# Analysis of three phase and five phase BLDC motors used in Aerospace applications

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## ABSTRACT

The paper describes the analysis, modeling and simulation of three phase and five phase, permanent magnet brushless dc machine. Smooth and efficient operation of the brushless dc motor relies on the energizing sequence of the windings by sensing the position of the rotor using the Hall Effect sensor. Analysis shows that the five phase motor provides better torque control over three phase motors. The MATLAB/ Simulink is used to simulate the BLDC motor drive and the simulation result is also included in this paper. The analysis is also done using finite element method (FEM) using COMSOL software. The fractional slot winding design minimizes the cogging torque.

**Key words:** Multiphase, Brushless DC, FEM analysis

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## INTRODUCTION

PERMANENT magnet (PM) brushless DC motors [1],[2] have been widely used because of their attractive features like compactness, low weight, high efficiency, and ease in control. A BLDC motor is considered to be a high performance motor that is capable of providing large amounts of torque over a vast speed range. These motors are increasingly used in various domestic and industrial applications. Among the various types of PM BLDC motors, the radial-flux, surface mounted type is widely used due to its ease to implement.

3-phase motors are the most popular and widely used. Now-a-days multiphase motors are gaining more interest due to reduction in failure chances. With multi phases, in the event of failure of one or more, the remaining healthy phases let the motor to operate properly. For aerospace applications, high reliability and fault tolerance of the machine is required or strongly desired due to the safety concerns. In a three phase machine, energy is taken at the rate of 6 pulses for one electrical revolution of the machine and for a five phase machine [3] each revolution requires 10 pulses per cycle. Therefore to deliver the same energy in one revolution a three phase machine require larger magnitude pulses leading to higher torque ripple. Multiple phase arrangement [4] for electrical machines minimizes torque ripple, increases power density and improves fault-tolerance [5] The problem resides in the higher number of phases is because of its more complex inverter control scheme and higher cost.

Multi-phase motor drives permit an increase in torque by reducing the amplitude and increasing the frequency of torque pulsation, reducing the stator current per phase without increasing the voltage per phase thereby increasing the reliability and power density, of the drives. This paper aims at the comparison of three phase and five phase BLDC motor. MATLAB and FEM analysis using COMSOL software were used for the analysis of both the phase motors ensuring that multiphase motors are more reliable due to increased torque production for the same current density.

## BRUSHLESS DC MOTOR

BLDC motor is highly reliable since it does not have any brushes to wear out and replace. The stator, stationary part of a BLDC motor consists of stacked steel laminations with windings placed in the slots. The rotor, rotating part is made of permanent magnet so that problems associated with connecting current to the moving armature can be eliminated. It can vary from two to twelve pole pairs with alternate north and south poles. The ratio of torque delivered to the size of the motor is higher, making the BLDC motor useful in applications [6],[7] where space and weight are critical factors.

BLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotates at the same frequency. BLDC motors do not experience the slip that is normally seen in induction motors [8]. BLDC motors do not use brushes for commutation; instead, they are electronically commutated. To control the machine using sensors, the present position of the rotor is required to determine the next commutation interval. Hall Effect sensors are mainly employed for this purpose. Brushless motor commutation can be implemented in software using a microcontroller. The driver circuit of BLDC motor for three phase motor is as shown in fig.1. It uses six switches which are commutated sequentially. For a five phase motor it uses ten switches instead of six.

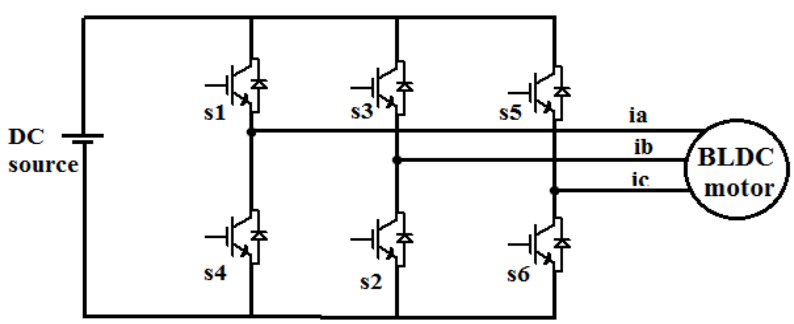



Fig.1 Inverter drive for three phase motor

A high number of phases yield a smaller magnetic yoke and decreased volume and weight. However, the number of poles is restricted physically to the size of the permanent magnets and the rotor diameter.

