

Comparison of 3-phase and 5-phase Induction motor performance for Electric vehicle motor selection

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Summary

The need of pollution free environment and the shortage of fossil fuel have led the world towards e-mobility. For the efficient and comfortable performance of electrical vehicles requires proper selection of suitable traction motor. Due to the rugged construction, ease of controllability and comparatively cheaper cost of materials induction motors are again becoming popular among the car manufacturers. Increasing the number of phases of the motor has several advantages such as less torque ripples, fault tolerance, stability, higher efficiency and reduced current per phase without increasing voltage per phase etc. So in this paper multiphase inverter driven 3-phase and 5-phase induction motors having identical ratings are considered for the performance comparison. Multiphase inverter with SPWM control is considered for supplying the motors. Motor performances are analysed for the torque ripples, stator current, and fault tolerant operation with damaged phase during the fault condition with the constant step changing load.

Keywords: electric drive, induction motor, PHEV, power density

1 Introduction

Indian automotive industry is one of the largest automotive markets in the world. Studies show that almost 72% of the air pollution in Delhi is due to the vehicular pollution. In Mumbai this share is almost 52% and in Kolkata it is approximately 30% [1], [2]. Major of them are the two wheelers and followed by the four wheelers like car, jeep, taxi etc. The main pollutants emitted from the automobiles are responsible for serious health related issues as well as high environmental temperature [2]. In [3] the authors had shown the comparison of cost and consumption of three different types of fuel like petrol, diesel and electricity with the realistic data available which confirms that the large scale introduction of electric and hybrid electric vehicles have the potential to improve the Indian energy and environment situation of personal transportation [3].

These days' two main technologies are in production, those are Battery Electric Vehicles (BEV) and the plug-in hybrid electric vehicles (PHEV). The car manufacturers like Toyota (Prius), Honda Accord, Ion Peugeot, chevy spark EV etc. are using Permanent Magnet Synchronous Motor as the traction motor in their drive train. Renault Twizy, Tesla Model S, Tazzari zero etc are using Induction motor as the traction motor. Renault-Nissan and Bolloré use a **wound rotor** synchronous motor, larger and heavier, and require

additional electronics (chopper) but not of rare earths. Very few like Holden Ecommadore are using switch Reluctance motor as the traction motor.

The performance of a vehicle is determined by Maximum cruising speed, gradeability and the acceleration performance, which are the key factor for selection of electric motor drivetrain.

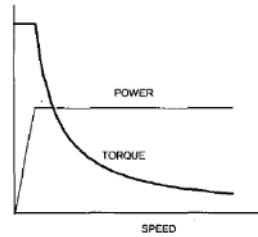


Figure 1: Ideal profile of tractive effort versus speed on the driven wheels [6]

Fig. 1 shows the ideal torque (power) – speed profile for traction application which is the constant power in all the speed ranges. Long constant power range of vehicle traction motor can maximize the vehicle acceleration performance at a given power rating or it can effectively reduce the requirement of motor power rating for the given vehicle acceleration performance. So in vehicle drivetrain design, one of the most important efforts is to reduce the power rating (volume and weight) of the drivetrain with a given vehicle performance. Also it reduces the required power capacity of the on board energy storage such as the batteries and it can also simplify the gear transmission system by allowing use of a single gear transmission [6]. Selection of motor is to be such that it can eliminate the use of gears/transmission and the associated weight, cost and inefficiencies. In other words traction motor should provide high torque at low speed during starting, high speed low but sufficient torque for cruising without or single gear transmission at economical cost and simplified cooling structure.

As a whole, the reliability, weight, power density, torque density, high efficiency over the large speed range, thermal robustness, complexity of controlling, design, fabrication and electromagnetic compatibility of the drive system are the important criterion based on which the traction motor drives are selected for electric vehicles. Based on these important features different authors have suggested different motor technologies as the traction motor in EV/HEV [4]-[13].

