Modeling and Analysis of Multi-Phase Inverter Fed Induction Motor Drive with Different Phase Numbers

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Abstract: - This paper presents a modeling and analysis of multi-phase inverter fed multi-phase induction motor drive with different number of phases. Multiphase induction motor drives possess several advantages over conventional three-phase drives such as lower torque pulsation, fault tolerance, stability, high efficiency and lower current ripple and reduced current per phase without increasing voltage per phase etc., In this paper, a detailed d-q modeling of multi-phase induction motor drive with offset injection method based multi-phase VSI is developed. The simulation results are presented for 3, 5, 7, 9 and 11 phase induction motor under varying load conditions. The performance of the drive is analyzed in terms of stator current, power, torque ripple and fault tolerant feature respectively. Feasibility of the developed approach has been identified with the optimum number of phases for electric vehicle applications.

Key-Words: - Dynamic response, EV (Electric Vehicle), fault-tolerant feature, multi-phase drive, Switching technique, transient response.

1 Introduction

Multi-Phase machine drives are fast increasing in recent years, due to their several inherent benefits such as lower torque pulsation, reduction in harmonic currents, reduced stator current per phase without the need to increase the phase voltage, greater reliability, fault tolerant feature and increased power in the same frame as compared to three phase machine. They are mostly used in high power applications, such as ship propulsion, electric aircraft, and electric/hybrid electric vehicles etc., as reported in [1]. Detailed modeling of multi-phase induction motor drive is described in [1-5].Multi-phase motors requires multi-phase voltage source inverter (VSI) for their input supply. An inverter topology uses two switches connected in series as one inverter pole. The number of inverter poles depends on number of phases. For example, a three-phase inverter will have three inverter poles whereas a nine-phase inverter will have nine inverter poles. The switching pattern of the three phase inverter should be modified according to the number of phases. For three phase inverters, the sinusoidal pulse width modulation (SPWM) method, space vector pulse width modulation (SVPWM), harmonic injection method and offset injection method are extensively discussed in literature [6-18].The SPWM and SVPWM techniques are extended for multi-phase VSI [6-15]. The SPWM schemes are more flexible and easy to implement. However the output waveforms contain more harmonics resulting in reduced fundamental component and efficiency. To achieve the better output voltage, the several space vector pulse width modulation (SVPWM) techniques are discussed, such as conventional SVPWM, space vector disposition SVPWM, discontinuous SVPWM and multi-dimensional SVPWM based drives are presented in [8-15]. The complexity involved in the SVPWM technique is more for higher number of phases. The inverter output voltage space vectors changes to 2^n states, since there are 2^n different switching configurations. Hence the SVPWM has complicated controlling algorithm for sector identification, look up table, angle information and voltage space vector amplitude measurements. Therefore a simple and efficient switching technique is needed for multi-phase voltage source inverter which would overcome the complexity involved with higher number of phases. In this paper to investigate the performance of the multi-phase VSI with the improved PWM techniques namely offset injection method, which is commonly used for three phase VSIs it can be extended for multi-phase VSIs. In the offset injection method, signal generation depends upon the sampled reference phase amplitude and sampling period [16-19].

In the proposed work offset injection method fed multi-phase induction motor drive is studied. The performance of the drive is investigated with these switching techniques and the results are presented for 3, 5, 7, 9 and 11 phases. Based on the simulation results to identify the optimum number of phases for EV applications in terms of current, torque ripple and power and fault tolerant feature.

2 D-Q Model of 5-Phase Induction Motor Drive

The per phase equivalent circuit of the induction machine is valid only for the steady- state condition and the dynamic axis and space vector model is developed in [20]. The d–q–o reference frame transformation has long been used successfully in the analysis and control of three-phase electric machines [4].The same approach is used for five phase drive. The axis components in the five-phase drive are d–q, α – β and 0 respectively. The α – β components do not contribute to torque production in a sinusoidal distribution of the flux around the air-gap is assumed. The zero-sequence components does not exist in any star-connected multiphase system. A stator to rotor coupling takes place only in *d–q* equations and the rotational transformation is applied only to these two pairs of equations. Its form is similar to a three-phase machine. The machine equations are transformed into a synchronous reference frame with sinusoidal winding distribution is given with

