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Comparative Performance Analysis of Induction Motor in Multi-phase scenario

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Abstract

Multi-phase systems were not used frequently because of non-availability of multi-phase supply. Now with the increase in techniques & advancement in power electronics system, it is possible to obtain multi-phase supply to run these systems by designing the multi-phase inverter with the help of power electronic devices. The mathematical modelling of induction motor is carried out, first for 3-phase, as only supply for 3-phase is available. it is then extended for 5-, 6- & 9-phase systems. A Multi-phase induction motor system states many advantages when compared to a 3-phase system such as reduced ripple of electromagnetic torque, reduced ripple of rotor speed, reduced current value per phase and reduced voltage value per phase. The simulation is done in MATLAB/Simulink software. The simulation results (waveform) for 3-, 5-, 6- and 9-phase Induction Motor are obtained where the supply is obtained from n-phase inverter for multi-phase system is presented. The analysis of the induction motor system is done in terms of stator voltage & current, electromagnetic torque & rotor speed.

Keywords: Mathematical Modelling, MATLAB/Simulink software, Multi-phase Induction Motor Drive, Multi-phase Inverter, PWM Inverter

I. INTRODUCTION

Three-phase induction motors (IM) are used frequently and are noted for the advantages such as reliability, ruggedness, simple construction self-starting & reliable leading to wide acceptance of IM in many industrial applications [1][2]. The multi-phase system was used as it possessed the advantage of reducing the torque ripple as well as speed ripple of induction motor which degrades the performance of a 3-phase system.

Multi-phase systems were not used frequently due to unavailability of multi-phase supply. Now with the increase in advancement in power electronics systems, it is possible to generate multi-phase supply by designing the multi-phase inverter with the help of power electronic devices. The viability of the multi-phase system drive has increased tremendously as high-power electronic devices is needed for construction of a multi-phase inverter that has become economical and is easily available. [2][3].

Multi-phase induction motor gives several advantages for instance reduction of torque pulsation, fault tolerance capacity, high efficiency, lower current & voltage value per phase etc. Multi-phase motor drives system with an increased number of phases have enabled its application requiring high reliability such as Electric vehicle / Hybrid electric vehicles, aerospace applications ship propulsion and locomotive traction [1]-[3].

More paper work has shown that the multi-phase induction motor system are used for applications such as traction drives, finishing mills, roughing mills, coiler/mandrel, roller tables, shears, ship propulsion, electric aircraft, oil pumping application and many more [3][5][6].

A general theory of electric systems has inspired studying & learning of mathematical representation of an induction machine with several phases even more than three which is already established as a standard. In order to get a multi-phase supply there is a need to generate Sinusoidal Waveforms with an equal lag between the respective pulses. To achieve this, there is a need of a Pulse Width Modulation (PWM) inverter.

The number of phases needed drive the number of poles/legs of an inverter. 3-phase, 5-phase supply need 3 and 5 inverter poles respectively. The mathematical modelling of induction motor is carried out first for 3-phase as 3-phase supply is already available. Subsequently mathematical modelling is extended for 5-, 6- & 9-phase systems. The complete mathematical modelling of the multi-phase induction motor system is completed in MATLAB/Simulink software & to analyze the performance of the multi-phase induction motor system, the PWM technique of inverter is used for 3-phase which can be extended for 5-, 6- & 9-phase systems as well.

In the proposed work, inverter as a supply of multi-phase induction motor is studied. The performance of the system is stated and the results are presented for 3-, 5-, 6- and 9-phase systems based on mathematical modelling for respective n-phase supply. The comparative analysis of 3-, 5-, 6- & 9-phase inverter as a supply of induction motor system is studied.

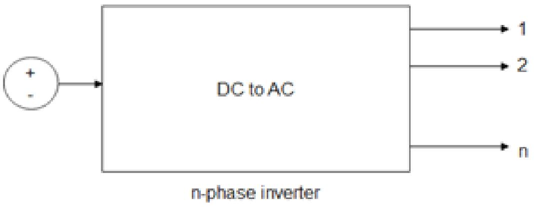


Fig. 1 Representation of Multi-phase Inverter

II. MATHEMATICAL MODELLING OF MULTI-PHASE INDUCTION MOTOR DRIVE

The phase variable of the multi-phase (3-, 5-, 6- & 9-phase) induction motor system is transformed using a mathematical transformation. The number of variables before & after mathematical transformation should be equal. The theory of reference frame has been used. They are assigned in order to understand the behaviour of induction motor system. The electromagnetic torque and rotor speed is obtained by with the help of dynamic modelling. The differential flux linkages, currents and voltages between the rotor as well as the stationary stator are modelled [5, 10].