## MATHEMATICAL MODEL OF BLDC MOTOR

A dc supply of 28V was taken as input to the motor. The other design specifications are listed in table 1.

Table 1: Technical Specifications

| **Parameters** | **Specifications** |
|---|---|
| Supply Voltage | 28V |
| Torque Constant, Kt | 0.2 |
| Back EMF constant, Kb | 0.2 |
| Outer Dia. | 60mm |
| Stack length | 20mm |
| No. of poles | 10 |
| No. of slots | 33 |
| Rated Speed | 1300rpm |
| Magnet | SmCo5 |

The model of the armature winding for the BLDC motor is expressed as follows.

$$V = Ri + L\frac{di}{dt} + E$$

Where V is the stator phase voltage, R is the stator resistance per phase, *i* is the stator phase currents, L is the self inductance, and E is the induced back electromotive force. The back EMF are displaced by 120 electrical degrees from one phase to another for a three phase motor and 72 electrical degrees for a five phase motor. The vector diagram is as shown in fig.2.

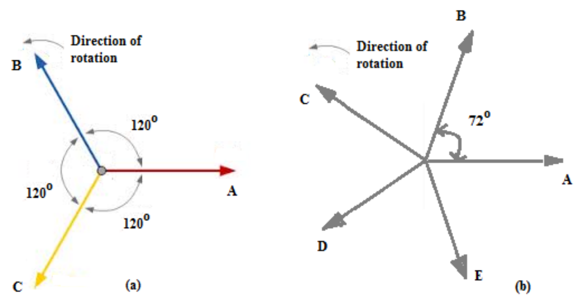



Fig.2 Vector diagram: (a)for three phase (b) for five phase

The electromagnetic torque produced by a brushless DC motor under steady-state operation can be expressed as

$$T_e = T_L + J\frac{d\omega_m}{dt} + \beta\omega_m$$

where $T_L$ is the load torque (Nm) ,J is the inertia of the rotor and coupled shaft ($kgm^2$) and β is the friction factor ($Nm.s.rad^{-1}$).

In general EMF contributing to the electromagnetic power is:

$$E = (N_{ph} - 1)2\pi N_t K_w \alpha D_r L B_g n = K_b n$$

where L is the active motor length, $D_r$ is the rotor outer diameter, $N_{ph}$ is the number of phases, $N_{ph} - 1$ is the number of phases conducting simultaneously, $N_t$is the number of turns per phase, $K_w$ is the winding factor, $B_g$ is the air-gap magnetic flux density and n the rotational speed in rev/s.
The general equation for electromagnetic torque is [9]:

$$T = (N_{ph} - 1)N_t K_w \alpha D_r L B_g i = K_t . i$$

where *i* is the current amplitude.

A fractional slot combination is used so that fewer pole edges line up with the slots and hence reduces the cogging torque. The no load speed to be obtained using the analytic analysis is 136 rad/s. The schematic diagram of the BLDC motor is as shown in fig.3. The back EMF used in both the simulation is sinusoidal. The output of the inverter is taken as the input to the motor. The output from this model is the electrical position, θ (degrees) obtained by integrating the no load speed, *ω* (rad/s).