$$\begin{bmatrix} V_d \\ V_q \\ V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \sqrt{\frac{2}{5}} \begin{bmatrix} 1 & \cos\alpha & \cos 2\alpha & \cos 3\alpha & \cos 4\alpha \\ 0 & \sin\alpha & \sin 2\alpha & \sin 3\alpha & \sin 4\alpha \\ 1 & \cos 2\alpha & \cos 4\alpha & \cos\alpha & \cos 3\alpha \\ 0 & \sin 2\alpha & \sin 4\alpha & \sin\alpha & \sin 3\alpha \\ \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \end{bmatrix} \quad (1)$$

Stator circuit equations:

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_e \psi_{qs} \quad (2)$$

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_e \psi_{ds} \quad (3)$$

Rotor circuit equations:

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr} \quad (4)$$

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \quad (5)$$

Flux linkage expressions in terms of the currents are

$$\psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \quad (6)$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \quad (7)$$

$$\psi_{qs} = L_{ls} i_{ds} + L_m (i_{qs} + i_{qr}) \quad (8)$$

$$\psi_{qr} = L_{lr} i_{dr} + L_m (i_{qs} + i_{qr}) \quad (9)$$

$$\psi_{dm} = L_m (i_{ds} + i_{dr}) \quad (10)$$

$$\psi_{qm} = L_m (i_{qs} + i_{qr}) \quad (11)$$

$$i_{ds} = \frac{\psi_{ds}(L_{lr} + L_m) - L_m \psi_{dr}}{(L_{ls}L_{lr} + L_{ls}L_m + L_{lr}L_m)} \quad (12)$$

$$i_{qs} = \frac{\psi_{qs}(L_{lr} + L_m) - L_m \psi_{qr}}{(L_{ls}L_{lr} + L_{ls}L_m + L_{lr}L_m)} \quad (13)$$

$$i_{dr} = \frac{\psi_{dr}(L_{ls} + L_m) - L_m \psi_{ds}}{(L_{ls}L_{lr} + L_{ls}L_m + L_{lr}L_m)} \quad (14)$$

$$i_{qr} = \frac{\psi_{qr}(L_{ls} + L_m) - L_m \psi_{qs}}{(L_{ls}L_{lr} + L_{ls}L_m + L_{lr}L_m)} \quad (15)$$

where symbols R and L stands for resistance and inductance. While indices *s* and *r* identify the stator and rotor and index *l* stands for leakage inductances. v, i, Ψ, L_m, L_s, and L_r denote voltage, current , flux linkage, magnetizing inductance, stator self-inductance and rotor self-inductance respectively. The torque and speed equation is given with

$$T_e = P L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (16)$$

$$w_r = \int \frac{P}{2J}(T_e - T_L)\, dt \quad (17)$$

3 Generalized Offset Injection Method for Multi-Phase VSI

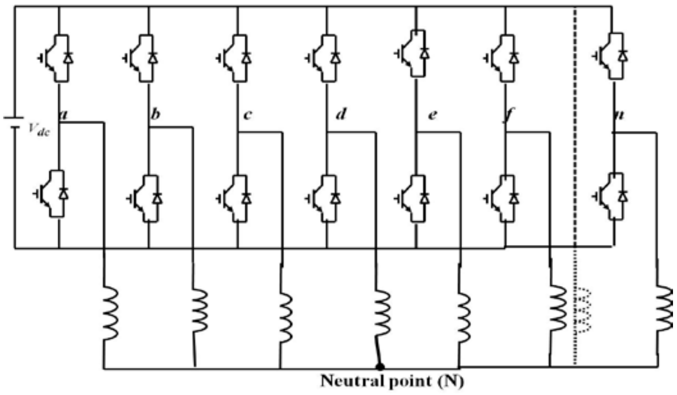

Fig.1: Power circuit diagram of multi-phase VSI.

