



Direct on Line Operation of Three Phase Induction Motor using MATLAB

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Article info	Abstract
Original: 20 November 2018 Revised: 25 August 2019 Accepted: 26 August 2019 Published online: 20 December 2019 Key Words: <i>Three-phase induction</i> Motor Matlab Modeling	Induction motors are most widely used motors due to their reliability, robustness and low cost. However, huge starting current and sudden change in load current of three phase induction motor are the most problems in high power applications since these lead to damage the motor. Therefore, controlling the current during transient is essential to protect the motor from damage. In order to control current instantaneously, it is required firstly to model the motor and secondly to represent the rotational three phase (current and voltage) instationary frame and this can be done using DQ modelling. The DQ modelling proposed in literature, the effect of friction was neglected and this reduces the correctness of the modelling. This Paper will look at the DQ modelling and method of starting up of the three phase induction motor. At first, the novelty of this paper is to find the friction of the motor practically and include it in the DQ model. Then, calculating three phase induction motor parameters which will help in the modelling process. Then, it uses the direct on line method (DOL) to validate the DQ model using MATLAB/Simulink.

Introduction

The use of asynchronous motors particularly squirrel-cage rotor has increased tremendously since the day of its invention. They are being used as actuators in many types of industrial processes, robotics, house appliances (generally single-phase) and other similar applications. The reason for its daily increasing popularity can be primarily attributed to its simplicity in design, robust construction and cost effectiveness, high efficiency, reliability and good self-starting capability [1-2].

The induction motor is a vital class of electric machines which finds wide applicability in industry and in its single phase form in several domestic applications. More than 85% of industrial motors in use today are in fact induction motors that is basically a constant speed motor with a shunt characteristic [3,4].

This model of machine describes the transient and the steady state behavior of the induction machine. The model can be used to simulate the asynchronous motor drives and evaluate their transient performances. It is also used when developing high performance control techniques for the asynchronous motor drives such as vector control or direct control (DTC) drives [5,6]. Various models have been developed and d-q axis model for the study of transient behavior has been well tested and proven to be reliable and accurate [7].

Three phase induction motors are widely used in industrial for many purposes due to robust construction, reliability and high efficiency when controlled. In general, two methods are used to start up induction motors and they are Direct on Line (DOL) and control method which is mostly vector control. Three phase induction

motors are the most essential machines for high power applications where high efficiency, high reliability and robust construction are required. Controlling the speed of the induction motor is one of the most important targets for most of the applications. However, in medium and high-power applications, the current will rise dramatically and this leads to damage the motor. DOL method must be prevented in medium and high power application because of the huge rise of the starting current. Therefore it is required to control the current and to be able to control it using PI controller the three phase rotary frame must be represented as it is stationary. With DQ modeling, three phase voltages and currents of the motor are represented in a stationary frame and they can be controlled using normal PI controller. As a result, it can be stated that DQ model is essential to control the AC current instantaneously to protect the motor from damage.

This paper will look at firstly, calculation of three phase induction motors' parameters includes electrical and mechanical parameters which will be needed for controllers purposes. Secondly, it will show the direct on line method to start up three phase induction motor.

Finally effect of moment of inertia has been represented.

Induction Motor Parameters:

A. *A. Dynamic Model of the Induction Motor in Stationary Reference Frame*

A three phase induction machine can be represented by an equivalent two phase machine as shown in Figure-1, where ds-qs axes correspond to stator direct and quadrature axes [8,9]. The dynamic model of the induction motor in the stationary reference frame, used for the analysis carried out in project has been explained here with equivalent circuits and a series of equations (1) to (10).

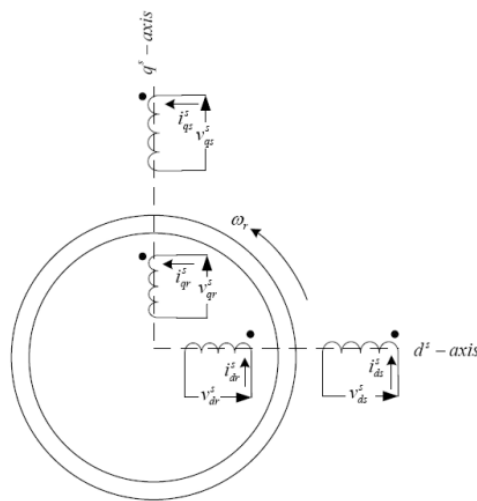


Figure-1: d-q representation of the Induction Motor

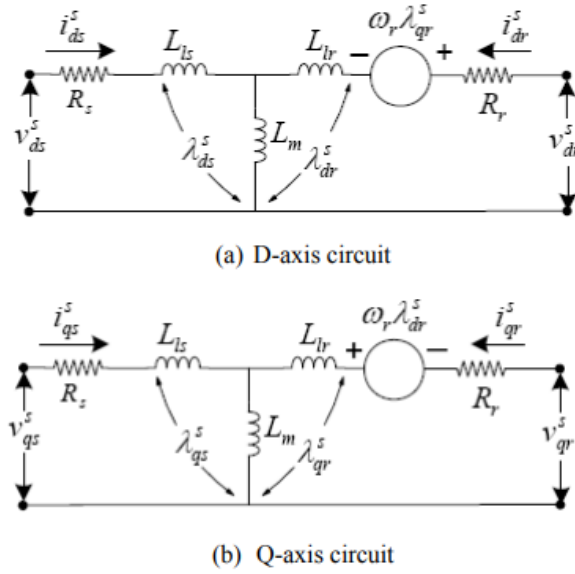


Figure-2: d-q equivalent circuit of Induction Motor in Stationary Reference Frame

