Simulation of Six Phase Split Winding Induction Machine Using the Matlab/Simulink Environment

Ogunjuyigbe A.S.O, Nnachi A.F, Jimoh A.A ***member IEEE*** **and Nicolae D.V** ***member IEEE***
Electrical Engineering Department, Tshwane University of Technology
P.O.Box X680, Pretoria 0001. South Africa
aogunjuyigbe@yahoo.com , nnachi_francis@yahoo.com

Abstract: *Six-phase induction machine presents several benefits over their conventional three-phase counterpart. This paper thus presents the model and described in detail the simulation of a Six-phase split winding induction machine in a Matlab/Simulink environment. The Simulink model is built in such a flexible manner such that various variables of the machine can be accessed easily for further purposes such as control. Finally, simulation results showing free acceleration as well as dynamic response of the machine were presented for both direct ac supply and the PWM inverter voltage source.*

Keywords: Six phase Induction machine, Matlab/Simulink, Split winding, PWM inverter.

1. Introduction

Electrical machine exists for the bulk of its time in the steady state, thus it has often been simulated in circuit simulators using the steady state model; however, it is during the brief period of transient, non-stationary behaviour that most of the stresses occur which limits the life of the machine.

Simulink is known to have the advantages of being capable of complex dynamic system simulations, graphical environment with visual real time programming and broad selection of tool boxes. The simulation environment of Simulink has a high flexibility and expandability which allows the possibility of development of a set of functions for a detailed analysis of the electrical drive. Its graphical interface allows selection of functional blocks, their placement on a worksheet, selection of their functional parameters interactively, and description of signal flow by connecting their data lines using a mouse device. System blocks are constructed from lower level blocks grouped into a single maskable block. It also provides an open system environment which provides access to algorithm and source codes.

Simulink has been used to model and simulate induction machine, but most often on three phase induction machine models [1-4]. Mostly, these models do not present the internal details and some commonly use the S-function programming knowledge. In addition, the complete model of three phase induction machine exists within the simulink power system blockset. This also makes use of the S-function which is not easy to work with as the rest of the simulink blocks.

Likewise, it is interesting that six phase induction machine has continued to gain research interest for ac drive application, because of the benefits it offers compared to its conventional three –phase counterparts [5, 6].

This paper uses Matlab/Simulink environment to simulate the dynamic behaviour of a six phase dual stator (split) winding Induction motor that is fed by two arrangements of voltage sources, firstly with the utility supply and secondly using a PWM voltage source inverter. A similar machine was discussed in [6, 7, 8], however they used an entirely different simulation environment, and did not express in detail the steps in the development of the simulation model as presented in this work.

2. Electrical Model

The non-linear differential equations that describe the dynamic behavior of an induction machine with multi-phase and arbitrary displacement between them is presented in [5] where the six phase induction machine was used as an example, and the equivalent circuit has been presented. Also, the dqo model for a six phase machine was developed in [6, 7].

The equations that describes the behavior of the six-phase induction machine when expressed in the arbitrary reference frame are listed in equations (1) through (13)

$$V_{q1} = r_1 I_{q1} + p\lambda_{q1} + \omega_k \lambda_{d1} \tag{1}$$

$$V_{d1} = r_1 I_{d1} + p\lambda_{d1} - \omega_k \lambda_{q1} \tag{2}$$

$$V_{01} = r_1 I_{01} + p\lambda_{01} \tag{3}$$

$$V_{qr} = r_r^{'} I_{qr}^{'} + p\lambda_{qr}^{'} - (\omega_k - \omega_r)\lambda_{dr}^{'} \tag{4}$$

$$V_{dr} = r_r^{'} I_{dr}^{'} + p\lambda_{dr}^{'} - (\omega_k - \omega_r)\lambda_{qr}^{'} \tag{5}$$

$$V_{0r} = r_r^{'} I_{0r} + p\lambda_{0r}^{'} \tag{6}$$

$$V_{q2} = r_2 I_{q2} + p\lambda_{q2} + \omega\lambda_{d2} \tag{7}$$

$$V_{d2} = r_2 I_{d2} + p\lambda_{d2} - \omega\lambda_{q2} \tag{8}$$

$$V_{02} = r_2 I_{02} + p\lambda_{02} \tag{9}$$

where ω_k is the speed of the reference frame, ω_r is the rotor speed. Also, the expressions for stator and rotor flux linkages are:

$$\lambda_{q1} = (L_{l1} - L_{lm}^{'})I_{q1} + L_{lm}^{'}(I_{q1} + I_{q2}) + L_m(I_{q1} + I_{q2} + I_{qr}^{'}) \tag{10}$$

$$\lambda_{d1} = (L_{l1} - L_{lm}^{'})I_{d1} + L_{lm}^{'}(I_{d1} + I_{d2}) + L_m(I_{d1} + I_{d2} + I_{dr}^{'}) \tag{11}$$

$$\lambda_{01} = L_{l1} I_{01} + L_{lm}^{'}(I_{01} + I_{02}) \tag{12}$$

$$\lambda_{q2} = (L_{l2} - L_{lm}^{'})I_{q2} + L_{lm}^{'}(I_{q1} + I_{q2}) + L_m(I_{q1} + I_{q2} + I_{qr}^{'}) \tag{13}$$

$$\lambda_{d2} = (L_{l2} - L_{lm}^{'})I_{d2} + L_{lm}^{'}(I_{d1} + I_{d2}) + L_m(I_{d1} + I_{d2} + I_{dr}^{'}) \tag{14}$$

$$\lambda_{02} = L_{l2} I_{02} + L_{lm}^{'}(I_{01} + I_{02}) \qquad (15$$

$$\lambda_{qr} = L_{lr}^{'} I_{qr} + L_m(I_{q1} + I_{q2} + I_{qr}^{'}) \tag{16}$$

$$\lambda_{dr} = L_{lr}^{'} I_{dr} + L_m(I_{d1} + I_{d2} + I_{dr}^{'}) \tag{17}$$

$$\lambda_{or} = L_{lr}^{'} I_{0r} \tag{18}$$

The electromagnetic torque equation is written in terms of λ_{md} and λ_{mq} as:

$$T_e = \tfrac{3}{2}\tfrac{P}{2}\left[\lambda_{md}(I_{q1} + I_{q2}) - \lambda_{mq}(I_{d1} + I_{d2})\right] \tag{19}$$

Similarly, the mechanical model of this machine comprises of the equation of the motor and the driven load, and this is usually represented as:

$$J\,\tfrac{2}{P}\frac{d\omega_r}{dt} = T_{em} - T_L \tag{20}$$

where J is the inertia and T_L is the load torque.

3. Preparing the Equations for Simulation

These equations that describe the electrical and mechanical behaviour of the machines contain mixed variables (flux linkages and current). Either of these two quantities could be eliminated from the differential equation by algebraic manipulations of equations (1)-(18). In this paper, the flux linkage is resolved as the state variables and currents as dependent variables. Thus, the currents when solved in terms of flux linkages are obtained as:

$$I_{d1} = \tfrac{1}{L_A}\left[(L_{l2} + L_{lm})\lambda_{d1} - L_{l2}\lambda_{md} - L_{lm}\lambda_{d2} - L_{ldq}(\lambda_{q2} - \lambda_{q12})\right] \tag{21}$$

$$I_{q1} = \tfrac{1}{L_A}\left[(L_{l2} + L_{lm})\lambda_{q1} - L_{l2}\lambda_{mq} - L_{lm}\lambda_{q2} + L_{ldq}(\lambda_{d2} - \lambda_{d12})\right] \tag{22}$$

$$I_{d2} = \tfrac{1}{L_A}\left[(L_{l1} + L_{lm})\lambda_{d2} - L_{l1}\lambda_{md} - L_{lm}\lambda_{d1} + L_{ldq}(\lambda_{q1} - \lambda_{mq})\right] \tag{23}$$

$$I_{q2} = \tfrac{1}{L_A}\left[(L_{l1} + L_{lm})\lambda_{q2} - L_{l1}\lambda_{mq} - L_{lm}\lambda_{q1} - L_{ldq}(\lambda_{d1} - \lambda_{md})\right] \tag{24}$$