The power circuit diagram of *n*-phase VSI is shown in Fig.1. The circuit consists of *n* half-bridges, which are mutually displaced by *2π/n* degrees to generate the n-phase voltage waves. The input dc supply is obtained from a single phase or 3-phase utility power supply through a diode-bridge rectifier circuit. The voltages $V_a, V_b, V_c, V_d, V_e, V_f \ldots V_n$ are the inverter pole voltages connected to load terminals. It is seen that the switching states of each pole should be combined with each other pole to create the required *n*-phase output voltages. The load phase voltages and inverter pole voltages is as given in the following relations (18):

$$
\begin{aligned}
V_{aN} &= \frac{n-1}{n}V_a - \frac{1}{n}(V_b + V_c + V_d + V_e + V_f + \ldots\ldots + V_n \\
V_{bN} &= \frac{n-1}{n}V_b - \frac{1}{n}(V_a + V_c + V_d + V_e + V_f + \ldots\ldots + V_n) \\
V_{cN} &= \frac{n-1}{n}V_c - \frac{1}{n}(V_a + V_b + V_d + V_e + V_f + \ldots\ldots + V_n \\
V_{dN} &= \frac{n-1}{n}V_d - \frac{1}{n}(V_a + V_b + V_c + V_e + V_f + \ldots\ldots + V_n \\
V_{eN} &= \frac{n-1}{n}V_e - \frac{1}{n}(V_a + V_b + V_c + V_d + V_f + \ldots\ldots + V_n \\
V_{fN} &= \frac{n-1}{n}V_f - \frac{1}{n}(V_a + V_b + V_c + V_d + V_f + \ldots\ldots + V_n \\
&. \\
&. \\
&. \\
V_{nN} &= \frac{n-1}{n}V_n - \frac{1}{n}(V_a + V_b + V_c + V_d + V_e + V_f \ldots\ldots
\end{aligned}
\quad (18)
$$

In the offset injection method signal generation depends upon the sampled reference phase amplitude and sampling period. The time duration for different voltages is maintained completely related to the voltage modulation task according to the equal volt-second principle. Therefore, the modulation task can be greatly simplified by considering the relation between the time duration and the output voltage. For that reason, an imaginary time value will be introduced. This value is directly related to the phase voltage and sampling time (T_s), as defined in (19)

$$
\begin{aligned}
&V_{as}^* : V_{dc} = T_{as} : T_s \Rightarrow T_{as} = \frac{T_s}{V_{dc}} V_{as}^* \\
&V_{bs}^* : V_{dc} = T_{bs} : T_s \Rightarrow T_{bs} = \frac{T_s}{V_{dc}} V_{bs}^* \\
&V_{cs}^* : V_{dc} = T_{cs} : T_s \Rightarrow T_{cs} = \frac{T_s}{V_{dc}} V_{cs}^* \\
&V_{ds}^* : V_{dc} = T_{ds} : T_s \Rightarrow T_{ds} = \frac{T_s}{V_{dc}} V_{ds}^* \\
&V_{es}^* : V_{dc} = T_{es} : T_s \Rightarrow T_{es} = \frac{T_s}{V_{dc}} V_{es}^* \\
&\vdots \\
&V_{ns}^* : V_{dc} = T_{ns} : T_s \Rightarrow T_{ns} = \frac{T_s}{V_{dc}} V_{ns}^*, n = a,b,c,d,e\ldots
\end{aligned}
\quad (19)
$$

Where $V_{as}, V_{bs}, V_{cs}, V_{ds}, V_{es}, V_{fs} \ldots V_{ns}$ are the (*a,b,c,d,e,f…n)* reference phase voltages respectively. $T_{as}, T_{bs}, T_{cs}, T_{es}, T_{fs} \ldots T_{ns}$ are the imaginary switching times of respective phases. Now, the effective time or offset time (T_{offset}) can be defined as the time duration between the smallest and the largest of *n*- imaginary times, as given by

$$T_{offset} = T_{\max} - T_{\min} \quad (20)$$

$$
\begin{aligned}
T_{\max} &= \max\{T_{as}, T_{bs}, T_{cs}, T_{ds}, T_{es} \ldots\ldots T_{xs}\} \\
T_{\min} &= \min\{T_{as}, T_{bs}, T_{cs}, T_{ds}, T_{es} \ldots\ldots T_{xs}\}
\end{aligned}
\quad (21)
$$

