

Dynamic and Steady State Analysis of 3-Phase Induction Motor.

¹Okoh K.I., ²Ugwuda A.U., ³Anih L.U.

^{1,2}Department of Electrical Engineering, Nnamdi Azikiwe University, Awka
³Department of Electrical Engineering, University of Nigeria, Nsukka

¹okohkevin@yahoo.com

Abstract

This paper presents the dynamic and steady state analysis of 3-phase induction motor. Given the supply voltage of 220v, 50HZ and machine's parameters generated, the average value of torque developed verses speed showing what is normally termed the braking, motoring and generating region of the machine was shown. In the motoring region, the developed torque is in the direction of rotation. The generating region is above synchronous speed, and the developed torque is opposite to the direction of rotation. In braking region, the developed torque is in the direction of the excitation m.m.f., but opposite to the direction of the rotor rotation. The simulation of the induction motor shows how the parameters such as q-axis current, d-axis current, electromagnetic torque and speed varies with the variation in externally applied mechanical torque.

Keywords: Motoring region, generating region, Braking region, D-axis current, Q-axis current, Mechanical torque.

1.0 Introduction

The induction machine has fixed stator windings that are electrically connected to the ac power source. Current is induced in the rotor circuit via transformer action, resulting in a magnetic field that interacts with the stator field causing rotation.

The rotor must rotate slower than the stator field for induction to occur, thus an induction motor operates at less than synchronous speed using no other source to excite the rotor's field.

Motors, especially those operating at 600r/min and below have lower operating efficiency and a lagging power factor that draws exciting current from connected source [1]. Since an induction machine draws all exciting current from the ac source, it may take in the range of 0.3 to 0.6 p.u. reactive magnetizing kilovolt-amperes per horsepower of operating load [2]. Most induction motors are of the rotary type with basically a stationary stator and a rotating rotor. The stator has a cylindrical annulus magnetic core that is housed inside a metal frame onto which are mounted the bed plates, end shields, and a terminal box. At the centre of the end shields are bearing to support the rotor's shaft.

The stator's magnetic core is formed by stacking a thin electrical steel laminations with uniformly spaced slots stamped in the inner circumference to accommodate the three distributed stator windings. For 60HZ machines, the lamination is about 0.5mm thick. The stator windings are formed by connecting coils of copper or aluminium conductors.

The coils are insulated from the slot walls. The axes of the stator windings of a p-pole machine are spaced $(p/2) (2\pi/3)$ mechanical radian apart, with each phase belt occupying then same number of slots. The terminals of the three stator phase windings can be star- or delta- connected.

The rotor consists of a cylindrical laminated iron core with uniformly spaced peripheral slots to accommodate the rotor windings. There are two main types of rotor windings: wound and squirrel-cage. In a wound rotor machine, rotor windings similar to those of the distributed windings on the stator are wound on a cylindrical laminated core and brought out via rings and brushes. These slip rings are insulated from one another and from shaft. A variable amount of external resistance can be connected to the rotor winding via slip rings to obtain

higher starting torque or limited control of speed below synchronous speed. In very large and expensive drives, the terminal of the rotor windings may be connected to a slip frequency source to recover part of the power flowing into the rotor circuit. The rotor of squirrel cage machine consists of a cylindrical laminated core with parallel slots for carrying rotor conductors which, it should be noted clearly, are not wires but consist of heavy bars of copper, aluminium or alloys. The bars are brazed or electrically welded or bolted to two heavy and short-circuiting end rings. Three phase induction machine are asynchronous speed machines, operating below synchronous speed when motoring and above synchronous speed when generating. They are comparatively less expensive to equivalent size synchronous or dc machines and range in size from a few watts to 10,000hp. They, indeed, are workhorse of today's industry [3]. As motor, they are rugged and require very little maintenance. However, their speeds are not easily controlled as with dc motors. They draw large starting currents, typically about (5-7) times their full load value, and operate with poor lagging power factor when lightly loaded. Several ways have been employed to improve the performance of induction machine. Eddy current and hysteresis loss in the stator core of an induction motor can be reduced by assembling the stator core of high grade, low electrical loss, silicon punching [4,5].