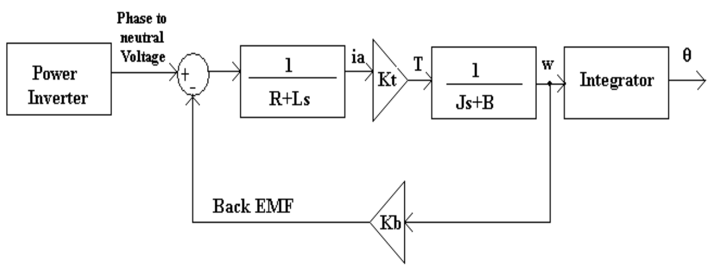



Fig.3 Schematic diagram of BLDC motor

## FINITE ELEMENT ANALYSIS

COMSOL software is a better tool to get the finite element analysis of any model. Here surface mounted permanent magnet BLDC motor is modeled and analyzed.The initial design of the BLDC includes the determination of the main dimensions including stator inner diameter andeffective length of the rotor.Samarium cobalt (SmCo5) is selected as the magnetic material, due to its low temperature coefficient.Flux linkage from the rotor is dependent upon the magnet. Radial flux motors are chosen for analysis and is arranged with alternate north and south poles. Therefore, saturation of magnetic flux linkage is typical for this kindof motors.

The motor has been modeled and drawn using AUTOCAD with 33 slots and 10 poles and has been imported to COMSOL for simulation. The properties of each motor part were suitably given and are meshed into small elements for the detailed analysis. Finer the mesh is, more accurate will be the result. The mesh generated is as shown in fig.4.

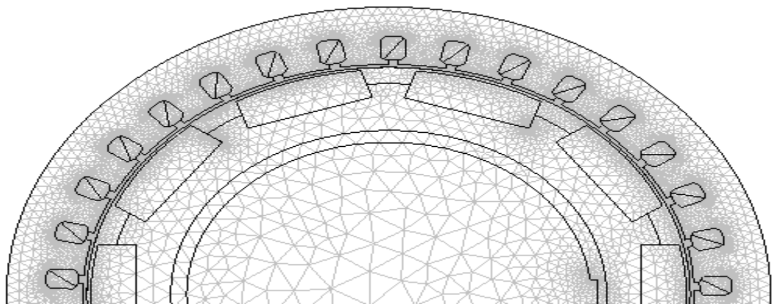


Fig. 4 Mesh generated during FEM Analysis

The same configuration was employed for both three phase and five phase motor with only difference in the number of turns in each slot which will vary as the number of phase changes.

## SIMULATION AND RESULTS

The simulation of BLDC motor byMATLAB/Simulink usingthe mathematical model described in the above section was done using for both three phase and five phase motor. The MATLAB models for the motors are as shown in fig. 5 and 6 respectively. The simulation parameters using MATLAB are given in table.2.