$$V_{ds}^s = R_s i_{ds}^s + \frac{d}{dt}(\lambda_{ds}^s) \quad (1)$$

$$V_{qs}^s = R_s i_{qs}^s + \frac{d}{dt}(\lambda_{qs}^s) \quad (2)$$

$$V_{dr}^s = R_r i_{dr}^s + \frac{d}{dt}(\lambda_{dr}^s) + \omega_r \lambda_{dr}^s = 0 \quad (3)$$

$$V_{qr}^s = R_r i_{qr}^s + \frac{d}{dt}(\lambda_{qr}^s) - \omega_r \lambda_{qr}^s = 0 \quad (4)$$

$$\lambda_{ds}^s = L_{ls} i_{ds}^s + L_m (i_{ds}^s + i_{dr}^s) \quad (5)$$

$$\lambda_{qs}^s = L_{ls} i_{qs}^s + L_m (i_{qs}^s + i_{qr}^s) \quad (6)$$

$$\lambda_{dr}^s = L_{lr} i_{dr}^s + L_m (i_{ds}^s + i_{dr}^s) \quad (7)$$

$$\lambda_{qr}^s = L_{lr} i_{qr}^s + L_m (i_{qs}^s + i_{qr}^s) \quad (8)$$

$$T_e = 1.5pL_m (i_{qs}^s i_{dr}^s - i_{ds}^s i_{qr}^s) \quad (9)$$

$$J_T \frac{d\omega_m}{dt} = \frac{1}{p} J_T \frac{d\omega_r}{dt} = T_e - T_L \quad (10)$$

B. Dynamic Model of the Induction Motor in Synchronously Rotating Reference Frame

The induction motor equations described in 2.1 are referred to the stationary reference frame. These equations can also be referred to the synchronously rotating reference aligned with d-q axes shown in Figure-3.

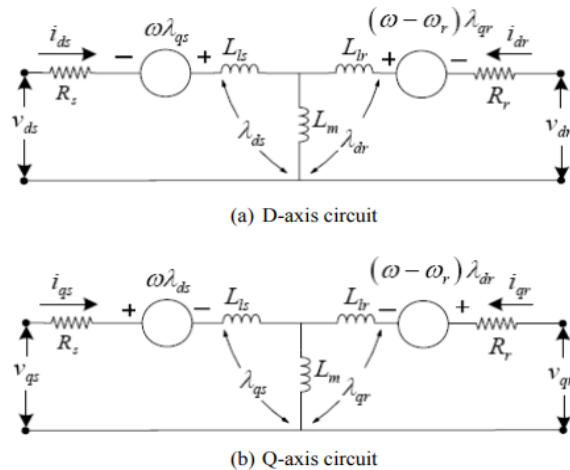


Figure-3: d-q equivalent circuit of Induction Motor in synchronously rotating reference frame

When equations (1) and (2) are referred to the synchronously rotating reference frame rotating at ω ,

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}(\lambda_{ds}) - \omega \lambda_{qs} \quad (11)$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}(\lambda_{qs}) - \omega \lambda_{ds} \quad (12)$$

The last terms in equations are defined as speed emfs due to the rotation of axes. That is, when $\omega=0$, the equations revert to the stationary reference frame form. The equations (3) and (4) for the rotor become:

$$V_{dr} = R_t i_{dr} + \frac{d}{dt}(\lambda_{dr}) - (\omega - \omega_r)\lambda_{dr} = 0 \quad (13)$$

$$V_{qr} = R_t i_{qr} + \frac{d}{dt}(\lambda_{qr}) - (\omega - \omega_r)\lambda_{qr} = 0 \quad (14)$$

All the sinusoidal variables at fundamental frequency in the stationary frame appear as dc quantities in the synchronously rotating reference frame. The flux linkage expressions can be written as:

$$\lambda_{ds} = L_{ls} i_{ds} + L_m(i_{ds} + i_{dr}) \quad (15)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m(i_{qs} + i_{qr}) \quad (16)$$

$$\lambda_{dr} = L_{lr} i_{dr} + L_m(i_{dr} + i_{ds}) \quad (17)$$

$$\lambda_{qr} = L_{lr} i_{qr} + L_m(i_{qr} + i_{qs}) \quad (18)$$

The torque expression of the motor can be derived as follows:

$$T_e = 1.5pL_m(i_{qs}i_{dr} - i_{ds}i_{qr}) = 1.5(\lambda_{dr}i_{qr} - \lambda_{qr}i_{dr}) \quad (19)$$

From above equations based on parameters we can model a three phase induction motor.

C.Determination of Motor Parameters

In general, motor parameters are provided by manufactures, either on motor nameplate or would be available in a data sheet[4,5]. For this paper, motor parameters have been given as shown in table 1.

Table.1: Motor parameters.

Motor parameter	Value
Rated Mechanical power	1.5KW
Line-to-Line Voltage (V _{L-L})	380 V
Frequency (Fe)	50 Hz
Connection Type	star connection
Rated Speed (ω_r)	144.5 rad/sec
Line-to-Line Rated Current	3.63 Amp
Full-Load Power Factor	0.8
Line-to-Line Starting Current	(15 Amp)
Stator Resistor	4.1 Ω found by ohmmeter

Moment of inertia (j)	0.0026kg.m ²
Magnetization Inductance(L ₀ and L _m)	0.32 H

Figure-4 shows equivalent circuit diagram and phisor diagram of three phase induction machine.