The n-phase system has stator flux, current and voltage components after the transformation. In a multi-phase system, the phase displacement (α) is equals to α = 360/n, where n is the number of phases (3-, 5-, 6- & 9-) is calculated. The phase number can be either odd or even. The machine model is transformed using Clarke's transformation matrix [5][10]. For a 3-phase system, the phase displacement is 360/3 = 120 degrees, similarly for a 5-phase system it has a phase displacement of 72 degrees, for a 6-phase it has 60 degrees & for a 9-phase system, it has 40 degrees phase displacement.

The variables leading to fundamental flux and torque production are indicated in the first two equations (α–β components). The stator and rotor coupling also appears in the same equations [9].

The zero sequence components are omitted because the n-phase system is balanced.

$$\begin{bmatrix} V_d \\ V_q \\ V_x \\ V_y \\ \cdot \\ \vdots \\ \cdot \\ O \end{bmatrix} = \sqrt{\frac{2}{n}} \begin{bmatrix} 1 & \cos\alpha & \cos2\alpha & \cos3\alpha & . & . & . & . & \cos n\alpha \\ 0 & \sin\alpha & \sin2\alpha & \sin3\alpha & . & . & . & . & \sin n\alpha \\ 1 & \cos2\alpha & \cos4\alpha & \cos6\alpha & . & . & . & . & \cos n\alpha \\ 0 & \sin2\alpha & \sin4\alpha & \sin6\alpha & . & . & . & . & \sin n\alpha \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & . & . & . & . & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & . & . & . & . & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \\ V_f \\ \cdot \\ \cdot \\ V_n \end{bmatrix} \tag{1}$$

As n-phase is balanced, no zero-sequence component in any star-connected multiphase system is present. As the rotor winding is short-circuited, x, y & zero-sequence terms do not appear here & it is also not taken in the equations. One needs to consider only the α–β equations of the rotor winding [5] [10] [11].

For stator-rotor coupling to take place transformation is applied to this pair of equations (α–β equations). The formation of other phases is similar to a 3-phase machine. The model of the n-phase induction motor with sinusoidal winding is given as

Stator voltage equations (2) - (3) are given as

$$V_{ds} = R_s i_{ds} + \frac{d}{dt}\lambda_{ds} - \omega_e\lambda_{qs} \tag{2}$$

$$V_{qs} = R_s i_{qs} + \frac{d}{dt}\lambda_{qs} - \omega_e\lambda_{ds} \tag{3}$$

Assumption: The machine equations are transformed into a frame of reference rotating at angular speed.

Where, V_{ds} & V_{qs} are the stator voltage in d axis & q axis respectively.

Rotor voltage equations (4) - (5) are given as

$$V_{dr} = R_r i_{dr} + \frac{d}{dt}\lambda_{dr} - (\omega_e - \omega_r)\,\lambda_{qr} \tag{4}$$

$$V_{qr} = R_r i_{qr} + \frac{d}{dt}\lambda_{qr} + (\omega_e - \omega_r)\,\lambda_{dr} \tag{5}$$

Where, V_{dr} & V_{qr} are the rotor voltage in d axis & q axis respectively.

After finding out the stator & rotor circuit equation, flux linkage equations are found.

Flux linkage equations (6) - (9) in d & q axis are

$$\lambda_{qs} = i_{qs}L_s + i_{qr}L_m \tag{6}$$

$$\lambda_{ds} = i_{ds}L_s + i_{dr}L_m \tag{7}$$

$$\lambda_{qr} = i_{qr}L_r + i_{qs}L_m \tag{8}$$

$$\lambda_{dr} = i_{dr}L_r + i_{ds}L_m \tag{9}$$

Where, λ_{qs} & λ_{ds} = stator flux linkages in d & q axis and λ_{qr} & λ_{dr} = rotor flux linkages in d & q axis.