Research has shown that the punching are insulated from one another by coating of varnish or oxide produced by heat treatment [6]. Careful alignment is required to prevent the rotor from rubbing against stator, the air-gap between the stator and rotor being very small. The rotor shaft of induction machine must be made short and stiff so that the rotor may not have any significant deflection [7, 8]. Even a minor deflection in the shaft would develop large irregularities in the air-gap which would lead to production of an unbalanced magnetic pull. It has been discovered by researchers that increase in air-gap length causes increase in magnetizing current necessary to set up air-gap flux [9, 10]. So in order to reduce the magnetizing

current, it is obvious to have air-gap between the stator and rotor as small as practicable.

2.0 Methodology

2.1 Dynamic Model of an Induction Motor in Arbitrary Reference Frame.

The voltage equations of induction motor in arbitrary are stated below. [11-13]

Stator Voltage Equation

$$\left. \begin{aligned} V_s &= r_s i_s + w \lambda_s + p \lambda_s \\ V_r &= r_r i_r - w \lambda_r + p \lambda_r \\ V_m &= r_m i_m + p \lambda_m \end{aligned} \right\} \quad (1)$$

Rotor Voltage Equation

$$\left. \begin{aligned} V'_s &= r'_s i'_s + (w - w_r) \lambda'_s + p \lambda'_s \\ V'_r &= r'_r i'_r - (w - w_r) \lambda'_r + p \lambda'_r \\ V'_m &= r'_m i'_m + p \lambda'_m \end{aligned} \right\} \quad (2)$$

Flux Linkage,

$$\left. \begin{aligned} \lambda_s &= (L_s + L_m) i_s + L_m i_r \\ &= L_s i_s + L_m (i_s + i_r) \\ \lambda_r &= (L_r + L_m) i_r + L_m i_s \\ &= L_r i_r + L_m (i_s + i_r) \\ \lambda_m &= L_m i_s + L_m (i_s + i_r) \end{aligned} \right\} \quad (3)$$

Substituting the values of flux from equation (3) into the rotor and stator voltage equations (1) and (2), gives

$$\left. \begin{aligned} V_s &= r_s i_s + w \lambda_s + p(L_s i_s + L_m (i_s + i_r)) \\ V_r &= r_r i_r + (w - w_r) \lambda_r + p(L_r i_r + L_m (i_s + i_r)) \\ V_m &= r_m i_m + p(L_m i_s + L_m (i_s + i_r)) \\ V'_s &= r'_s i'_s + (w - w_r) \lambda'_s + p(L_s i_s + L_m (i_s + i_r)) \\ V'_r &= r'_r i'_r - (w - w_r) \lambda'_r + p(L_r i_r + L_m (i_s + i_r)) \\ V'_m &= r'_m i'_m + p(L_m i_s + L_m (i_s + i_r)) \end{aligned} \right\} \quad (4)$$

2.2 Induction Machine Equation in Stationary Reference Frame

By setting speed, $w=0$ in equation (1) and (2) gives:

$$\left. \begin{aligned} V_s^* &= r_s i_s^* + p \lambda_s^* \\ V_r^* &= r_r i_r^* + p \lambda_r^* \\ V_m^* &= r_m i_m^* + p \lambda_m^* \end{aligned} \right\} \quad (5)$$

$$V_s^* = r_s i_s^* + p \frac{w_r}{w_s} \lambda_s^*$$

$$\Rightarrow V_s^* = r_s i_s^* + \frac{p}{w_s} \psi_s^*$$

$$\text{Where } \psi = w_s \lambda$$

Therefore, stator voltage equation,

$$\left. \begin{aligned} V_s^* &= \frac{p}{w_s} \psi_s^* + r_s i_s^* \\ V_r^* &= \frac{p}{w_r} \psi_r^* + r_r i_r^* \\ V_m^* &= \frac{p}{w_m} \psi_m^* + r_m i_m^* \end{aligned} \right\} \quad (6)$$

