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IFOC of a Nine Phase Induction Motor Drive

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Abstract*— This paper presents an Indirect Field Oriented Control of nine-phase induction motor drive fed by a nine-phase inverter using mat lab/Simulink. IFOC is an established control method for high dynamic performance AC drives and the control is simple and highly reliable. Three phase induction motors have many well recognized advantages however their applications are limited to lower end of high power range due to limitations on rating of power semiconductor devices. A strong contender in achieving high power is multiphase inverter fed induction motor drive. D-Q axis model of nine phase induction motor fed by a nine leg inverter is developed and an IFOC controller is presented. Simulation results are included to illustrate the performance of the nine phase induction motor with IFOC.

Index Terms— **IFOC, nine-phase induction motor drive, D-Q-axis model, mat lab/Simulink**

I. INTRODUCTION

Three phase induction motors are normally used, since the standard power supply is three phase. However, when fed by an inverter, there is no need of fixed number of phases. Multi-phase induction motors have more advantages over conventional three phase drives, such as reduced torque pulsations, reduced harmonic current and reduced current per phase [1]. They are applicable in areas where high power and reliability is demanded such as electric/hybrid vehicles, aerospace application, warship, and submarine propulsion and circulation pumps in nuclear power plant [2]. Due to identifiable merits and application it is necessary and prudent to investigate the performance of multiphase drives. Vector control techniques have made the induction motors for high performance applications where traditionally only DC drives were applied. There are essentially two methods of vector control direct or feedback method and indirect or feed forward method. Indirect field-oriented control is the most popular method of obtaining high performance in induction motor drives. IFOC drives are most popularly used in industrial application due to their simple configuration which do not require flux and torque estimator [3]. This paper focus on developing a D-Q model of 9-phase induction motor and its control through IFOC by a simple approach of utilizing the built in blocks of mat lab/Simulink environment.

A. Nine phase Inverter

A voltage source inverter is less rugged, capable of high waveform fidelity with pulse width modulation operation and involves high performance but are limited on the ratings of semiconductor power devices. To achieve high-power rating in such systems, multiphase inverters (nine-phase) are developed [4]. A 9Φ voltage source inverter is shown in Fig.1.DC voltage source to the inverter is ripple-free and switching devices are assumed to be ideal.

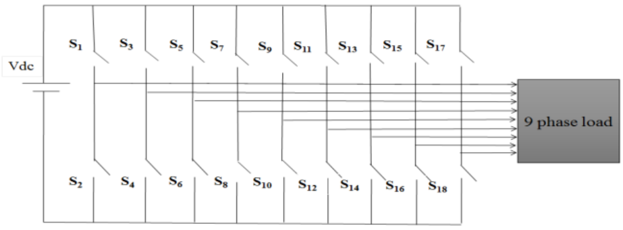


Fig.1 Nine Phase Inverter Topology

There are nine legs and each contributing one of the nine phases. The switches can take either 1 or 0 value based on the state of upper or lower switch. The pulse to the inverter switches are generated through Sinusoidal Pulse Width modulation (SPWM) scheme. In SPWM nine-phase sinusoidal reference signal is compared with high frequency triangular carriers to generate pulse. The amplitude of the reference decides the modulation index. As the modulation reaches towards unity, harmonics is reduced. A suitable modulation index that results in lesser harmonics at the output is chosen to generate pulse for the inverter. Utilization of more than three-phases enables splitting of the power across a larger number of inverter legs, thus enabling use of semiconductor switches of lower rating.

B. Nine phase Induction Motor

An n-phase induction dri.ve there is ‘n’ no of stator windings that are displaced by (360˚/n) hence a nine phase induction motor has nine stator windings with a phase difference of 40˚ degree and the rotor is of squirrel-cage type. It is fed by a nine phase inerter. As the phase number increases stator excitation in the machine produces a field with a lower space-harmonic content, hence the efficiency is higher[5].