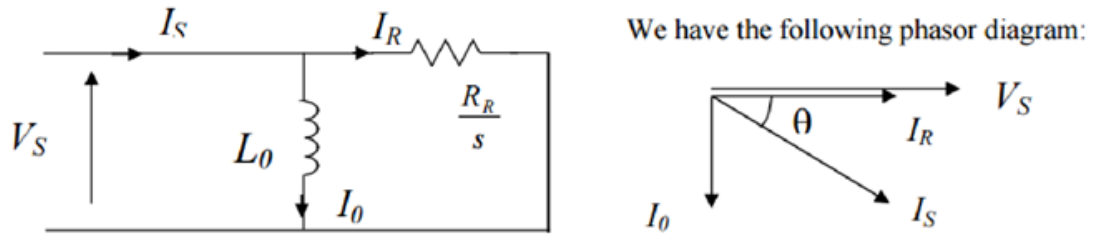


Figure 4:Circuit diagram with phisor diagram of IM

Based on the phasor diagram of the equivalent circuit of the induction motor, the magnetization inductance and stator resistor have been calculated, with the following values 0.32H and 4.1Ω, respectively. Using simple linear equations, the stator and the rotor self-inductances as well as the leakage factors have been determined and the equivalent values are: $L_R = 0.348H$, $L_S = 0.339H$, and $\sigma = 0.145$, respectively.

The mechanical parameters of the induction motor have been measured experimentally. A DC shunt motor has been used to drive the IM and the motor speed has been changed by armature voltage variation, Figure-5. Based on the proportional relation between the output power and the squared IM speed, the friction coefficient has been estimated from the curve slope as $D=0.0084 \text{ Nm/r/s}$.

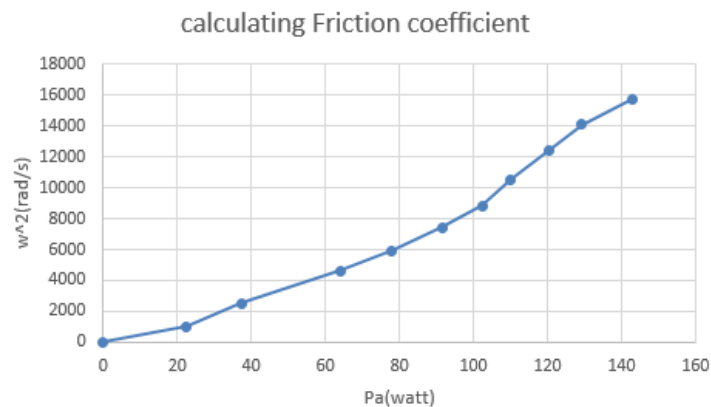


Figure-5: calculation of friction coefficient

Motor Performance DOL

In general, there are several approaches to start a three phase induction motor (IM) depending on the load accelerating, starting current and torque requirement. The most common method is Direct on Line (DOL). This method is as a basic approach to start IM and it is not advised to be used in applications which are required high efficiency, and high accuracy speeds because of its instability and poor transient response caused by starting torque and high inrush of current at the starting with high oscillation.

The DOL method will be modeled and simulated with different values of load torque (no-load, half load and full-load) and at different load inertia (0.02 Kg.m²) in order to investigate the motor performance. At first, the nameplate and the calculated parameters have been set to the motor. The motor has been supplied by 50Hz, 380V-three phase voltage source which converted to $\alpha\beta$ coordination to feed the motor with smooth starting current. Figure-6 shows the DOL model [10,11]. The outputs (I_s , R-flux and S-flux) have been converted to three phase values to be able to see and evaluate their peak and RMS values. Motor speed is designed based on the speed equation shown below and it has been converted to rpm values to be fed to the motor.

$$\dot{\omega}_r = \frac{1}{J_s} (T_e - T_L) - \omega_r D \quad (20).$$

- Where: D is Friction Coefficient
 : J is Moment of Inertia
 : T_e is Electrical Torque
 : T_L is Mechanical Torque
 : ω_r is Rated Speed

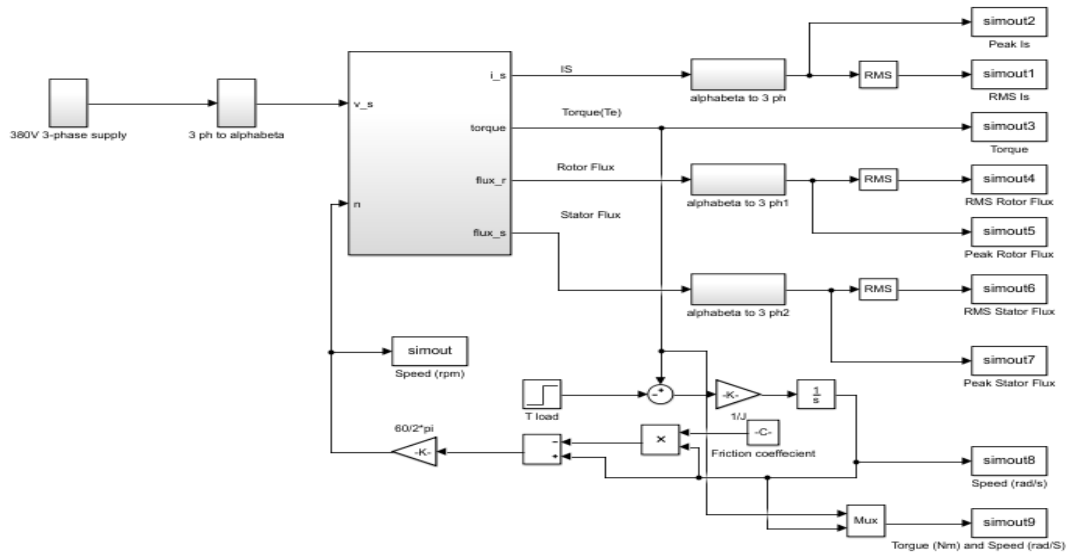


Figure-6: Direct online model

Induction motor model description:

A. Three phase to alpha beta model

Three phase voltage source which converted to $\alpha\beta$ coordinate and vice versa also alpha beta to DQ model by following equations:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 3/2 & 0 & 0 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (21)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 2/3 & 0 \\ -1/3 & 1/\sqrt{3} \\ -1/3 & 1/\sqrt{3} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (22)$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (23)$$

From above equations block diagram of three phase to alpha beta model and alpha beta to three phase as shown figures 7,8. Finally, block diagram of converting alpha beta to DQ model has been represented in figure-9.

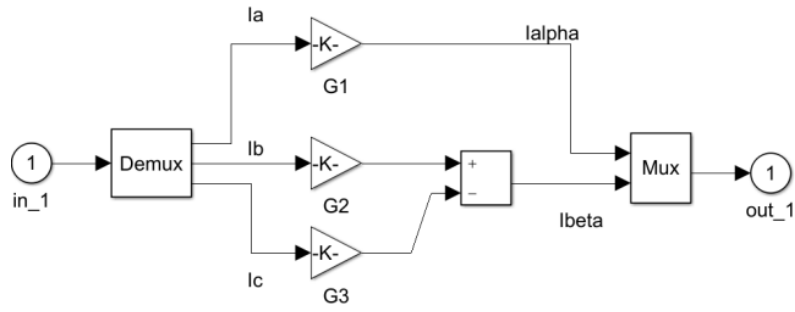


Figure-7: Block diagram of three phase to alpha beta

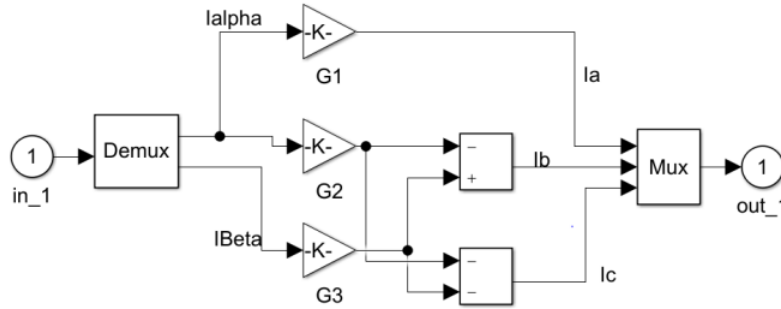


Figure-8: Block diagram of alpha betathree phase

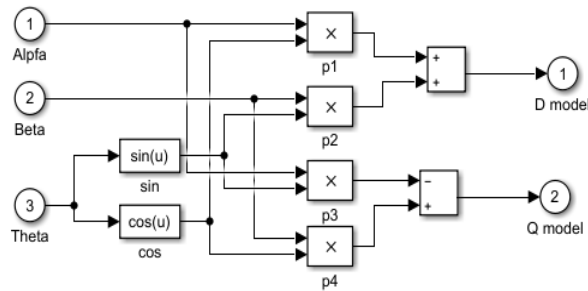


Figure-9: Block diagram of alpha betathree phase

B. DQ model

Equations (11) and (12) can be rewriting as follow:

$$\begin{aligned}
 u_{sd} &= R_s i_{sd} + \sigma L_s \frac{d}{dt} i_{sd} - \omega_e \sigma L_s i_{sq} + \frac{L_o}{L_r} \frac{d}{dt} \Psi_{rd} \\
 u_{sq} &= R_s i_{sq} + \sigma L_s \frac{d}{dt} i_{sq} - \omega_e \sigma L_s i_{sd} + \frac{L_o}{L_r} \Psi_{rd}
 \end{aligned}
 \tag{24}$$

From the system equation (24), modeling of a direct and quadrature current, Torque and rotor and stator flux was represented using Matlab/Simulink as shown in figure-10.

