

# Design and Analysis of Enclosed Rotor Halbach Array Brushless DC Motor for Spacecraft Applications

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**Abstract**— This paper presents the design and analysis of a novel machine family-Enclosed Rotor Radial flux Halbach array Permanent Magnet Brushless DC motor (PMBLDC) for spacecraft applications. Initial design, selection of major parameters and air gap magnetic flux density are estimated using the analytical model of the machine. The proportion of the halbach array in the machine was optimized using FE to obtain near trapezoidal flux pattern. Enclosed Rotor Halbach array motor configuration is found to deliver high torque density, high efficiency, zero cogging torque, better positional stability, high torque to inertia ratio and zero magnetic stiction suiting space requirements. The machine provides uniform air gap flux density along the radius thus avoiding circulating currents in stator conductors and hence reducing torque ripple.

**Index Terms**— Brushless DC motor, Coreless, Enclosed Rotor, FEA, Halbach Array, Zero Cogging.

## I. INTRODUCTION

The effects of torque ripple are undesirable in demanding spacecraft applications such as in CMG (Control Moment Gyroscope) [1] that requires positional accuracy of less than an arc second. They lead to speed oscillations which cause deterioration in the performance. In addition, the torque ripple may excite resonances in the mechanical portion of the drive system, producing acoustic noise. The most important design consideration in the choice of low speed high performance torquer motors for spacecraft applications is not only to obtain high torque density and efficiency but also to minimize the torque ripple and its related harmonics. This paper aims to provide a solution to this problem by proposing and investigating a novel machine class –Enclosed Rotor Radial Flux Halbach Array PMBLDC machines. Although a few core type radial-flux dual-rotor [2],[3] and dual-stator PM machines [4] have been reported, the possibility of a radial flux enclosed rotor coreless configuration utilizing halbach array is not explained much in available literature. Brushless direct current motors (BLDC) have been proven to be the best all-around type of motors for aerospace applications because of their long life, high torque, high

efficiency, and low heat dissipation [5]. Stepper motors, a special case of BLDC motors cannot be used for critical spacecraft applications because of its high ripple torque. Moreover the earlier work carried out by the authors [6] clearly reveals the magnitude of the detent torque present in the stepper motor which is almost 13% of the developed torque.

Permanent magnet BLDC motors contain ripple torque which includes cogging torque produced by the machine and commutation torque associated with drive circuits. Cogging is one of the disadvantages faced in the slotted motor design, as it causes a ripple in the torque generated by the motor. Cogging Torque is caused by the variation of the magnetic energy stored in the air gap, due to the PM flux with the angular position of the rotor. It is due to the interaction between the rotor magnetic flux and the variation of stator reluctance by slotting. A slotless BLDC motor design however eliminates the tooth ripple component of cogging as well as has little slot harmonic effects thereby facilitating the need of smooth torque output required for the application. A slotless machine, however suffers from a generally lower magnetic flux crossing the motor air gap which results in a lower power output compared to an equivalent slotted design [7],[8].The use of Halbach magnetization can compensate for this reduced output to an extent due to its strong and uniform magnetic field.