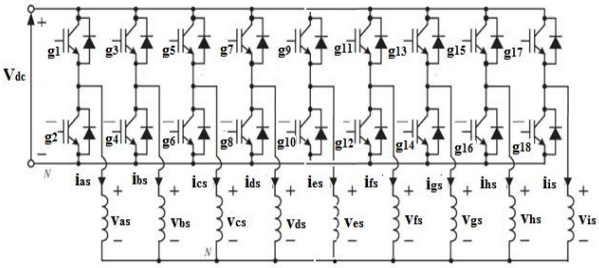


Fig.2 Nine Phase Inverter Fed Nine Phase Induction Motor

Per phase equivalent circuit of the induction machine is valid only for the steady- state condition. In an adjustable speed drive, the machine normally constitute an element within a feed- back loop, and therefore is transient behavior has to be taken into account for which dynamic modelling is essential.

C. Dynamic model of 9Φ Induction Motor

High performance drive control, such as vector or field oriented control is based on the dynamic D-Q model of the machine. Nine phase machine can be represented as a two phase equivalent with d_s -q_s corresponding to stator direct and quadrature axes that are fixed on the stator axis and d_r -q_r corresponding to rotor direct and quadrature axes that are rotating with a fixed speed on the rotor axis. The effect of time varying inductance can be eliminated by referring the stator and rotor variables to a common reference frame which rotates at any speed[6]. A nine phase induction motor can be modeled by the following steps as follows. A 9Φ inverter with its pulse given through SPWM technique is used to provide a 9Φ supply to the induction motor

$$\begin{aligned}
V_a &= \mathrm{V}\cos\theta_{\mathrm{e}}\\
V_b &= \mathrm{V}\cos(\theta_{\mathrm{e}}-\mathrm{a})\\
V_c &= \mathrm{V}\cos(\theta_{\mathrm{e}}-2\mathrm{a})\\
V_d &= \mathrm{V}\cos(\theta_{\mathrm{e}}-3\mathrm{a})\\
V_e &= \mathrm{V}\cos(\theta_{\mathrm{e}}-4\mathrm{a})\\
V_f &= \mathrm{V}\cos(\theta_{\mathrm{e}}-5\mathrm{a})\\
V_g &= \mathrm{V}\cos(\theta_{\mathrm{e}}-6\mathrm{a})\\
V_h &= \mathrm{V}\cos(\theta_{\mathrm{e}}-7\mathrm{a})\\
V_i &= \mathrm{V}\cos(\theta_{\mathrm{e}}-8\mathrm{a})
\end{aligned} \qquad (1)$$

Where, $a = \dfrac{2\pi}{9},\ \theta_{\mathrm{e}} = \int \omega_{\mathrm{e}}$

To transform the 9Φ stationary reference frame variables to 2Φ stationary reference frame variables

$$\begin{bmatrix} V_{qs}{}^{s} \\ V_{ds}{}^{s} \\ V_{xs}{}^{s} \\ V_{ys}{}^{s} \\ . \\ V_{0s}{}^{s} \end{bmatrix} = \sqrt{\frac{2}{n}} \begin{bmatrix} 1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha & . & \cos n\alpha \\ 0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha & . & \sin n\alpha \\ 1 & \cos 2\alpha & \cos 4\alpha & \cos 6\alpha & . & \cos 2n\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha & \sin 6\alpha & . & \sin 2n\alpha \\ . & . & . & . & . & . \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ . \\ V_n \end{bmatrix}$$

Fig.3 Clarke’s Decoupling Transformation Matrix for a Symmetrical Nine -Phase System

The first two rows of the matrix in Fig.3 define variables that will lead to fundamental flux and torque production. The last row defines the zero sequence components. Equations for pairs of *x*–*y* components are completely decoupled and do not contribute to torque production when sinusoidal distribution of the flux around the air-gap is assumed[7]. Stator variables in stationary reference frame are transformed to synchronous reference frame. In this transformation the q- axis of the voltage variable is aligned to zero and only the d- axis variable is present for easy control.

$$\begin{bmatrix} V_{ds}^{e} \\ V_{qs}^{e} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} * \begin{bmatrix} V_{ds}^{s} \\ V_{qs}^{s} \end{bmatrix} \qquad (2)$$