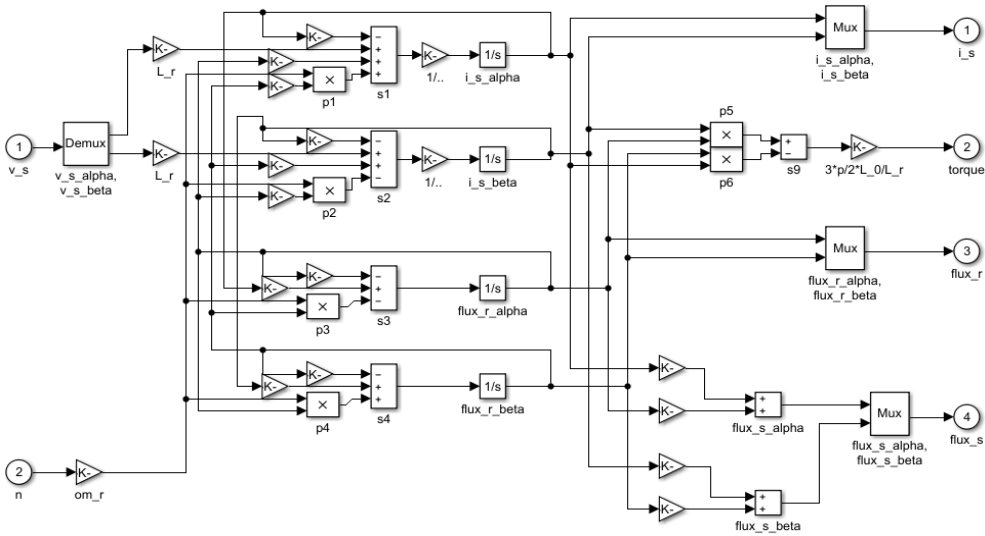


Figure 10: Induction motor model

Simulation Results

Firstly, zero load torque has been applied to the motor to investigate the behavior of induction motor at no-load. Figures (11, 12, 13 and 14) show the performance of induction motor (stator I_a I_b I_c , stator R_{ms} current, stator flux, rotor flux and torque speed characteristic, respectively) at $J= 0.02 \text{ kg.m}^2$.

