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Modeling and Simulation of Five Phase Induction Motor using MATLAB/Simulink

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ABSTRACT
Three phase Induction motors are invariably used in many residential, commercial, industrial & utility applications because of low cost, reliable operation, robust operation and low maintenance. Multiphase motor drives with phase number greater than three phase leads to an improvement in the medium to high power drives application. The multiphase induction motor find application in special and critical area where high reliability is demanded such as Electric vehicles/Hybrid Electric vehicles, aerospace application, ship propulsion and locomotive traction and in high power application. This paper presents the MATLAB/Simulink implementation of Induction motor. Reference frame theory is used for simulation of the five phase induction motor. Dynamic model are employed to better understand the behavior of the induction motor in both steady state and transient state.
Keywords: Five phase Induction motor, dynamic model, MATLAB/Simulink.

NOMENCLATURE
f = Frequency (Hz)
I = Current (A)
V = Voltage (V)
n = Number of stator phases.
N_s = Synchronous speed (rpm)
P = Number of pole pairs.
B = Flux density (T)
L= Inductance (H)
R = Resistance (Ohm)
T_e = Electromechanical torque (N-m)
α =Angle between successive phases in electrical degrees.
φ = Flux, (Wb)
ω =Angular frequency (rad/sec)
Subscripts
d, q Direct and quadrature axes.
mMagnetizing.
s Stator.
r Rotor.

I. INTRODUCTION
Three phase squirrel cage induction motor are well known for their simple and robust construction, reliability, ruggedness, low maintenance and low cost.The speed control of induction motor is complicated when used for variable speed application. However, due to the development in the power electronic devices, the control of induction motor have become easier and flexible. In addition to this, the numbers of phases have become a design parameter. The development of the solid-state inverter and control schemes has opened a new range of applications for induction machines in areas where dc machines were dominant. In almost any kind of application, three phase induction machines have been employed.

However, when the machine is not directly fed from standard power sources, there is no need for specified number of phases. Higher numbers of phases are more advantageous. Multiphase machine has several advantages over the conventional three phase motor such as reduced torque pulsation [1], reduced per phase rotor harmonic current, high reliability and high fault tolerance [2, 3].

E.E. Ward and Harrer [1], for the first time in 1969 have presented the preliminary investigation on inverter fed five phase induction motor and suggested that the amplitude of the torque pulsation can be reduced by increasing the number of phases. H.A. Toliyat, J.C. White, and T.A. Lipo [4], has evaluated the performance of induction machine with different number of phases for operation with static converter in, "Analysis of a concentrated winding induction machine for adjustable speed dive application part (i) and (ii)" in 1991. The analysis of standard symmetrical multi-phase induction machines is presented in several texts [5]. The derivation of the voltage equations in phase variables and the transformation to the d–q–o reference frame of a multi-phase machine with unsymmetrical phase displacement has been reported by Nelson and Krause [6]. The most commonly used analytical tool for the analysis of unbalanced operation of electric machines has been the well-known symmetrical component method. In this method, a balanced structure is assumed after the machine loses one or more of its phases. Although it has been used successfully in the steady-state analysis of sinusoidal excitation, however, as far as the dynamics of machine is concerned, the method loses its utility due to the fact that the interaction

between the lost phases and remainder of the machine windings no longer exists and this drastically alters the dynamic behavior of the machine. Two separate models have been used by Zhao et.al. [7, 8] to analyze the dynamic behavior of machines for balanced and unbalanced excitation due to open circuit. These models are silent about the analysis of unbalanced condition caused by the short circuit at stator terminals. The two-axis (d–q) model of the multi-phase machine in an arbitrary reference frame was developed by the G.K. Singh [9] and a detailed analysis of the machine under balanced, and unbalanced (open circuit and short circuit both) operating condition has been carried out [10] .

This paper presents the modeling of five phase induction motor using reference frame theory. The structure of the paper is organized as follows. Section-II deals with the construction and principle of working of multi-phase induction motor. Section-III gives the characteristic, advantages, disadvantages and application of multiphase induction motor. Section-IV deals with the mathematical modeling of five phase induction motor which includes the d-q-0 axis equivalent circuit of five phase Induction machine in arbitrary reference frame. Mathematical model using is implemented using MATLAB/Simulink in Section-V. Results of the induction motor model are discussed in detail in Section-VI.