The stator and the rotor voltage equations in synchronous reference frame are given by equations (3) and (4)

$$V_{ds}^{e} = \mathrm{i}_{ds}^{\mathrm{e}}\,\mathrm{R}_s + \frac{\mathrm{d}}{\mathrm{dt}}\psi_{dr}^{e} - \omega_{\mathrm{e}}\psi_{qs}^{e}$$

$$V_{qs}^{e} = \mathrm{i}_{qs}^{\mathrm{e}}\,\mathrm{R}_s + \frac{\mathrm{d}}{\mathrm{dt}}\psi_{qs}^{e} + \omega_{\mathrm{e}}\psi_{ds}^{e} \qquad (3)$$

$$V_{dr}^{e} = \mathrm{i}_{dr}^{\mathrm{e}}\,\mathrm{R}_r + \frac{\mathrm{d}}{\mathrm{dt}}\psi_{dr}^{e} - (\omega_{\mathrm{e}} - \omega_{\mathrm{r}})\psi_{qr}^{e}$$

$$V_{qr}^{e} = \mathrm{i}_{qr}^{\mathrm{e}}\,\mathrm{R}_r + \frac{\mathrm{d}}{\mathrm{dt}}\psi_{qr}^{e} + (\omega_{\mathrm{e}} - \omega_{\mathrm{r}})\psi_{dr}^{\mathrm{e}} \qquad (4)$$

Fulx Expressions are obtained by rearranging the equations (3) and (4)

$$\begin{aligned} \psi_{ds}^{\mathrm{e}} &= \int V_{ds}^{\mathrm{e}} - \mathrm{i}_{ds}^{\mathrm{e}}\,\mathrm{R}_s + \omega_{\mathrm{e}}\psi_{qs}^{e} \\ \psi_{qs}^{\mathrm{e}} &= \int V_{qs}^{e} - \mathrm{i}_{qs}^{\mathrm{e}}\,\mathrm{R}_s - \omega_{\mathrm{e}}\psi_{ds}^{\mathrm{e}} \\ \psi_{dr}^{\mathrm{e}} &= \int V_{dr}^{\mathrm{e}} - \mathrm{i}_{dr}^{\mathrm{e}}\,\mathrm{R}_r + (\omega_{\mathrm{e}} - \omega_{\mathrm{r}})\psi_{qr}^{e} \\ \psi_{qr}^{\mathrm{e}} &= \int V_{qr}^{\mathrm{e}} - \mathrm{i}_{qr}^{\mathrm{e}}\,\mathrm{R}_r - (\omega_{\mathrm{e}} - \omega_{\mathrm{r}})\psi_{dr}^{\mathrm{e}} \end{aligned} \qquad (5)$$

Current expression in terms of flux linkage and leakage inductance of the motor

$$\begin{aligned} i_{qs}^{e} &= \frac{\psi_{qs}^{e}[L_{lr} + L_m] - L_m\psi_{qr}^{e}}{(L_{ls}L_{lr} + L_{ls}L_m + L_mL_{lr})} \\ i_{ds}^{e} &= \frac{\psi_{ds}^{e}[L_{lr} + L_m] - L_m\psi_{dr}^{e}}{(L_{ls}L_{lr} + L_{ls}L_m + L_mL_{lr})} \\ i_{qr}^{e} &= \frac{\psi_{qr}^{e}[L_{ls} + L_m] - L_m\psi_{qs}^{e}}{(L_{ls}L_{lr} + L_{lr}L_m + L_mL_{ls})} \\ i_{dr}^{e} &= \frac{\psi_{ds}^{e}[L_{ls} + L_m] - L_m\psi_{ds}^{e}}{(L_{ls}L_{lr} + L_{lr}L_m + L_mL_{ls})} \end{aligned} \qquad (6)$$

Transformation of stator current in synchronous reference frame to stationary reference frame

$$\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & -\sin\theta_e \\ \sin\theta_e & \cos\theta_e \end{bmatrix} * \begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix} \qquad (7)$$

