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Design and Analysis of Fault Tolerate feature of n-Phase Induction Motor Drive

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***Abstract*—**This paper presents design and analysis of fault tolerate feature of n-phase induction motor drive. The n-phase induction motor (more than 3-phases) has a number of advantages over conventional 3-phase induction motor, it has low torque pulsation with increased torque density, more fault tolerant feature, low current ripple with increased efficiency. When increasing the number of phases, it has reduced current per phase without increasing per phase voltage, resulting in an increase in the total power rating of n-phase motors in the same volume machine. In this paper, the theory of operation of a multi-phase induction motor is discussed. The detailed study of d-q modeling of n-phase induction motors is elaborated. The d-q model of n-phase (5, 6, 7, 9 and 12) induction motors is developed in a MATLAB/Simulink environment. The steady state and dynamic performance of the multi-phase induction motor is studied under varying load conditions. Comparison of 5-phase induction **is** presented under normal and fault conditions.

***Keywords*—**d-q model, dynamic Response, fault tolerant feature, matlab/simulink, multi-phase induction motor, transient response.

I. Introduction

ELECTRIC drives are employed for systems that require motion control – like transportation system, fans, robots, pumps, machine tools, etc. They have several inherent advantages such as flexible control characteristic, wide range of speed, torque and power and also it has high efficiency, lower noise, less maintenance and cleaner operation. The three-phase induction motor drives are most widely used electric motors in industry. They are simple, rugged, self-starting and low-cost rotor structures requiring less maintenance. They have high efficiency and good power factor. They are suitable for most industrial applications. However, they have some limitations for high power applications due to the following reasons, the voltage and current rating of the power converter device are increased. Its torque ripple frequency is low and amplitude of torque ripple is high resulting in higher operating noise and mechanical vibration. With loss of one or more of stator winding, it cannot continue to operate with an asymmetrical winding structure. The above said drawbacks can be overcome by the multi-phase induction motor drives, and they have been receiving a great deal of attention in recent years. It has reduced current per phase without increasing per phase voltage, resulting in an increase in the total power rating of multi-phase motors in the same frame significantly.

A single-phase is not overloaded as the current is shared by number of phase windings, so that the conductor size and power converter device ratings are reduced. Also they have better fault-tolerant capability, which is important in some reliability and crucial applications. Multi-phase motor has more than 3-phase stator winding (n > 3). It requires an n-phase input supply. This is derived from a conventional single-phase or three-phase utility power supply through a diode bridge rectifier-inverter circuit. It finds many applications such as electric/hybrid vehicles, traction drives, electrical ship propulsions, high power pumps and aerospace The multiphase induction motor dynamic model is derived by direct and quadrature (d-q) axes of two-phase motor. The d-q approach is most popular because the simple mathematical relation is obtained with two sets of windings, one for stator and the other on the rotor. The equivalence between the 3-phase to 2-phase machine is derived from easy inspection, and this d-q approach is most suitable for extending to multi-phase induction (n > 3). The d-q model of a six-phase machine is discussed in detail in [1]. A six-phase six-step voltage-fed induction motor model is presented in [2]-[5].

This paper discusses six-step voltage source inverter, while the motor is a modified standard three-phase squirrel-cage motor. The stator is rewound with two three-phase winding sets displaced from each other by 30 electrical degrees. A comparative study of six-phase drive with three-phase induction motor has been carried out in [6]-[8]. It is proved that the torque ripple of a six-phase drive is much lower than that of a three-phase drive, and of a higher frequency, causing significantly less mechanical stress and noise. A survey of asymmetrical six-phase induction motor modeling with control schemes and associated methods of VSI-PWM control is presented in [9]-[12]. The performance investigations of 5-phase induction motor and 6-phase induction motor with asymmetrical and symmetrical configurations respectively have been reported in [13]-[17]. The closed loop control scheme and experimental verification is presented. A five-phase induction machine including the effects of higher space and time harmonics is discussed in [18]. The asymmetrical, as well as symmetrical multiphase induction machines modeling are carried out in [19]-[25].

Generalized d−q models for machines with a high number of phases are generally not available in the commonly used MATLAB/Simulink environment. This paper focuses on the design and performance analysis of n-phase induction motor drive with fault tolerant features. An attempt is made in this paper for various simulation results obtained for n-phase induction machines are run at different load conditions under normal and fault conditions.

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II. Theory of Multi-Phase Induction Motor

In multi-phase induction motor, the stator carries an *n*-phase winding while the rotor is of squirrel cage type. The stator winding and its phase displacement is shown in Fig. 1 for different number of phases.

