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Multiphase Induction Motor Drive for Energy and Electrical Transportation Applications

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Abstract: Multiphase motors are induction motors in which stator has more than three phases. These motor drives (more than three phases) have attracted more attention in recent automation as they possess several advantages over conventional three-phase drives such as lower space-harmonic content, can operate even during phase open fault, higher torque density, and higher efficiency. For applications operating with electric cars, multiphase system could satisfy potential demand for electric drive systems of power, which are both robust and energy efficient. This paper presents dynamic modeling of five-phase induction motor drive, also simulation results of a five phase induction machine supplied from a five phase inverter.
Keywords: EV (Electric Vehicle), 5ϕ induction motor, mathematical modeling, Multiphase induction motor drive

I. INTRODUCTION

Multiphase AC machines generally have more than 3 phases. Generally five phase and six phase inductions motors are available for high power applications like ship propulsion, electric aircraft, and high power compressor system. Earlier multiphase machines were not be used widely at that time multiphase supply was not available easily [1-3]. Now a day's due to advancement in power semiconductor devices and use of digital controllers, multiphase machines are becoming popular and gaining more research interest [4-7]. Now days high power devices are used in Voltage Source Inverter (VSI). The output of the VSI is given to the Multiphase machine [8-9]. Fig.1 shows the diagram of the five phase induction motor drive system.

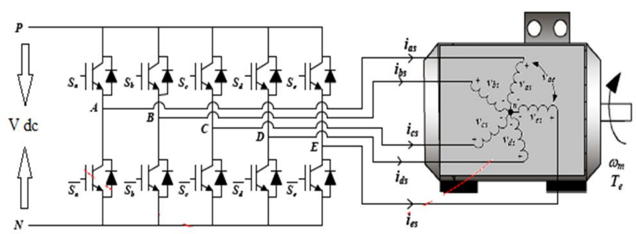


Fig. 1 Five phase induction motor drive

There are various advantages 5ϕ machine over three phase machine are explained in detail which includes higher efficiency compared to the three-phase counterpart, higher torque density, reducing the amplitude of torque pulsation and increased frequency of torque pulsation, greater fault tolerance, lower DC link current harmonics, less weight to volume ratio and better noise and vibration characteristics.

E.E. Ward etal [1], presented the first research publication on inverter fed 5ϕ phase induction motor recommended to increase the number of phases for reducing the torque ripple. In the following years the multiphase motor drives have attracted a limited attention. References [9-12] addresses types and advantages of multiphase machines for variable-speed applications, modeling of multiphase machines, control of variable-speed multiphase motor drives, PWM methods for multiphase VSI control, fault-tolerant operation, multiphase machines for electric power generation and other multiphase motor drive solutions. The early interest in multiphase machines was caused by the possibility of reducing the torque ripple in inverter fed drives, when compared to the three-phase case. Advantage of a multiphase motor drive over a three phase motor drive is an improved reliability due to fault tolerance features. Other advantages of multiphase machines over their three-phase counterparts include better fault tolerance, reduced torque pulsation; greater efficiency is elaborated in [5-8].

Multiphase machines are currently being used where both the machine and its control electronics are designed as a system, rather than as individual components. They have been found to be ideally suited, for example for the electric vehicles propulsion, where their fault tolerance, high efficiency, low acoustic noise and the ability to distribute the drive electronics are seen as particularly advantageous [7].

A considerable body of knowledge has been developed regarding the modeling of these machines [2], and their control techniques (based on field oriented [3-4], direct torque or predictive control or modulation strategies.

For Electrical vehicle's applications electrical machines requires, Higher Efficiency, lower mass, reliability, and wide range of speed controllability. The five phase induction motor has gained popularity because of these attributes. As we seen growth of the multiphase drive system, in wider application mange, the next ten years will see a substantial increase in the number of hybrid electrical vehicles, electric vehicles and other industrial applications using power electronics converters operating as a variable speed drive system[13]. This paper will discuss the use of electrical machines with higher phase orders the compared a performance of five phase drive system with three phase electric drive system are presented.