To obtain the five phase stator current from the stator currents in stationary reference frame by 2 Φ to 9 Φ transformation

$$\begin{aligned}
i_a &= i_{qs}{}^{s}\cos\theta_e + i_{ds}{}^{s}\sin\theta_e \\
i_b &= i_{qs}{}^{s}\cos(\theta_e-\alpha) + i_{ds}{}^{s}\sin(\theta_e-\alpha) \\
i_c &= i_{qs}{}^{s}\cos(\theta_e-2\alpha) + i_{ds}{}^{s}\sin(\theta_e-2\alpha) \\
i_d &= i_{qs}{}^{s}\cos(\theta_e-3\alpha) + i_{ds}{}^{s}\sin(\theta_e-3\alpha) \\
i_e &= i_{qs}{}^{s}\cos(\theta_e-4\alpha) + i_{ds}{}^{s}\sin(\theta_e-4\alpha) \\
i_f &= i_{qs}{}^{s}\cos(\theta_e-5\alpha) + i_{ds}{}^{s}\sin(\theta_e-5\alpha) \\
i_g &= i_{qs}{}^{s}\cos(\theta_e-6\alpha) + i_{ds}{}^{s}\sin(\theta_e-6\alpha) \\
i_h &= i_{qs}{}^{s}\cos(\theta_e-7\alpha) + i_{ds}{}^{s}\sin(\theta_e-7\alpha) \\
i_i &= i_{qs}{}^{s}\cos(\theta_e-8\alpha) + i_{ds}{}^{s}\sin(\theta_e-8\alpha)
\end{aligned} \qquad (8)$$

Electromechanical torque and rotor speed of the five phase induction motor is obtained by (9) and (10) respectively

$$\begin{aligned} T_e &= p * L_m * (i_{qs} i_{dr} - i_{ds} i_{qr}) \\ &= p * (\psi_{qs} i_{dr} - \psi_{ds} i_{qr}) \end{aligned} \qquad (9)$$

$$\omega_r = \int \frac{p}{2} * \frac{(T_e - T_l - B)}{J} dt \qquad (10)$$

II. INDIRECT FIELD ORIENTED CONTROLLER

IFOC scheme as for a three-phase induction machine are directly applicable for a 9-phase induction machine regardless of number of phases. The only difference is the co-ordinate transformation has to produce nine sets of stator current or stator voltage references instead of three. This control strategy allows very precise and rapid control of the torque produced by an induction machine[7]-[8]. However, the control of the rotor field is made more difficult by the interaction of the rotating stator and rotor magnetic fields and is not easily controlled in the stationary reference frame. Therefore, a transformation to synchronously rotating reference frame whose d-axis is aligned with the rotor field is required[9]-[10]. Simulink model of IFOC is shown in Fig.4 Reference speed is compared with the actual speed of the nine phase induction motor and the error signal is given to a speed controller. The speed controller is a PI controller who's proportional and integral gain constants are tuned to make the controller to produce suitable pulses for obtaining desired speed. Reference currents i_q^* and i_d^* are obtained using the equations (11) and (12)

$$i_q^* = \left(\frac{2}{9}\right) * \left(\frac{2}{p}\right) * \left(\frac{L_r}{L_m}\right) * \left(\frac{T_e}{\psi}\right) \qquad (11)$$

$$\mathrm{i_d}^* = \left(\frac{\psi^*}{L_m}\right) \qquad (12)$$

The reference flux linkage ψ^* is commanded to be 1.68 and ψ is obtained from the equation (13)

$$\psi = \left(\frac{L_m * i_d}{1 + T_r . s}\right) \qquad (13)$$

Here i_d is the actual d-axis stator current. The currents i_d and i_q obtained through transformation of actual stator currents of the nine phase induction motor from equation (8) and T_r is the time constant that depends upon the machine parameters L_r and R_r

$$T_r = \left(\frac{L_r}{R_r}\right) \qquad (14)$$

The electrical or field angle θ_e required for the transformations is calculated by the following equation

$$\theta_e = \int (\omega_r + \omega_m) . dt \qquad (15)$$

Where ω_m is the rotor mechanical speed and ω_r the rotor electrical speed and it is given by