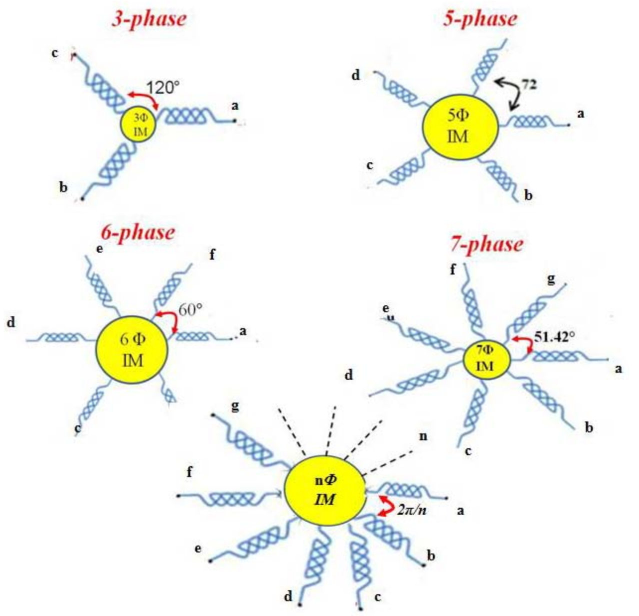

Fig. 1 Phase displacement of *n*-phase induction motor

The stator winding is fed from *n*-phase supply. The *n*-phase supply (1) is obtained from a single-phase or 3-phase utility power supply through a diode bridge rectifier-inverter circuit. The rotor winding derives its voltage and power from the externally energized stator winding through electromagnetic induction principle.

$$\begin{aligned} v_a &= v\cos\theta \\ v_b &= v\cos(\theta-\alpha) \\ v_c &= v\cos(\theta-2\alpha) \\ v_d &= v\cos(\theta-3\alpha) \\ v_e &= v\cos(\theta-4\alpha) \\ v_f &= v\cos(\theta-5\alpha) \\ &. \\ &. \\ v_n &= v\cos(\theta-n\alpha) \\ \alpha &= \frac{2\pi}{n} \end{aligned} \quad (1)$$

The phases are mutually displaced by *2π/n* degrees. Equal phase displacement is achieved in the 3-phase while unequal phase displacement is observed in the *n*-phase induction motor. Fig. 2 shows the adjacent and non-adjacent phase displacement of 5-phase system. The line and phase voltage of the 5-phase is derived from (2)-(4). The maximum line to line voltage is attained in the non-adjacent side. Table I shows the possible line-to-line voltages and the maximum voltages for 3, 5, 6 and 7-phases.

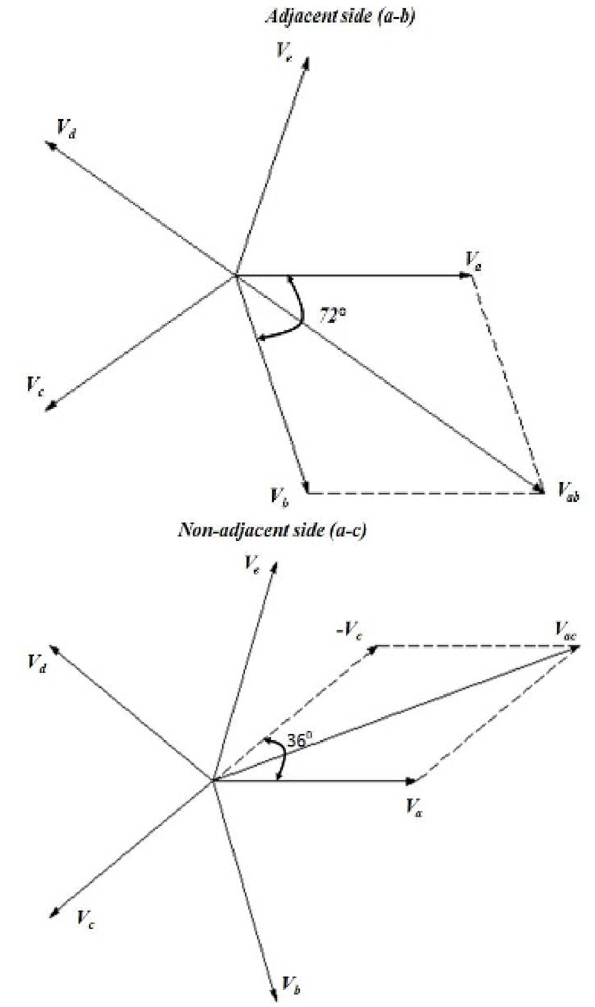

Fig. 2 Adjacent and Non-adjacent phase displacement of 5-phase system

$$\begin{aligned} V_a &= V_m\angle 0^\circ \\ V_b &= V_m\angle -72^\circ \\ V_c &= V_m\angle -144^\circ \\ V_d &= V_m\angle -216^\circ \\ V_e &= V_m\angle -288^\circ \end{aligned} \quad (2)$$

where $V_a=V_b=V_c=V_d=V_e=V_{ph}$ and $V_{ab}=V_{ac}=V_L$.