Rotor Voltage Equations

$$\left. \begin{aligned} I_{\alpha}^{\prime} &= \frac{P}{\omega_r} \psi_{\alpha}^{\prime} - \frac{\omega_r}{\omega_s} \psi_{\beta}^{\prime} + r_s I_{\alpha}^{\prime} \\ I_{\beta}^{\prime} &= \frac{P}{\omega_r} \psi_{\beta}^{\prime} + \frac{\omega_r}{\omega_s} \psi_{\alpha}^{\prime} + r_s I_{\beta}^{\prime} \\ I_{\gamma}^{\prime} &= \frac{P}{\omega_r} \psi_{\gamma}^{\prime} + r_s I_{\gamma}^{\prime} \end{aligned} \right\} \quad (7)$$

Flux Linkage Equations.

$$\begin{bmatrix} \psi_{\alpha}^{\prime} \\ \psi_{\beta}^{\prime} \\ \psi_{\gamma}^{\prime} \\ \psi_{\alpha} \\ \psi_{\beta} \\ \psi_{\gamma} \end{bmatrix} = \begin{bmatrix} x_{\alpha\alpha} & 0 & 0 & x_{\alpha\beta} & 0 & 0 \\ 0 & x_{\beta\beta} & 0 & 0 & x_{\beta\alpha} & 0 \\ 0 & 0 & x_{\gamma\gamma} & 0 & 0 & 0 \\ x_{\alpha\beta} & 0 & 0 & x_{\beta\alpha} & 0 & 0 \\ 0 & x_{\beta\alpha} & 0 & 0 & x_{\beta\beta} & 0 \\ 0 & 0 & 0 & 0 & 0 & x_{\gamma\gamma} \end{bmatrix} \begin{bmatrix} i_{\alpha}^{\prime} \\ i_{\beta}^{\prime} \\ i_{\gamma}^{\prime} \\ i_{\alpha} \\ i_{\beta} \\ i_{\gamma} \end{bmatrix} \quad (8)$$

Torque equations

Electromagnetic torque can be given as,

$$\begin{aligned} T_{em} &= \frac{3}{2} \frac{P}{\omega_r} (\psi_{\alpha}^{\prime} i_{\beta}^{\prime} - \psi_{\beta}^{\prime} i_{\alpha}^{\prime}) \\ &= \frac{3}{2} \frac{P}{\omega_r} (\psi_{\alpha}^{\prime} i_{\alpha}^{\prime} - \psi_{\beta}^{\prime} i_{\beta}^{\prime}) \\ &= \frac{3}{2} \frac{P}{\omega_r} x_{\alpha\alpha} (i_{\alpha}^{\prime} i_{\alpha}^{\prime} - i_{\beta}^{\prime} i_{\beta}^{\prime}) \quad N.m \end{aligned} \quad (9)$$

1.2 Equations for Simulation of Induction Motor in Stationary Reference Frame

The model equations 6, 7 and 8 may be rearranged into the following form for simulation:

Voltage and flux linkage equations are:

$$\left. \begin{aligned} \psi_{\alpha}^{\prime} &= \omega_s \int (\psi_{\alpha}^{\prime} + \frac{r_s}{\omega_s} (\psi_{\alpha}^{\prime} - \psi_{\beta}^{\prime})) dt \\ \psi_{\beta}^{\prime} &= \omega_s \int (\psi_{\beta}^{\prime} - \frac{r_s}{\omega_s} (\psi_{\alpha}^{\prime} - \psi_{\beta}^{\prime})) dt \\ i_{\gamma}^{\prime} &= \frac{\omega_s}{x_{\gamma\gamma}} \int (\psi_{\gamma}^{\prime} - i_{\gamma}^{\prime} r_s) dt \end{aligned} \right\} \quad (10)$$

$$\left. \begin{aligned} \psi_{\alpha}^{\prime} &= \omega_s \int (\psi_{\alpha}^{\prime} + \frac{\omega_r}{\omega_s} \psi_{\beta}^{\prime} + \frac{r_s}{\omega_s} (\psi_{\alpha}^{\prime} - \psi_{\beta}^{\prime})) dt \\ \psi_{\beta}^{\prime} &= \omega_s \int (\psi_{\beta}^{\prime} - \frac{\omega_r}{\omega_s} \psi_{\alpha}^{\prime} + \frac{r_s}{\omega_s} (\psi_{\alpha}^{\prime} - \psi_{\beta}^{\prime})) dt \\ i_{\gamma}^{\prime} &= \frac{\omega_s}{x_{\gamma\gamma}} \int (\psi_{\gamma}^{\prime} - i_{\gamma}^{\prime} r_s) dt \end{aligned} \right\} \quad (11)$$