Now from the flux linkage equations, the current equations in the d & q axis can be obtained using equations (10) to (13) are given as

$$i_{ds} = \int \frac{V_{ds}}{L_s} - \frac{i_{ds}r_s}{L_s} - \frac{L_m P i_{dr}}{L_s} + \omega_e i_{qs} + \frac{\omega_e L_m i_{qr}}{L_s} \tag{10}$$

$$i_{qs} = \int \frac{V_{qs}}{L_s} - \frac{i_{qs}r_s}{L_s} - \frac{L_m P i_{qr}}{L_s} - \omega_e i_{ds} - \frac{\omega_e L_m i_{dr}}{L_s} \tag{11}$$

$$i_{dr} = \int \frac{V_{dr}}{L_r} - \frac{i_{dr} r_r}{L_r} - \frac{L_m P i_{ds}}{L_r} + \omega_c i_{qr} + \frac{\omega_c L_m i_{qs}}{L_r} \tag{12}$$

$$i_{qr} = \int \frac{V_{qr}}{L_r} - \frac{i_{qr} r_r}{L_r} - \frac{L_m P i_{qs}}{L_r} - \omega_c i_{dr} - \frac{\omega_c L_m i_{ds}}{L_r} \tag{13}$$

where, $\omega_c = \omega_e - \omega_r$

Lastly the electromagnetic torque (T_e), rotor speed (ω_r), angular speed (ω_e) are obtained & they are given in (14), (15) & (16) as

$$T_e = P\, L_m\, (i_{qs} i_{dr} - i_{ds} i_{qr}) \tag{14}$$

$$\omega_r = \int \frac{1}{J} (T_e - T_l) \tag{15}$$

$$\omega_e = \frac{P}{2} \int (T_e - T_l) \tag{16}$$

Nomenclature

P = Power

V = Voltage

f = Frequency

p = No. of poles

L_s = Stator inductance

R_s = Stator resistance

R_r = Rotor resistance

J = Inertia

L_r = Rotor inductance

The torque and speed equations are obtained for a 3-phase induction motor. The same method is carried out for 5-, 6- & 9-phase induction motors. For example, for a 5-phase system, a 5-phase supply is required which is then transformed into an arbitrary reference frame [9]. Similarly, for a 6-phase system, 6-phase supply and a 9-phase system, a 9-phase supply is required.

III. INVERTER SUPPLY OF MULTI-PHASE INDUCTION MOTOR SYSTEM

The n-phase PWM inverter's power circuit diagram is given in Fig.2. The circuit comprises of 'n' half-bridges, which have a phase displacement of 360/'n' degrees leading to generation of n-phase voltage waves. The input dc supply is obtained from a 3-phase power supply through a diode bridge rectifier circuit. The voltages V_a, V_b, V_c, V_d, V_e, V_f……………..….,Vn are the inverter pole voltages are connected to the load terminals. The simple representation of the inverter supply for induction motor is given in Fig.3.