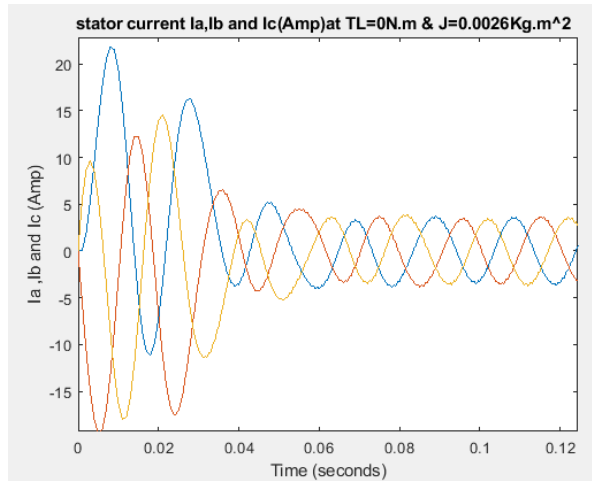


Figure-11: Stator Current at $J= 0.0026\text{kg.m}^2$

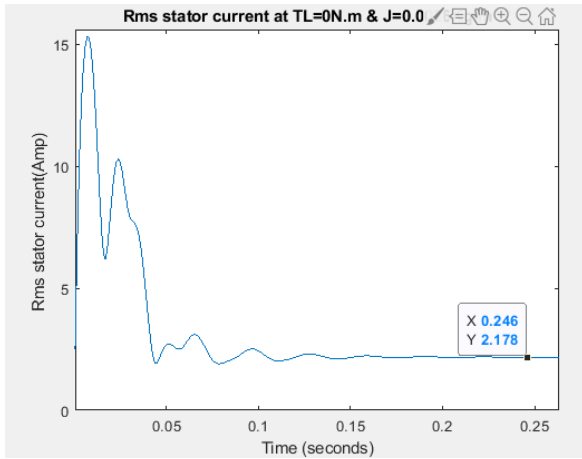


Figure-12: RMS Stator Current at $J= 0.0026\text{kg.m}^2$

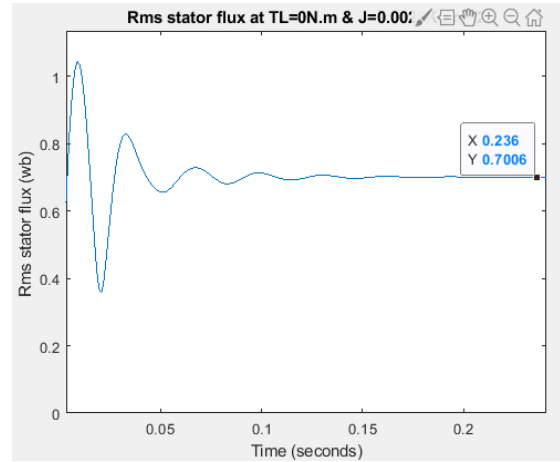


Figure-13: RMS Stator Flux at $J= 0.0026\text{kg.m}^2$

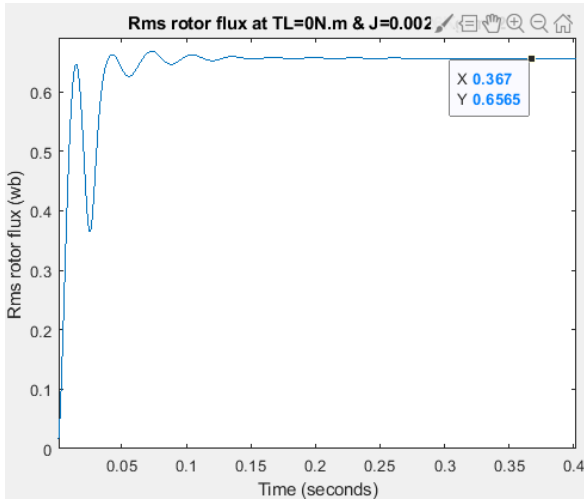


Figure-14: RMS Rotor Flux at $J= 0.0026\text{kg.m}^2$

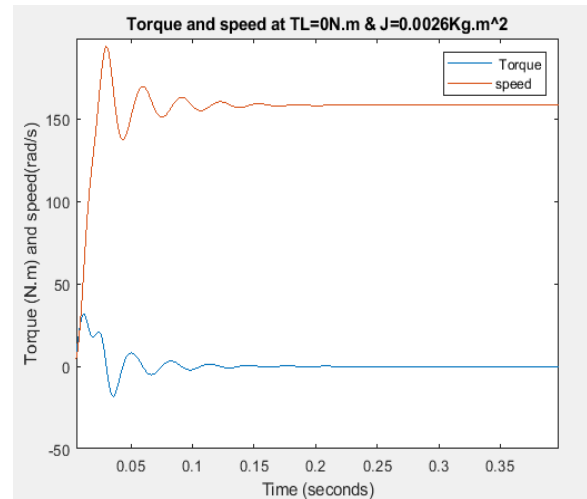


Figure-15: IM torque and speed at $J= 0.0026\text{kg.m}^2$

From figure above important point to be noticed from figures (12, 14), the RMS values of stator current and rotor flux are 2.178 Amp and 0.6565 Wb, respectively and these values are near the rated values which have been calculated previously.

In order to investigate the effect of load torque on the behavior of the IM, moment of inertia has been fixed ($J=0.0026 \text{ kg.m}^2$) and several values of load torque (like 5 Nm, and 10.1Nm) have been applied.

Figures (16, 17, 18 and 19) show stator current, stator flux, rotor flux and speed torque characteristic respectively and it can be noticed that transient duration is around 0.15 second. The RMS values of stator current and rotor flux are 2.556 Amp and 0.6846 respectively and torque is 5 Nm (see figure 19).

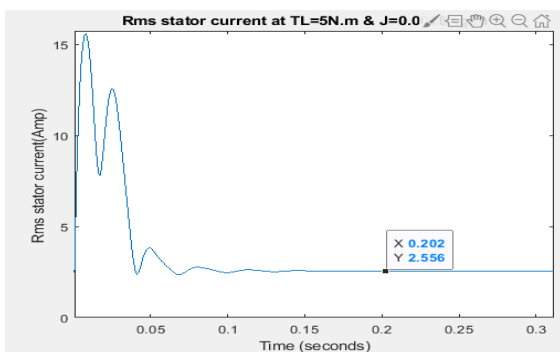


Figure-16: RMS Stator Current at $T_L=5 \text{ NM}$

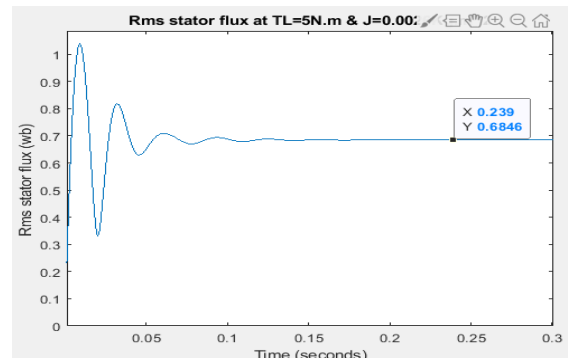


Figure-17: RMS Stator Flux at $T_L=5 \text{ NM}$

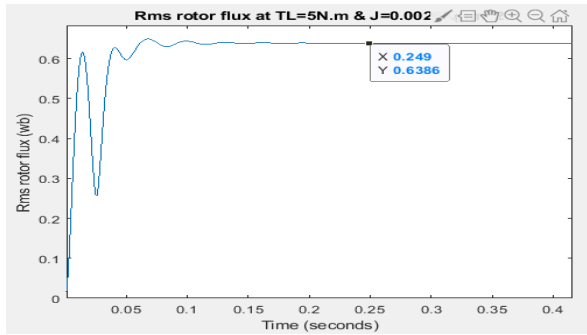


Figure-18: RMS Rotor Current at $T_L=5$ NM

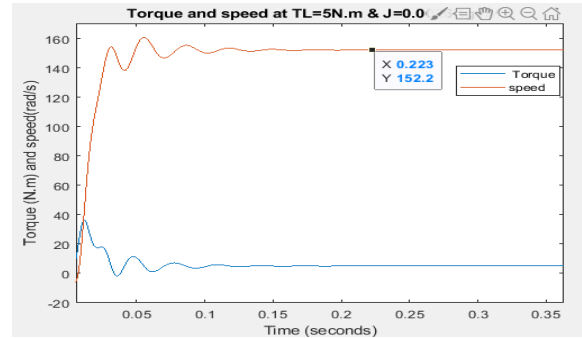


Figure-19: IM torque and speed at $T_L=5$ NM

Figures (20, 21, 22 and 23) present the motor performance at full load (10.1N.m). As it is shown in figures, the transient duration is slightly more than 0.2 second and from figures (20 and 21) it can be seen that the RMS values of the stator current and rotor flux are 3.636 Amp and 0.667 Wb, respectively. In comparison to rated values ($I_s = 3.63$ Amp and $\Psi_r = 0.698$) which have been calculated theoretically, it can be seen that they are not exactly the same because in theoretical calculation to be able to calculate, in each step certain parameters have been neglected due to minor effect such as neglecting magnetization inductance for calculating leakage inductances and neglecting leakage inductances and stator resistor in calculation of L_o and R_R .