The adjacent line voltage (V_{ab}) is

$$\begin{aligned} V_{ab} &= V_a - V_b = V_m\angle 0^\circ - V_m\angle -72^\circ \\ &= V_m[(Cos0^\circ - jSin0^\circ)-(Cos72^\circ - jSin72^\circ)] \\ &= V_m[1-0.309-j0.9510] \\ &= V_m[0.691-j0.6510] \end{aligned} \quad (3)$$

Converting to polar form,

$$V_{ab} = 1.1755 V_m \angle 36°$$

The non-adjacent line voltage (V_{ac}) is

$$\begin{aligned} V_{ac} &= V_a - V_c = V_m \angle 0° - V_m \angle -144° \\ &= V_m[(Cos0° - jSin0°) - (Cos144° - jSin144°)] \\ &= V_m[1 + 0.809 - j0.5877] \\ &= V_m[1.809 - j0.5877] \end{aligned} \quad (4)$$

Converting to polar form,

$$V_{ac} = 1.902 V_m \angle 18°$$

TABLE I
VOLTAGE EQUATION FOR DIFFERENT PHASE NUMBERS

Phase Number	Line voltage			Power
	V_{ab}	V_{ac}	V_{ad}	
3-Phase	1.732 V_{Ph}	-	-	1.732 $V_L I_L cos\Phi$
5-Phase	1.1755 V_{Ph}	1.902 V_{Ph}	-	2.6288$V_L I_L cos\Phi$
6-Phase	0.999 V_{Ph}	1.732 V_{Ph}	2 V_{Ph}	3 $V_L I_L cos\Phi$
7-Phase	0.8676 V_{Ph}	1.5629 V_{Ph}	1.949 V_{Ph}	3.59$V_L I_L cos\Phi$