The offset time T_{offset} *should* satisfy the following constraint

$$0 \le T_{\min} + T_{offset}, T_{\max} + T_{offset} \le T_s \quad (22)$$

Therefore, the range of T_{offset} *can* be computed as follows:

$$T_{\min offset} \le T_{offset} \le T_{\max offset} \quad (23)$$

Where

$$
\begin{aligned}
T_{\min offset} &= -T_{\min} \\
T_{\max offset} &= T_s - T_{\max}
\end{aligned}
\quad (24)
$$

$$T_{offset} = 0.5(T_{\max offset} + T_{\min offset}) \quad (25)$$

n = Number of phases

When the actual gating signals for power devices are generated in the PWM algorithm, there is one degree of freedom by which the effective time can be relocated anywhere within the sampling interval. Therefore, a time-shifting operation will be applied to the imaginary switching times to generate the actual gating times (T_{ga}, T_{gb}, T_{gc}, T_{gd}, $T_{ge}\ldots$ T_{gn}) for each inverter pole. This task is accomplished by adding the same value to the offset times as follows:

$$\begin{aligned} T_{ga} &= T_{as} + T_{offset} \\ T_{gb} &= T_{bs} + T_{offset} \\ T_{gc} &= T_{cs} + T_{offset} \\ T_{gd} &= T_{ds} + T_{offset} \\ T_{ge} &= T_{es} + T_{offset} \\ &\vdots \\ T_{gn} &= T_{ns} + T_{offset} \end{aligned} \qquad (26)$$

4 Simulation Results

A simulation is performed in order to prove the efficiency of multi-phase inverter fed induction motor drive in terms of load torque, speed, stator current and torque ripple. The simulation model developed in Matlab/Simulink environment. Simulation results are obtained for different phase numbers of induction motors with the help of simulation parameters are shown in Appendix. In the simulation the dc link voltage is set to 622.63 volts and the modulation index *M* is set to 1. The switching frequency of the VSI is chosen as 10 kHz and the reference fundamental frequency is kept equal to 50 Hz. Fig.2 to Fig.4 shows the offset injection simulated results. Fig.2 shows the resultant modulating signal for 5-phase VSI. Fig. 3 shows the range of the *Tmaxoffset* and *Tminoffset* and *Toffset* respectively when the modulation index is 0.9. Fig.4 represents the *Tminoffset* and *Tmaxoffset* with a variation of the modulation index from 0.2 to 1.0515. According to Fig.4, *Tmaxoffset* and *Tminoffset* intersect with each other is the maximum modulation index point (1.0515) in the offset injection method. Fig.5 to Fig.9 shows the inverter fed induction motor results for 3, 5, 7, 9 and 11 phases under different loading conditions. It is seen that Fig.5 shows the response of 3-phase induction motor. At t=0, motor is no loaded and the load is varied in steps as 25%, 50%, 75% and full load at every 0.5 sec respectively. It is seen that the load torque is varied in steps and the corresponding variations in stator current, torque and speed are observed. From the simulation results when the speed decreases with increasing load and the motor torque follows the load torque are observed. Simulation is repeated for 5, 7, 9 and 11 phase induction motors respectively for the same step load conditions. The transient response of multi-phase drive is shown in Fig.10 to Fig.14. It is seen that the peak overshoot is 3.2 times of rated torque, the torque oscillation exists for about 0.25 sec and the torque ripple is 1.2% is observed in the 3 phase drive. Simulation is repeated for 5, 7, 9 and 11 phase induction motors. It is seen that increasing phase numbers the peak overshoot, settling time and torque ripple is significantly reduced. Fault tolerant feature of the 5-phase induction motor is observed from 1st and 5th stator winding open condition is shown in Fig.15. It is seen that the some of two phases opened, the starting current of the rest of the phase increases and rated torque decreases gradually. Table.1 shows the steady state results for different phase numbers. It is seen that the results are observed for variation of the current, speed, torque ripple, power and torque frequency with rated load conditions.

