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Regular paper

Modeling and Analysis of Five Phase Surface PMSM for Application in Electric Vehicle

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Polyphase permanent magnet synchronous motors (PMSM) model outstanding performance in comparison to three phase permanent magnet synchronous motors and this is possible because of the recent development in power electronics. Five phase permanent magnet synchronous motors have significant applications in aerospace and electric vehicles where highly accurate speed and torque control of the motor are a major requirement. This paper presents a detailed analysis of vector controlled five phase permanent magnet synchronous motors in terms of efficiency, power, speed and torque ripple analysis along with the power factor analysis at different speeds. The average torque, torque ripple, speed, speed ripple and power factor for same are calculated and analyzed. The analysis has been carried out through MATLAB Simulink Power Graphical User Interface.

Keywords: Permanent Magnet Synchronous Motor, Phase Sequence, Torque Ripple, Speed Ripple, Hybrid Electric Vehicle.

1. Introduction

The permanent magnet synchronous motors can be of two types: sinusoidally fed PMSM and rectangular fed brushless DC PM Motors [1]. Motors that are currently used in EVs are permanent magnet synchronous motor (PMSM), induction motor (IM) and switched reluctance motor (SRM). PMSM is the most preferred one due to the high torque and high-power density [2]. The stator winding of a PMSM motor is wound such that back emf is sinusoidal which results in a constant torque. It has 32 voltage vectors that has various effects on torque and current is a challenge in selecting the optimal switching state to give best performance. A direct torque control strategy reduces harmonics current and torque ripple [3]. The third order harmonic component can be used for achieving optimal performance of torque per ampere. The direct torque model predictive control helps in optimizing the torque and reducing the higher order harmonics, minimizes the losses thereby increasing the efficiency [4]. More advanced vector control techniques are applicable to sinusoidally fed PMSMs for better controllability over the complete speed range. A five-phase brushless PM motor has concentrated winding so that is produces trapezoidal back emf and overcomes the disadvantages of a PMBLDC motor [5-6]. The conventional hysteresis current controller has been replaced by synchronous frame current controller. This controller not only possesses the advantage of linear controller but also facilitates the current regulation without a steady state error [7]. Harmonics are undesirable frequencies that are superimposed on the fundamental waveform resulting in a distorted waveform. The theory of the sequence components is usually considered to analyze the unbalanced system. This theory enables one to transform the five unbalanced phases into a set of three balanced phasors. Phase sequence is the order in which the voltage waveforms

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of a polyphase AC source reach their respective peaks. In a five-phase system According to the sequence component theory/mathematical manipulation, in a balanced system the negative and zero sequence components will not be present. However, in practice a perfectly balanced system does not exist. In a 50Hz five phase power system, the phases A, B, C, D and E are 720 apart. The fifth harmonic that is of frequency of 250Hz and its multiples are exactly in phase with each other.

A PMSM driven mini electric vehicle model is observed. An efficiency map is developed and implemented in the Advanced Vehicle Simlutor Program to calculate the performance of the Electric Vehicle [8]. A double tuned filtering method which traps two harmonics with one filter has been introduced to mitigate Zero-sequence harmonics in power distribution system [9]. It has proved to be a low-cost solution. The zero-sequence harmonic in a three-phase system can be attenuated by 80% using a shunt electromagnetic filter [10]. This is simple cheap and robust equipment. Axial flux PMSM has prevalence over other motors in terms of noise, vibration and efficiency. Torque ripple inn these motors can be reduced by 86.71% by applying skew of upto 40^0 with an angle of 5^0 to the rotor magnets [11].

2. Phase Sequence in Five Phase Power Supply

When a five-phase permanent magnet synchronous motor is fed from an inverter, the machine terminal voltage is non-sinusoidal and has half wave symmetry due to which only odd harmonics will be present. A sinusoidal waveform is a combination of fundamental and harmonics and the waveform can be analyzed using Fourier Transform. The harmonics in a three-phase supply can be positive sequence, negative sequence and zero sequence. Whereas in a five-phase supply, the harmonics can be positive sequence, negative sequence, zero sequence along with two more sequences. The additional sequences can be referred to as double positive sequence and double negative sequence. The fundamental phase voltage components can be assumed as $V_{AN} = V_m \sin \omega t$, $V_{BN} = V_m \sin (\omega t - 2\pi/5)$, $V_{CN} = V_m \sin (\omega t - 4\pi/5)$, $V_{DN} = V_m \sin (\omega t - 6\pi/5)$ and $V_{EN} = V_m \sin (\omega t - 8\pi/5)$ having phase sequence of ABCDE. The corresponding 3rd and 7th harmonic voltages are :