This paper is organized in total five sections. First section is the introduction to the need and overview of the electric vehicle drive system technology. In the second section different motor technologies are reviewed based on their suitability with vehicle requirements. It is found that squirrel-cage induction motors are regaining their popularity in the vehicle industries due to their simplicity, ruggedness, cheapness, reliability and having the matured technology [8],[12],[14]. However three phase Induction motors are mainly suffering from the disadvantages of unstable operation at high speed due to pull out torque, weak fault tolerance and higher rotor losses and poor cooling capabilities. To overcome such limitations multiphase systems having more than 3 phases can be employed, which are in depth modeled and explained in section three. Multiphase motors require multi-phase voltage source inverter (VSI) for their input supply. Depending upon the number of phases inverter legs having two switched in series are required. Similar to three phase inverters, the sinusoidal pulse width modulation (SPWM) method, space vector pulse width modulation (SVPWM), harmonic injection method and offset injection method can be extended for multi-phase VSI [19]. 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 employed. The complexity involved in the SVPWM technique is more for higher number of phases. The inverter output voltage space vectors changes to $2n$ states, since there are $2n$ 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 switching technique SPWM is used in this paper for five phase voltage source inverter which would overcome the complexity involved with higher number of phases. Forth section is dedicated to SPWM controlled five phase inverters which are required to drive multiphase motors. The performance

of the 3 phase and 5 phase drive is investigated with this switching technique. Detailed simulation and related discussion of three phase and 5 phase induction motor is covered in section five.

2 Selection of traction motors for EV/HEV

In the recent days there are 3 major technologies which are in demand for the traction motor candidature, those are Induction motors, Permanent Magnet synchronous motors and Switch reluctance motors.

First candidate is the conventional IMs having the constant power range typically extending upto 2-3 times the base speed. For the traction applications it is desirable to extend this to 4-5 times the base speed. Extended speed range operation with constant power beyond base speed is accomplished by flux weakening. However, the presence of breakdown torque limits its extended constant power operation [9]. Second candidate is the permanent magnet synchronous motor (PMSM) having the variants as IPM (interior PM), SPM (surface mounted PM) and PM hybrid motors. They are adopted by well-known automaker for their HEVs as mentioned in above sections. Interior PMSM motors having high flux density are very popular in parallel HEVs. The reason is that a relatively low-power motor is sufficient to supply the drive train of a medium sized car, so do not require large, expensive permanent magnets [10]. The **PM hybrid motor** configuration is the combination of PM motor and reluctance motor. They offer wider speed range (speed ratio of around four) and higher overall efficiency but more complex construction [11]. The speed ratio is still not enough to meet the vehicle performance requirement, especially for off-road vehicles. Thus, a multiyear transmission may be the planetary gear with appropriate reduction ratio is required. Other major issues with these types of motors are failure modes and the high cost of the motor. Third candidate is the Switch Reluctance Motors. They can inherently operate with extended constant power range with the speed ratio of around 6-8 which is highly favorable for vehicle traction application. But high speed operation causes high mechanical losses due to aerodynamics drag and viscosity losses. With the current technology, these motors have inherently high torque ripple. In addition, the high radial forces can create excessive noise levels if not carefully designed. Considerable research efforts to eliminate or sufficiently reduce the torque ripple and noise problems have been applied but it is at the cost of efficiency and/or power density and cost. The torque density of the electric motor reflects the volume and weight of machines at given torque demand. PMSMs offer the highest torque density in the range of 5 Nm/kg but they fail to present an acceptable power density of about 1kW/kg. So any compactness gained at low speed is undermined by power demands at higher speed where the motor mostly works. The induction machine and switched reluctance machine have similar torque density of 4 Nm/kg.

As power density of IM is higher than the PMSM, Unlike PMSMs, IMs can be rated for high power levels and, unlike SRMs; their acoustic noise is comparatively lower. Various comparative studies have also shown that the efficiency and power density of the SRM and ac induction machine with copper rotor bars are roughly equivalent. In actual vehicle operation (with a typical driving cycle), the induction machine has a substantial advantage because it can be de-excited when it is not producing torque. So with the regenerative braking operation of induction motor dynamic efficiency of induction motor operated vehicle is higher. This feature of induction motor makes it highly preferable to use in electric drive system of EV.

With the improved power electronics control at reduced cost, induction motor performance has been improved significantly. On the other hand the rare earth material prices are growing very high due to their concentrated availability to certain countries. Due to these reasons car manufacturers are searching for the traction motors with no permanent magnets. Toyota one of the leaders in EV manufacturers is using asynchronous motors for its forklifts and buses and has now developed them for possible use on its cars, which currently use permanent magnet motors [17].