$$\begin{aligned} \psi_{\alpha}^{\prime} &= x_{\alpha\alpha} (i_{\alpha}^{\prime} + i_{\alpha}^{\prime}) \\ \psi_{\beta}^{\prime} &= x_{\beta\beta} (i_{\beta}^{\prime} + i_{\beta}^{\prime}) \end{aligned} \quad (12)$$

$$\left. \begin{aligned} \psi_{\alpha}^{\prime} &= x_{\alpha\alpha} i_{\alpha}^{\prime} + \psi_{\alpha}^{\prime} & i_{\alpha}^{\prime} &= \frac{\psi_{\alpha}^{\prime} - \psi_{\alpha}^{\prime}}{x_{\alpha\alpha}} \\ \psi_{\beta}^{\prime} &= x_{\beta\beta} i_{\beta}^{\prime} + \psi_{\beta}^{\prime} & i_{\beta}^{\prime} &= \frac{\psi_{\beta}^{\prime} - \psi_{\beta}^{\prime}}{x_{\beta\beta}} \\ \psi_{\gamma}^{\prime} &= (x_{\gamma\gamma} i_{\gamma}^{\prime} - \psi_{\gamma}^{\prime}) & i_{\gamma}^{\prime} &= \frac{\psi_{\gamma}^{\prime} - \psi_{\gamma}^{\prime}}{(x_{\gamma\gamma})} \\ \psi_{\gamma}^{\prime} &= (x_{\gamma\gamma} i_{\gamma}^{\prime} + \psi_{\gamma}^{\prime}) & i_{\gamma}^{\prime} &= \frac{\psi_{\gamma}^{\prime} - \psi_{\gamma}^{\prime}}{(x_{\gamma\gamma})} \end{aligned} \right\} \quad (13)$$

Where

$$\frac{1}{x_{\alpha\alpha}} = \frac{1}{x_{\alpha\alpha}} + \frac{1}{x_{\beta\beta}} + \frac{1}{x_{\gamma\gamma}} \quad (14)$$

and

$$\begin{aligned} \psi_{\alpha}^{\prime} &= x_{\alpha\alpha} \left(\frac{\psi_{\alpha}^{\prime}}{x_{\alpha\alpha}} + \frac{\psi_{\beta}^{\prime}}{x_{\beta\beta}} \right) \\ \psi_{\beta}^{\prime} &= x_{\beta\beta} \left(\frac{\psi_{\alpha}^{\prime}}{x_{\alpha\alpha}} + \frac{\psi_{\beta}^{\prime}}{x_{\beta\beta}} \right) \end{aligned} \quad (15)$$

The torque equation is

$$T_{em} = \frac{3}{2} \frac{P}{\omega_r} (\psi_{\alpha}^{\prime} i_{\beta}^{\prime} - \psi_{\beta}^{\prime} i_{\alpha}^{\prime}) \quad N.m$$

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

$$\frac{dw_r}{dt} = T_{em} + T_{mech} - T_{damp} \quad N.m \quad (16)$$

Where

T_{mech} = the externally applied mechanical torque in the direction of the rotor speed.

T_{damp} = the damping torque in the direction opposite to rotation.