$$V_{AN3} = V_3 \, sin3\omega t$$
$$V_{BN3} = V_3 \sin (3\omega t - \frac{6\pi}{5})$$
$$V_{CN3} = V_3 \sin (3\omega t - \frac{2\pi}{5})$$
$$V_{DN3} = V_3 \sin (3\omega t - \frac{8\pi}{5})$$
$$V_{EN3} = V_3 \sin (3\omega t - \frac{4\pi}{5})$$
$$V_{AN7} = V_7 \, sin7\omega t$$
$$V_{BN7} = V_7 \sin (7\omega t - \frac{4\pi}{5})$$
$$V_{CN3} = V_7 \sin (7\omega t - \frac{8\pi}{5})$$
$$V_{DN7} = V_7 \sin (7\omega t - \frac{2\pi}{5})$$
$$V_{EN3} = V_7 \sin (7\omega t - \frac{6\pi}{5})$$

Table 1: Mathematical Table with Odd Numbered Harmonics

Fundamental	A 0^0	B 72^0	C 144^0	D 216^0	E 288^0	A-B-C-D-E
3^{rd} Harmonic	3×0^0 0^0	3×72^0 216^0	3×144^0 72^0	3×216^0 288^0	3×288^0 144^0	A-D-B-E-C
5^{th} Harmonic	5×0^0 0^0	5×72^0 $360^0 = 0^0$	5×144^0 $720^0 = 0^0$	5×216^0 $1080^0 = 0^0$	5×288^0 $1440^0 = 0^0$	No rotation
7^{th} Harmonic	7×0^0 0^0	7×72^0 144^0	7×144^0 288^0	7×216^0 72^0	7×288^0 216^0	A-C-E-B-D
9^{th} Harmonic	9×0^0 0^0	9×72^0 288^0	9×144^0 216^0	9×216^0 144^0	9×288^0 72^0	A-E-D-C-B
11^{th} Harmonic	11×0^0 0^0	11×72^0 72^0	11×144^0 144^0	11×216^0 216^0	11×288^0 288^0	A-B-C-D-E

Table I shows that that the 11th harmonic has the fundamental phase sequence ABCDE that produces a magnetic field which rotates in the same direction as the fundamental. The 9th harmonic has a negative phase sequence AEDCB that produces a magnetic field which rotates in a direction opposite to the fundamental. Also, the 5th harmonic has zero phase sequence that does not produce any rotating magnetic field.

3. Mathematical Model of Five Phase PMSM

The mathematical model of a five phase PMSM is derived and the equations are developed in the rotating reference frame.

The stator voltage equation is:

$$V_s = R_s I_s + \frac{d\lambda_s}{dx} \tag{1}$$

where R_s, I_s and λ_s are the stator resistance, current and flux linkages respectively.

The air gap flux linkages are:

$$\lambda_s = \lambda_{ss} + \lambda_m \tag{2}$$

Substituting for the flux linking stator windings due to the currents in the stator windings in terms of the stator currents and stator winding inductances,

$$\lambda_s = L_{ss} i_s + \lambda_m \tag{3}$$

L_{ss} is the stator inductance matrix which contains the self and mutual inductances of the stator phases, and λ_m is the established flux linkage matrix due to the permanent magnets viewed from the stator phase windings.

The stator current i_s is:

$$i_s = [i_{as} \quad ibs \quad ics \quad ids \quad ies]^t \tag{4}$$

$$V_{d1} = R_s i_{d1} + L_d \frac{di_{d1}}{dt} - \omega L_q i_{q1} \tag{5}$$

$$V_{q1} = R_s i_{q1} + L_q \frac{di_{q1}}{dt} + \omega L_d i_{d1} + \omega \lambda_m \tag{6}$$

$$V_{d2} = R_s i_{d2} + L_d \frac{di_{d2}}{dt} \tag{7}$$

$$V_{q2} = R_s i_{q2} + L_q \frac{di_{q2}}{dt} \tag{8}$$

For simplifying the model, only the fundamental component of the magnet flux linkage is taken into account. Hence the electromagnetic torque equation is given as :

$$T_e = \frac{5}{2}\frac{P}{2}\lambda_m i_{q1} \tag{9}$$

4. Zero direct axis current control

The direct axis current is forced to be zero by maintaining the torque angle δ at 90 degrees. Hence only the quadrature axis current exists. This mode of operation is preferred for speeds lower than the base speed. Figure 1 shows the phasor diagram for zero direct axis current control.

