Performance Analysis of Six-Phase Induction Motor

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***Abstract*— This paper presents a mathematical d-q model of six-phase, two pole induction motor in rotating reference frame. The model is simulated in Simulink environment to evaluate its performance under load and no-load conditions. The results show reliable and good performance of the motor.**

Keywords—D-q model, six-phase induction motor.

I. INTRODUCTION

Asynchronous, induction motor is one of the very important and widely used ac motors. Single phase and three-phase both induction motors are popular and widely used because of its simplicity, robustness, good performance. But multiphase (more than three) induction motors are becoming popular and have been being studied from many years because of its several advantages over conventional three-phase induction motors or induction motors having lesser phases. The advantages are better fault tolerance[1][2][3][4], higher efficiency, lower current ripple, less torque pulsation, reliability[5] and facility to split certain amount of power in to multiple phases to reduce the power per-phase. This power splitting enables to use devices of less rating in case of high power applications[6]. Multi-phase motors are used in case of ship propulsion, traction, electric vehicles etc. where high power and reliability is required.

Simulation of symmetrical induction machinery was done in [7]. Multiphase machines' use in electric vehicles was studied in [8]. R. Gregor, F. Barrero, S. Toral and M.J. Durán studied induction motor drive test-rig to obtain superior performance[9]. Anushree Kadaba, Shaohua Suo, Gennadiy. Sizov, Chia-Chou Yeh, Ahmed Sayed-Ahmed, Nabeel A.O. Demerdash designed reversible three-phase to six-phase induction motor[10]. A spectral method of speed ripple analysis for a fault-tolerant six-phase squirrel-cage induction machine was presented in [11]. Matrix converter has been used to drive six-phase induction motor in [12]. Transient analysis of three-phase induction machine using different reference frames has been done in [13]. Rangarajan M. Tallam, Thomas G. Habetler and Ronald G. Harley studied transient model of induction motor with winding faults[14]. [15] presents experimental investigation of a naval propulsion drive model with the PWM-based attenuation of the acoustic and electromagnetic noise. G.Renukadevi, K.Rajambal developed a generalized model of multiphase induction motor with symmetrical winding displacement[16]. Use of multiphase machines is proposed in [17]. Control of five phase induction motor using space vector modulation, is discussed in [18]. [19] This paper deals with the high performance Backstepping control strategy which is based on laws allowing an explicit control of system stability in closed-loop operation of five-phase induction motor drives. Using flux-linkage model, stability analysis of five phase induction motor has been done in [20]. Y. Maouche, A. Boussaid, M. Boucherma, A. Khezzar studied pulsating torque and harmonic components in rotor current of six-phase induction motor under healthy and faulty conditions.

In this paper a dynamic model of asymmetrical six-phase, cage type induction motor is developed to study the performance of the motor in detail. The model is simulated in MATLAB/Simulink environment. The study gives a detailed idea about the motor and indicates towards the smooth and promising performance of the motor.

II. MATHEMATICAL MODEL OF THE MOTOR

A simplified and equivalent diagram of a six phase induction motor is shown in fig.1. To develop this model some assumptions are made and those are as follows: The air gap is uniform and the windings are sinusoidally distributed around the air gap. There is no core loss and magnetic saturation in the core. There is no friction and windage loss in the system.

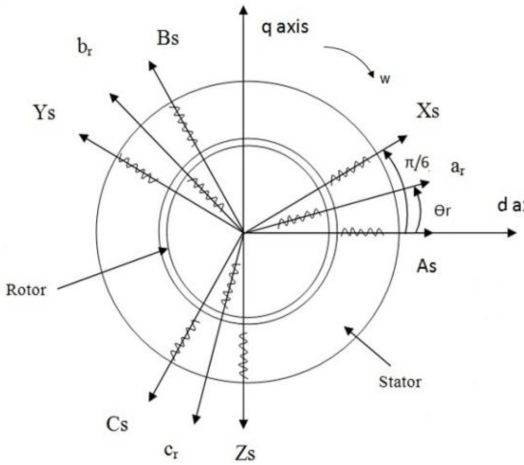

Fig.1. Simplified Diagram of Six- Phase Induction Motor

The voltage equations of the motor are mentioned below:

$$V_{qs1} = r_s i_{qs1} + \rho\lambda_{qs1} + \omega\, \lambda_{ds1} \quad (1)$$
$$V_{ds1} = r_s i_{ds1} + \rho\lambda_{ds1} - \omega\, \lambda_{qs1} \quad (2)$$
$$V_{qs2} = r_s i_{qs2} + \rho\lambda_{qs2} + \omega\, \lambda_{ds2} \quad (3)$$

