Transient Analysis and Modelling of Sixphase Asynchronous Machine

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Abstract: Multiphase Induction machine offers numerous advantages compared to the conventional three phase induction machine. Among the different types, the six-phase induction machine is most common, due to the flexibility in converting a three phase to six phase. By splitting the phase belt of a three phase induction machine, a six-phase induction machine is realized. The areas of application of multiphase (>3) machines are enormous, mostly where reliability is paramount. This paper presents the analysis, modeling and simulation of a 5Hp, 50HZ, 4 pole, 24 slots asymmetrical six-phase induction machine for submarine application. With the help of MATLAB software, the models developed are simulated and results in the form of computer traces of the dynamic performance of the machine at start-up are presented and discussed. This investigation shows that the replacement of three phase with a six phase machine is both technically and economically advantageous.

Keywords: Modeling, Six-Phase, Submarines, Computer Simulation, MATLAB, Transients Studies

1. Introduction

Three phase induction machines are asynchronous speed machines. They are operated as motors and generators, comparatively less expensive to equivalent synchronous or dc machines. It is considered as the workhorse of the industry. Induction machines has almost replaced the DC machine in the industry due to the simplicity of design, ruggedness, low-cost, low maintenance cost and direct connection to AC power source compared to the DC motors[1, 2, 3]. In fact 85% of the total power consumption in the industrial sector is from induction motors. Due to the above, new strategies, new methods of analysis and design are being sought that will improve the performance of this machines and increase efficiency. Investigation has shown that multiphase machines are possible and advantageous [4]. Among the groups of multiphase machines, the six-phase has received more attention due the simplicity in converting a three phase machine to six-phase machine [5]. This is achieved by splitting the phase belt of three phase machine, that is, two sets of three phase stator winding of the original three phase, with set I spanning 30^0 electrical from set II, having a common magnetic structure[6-7].

The use of a common magnetic structure shared by two sets of stator winding dated since 1930 [4, 8], where in an attempts to increase the power capability of a large synchronous generator, the stator winding has to be doubled. From that time, research activities of the dual stator induction machine (DSIM) increased. These type of machines are normally constructed by "splitting" the stator winding into two identical windings [9-12]. Phase orders of multiples of 3, i.e. 6,9, etc, are very possible. Presently, there is evidence of current research on higher phase AC machines of phase order 5, 6, 9 even 15 [13-15]. Multiphase induction machine finds its applicability in the area of high degree of reliability demand as in more electric aircrafts, electric ship propulsion, electric vehicles, (EH) and hybrid electric vehicles (HEV).

Particularly for ship propulsion, there is an ongoing research in the application of six phase induction motor by this author, where a six phase motor is to replace two three phase motors.

Analysis of multiphase induction machine is carried out in [16, 17]. Lipo in [8] presented a six-phase induction machine model in d-q transformation, the analysis here uses a split-phase configuration where the 60^0 phase belt was split into two portions each spanning 30^0. The simulated results for

three phase and six-phase were compared. B. Kundrotas et al [12] modelled a six phase induction motor in the dynamic mode. In [18], a six-phase induction motor was used to reduce the noise level in an electric traction system. Improved reliability is guaranteed in submarine with the application of two sets of star connected stator winding spatially shifted by 30^0 electrical with isolated neutral point as reported in [19]. A transition design based on the Markov chain was used to analyse the availability index of multiphase induction machine, [20, 21]. The submarine is rapidly emerging in the last couple of years as the main potential application area for multi-phase motor drives. The idea of multiphase suggests a replacement of two electric machines with a single machine of DSIM. A lot of research is ongoing in multiphase induction machines. The concept of multiphase is still in the infant stage, though much research is ongoing. It is the aim of this paper to investigate the transient performance of a six-phase split wound induction machine for submarines.