The per unit speed, w_r/w_b needed for building the speed voltage terms in the rotor voltage equations, can be obtained by integrating (17)

$$\frac{2Jw_b}{P} \frac{d(w_r/w_b)}{dt} = T_{em} + T_{mech} - T_{damp} \quad N.m \quad (17)$$

Equation (16) can be written in terms of the inertia constant, H, defined as the ratio of the kinetic energy of the rotating mass at base speed to the rated power, that is

$$H = \frac{Jw_b^2}{2S_b} \quad \text{in per unit} \quad (18)$$

Expressed in per unit values of the machine's own base power and voltage, equation (16) can be rewritten as

$$2H \frac{d(w_r/w_b)}{dt} = T_{em} + T_{mech} - T_{damp} \quad \text{in per unit} \quad (19)$$

The equation for transforming abc phase voltage to qd0 voltage is given as:

$$\begin{aligned} v_{\alpha}^{\prime} &= 2/3 v_{\alpha} - 1/3 v_{\beta} - 1/3 v_{\gamma} \\ &= 2/3 v_{\alpha} - 1/3 v_{\beta} - 1/3 v_{\gamma} \end{aligned} \quad (20)$$

$$v_{\beta}^{\prime} = 1/\sqrt{3} (v_{\alpha} - v_{\beta}) = 1/\sqrt{3} (v_{\alpha} - v_{\beta}) \quad (21)$$

$$v_{\gamma}^{\prime} = 1/3 (v_{\alpha} + v_{\beta} + v_{\gamma}) = 1/3 (v_{\alpha} + v_{\beta} + v_{\gamma}) \quad (22)$$

The equation for transforming of qd0 stator current back to phase current is given as:

$$i_{\alpha} = i_{\alpha}^{\prime} + i_{\gamma}^{\prime} \quad (23)$$

$$i_{\beta} = -1/2 i_{\alpha}^{\prime} - \sqrt{3}/2 i_{\beta}^{\prime} + i_{\gamma}^{\prime} \quad (24)$$

$$i_{\gamma} = -1/2 i_{\alpha}^{\prime} - \sqrt{3}/2 i_{\beta}^{\prime} + i_{\gamma}^{\prime} \quad (25)$$

The simulink model for simulation of induction motor is shown in figure 1. This simulink model was developed using equation (10) to equation (25)

(26)

$$V_{\pi} = r; l_{\pi} + (w - w_{\pi}) \lambda_{\pi}$$
$$\left. \begin{aligned} V_{\pm} &= r_{\pm} I_{\pm} - j\omega L_{\pm} \\ V_{\pm} &= r_{\pm} I_{\pm} + j(\omega - \omega_c) L_{\pm} \end{aligned} \right\} \quad (28)$$
$$\begin{aligned}\lambda_r &= (L_{12} + L_{21})i_r + L_{22}i_r \\ &= L_{12}i_r + L_{21}i_r + L_{22}i_r \\ &= L_{12}i_r + L_{22}(i_r + i_r')\end{aligned}\quad (29)$$
$$\begin{aligned}\lambda_r &= L_u i_r + (L_u + L_n) i_r \\ &= L_u i_r + L_u i_r + L_n i_r \\ &= L_u i_r + L_n (i_r + i_r)\end{aligned}$$
$$\begin{aligned} F_{\varphi} &= r_{\varphi} i_{\varphi} + j\omega [L_{\varphi} i_{\varphi} + L_m (i_{\varphi} + i_c)] \\ &= r_{\varphi} i_{\varphi} + j\omega L_{\varphi} i_{\varphi} + j\omega L_m (i_{\varphi} + i_c) \\ &= r_{\varphi} i_{\varphi} + jX_{\varphi} i_{\varphi} + jX_m (i_{\varphi} + i_c) \end{aligned} \quad (31)$$

(32)

The equivalent circuit of figure 3 can be

redrawn to account for the loss in the rotor as shown in figure

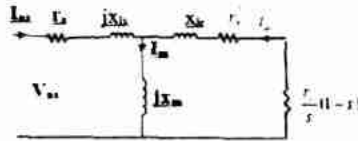


Figure 4: Equivalent circuit of an induction motor.

3.4 Steady State Performance Equations of Induction Machines

By applying Thevenin's theory to figure 3, looking into the circuit from left,

$$\left. \begin{aligned} V_{th} &= \frac{jX_m}{R_s + j(X_{ls} + X_m)} V \\ Z_{th} &= \frac{jX_m (R_s + j(X_{ls} + X_m))}{R_s + j(X_{ls} + X_m)} \end{aligned} \right\} \quad (36)$$

where V_{th} and Z_{th} are Thevenin equivalent voltage and impedance respectively.