$$I_{qr}^{'} = \frac{\lambda_{qr} - \lambda_{mq}}{L_{lr}^{'}} \tag{25}$$

$$I_{dr}^{'} = \frac{\lambda_{dr} - \lambda_{md}}{L_{lr}^{'}} \tag{26}$$

$$\lambda_{md} = L_D\left[\lambda_{d1}L_{l2} + \lambda_{d2}L_{l1} - L_{ldq}(\lambda_{q2} - \lambda_{q1})\right] \tag{27}$$

$$\lambda_{mq} = L_Q\left[\lambda_{q1}L_{l2} + \lambda_{q2}L_{l1} + L_{ldq}(\lambda_{d2} - \lambda_{d1})\right] \tag{28}$$

where

$$L_D = \left[\frac{L_A}{L_m} + (L_{l1} + L_{l2})\right]^{-1} \tag{29}$$

$$L_A = L_{l1}L_{l2} + L_{lm}(L_{l1} + L_{l2}) \tag{30}$$

$$L_Q = \left[\frac{L_A}{L_m} + (L_{l1} + L_{l2})\right]^{-1} \tag{31}$$

Substituting equations (21)-(28) into (1) – (8) and solving the equation in the rotor reference frame, (that is ω_k becomes ω_r) the integral form of the machine voltage and torque equations with flux linkage as state variables is given as:

$$\lambda_{d1} = \int\left[V_{d1} + \omega_r\lambda_{q1} - \tfrac{R_1}{L_A}\left\{(L_{l2} + L_{lm})\lambda_{d1} - L_{l2}\lambda_{md} - L_{lm}\lambda_{d2} - L_{ldq}(\lambda_{q2} - \lambda_{mq})\right\}\right] \tag{32}$$

$$\lambda_{q1} = \int\left[V_{q1} - \omega_r\lambda_{d1} - \tfrac{R_1}{L_A}\left\{(L_{l2} + L_{lm})\lambda_{q1} - L_{l2}\lambda_{mq} - L_{lm}\lambda_{q2} - L_{ldq}(\lambda_{d2} - \lambda_{md})\right\}\right] \tag{33}$$

$$\lambda_{d2} = \int\left[V_{d2} + \omega_r\lambda_{q2} - \tfrac{R_2}{L_A}\left\{(L_{l1} + L_{lm})\lambda_{d2} - L_{l1}\lambda_{md} - L_{lm}\lambda_{d1} + L_{ldq}(\lambda_{q1} - \lambda_{mq})\right\}\right] \tag{34}$$

$$\lambda_{q2} = \int\left[V_{q2} - \omega_r\lambda_{d2} - \tfrac{R_{12}}{L_A}\left\{(L_{l1} + L_{lm})\lambda_{q2} - L_{l1}\lambda_{mq} - L_{lm}\lambda_{q1} - L_{ldq}(\lambda_{d1} - \lambda_{md})\right\}\right] \tag{35}$$

$$\lambda_{dr} = \int\tfrac{r_r^{'}}{L_{lr}^{'}}(\lambda_{dr} - \lambda_{md}) \tag{36}$$

$$\lambda_{qr}^{'} = \int\tfrac{r_r^{'}}{L_{lr}^{'}}(\lambda_{qr} - \lambda_{mq}) \tag{37}$$

$$\omega_r = \tfrac{P}{2J}\int\left[T_{em} - T_L\right]dt \tag{38}$$

$$\theta_r = \int\omega_r dt \tag{39}$$

Thus equations (19), (21)-(39) essentially will be used to simulate the six phase (dual) split winding induction machine. These equations are arranged in integral form rather than in the differential form

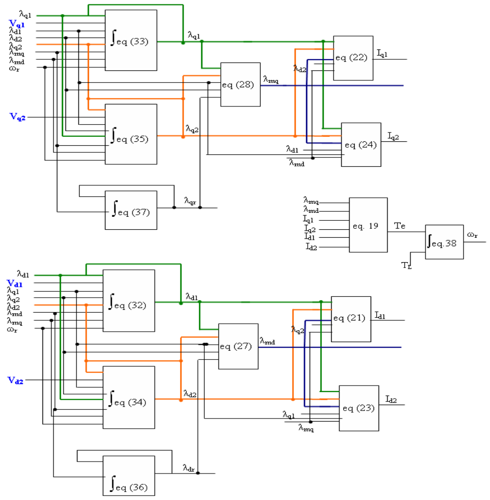


Fig. 1: Flow diagram of the electrical part for the simulation of the six-phase machine

so as to avoid having spikes as a result of differentiation of signals with ripples

4. Implementation in Simulink

In order to implement this in simulink, the equations are arranged into four major blocks as listed below:

- Inputs (three-phase voltages and load torques)
- Outputs (three phase currents , electrical torque and other component as may desired for identification)
- Electrical part of the machine
- Mechanical part of the machine

Similarly, to maintain a proper flow of variables and for convenience of simulation, the equations have been separated into the q-axis and the d-axis blocks as indicated in figure1.