II. 5 Φ (PHASE) INDUCTION MOTOR DRIVE

The working of 5ϕ induction motor is similar to the 3ϕ induction motor which will work on Faradays law of electromagnetic induction. Only the difference is that they need a five-phase incoming ac voltage and the stator consist of five-phase winding. In a balanced five-phase induction motor, the five groups of stator winding are distributed with a spacing of 72°. This lower number of phase difference contributes to a higher power density of the machine.

When 5ϕ supply is given to the stator winding of 5ϕ induction machine the rotation magnetic field is produced which rotates at synchronous speed. This field links with the short circuited rotor (squirrel cage) which may cause an emf to get induced in the rotor conductors, due to electromagnetic induction. This emf will develop current in the short circuited rotor conductors which set up its own magnetic field. Due to interaction of these two magnetic fields, torque is developed.

III. 5Φ INVERTER

In VSI, for the output power same as that of 3ϕ inverter, if 5- phases are preferred, then the power gets distributed among 5-arms. Therefore the devices ratings can be reduced, since they have to handle less current. Hence the overall ratings of the switching devices can be reduced. For 5ϕ induction motor drive three switches from top and two switches from bottom turn ON at a time and vice versa. The two switches from same leg not turn ON at a time because it may cause short circuit. 5ϕ VSI is shown in Fig.2.

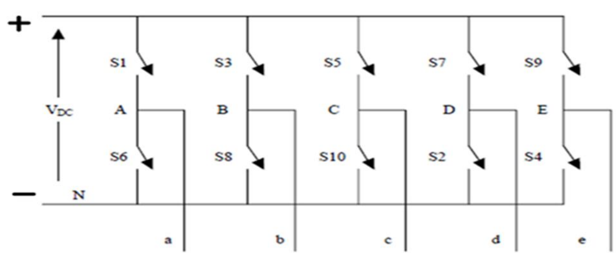


Fig.2 Five-phase voltage source inverter.

Table1. Switching sequence of five leg inverter

Mode	Switches ON
9	1,7,8,9,10
10	8,9,10,1,2,3
1	9,10,1,2,3,4
2	10,1,2,3,4,5
3	1,2,3,4,5,
4	2,3,4,5,1
5	3,4,5,6,7
6	4,5,6,7,8
7	5,6,7,8,9
8	6,7,8,9,10

At every 30^0, commutation of conducting switches takes place in sequence. Each switch will be conducting for $180^{0.}$ Two switches in the same leg should be complementary to each other to avoid shoot through fault. Therefore it is necessary to introduce delay between their conduction periods to avoid overlaps.

5^{th} order harmonics and harmonics which are multiples of 5 are absent in both the phase and line voltages and consequently absent from the current. The switching sequence is given in Table 1.

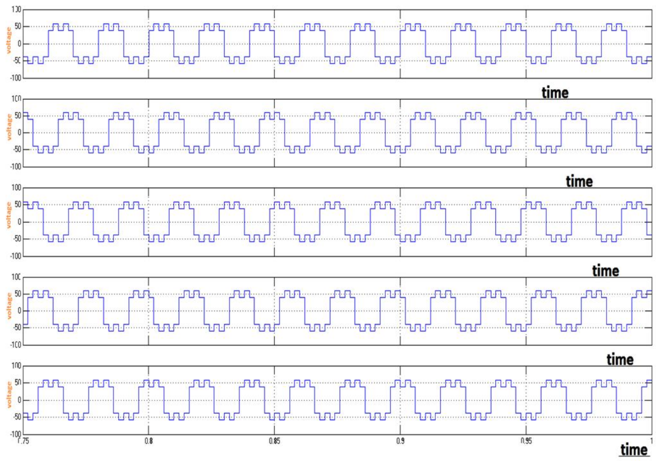


Fig.4 Output voltage of five-phase voltage source.

IV. DYNAMIC MODELING OF 5Φ INDUCTION MOTOR

A model of a five-phase induction motor is developed initially in phase variable form.

In order to simplify the model by removing the time variation of inductance terms, a transformation is applied and so-called d-q-x-y-o model of the machine is constructed. In deriving the five-phase induction machine model, it is assumed that the machine windings are sinusoidally distributed and the flux path is linear. Under these assumptions, the voltage equations for the stator phases in the natural coordinate of systems are.

To avoid this dynamic model of induction motor is developed where in 5-phase quantities are transformed to 2-phase dynamic quantities for control purpose.