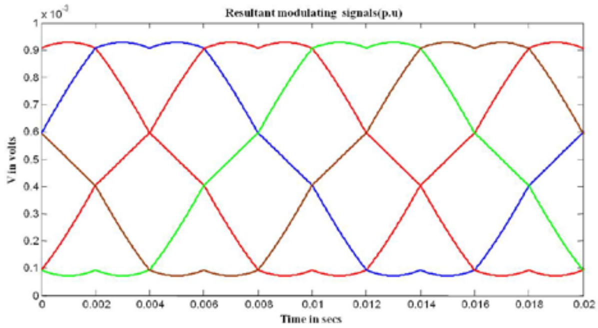

Fig.2: Resultant modulating signal.

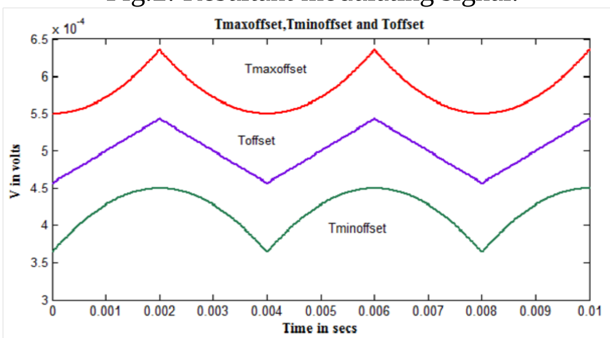

Fig.3: $T_{maxoffset}$,$T_{minoffset}$ and T_{offset} at MI-0.9.

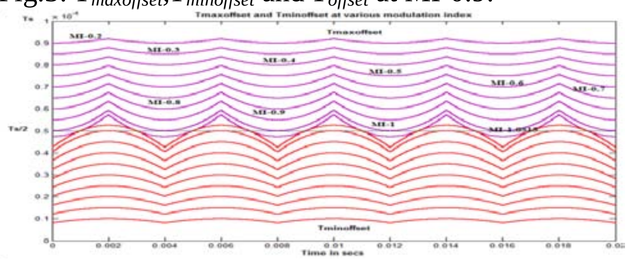

Fig.4: $T_{maxoffset}$, $T_{minoffset}$ and T_{offset} for different modulation indices.

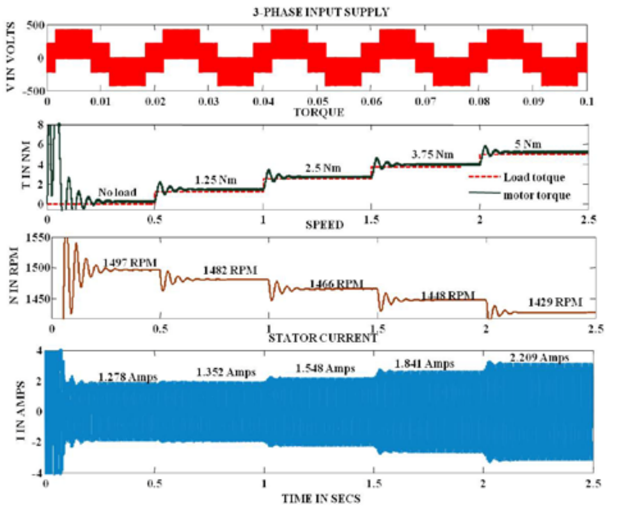

Fig.5: Simulation results for 3-phase machine with different load conditions.

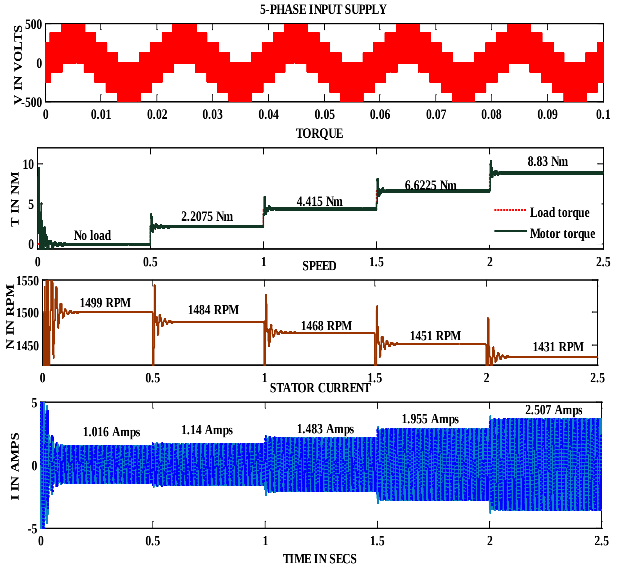

Fig.6: Simulation results for 5-phase machine with different load condition.