2. Modelling of Six-Phase Induction Machine

Multiphase electric machine (MPEM) which is more advantageous and has improved performance compared to the three phase counterpart come as both synchronous and asynchronous machines. Figure 1, shows the V_{abcxyz} voltages of a six-phase induction machine with their phase displacement. In order to model the six-phase induction machine, the dq transformation is applied, and the rotor reference frame is adopted [16].
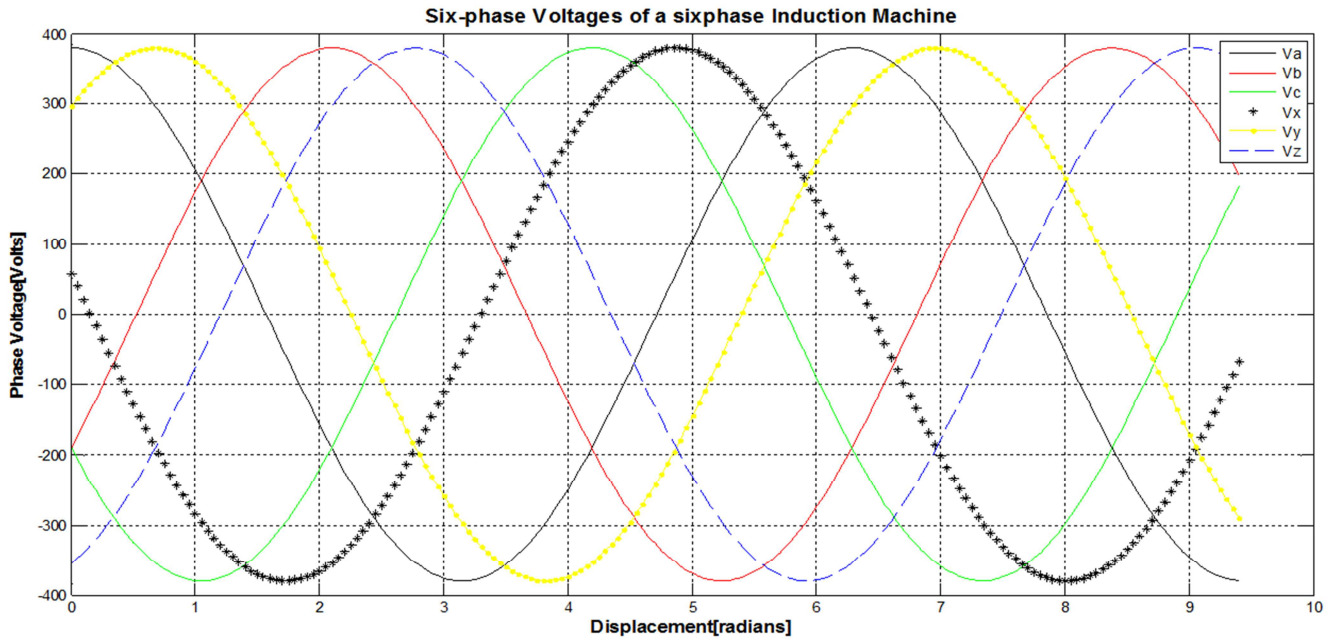

Fig. 1. *Six-phase source voltages of six-phase induction machine.*

2.1. Electrical Model

The voltage equation of a split phase induction machine is written as, where $\alpha=30^0$ elect

$$V_{as}=Vcos\omega_e t \tag{1}$$

$$V_{bs}=Vcos(\omega_e t-2\pi/3) \tag{2}$$

$$V_{cs}=Vcos(\omega_e t+2\pi/3) \tag{3}$$

$$V_{xs}=Vcos(\omega_e t-\alpha) \tag{4}$$

$$V_{ys}=Vcos(\omega_e t-2\pi/3-\alpha) \tag{5}$$

$$V_{zs}=Vcos(\omega_e t+2\pi/3-\alpha) \tag{6}$$

Using the appropriate transformation, the phase voltage of set I, abc, is transformed to its equivalent d-q axis as below;

$$V_{qs}=2/3(V_{as}-V_{bs}/2-V_{cs}/2) \tag{7}$$

$$V_{ds}=2/3(\sqrt{3}/2[-V_{bs}-V_{cs}]) \tag{8}$$

For a balance system, since

$$V_{as}=-V_{bs}-V_{cs} \tag{9}$$

Then equation (7) becomes

$$V_{qs}=V_{as}=Vcos\omega_e t \tag{10}$$

Simplifying equation (8)

$$V_{ds}=1/\sqrt{3}(V_{cs}-V_{bs}) \tag{11}$$

$$V_{ds}=1/\sqrt{3}(Vcos(\omega_e t+2\pi/3)-Vcos(\omega_e t-2\pi/3)) \tag{12}$$

Applying Euler's identity to equation (9), the result becomes

$$V_{ds}=-Vsin\,\omega_e t \tag{13}$$

The same analysis is carried out on the second set II. The dq voltage equations of a six-phase induction machine are readily written as in [24]:

$$V_{q1}= r_1 i_{q1}+ \omega_k\lambda_{d1}+p\lambda_{q1} \tag{14}$$

$$V_{d1}= r_1 i_{d1}- \omega_k\lambda_{q1}+p\lambda_{d1} \tag{15}$$

$$V_{q2}= r_2 i_{q2}+ \omega_k\lambda_{d2}+p\lambda_{q2} \tag{16}$$

$$V_{d2}= r_2 i_{d2}- \omega_k\lambda_{q2}+p\lambda_{d2} \tag{17}$$

$$V_{qr}=0= r_r i_{qr}+ (\omega_k-\omega_r)\lambda_{dr}+p\lambda_{qr} \tag{18}$$

$$V_{dr}=0= r_r i_{dr}- (\omega_k-\omega_r)\lambda_{qr}+p\lambda_{dr} \tag{19}$$

The flux linkage equations are given below

$$\lambda_{q1}=L_{l1}i_{q1}+L_{lm}(i_{q1}+i_{q2})+L_{dq}i_{d2}+L_{mq}(i_{q1}+i_{q2}+i_{qr}) \tag{20}$$

$$\lambda_{d1}=L_{l1}i_{d1}+L_{lm}(i_{d1}+i_{d2})+L_{dq}i_{q2}+L_{md}(i_{d1}+i_{d2}+i_{dr}) \tag{21}$$

$$\lambda_{q2}=L_{l2}i_{q2}+L_{lm}(i_{q1}+i_{q2})+L_{dq}i_{d1}+L_{mq}(i_{q1}+i_{d2}+i_{qr}) \tag{22}$$

$$\lambda_{d2}=L_{l2}i_{d2}+L_{lm}(i_{d1}+i_{d2})+L_{dq}i_{q1}+L_{md}(i_{d1}+i_{d2}+i_{dr}) \tag{23}$$

$$\lambda_{qr}=L_{lr}i_{qr}+L_{mq}(i_{q1}+i_{q2}+i_{qr}) \tag{24}$$

$$\lambda_{dr}=L_{lr}i_{dr}+L_{md}(i_{d1}+i_{d2}+i_{dr}) \tag{25}$$

Equations 14-25, suggested the equivalent circuit of Fig. 2
Let

$$Ldq = 0 \tag{26}$$

$$L_m=L_{mq}=L_{md} \tag{27}$$

$$L_1=L_{l1}+L_{lm}+L_m \tag{28}$$

$$L_2 = L_{l2}+L_{lm}+L_m \tag{29}$$

$$L_3 = L_{lm}+L_m \tag{30}$$

$$L_r = L_{lr}+L_m \tag{31}$$

Using state variable method, equation (32) is put in state variable form [17];

$$\begin{bmatrix}V_{q1}\\V_{d1}\\V_{q2}\\V_{d2}\\V_{qr}\\V_{dr}\end{bmatrix}=\begin{bmatrix}r_1 & \omega_kL_1 & 0 & \omega_kL_2 & 0 & \omega_kL_m\\-\omega_kL_1 & r_1 & -\omega_kL_2 & -0_2 & -w_kL_m & 0\\0 & \omega_kL_3 & r_2 & \omega_kL_2 & 0 & \omega_kL_m\\-\omega_kL_3 & 0 & -\omega_kL_2 & r_2 & -\omega_kL_m & 0\\0 & \alpha L_m & 0 & \alpha L_m & r_r & \alpha L_r\\-\alpha L_m & 0 & -\alpha L_m & 0 & -\alpha L_r & r_r\end{bmatrix}\begin{bmatrix}i_{q1}\\i_{d1}\\i_{q2}\\i_{d2}\\i_{qr}\\i_{dr}\end{bmatrix}+\begin{bmatrix}Pi_{q1}\\Pi_{d1}\\Pi_{q2}\\Pi_{d2}\\Pi_{qr}\\Pi_{dr}\end{bmatrix}$$