With the flow of signal shown in Fig.1 the external inputs V_{d1}, V_{d2}, V_{q1}, V_{q2} will be obtained from the transformation of the three phase variables to the two phase rotating reference frame. Thus, the simulation block that implements the transformation of the 'abc' phase variables to the 'dq' rotating reference frame and vice versa is here firstly discussed.

4.1 Inverter modelling equation

The converter output line-to-ground voltages are related to the switching states and the dc link voltage by the equation [9, 10, 11]:

$$\begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} = \left(\frac{V_{dc}}{n-1} \right) \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix} \qquad (40)$$

Where V_{ag}, V_{bg}, V_{cg} are the phase nodes a, b, c to the negative rail of the dc bus, V_{dc} is the dc bus voltage, n is the number of levels (and in this case equals 3) and S_a, S_b, S_c are the switching states.
The switching states is however determined by Pulse width Modulator, hence depicts the inverter output.

The line-to-neutral voltages are determined directly from the line-to-ground voltages using the equation

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} \qquad (41)$$

4.2 Transformation Block

The three phase voltages variables in 'abc' obtained from either the power utility or the PWM inverter source is converted to the rotating reference frame using:

$$\begin{bmatrix} V_{qs}^s \\ V_{ds}^s \\ V_o^s \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (42)$$

$$V_{qs} = V_{qs}^s \cos\theta_r - V_{ds}^s \sin\theta_r \qquad (43)$$

$$V_{ds} = V_{qs}^s \sin\theta_r - V_{ds}^s \cos\theta_r \qquad (44)$$

These sets of equations are implemented in the simulink environment by the use of basic simulink function blocks as shown in Fig. 2

The entire block in figure 2 is easily cast into a single subsystem block identified as abc_dq in figure 7.

In a similar way, the inverse transformation of the dq component can be done to obtain the phase variables (e.g current) using the following equations.

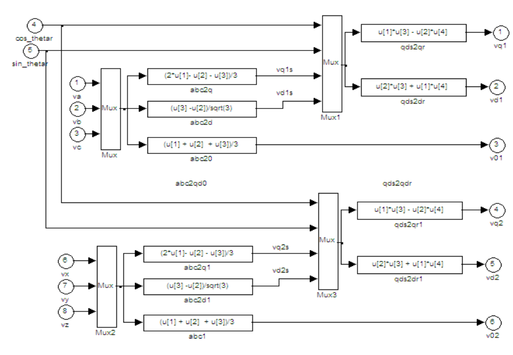


Fig. 2: abc to dq transformation block

$$I_{qs}^{s} = I_{qs}\cos\theta_r + I_{ds}\sin\theta_r \tag{45}$$

$$I_{ds}^{s} = -I_{qs}\sin\theta_r + I_{ds}\cos\theta_r \tag{46}$$

and

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{qs} \\ I_{ds} \end{bmatrix} \tag{47}$$

This is likewise created in the simulink environment by using the *function, signal routing, multiplexer* blocks all listed under the simulink commonly used blocks. Equations 44, 45, 46 are then arranged in simulink worksheet as in Fig.3.
Figure 3 is also made a single block subsystem dq_abc, and it is basically used to extract phase quantities from the dq components.