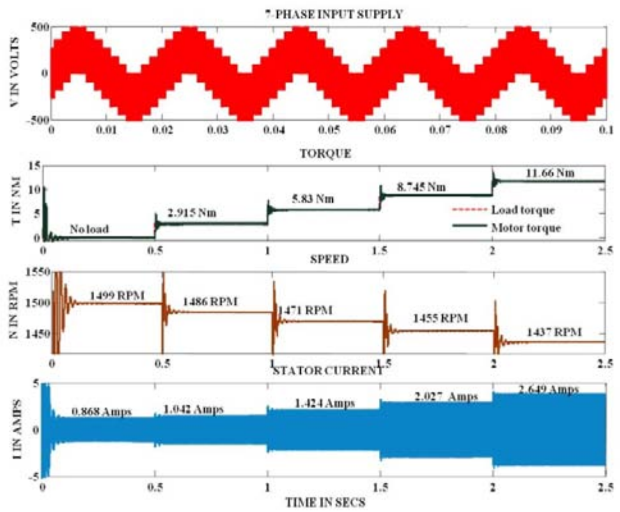

Fig.7: Simulation results for 7-phase machine with different load conditions.

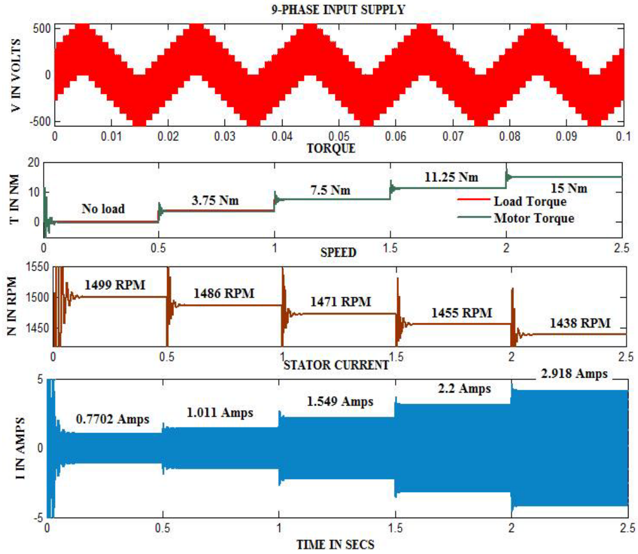

Fig.8: Simulation results for 9-phase machine with different load conditions.

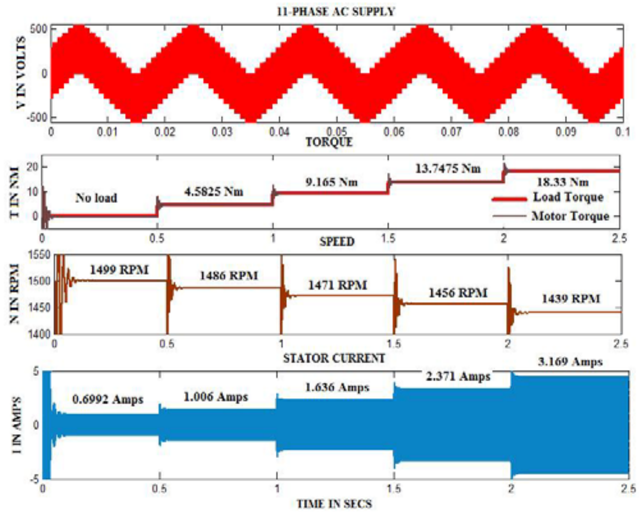

Fig.9: Simulation results for 11-phase machine with different load conditions.