$$\begin{bmatrix}L_1 & 0 & L_2 & 0 & L_m & 0\\0 & L_1 & 0 & L_2 & 0 & L_m\\L_3 & 0 & L_2 & 0 & L_m & 0\\0 & L_3 & 0 & L_2 & 0 & L_m\\L_m & 0 & L_m & 0 & L_r & 0\\0 & L_m & 0 & L_m & 0 & L_r\end{bmatrix}\begin{bmatrix}Pi_{q1}\\Pi_{d1}\\Pi_{q2}\\Pi_{d2}\\Pi_{qr}\\Pi_{dr}\end{bmatrix} \tag{32}$$

$$idot = [L][V] - [L]^{-1} [G] [1] \tag{33}$$

where,

$$[V] = \begin{bmatrix}V_{q1} & V_{d1} & V_{q2} & V_{d2} & V_{qr} & V_{dr}\end{bmatrix} \tag{34}$$

$$[I] = \begin{bmatrix}i_{q1} & i_{d1} & i_{q2} & i_{d2} & i_{qr} & i_{dr}\end{bmatrix} \tag{35}$$

$$[G]=\begin{bmatrix}r_1 & \omega_kL_1 & 0 & \omega_kL_2 & 0 & \omega_kL_m\\-\omega_kL_1 & r_1 & \omega_kL_2 & 0 & -\omega_kL_m & 0\\0 & \omega_kL_3 & r_2 & \omega_kL_2 & 0 & \omega_kL_m\\-\omega_kL_3 & 0 & -\omega_kL_2 & r_2 & -\omega_kL_m & 0\\0 & \alpha L_m & 0 & \alpha L_m & r_r & \alpha L_m\\\alpha L_m & 0 & -\alpha L_m & 0 & -\alpha L_m & r_r\end{bmatrix} \tag{36}$$
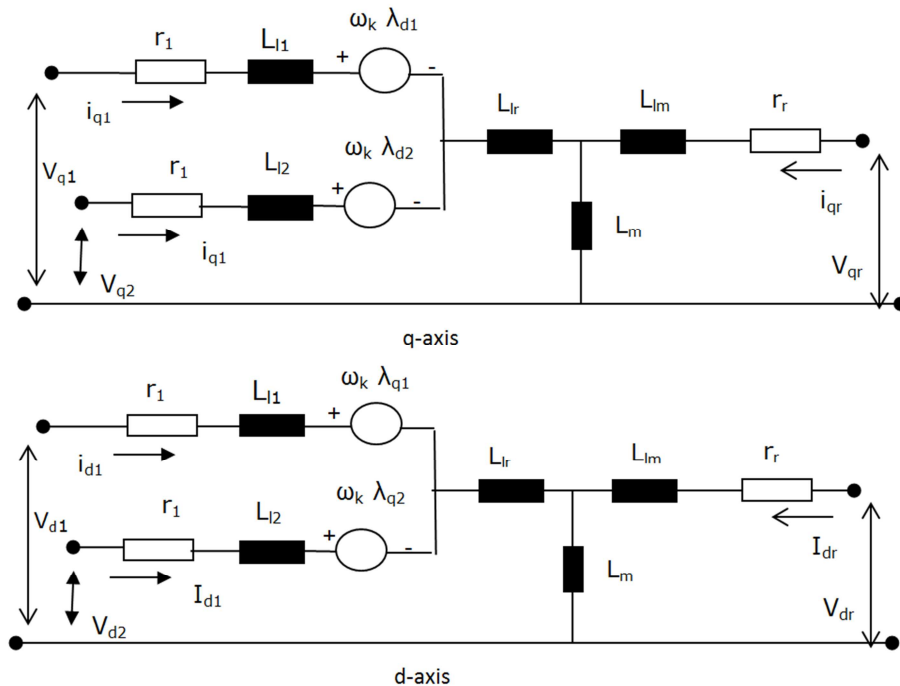

Fig. 2. DQ equivalent circuit of a six-phase Induction Machine.