$V_{ds2} = r_s i_{ds2} + \rho\lambda_{ds2} - \omega\,\lambda_{qs2}$ (4)

$V_{qr}' = r_r'\, i_{qr}' + \rho\lambda_{qr}' + (\omega-\omega_r)\,\lambda_{dr}'$ (5)

$V_{dr}' = r_r'\, i_{dr}' + \rho\lambda_{dr}' - (\omega-\omega_r)\,\lambda_{qr}'$ (6)

The flux linkage equations are as follows:

$\lambda_{qs1} = L_{ls} i_{qs1} + L_{lm}\,(i_{qs1} + i_{qs2}) + L_m\,(i_{qs1} + i_{qs2} + i_{qr}')$ (7)

$\lambda_{ds1} = L_{ls} i_{ds1} + L_{lm}\,(i_{ds1} + i_{ds2}) + L_m\,(i_{ds1} + i_{ds2} + i_{dr}')$ (8)

$\lambda_{qs2} = L_{ls} i_{qs2} + L_{lm}\,(i_{qs1} + i_{qs2}) + L_m\,(i_{qs1} + i_{qs2} + i_{qr}')$ (9)

$\lambda_{ds2} = L_{ls} i_{ds2} + L_{lm}\,(i_{ds1} + i_{ds2}) + L_m\,(i_{ds1} + i_{ds2} + i_{dr}')$ (10)

$\lambda_{qr}' = L_{lr}' i_{qr}' + L_m\,(i_{qs1} + i_{qs2} + i_{qr}')$ (11)

$\lambda_{dr}' = L_{lr}' i_{dr}' + L_m\,(i_{ds1} + i_{ds2} + i_{dr}')$ (12)

The electromagnetic torque can be calculated from the equation below:

$T_e = (P/2)(L_m/L_r')[\,\lambda_{dr}'(i_{qs1} + i_{qs2}) - \lambda_{qr}'(i_{ds1} + i_{ds2})]$ (13)

The rotor speed equation is,

$\omega_r = (1/J_r)\int(T_e - T_L)\,dt$ (14)

The position of d-q axis with respect to α-β axis can be measured in terms of θ and it can be calculated by integrating ω with respect to time.

$\theta = \int\omega\,dt$ (15)

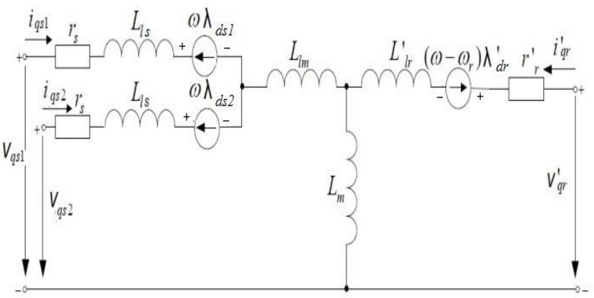

Fig.2. q-Axis Dynamic Equivalent Circuit Per Phase

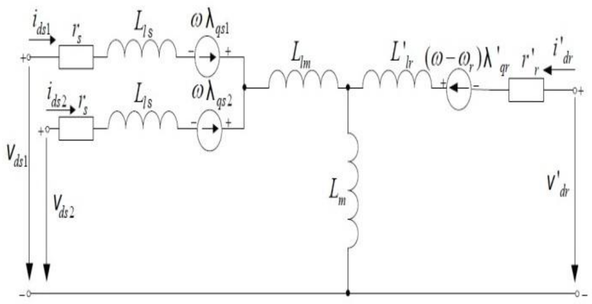

Fig.3. d-Axis Dynamic Equivalent Circuit Per Phase

III. Simulation of The Model

Six phase stationary axis voltages are transformed in to dq synchronous axis voltages and dq axis currents are transformed in to stationary axis voltages. The transformation equations are as follows:

ABC and XYZ to αβ (stationary axis) conversion;

$$\begin{bmatrix} V_{\beta s1} \\ V_{\alpha s1} \end{bmatrix} = \sqrt{2}/\sqrt{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix}$$

$$\begin{bmatrix} V_{\beta s2} \\ V_{\alpha s2} \end{bmatrix} = \sqrt{2}/\sqrt{3} \begin{bmatrix} \sqrt{3}/2 & -\sqrt{3}/2 & 0 \\ 1/2 & 1/2 & -1 \end{bmatrix} \begin{bmatrix} V_{xn} \\ V_{yn} \\ V_{zn} \end{bmatrix}$$

Now, αβ to dq conversion;

$V_{qs1} = V_{\beta s1}.\mathrm{Cos}\theta + V_{\alpha s1}\,\mathrm{Sin}\theta$

$V_{ds1} = V_{\alpha s1}.\mathrm{Cos}\theta - V_{\beta s1}\,\mathrm{Sin}\theta$

$V_{qs2} = V_{\beta s2}.\mathrm{Cos}\theta + V_{\alpha s2}\,\mathrm{Sin}\theta$

$V_{ds2} = V_{\alpha s2}.\mathrm{Cos}\theta - V_{\beta s2}\,\mathrm{Sin}\theta$

dq to αβ conversion;

$i_{\beta s1} = i_{qs1}.\mathrm{Cos}\theta - i_{ds1}\,\mathrm{Sin}\theta$

$i_{\alpha s1} = i_{ds1}.\mathrm{Cos}\theta + i_{qs1}\,\mathrm{Sin}\theta$

$i_{\beta s2} = i_{qs2}.\mathrm{Cos}\theta - i_{ds2}\,\mathrm{Sin}\theta$

$i_{\alpha s2} = i_{ds2}.\mathrm{Cos}\theta + i_{qs2}\,\mathrm{Sin}\theta$

αβ to ABC and XYZ conversion;

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{2}/\sqrt{3} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{\beta s1} \\ i_{\alpha s1} \end{bmatrix}$$

$$\begin{bmatrix} i_x \\ i_y \\ i_z \end{bmatrix} = \sqrt{2}/\sqrt{3} \begin{bmatrix} \sqrt{3}/2 & 1/2 \\ -\sqrt{3}/2 & 1/2 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} i_{\beta s2} \\ i_{\alpha s2} \end{bmatrix}$$

Table1.

Motor Parameters	L_{ls} (H)	L_{lm} (H)	L_m (H)	L_{lr}' (H)	R_s (Ω)	R_r' (Ω)	Van (V)	ω (rad/sec)	J_r ($Kg.m^2$)	P	Rated Power (KW)
	0.0132	0.011	1	0.0132	1.9	2.1	230	314	0.02	2	3