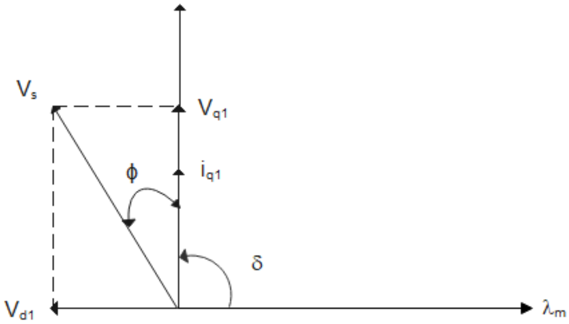

Fig.1. Zero Direct Axis Current Control

The equations for this mode of operation are

$$T_e = \frac{5}{2}\frac{P}{2}\lambda_m i_{q1} \tag{10}$$

The q and d axes voltage in steady state with this control strategy are

$$V_{q1} = R_s i_{q1} + L_q \frac{di_{q1}}{dt} + \omega\lambda_m = R_s i_{q1} + \omega\lambda_m \tag{11}$$

$$V_{d1} = -\omega L_q i_{q1} \tag{12}$$

$$V_{d2} = V_{q2} = 0 \tag{13}$$

Since the current is constant, the rate of change of current is zero.
The magnitude of voltage phasor is given by

$$V_s = \sqrt{(V_{q1})^2 + (V_{d1})^2} \tag{14}$$

$$\cos\phi = \frac{V_{q1}}{V_s} = \frac{V_{q1}}{\sqrt{(V_{q1})^2 + (V_{d1})^2}} = \frac{1}{\sqrt{1 + \frac{(L_q I_{q1})^2}{(\frac{R_s I_{q1}}{\omega} + \lambda_m)^2}}} \tag{15}$$

Equation (15) implies that the power factor degrades with increase in rotor speed and increase in stator current. We can control the power factor by controlling the direct axis current.

5. Simulation Result

Several cases have been presented here considering constant load torque of 30N-m and variable rotor speed. The electromagnetic torque, five phase stator current, d-q axis current, efficiency, dc link capacitor voltage, power, and power factor has been analyzed here. In each case, the speed changes after 3secs and the simulation is set to run for 6secs. Table II show the PMSM model parameters and Table III shows the PMSM model control parameters. From Table IV it can be observed that there is a smooth change in rotor speed with percentage of ripple being less than 0.5 except in case 2 where speed changes from 1000 rpm to 50 rpm. Here the speed ripple is 3.8%. In each case, the permanent magnet motor operates in different modes. When speed is positive, machine runs in forward motoring mode. When speed changes from positive to zero, it is forwarding braking mode. When the machine is running at negative speed, it is said to be reverse motoring mode and when speed changes from negative to zero, it is reverse braking.

For all the cases, there is a smooth transition of the motor speed. As shown in figure 9 and 13, with the reversal of motor speed, the phase sequence of the stator current gets changed. Figure 4, 8, 12 and 16 shows that in each of the cases, the speed changes smoothly for the five phase PMSM. Figure 2, 6,10 and 14 shows that $id_1 = id_2 = iq_2 = 0$ as vector control method is applied. The torque ripple and speed ripple are calculated from figure 3, 7, 11, 15 and figure 4, 8, 12, 16 respectively.

Table 2 : PMSM Model Parameters

Parameter	Value	Unit
Output Power	2	KW
Resistance	0.2468	ohm
Inductance	8.5e-3	Henry
Flux Linkage	0.105	Wb
Pole pairs	4	
Inertia	0.089	Kg*m^2
Friction	0.005	Nm*s

Table 3 : PMSM Model Control Parameters

A. Speed Controller

Parameter	Value	Unit
Speed cut off frequency	250	Hz
Sampling time	80e-6	Sec
Output torque limit	-35 to 35	Nm

B. Vector Control

Parameter	Value	Unit
Current Controller Hysteresis Band	250	A
Sampling time	20e-6	Sec
Maximum Switching Frequency	50e3	Hz

Table 4 : Speed and Torque Ripple for different cases

Case	Speed (rpm)	Torque Ripple (%)	Speed Ripple (%)
1	500	14.7	0.4
	1000	15.3	0.21
2	1000	15.3	0.22
	50	14.1	3.8
3	1000	15.8	0.208
	-1200	23	0.277
4	-1200	23.2	0.29
	1000	15.9	0.2