Where

$$\alpha = \omega_r - \omega_k \qquad (37)$$

$$[L] = \begin{bmatrix} L_1 & 0 & L_2 & 0 & L_m & 0 \\ 0 & L_1 & 0 & L_2 & 0 & L_m \\ L_3 & 0 & L_2 & 0 & L_m & 0 \\ 0 & L_3 & 0 & L_2 & 0 & L_m \\ L_m & 0 & L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_m & 0 & L_r \end{bmatrix} \qquad (38)$$
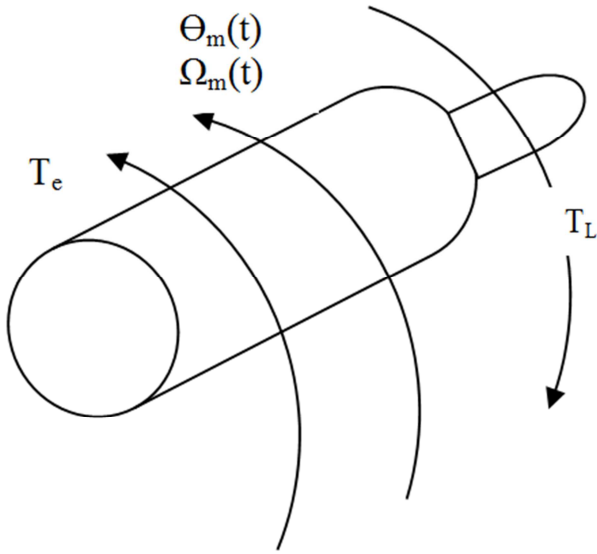
2.2. Mechanical Model

Fig. 3. *Induction Motor Mechanical Model.*

The mechanical model of the six-phase induction machine is the equation of motion of the machine and driven load as in fig. 3, the figure suggest equation (39),

$$J_m p^2 \theta_m = T_e - F\omega_r - T_L \qquad (39)$$

The mechanical data of the experimental machine indicates that the combined rotor and load viscous friction 'F' is appropriately zero, so that, equation (38) becomes.

$$J_m p^2 \theta_m = T_e - T_L \qquad (40)$$

Breaking equation (40) into two first-order differential equation gives

$$J_m p(\omega_m) = (T_e - T_L) \qquad (41)$$

Because

$$p\theta_m = \omega_m \qquad (42)$$

We know that

$$\omega_r = \omega_m p \qquad (43)$$

And

$$\theta_r = \theta_m p \qquad (44)$$

Where $P = \dfrac{d}{dt}$, and ω_m, θ_m, θ_r, ω_r, J_m and T_L represent angular velocity of the rotor, rotor angular position, electrical rotor angular position, electrical angular velocity, combined rotor and load inertia coefficient, and applied load torque respectively. Matlab m-files are developed to simulate the transient performance of a six-phase, 4 pole, 50Hz squirrel cage induction machine.

3. Experiment

In order to get data for simulation, a 5.5 Hp 3Ø, 24 slot, 4 pole induction motor was reconfigured into a split phase (6-phase) motor with two set of 3-phase displaced 30^0 elect from each other. The new motor maintains all specifications of the old, except that, the motor is now a split winding motor (6-phase). The construction motor tested on No-load and On-load. Retardation test was also carried out. The experimental results and the computed results is shown in table 1.
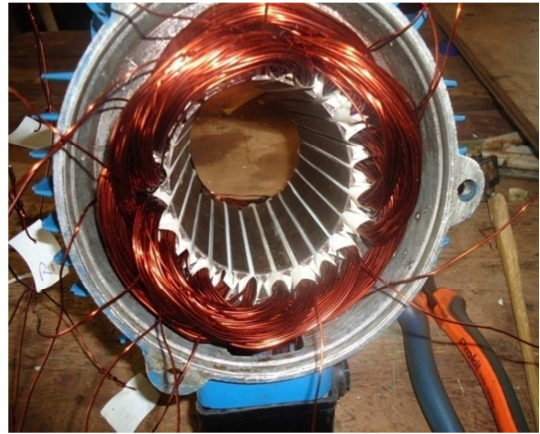