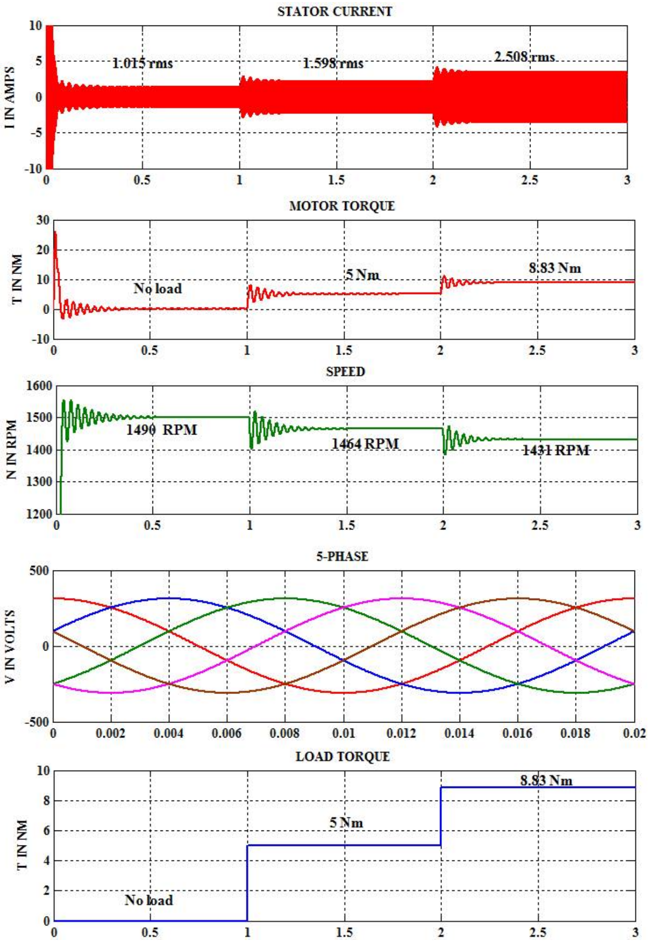

Fig. 3 Simulation results for 5-phase machine at different load conditions

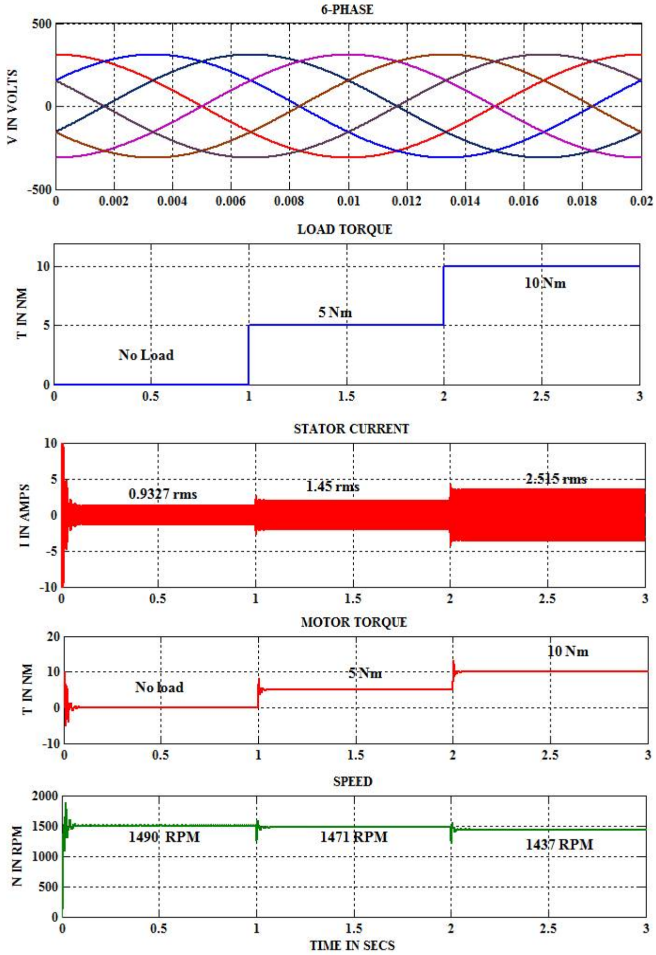

Fig. 4 Simulation results for 6-phase machine at different load conditions

III. MODELING OF MULTI-PHASE INDUCTION MOTOR

The multiphase induction motor dynamic model is derived by direct and quadrature (d-q) axes of two-phase motor. The d-q approach is most popular because of the simple mathematical relation is obtained with two sets of windings, one for stator and the other on the rotor. The equivalence between the 3-phase to 2-phase machine is derived from easy inspection, and this d-q approach is most suitable for extending to multi-phase induction ($n > 3$) by means of a 2-phase machine. In *n*-phase induction machine, the spatial displacement between any two consecutive stator phases is $\alpha = 2\pi/n$. The number of phases of multi-phase machine can be either even or odd. The mathematical model of n-phase machine is transformed by using Clarke's transformation matrix. In decoupling transformation matrix for an arbitrary phase number n can be given in power invariant form shown in (5), where $\alpha = 2\pi/n$. The first two rows of (5) represent fundamental flux and torque of d_1–q_1 components; stator to rotor coupling appears only in the equations for d_1–q_1 components.

$$\begin{bmatrix} v_{d_1} \\ v_{q_1} \\ v_{d_2} \\ v_{q_2} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ 0_+ \\ 0_- \end{bmatrix} = \sqrt{\frac{2}{n}} \begin{bmatrix} 1 & \cos\alpha & \cos2\alpha & \cos3\alpha & . \; . \; . & \cos n\alpha \\ 0 & \sin\alpha & \sin2\alpha & \sin3\alpha & . \; . \; . & \sin n\alpha \\ 1 & \cos2\alpha & \cos4\alpha & \cos6\alpha & . \; . \; . & \cos n\alpha \\ 0 & \sin2\alpha & \sin4\alpha & \sin6\alpha & . \; . \; . & \sin n\alpha \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & . \; . \; . & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & . \; . \; . & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \\ v_d \\ v_e \\ v_f \\ \cdot \\ \cdot \\ \cdot \\ v_n \end{bmatrix} \quad (5)$$