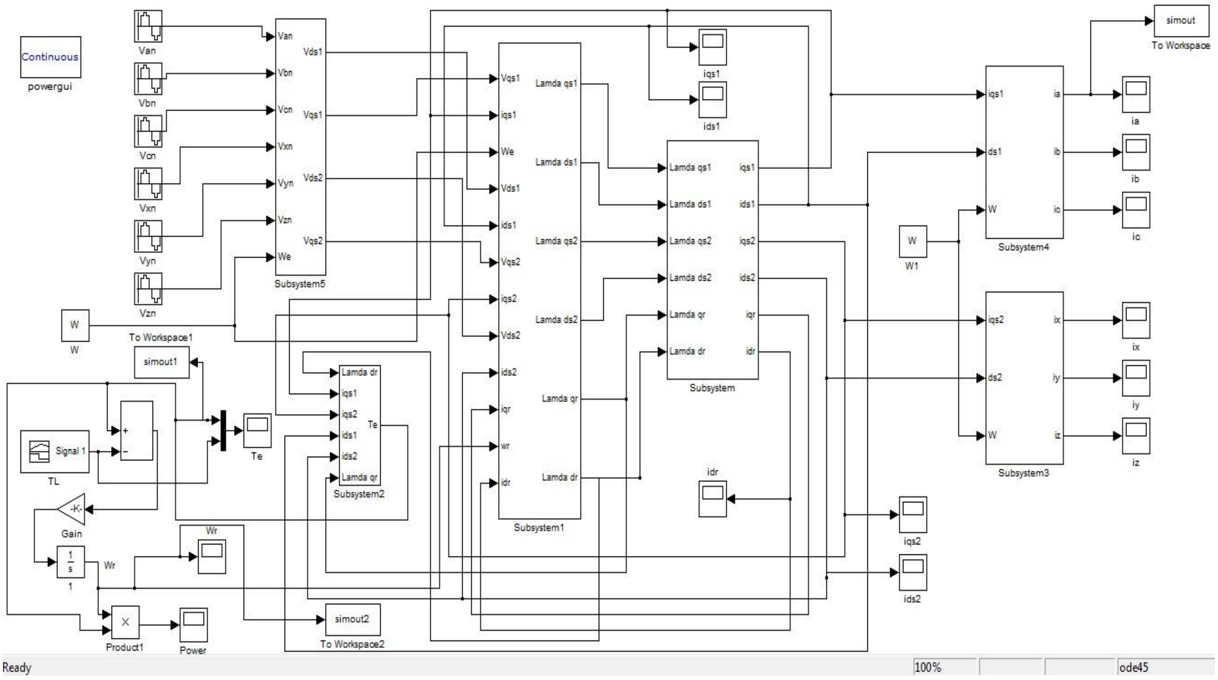

Fig.4. Simulink Model Of The Motor

IV. SIMULATION RESULTS

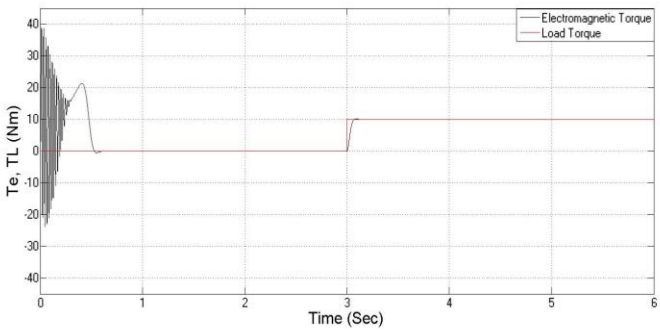

Fig.5. Electromagnetic Torque

Transient period lasts up to 0.305 sec. Motor gains steady state at 0.64 sec. During transient period high torque and speed oscillations are noticed. Steady state no-load torque is zero Nm. Constant rated load of 10 Nm is applied to the motor at 3 sec. steady state electromagnetic torque at load condition is 10Nm.

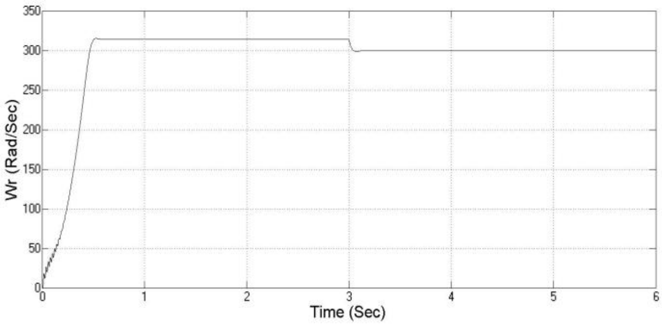

Fig.6. Rotor speed

No load speed is 314.15 rad/sec. Rotor speed at load condition is 299.46 rad/sec.