$$\omega_r = \left(\frac{L_m * i_q}{\psi_r * T_r} \right) \tag{16}$$

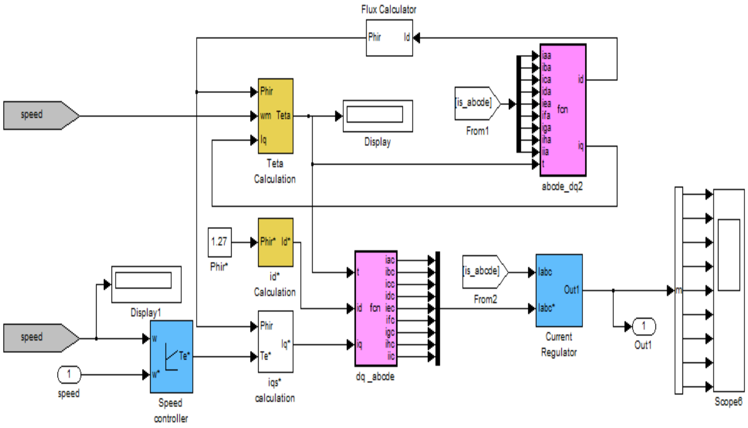
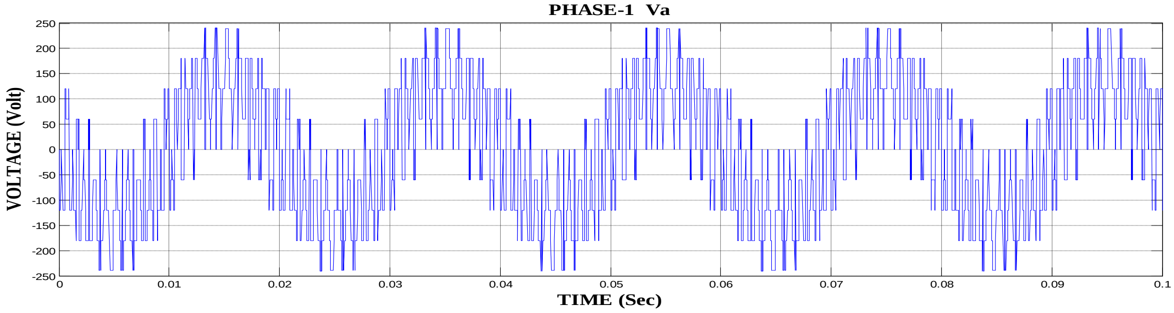


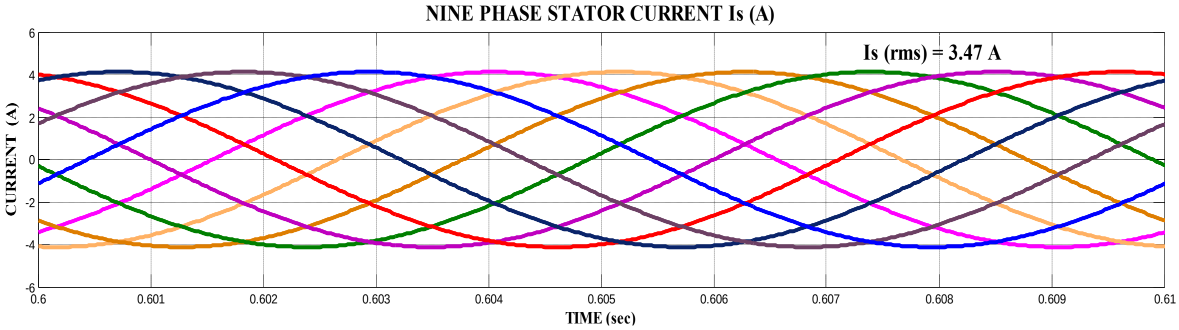
Fig.4 IFOC for a Nine phase induction motor

Pulse to the nine phase inerter that feed the induction motor is generated by a fixed hysteresis current controller. It is used because of its simplicity, robust performance with good stability, fast response, inherent ability to control peak current and ease of implementation. This technique does not need any information about system parameters and its purpose is to control the load current by forcing it to follow a reference current. It is achieved by the switching action of the inverter to keep the current within the hysteresis band. The load currents are sensed and compared with respective command currents by the hysteresis comparators having a hysteresis band HB. The output signal of the comparator is used to activate the inverter power switches.

