Dynamic Modeling and Simulation of a 3-HP Asynchronous Motor Driving a Mechanical Load.

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ABSTRACT

The qd0 transformation theory is applied in dynamic modeling and simulation, on the stationary reference frame, of a 3-hp asynchronous motor driving a 20N-m mechanical load. The systems of differential equations representing the dynamic state behaviors of the machine, as developed, are implemented in SIMULINK®. The effects of the programmed sequence of mechanical loading on the motor output variables namely: Phase Currents, Motor Speed, and Electromechanical Torque are examined. The results obtained clearly show the elegance of the qd0 transformation theory in machine modeling and the inherent limitations of the direct-on-line starting of asynchronous motors as evident in the excess starting currents.

(Keywords: asynchronous motor, dynamic modeling, stationary reference frame, MATLAB/SIMULINK®)

INTRODUCTION

Asynchronous (Induction) machines are the most widely used in industry because of their robustness, reliability, low cost, high efficiency and good self-starting capability [1, 2]. The induction motor, particularly with a squirrel cage rotor, is the most widely used source of mechanical power fed from an AC power system. Its low sensitivity to disturbances during operation make the squirrel cage motor the first choice when selecting a motor for a particular application [3]. Induction motors are being used more than ever before in industry and individual machines of up to 10 MW in size are no longer a rarity [4].

During start-up and other severe motoring operations, the induction motor draws large currents, produce voltage dips, oscillatory torques and can even generate harmonics in the power system [5, 6]. It is, therefore, important to be able to predict these phenomena. Various models have been developed and the qd0 or two axis model for the study of transient behaviors has been tested and proved to be very reliable and accurate [4].

It has been shown that the speed of rotation of the d,q axes can be arbitrary although there are three preferred speeds or reference frames as follows [7]:

(a) The stationary reference frame when the d,q axes do not rotate.

(b) The synchronously rotating reference frame when the d,q axes rotate at synchronous speed.

(c) The rotor reference frame when the d,q axes rotate at rotor speed.

It is usually more convenient to simulate an induction machine and its converters on a stationary reference frame; the model presented in this paper is on a stationary reference frame [8]. This offers a sound foundation for the various variable speed closed loop control schemes of three phase induction motor [9].

ASYNCHRONOUS (INDUCTION) MACHINE MODEL IN STATIONARY qd0 REFERENCE FRAME

The model equations of the Three Phase Asynchronous (Induction) Machine in the stationary qd0 reference frame may be rearranged into the following form for the purpose of dynamic simulation [8].

$$\psi_{qs}^{s} = \omega_b \int \left(v_{qs}^{s} + \frac{r_s}{x_{ls}} (\psi_{mq}^{s} - \psi_{qs}^{s}) \right) dt \qquad \textbf{(1)}$$

$$\psi_{ds}^{s} = \omega_b \int \left(v_{ds}^{s} + \frac{r_s}{x_{ls}} (\psi_{md}^{s} - \psi_{ds}^{s}) \right) dt \quad \textbf{(2)}$$

$$i_{0s} = \frac{\omega_b}{x_{ls}} \int (v_{0s} - i_{0s} r_s) dt \quad \textbf{(3)}$$

$$\psi_{qr}^{'s} = \omega_b \int \left(v_{qr}^{'s} + \frac{\omega_r}{\omega_b} \psi_{dr}^{'s} + \frac{r_r^{'}}{x_{lr}^{'}} (\psi_{mq}^{s} - \psi_{qr}^{'s}) \right) dt \quad \textbf{(4)}$$

$$\psi_{dr}^{'s} = \omega_b \int \left(v_{dr}^{'s} - \frac{\omega_r}{\omega_b} \psi_{qr}^{'s} + \frac{r_r^{'}}{x_{lr}^{'}} (\psi_{md}^{s} - \psi_{dr}^{'s}) \right) dt \quad \textbf{(5)}$$

$$i_{0r}^{'} = \frac{\omega_b}{x_{lr}^{'}} \int (v_{0r}^{'} - i_{0r}^{'} r_r^{'}) dt \quad \textbf{(6)}$$

$$\psi_{mq}^{s} = x_m (i_{qs}^{s} + i_{qr}^{'s})$$
$$\psi_{md}^{s} = x_m (i_{ds}^{s} + i_{dr}^{'s}) \quad \textbf{(7)}$$