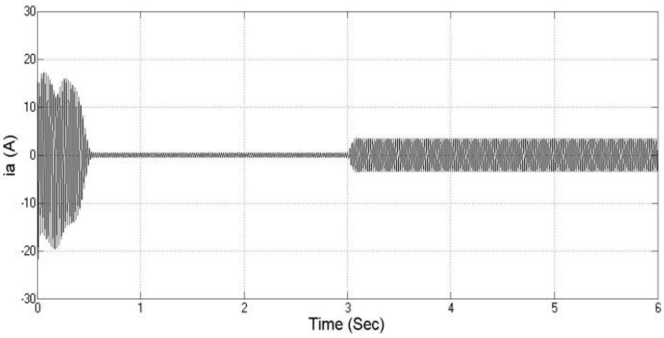

Fig.7. Phase current

Input phase current at no-load and rated load are 0.5 A and 3.5 A respectively

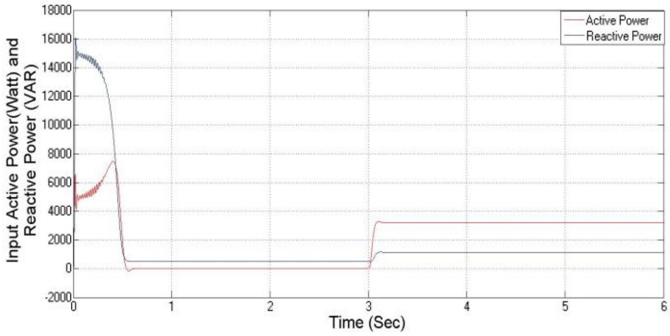

Fig.8. Input Power

At no-load motor consumes 1.475 watt real power as loss. At rated load input electrical power is 3211 watt. At no-load input reactive power is 496 VAR. At rated load input reactive power is 1148 VAR

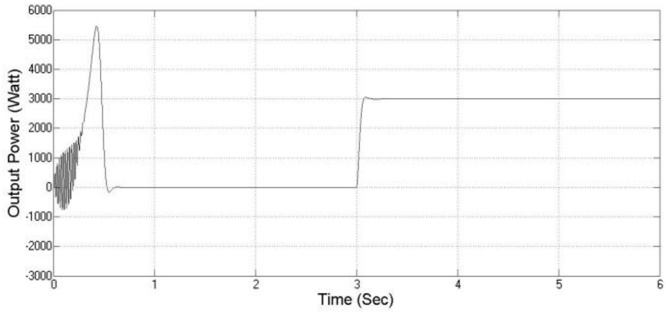

Fig.9. Output mechanical power

At no load and rated load mechanical output of motor are 0 watt and 3000 watt respectively. During transient period high oscillations are observed in output power. At rated load motor's efficiency is 93.4%.

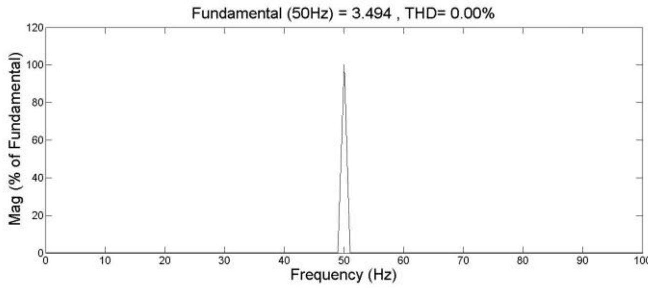

Fig.10. Harmonic analysis of phase current

0.00% THD observed in harmonic analysis of phase current

V. CONCLUSION

The result indicates towards high performance, good efficiency, less current per phase. Torque generation is smooth. Torque and speed ripples are negligible at steady state. As phase currents are not high and efficiency is good, it is suitable for high power applications. With respect to three-phase motor devices of less rating can be used per phase for certain amount of power

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VI. APPENDIX

V_{qs1}, V_{qs2} = q axis stator voltages
V_{ds1}, V_{ds2} = d axis stator voltages
V_{qr}', V_{dr}' = d-q axis rotor voltages
V_a, V_b, V_c, V_x, V_y, V_z = Six-phase input voltages
i_a, i_b, i_c, i_x, i_y, i_z = Six-phase input currents
L_{ls} = Stator leakage inductance
L_{lm} = Stator mutual leakage inductance
L_m = Air gap inductance
L_{lr}' = Rotor leakage inductance
L_r' = Rotor self-inductance
λ_{qs1}, λ_{qs2} = q axis stator flux linkages
λ_{ds1}, λ_{ds2} = d axis stator flux linkages
λ_{qr}', λ_{dr}' = d-q axis rotor flux linkages
i_{qs1}, i_{qs2} = q axis stator currents
i_{ds1}, i_{ds2} = d axis stator currents
i_{qr}', i_{dr}' = d-q axis rotor currents
ω, ω_r = speed of reference frame and rotor speed respectively
T_e = Electromagnetic torque
T_L = Load torque
P = Number of poles
ρ = d/dt

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