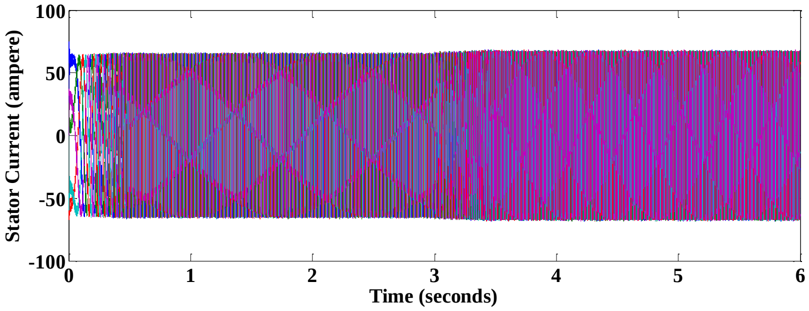

Fig.2. Five phase stator current when speed changes from 500rpm to 1000rpm

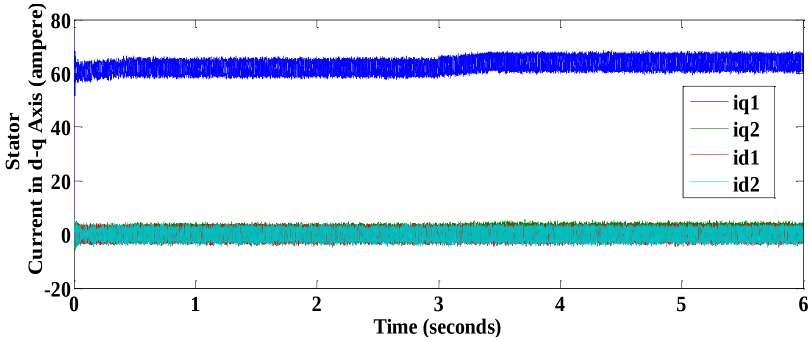

Fig.3. d-q axis current when speed changes from 500rpm to 1000rpm

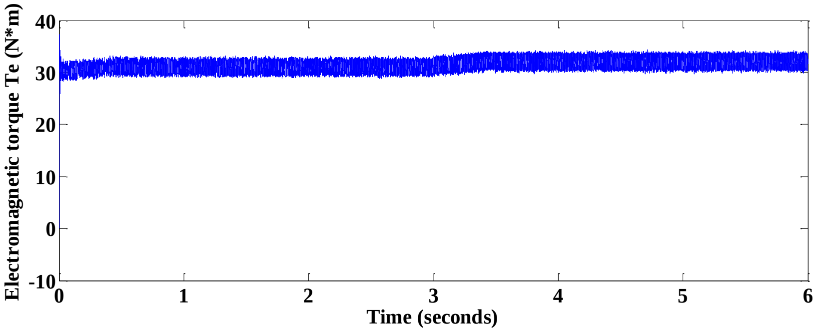

Fig.4. Electromagnetic Torque when speed changes from 500rpm to 1000rpm

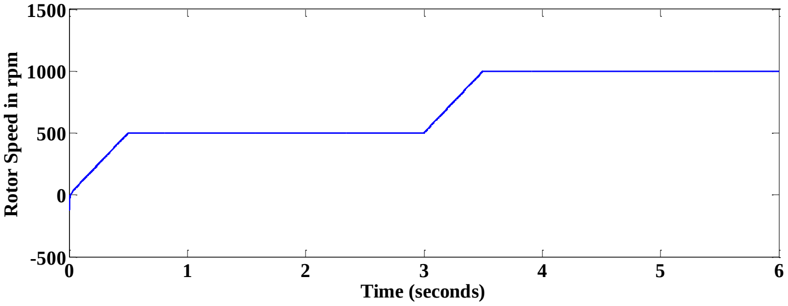

Fig.5. Rotor Speed when speed changes from 500rpm to 1000rpm

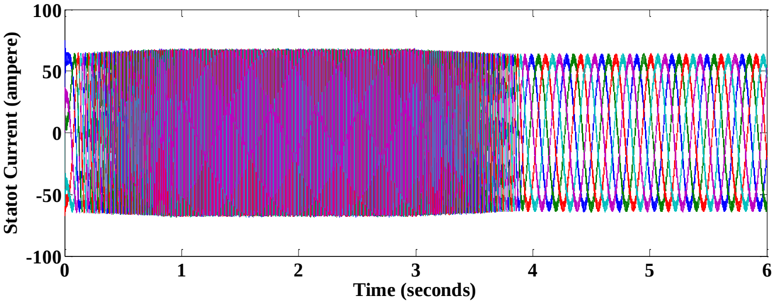

Fig.6. Five phase stator current when speed changes from 1000rpm to 50rpm

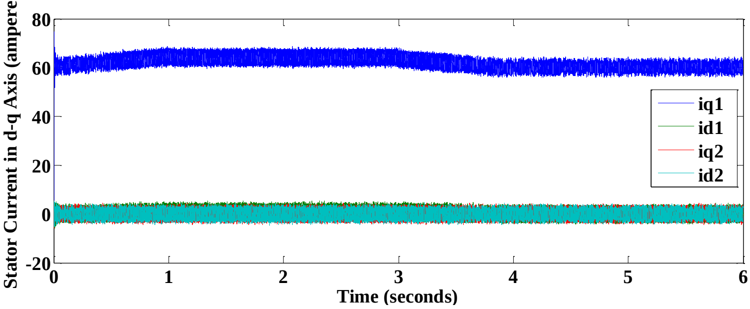

Fig.7. d-q axis current when speed changes from 1000rpm to 50rpm

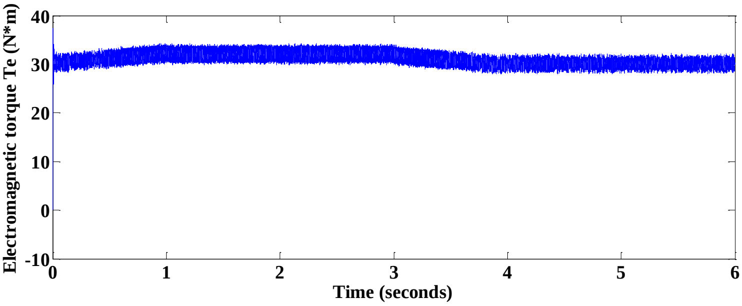