$\psi_{qs}^{s} = x_{ls} i_{qs}^{s} + \psi_{mq}^{s}$ Implying that,

$$i_{qs}^{s} = \frac{\psi_{qs}^{s} - \psi_{mq}^{s}}{x_{ls}} \quad \textbf{(8)}$$

$\psi_{ds}^{s} = x_{ls} i_{ds}^{s} + \psi_{md}^{s}$ Implying that,

$$i_{ds}^{s} = \frac{\psi_{ds}^{s} - \psi_{md}^{s}}{x_{ls}} \quad \textbf{(9)}$$

$\psi_{qr}^{'s} = x_{lr}^{'} i_{qr}^{'s} + \psi_{mq}^{s}$ Implying that,

$$i_{qr}^{'s} = \frac{\psi_{qr}^{'s} - \psi_{mq}^{s}}{x_{lr}^{'}} \quad \textbf{(10)}$$

$\psi_{dr}^{'s} = x_{lr}^{'} i_{dr}^{'s} + \psi_{md}^{s}$ Implying that,

$$i_{dr}^{'s} = \frac{\psi_{dr}^{'s} - \psi_{md}^{s}}{x_{lr}^{'}} \quad \textbf{(11)}$$

Where,

$$\frac{1}{x_M} = \frac{1}{x_m} + \frac{1}{x_{ls}} + \frac{1}{x_{lr}^{'}} \quad \textbf{(12)}$$

and

$$\psi_{mq}^{s} = x_M \left(\frac{\psi_{qs}^{s}}{x_{ls}} + \frac{\psi_{qr}^{'s}}{x_{lr}^{'}} \right) \quad \textbf{(13)}$$

$$\psi_{md}^{s} = x_M \left(\frac{\psi_{ds}^{s}}{x_{ls}} + \frac{\psi_{dr}^{'s}}{x_{lr}^{'}} \right) \quad \textbf{(14)}$$

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

$$J \frac{d\omega_r}{dt} = T_{em} + T_{mech} - T_{damp} \quad \textbf{(15)}$$

Where ω_b =base speed,
ω_r =rotor speed,
r_s =stator resistance,
x_{ls} =stator reactance,
$r_r^{'}$ =rotor referred resistance,
$x_{lr}^{'}$ =rotor referred reactance,
x_m =magnetizing reactance,
x_M =machine equivalent star reactance,
T_{em} =electromechanical torque,
T_{mech} =externally applied mechanical load torque,
T_{damp} =damping torque,
J =combined moment of inertia,
v_{qs}^{s} =q-axis stator voltage,
v_{ds}^{s} =d-axis stator voltage,
$v_{dr}^{'s}$ =d-axis referred rotor voltage,
$v_{qr}^{'s}$ =q-axis referred rotor voltage,
v_{0s} =zero sequence stator voltage,
v_{0r} =zero sequence rotor voltage,
i_{qs}^{s} =q-axis stator current,
i_{ds}^{s} =d-axis stator current,
i_{0s} =zero sequence stator current,
$i_{qr}^{'s}$ =q-axis referred rotor current,
$i_{dr}^{'s}$ =d-axis referred rotor current,
i_{0r} =zero sequence rotor current,

ψ_{qs}^{s} =q-axis stator flux linkage per second, ψ_{ds}^{s} =d-axis stator flux linkage per second, $\psi_{qr}^{'s}$ =q-axis referred rotor flux linkage per second, $\psi_{dr}^{'s}$ =d-axis referred rotor flux linkage per second, ψ_{md}^{s} =d-axis magnetizing flux linkage per second, and ψ_{mq}^{s} =q-axis magnetizing flux linkage per second.

SIMULINK® IMPLEMENTATION OF THE ASYNCHRONOUS MACHINE MODEL

The derived equations represented above are modeled using the subsystem approach in SIMULINK®. SIMULINK® is a tool box extension of the MATLAB® program. It is a graphical mouse-driven program for simulating dynamic systems. It is a software package that enables the user to simulate linear as well as non-linear systems easily and efficiently. The Graphical User Interface (GUI) of SIMULINK® enables the building of models using clicks and drag mouse operations.