II. CONSTRUCTION AND WORKING PRINCIPLE OF MULTIPHASE INDUCTION MOTOR

Similar to the working of three phase induction motor, five phase induction motor works on the application of Faraday's law and Lorentz force on conductor. When five phase ac supply is given to the stator winding which are spatially and time displaced by displaced by 72°the rotating magnetic field is produce which rotates at synchronous speed. When short circuited rotor (squirrel cage) is placed in rotating magnetic field an EMF is induced in the rotor conductor due to electromagnetic induction. Due to this EMF, current starts flowing in the rotor conductor and sets up its own magnetic field. Due to interaction of these two magnetic fields, a torque is produced and conductor tends to move. The scheme of five phase motor drive is shown in Fig. (1) [11]. The field winding of the induction motor is housed in the stator which is excited by five leg inverter. Stator winding of an n-phase machine can be designed in such a way that the spatial displacement between any two consecutive stator phases equals,$\alpha = 2\pi/n$ in this case a symmetrical multiphase machine results. This will always be a case if the number of phases is an odd prime number. In three phase induction machine the three phases are spatially

displaced by 120 degree whereas in five phase machine by 72 degrees as shown in Fig. (2) [12].
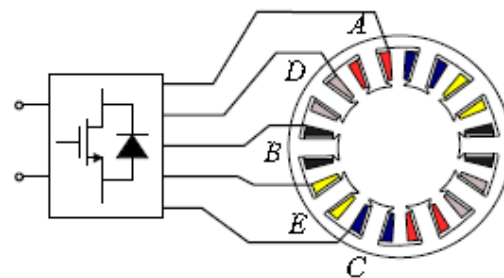

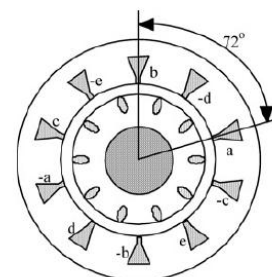**Fig.1** Scheme of the five–phase motor drive.

Fig. 2 five-phase concentrated winding induction machine

However, if the number of phases is an even number or an odd number that is not a prime number (e.g. 6 or 9) , stator winding may be realized in different manner, as 'k' windings having 'a' sub-phases each.(where $n = a \cdot k$). Typically, $\alpha = 3$ (although$\alpha = 5$) also exist as well and k = 2,3,4,5, ... In such case, the spatial displacement between the first phases of the two consecutive 'a' sub-phase windings is $\alpha = \pi/n$, leading to an asymmetrical distribution of magnetic winding axes in cross section of the machine.(i.e. asymmetrical multi-phase machine)

It is not practically possible to directly implement the five phase stator winding into standard three phase machine stator slots. Five phase machine requires custom laminations for the machine stator and custom inverter to supply the five phase motor. The standard squirrel cage rotor of three phase off the shelf machine can be used, [13]. The advantage of using squirrel cage rotor is that, it can adjust to any number of phases which is not possible in case if wound rotor. A five phase induction machine may have five phase distributed winding or fractional slot concentrated winding.

Two kinds of converter can be used for five phase machines: a half–bridge and a full–bridge converter. The second solution has two main advantages: (i) the phase currents are independent; (ii) there is not electrical interaction among phases, so that one can be disconnected independently from the others [16]. The Volt–Amps rating (given by the product of rated current by dc voltage and by

the switch numbers) of the full–bridge converter is about 105 % the Volt–Amps rating of the half–bridge one. On the contrary the use of full-bridge converter requires both terminals of the motor winding to be available. A comparison of the performance of the motor drive under faulty operating condition using half–bridge and full–bridge converter is reported in [15]

III. CHARACTERISTICS FMULTIPHASE INDUCTION MACHINES

To achieve a motor drive with high fault tolerance, it is important to choose the motor exhibiting an intrinsic fault–tolerant capability. Fractional slot winding motors with non–overlapped coils are suitable for fault–tolerant applications [16]. They allow a physical separation among the phases, limiting the propagation of the fault. They are also characterized by a high self-inductance, necessary to limit the short circuit current. In addition, a suitable combination of slots and poles yields a very low mutual coupling between phases. For better performance of the machine, the mutual coupling between the phases should be less, so that when fault occurs on one phase of a machine it is not carried to the other phase mutually.