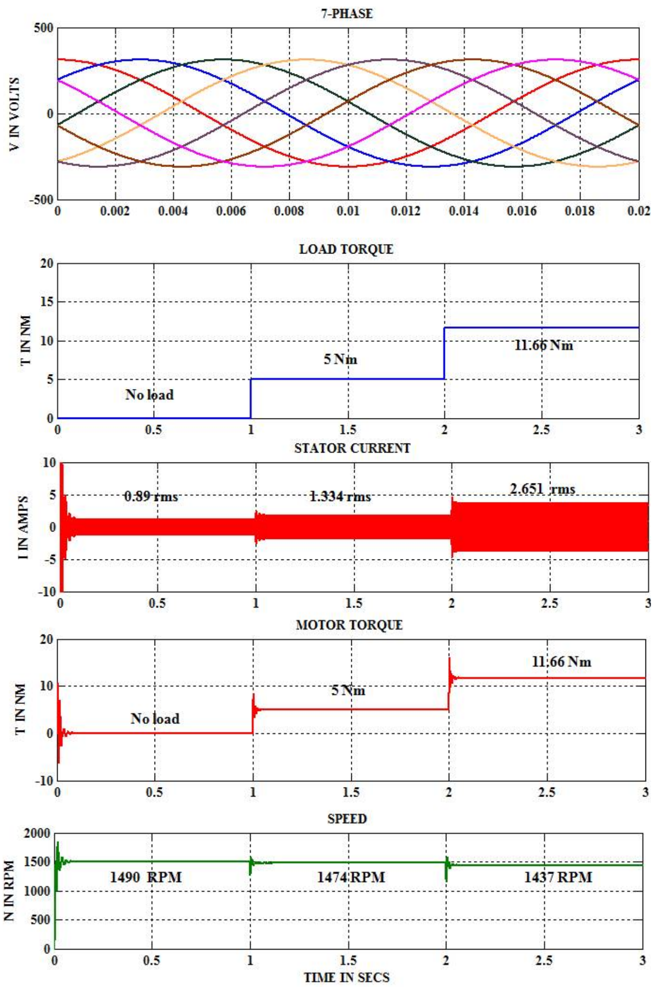

Fig. 5 Simulation results for 7-phase machine at different load conditions

Equations for pairs of d_2–q_2 components are completely decoupled from all the other components. When sinusoidal distribution of the flux around the air-gap is assumed that these d_2–q_2 components do not contribute to torque production Ina multi-phase star connected system the zero sequence components do not exist In a d_1–q_1 axes the stator to rotor coupling takes place and the rotational transformation is applied only to these two pairs of equations. Assume that the multi-phase machine equations are transformed into an arbitrary reference frame and rotating with angular speed of ω_e, the mathematical model of *n*-phase induction machine with sinusoidal winding distribution is given by (6)-(21), which are identical to three-phase machines.

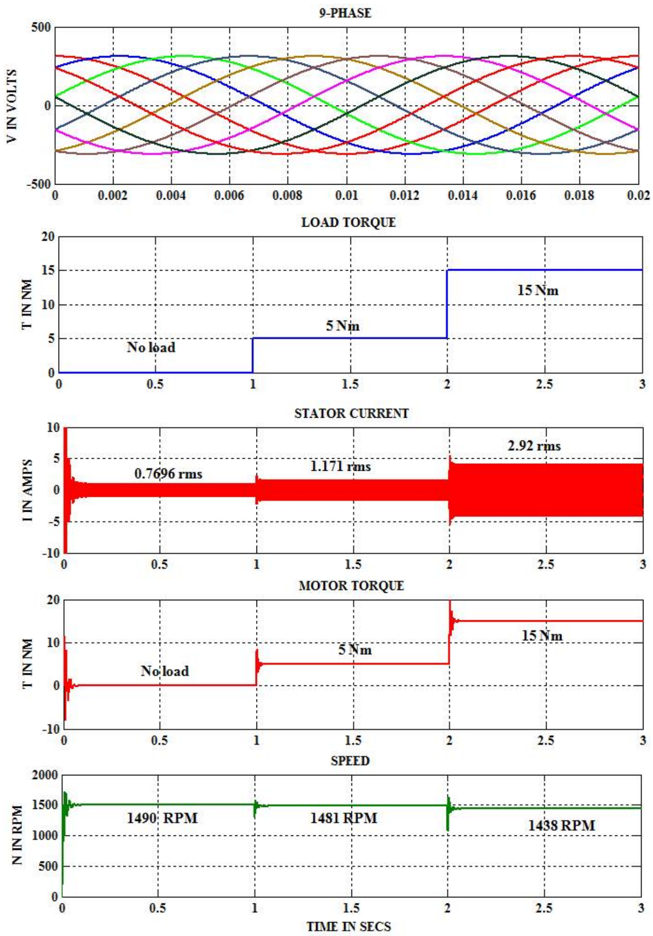

Fig. 6 Simulation results for 9-phase machine at different load conditions

Stator circuit equations:

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_e \psi_{qs} \quad (6)$$

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_e \psi_{ds} \quad (7)$$

Rotor circuit equations:

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr} \quad (8)$$

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \quad (9)$$

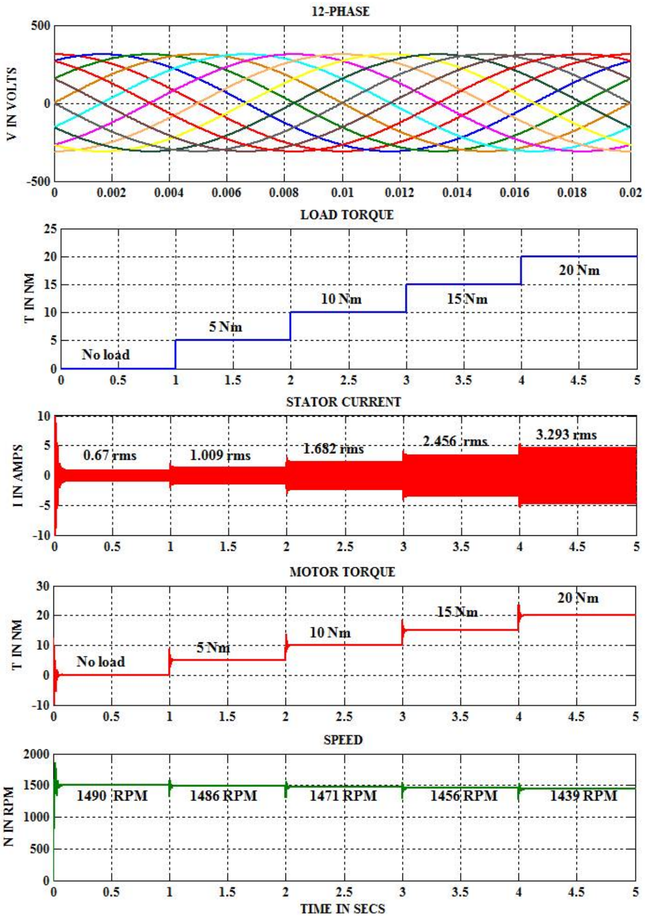

Fig. 7 Simulation results for 12-phase machine at different load conditions

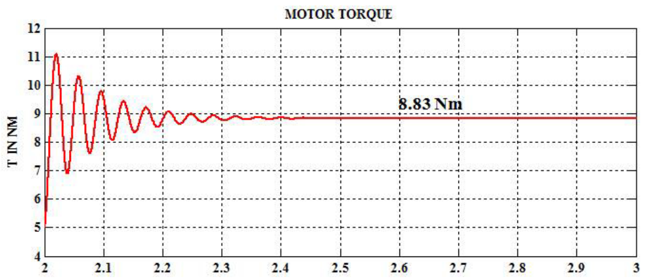

Fig. 8 Transient torque oscillations of 5-phase induction motor

Flux linkage expressions in terms of the currents are

$$\psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \tag{10}$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \tag{11}$$

$$\psi_{qs} = L_{ls} i_{ds} + L_m (i_{qs} + i_{qr}) \tag{12}$$

$$\psi_{qr} = L_{lr} i_{dr} + L_m (i_{qs} + i_{qr}) \tag{13}$$

$$\psi_{dm} = L_m (i_{ds} + i_{dr}) \tag{14}$$

$$\psi_{qm} = L_m (i_{qs} + i_{qr}) \tag{15}$$

$$i_{ds} = \frac{\psi_{ds}(L_{lr} + L_m) - L_m \psi_{dr}}{(L_{ls} L_{lr} + L_{ls} L_m + L_{lr} L_m)} \tag{16}$$

$$i_{qs} = \frac{\psi_{qs}(L_{lr} + L_m) - L_m \psi_{qr}}{(L_{ls} L_{lr} + L_{ls} L_m + L_{lr} L_m)} \tag{17}$$

$$i_{dr} = \frac{\psi_{dr}(L_{ls} + L_m) - L_m \psi_{ds}}{(L_{ls} L_{lr} + L_{ls} L_m + L_{lr} L_m)} \tag{18}$$

$$i_{qr} = \frac{\psi_{qr}(L_{ls} + L_m) - L_m \psi_{qs}}{(L_{ls} L_{lr} + L_{ls} L_m + L_{lr} L_m)} \tag{19}$$

where $L_m = (n/2)\, M$ and M is the maximum value of the stator to rotor mutual inductances in the phase-variable model.