Fig.8. Electromagnetic Torque when speed changes from 1000rpm to 50rpm

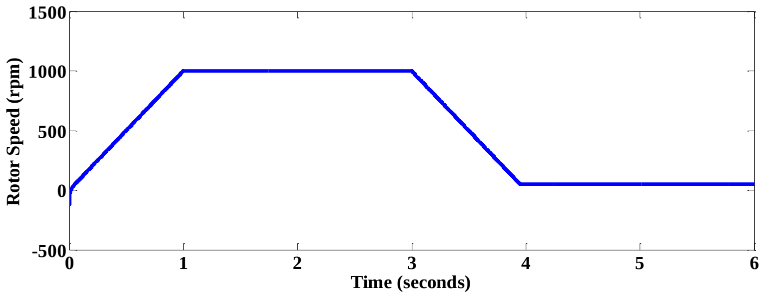

Fig.9. Rotor Speed when speed changes from 1000rpm to 50rpm

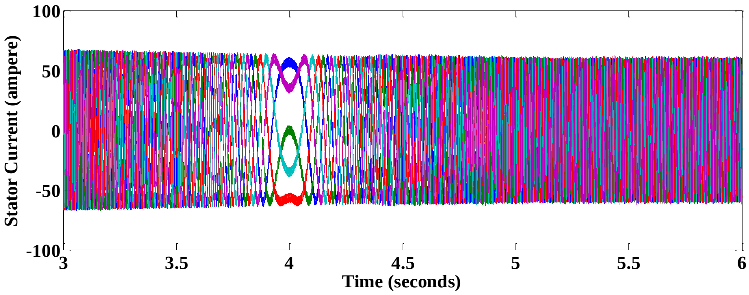

Fig.10. Five phase stator current when speed changes from 1000rpm to -1200rpm

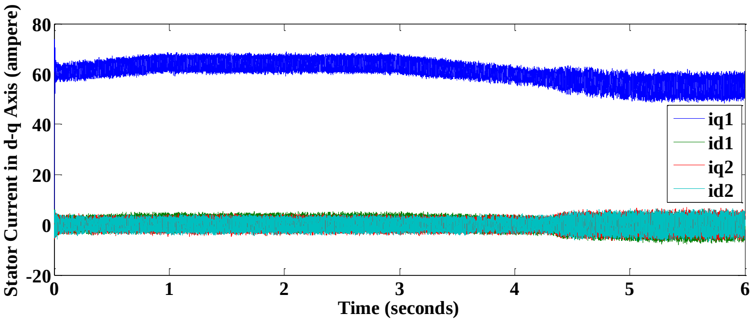

Fig.11. d-q axis current when speed changes from 1000rpm to -1200rpm

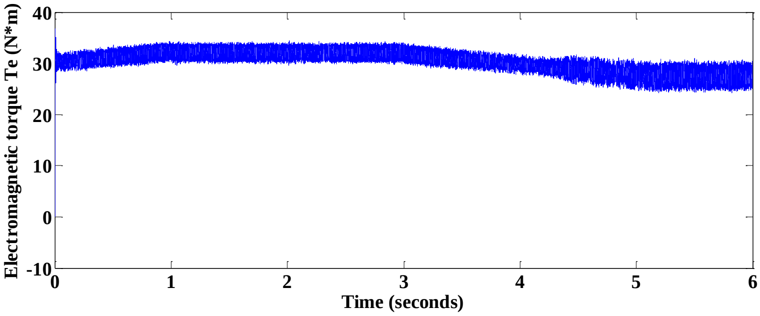

Fig.12. Electromagnetic Torque when speed changes from 1000rpm to -1200rpm

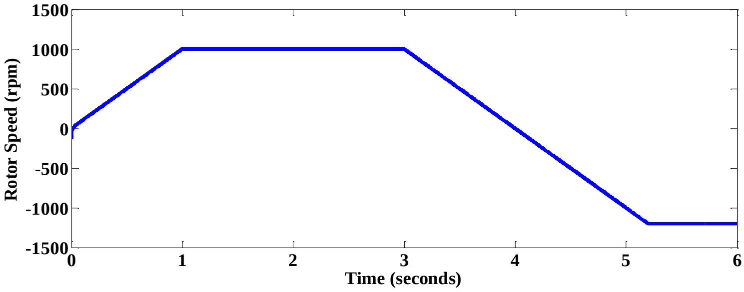

Fig.13. Rotor Speed when speed changes from 1000rpm to -1200rpm

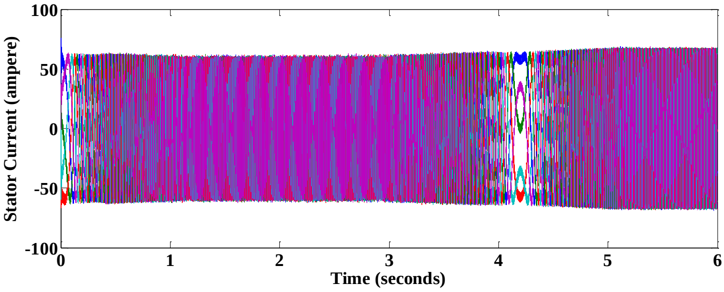

Fig.14. Five phase stator current when speed changes from -1200rpm to 1000rpm