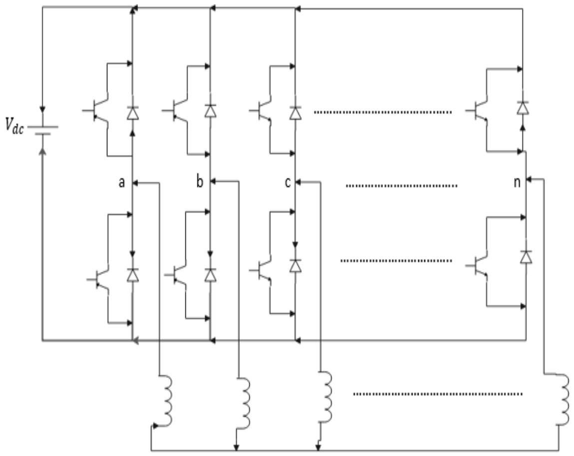


Fig. 2 Representation of Multi-phase Inverter

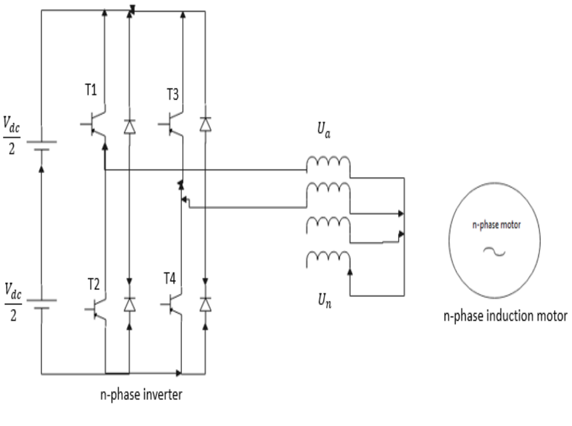
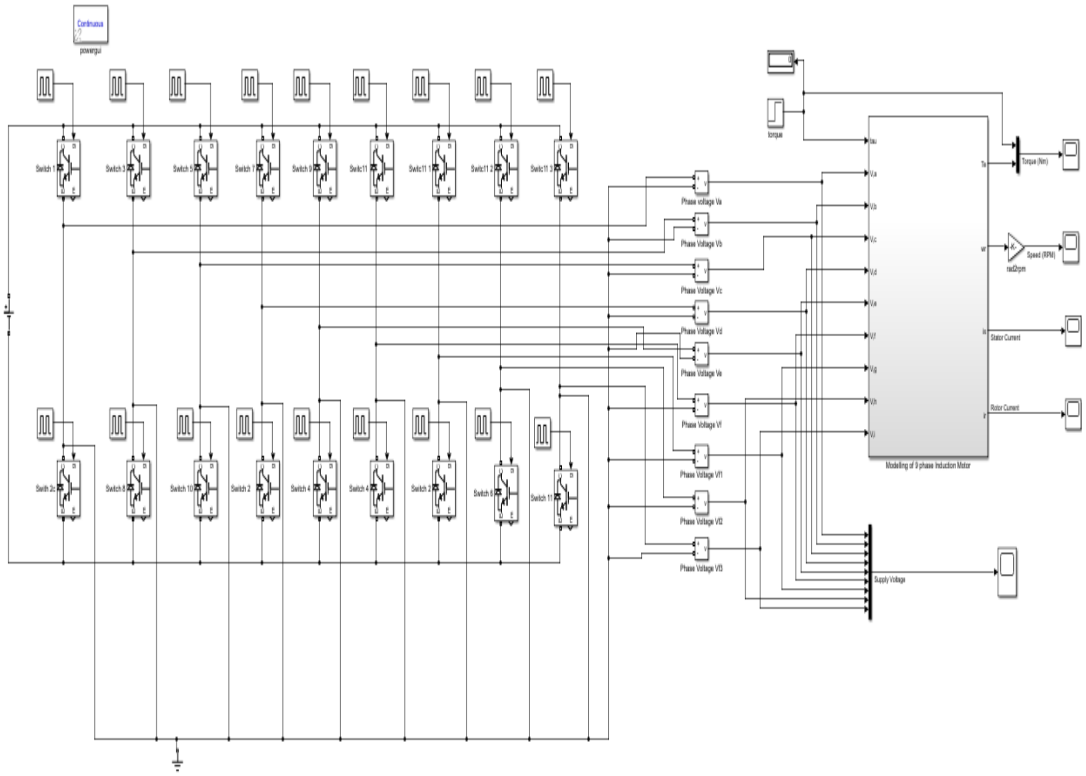


Fig. 3 Simple representation of inverter as a supply of induction motor



IV. SIMULATION RESULTS

Simulation is studied to obtain the result & performance of the multi-phase system is shown in terms of electromagnetic torque, rotor speed, stator voltage & stator current. The simulation of the model is developed in the MATLAB/Simulink software & is indicated in Fig.5. The results (waveform) are obtained for 3-, 5-, 6- & 9-phase induction motor with the help of parameters stated in Table I.

It also includes the waveform results of stator voltage, stator current, electromagnetic torque & rotor speed when inverter is kept as a supply. The simulation results are obtained for a 3-phase system & accordingly, further the simulation is done for 5-, 6- and 9-phase induction motor system.

It is seen that with the increase in the phase numbers, torque ripple & speed ripple is significantly reduced. It is seen that as the phases are increasing, voltage per phase is reduced.

The waveforms for torque, current, and speed show reduced ripples as the number of phases increase .This behaviour makes the system capable for high power application.

The values of torque & speed are almost the same even when the numbers of phases are altered. They demonstrate significantly reduced ripples and the values of current &

voltage also decrease, giving the advantage of small current & voltage per phase. The values are shown in Table II.