## II. MACHINE DETAILS AND SPECIFICATIONS

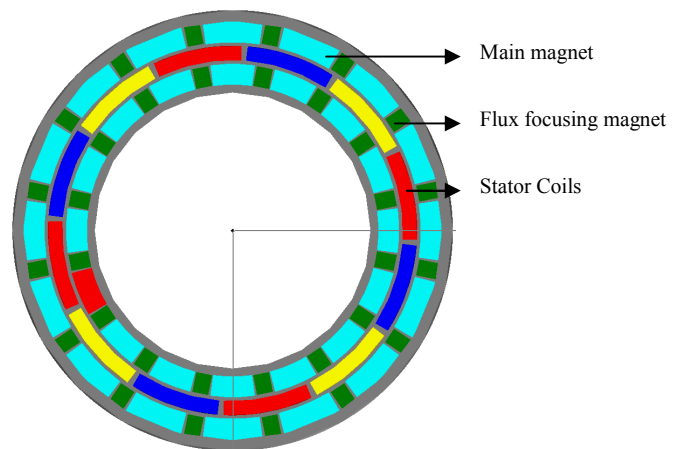


Figure 1. Enclosed Rotor, Radial Flux PMBLDC Motor with Halbach array

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Fig.1. shows an Enclosed Rotor Zero Cogging permanent magnet BLDC motor with Halbach array. The inherent self shielding property of Halbach Array is utilized in the design as it permits the use of coreless configuration permitting high torque to inertia ratio. Unlike that of conventional slotted type PMSBLDC motors the Enclosed Rotor BLDC motor employs slotless stator winding. Concentrated type of winding is employed as it gives less end winding and avoids overlapping of phase windings. Being air-cored, this machine possesses zero cogging torque and zero stiction. Introduction of flux focusing magnet eliminates the flux through the rotor iron core and hence the core loss. In addition to that mean air gap flux density also increases and hence the torque. One of the main challenges faced in the design of low speed single rotor coreless machines is the existence of circulating currents in the stator conductors. This can be attributed to the variation of flux linking them across the large air gap of the machine. Enclosed Rotor Halbach BLDC Motor provides uniform air gap flux along the radius of the machine and hence eliminates circulating currents in stator conductors. With these advantages, this machine is an ideal candidate for low speed high torque spacecraft applications that require positional accuracy of less than an arc second. As per the requirements of the spacecraft application the outer diameter and axial length of the machine is selected as 123 mm and 40 mm respectively. Hence a design is to be developed in accordance with the specifications for CMG as well as other spacecraft applications.

### III. ANALYTICAL MODELING OF THE MACHINE

There are different types of analytical methods that can be used for design of electric motors. The most commonly used methods range from Method of images, analysis using tensors and solutions using magnetic vector potential. The analytical method employed in this work uses scalar magnetic potentials derived from the solutions of Laplace's and Poisson's equations. The general schematic of the machine shown in Fig.2. is divided into three annular regions, in which region II is the halbach magnetized magnets and the other regions are airspaces.

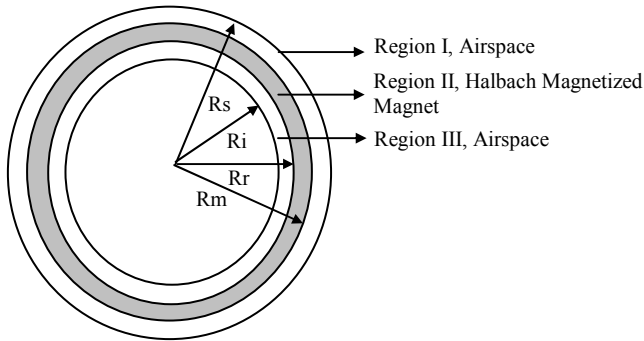


Figure 2. General Schematic diagram of a coreless Halbach Array PMSBLDC Motor

Windings can be inserted in either region I or III depending upon interior or exterior configurations. In order to obtain analytical solution for the field distribution produced in a multipole halbach machine, the following assumptions are made:

- i) The magnet is oriented according to Halbach magnetization and is fully magnetized in the direction of magnetization.
- ii) The effect of finite axial length is neglected.
- iii) The back iron is infinitely permeable.

Here, for the analytical modeling, the enclosed rotor configuration is approximated as the sum of coreless internal and external rotor machines. In the case of internal rotor machine the region inside the halbach array is considered as air ( $R_i = 0$ ) and in the external rotor machine, the region outside the halbach array is considered as air ( $R_s = \infty$ ), where  $R_i$  and  $R_s$  are the stator inner bore and outer bore radius respectively. From the schematic diagram of the machine shown in Fig.2 the region inside the Halbach array is considered as air as coreless machine configuration is considered which suits space requirements.