With above all discussions induction motor can be a good choice for higher electrical driving range and high power vehicles until some new materials are invented. For the vehicle operation induction motor is to be operated in alternator mode where it operates with high speed low torque but above pull out torque limit. If operated as starter it has to work in low speed high torque region. And for the combination of these two the motor must be oversized, thus becoming more expensive [18]. These main drawbacks can be improved by using the multiphase induction motors which can provide high starting torque upto 8- 10 time that of conventional comparable motor, which is required for only initial 10-15sec.

3 Mutiphase induction motors and their modelling

The first proposal of a multiphase variable speed electric drive dates back to 1969 [19]. While [20, 21] proposed a five phase induction motor drive, a six phase (double star) induction machine supplied from a six phase inverter was examined in [22,23]. The early interest in multiphase machines was caused by the possibility of reducing the torque ripple in inverter fed drives, when compared to the three phase case.

Many researchers have focused on multiphase motor technologies for their fault tolerant feature [24]-[27]. In reference [28], a system is developed to optimize the phase number, which uses the total loss as a reference parameter. It is shown that the five-phase motor produces the lowest copper loss and total loss, followed by four-phase and seven-phase motors. Importantly the optimization did not incorporate complexity and system cost, thus overestimates the benefits of motors with higher phase numbers. The performance of a motor is degraded by winding it with an even number of phases, since its poles coincide in pairs; practically it is better to select 5 phase motor for vehicle application [29].

There is a large variety of multiphase machines depending on:

1. The number of phase's n constituting the stator winding;
2. The way in which the n phases are physically arranged;
3. The kind of rotor (which may be of squired-cage, permanent-magnet, reluctance, assisted-reluctance type as well as in ordinary three-phase machines).

As per the phase arrangement, the n phases may be distributed symmetrically around the stator circumference with a phase shift of $360/n$ electrical degrees, which is the case in five-phase and seven-phase symmetrical machines (Fig. 2a). Otherwise, the n phases (with n necessarily being an integer multiple of 3) may be grouped into N three-phase sets, displaced by $60/N$ electrical degrees apart: this is the case of the so called split-phase winding configurations (Fig. 2b). There can be more complicated solutions are also be implemented, such as in the propulsion motor where $n=15$ stator phases are grouped into three five-phase sets.

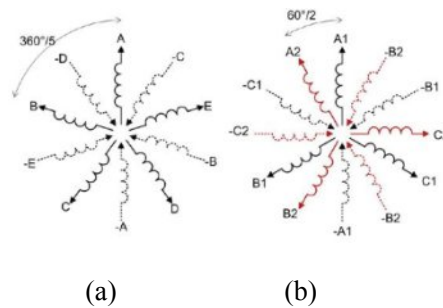


Figure 2: Examples of multiphase winding schemes: (a) symmetrical 5-phase; (b) split-phase double-star.

In this paper mathematical modelling of five phase squirrel cage induction motor is presented. The main difference between mathematical modelling of five-phase induction Motor and three-phase Induction Motor is the presence of x-y component equations. Rotor is assumed to be of squirrel cage type so short circuited. Therefore x-y components in rotor circuit are absent. Zero sequence component equations are due to short-circuited rotor winding and star connection of the stator winding. Stator x-y components are decoupled with d-q components and only d-q axis current components are generated, the equations for x-y components can be omitted. Thus the mathematical modelling of the five-phase induction motor in an arbitrary reference frame becomes identical to the mathematical modelling of a three phase induction motor.