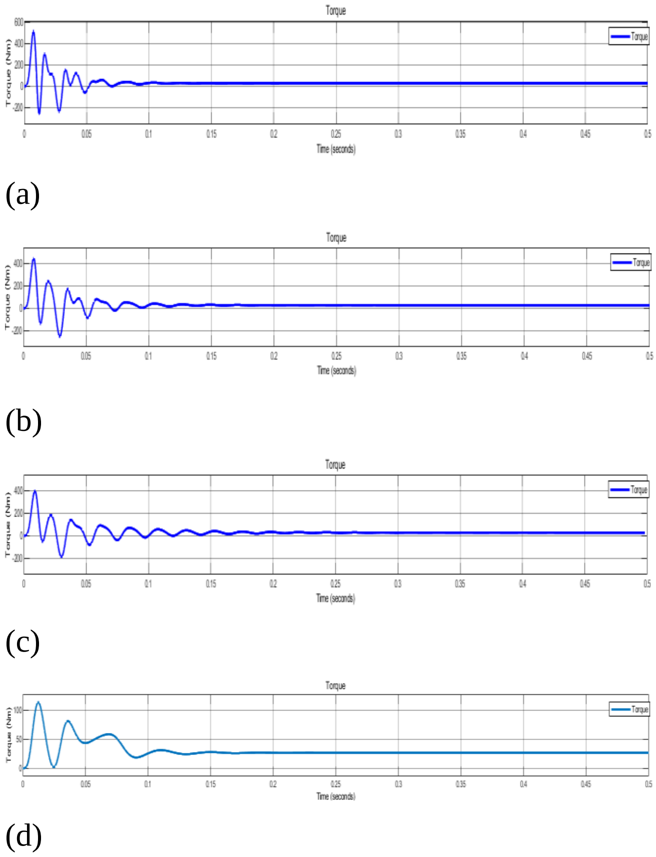
Table I. Simulation Parameters

PARAMETERS	VALUES
Power	6 HP
Voltage	400 V
Phase	3-,5-,6-& 9-phase
Frequency	50 Hz
No. of poles	4
Stator resistance (R_s)	1.405 Ω
Rotor resistance (R_r)	1.395 Ω
Stator inductance (L_s)	0.178 mH
Rotor inductance (L_r)	0.178 mH
Mutual inductance (L_m)	0.1722 mH
Inertia (J)	0.0131 kg/m^2

Table II. Results obtained for Inverter as a supply of Induction Motor

No. of phase	Voltage	Current	Electromagnetic Torque	Rotor Speed
	(Volts)	(Amperes)	(Newton meter)	((rpm)
3	230.94	6.46	26.50	1456
5	178.88	5	27.05	1465
6	163.29	4.56	27.85	1472
9	133.33	3.73	28.05	1483

Fig. 4 shows the electromagnetic torque for 3-, 5-, 6- & 9-phase system. Here ripples of electromagnetic torque are reduced as the number of phases are increased with a slight difference as compared to AC supply is that ripples seen are more in this case compared to AC supply but still the ripples are reducing as the number of phases are increasing.



(a)

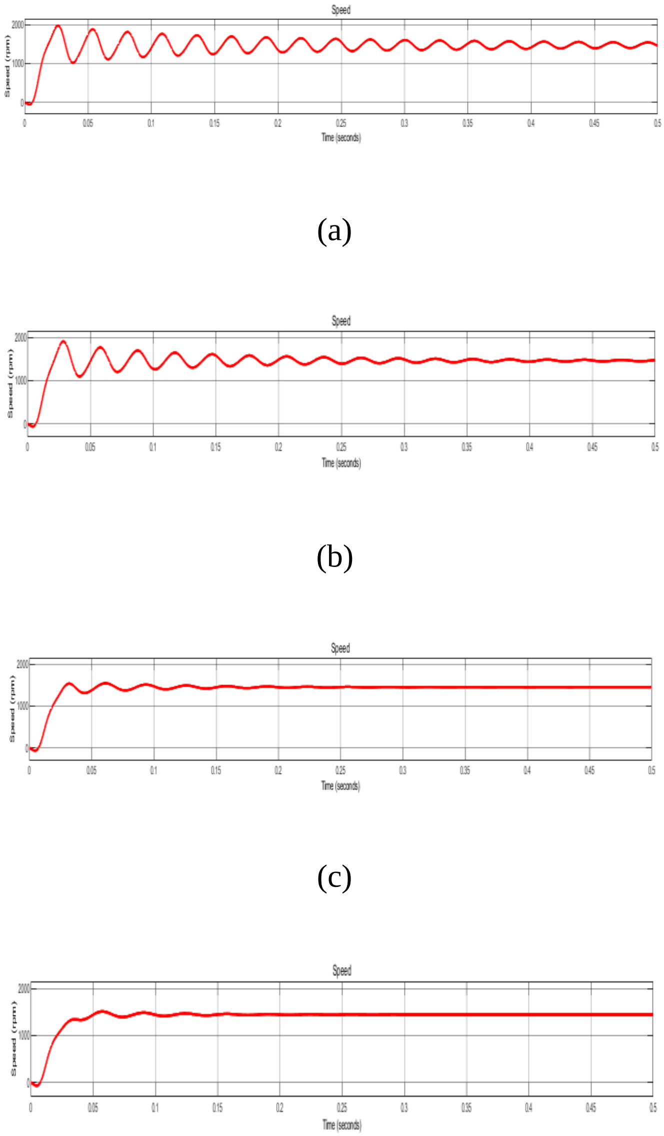
(b)