The stator excitation in multiphase machine produces a field with lower harmonic content, so the efficiency of the machine is increased than that with three phase machine. Multiphase machine have greater fault tolerance than their three phase counterparts. If one phase of the three phase machine becomes open-circuited the machine becomes single phase. It may continue to run but requires some external means for starting, and must be massively de-rated. But in case of multi-phase machine if one phase is open circuited, it will self-start and will run with minimal de-rating. Multiphase machines are less susceptible than their three phase counterparts to time harmonic components in the excitation waveform. Such excitation components produce pulsating torques at even multiple of fundamental excitation frequency. All the above aspects are elaborated in detail in [18].

Over the years, many advantages of multiphase machines have been recognized, including higher machine torque density, reduced torque ripples, reduced harmonic currents, better transient and steady-state performance, and more robust control offered by current harmonic injection.

Concerning the five phase motor drive advantages and drawbacks are as follow:

- The main advantages of using a five phase motor drive are found in its reliability to operate properly also in faulty conditions. It can operate with one or two open circuited phases giving the drive a high tolerance to faults. In both cases the disconnected phases are the faulty ones only, while other phases remain operating as in the normal working conditions.
- In all faulty cases, a proper current control strategy is required so as to limit the torque ripple, and this could be a mandatory requirement in several applications.
- Custom laminations have to be designed and stamped for the five phase motor stator.
- A nonstandard five phase converter is needed to control the motor.

The multiphase machine finds their applications in safety critical applications that require wide fault tolerant capabilities and higher system reliability such as, electric ships, hybrid vehicle, pumps, Compressors, electric aircrafts. In naval applications high availability is must. To avoid stability problems and to prove the redundancy of the five phase machine the complex power electronic system is simulated in [20] in addition to that, reproduction of fault and detail analysis of this major topic is also stated. With the higher number of phases, and consequently the available degrees of freedom offered by multiphase machines, the motor power is split across the phases, thus, reducing the per-phase converter ratings, a highly desirable feature in medium-voltage applications.

IV. MATHEMATICAL MODEL OFFIVE-PHASE INDUCTION MOTOR

The parameter equations such as voltage and torque that describe the dynamic behavior of an induction motor are time-varying in nature. Such equations involve complexity while solving as differential equations. A change of variables from time varying to time invariant can be used to minimize the complexity from the voltage equations of motor due to relative motion of electric circuit. By this technique, a multi-phase winding can be reduced to a set of two phase winding (d-q) which are in quadrature to each other. In other words, the stator and rotor variables (voltage, current and flux linkages) of an induction motor are transferred to arbitrary reference frame.

The steady state model and equivalent circuit of induction motor are useful for studying the performance of the machine in steady state. Fig.3 shows a q-d-0 equivalent circuit of an Induction motor. The circuit comprises of various time varying inductances which are to be simulated to analyze the dynamic behavior of five-phase Induction motor.
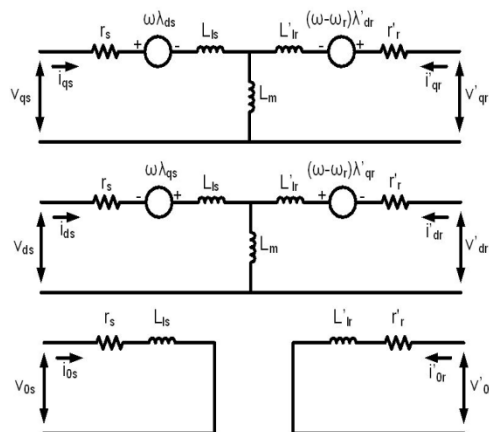
Fig. 3 A d-q-0 axis equivalent circuit of five phase Induction machine in arbitrary reference frame

Five phase stator voltage of induction motor under balanced condition is expressed as follows.

$$V_a = \sqrt{2}V_{rms} \sin(\omega_t)(1)$$
$$V_b = \sqrt{2}V_{rms} \sin\left(\omega_t - \frac{2\pi}{5}\right)(2)$$
$$V_c = \sqrt{2}V_{rms} \sin\left(\omega_t - \frac{4\pi}{5}\right)(3)$$
$$V_d = \sqrt{2}V_{rms} \sin\left(\omega_t + \frac{4\pi}{5}\right)(4)$$
$$V_e = \sqrt{2}V_{rms} \sin\left(\omega_t + \frac{2\pi}{5}\right)(5)$$