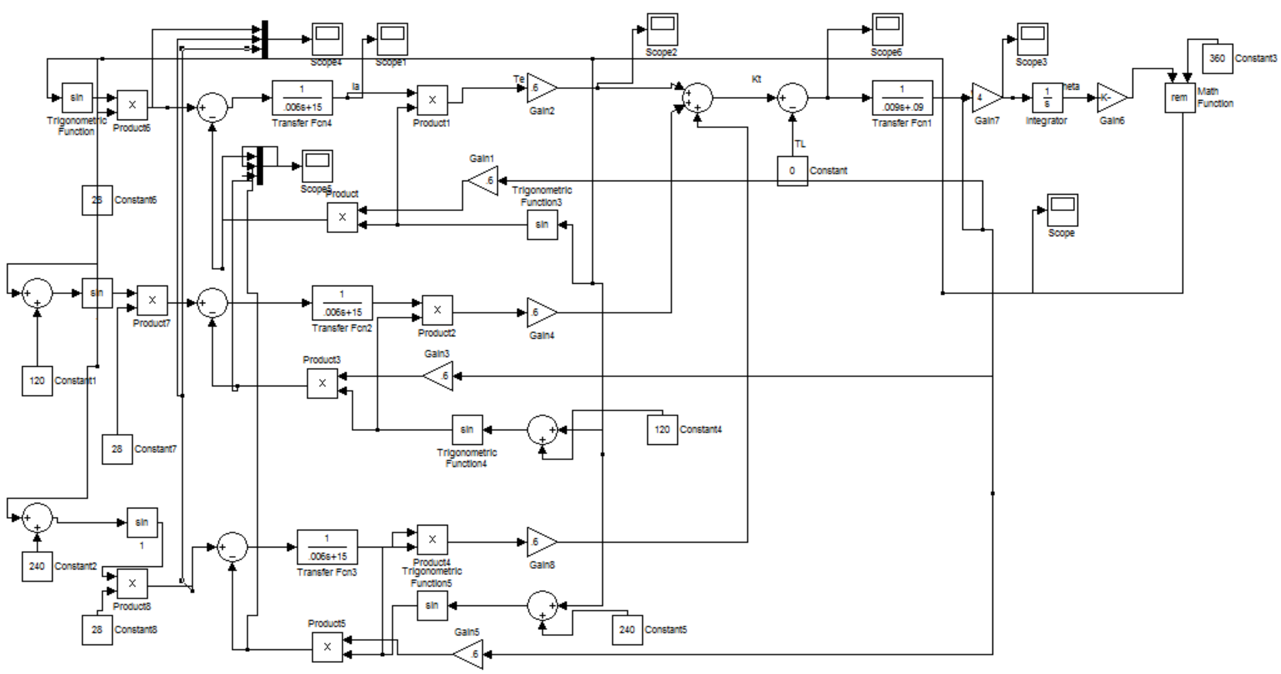



Fig.5 MATLAB model of three phase BLDC motor

Table 2. Simulation Parameters

| Parameters | Specifications |
|---|---|
| Resistance, R | 15Ω |
| Inductance, L | 6 mH |
| J | 0.009 $kgm^2$ |
| B | 0.09 $Nm.s.rad^{-1}$ |
| Kt | 0.2 |
| Kb | 0.2 |