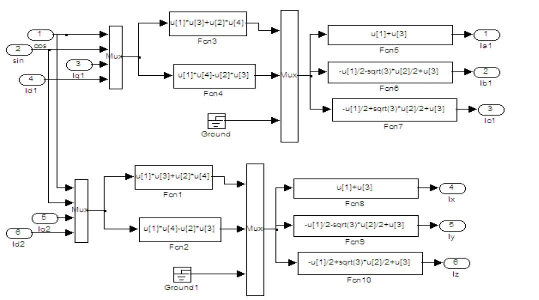


Fig. 3: dq to abc transformation block

4.3. dq model of the six phase Induction Machine

This model is developed by following the signal flow diagram of Fig. 1. This has been grouped into the d and q subsystems. Each block within the d and the q subsystem are simply taken and built one after the other using the *function blocks, Mux, and the integral blocks.* As an example, the blocks that implement the q-subsystem of the six phase induction machine is as shown in figure 4.

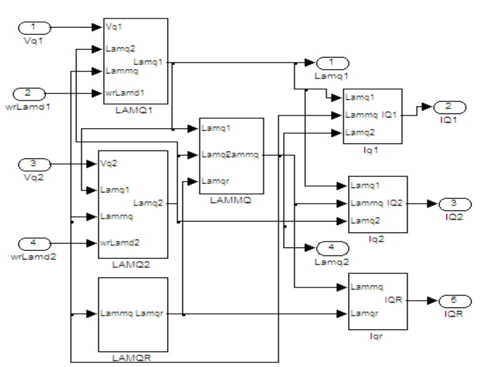


Fig. 4: Q-axis subsystem

It is clearly seen from figure 4 that most of the blocks are presented as a subsystems, each of which is used to solve the equation as labelled in figure 1. As an example, the subsystem LAMQ1 in figure 4 is used to solve equation (33) and its internal details is presented in figure 5.
Similarly, the internal detail of the subsystem that solves equations (19) and (38), that is, the mechanical part of the machine is shown in fig. 6

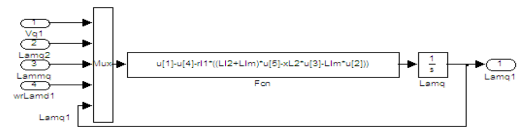


Fig. 5: Internal detail of subsystem LAMQ1

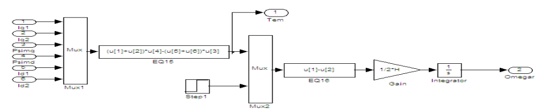


Fig. 6 Internal detail of the subsystem that implement the mechanical part of the machine

Furthermore, the PWM three level inverter voltage sources is achieved using the simulink model block of figure 7.
This format of implementation is carried out for each block that forms a subsystem as indicated in figure 1. When all these subsystems are built, they are combined together to form the complete simulation model for the six phase split winding induction machine shown in figure 8.

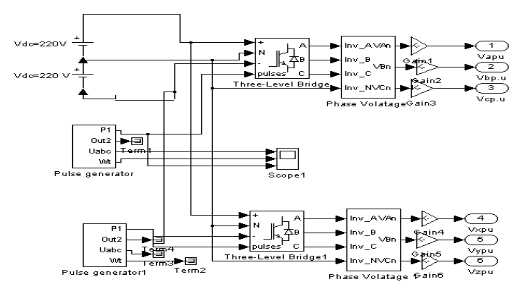


Fig. 7: PWM inverter voltage source

4.4 Data Input to the model References

Following a successful preparation of the simulink model, necessary machine data obtained from experimental data has to be allocated to every element already used in the model. This is achieved by the listing of these data in a Matlab M-file that is configured as an input into the simulink model. This M-file forms the initialisation characteristics in the workspace from which the simulink models will extract all its necessary information for the effective simulation of the model.