The field vectors  $\mathbf{B}$  and  $\mathbf{H}$  are coupled by,

$$\mathbf{B} = \mu_0 \mathbf{H}, \text{ in airspace} \quad (1)$$

$$\mathbf{B} = \mu_0 \mu_r \mathbf{H} + \mu_0 \mathbf{M}, \text{ in the permanent magnet} \quad (2)$$

where  $\mu_0$  is the permeability of free space,  $\mu_r$  is the relative permeability of the magnet and  $\mathbf{M}$  is the magnetization vector. For an ideal Halbach magnetized machine the magnetic distribution  $\mathbf{M}$  varies sinusoidally. In cylindrical coordinates it is given by,

$$\mathbf{M} = M_r \mathbf{r} + M_\theta \boldsymbol{\theta} \quad (3)$$

Hence for an Ideal halbach machine,

$$\mathbf{M} = M \cos p\theta \mathbf{r} \pm M \sin p\theta \boldsymbol{\theta} \quad (4)$$

where '+' and '-' is for external and internal halbach rotor approximations respectively,  $M$  is the amplitude of magnetization which is equal to  $Br/\mu_0$ ,  $Br$  is the remanent flux density of the magnet,  $\mathbf{r}$  and  $\boldsymbol{\theta}$  are the magnetic vectors in the radial and circumferential direction respectively.

The governing Laplacian (in air gap) and quasi-Poissonian (in magnets) equations, in cylindrical coordinates are given by:

$$\nabla^2 \phi I = \frac{\partial^2 \phi I}{\partial r^2} + \frac{1}{r} \frac{\partial \phi I}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \phi I}{\partial \theta^2} = 0 \quad \text{In air gap, i.e. } (R_m < r < R_s) \quad (5a)$$

$$\nabla^2 \phi II = \frac{\partial^2 \phi II}{\partial r^2} + \frac{1}{r} \frac{\partial \phi II}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \phi II}{\partial \theta^2} = \frac{\text{div} \mathbf{M}}{\mu_r} \quad \text{In the Magnets, i.e. } (R_r < r < R_m) \quad (5b)$$

$$\nabla^2 \Phi_{III} = \frac{\partial^2 \Phi_{III}}{\partial r^2} + \frac{1}{r} \frac{\partial \Phi_{III}}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \Phi_{III}}{\partial \theta^2} = 0$$

In air gap, i.e. ( $R_i < r < R_r$ )

(5c)

where  $\Phi_I$  and  $\Phi_{II}$  are the scalar magnetic potentials in the air gap and magnets respectively. The magnetization source for (5b) is given as,

$$\text{div} \mathbf{M} = \frac{M_r}{r} + \frac{\partial M_r}{\partial r} + \frac{1}{r} \frac{\partial M_\theta}{\partial \theta}$$
(6)

The boundary conditions to solve the above governing equations are defined by equations (7) to (10):

$$H_{\theta I} \text{ at } (r = R_s) = 0$$
(7)

$$H_{\theta III} \text{ at } (r = R_i) = 0$$
(8)

$$B_{rI} = B_{rII} \text{ at } (r = R_m)$$
(9)

$$B_{rII} = B_{rIII} \text{ at } (r = R_r)$$
(10)

$$H_{\theta I} = H_{\theta II} \text{ at } (r = R_m)$$
(11)

$$H_{\theta II} = H_{\theta III} \text{ at } (r = R_r)$$
(12)

The magnetic field intensity vector  $\mathbf{H}$  can be related to the scalar magnetic potential by the expressions (11), (12).

$$\mathbf{H} = -\text{grad } \Phi$$
(13)

$$H_r = -\frac{\partial \Phi}{\partial r}; H_\theta = -\frac{1}{r} \frac{\partial \Phi}{\partial \theta}$$
(14)