Five phase stator voltages of an induction motor under balanced condition are as follows:

$$V_{as} = V_m \sin(2\pi f t) \quad (1)$$

$$V_{bs} = V_m \sin(2\pi f t - {}^{2\pi}/_{5}) \quad (2)$$

$$V_{cs} = V_m \sin(2\pi f t - {}^{4\pi}/_{5}) \quad (3)$$

$$V_{ds} = V_m \sin(2\pi f t + {}^{2\pi}/_{5}) \quad (4)$$

$$V_{es} = V_m \sin(2\pi f t + {}^{4\pi}/_{5}) \quad (5)$$

$$\underline{C} = \sqrt{\frac{2}{n}} \begin{matrix} \alpha \\ \beta \\ x_1 \\ y_1 \\ x_2 \\ y_2 \\ \dots \\ x_{(n-4)/2} \\ y_{(n-4)/2} \\ 0_+ \\ 0_- \end{matrix} \begin{bmatrix} 1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha & \dots & \cos 3\alpha & \cos 2\alpha & \cos\alpha \\ 0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha & \dots & -\sin 3\alpha & -\sin 2\alpha & -\sin\alpha \\ 1 & \cos 2\alpha & \cos 4\alpha & \cos 6\alpha & \dots & \cos 6\alpha & \cos 4\alpha & \cos 2\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha & \sin 6\alpha & \dots & -\sin 6\alpha & -\sin 4\alpha & -\sin 2\alpha \\ 1 & \cos 3\alpha & \cos 6\alpha & \cos 9\alpha & \dots & \cos 9\alpha & \cos 6\alpha & \cos 3\alpha \\ 0 & \sin 3\alpha & \sin 6\alpha & \sin 9\alpha & \dots & -\sin 9\alpha & -\sin 6\alpha & -\sin 3\alpha \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 1 & \cos\left(\frac{n-2}{2}\right)\alpha & \cos 2\left(\frac{n-2}{2}\right)\alpha & \cos 3\left(\frac{n-2}{2}\right)\alpha & \dots & \cos 3\left(\frac{n-2}{2}\right)\alpha & \cos 2\left(\frac{n-2}{2}\right)\alpha & \cos\left(\frac{n-2}{2}\right)\alpha \\ 0 & \sin\left(\frac{n-2}{2}\right)\alpha & \sin 2\left(\frac{n-2}{2}\right)\alpha & \sin 3\left(\frac{n-2}{2}\right)\alpha & \dots & -\sin 3\left(\frac{n-2}{2}\right)\alpha & -\sin 2\left(\frac{n-2}{2}\right)\alpha & -\sin\left(\frac{n-2}{2}\right)\alpha \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & \dots & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} & \dots & -1/\sqrt{2} & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix}$$

Clarke's decoupling transformation matrix for a symmetrical n-phase system

Standard Clarkes transformation matrix for N-Phase system [1].

The transformation matrix to transform 5ϕ stator variables for voltages ($V_{as}, V_{bs}, V_{cs}, V_{ds}, V_{es}$) is as into two-phase stationary reference frame *ds-qs* variables in given in equation (6) :

$$\begin{bmatrix} V_q \\ V_d \\ V_x \\ V_y \\ V_0 \end{bmatrix} = \begin{bmatrix} 1 & \cos\alpha & \cos2\alpha & \cos3\alpha & \cos4\alpha \\ 0 & -\sin\alpha & -\sin2\alpha & -\sin3\alpha & -\sin4\alpha \\ 1 & \cos3\alpha & \cos6\alpha & \cos9\alpha & \cos12\alpha \\ 0 & -\sin3\alpha & -\sin6\alpha & -\sin9\alpha & -\sin12\alpha \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} \quad (6)$$

Where $= \frac{2\pi}{5}$; V_{as}, V_{bs}, V_{cs}, V_{ds} and V_{es} are stator phase voltages. V_{ds} and V_{qs} presents direct and quadrature axis stator voltages respectively and V_{os}: zero sequence component.