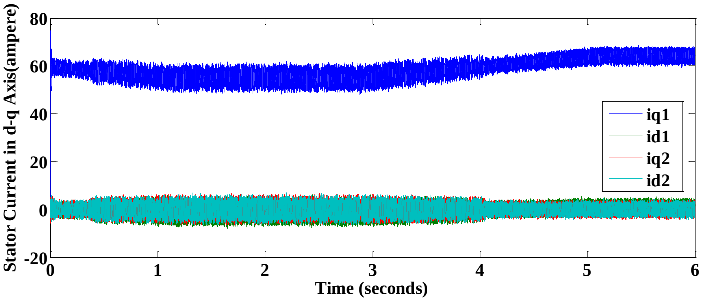

Fig.15. d-q axis current when speed changes from -1200rpm to 1000rpm

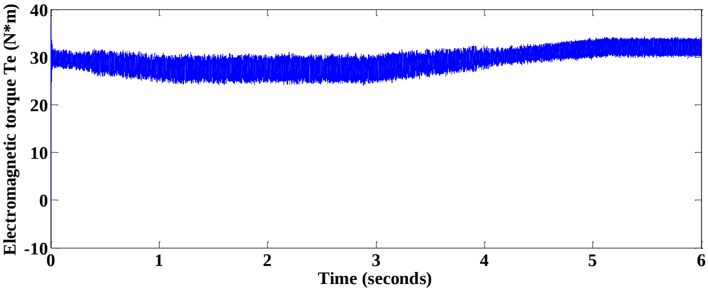

Fig.16. Electromagnetic Torque when speed changes from -1200rpm to 1000rpm

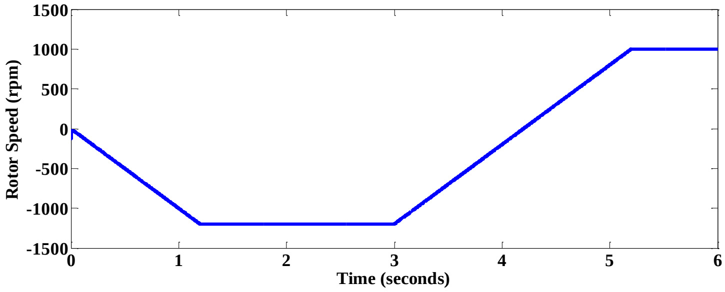

Fig.17. Rotor Speed when speed changes from -1200rpm to 1000rpm

Figure 18 show that the efficiency is constant after 1/10th of the rated speed. Five phase PMSM is more efficient than its three-phase counterpart. Ripple in dc link voltage increases with larger slope post the rated speed whereas the slope is smaller for speed lower than the rated. The ripple in five phase dc link voltage is less than it 3phase, hence the reliability of the capacitor