Hence the complete solution for the Enclosed rotor Halbach array zero cogging motor under study is obtained by the solution of Laplace's and quasi-Poisson's equation given by (5a),(5b),(5c) and by the application of boundary conditions(7)to(12). The analytical equations are derived in line with [9], [10]. For an internal rotor coreless zero cogging halbach array motor, the radial flux density at the air gap,  $B_{rI}$  is given by (13) as,

$$B_{rI} = \frac{-4Brp}{M_0(1+p)} (1+\mu_r) \times \left[ 1 - \left( \frac{Rr}{Rm} \right)^{p+1} \right] \times \left[ \left( \frac{r}{Rs} \right)^{p-1} \left( \frac{Rm}{Rs} \right)^{p+1} + \left( \frac{Rm}{r} \right)^{p+1} \right] \cos p\theta$$
(13)

where  $M_0$  is given by (14)

$$M_0 = 2 \left\{ (1-\mu_r) \left( \frac{Rr}{Rm} \right)^{2p} \left[ (1-\mu_r) + (1+\mu_r) \left( \frac{Rm}{Rs} \right)^{2p} \right] - (1+\mu_r) \left[ (1+\mu_r) + (1-\mu_r) \left( \frac{Rm}{Rs} \right)^{2p} \right] \right\}$$
(14)

For an external rotor coreless zero cogging halbach array motor, the radial flux density at the air gap,  $B_{rIII}$  is given by (15) as,

$$B_{rIII} = \frac{4Brp}{M_1(1-p)} (1+\mu_r) \times \left[ 1 - \left( \frac{Rr}{Rm} \right)^{p-1} \right] \times \left[ 1 + \left( \frac{Ri}{r} \right)^{2p} \right] \left( \frac{r}{Rr} \right)^{p-1} \cos p\theta$$
(15)

where  $M_1$  is given by (16)

$$M_1 = 2 \left\{ (1-\mu_r) \left[ (1-\mu_r) \left( \frac{Rr}{Rm} \right)^{2p} + (1+\mu_r) \left( \frac{Ri}{Rm} \right)^{2p} \right] - (1+\mu_r) \left[ (1+\mu_r) + (1-\mu_r) \left( \frac{Ri}{Rr} \right)^{2p} \right] \right\}$$
(16)

where  $p$  is the pole pair number,  $\mu_r$  is the relative recoil permeability of the magnet,  $\theta$  is the relative position of the stator with respect to the rotor,  $R_r$  is the internal radius of the magnet,  $R_m$  is the magnet outer radius,  $R_s$  is the stator outer bore radius,  $R_i$  is the stator inner bore radius and  $r$  is the mean air gap radius where the flux density has to be calculated. Hence the radial flux component of an enclosed rotor configuration can be approximated as the sum of the internal and external rotor halbach configuration.

From (13) to (16), the radial flux density at the air gap,  $B_{r \text{ enclosed}}$  of an Ideal Enclosed rotor coreless zero cogging halbach array motor is given as,

$$B_{r \text{ enclosed}} = h(B_{rI} + B_{rIII})$$
(17)

where  $h$  is the halbach approximation factor arised due to the discretization of magnet segments to form halbach array. For the Enclosed Rotor Halbach Array PMBLDC Motor investigated the halbach approximation factor is found to be 0.65 for ideal halbach magnetization. A code is developed in MATLAB for analytical modeling of Enclosed Rotor Halbach Array PMBLDC Motor. They are formulated in polar coordinates and account for relative recoil permeability of the magnets.

#### IV. ANALYTICAL RESULTS AND DISCUSSION

The closed form solution derived in the previous section is used for computing the radial component of the mean air gap flux density ( $B_{r \text{ enclosed}}$ ) for the Enclosed Rotor Halbach Array PMBLDC Motor. Fig.3.gives the variation of peak air gap flux density at mean air gap radius with pole pair number of the Enclosed Rotor Halbach Array PMBLDC motor to be designed. The length of the magnetic flux path in a halbach magnetized rotor is dependent on the pole pair number and hence there exist an optimum number of poles at which the flux density is maximum. The same is not applicable for radial and parallel magnetized machines since the length of the magnetic flux is constant (equal to the magnetic thickness) [6].