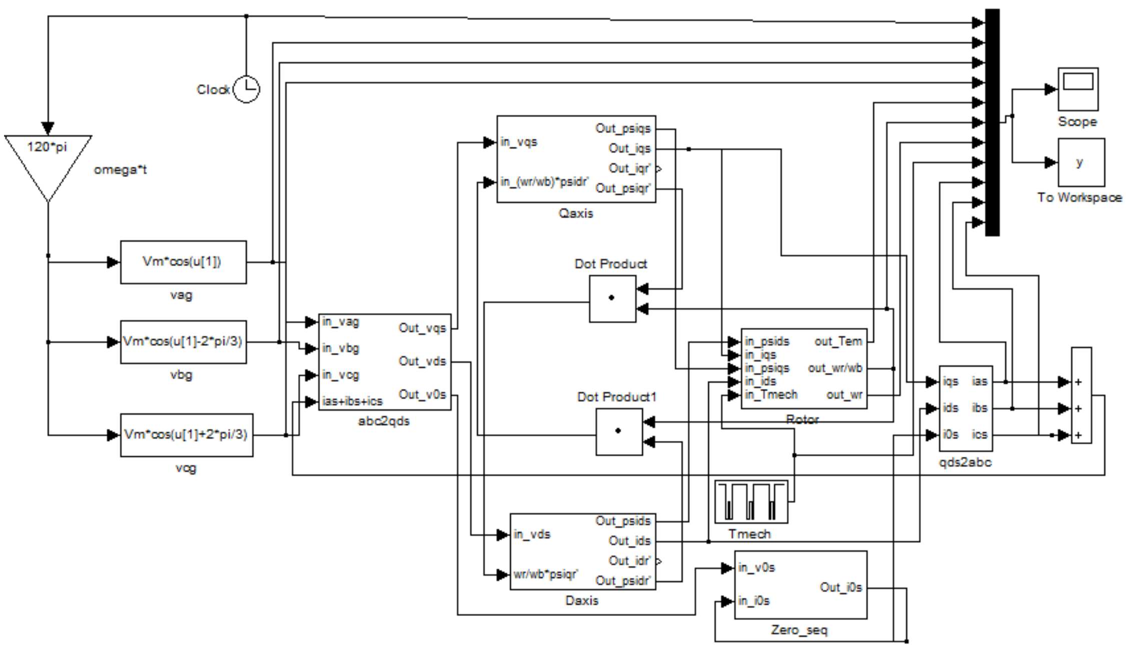
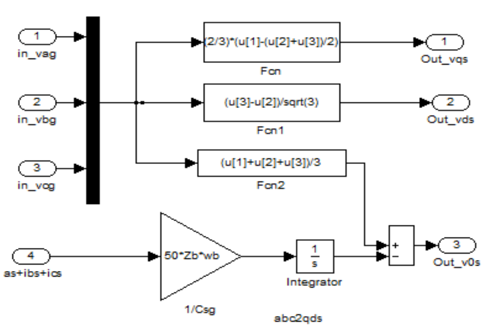
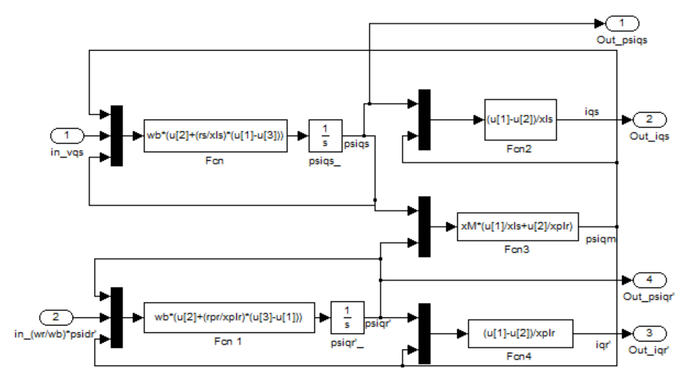


Figure 1: The Complete SIMULINK® Model of Three Phase Asynchronous Machine

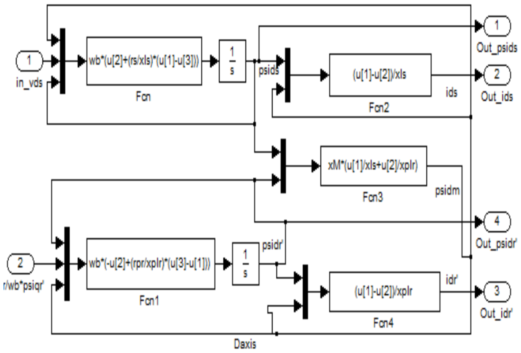
The sub-models of the various subsystems in the complete SIMULINK model are shown below (Figures 2 A-F).