Stator side voltage equations in *ds* and *qs* reference frame are given as follows:

$$V_{qs} = Rs i_{qs} + \frac{d}{dt}\Psi_{qs} \quad (7)$$

$$V_{ds} = Rs i_{ds} + \frac{d}{dt}\Psi_{ds} \quad (8)$$

$$V_{XS} = R_S\ i_{xs} + \frac{d}{dt}\Psi_{xs} \quad (9)$$

$$V_{yS} = R_S\ i_{ys} + \frac{d}{dt}\Psi_{ys} \quad (10)$$

$$V_{0S} = R_S\ i_{0s} + \frac{d}{dt}\Psi_{0s} \quad (11)$$

Rotor side voltage equations in *dr* and *qr* reference frame are given as:

$$V_{qr} = Rr i_{dr} + \frac{d}{dt}\Psi_{qr} - w_r \Psi_{dr} \quad (12)$$

$$V_{dr} = Rr i_{dr} + \frac{d}{dt}\Psi_{dr} + w_r \Psi_{qr} \quad (13)$$

$$V_{xr} = R_r\ i_{xr} + \frac{d}{dt}\Psi_{xr} \quad (14)$$

$$V_{yr} = R_r\ i_{yr} + \frac{d}{dt}\Psi_{yr} \quad (15)$$

$$V_{0r} = R_r\ i_{0r} + \frac{d}{dt}\Psi_{0r} \quad (16)$$

The difference between the 5ϕ machine model and 3ϕ phase machine model is the presence of V_x and V_y components. Rotor *x-y* components are in quadrature with *d-q* components. For a squirrel cage rotor x-*y* components are zero.

For a balanced (symmetrical) system, zero sequence components are not present. Therefore they are not considered for analysis.

From equations (7)-(8) and (12)-(13), flux linkages are found using equations (18)-(21),

$$\psi_{qs} = \int (V_{qs} - Rs \cdot i_{qs}) dt \quad (18)$$

$$\psi_{ds} = \int (V_{ds} - Rs \cdot i_{ds}) dt \quad (19)$$

$$\psi_{qr} = \int (V_{qr} - Rr \cdot i_{dr} + w_r \psi_{dr}) dt \quad (20)$$

$$\psi_{dr} = \int (V_{dr} - Rr \cdot i_{dr} - w_r \psi_{qr}) dt \quad (21)$$

Flux equations of stator side and rotor side of five phase induction motor are given by,

$$\psi_{ds} = (L_s . i_{ds} + L_m i_{dr}) \quad (22)$$

$$\psi_{qs} = (L_s . i_{qs} + L_m i_{qr}) \quad (23)$$

$$\psi_{dr} = (L_s . i_{dr} + L_m i_{ds}) \quad (24)$$

$$\psi_{qr} = (L_s . i_{qr} + L_m i_{qs}) \quad (25)$$

The currents of 5ϕ induction motor are given by:

$$i_{ds} = \left(\frac{L_r}{L_s L_r - L_m^2}\right) \times \psi_{ds} - \left(\frac{L_m}{L_s L_r - L_m^2}\right) \times \psi_{dr} \quad (26)$$

$$i_{qs} = \left(\frac{L_r}{L_s L_r - {L_m}^2}\right) \times \psi_{qs} - \left(\frac{L_m}{L_s L_r - {L_m}^2}\right) \times \psi_{qr} \qquad (27)$$

$$i_{dr} = \left(\frac{L_r}{L_s L_r - {L_m}^2}\right) \times \psi_{dr} - \left(\frac{L_m}{L_s L_r - {L_m}^2}\right) \times \psi_{dr} \qquad (28)$$

$$i_{qr} = \left(\frac{L_r}{L_s L_r - {L_m}^2}\right) \times \psi_{qs} - \left(\frac{L_m}{L_s L_r - {L_m}^2}\right) \times \psi_{qr} \qquad (29)$$

From the above equations the electromechanical torque is developed and rotor speed can be determined using the equations (30) & (40) respectively.

$$T_e = \frac{P}{2} \times \frac{5}{2} \times \left(\Psi_{ds}.i_{qs} - \Psi_{qs}.i_{ds}\right) \qquad (30)$$

$$\omega_r = \int \frac{Te - TL}{J} dt \qquad (31)$$

Where, P - is the number of poles
J - Moment of inertia;
TL - Load Torque;
Te- Electromechanical torque and
ω_r- Rotor Speed.