An important point to be declared, from all figures in this section, it can be noticed that the increase of load torque has affected the transient time and it has shown that by increasing the load torque (0, 5, and 10.1) the transient duration increases. As shown in all figures, during transient starting current is very high (about 5 times rated value) therefore, with more transient duration, this high current will affect the motor and it may damage the windings. This is one of the reasons which makes the direct operation method is not preferred to be utilized when good transient performance is required. This high starting current need to be controlled as will be shown in other methods of operation.

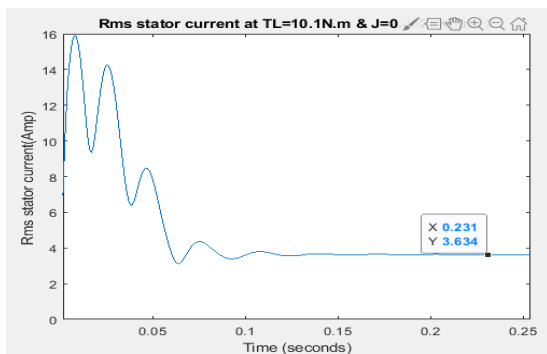


Figure-20: RMS Stator Current at $T_L=10$ NM

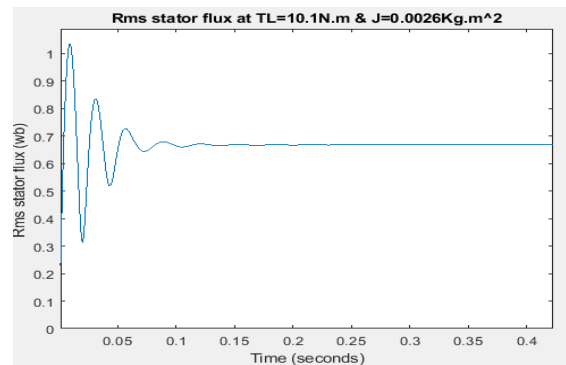


Figure-21: RMS Stator Flux at $T_L=10$ NM

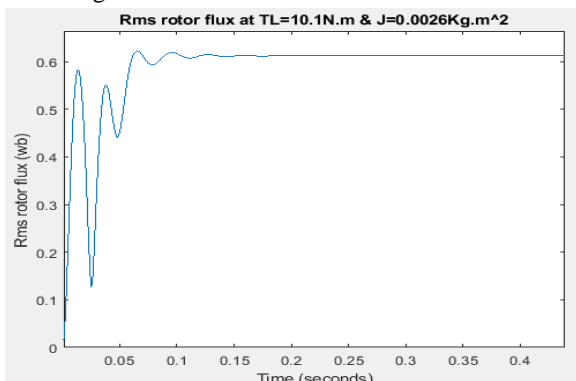


Figure-22: RMS Rotor Flux at $T_L=10$ NM

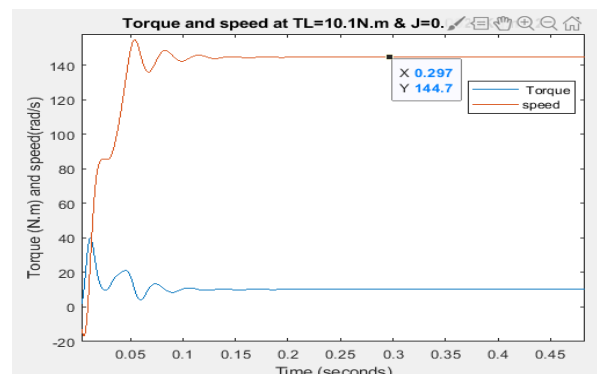


Figure-23: IM torque and speed at $T_L=10$ NM

Finally, Rotor voltage and current has been plotted in simulation as showed in figure-24 and the power factor and efficiency of induction motor when the load torque (0,5 and 10) which have been plotted in simulation as shown in Figures below (25, and 26). In these figures it can be clearly showed that by increasing load torque efficiency is increased. In addition, power factor also increases this is due to angle between voltage and current at no load the angle about 84 degrees cosine theta near 0.2 but by increasing the load torque it is about 140 degrees cosine theta increasing and which is equal near 0.8 as described in figure (27 and 28). Consequently, it can be certainly said that the load torque is the important factor which has been affected to the machine start up.