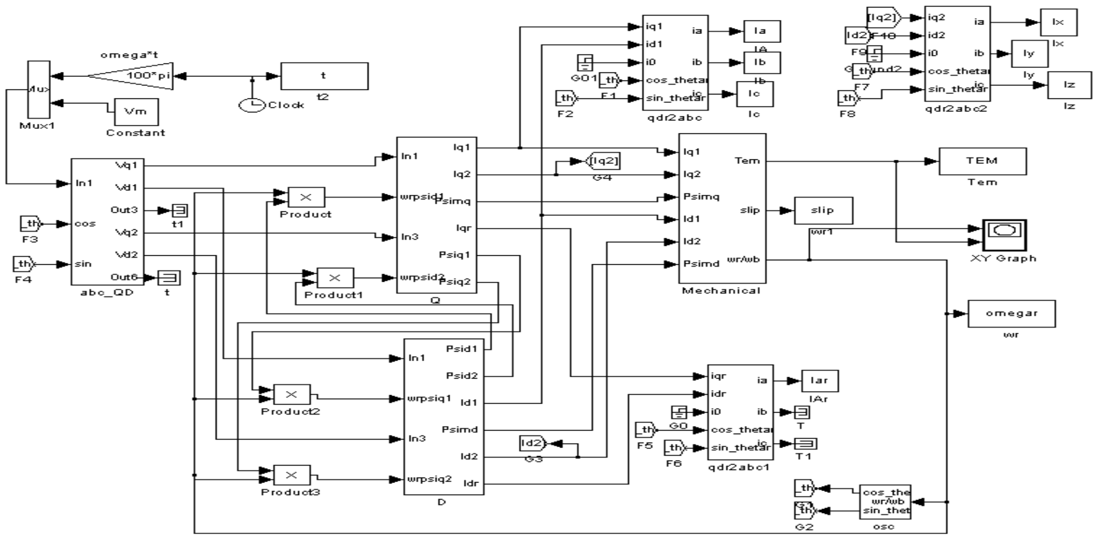
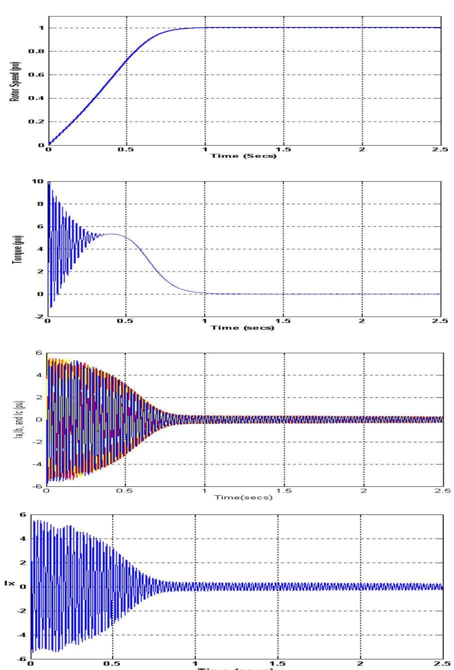


Fig. 8: Complete Simulink model for six phase induction Machine

5.0 Simulation Results

The six–phase machine discussed in this paper was simulated with two different sources, first with a direct ac start up and secondly as an inverter fed machine. The free acceleration characteristics are as displayed respectively in figures 8 and 9. The figures include the rotor speed, torque and the three phase currents of the machine as well as the inverter source voltage. It is observed that the machine comes to steady state in about 0.6secs.

The dynamic behaviour of the machine was likewise examined with the application of a step load torque of 1.0 p.u at a time of 2 seconds. The dynamic response of the machine is clearly displayed in figure 10(a-d). This is displayed only for the PWM inverter voltage source. The steady state characteristics of this machine can easily be extracted from these characteristics. In addition, the model simulated in this paper can also be arranged for different control arrangement as may be desired



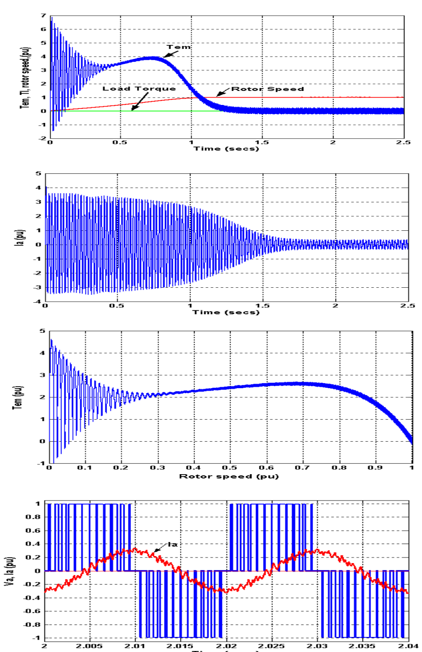
(a)

(b)

(c)

(d)

Fig. 8: Free acceleration characteristics of six phase induction machine using direct ac source