The voltage and torque equation that describe the dynamic behaviour of an induction motor are time varying. The equations involved have some complexity therefore change of variable can be used to reduce the complexity of these equations by eliminating all time varying inductance from the voltage equation of the machine. By this approach a poly phase winding can be reduce to a set of two phase winding i.e. the stator and rotor variables of the induction machine are transferred to a reference frame which may rotate at angular speed or remain stationary[27].

$$f_{dqxyo} = K_s f_{abcde} \quad (1)$$

Where

$$(f_{dqxyo})^T = [f_d \quad f_q \quad f_x \quad f_y \quad f_0]$$

$$(f_{abcde})^T = [f_a \quad f_b \quad f_c \quad f_d \quad f_e]$$

$$K_s = \begin{bmatrix} \cos \theta & \cos\left(\theta - \frac{2\pi}{5}\right) & \cos\left(\theta - \frac{4\pi}{5}\right) & \cos\left(\theta + \frac{4\pi}{5}\right) & \cos\left(\theta + \frac{2\pi}{5}\right) \\ \sin \theta & \sin\left(\theta - \frac{2\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta + \frac{2\pi}{5}\right) \\ \cos \theta & \cos\left(\theta + \frac{4\pi}{5}\right) & \cos\left(\theta - \frac{2\pi}{5}\right) & \cos\left(\theta + \frac{2\pi}{5}\right) & \cos\left(\theta - \frac{4\pi}{5}\right) \\ \sin \theta & \sin\left(\theta + \frac{4\pi}{5}\right) & \sin\left(\theta - \frac{2\pi}{5}\right) & \sin\left(\theta + \frac{2\pi}{5}\right) & \sin\left(\theta - \frac{4\pi}{5}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (2)$$

Using the transformation the voltage equations are now expressed as in equation 3.

$$\begin{aligned} v_{dqxy0s} &= r_s i_{dqxy0s} + \omega \lambda_{dqxy0s} + p \lambda_{dqxy0s} \\ v'_{dqxy0r} &= r_s i_{dqxy0r} + (\omega - \omega_r) \lambda_{dqxy0r} + p \lambda_{dqxy0r} \end{aligned} \quad (3)$$

The machine and the power system parameters are nearly always given in ohms or percent or per unit of base impedance, it is convenient to express the voltage and flux linkages in terms of reactance's rather than inductance. Hence the flux and voltage equations are written as in equation 4 and 5, where, R_s and

$$\begin{aligned} v_{ds} &= R_s i_{ds} - \frac{\omega}{\omega_b} \psi_{qs} + \frac{p}{\omega_b} \psi_{ds} \\ v_{qs} &= R_s i_{qs} + \frac{\omega}{\omega_b} \psi_{ds} + \frac{p}{\omega_b} \psi_{qs} \\ v_{xs} &= R_s i_{xs} + \frac{p}{\omega_b} \psi_{xs} \\ v_{ys} &= R_s i_{ys} + \frac{p}{\omega_b} \psi_{ys} \\ v_{0s} &= R_s i_{0s} + \frac{p}{\omega_b} \psi_{0s} \end{aligned} \quad (4)$$

Where ω_b is the base electrical angular velocity used to calculate the inductive reactances. Flux linkages now become flux linkages per second with the unit of volts.

$$\begin{aligned} \psi_{ds} &= (X_{ls} + X_m) i_{ds} + X_m i'_{dr} & \psi'_{dr} &= (X_{lr} + X_m) i'_{dr} + X_m i_{ds} \\ \psi_{qs} &= (X_{ls} + X_m) i_{qs} + X_m i'_{qr} & \psi'_{qr} &= (X_{lr} + X_m) i'_{qr} + X_m i_{qs} \\ \psi_{xs} &= X_{ls} i_{xs} & \psi'_{xr} &= X_{lr} i'_{xr} \\ \psi_{ys} &= X_{ls} i_{ys} & \psi'_{yr} &= X_{lr} i'_{yr} \\ \psi_{0s} &= X_{ls} i_{0s} & \psi'_{0r} &= X_{lr} i'_{0r} \end{aligned} \quad (5)$$

The expression for the electromagnetic torque in terms of arbitrary reference frame variables may be obtained by transforming the expression and is written as

$$T_e = \frac{3}{2} \frac{p}{2} \frac{v_{ds} i_{ds} + v_{qs} i_{qs} + v_{xs} i_{xs} + v_{ys} i_{ys} + v_{0s} i_{0s}}{v_{ds} i_{ds} + v_{qs} i_{qs} + v_{xs} i_{xs} + v_{ys} i_{ys} + v_{0s} i_{0s}} - \frac{3}{2} \frac{p}{2} \frac{v'_{dr} i'_{dr} + v'_{qr} i'_{qr} + v'_{xr} i'_{xr} + v'_{yr} i'_{yr} + v'_{0r} i'_{0r}}{v'_{dr} i'_{dr} + v'_{qr} i'_{qr} + v'_{xr} i'_{xr} + v'_{yr} i'_{yr} + v'_{0r} i'_{0r}} \quad (6)$$