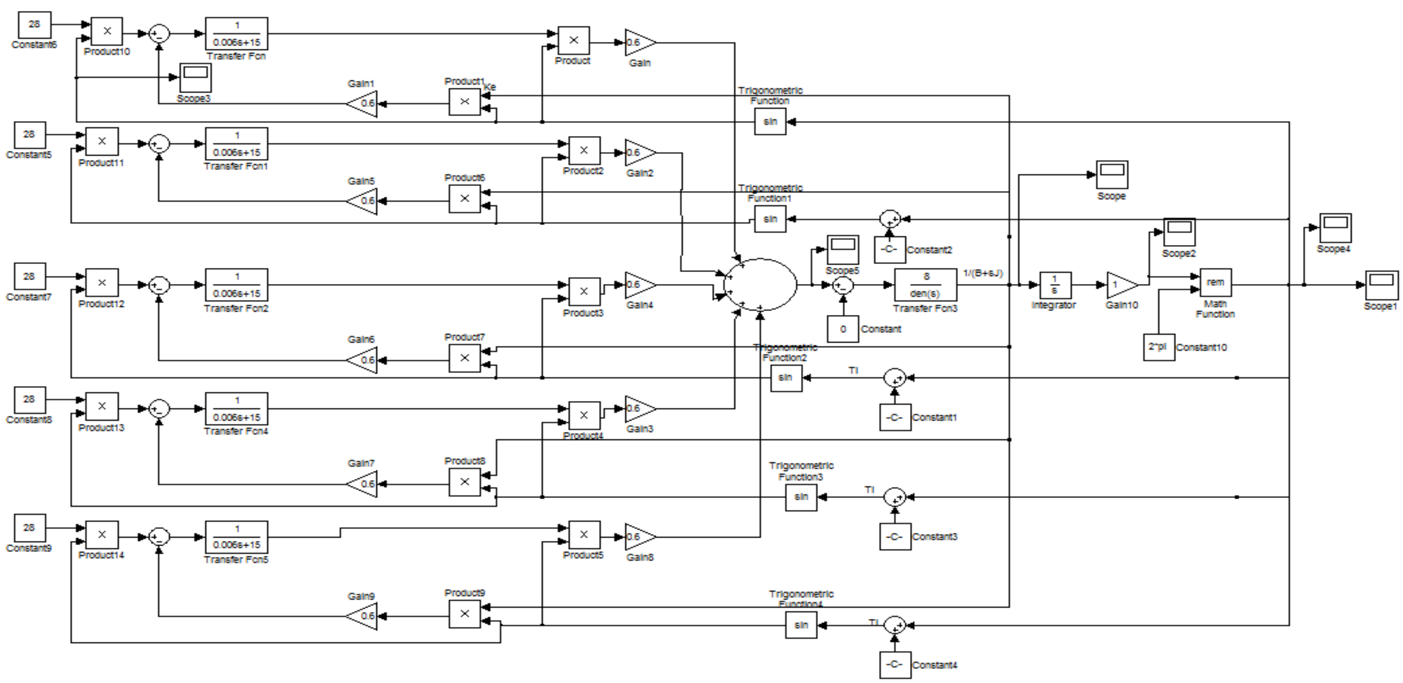


Fig.6 MATLAB model of three phase BLDC motor

The speed waveform obtained is as shown in fig.7 and is about 46 rad/s (28/0.2 = 140 rad/s numerically).The electrical position which varies from 0 to 360 electrical degrees is shown in fig.8. Speed ,Current and position are same for both three phase and five phase motors.

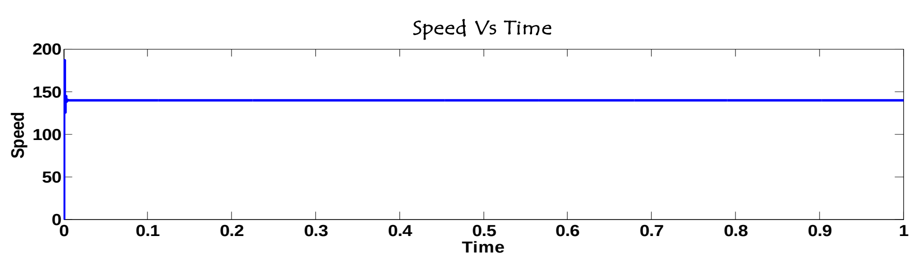



Fig.7Speed, $\omega$ versus time plot

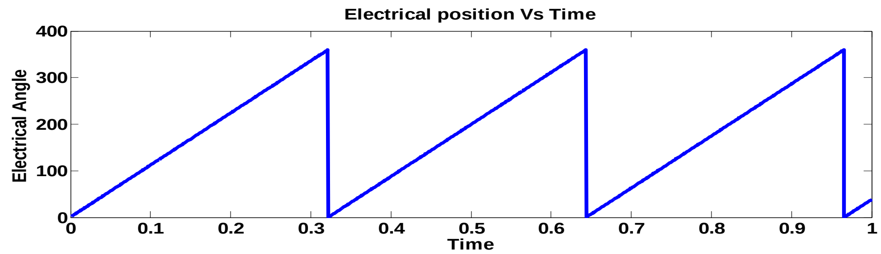



Fig.8 Electrical position Vs time profile

The current waveform is obtained as shown infig.9. The amplitude of current is obtained about 1.5 A.

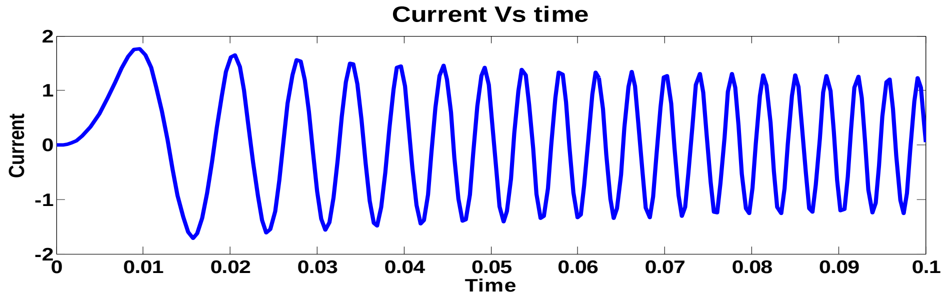
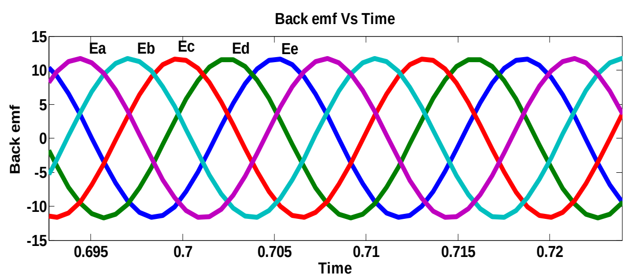
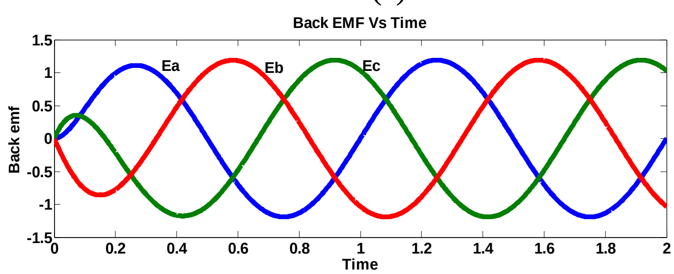