III. OPEN LOOP RESULTS

The Simulation model of the 9Φ Induction motor is simulated with the parameters given in the appendix at rated operating condition and the results are presented in Fig.5





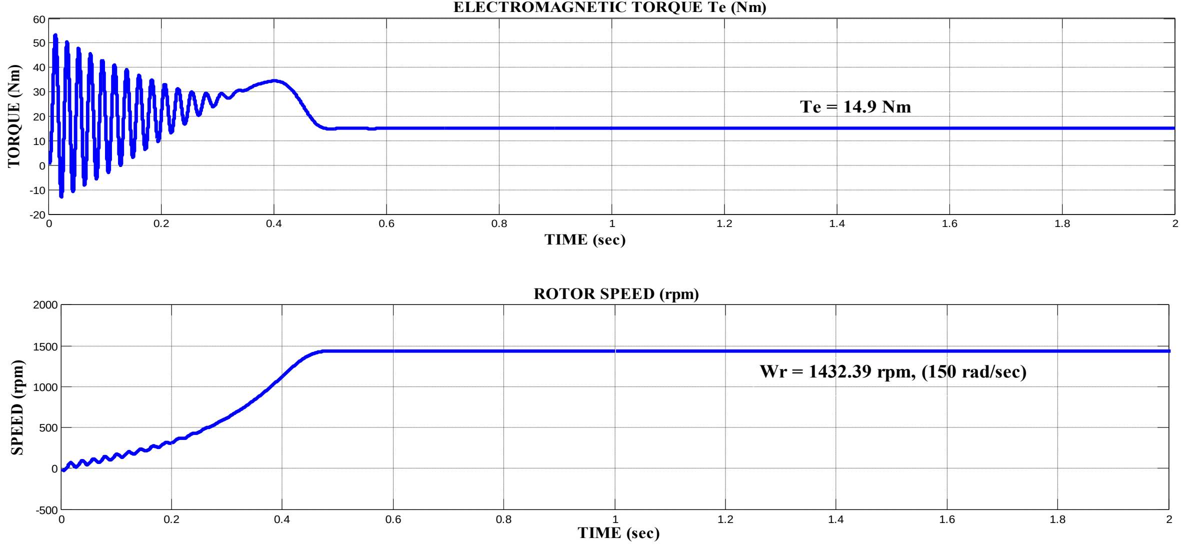


Fig.5 Simulated Open loop Results of 9Φ Induction Motor at Rated Load Condition

The 9Φ Inverter supplies 220V (rms fundamental) to the 9Φ Induction motor with a DC input supply of 725V at 0.85 modulation index. The machine draws 3.47A (rms) to drive the rated load at rated speed.

IV. CLOSED LOOP RESULTS

The simulation of 9 phase drive is carried out with IFOC controller. Fig presents the performance of the controller at different load and speed variations respectively.

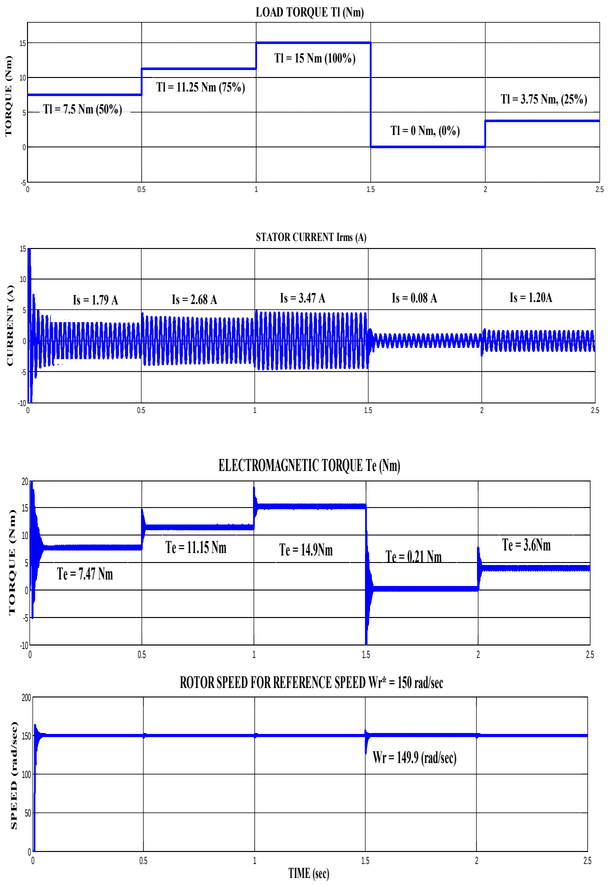


Fig.6 Simulation Results of IFOC Nine Phase Drive for Fixed Reference Speed at Variable Load