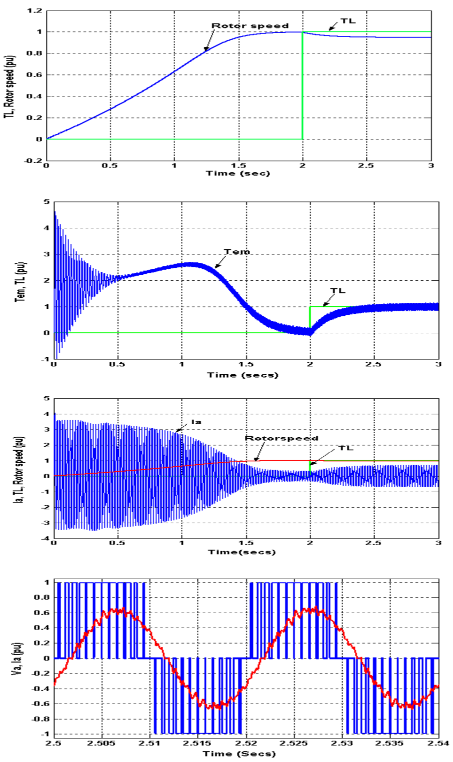
(a)

(b)

(c)

(d)

Fig. 9: Free acceleration characteristics of six phase induction machine with PWM three inverter source.



(a) (b) (c) (d)

Fig. 10: Dynamic response with the application of TL=1.0 p.u at time 2secs.(a) Rotor speed, Load Torque, (b) Electromagnetic Torque, Load torque, (c) winding current, rotor speed (d) Inverter source voltage, winding current

5. Conclusions

This paper demonstrates the stepwise development of Matlab/Simulink model to simulate the starting and dynamic behaviours of six-phase split winding induction machines. The free acceleration characteristics as well as the dynamic response to load variation were tested on the simulation and the results were likewise displayed. The steady state voltages and current were extracted and displayed. The poor factor of this machine under no load condition is easily observed from Fig.10 (d). The simulink implementation in this work provides access to various internal variables so as to be able get an insight into the machine operation. The performance of the machine was simulated with both direct ac and a three level inverter voltage source inputs.

6 References

[1]. Le-Huy, H, "Modelling and Simulation of electrical drives using Matlab/Simulink Power System Blockset," *The 27th Annual Conf. of the IEEE Industrial Electronics Society (IECON'01),* Denver/Colorado, pp. 1603-1611.

[2]. Ozpinechi, B, Tolbert, L.M, "Simulink implementation of induction machine model-A modular approach" *IEEE Electrical machines and drives conf. IEMDC'03,* Capos, Vol. 2, pp. 728-734, 2003.

[3]. Okoro, O.I, "Matlab simulation of induction machine with saturable leakage and magnetising inductances" *The pacific journal of Science and Technology*, Vol. 5, No. 1, pp. 5-14, 2003.

[4]. Ong, C.M, *Dynamic Simulation of Electric machinery using Matlab/Simulink*, Prentice-Hall PTR, New Jersey, 1998.

[5]. Nelson, R.H, Krause, P.C , "Induction Machine Analysis for Arbitrary Displacements Between multiple winding sets," *Proc. IEEE Trans. on PAS-93,* pp. 841-848, 1974.

[6]. Lipo, T.A, "A dq model of a six-phase induction machine," *Int. conf. of Electrical Machines, ICEM, Athenes, pp 860-867, 1980.*

[7]. Singh, G.K, Pant, V, Singh, Y.P "Voltage source inverter driven multi-phase induction machine' *Computers and Electrical Engineering* 29, pp. 813-834. 2003.

[8]. A.R Munoz, T.A Lipo, "Dual stator winding induction machine drive," IEEE Trans. Ind. Appl. 36 (5), pp.1369–1379, 2000.

[9]. Smith, J.R, *Response analysis of A.C Electrical machines – Computer models and Simulation*. John Wiley and sons, New-York, 1990.

[10]. Novotny, D.W and Lipo, T.A, *Vector control and Dynamics of Electric Drives,* Oxford University Press, New York, 2000.

[11]. Corzine, K.A, "Operation and design of Multi-Level Inverters". *University of Missouri Rolla.* Keith@corzine.net , pp. 1-79, 2000.