V. SIMULATION RESULTS

The simulation is done using Matlab /simulink. 5ϕ induction motor specifications are given in Table 2. The simulation circuit is shown in Fig.5. The inverter output voltage for an input 100 V DC supply for various conduction modes is given in Table 3. From Table 3, it is observed that in 180^0 conduction mode, the total harmonic distortion is less and output voltage is more compared to other modes of operation. Therefore 180^0 conduction mode is considered.

TABLE 2: MOTOR SPECIFICATIONS

Rated voltage (V)	300 (Phase)
Rated Power (Hp)	1
Frequency (Hz)	50
Poles	4
Rated Speed (rpm)	1440
Stator resistance (Rs)	10 Ω
Rotor resistance (Rr)	6.3 Ω
Stator inductance *(Ls)*	0.46 mH
Rotor inductance *(Lr)*	0.46 mH
Mutual inductance *(Lm)*	0.4 mH
Moment of Inertia *(J)*	0.00488 kg.m^2
Friction coefficient (B)	0.001 N.m.s

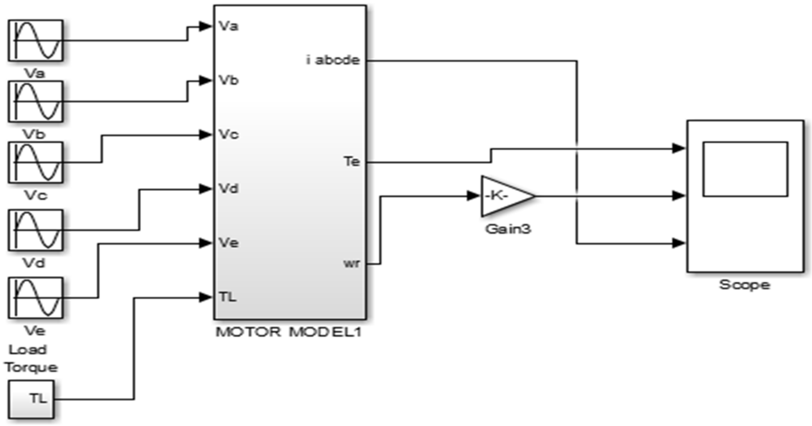
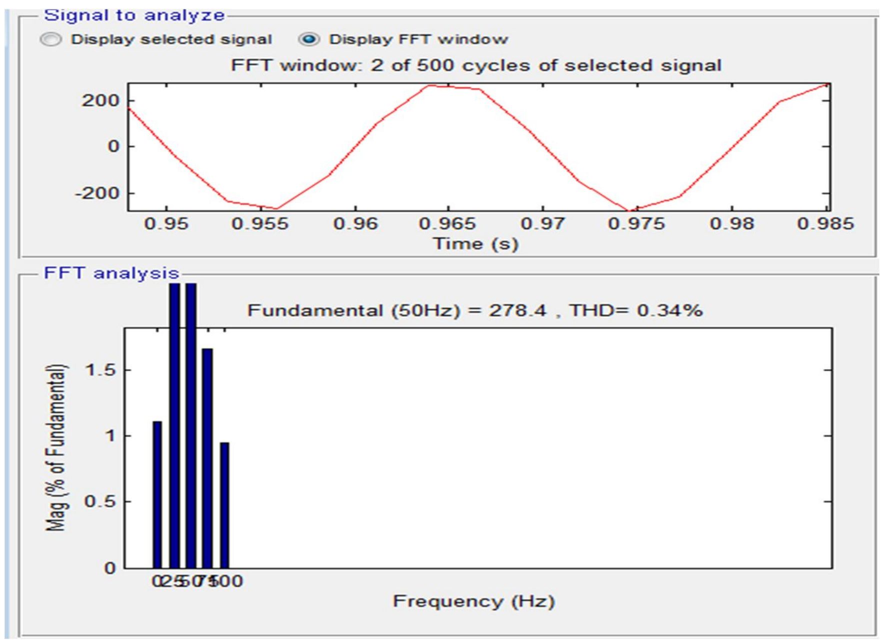


Fig.5**:** Simulation circuit with five phase source.