Fig.9Current waveform

Back EMF waveform using MALTAB for the five phase and three phase motor is obtained as in figure 10.




(a)




(b)

Figure 10. Back emfVs time using MATLAB (a) five phase motor (b)three phase motor

The cogging torque versus time plot is obtained from COMSOL (Fig.10). Due to the fractional slot winding design it is very low. The magnitude of cogging torque is 2.5e-3 Nm which is only 0.25% of the actual torque.

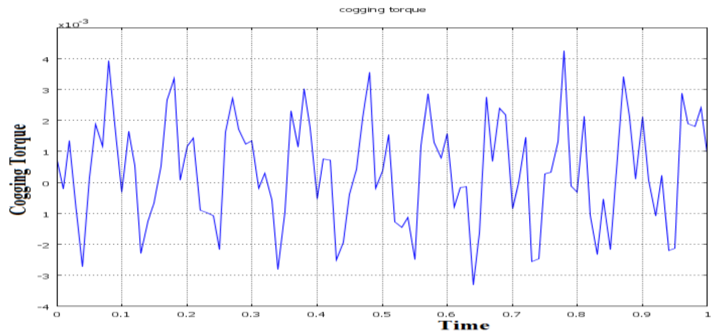



Fig.10 Cogging Torque

The magnetic flux density in the airgap is about 0.7 Wb/m$^2$ and its waveform is as shown in fig.11

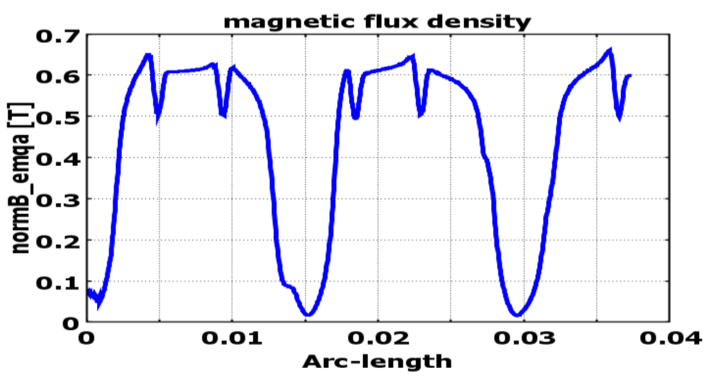



Fig.11 Magnetic flux density in airgap

The phase voltage across a phase and the back EMF obtained is shown in fig. 12 .This is same for both the motors.

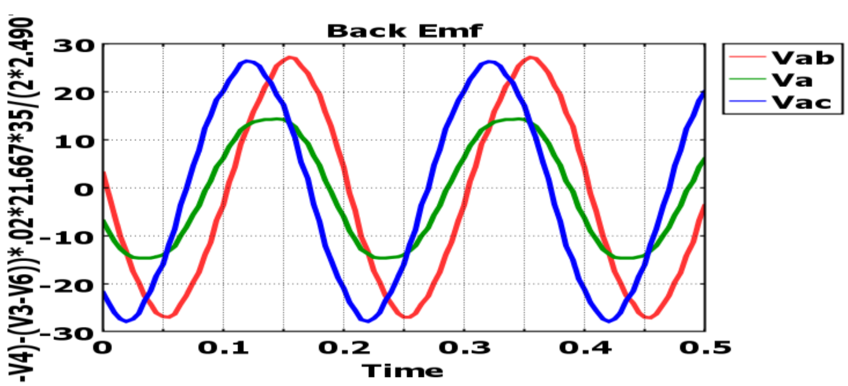



Fig.12 Voltage waveforms including the induced EMF.