The machine model in original form is transformed using decoupling transformation matrix, which transforms original sets of n variables with new sets of n variables. The decoupling transformation matrix is given as [11],

$$\begin{bmatrix} V_q \\ V_d \\ V_x \\ V_y \\ V_0 \end{bmatrix} = \frac{2}{5} \begin{bmatrix} 1 & \cos\alpha & \cos2\alpha & \cos3\alpha & \cos4\alpha \\ 0 & -\sin\alpha & -\sin2\alpha & -\sin3\alpha & -\sin4\alpha \\ 1 & \cos3\alpha & \cos6\alpha & \cos9\alpha & \cos12\alpha \\ 0 & -\sin3\alpha & -\sin6\alpha & -\sin9\alpha & -\sin12\alpha \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix}$$
$$\dots (6)$$

Where $\alpha = \frac{2\pi}{5}$

The five phase voltages given in equation (1) - (5) are simulated in MATLAB/Simulink and transformed using decoupling transformation matrix and the result obtained are shown in Fig. 4. (a) and (b). Fig. 4 (a) shows the five phase sinusoidal supply voltages fed to the motor and Fig. 4 (b) shows the q- and d- axis stator voltages after transformation.
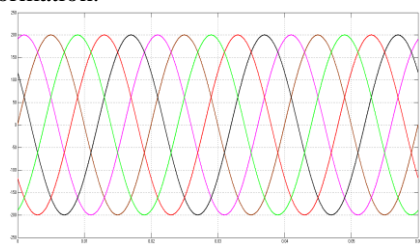
Fig. 4 (a) five phase supply voltage
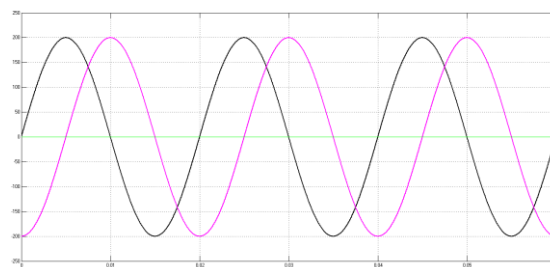
(b) q- and d- axis stator voltages

As stator to rotor coupling takes place in only d-q equations, rotational transformation is applied to these two pairs of equation. The nature of this equation is identical to the three phase machine equations. Assuming that the machine equations are transformed into arbitrary frame of references rotating at angular speed,ω_a, the model of five phase induction machine with Stator side voltage equations in d- and q- reference frame are given as follows

$$V_{ds} = R_s i_{ds} - \omega_a \varphi_{qs} + \rho\varphi_{ds} \ (7)$$
$$V_{qs} = R_s i_{qs} + \omega_a \varphi_{ds} + \rho\varphi_{qs} \ (8)$$
$$V_{xs} = R_s i_{xs} + \rho\varphi_{xs} \ (9)$$
$$V_{ys} = R_s i_{ys} + \rho\varphi_{ys} \ (10)$$
$$V_{0s} = R_s i_{0s} + \rho\varphi_{0s} \ (11)$$

Rotor side voltage equations in d- and q- reference frame are given as,

$$V_{dr} = R_r i_{dr} - (\omega_a - \omega)\varphi_{qr} + \rho\varphi_{dr}(12)$$
$$V_{qr} = R_r i_{qr} + (\omega_a - \omega)\varphi_{dr} + \rho\varphi_{qr}(13)$$
$$V_{xr} = R_r i_{xr} + \rho\varphi_{xr}(14)$$
$$V_{yr} = R_r i_{yr} + \rho\varphi_{yr}(15)$$
$$V_{0r} = R_r i_{0r} + \rho\varphi_{0r}(16)$$