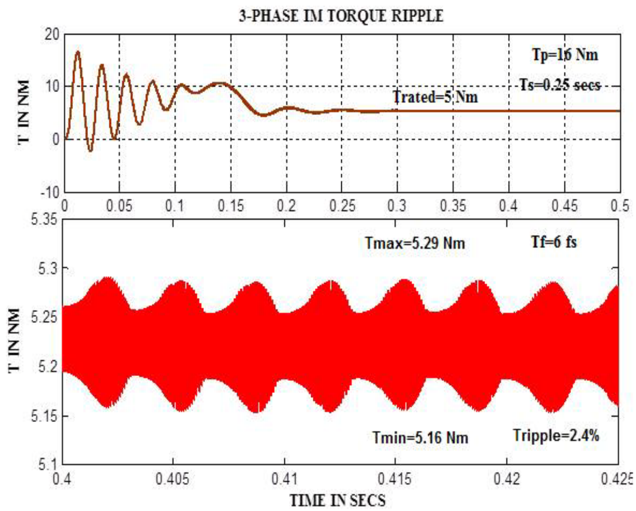

Fig.10: Transient response of 3-phase induction motor drive.

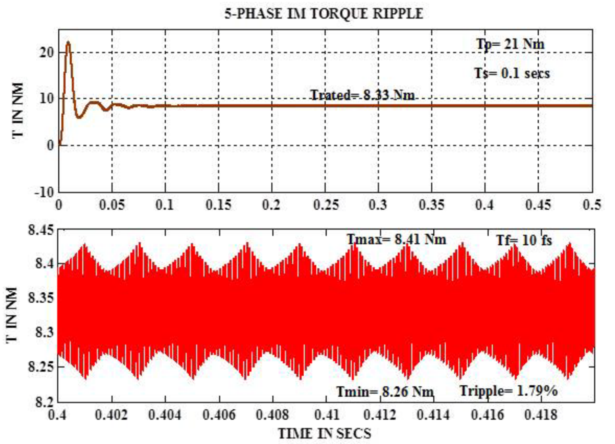

Fig.11: Transient response of 5-phase induction motor drive.

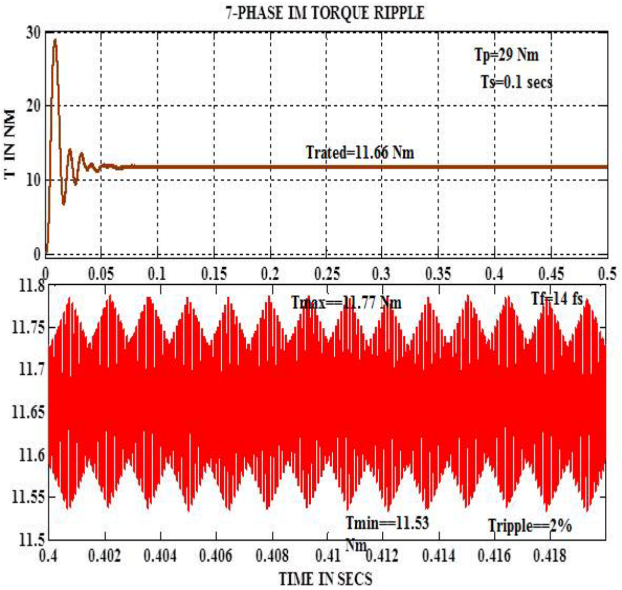

Fig.12: Transient response of 7-phase induction motor drive.

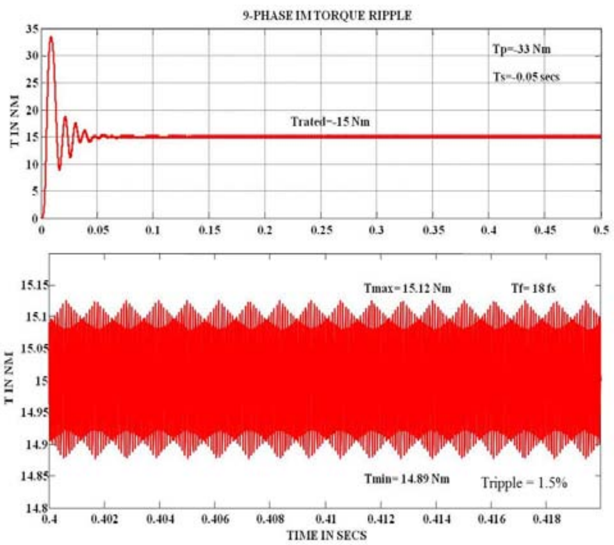

Fig.13: Transient response of 9-phase induction motor drive.