$$T_e = P L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \tag{20}$$

$$\omega_r = \int \frac{P}{2J} (T_e - T_L)\, dt \tag{21}$$

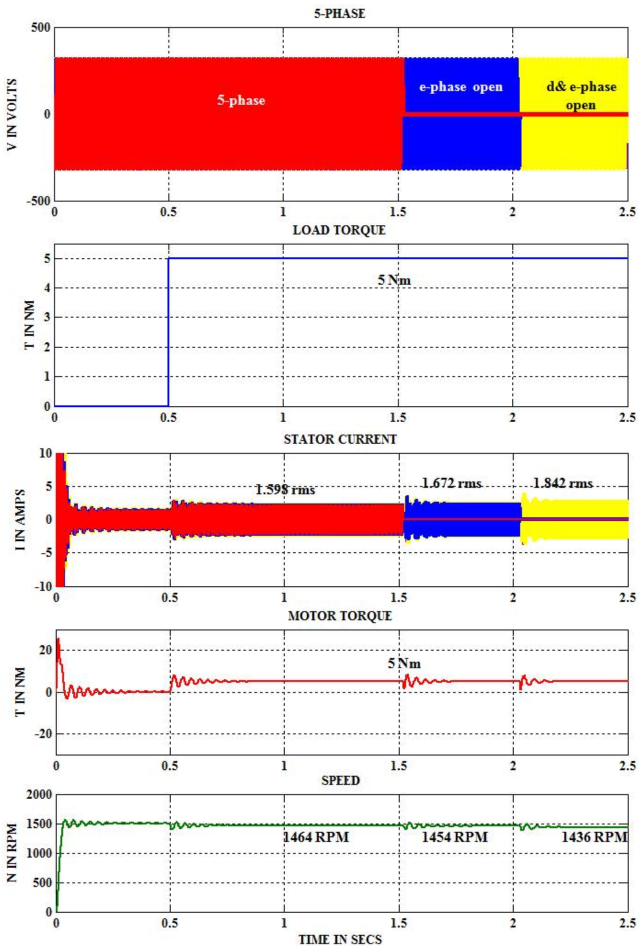

Fig. 9 Five-phase induction motor with one and two of the phases are opened

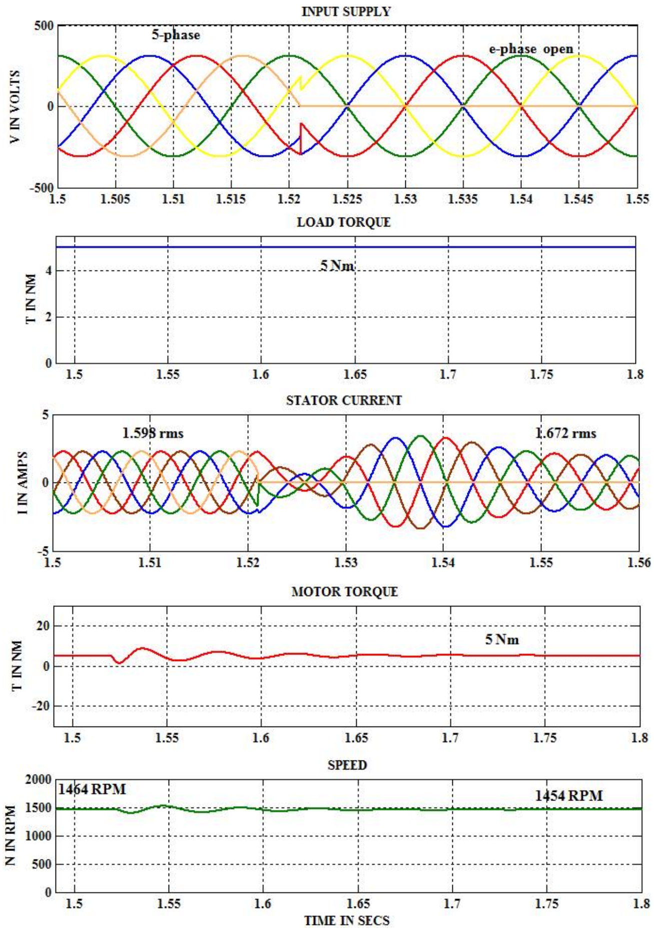

Fig. 10 Five-phase induction motor with e-phase open condition

The mathematical equations presented in (6)-(21) are used to model the multiphase induction motor in MATLAB/ Simulink environment. The stator voltage (V) and number of phases (n) are the inputs to the model. The stator current, speed and power are observed for different number of phases under normal and fault conditions and the results are discussed in detail in the following section.

IV. Simulation Results for Multi-Phase Induction Motor at Different Load Conditions

The simulation model of the n-phase induction motor given by (5)-(21) is simulated with the parameters given in Appendix A. The results are observed for n = 5, 6, 7, 9 and 12 under different loading conditions. The load torque is varied in steps and the corresponding variations in stator current, torque and speed are observed and discussed below. Fig. 3 shows the response of 5-phase induction motor at rated voltage and varying load conditions. At t = 0, motor is operated at no load and the load is varied in steps. It is seen that when the stator current increases and speed decreases with increasing load and the motor torque follows the load torque. The simulation is repeated for 6, 7, 9 and 12 phase to observe the waveforms for different loading conditions from no load to full load as shown in Figs. 4-7. The steady state results are presented in Table II. When number of phases increases, the current per phase decreases, whereas speed and output power increases. It is observed that when phase number is increased from 3Φ to 12Φ, the output power nearly is increased by 61%. Fig. 8 shows the transient torque oscillation during step change in torque condition. The result shows that the peak value of the transient torque is about 0.8 times of the rated torque and the duration of transient is about 0.04 sec. Fig. 9 shows the fault tolerant capability of the 5-phase motor and the simulation is done with one or two phase open condition. In Fig. 10 one of the a-phase is opened. The motor is allowed to run with 4Φ and the corresponding torque, speed and current are observed. The motor continues to run with reduced speed and power. Further reduction in speed is observed for 2Φ open condition and shown in Fig. 11. The performance comparison of 5-phase motor under normal and fault condition is shown in Table III.