4 Five phase voltage source inverter

The inputs to the five-phase induction motor are the five-phase voltages, which is obtained from sine PWM controlled five-phase voltage source inverter (VSI). The basic power circuit topology of five-phase VSI is shown in fig 3. IGBTs are used as the power switches. The anti-parallel diodes provides reverse current path such that when a particular IGBT is gated on, one output terminal and one input terminal will be connected.

In multiphase inverter we can generate n number of phases. As each leg of the inverter represent the phase, by increase the number of legs in the inverter we can increase the number of phases. The input to the inverter is a dc supply.

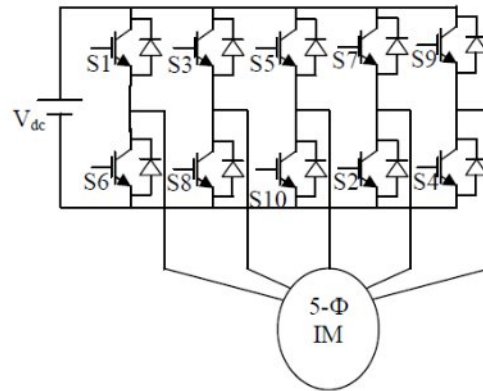


Figure 3: Five Phase/Leg Inverter Topology

Single-phase VSIs cover low-range power applications, three-phase VSIs cover the medium- to high-power applications and five-phase VSIs cover above the three-phase power applications. The main purpose of these topologies is to provide a five-phase voltage source, where the amplitude, phase, and frequency of the voltages should always be controllable. As in single-Leg of VSIs, the two switches (S1 and S6, S3 and S8, S5 and S10, S7 and S2 or S9 and S4) cannot be switched on at a time, because this would result in a short circuit across the dc link voltage supply. Similarly, in order to avoid undefined states in the VSI, and thus undefined ac output line voltages, the switches of any leg of the inverter cannot be switched off simultaneously as this will result in voltages that will depend upon the respective line current polarity. The five-phase VSI is operated in 180° conduction mode for the star connected five phase induction motor, i.e. each switch is conducting for 180° leading to the ten step operating mode. Phase delay between firing of two switches in any subsequent two phases is equal to $360^\circ/5 = 72^\circ$. The switching sequence of a five phase inverter is shown below.

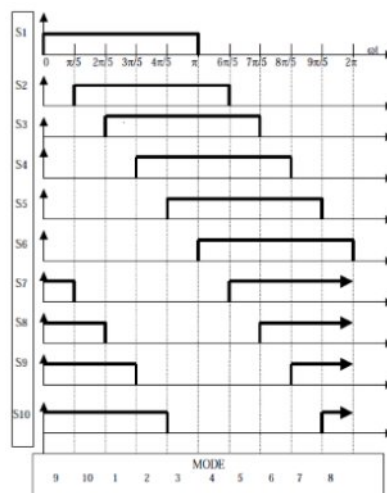


Figure 4: Switching Sequence of Five Phase Inverter

The gate pulses are generated using Sinusoidal pulse width modulation (SPWM) technique. In this technique a carrier wave is compared with the sine wave. Simulink model of SPWM technique is shown in fig 5. In the simulation constant DC voltage is considered at 622.63 V. Switching frequency of triangular carrier waveform is set to 10 kHz and reference frequency is kept at 50 Hz. Modulation index is kept as 1.