Fig. 4. *Stator winding of the sample motor.*

Table 1. *Simulation Parameters.*

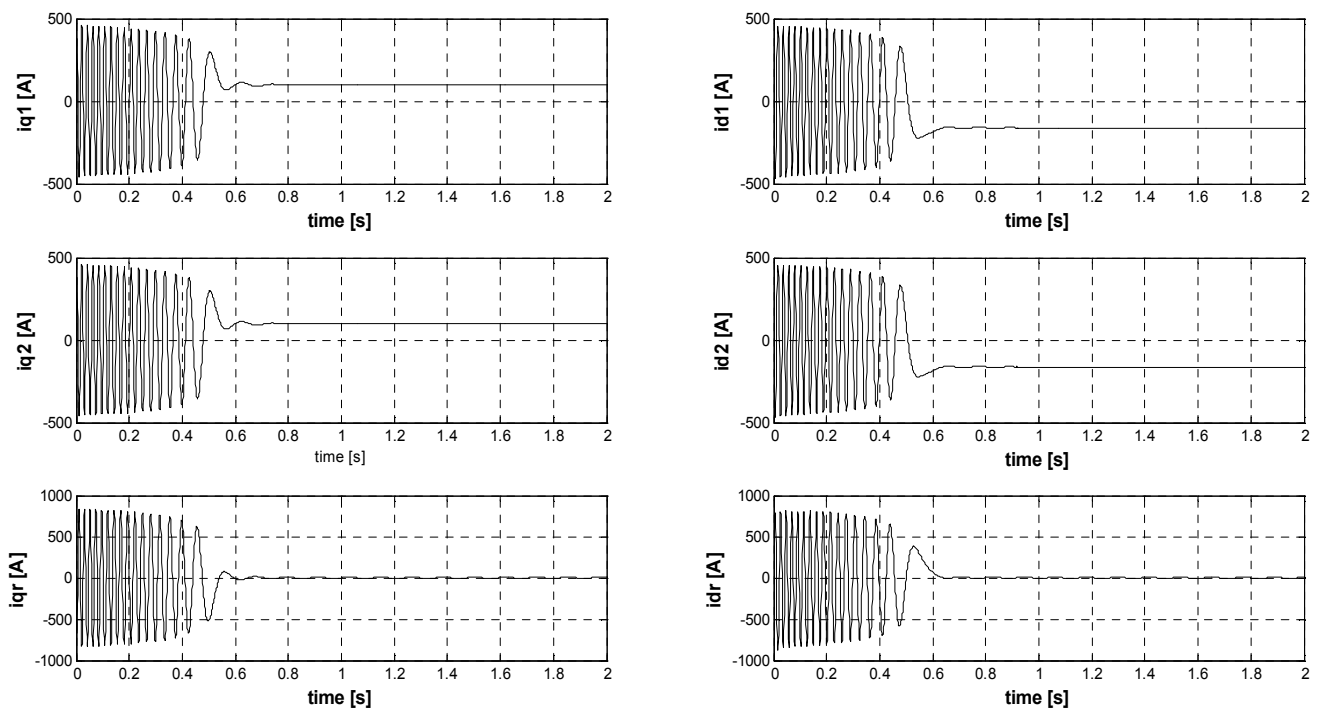| Parameter	Value
Power Rating	5HP
Phase Number	6
No of Poles	4
Efficiency	85%
Power Factor	0.8 lag
Mechanical Speed	1400rev/min
Frequency (f)	50Hz
Stator Resistance (R_s)	0.28Ω
Rotor Resistance (R_r)	2.14 Ω
Stator winding reactance (X_s)	1.24989 Ω
Rotor winding reactance (X_r)	1.24989 Ω
Magnetizing reactance (X_m)	35.718 Ω
Rotor inertia(J_m)	0.25Kgm^2
Load inertia (T_L)	0.52Kgm^2