is more and chances of failure is less in five phase PMSM. Figure 19 shows the ripple in dc link voltage at different speed.

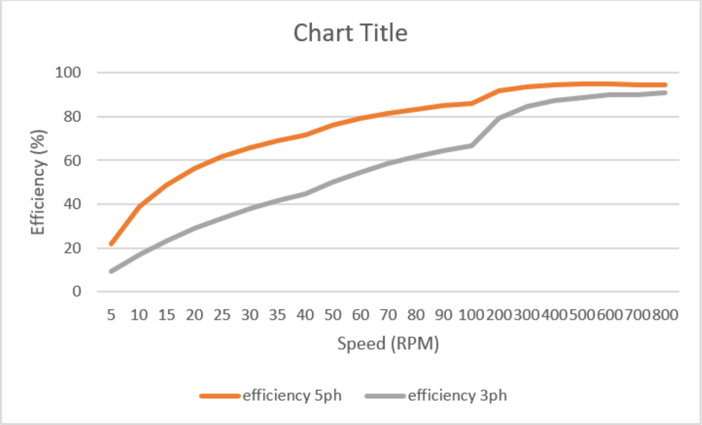

Fig. 18. Efficiency at different speed

Torque ripple is less in five phase PMSM as compared to three phase. Oscillation is less in five phase machine at low speed which helps in eliminating jerking. Figure 20 shows the torque ripple at different speed for three phase and five phase PMSM. Power consumption in three phase PMSM is more compared to five phase.Therefore five phase machine is economical than three phase PMSM. Also, the running cost of five phase PMSM is reduced due to higher efficiency. Figure 21 shows the power consumption at different speeds.

