillations in the torque/speed characteristic are reduced and decay more rapidly, but the run up time of the motor is longer.

### 2.0 PRINCIPLE OF OPERATION OF A THREE-PHASE INDUCTION MOTOR

The stator of the motor consists of overlapping winding offset by an electrical angle of 120° [6]. When the stator or primary winding of a three-phase induction motor is connected to a three phase AC supply, a rotating magnetic field is established which rotates at synchronous speed [7]. The direction of revolution of this field will depend on the phase sequence of the primary currents and therefore will depend on the connection of the primary terminals to supply. The speed at which the field produced by the primary currents will revolve is called the synchronous speed of the motor and is expressed as  $N_s = \frac{120f}{P}$ , where f is supply frequency, P

is number of poles on stator. This rotating magnetic field induces an electromagnetic force (EMF) on the rotor conductors which causes a current to flow in the rotor conductors. When the rotor is stationary and about to start, the frequency of induced EMF in the rotor is equal to that of the supply fed to the stator because the relative motion is at synchronous speed. As the speed of the motor increases the relative motion between the rotor and the synchronously rotating magnetic field becomes less and the frequency of EMF induced in the rotor decreases. If relative motion in the machine is zero, i.e. rotor runs at synchronous speed, there will be no induced EMF, no current in the rotor conductors, no rotor field and no torque. Some of the characteristics of an induction motor include;

**a. Slip:** This is the difference between the synchronous speed  $N_s$  of the rotating stator field and the actual rotor speed  $N$  is called slip. At normal load, slip is usually between 2 and 5 percent and at normal load, it is as small as 0.5 percent. When the rotor is stationary, slip = 1 or 100%.

**b. Frequency of Rotor current ( $f'$ ):** This is also called slip frequency and is given by the equation;

$$f' = s \times \frac{120f}{p} \times \frac{p}{120f} = sf \quad (1)$$

**c. Rotor EMF:** When the rotor is at standstill, the motor is equivalent to a 3-phase transformer with its secondary shorted. So induced EMF in the rotor  $E_2$  is given by:

$$E_2 = E_1 \times \frac{N_2}{N_1} \quad (2)$$

Where  $E_1$  is applied voltage per phase to primary,  $N_2$  and  $N_1$  are the number of turns per phase on rotor and stator respectively [2]

**d. Rotor Torque:** The torque of an induction motor depends on the strength of the rotor and stator fields and the phase relation between them and is given by the equation below;

$$T \propto \phi I_2 \cos \theta_2 \quad (3)$$

Where,  $T$  is the torque produced by induction motor,  $\phi$  is flux responsible for producing induced EMF,  $I_2$  is rotor current,  $\cos \theta_2$  is the power factor of rotor circuit. The flux  $\phi$  produced by the stator is proportional to stator EMF  $E_1$  ( $\phi \propto E_1$ ).

**Power factor:** This is defined as the ratio of resistance to that of impedance. The power factor of the rotor circuit is

$$\cos \theta_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}} \quad (4)$$

Substituting the value of flux  $\phi$ , rotor current  $I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$ , the equation of torque becomes,

$$T = sE_2^2 \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{3}{2\pi n_s} \quad N - m \quad (5)$$

Where  $n_s$  is synchronous speed in r. p. s,  $n_s = N_s / 60$ . The torque will be maximum when slip  $s = R_2 / X_2$ . Substituting the value of this slip in above equation gives the maximum value of torque as,

$$T_{max} = \frac{KE_2^2}{2X_2} \quad N - m \quad (6)$$

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$$T_{max} = \frac{KE_2^2}{2X_2} \quad N - m \quad (7)$$

### 3.0 METHODOLOGY

This work makes use of the embedded MATLAB function to simulate the performance characteristics of a three-phase induction motor (speed, torque, current slip and efficiency). Induction motors are seldom simulated in the arbitrary rotating reference frame. In this work, the stationary reference is used. To conduct a rigorous analysis of an induction machine, it is necessary to perform a change of variables (using Park's transformation) which eliminates the time varying mutual inductances which occur because of windings in relative motion, using a change of variables to replace the rotor windings with fictitious windings fixed in the stator. Machine equations are oftentimes expressed in

terms of flux linkages per second ( $\psi$ ), and reactance ( $x$ ), instead of  $\lambda$ 's and  $L$ 's. These are simply related by the base or rated value of angular frequency,  $\omega_b$  that is  $\psi = \omega_b \lambda$  V or per unit and

$x = \omega_b L$  H or per unit. Where  $\omega_b = 2\pi f_{rated}$  electrical radians per second,  $f_{rated}$  being the rated frequency in Hertz of the machine.