The Thevenin's equivalent circuit is shown in figure 5

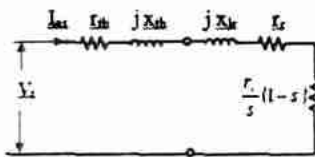


Figure 5: Thevenin equivalent circuit of an induction motor.

$$I_r = \frac{V_{th}}{\left(R_s + \frac{R_r}{s} \right) + j(X_{ls} + X_m)} \quad (37)$$

The mechanical power developed is given as the power dissipated in $\frac{R_r}{s}(1-s)$ which is given by

$$P = 3I_r^2 \frac{R_r}{s} (1-s) = \frac{3I_r^2 \frac{R_r}{s} (1-s)}{\left(R_s + \frac{R_r}{s} \right)^2 + (X_{ls} + X_m)^2} \quad (38)$$

The developed torque is given as:

$$T = \frac{P}{\omega_s} = \frac{P}{\omega_s (1-s)} \quad (39)$$

Substituting equation (38) into equation (39) gives

$$T = \frac{1}{\omega_s (1-s)} \times \frac{3I_r^2 \frac{R_r}{s} (1-s)}{\left(R_s + \frac{R_r}{s} \right)^2 + (X_{ls} + X_m)^2} = \frac{1}{\omega_s} \times \frac{3I_r^2 \frac{R_r}{s}}{\left(R_s + \frac{R_r}{s} \right)^2 + (X_{ls} + X_m)^2} \quad (40)$$

4.1 Torque Speed characteristic of The Induction Motor

For the induction motor with parameters shown in table 1, the torque speed characteristics curve is plotted using equation (40) and is shown in figure (6) and (7a)

Table 1: 4-pole induction motor

Parameters	Values
V_s	220V
P	4
F	50Hz
R_s	0.34 Ω
R_r	0.278 Ω
X_{ls}	0.15 Ω
X_{lr}	1.20 Ω
X_m	20 Ω
Moment of inertia, J_{motor}	0.1 kgm ²

The values of the resistance and reactance in the table 1 were obtained by changing their values in Matlab environment until the appropriate torque speed curve is obtained as shown in figure 6.

Torque speed characteristic of induction motor is shown in figure 6. It was plotted with Matlab by substituting the values of parameters in table 1 into equation (40) and varying the slip from 1 to 0

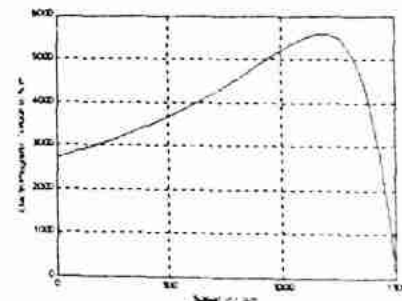


Figure 6: Torque-speed characteristics of induction motor in motoring mode.

Plot of torque-speed characteristic of induction motor showing motoring, generating and braking region is shown in figure 7a. It was plotted with Matlab by substituting the values of parameters in table 1 into equation (40) and varying the slip from 2 to -1

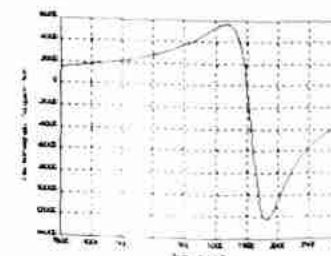


Figure 7a: The plot of torque-speed characteristics showing motoring, generating and breaking region.

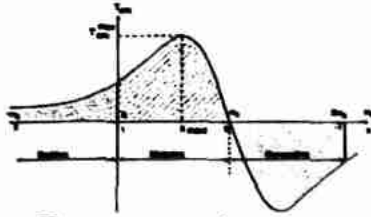


Figure 7b: Torque-speed characteristics of induction motor showing breaking, motoring and generating region [14]

4.2 Determination of the output power of the induction motor.

Operating slip

The mechanical power developed by an induction motor is given as $P_{mech} = (1-s)p_{gap}$

Where p_{gap} is the power transferred across the air gap to the rotor circuit. Also the power losses to the rotor circuit is given by $P_{rotor} = sp_{gap}$

From this it is obvious that the less the slip (as the motor operates close to the synchronous speed, w_s), the less the rotor loss and hence the higher the efficiency. For a typical induction motor, between the slip ranges of 0.06 to 0.02, the motor is relatively most efficient. In this paper, slip is assumed to be 0.02.