Flux equation of stator side of five phase induction motor is given as,

$$\varphi_{qs} = (L_{ls} + L_m)i_{ds} + L_m i_{dr} \ (17)$$
$$\varphi_{ds} = (L_{ls} + L_m)i_{qs} + L_m i_{qr} \ (18)$$
$$\varphi_{xs} = L_{ls} i_{xs}(19)$$
$$\varphi_{ys} = L_{ls} i_{ys}(20)$$
$$\varphi_{0s} = L_{ls} i_{0s}(21)$$

Flux equation of rotor side of five phase induction motor is given as,

$$\varphi_{qr} = (L_{lr} + L_m)i_{dr} + L_m i_{ds} \quad (22)$$
$$\varphi_{dr} = (L_{ls} + L_m)i_{qr} + L_m i_{qs}(23)$$
$$\varphi_{xr} = L_{lr} i_{xr}(24)$$
$$\varphi_{yr} = L_{lr} i_{yr}(25)$$
$$\varphi_{0r} = L_{lr} i_{0r}(26)$$

Where, $L_m = (n/2)M$ and M is the maximum value of the stator to rotor mutual inductances in the phase-variable model. Symbols R and L stand for resistance and inductance, v, i and φ denote voltage, current and flux linkage, while indices s, r identify stator/rotor variables/parameters. Index l identifies leakage inductances.

From the above equations the Torque and rotor speed can be determined as,

$$T_e = \frac{5}{2}\left(\frac{P}{2}\right)\frac{1}{w_b}\left(\varphi_{ds}i_{qs} - \varphi_{qs}i_{ds}\right) \quad (27)$$

$$\omega_r = \int \frac{P}{2J}(T_e - T_L) \quad (28)$$

Where, P is the number of poles; J moment of inertia; T_L Load Torque; T_e Electromechanical torque; ω_r Rotor Speed.

Mathematical model equations for d-q components and the torque equation are identical as for a three-phase induction machine. The only difference between five phase machine model and corresponding three phase machine model is the presence of x-y components in voltage and flux equations. Rotor x-y components are fully decoupled from d-q components and one from other. Since rotor winding is short circuited, x-y components does not appear in the rotor winding. Zero sequence component equations for both stator and rotor can be omitted from further consideration due to short-circuited rotor winding and star connection of stator winding. Finally, since stator x-y components are fully decoupled from d-q components and one from the other, the equations for x-y components can be omitted from further consideration as well. This means that the model of five phase induction motor in arbitrary reference frame is identical to the model of three phase induction machine and the same control schemes can be apply to multiphase induction machines as for three-phase machines. However, existence of x-y equations means that utilization of a voltage source that creates stator voltage x-y components will lead to a flow of potentially large stator x-y current components, since these are restricted only by stator leakage impedance. These x-y components correspond to certain voltage and current harmonics, the order of which depends on the machine's number of stator phases. Hence the inverter, used to supply a multiphase induction machine, must not create low-order voltage harmonics that will excite stator current low-order harmonic flow in x-y circuits [17].

Once the stator voltage $V_a, V_b, V_c, V_d,$ and V_e are transformed to d-q frame then we implement the flux linkages equations, current equations, torque equations and rotor speed equations so as to obtain current in terms of i_{qs}, i_{ds}, i_{qr} and i_{dr} then we use inverse transformation equations to obtain the stator currents in machine variable form. Inverse Transformation equations to transform current in arbitrary reference frame to current in machine

ariables to study the nature of current in stator is expressed as,

$$\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \\ i_{ds} \\ i_{es} \end{bmatrix} = \sqrt{\frac{2}{5}}\begin{bmatrix} 1 & 0 & 1 & 0 & 1 \\ \cos\alpha & \sin\alpha & \cos2\alpha & \sin2\alpha & 1 \\ \cos2\alpha & \sin2\alpha & \cos4\alpha & \sin4\alpha & 1 \\ \cos3\alpha & \sin3\alpha & \cos6\alpha & \sin6\alpha & 1 \\ \cos4\alpha & \sin4\alpha & \cos8\alpha & \sin8\alpha & 1 \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{xs} \\ i_{ys} \\ i_{0s} \end{bmatrix}$$
… (29)

V. MATALB/SIMULINK IMPLIMENTATION

The voltage, flux, torque equations and transformation matrices are used to implement the model of five phase induction motor inMATLAB/Simulink as shown in Fig. 5. The input to the motor is the five phase sinusoidal voltage supply. The five phase to two phase conversion block transfers the five phase stator voltages to d- and q- axis voltages. This block gives stator current, rotor currents and fluxes in direct and quadrature axis. Current-flux to torque-speed block gives the rotor speed and torque using equations (27) and (28). The simulation of the internal structure of five phases induction motor is run assuming no load condition.The stator and rotor currents in d- and q- references frame are transferred to machine variable as $i_{as}, i_{bs}, i_{cs}, i_{ds}$ and i_{es} using inverse transformation matrices to analyze the nature of the stator and rotor currents.