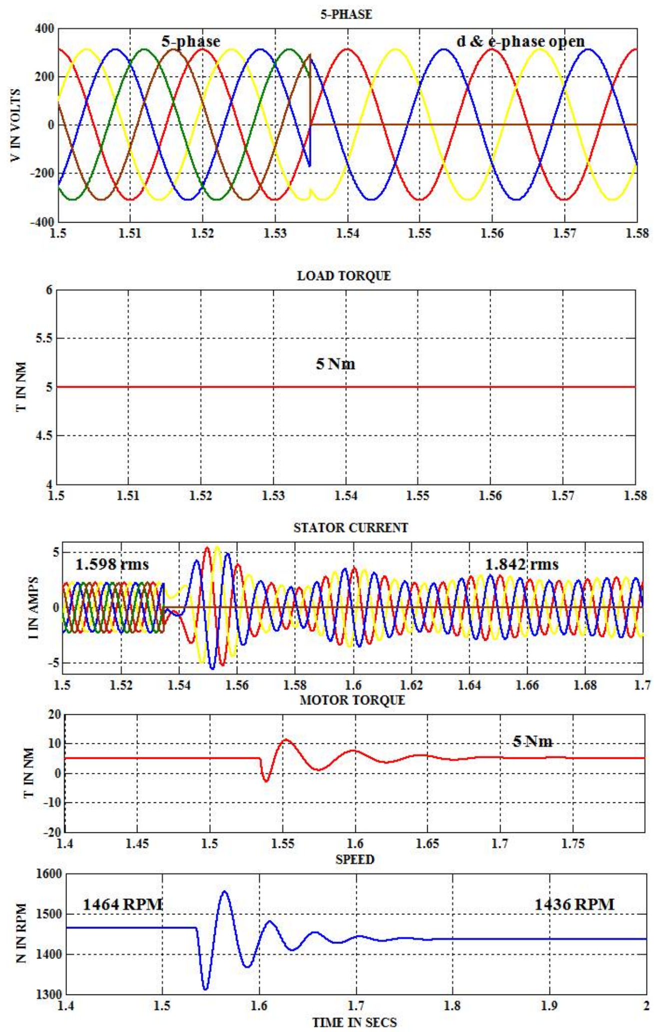

Fig. 11 Five-phase induction motor with d and e -phase open condition

TABLE II
STEADY-STATE RESULTS FOR DIFFERENT PHASE NUMBERS AT T_L=5 NM AND PHASE VOLTAGE IS 220 V

No of phases	N_r (RPM)	I_s/Phase (Amps)	Power in watts
3	1428	2.5	1320
5	1464	1.598	1406
6	1471	1.45	1531
7	1474	1.334	1643
9	1481	1.171	1855
12	1486	1.009	2131

TABLE III
COMPARISON UNDER NORMAL AND FAULT CONDITION

No of phases	Normal 5-phase	Fault Condition	
		1-phase open	2-phase open
Nr(RPM)	1464	1454	1436
Is/Phase (Amps)	2.599	1.672	1.842
Power in watts	1494	1250	1033

V. CONCLUSION

A generalized *d-q* model of *n*-phase induction motor drive is presented in this paper. The simulation model is developed using simpower system block set of the MATLAB/Simulink software. The model equations are presented in Section II *C*, and the simulation results for 5, 6, 7, 9 and 12 phases are discussed under varying load conditions. The performance of the motor with one or two phase open condition is studied. Based on the simulation results it is found that the multi-phase structure is able to start and run with 1 or 2-phase open conditions.

APPENDIX

TABLE IV
SIMULATION PARAMETERS OF MULTI- PHASE INDUCTION MOTOR DRIVE

Parameters	Values
Power	1 hp
Voltage	220 V
Phase	n-phase
Frequency	50 Hz
No. of poles	4
Stator resistance (Rs)	10 ohm
Rotor resistance (Rr)	6.3 ohm
Stator inductance (Ls)	0.04 mH
Rotor inductance (Lr)	0.04 mH
Mutual inductance (Lm)	0.42 mH
Inertia (J)	0.03 kg.m^2
Friction (F)	0.0015N.m.s

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