**Induction Machine Equations Used for the Simulation.**

Stator and rotor voltage equations in stationary reference frame are

$$v_{qs}^s = r_s i_{qs}^s + \frac{p}{\omega_b} \psi_{qs}^s \quad (8)$$

$$v_{ds}^s = r_s i_{ds}^s + \frac{p}{\omega_b} \psi_{ds}^s \quad (9)$$

$$v_{qr}^s = r'_r i'_{qr}{}^s - \frac{\omega_r}{\omega_b} \psi'_{dr}{}^s + \frac{p}{\omega_b} \psi'_{qr}{}^s \quad (10)$$

$$v_{dr}^s = r'_r i'_{dr}{}^s + \frac{\omega_r}{\omega_b} \psi'_{qr}{}^s + \frac{p}{\omega_b} \psi'_{dr}{}^s \quad (11)$$

$$v_{0s} = r_s i_{0s} + \frac{p}{\omega_b} \psi_{0s} \quad (12)$$

$$v'_{0r} = r'_{lr} i'_{0r} + \frac{p}{\omega_b} \psi'_{0r} \quad (13)$$

Flux linkage equations are,

$$\begin{bmatrix} \psi_{qs}^s \\ \psi_{ds}^s \\ \psi_{0s}^s \\ \psi_{qr}^s \\ \psi_{dr}^s \\ \psi_{0r}^s \end{bmatrix} = \begin{bmatrix} x_{ls} + x_m & 0 & 0 & x_m & 0 & 0 \\ 0 & x_{ls} + x_m & 0 & 0 & x_m & 0 \\ 0 & 0 & x_{ls} & 0 & 0 & 0 \\ x_m & 0 & 0 & x'_{lr} + x_m & 0 & 0 \\ 0 & x_m & 0 & 0 & x'_{lr} + x_m & 0 \\ 0 & 0 & 0 & 0 & 0 & x'_{lr} \end{bmatrix} \begin{bmatrix} i_{qs}^s \\ i_{ds}^s \\ i_{0s}^s \\ i'_{qr}{}^s \\ i'_{dr}{}^s \\ i'_{0r}{}^s \end{bmatrix} \quad (14)$$

**Torque equations**

$$\frac{3}{2} \times \frac{P}{2\omega_r} \left( \psi'_{qr}{}^s i'_{dr}{}^s - \psi'_{dr}{}^s i'_{qr}{}^s \right) \quad N.m \quad (15)$$

The model equations of the induction machine in the stationary qd0 reference frame were rearranged into the following form for simulation [8]

Base voltage

$$V_b = \frac{\sqrt{2}}{3} V_{rated} \quad (16)$$

$$\text{Base volt-amperes } S_b = S_{rated} \quad (17)$$

$$\text{Base peak current } I_b = 2S_b / 3V_b \quad (18)$$

$$\text{Base impedance } Z_b = V_b / I_b \quad (19)$$

$$\text{Base torque } T_b = S_b / \omega_{bm} \text{ where } \omega_{bm} = \frac{2\omega_b}{p}. \quad (20)$$

$$\psi_{qs}^s = \omega_b \int \left\{ v_{qs}^s + \frac{r_s}{x_{ls}} (\psi_{mq}^s - \psi_{qs}^s) \right\} dt \quad (21)$$

$$\psi_{ds}^s = \omega_b \int \left\{ v_{ds}^s + \frac{r_s}{x_{ls}} (\psi_{md}^s - \psi_{ds}^s) \right\} dt \quad (22)$$