(A)



(B)



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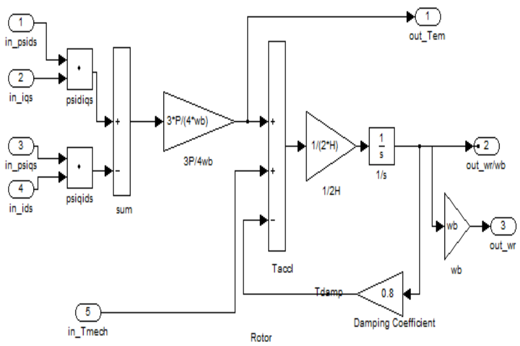

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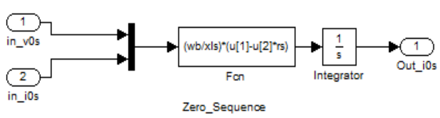
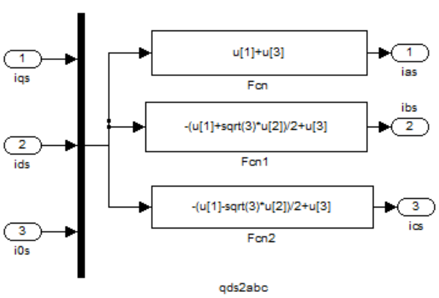


(E)



(F)

Figure 2 (A-F): Subsystems Models of the Complete SIMULINK® Model.

SAMPLE MACHINE DATA

Rated Phase Voltage	220V
Winding Connection	Star
Rated Frequency	60Hz
Number of Poles	4
Rated Speed	1800rpm
Stator Resistance	0.435Ω
Rotor Referred Resistance	0.816Ω
Stator Reactance	0.754Ω
Rotor Referred Reactance	0.754Ω
Magnetizing Reactance	26.13Ω
Moment of Inertia	0.089Kg.m^2
Power Rating	3-Hp

SIMULATION RESPONSE CURVES

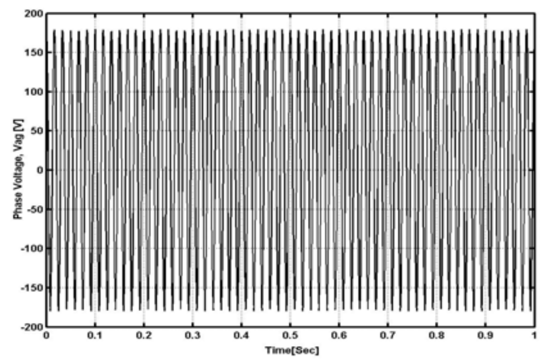


Figure 3: Phase Voltage V_{ag} against Time.

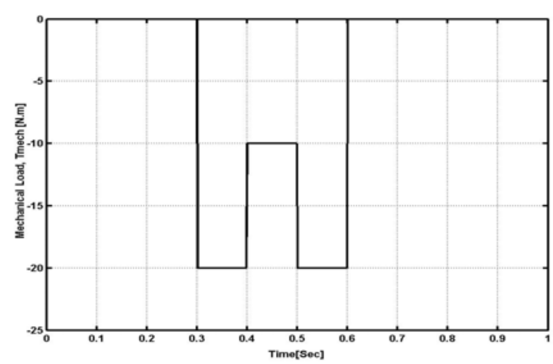


Figure 4: Externally Applied Mechanical Load Torque T_{mech} against Time.

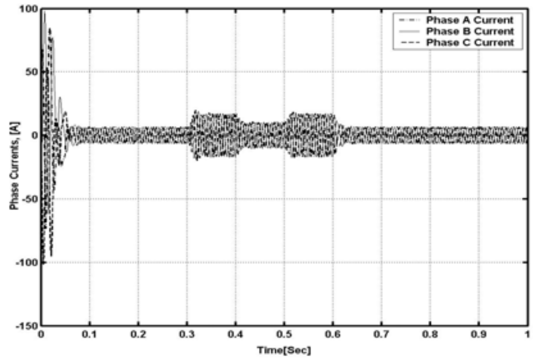


Figure 5: Phase Currents i_{as}, i_{bs}, and i_{cs} against Time.