From figure 4, the total circuit impedance is given as,

$$Z = r_s + jx_{ls} + \frac{jx_m \left(\frac{r_r}{s} + jx_{lr} \right)}{\frac{r_r}{s} + j(x_m + x_{lr})} \quad (41)$$

Substituting the values of parameters from table 1 into equation (41).

$$Z = 0.34 + j0.15 + \frac{j20 \left(\frac{0.278}{0.02} + j1.20 \right)}{\frac{0.278}{0.02} + j(20 + 1.2)} = 11.18 \angle -36.5^\circ$$

$$I_s = \frac{V}{Z} = \frac{220}{11.18 \angle 131.828} = 19.68 \angle -36.5^\circ$$

Output power, $P_{out} = 3I_{as}^2 r_r / s (1-s) = 3 \times 19.68^2 \times 0.278 / 0.02 \times (1-0.02) = 16480.11$ watts

4.3 Simulation result of the 4-pole induction motor

The simulation result of the 4-pole induction motor is shown in figure 8. They are obtained by substituting the values of the parameters of induction motor in table 1 into the simulink model of figure 1 built with equations (10) to (25).

The time and value arrays of the mechanical torque, T_{mech} repeating sequence source signal for simulation of the 4-pole induction motor is shown below:

$$T_{mech_time} = [0 \ 0.75 \ 0.75 \ 1.25 \ 1.25 \ 1.5 \ 1.5 \ 2]$$

$$T_{mech_value} = [0 \ 0 \ -80 \ -80 \ -80 \ -80 \ 0 \ 0]$$

Other parameters for simulation of the induction motor are calculated as shown below.