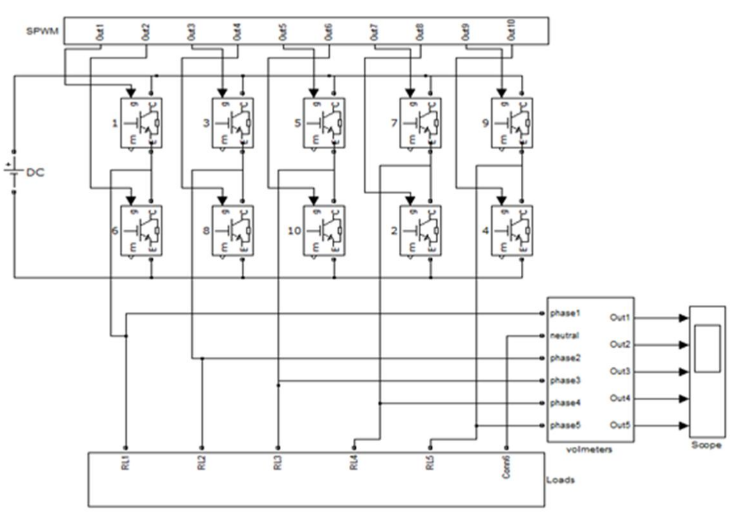
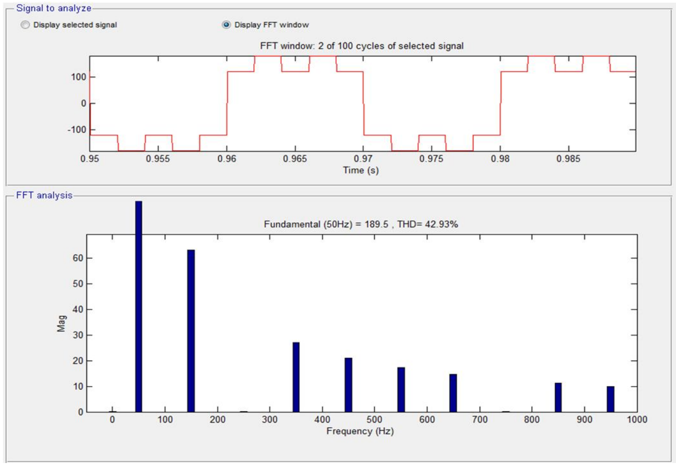


Fig.6**:** Simulation circuit.



5ϕ inverter output voltages are shown in Fig.7.

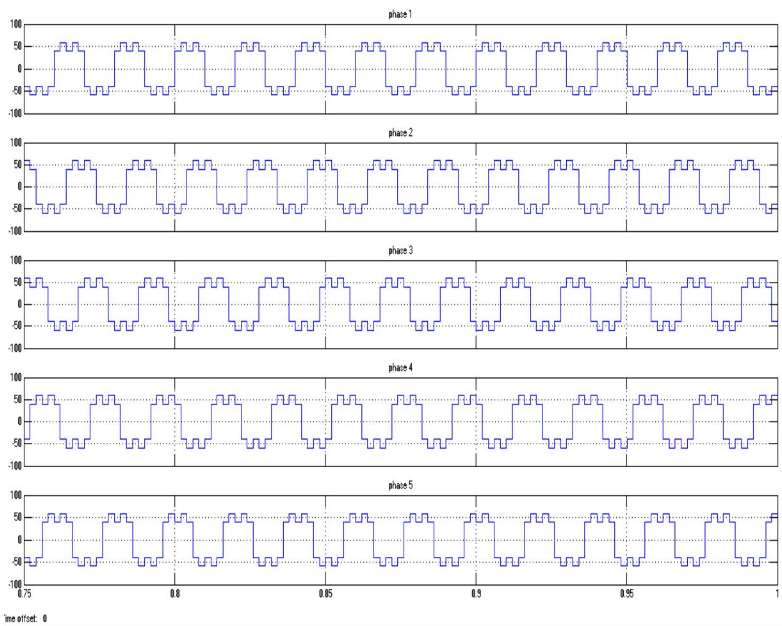


Fig. 7: Inverter Output voltages (Phase)

The 5 phase inverter output voltages are transformed to *dq* axis voltages using equation (6), and *dq* axes voltages are shown in Fig.8. Direct and quadrature axes currents are shown in Fig.9