$$i_{0s} = \frac{\omega_b}{x_{ls}} \int [v_{0s} - i_{0s} r_s] dt \quad (23)$$

$$\psi_{qr}^s = \omega_b \int \left\{ v_{qr}^s + \frac{\omega_r}{\omega_b} \psi_{dr}^s + \frac{r'_r}{x'_{lr}} (\psi_{mq}^s - \psi_{qr}^s) \right\} dt \quad (24)$$

$$\psi_{dr}^s = \omega_b \int \left\{ v_{dr}^s + \frac{\omega_r}{\omega_b} \psi_{qr}^s + \frac{r'_r}{x'_{lr}} (\psi_{md}^s - \psi_{dr}^s) \right\} dt \quad (25)$$

$$i_{0r} = \frac{\omega_b}{x'_{lr}} \int [v'_{0r} - i'_{0r} r'_r] dt \quad (26)$$

$$\psi_{mq}^s = x_m (i_{qs}^s + i'_{qr}{}^s) \quad (27)$$

$$\psi_{md}^s = x_m (i_{ds}^s + i'_{dr}{}^s) \quad (28)$$

$$i_{qs}^s = \frac{\psi_{qs}^s - \psi_{mq}^s}{x_{ls}} \quad (29)$$

$$i_{ds}^s = \frac{\psi_{ds}^s - \psi_{md}^s}{x_{ls}} \tag{30}$$

$$i_{qr}^s = \frac{\psi_{qr}^s - \psi_{mq}^s}{x'_{lr}} \tag{31}$$

$$i_{dr}^s = \frac{\psi_{dr}^s - \psi_{md}^s}{x'_{lr}} \tag{32}$$

Where  $\frac{1}{x_M} = \frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x'_{lr}}$  (33)

And,

$$\psi_{mq}^s = x_M \left( \frac{\psi_{qs}^s}{x_{ls}} + \frac{\psi_{qr}^s}{x'_{lr}} \right) \tag{34}$$

$$\psi_{md}^s = x_M \left( \frac{\psi_{ds}^s}{x_{ls}} + \frac{\psi_{dr}^s}{x'_{lr}} \right) \tag{35}$$

The equation of motion of the rotor is obtained by equating the inertia torque to the accelerating torque, that is

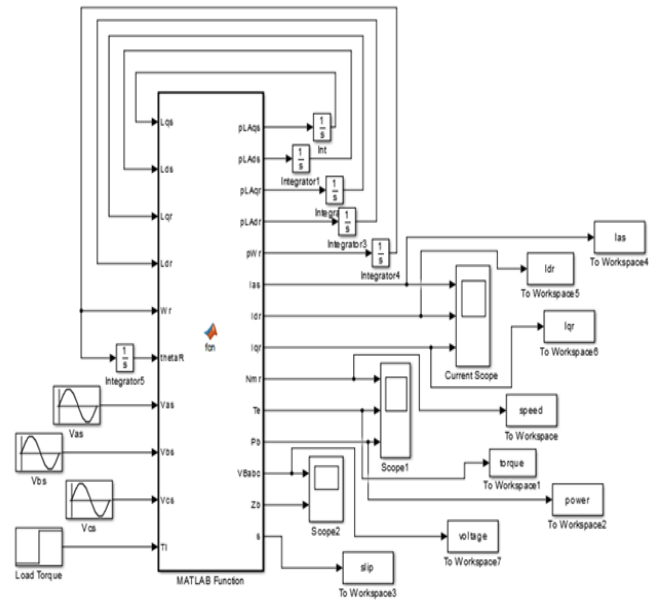
$$J \frac{d\omega_{rm}}{dt} = T_{em} + T_{mech} - T_{damp} \quad N \cdot m \tag{36}$$