VI. MATLAB/SIMULINK RESULTS AND DISCUSSION:

The mathematical model given in the paper is implemented in MATLAB/ Simulink is designed for the machine having the ratings as given in Table I. The machine is 1.5 hp, 100V, 50Hz, 4 Pole squirrel cage induction motor. The machine parameters used for modeling are given in Table II [12]. The stator and rotor resistances in table II are for fundamental sequence.

The simulation results obtained from the MATLAB/Simulink are depicted in Fig. 6 to Fig. 9.The typical behavior of the five phase induction motor is observed.
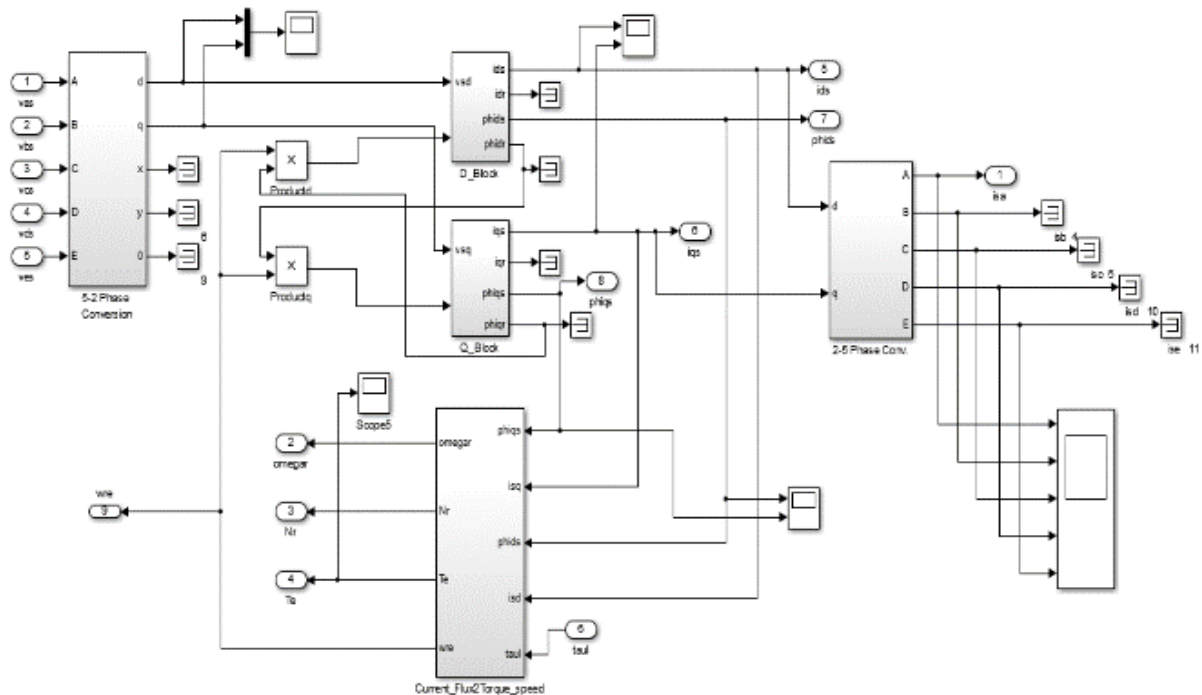
Fig. 5: The internal structure of the 5-phase induction motor d-q model

Table I Machine rating

Rated phase voltage (V)	200
Rated Power (Hp)	1.5
Rated Phase current (A)	3.5
Rated frequency (Hz)	50
Number of Poles	4
Rated Speed (rpm)	1425

Table II Machine parameters

$R_s = 2.6\ \Omega, R_r = 1.88\ \Omega$
$l_s = 5\ mH, l_r = 23.6\ mH$
$l_m = 149.6\ mH$