The torque profile for three phase motor and five phase motors are shown in fig 13 and 14 respectively. This result is taken with 1A current. The waveforms show that there is a slight increase in its magnitude for five phase motor.

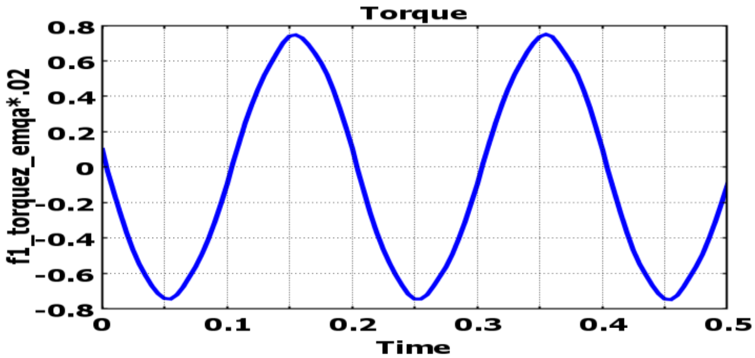



Fig.13. Torque obtained for three phase motor

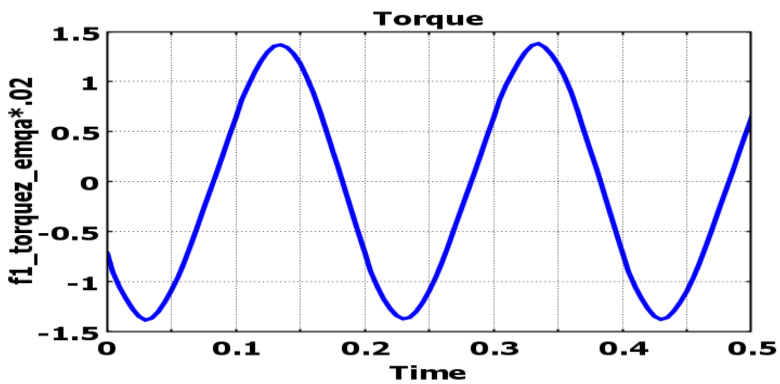



Fig.14 Torque obtained for five phase motor

For experimental needs a five phase motor has been implemented (Figure. 15)

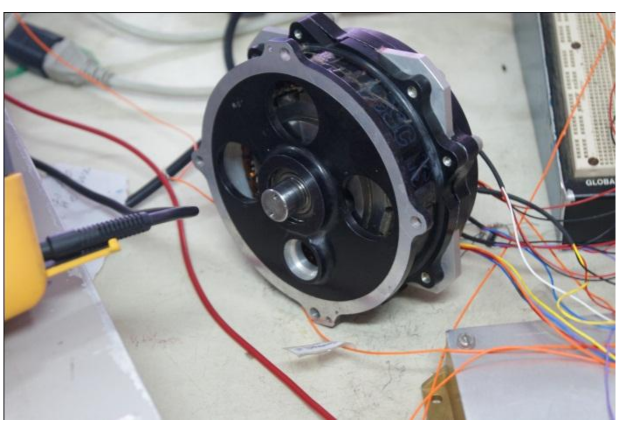


Fig.15. A five phase BLDC motor

## CONCLUSION

Analysis of permanent magnet BLDC motor has been performed with a motor with 33 slots and 10 poles. A comparison between the three phase and five phase motors have been presented and has been analyzed that multiphase motors shows improvement in the torque profile when compared with the three phase motor. MATLAB/Simulink simulation has been carried out and the results have been presented.Finite element analysis was done using COMSOL. The cogging torque obtained is less than 1% of the actual torque due to the fractional slot pitch windingswhich is also verified by simulation.

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