$$\text{Base speed, } w_s = 2\pi f = 2 \times \pi \times 50$$

$$= 100\pi$$

$$J_{rotor} = 0.8 \text{ kgm}^2$$

$$w_{bm} = \frac{2w_s}{p} = \frac{2 \times 100\pi}{4} = 50\pi$$

$$\text{Inertia constant, } H = \frac{J_{rotor}}{2P_{mech}}$$

$$H = \frac{0.8 \times (50\pi)^2}{2 \times 16480.11} = 0.6$$

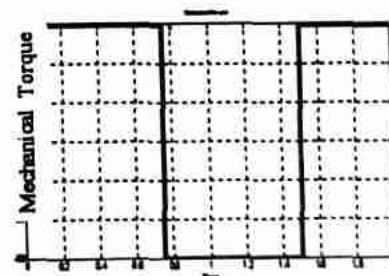


Figure 9a: Mechanical Torque

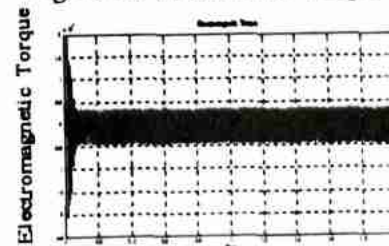


Figure 9b: Electromagnetic torque

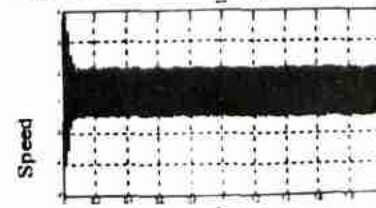


Figure 9c: Speed

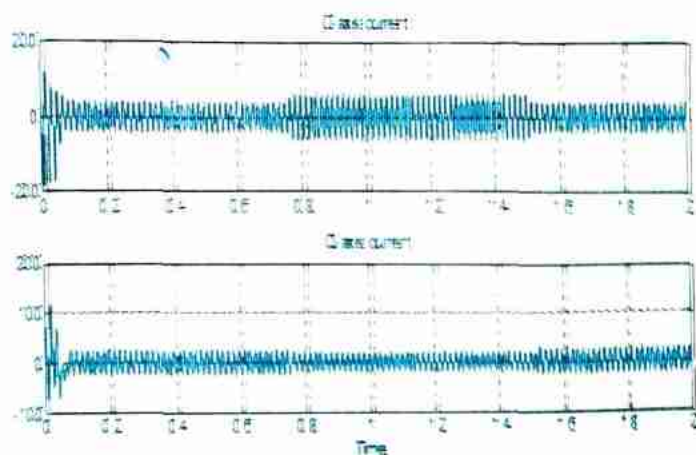


Figure 9d: D-axis current and Q-axis current

5.0 Conclusion

Figure 6 and 7 are the plot of the average value of the torque developed versus speed of an induction machine. Figure 6 is Figure 7 shows what is normally termed the braking, motoring and generating regions of the machine's operation. In motoring region (slip range of 1 to 0), the developed torque is in the direction of rotation. The generating region (slip range of 0 to -1) is above synchronous speed and the developed torque is opposite to the direction of the rotor rotation.

As shown in figure 9a, for the 4-pole induction motor, the machine will be motoring when mechanical Torque (T_{mech}) is negative and generating when T_{mech} is positive.

The step responses for the simulation of the machine are shown in figure 9a, 9b, 9c, 9d. It follows that as the value of parameter, mechanical torque varies, there is corresponding change in electromagnetic torque, speed, Q-axis current and D-axis current.

References

- [1] G. Mcpherson, (1981), "An introduction to Electrical Machines and Transformer", John Willey and sons, New York. Pp 35-36.
- [2.] P.C Krause ,(1981) "Analysis of Electric Machinery", Purdue University, Lafayette Indiana 47907, pp 3-4.
- [3] D.W Novonty and J.H Wouterse, (1976), "Induction Machine Transfer Functions and Complex Time Variables", IEEE Trans. Power apparatus and systems, vol 95 No4. Pp 1325-1335
- [4.] J.B Gupter, (2009), "Theory and Performance of Electrical Machines" (S.K Kataria and,4424/6 Guru Nanak market, nai Sarak Delhi- 110006)pp580,373.
- [5.] B.L Theraja and A.K Theraja,(2002) "Electrical Technology", (S.Chand and Company Ramnagar, New Delhi-110055) pp 1183
- [6] G. J. Roger; J.Di Manno and R.T.H Alden (1984), "An aggregate induction motor models for industrial plants", IEEE Trans. Power apparatus and systems, Vol 103. No. 4. Pp 683-690.
- [7] G.J Rogers, (1965), "Linearized Analysis of Induction Motor Transients", Proc. Iee, Vol112, pp 1917-11926.
- [8] J.R Willis, G.J Brock and J.S Edmonds,(1989), "Derivation of Induction motor Models from Standstill Frequency Response Tests", IEEE Trans. on Energy Conversion, Vol.4 No. 4. pp 608-615
- [9] A.E Fitzgerald, C. Kingsley, Jr; and A. Kusko, (1971) "Electric Machinery: The Process, Devices and Systems of Electromechanical Energy Conversion", 3rd Ed. New York: Mcgraw Hill, pp 26-30
- [10] T.C Lloyd,(1969) "Electric Motors and their Applications", New York, Wiley- Inter-Science. PP 240- 250
- [11] Chee- Mun ong,(1997) "Dynamic Simulation of Electric Machinery Using Matlab/Simuink" (Prentice Hall PTR Upper Sadde River New Jersey 07458) pp 173
- [12] P.C Krause and C. H Thomas, (1965), "Simulation of symmetrical induction machinery", IEEE Trans on Power Apparatus and System, Vol. 84, No.11. pp 1038-1053.
- [13] P.L Alger, M. Ivanes and M. Poloujadoff, (1974), "Equivalent Circuits for Double Squirrel Cage Induction Motors", Paper C 74 222-6 Winter Power Meeting. Pp 26-27.
- [14] L.U Anih, S.E Obeh and E. O Ogbachi (2011), "Analytic Synthesis of Hysteresis Motor", Energy Conversion Management, Vol.52, pp391-396,