(c)

(d)

Fig. 4 Electromagnetic torque produced by (a)3-phase (b) 5-phase (c) 6-phase (d) 9-phase

Fig. 5 shows the rotor speed for 3-, 5-, 6- & 9-phase system. Here the same thing is observed that as the phases are increased, the ripples are reduced making 9-phase system more efficient for high-power applications**.**



(a)

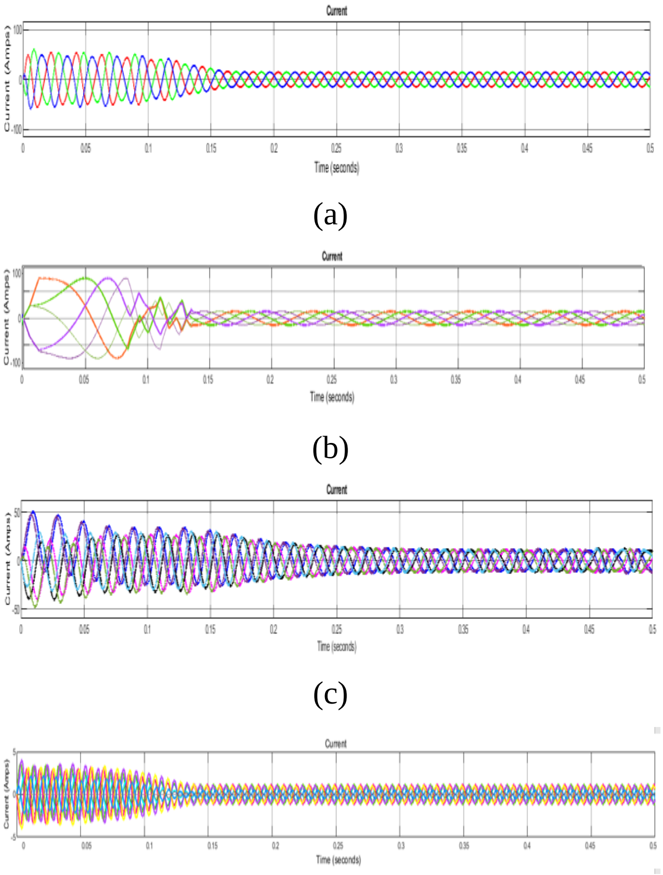
(b)

(c)

(d)

Fig. 5 Speed in rpm (a)3-phase (b) 5-phase (c) 6-phase (d) 9-phase

Fig. 6 shows the stator current for 3-, 5-, 6- & 9-phase system. Here the same thing is observed that as the phases are increased the stator current per phase value are reduced making 9-phase system more efficient for high-power applications.



(a)

(b)

(c)

(d)

Fig. 6 Stator Current for (a) 3-phase (b) 5-phase (c) 6-phase (d) 9-phase

V. CONCLUSION

This paper presents a modeling and analysis of multi-phase induction motor system (3-, 5-, 6- & 9-phase) with the help of inverter (n-phase).

The simulation results are shown for 3-, 5-, 6- and 9-phases.

From the simulation results, it is concluded that the 9-phase system has reduced ripples for torque, reduced ripples for speed, and reduced value of current per phase & reduced value for voltage per phase compared to 3-, 5- & 6-phase system.

When the waveforms of the 3-, 5-, 6- & 9- are compared, 9-phase system are smoothened earlier than 3-, 5- & 6-phase system that means 9-phase system is way more efficient.

As the number of phase is increasing, more efficient system is obtained.

Hence the results prove that the 9-phase system is highly efficient for high power applications and as we go on increasing the number of phases, more smoothened waveforms are obtained & it is more efficient for high power applications.

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