$T_{mech}$  is the externally applied mechanical force in the direction of the rotor speed and  $T_{damp}$  is the damping torque in the direction opposite to rotation.  $T_{mech}$  will be negative for the motoring action and will be positive for the generating condition [9].  $v'_{qr}$ ,  $v'_{dr}$ ,  $v'_{or}$  and are the referred q-axis, d-axis and zero sequence rotor voltages.  $r_s$  is stator resistance per phase,  $r'_r$  is referred rotor resistance per phase,  $x_{ls}$  is stator leakage reactance,  $x'_{lr}$ : rotor leakage reactance and is equal to  $x_m$ , magnetizing reactance and  $\psi_{mq}^s$ ,  $\psi_{md}^s$  are the q-axis and d-axis magnetizing flux linkages per second. The three phase induction machine parameters used for this study are presented in table 1 below. It is a 4-pole 50HZ, 5HP star connected induction motor with synchronous speed of 1500rpm, measured speed of 1420rpm, 0.8 power factor and 84% efficiency.

**Table 1. Machine Parameters.**

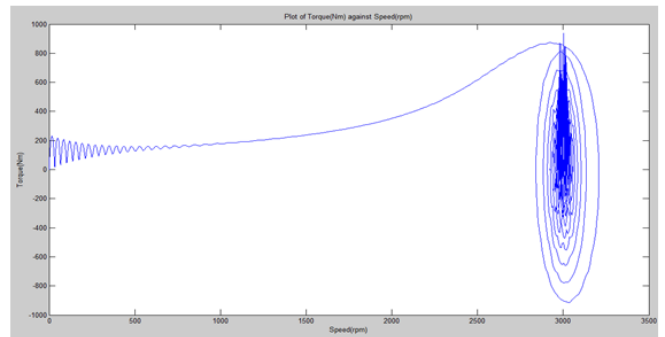
Parameters	Symbol	Values
Stator current	$I_1$	7.9A
Rotor current	$I_2$	4.0A
Stator resistance	$R_1$	2.250 $\Omega$
Rotor resistance	$R_2$	1.890 $\Omega$
Stator core loss current	$I_c$	6.356A
Magnetizing current	$I_m$	4.74A
Excitation current	$I_o$	2.72A
Stator core loss resistance	$R_c$	37.72 $\Omega$
Stator magnetizing inductor	$L_m$	0.1542H
Magnetizing reactance	$X_m$	48.44 $\Omega$
Slip	S	5.30%
Rotor frequency	$f_r$	2.65Hz
Shaft load torque	T	25.08N-m
R. M. S. voltage	$V_{r.m.s}$	415V