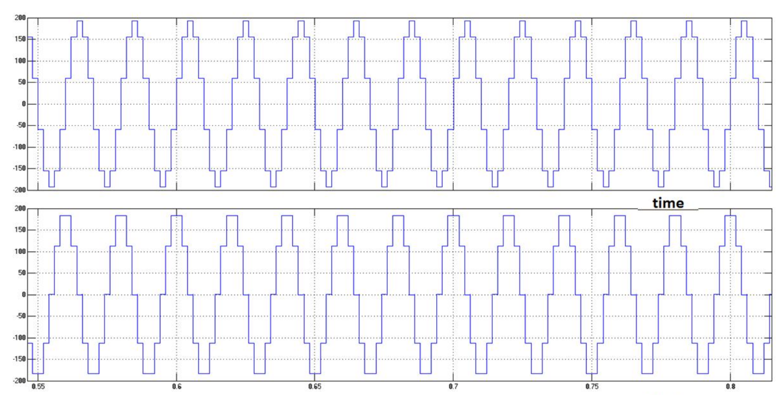


Fig.8: V_{ds} and Vqs voltages

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A. Currents IDS and IQS

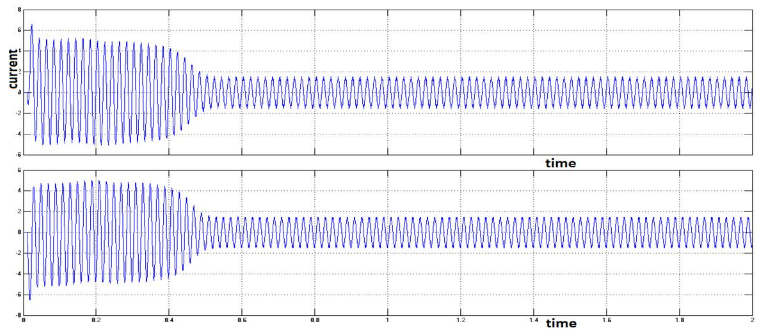

Fig.9: (a) I_{ds} and (b) I_{qs} currents

At the starting of the induction motor the inrush current flows through the motor which lasts for few cycles and disappears as motor attains the steady state speed.

The electromagnetic torque developed in shown in Fig.10 and the motor speed is shown in Fig.11

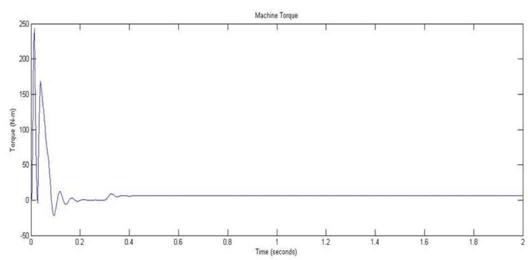

Fig.10: Motor torque

Fig.10 shows that there is variation in torque during starting because of heavy inrush current .The torque attained steady state condition after 0.2 sec. At no load the motor speed is equal to the rated speed.

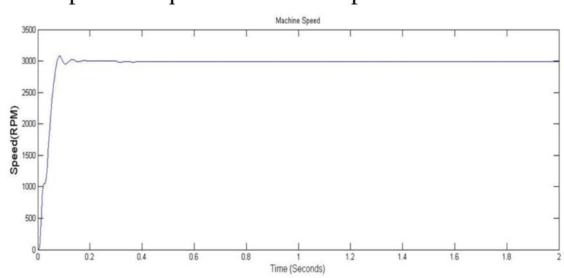

Fig.11: Motor speed

From starting to running condition variation in rotor speed is shown in Fig.11. The small over shoot in the speed response is observed.

VI. CONCLUSION

The advantages of 5-phase induction motors were highlighted in the paper. Stationary frame reference model of induction motor was obtained. Simulation results of five phase induction motor are carried out. The performance of motor was analyzed using the developed dynamic model of motor. From the results, it is conclude that Multiphase motor drives (more than three phases) have several advantages over conventional three-phase drives such as lower space-harmonic content, can operate even during phase open fault, higher torque density, and higher efficiency, so this can be used in various applications like Locomotive traction, High power compressor, Electric ship propulsion, More-electric aircrafts etc.

VII. ACKNOWLEDGEMENT

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