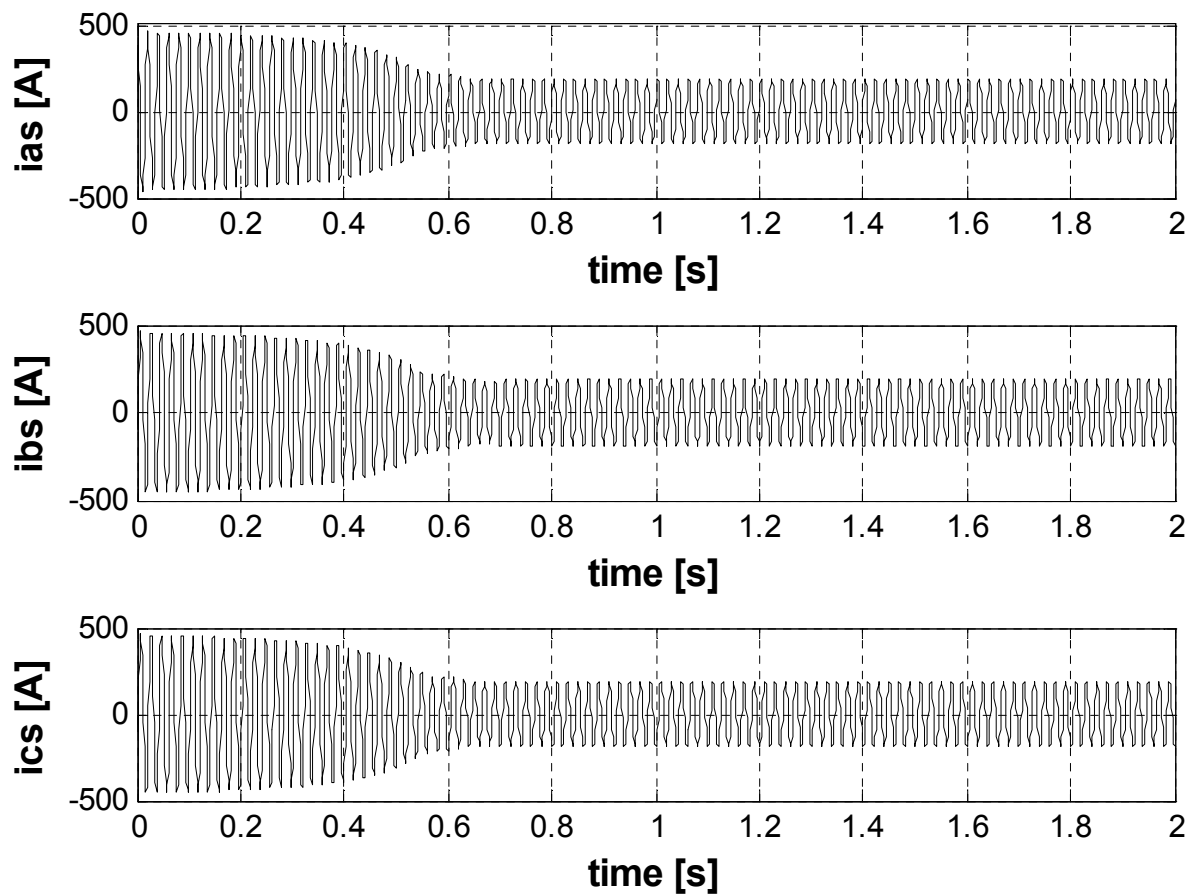**Fig. 5.** *A graph of dq currents against time.*

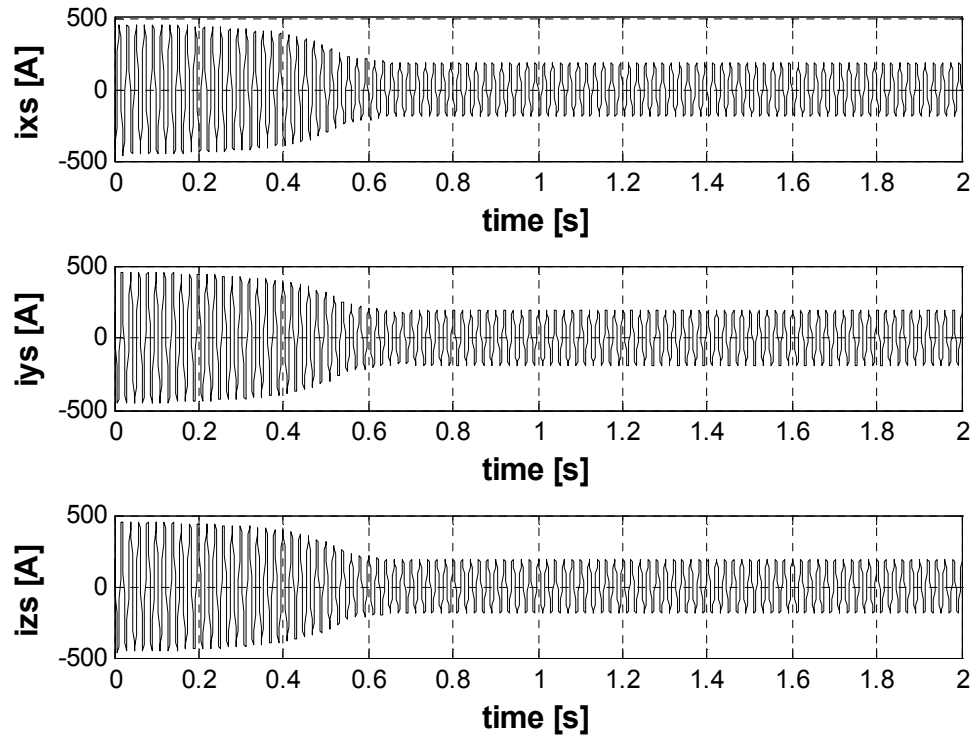**Fig. 6.** *A graph of xyz phase currents against time.*