### A. Stator currents in each A, B, C, D and E phases:

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 constant no load steady state current in stator after high starting current is observed as shown in Fig. 6.
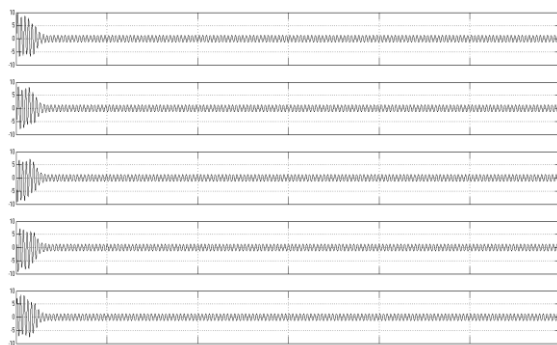
Fig. 6 Stator Current

B. Rotor currents in each A, B, C, D and E phases:

At starting of the induction motor the induction motor acts as a transformer with short circuited secondary winding because the rotor bars are short circuited. So a large starting current in short circuited rotor bars flow which vanishes as the motor attains the steady state speed. A small constant no load steady state current in rotor after starting transient current is observed as shown in Fig. 7.
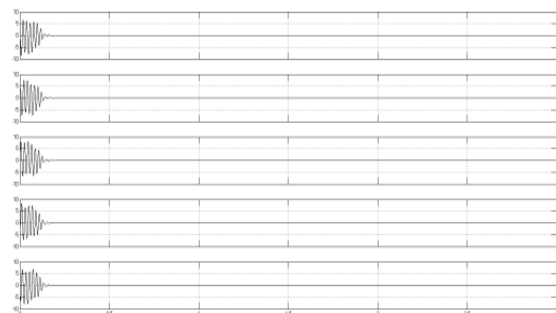
Fig. 7 Rotor Current

C. Electromagnetic torque developed:

The variation in torque during starting is observed which occurs due to heavy inrush current. Steady state torque is attained after few cycles (about 0.2 sec) as shown in Fig. 8.
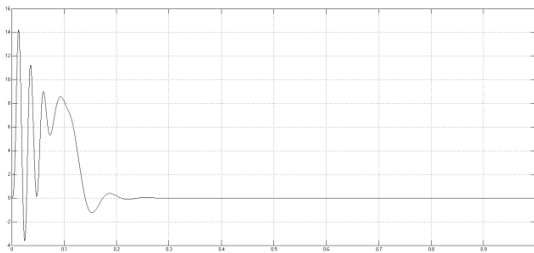
Fig. 8 Electromagnetic Torque developed

D. Rotor speed in RPM:

Rotor speed variation from starting to running condition is shown in Fig.9. The small over shoot in the speed response is observed.
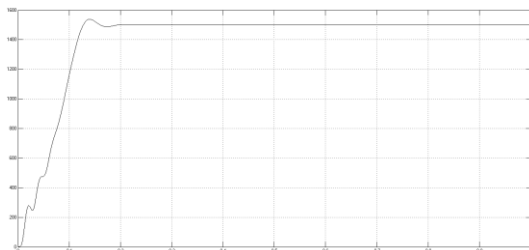

Fig. 9 Rotor Speed

VII.   CONCLUSION

The investigation in the area of multi-phase induction machines indicates that it is technically viable to use phase number higher than three in induction machine. The technology of multiphase induction machine has many advantages, such as high reliability as machine continues to run even if one of its many phases is open or short circuited with not much degradation in performance, lower per phase current which is advantageous feature when used in electric vehicle and similar applications. The most important feature is increase in power rating and torque of machine on higher phase order connection in same frame size.

The mathematical model of five phase induction motor is simulated in MATLAB/Simulink using d- and q- reference frames. The multi-phase machine variables are transformed into two variables d- and q- axis. The obtained d-q model of five phase machine is identical to that of three phase machine. Therefore the model is simulated for five phase system. Implemented model of machine gives a satisfactory response in terms of stator currents, torque and speed characteristics.

The model can be implemented for higher number of phases using transformation matrices for n-phase machine. The authors believe that the paper will be useful for all those who are new into the area of multi-phase motor drive in general and five phase induction motor drive in particular.

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