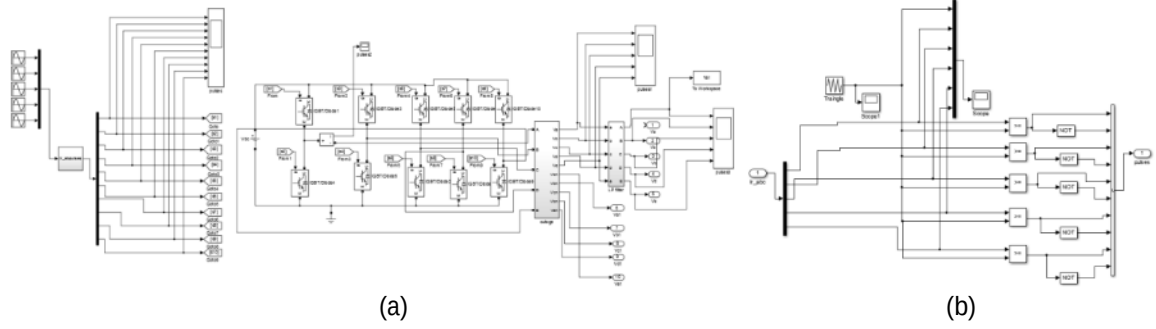


Figure 5: (a) Simulink model of SPWM controlled 5-phase inverter (b) switching pulse generation

5 Performance analysis of 3 phase and 5 phase induction motor under steady state

The matlab/simulink models of five-phase and three-phase squirrel cage induction motors are developed. The power rating of the motor required for vehicle drive train is of the order of 10 kW. But due to the unavailability of higher power rating five phase motor data in the presented paper 3 kW motors having following data are used for the performance analysis.

5 phase induction motor parameters: KW =3; Pole =4; Frequency =50Hz; Base speed=314 rad/s; Stator Resistance =1.26Ω; Rotor Resistance =1.03Ω; Stator Impedance =1.495H; Rotor Impedance =0.5340H; Mutual Impedance =47.595H; Moment of Inertia =0.0040kg/sq. m;

3 phase induction motor parameters: KW =3; Pole =4; Frequency =50Hz; Base speed=314 rad/s; Stator Resistance =0.435 Ω; Rotor Resistance =0.816Ω; Stator Impedance = 0.00200106H; Rotor Impedance = 0.00200106H; Mutual Impedance = 0.0693471 H; Moment of Inertia =0.089kg/sq. M

Fig. 6 shows the matlab/simulink diagram for the five-phase induction motor model used for the performance analysis.

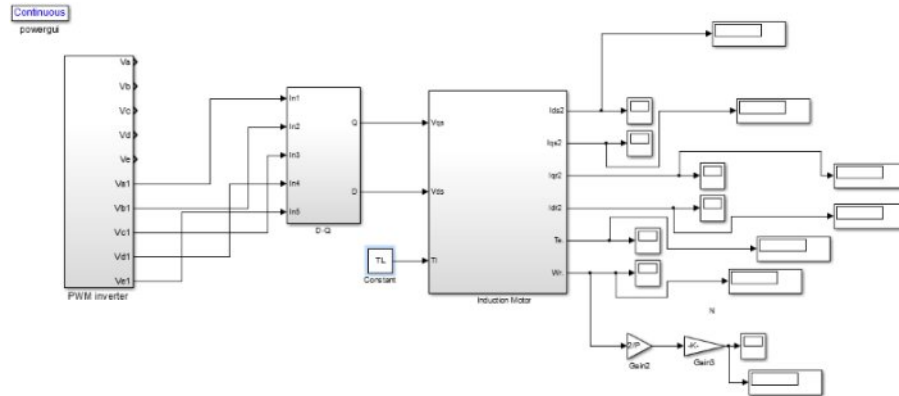


Figure 6: Simulink model of 5-phase induction motor

The five-phase motor model is verified by applying various step load torque of 0 , 2, 5, and 8 Nm and observing speed and torque outputs as shown in fig7. The speed and torque curve of the five phase motor model at load torque of 8 Nm are shown in fig. 8. Fig. 9 shows the stator current, inverter phase voltage and electromagnetic torque generated by the motor for the rated load torque of 8 Nm. Fig. 10 and fig. 11 shows stator current and electromagnetic torque for the rated load torque of 5 Nm. Fig. 12a and fig. 12b

shows the steady state torque ripples in three-phase and five-phase induction motors respectively which is enlarged view of fig.9 and fig. 11. In all the results horizontal axis is time axis showing time in seconds.