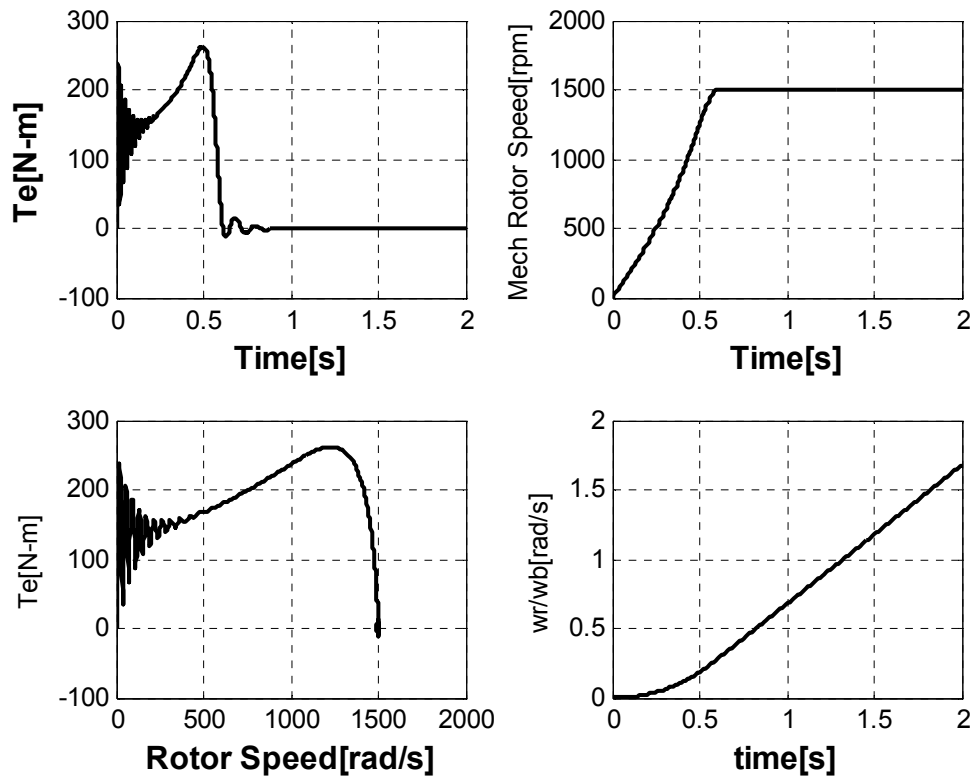*Fig. 7. A graph of xyz phase currents against time.*

Fig. 8. Mechanical Model plots.

4. Simulation Results

The simulation results in the form of computer traces are presented of the performance of a six-phase induction machine is presented in figs 5-8. The simulation for phase currents and qd currents, mechanical rotor speed and Electromagnetic Torque are simulated and presented using the data in table1.

5. Discusion of Results

Electromagnetic Torque in fig. 8, stabilizes at 0.7s. The mechanical rotor speed reaches synchronous speed at 0.6s, this agrees favorably with the theoretical concept. The phase currents also stabilize at 0.6s. Looking at the simulations, the redesigned motor can work as a three phase machine or/and as six phase. In submarines, the idea here is to use a six phase motor to replace two three phase motors, and money is saved redesigning the machine with higher reliability. The loss of a phase does not stop the motor from running. In submarines mostly Naval War ships, reliability is a criterion in designing a submarines.

6. Conclusion

The simulation result shows that, the split six phase is a dual stator induction machine with sets of three phase currents; I_{abc} and I_{xyz}. This is expected because DSIM is like paralleling two three phase induction motors. So, instead of using two three phase induction motors for propulsion (submarines), a single DSIM can replace the two and the cost is reduced and reliability increased which is the actual aim of this work.

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