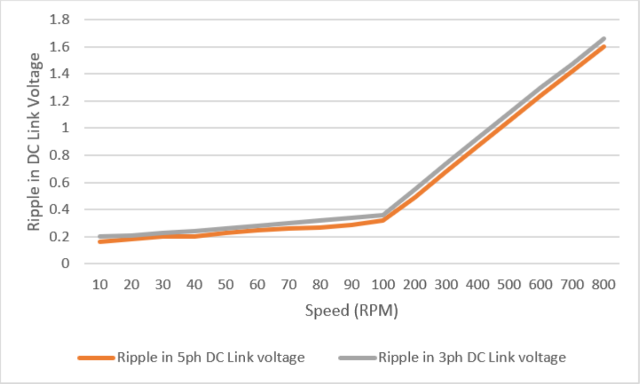

Fig.19. Ripple in dc link voltage at different speed

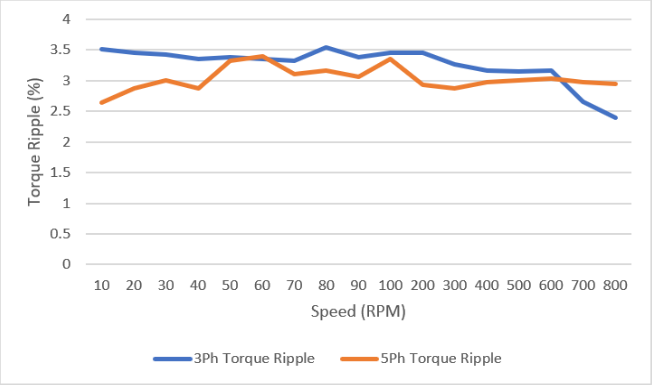

Fig.20. Torque ripple at different speed

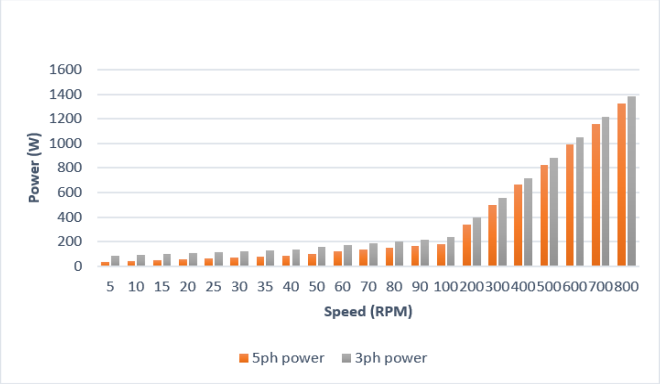

Fig.21. Input Power at different speed

Figure 22, 23 and 24 shows the power factor of three phase and five phase PMSM at rated speed, 600rpm and 150rpm respectively. When three phase PMSM is running at rated speed, the power factor is leading till 18Nm and lagging beyond that. Whereas in five phase the power factor is initially leading and thwn lagging. At low speed, the power factor for both the machines in leading. We can control the power factor by controlling the direct axis current. The overload at low speed in five phase PMSM is much more compared to three phase without compromising the reliability.

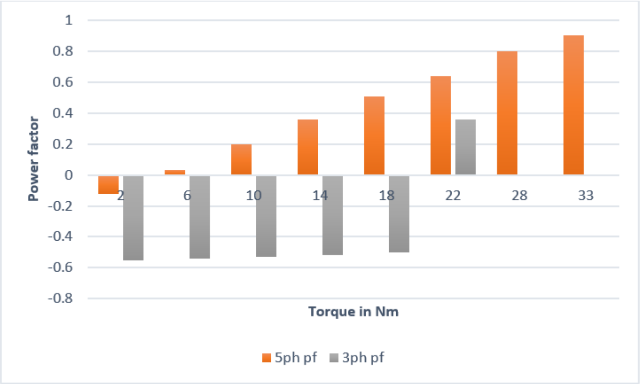

Fig.22. Power factor at 900rpm

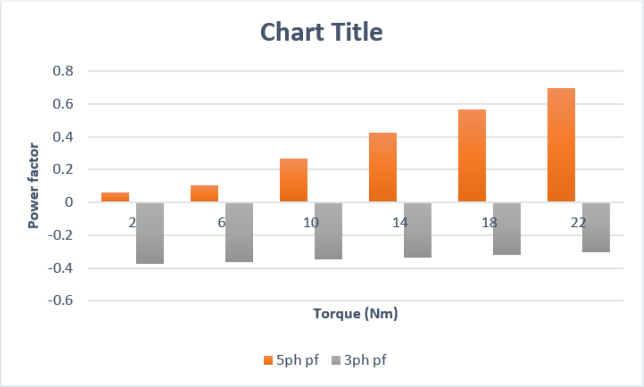

Fig.23. Power factor at 600rpm

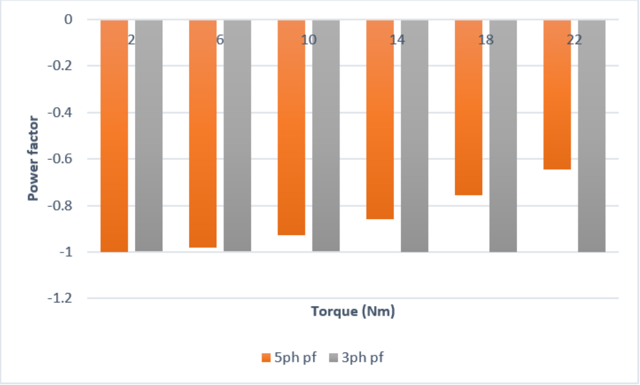

Fig.24. Power factor at 150rpm

6. Conclusion

Mathematical modeling, simulation and analysis of vector controlled five phase permanent magnet synchronous motor provides a clear picture of the reason for its wide application in electric vehicles. The five phase PMSM has been run at different speed and the speed is changed after 3secs. From the performance analysis of the machine in can be concluded that the speed changes smoothly in each case. The analysis torque and speed ripple show that speed ripple is comparatively higher at low speed. The results are compared with its three-phase counterpart. PMSM has higher efficiency and increased power density. Power consumption is less compared to three phase PMSM. By controlling the direct axis current that is forced to be zero here, the power factor of the motor can be controlled. At very low speed, the power factor of PMSM is leading whereas its lagging at high speed and rated speed.

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