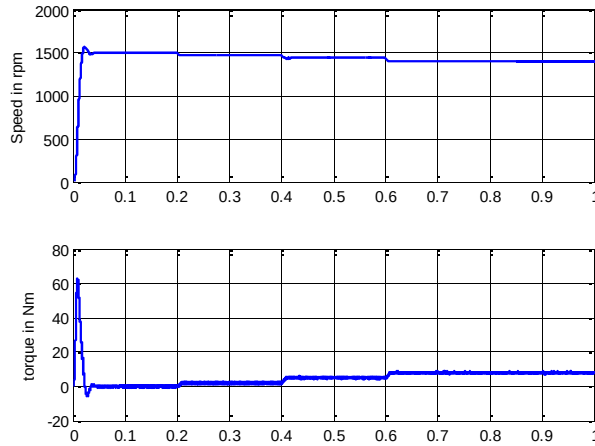


Figure 7: Speed and Electromagnetic torque for different step load condition for 5 phase motor

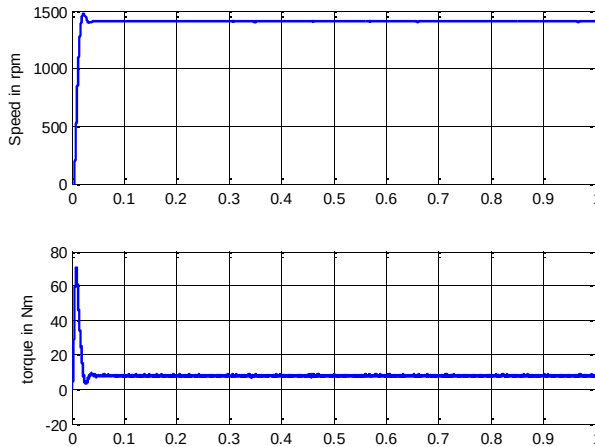
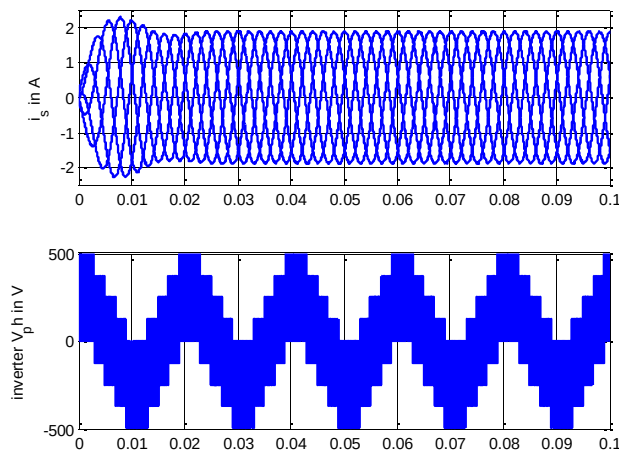


Figure 8: Speed and Torque curves for Trated = 8 Nm



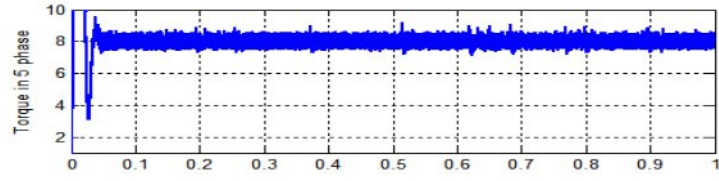


Figure 9: Stator current, inverter output phase voltage and torque T_e for 5 phase motor at rated torque $T_L = 8$ Nm