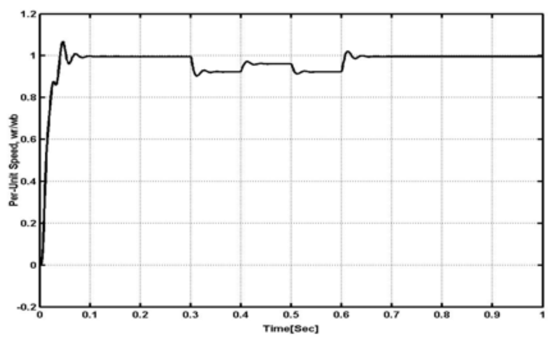


Figure 6: Per-Unit Speed ω_r / ω_b against Time.

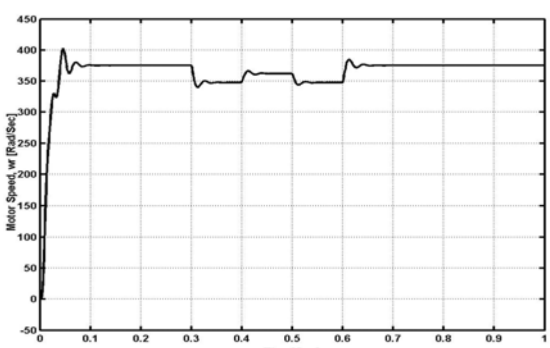


Figure 7: Motor Speed ω_r against Time.

OBSERVATIONS

At stall, the input impedance of the asynchronous motor is essentially the stator resistance and leakage reactance in series with the rotor resistance and leakage reactance.

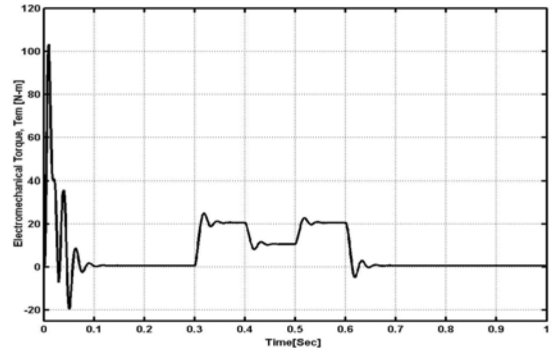


Figure 8: Electromechanical Torque T_{em} against Time

Consequently, with rated voltage applied, the starting current is large, in some cases in the order of 10 times the rated value. This is observed in Figure 5 and is a major limitation of the direct-on-line starting of the motor. It is, therefore, recommended that reduced voltage starting methods such as star/delta, auto transformer, and soft start methods be employed to reduce the excess starting current.

It is observed in Figure 7 that the rotor accelerates from stall with zero mechanical load torque and, since friction and windage losses are not taken into account, the machine accelerates to synchronous speed. The application of 20N-m mechanical load torque at 3 seconds, as illustrated in Figure 4, results in a sharp drop in the motor speed of Figure 7 and an increase in the electromechanical torque in sympathy with the applied mechanical loading from [20 10 20] N-m in the time sequence [0.3-0.4] Seconds, [0.4-0.5] Second, [0.5-0.6] Seconds respectively as shown in Figure 8. Figure 6 is the per-unit speed used to compare the actual motor speed and the rated speed. The applied mechanical loading shown in Figure 4 is in negative sense since the machine is operating as a motor.

CONCLUSION

Finally, this paper has demonstrated the elegance of SIMULINK® in the Dynamic Modeling and Simulation of a 3-hp Asynchronous Motor Driving a Mechanical Load**.** With the model developed, the user has access to all internal variables for getting an insight into the motor operation. The simulated motor is symmetrical and windage and friction losses are assumed negligible for ease of analysis. Further researches are recommended in the area of closed loop speed control for adjustable voltage and speed drives.

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SUGGESTED CITATION

Ogbuka, C.U. 2009. "Dynamic Modeling and Simulation of a 3-HP Asynchronous Motor Driving a Mechanical Load". *Pacific Journal of Science and Technology*. 10(2): 77-82.

Pacific Journal of Science and Technology