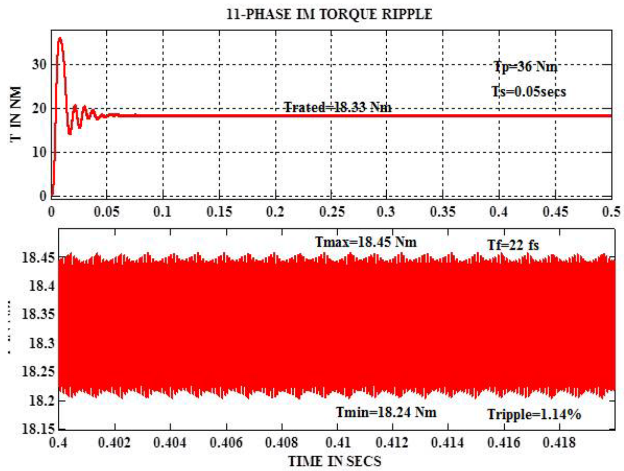

Fig.14: Transient response of 11-phase induction motor drive.

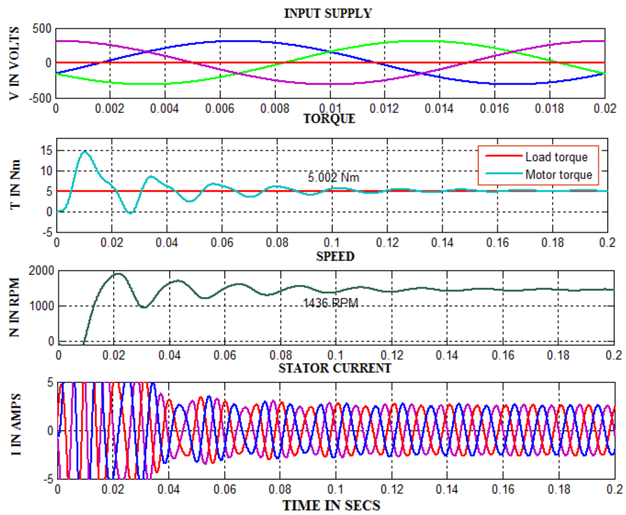

Fig.15: Fault tolerant simulation results of 5-phase induction motor with two (1st and 5th) of the phase is opened.

Table I: Steady state results of different phase numbers under rated load conditions

No of phases	MI	V_L	Rated Torque (T_L)	N_r	I_s/Phase	Power in watts	T_{ripple}	T_f
3	1	220	5	1429	2.209	841	2.4%	$6f_s$
5	**1**	**220**	**8.83**	**1431**	**2.507**	**1233.28**	**1.79%**	**$10f_s$**
7	1	220	11.66	1437	2.649	1541.89	2%	$14f_s$
9	1	220	15	1438	2.918	1925.88	1.5%	$18f_s$
11	1	220	18.33	1439	3.169	2312.28	1.14%	$22f_s$

5 Conclusion

This paper presents a modeling and analysis of multi-phase inverter fed multi-phase induction motor drive with different number of phases. The simulation model is developed using Simpower systems block set of the Matlab/Simulink software. The model is simulated to identify the optimum number of phases for EV applications. The simulation results are presented for 3, 5, 7, 9 and 11 phases under varying load conditions. The transient responses during step load changes are observed. From the simulation results the five phase drive has less torque ripple, reduced current per phase, increasing power, fault tolerant feature and low cost (only 10 switches are needed) compared to higher number of phases. The results prove that the 5-phase drive is optimum for EV applications. For future work the developed multi-phase VSI fed multi-phase induction motor drive is suitable for other high power applications.

Appendix

Parameters of the multi-phase induction motor

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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