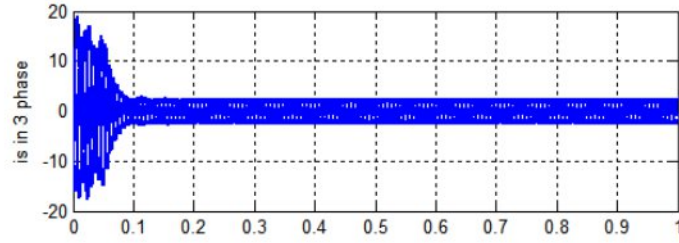


Figure 10: stator current in 3 phase motor

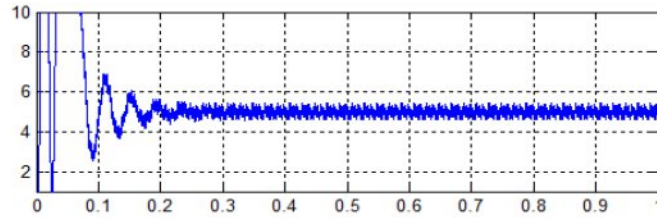
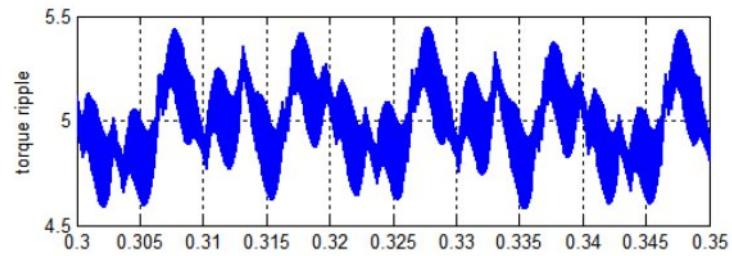
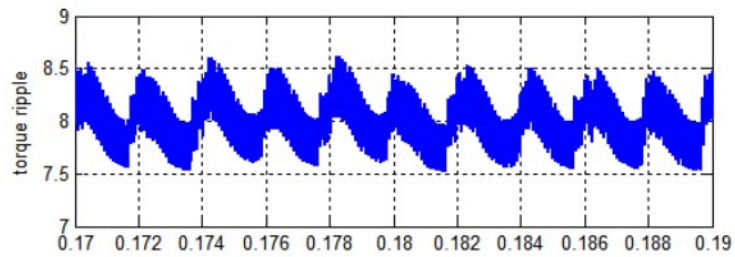


Figure 11: torque T_e in 3 phase motor for $T_L = 5$ Nm



(a)



(b)

Figure 12: steady state torque ripples for (a) 3 phase, (b) 5 phase

$$\% \text{ Torque ripples in 3 phase motor} = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{avg}}} = 16\%, T_{\text{max}} = 5.4 \text{ Nm}, T_{\text{min}} = 4.6 \text{ Nm}$$

$$\% \text{ Torque ripples in 5 phase motor} = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{avg}}} = 11.25\%, T_{\text{max}} = 8.12 \text{ Nm}, T_{\text{min}} = 7.98 \text{ Nm}$$

TABLE I: Comparison of 3 phase and 5 phase motor

No. Of phases	Line voltage	Power (kW)	T _L (Nm)	% torque ripples	Per phase Stator current
3	400 V	3	5Nm	16%	1.3A
5	400 V	3	8Nm	8%	0.92A

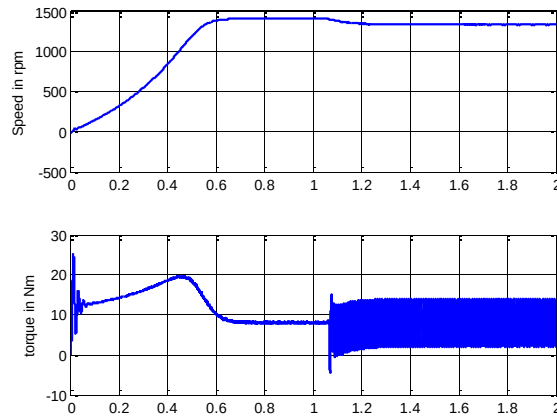


Figure 13: torque and speed change when one phase unhealthy

Fig.13 shows speed and torque ripples in the 5 phase motor when phase A phase is unhealthy with no control mechanism employed. It is observed that motor keeps on running with slightly lower speed and higher torque ripples.

CONCLUSION

Five phase symmetrical induction motor is modelled and performance parameters are analysed in comparison with three phase motor having the similar power rating for steady state torque ripples and stator current. It is observed that performance is considerably improved as compared to 3 phase motor. It is observed that the higher the number of stator phases the torque ripples and stator currents are reducing. Five phase motor is also simulated open circuit fault condition in one of the phase. It is observed that the motor keeps on running with higher torque ripples as compared to three phase motor which stops running when even one phase become faulty. That means less the degradation and the power de-rating that is to be expected following a fault on a five phase machine. Though the power rating used for the simulation here is not enough for electric vehicle drive, the higher rating motor can show more significant improvement in the performance.

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