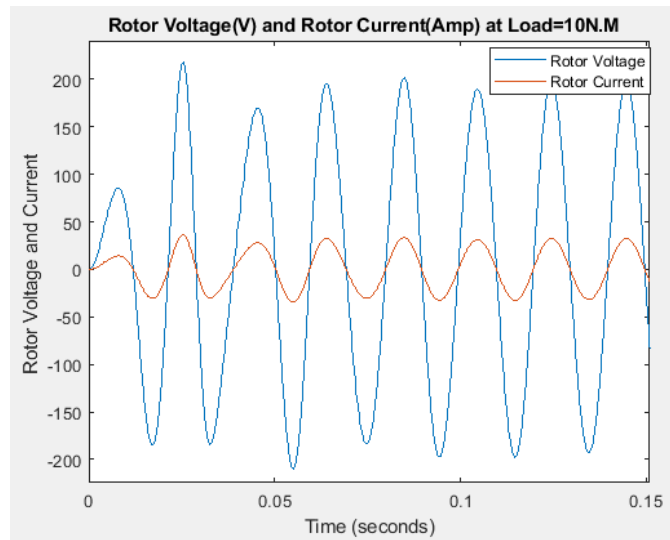


Figure-24: Rotor Voltage and Current at $T_L=10\text{NM}$

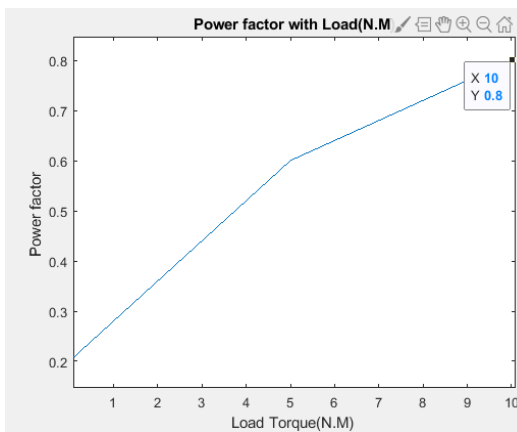


Figure-25: Power factor with $T_L=0,5,10\text{ NM}$

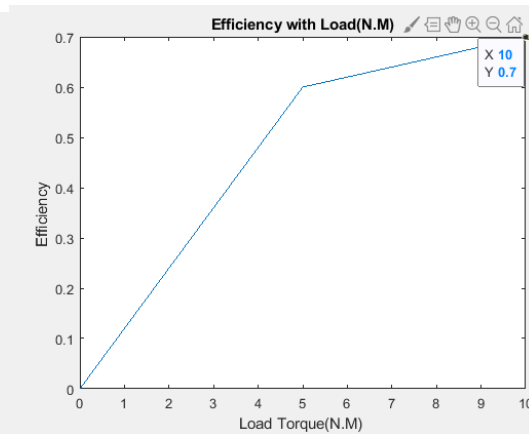


Figure-26: Efficiency with $T_L=0,5,10\text{NM}$

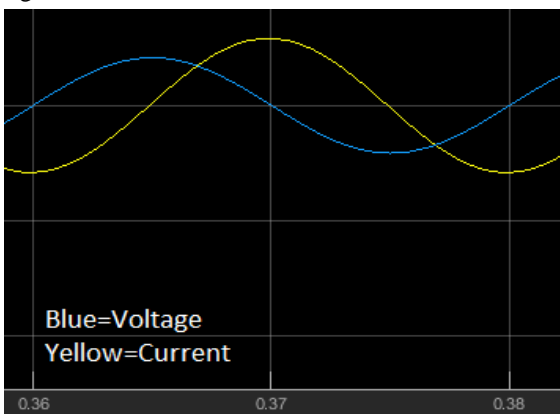


Figure-27: Angle between volt and current at $T_L=0\text{ NM}$

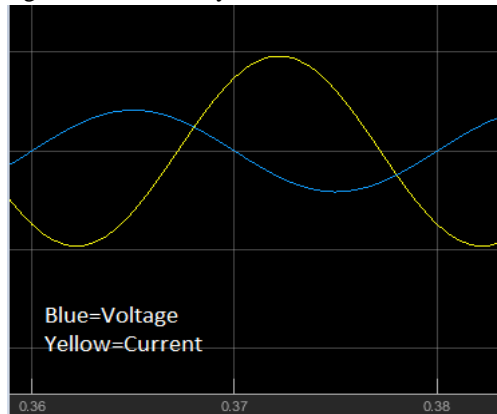


Figure-28: Angle between volt and current at $T_L=10\text{ NM}$

Finally ,when the friction coefficient increased the value of the speed during transient is decreased because of it is developed mechanical loss of the motor, as shown in Figure-24.

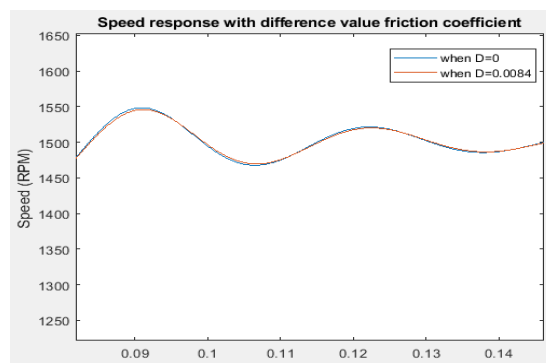


Figure-29: Effect of Friction coefficient on motor performance

Conclusion

This work shows several aspects of three phase induction motor. firstly, it describe direct on line method of induction mator. The parameters of the motor were found and the transient response of the starting current was shown. This huge starting current can damage the motor if the its not controlled. Secondly, to be able to control the current, three phase motor were modelled using DQ model however due to the scope of this paper only, DQ model was presented the controllers was omitted. Additionally, in the model the friction factor of the motor was found practically and used in the DQ model which is one of the novilety of this paper.

The theory behind this model is based on representing the real motor by a set of equations and values in MATLAB using the subsystem feature ,the most interesting point is that ,there was a small difference between MATLAB/Simulink data and the practical data which have received from real motor in laboratory , the RMS value of the stator current and speed at no-load which have been calculated by MATLAB /Simulink near 2.178 Amp and 1500 RPM respectively and these values are near the values which have been recorded in the lab which was 2.23Amp and 1492 RPM ,(at about $\frac{3}{4}$ load RMS stator current and speed by MATLAB /Simulink 3.14 Amp and 1400 RPM while in real motor 3.16 Amp and 1378 RPM) , at near full load RMS stator current and speed in MATLAB /Simulink was 3.4 Amp 1380 RPM and while in practice 3.33 Amp and 1366 Rpm).

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