### 4.0 MATLAB/SIMULINK MODEL

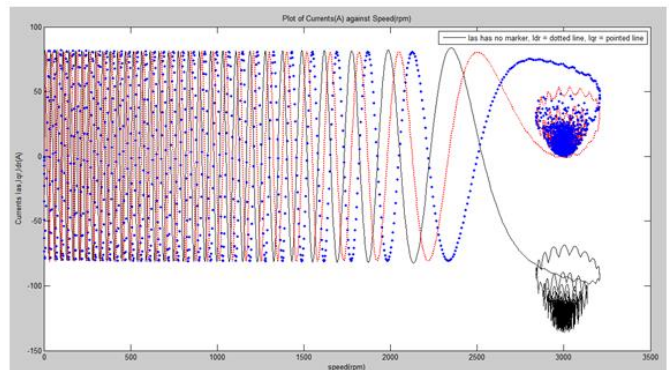


**Figure 1. MATLAB model of a three-phase 5HP Induction motor.**

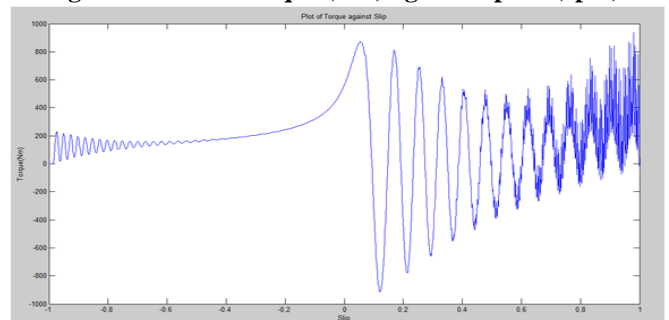
### 5.0 SIMULATION RESULTS



**Figure 2. Plot of Torque (Nm) against Speed (rpm).**



**Figure 3. Plot of Torque (Nm) against Speed (rpm).**



**Figure 4. Plot of torque against Slip.**

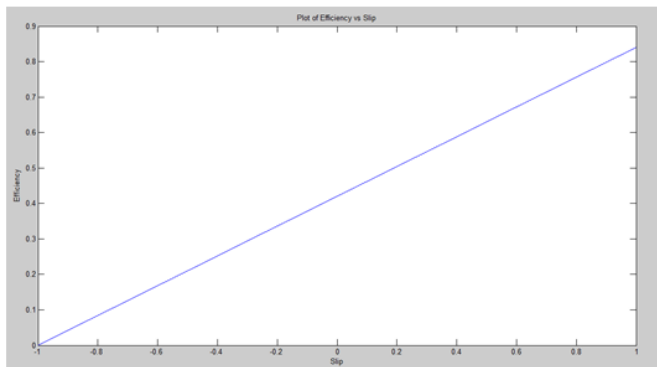


Figure 5. Plot of Efficiency vs Slip.

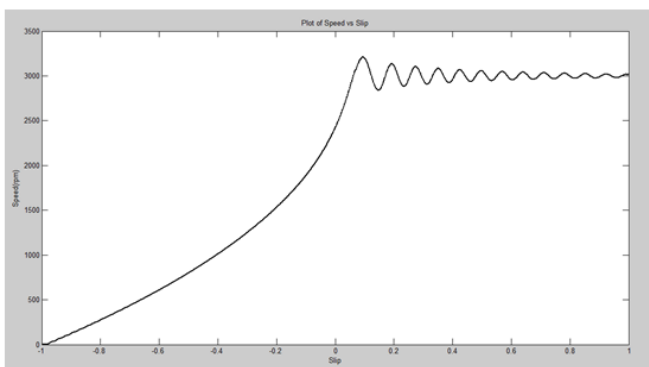


Figure 6. Plot of Speed vs Slip.

### 6.0 Discussion of Performance Characteristics Results

Figure 2 shows the motor's torque versus speed. The motor shows a pulsating torque during startup, but on the average, this torque is positive and helps to overcome the inertia torque. When the load is applied, the motor reacts to produce an almost steady torque after a while to overcome the load torque. When the machine reaches synchronous speed, it drops sharply and oscillates with large variations. Figure 3 shows the plot of currents with respect to time, the currents are positive in forward motoring and are negative in reverse motoring. It can be seen that after the motor starts up, the frequency of the rotor current becomes relatively low because the speed of the motor is now close to the synchronous speed. The currents vary till speed reaches synchronous speed where they are then equal to zero. Figure 4 is the electromagnetic torque against slip. At start, it goes from zero to full load and then has a slight variation as the speed rises. The motor shows a pulsating torque during startup, but on the average, this torque is positive and helps to overcome the inertia torque. When the load is applied, the motor reacts to produce an almost steady torque after a while to overcome the load torque. When the machine reaches synchronous speed, it drops sharply and continues with large variations which decrease from that point onwards. Figure 5 shows efficiency versus slip, the graph is linear thus the machines efficiency increases with increase in speed. Figure 6 displays the plot of speed with respect to slip. This shows how the machine starts up from rest and gains speed till it reaches the maximum speed. When the motor is loaded the speed drops and if it is unloaded, the speed increases thus increasing the slip. These characteristics are in tune with those obtained in [11]. The reason for this is because when the induction motor is loaded, its speed drops so that more emf will be induced in the rotor, consequently more current and torque would be produced to counter this load.

### 7.0 CONCLUSION

With the model (MATLAB Embedded function) developed, the user has access to all internal variables for getting an insight into the motor operation. Thus from the Matlab/Simulink simulation, the simulated machine has given a satisfactory response in terms of the torque and speed characteristics. This goes a long way to appraise the Matlab/Simulink as a reliable and sophisticated mathematical calculator [12] that is well used to analyse and predict the behaviour of induction motors using the theory of reference frames and direct quadrature method. The results obtained herein are very useful to academics just as the designers in machinery fields would value them.

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