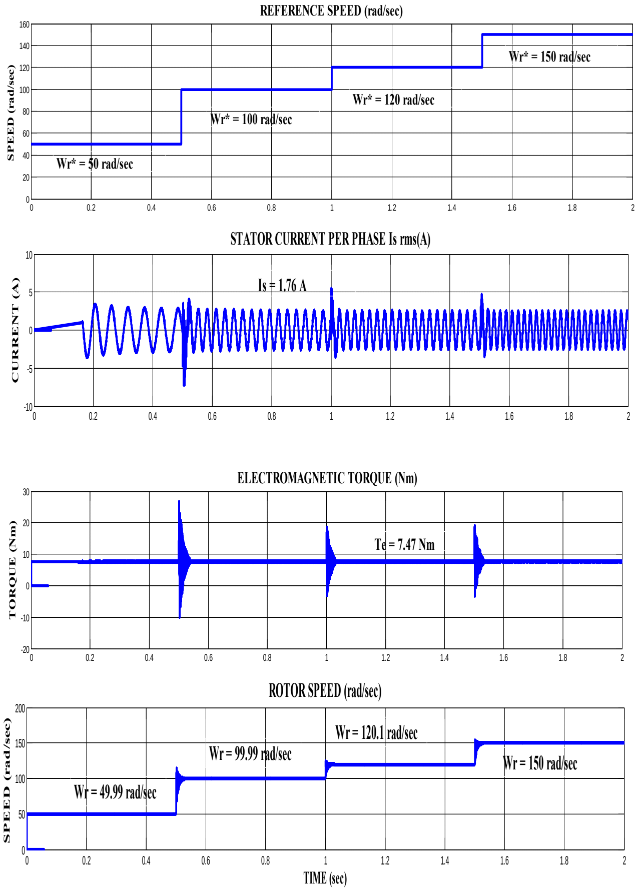


Fig.7 Simulation Results of IFOC Nine Phase Drive for Fixed Reference Speed at Variable Load

A. Fixed Reference Speed at Variable Load

The reference speed is set 150 rad/sec and it is seen from the Fig.6 that the load is varied in steps. The modulation index is automatically adjusted to supply the required voltage and maintains the speed at desired value. As there is a change in load the stator current varies with load and electromagnetic torque follows the load torque.

B. Variable Reference Speed at Fixed Load

The load is fixed to 50% with the reference speed varied in steps every 0.5 second. It is seen from the Fig.7 that the stator current corresponding to 50%load is maintained as there is no change in load and the motor torque follows the load torque. The speed is regulated according to the reference speed

V. CONCLUSION

IFOC controller is designed for the nine phase induction motor. It achieves decoupled torque and flux dynamics leading to independent control of torque and flux as that of separately excited DC motor. From the simulation results it is found that the controller tracks the reference speed or torque in the operating range (no load to full load). Some machine parameters, in particular the rotor resistance, may vary with temperature and loading of the machine. However this control strategy is excellent for low speed operations and for motion control applications.

APPENDIX

The nine phase induction motor parameters: Power(P) =3.7 HP, voltage (V) = 220V, current (I) =3.5 A, Frequency (f) = 50Hz, speed () = 1440rpm, stator resistance (R_s)= 10 Ω , rotor resistance (R_r) = 6.3 Ω, stator leakage inductance (L_{ls})= 0.04 H , rotor leakage inductance (L_{lr})=0.04 H , Mutual inductance(L_m) =1.89 H , no. of poles (p) =4, Friction (B) =0.003 Kgm^2 , Inertia (J) =0.00015 Nms.

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