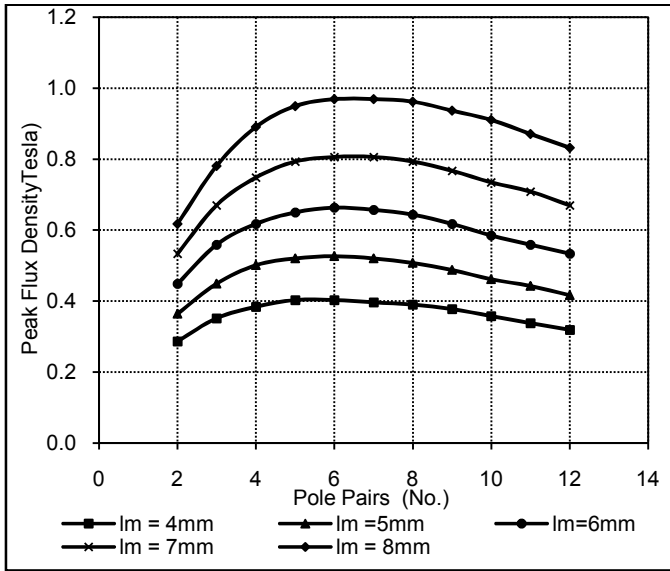


Figure 3. Variation of peak Flux Density with change in length of magnet and pole pairs (Analytical Results)

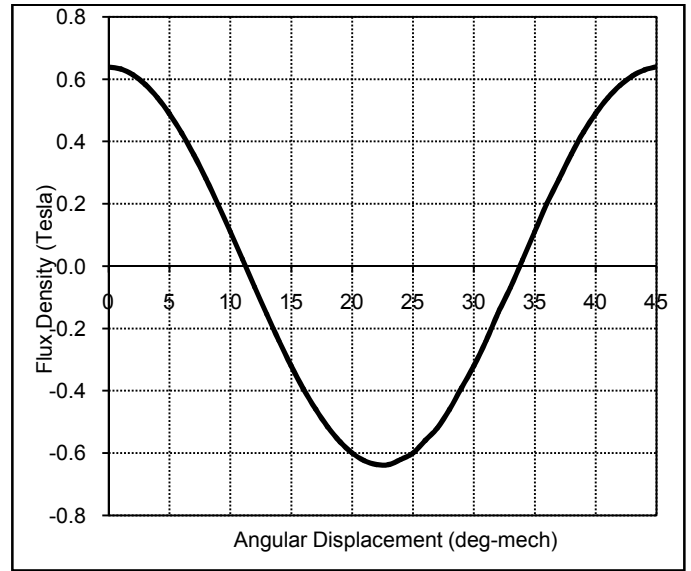


Figure 5. Variation of mean air gap flux density under one pole pitch

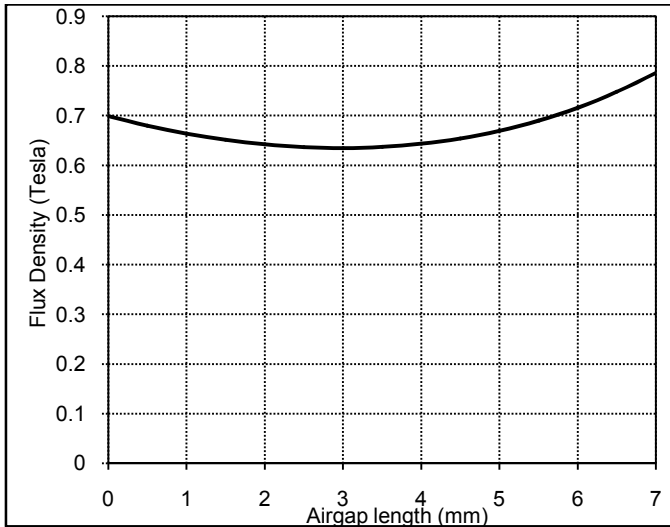


Figure 4. Variation of mean air gap flux density along the length of the air gap (Analytical Results)

From Fig.3. peak flux density is obtained when the total number of rotor pole pairs is selected as 6. Since the motor to be designed is meant for low speed aerospace applications, optimum performance can be achieved when the total number of rotor poles is selected as high as possible without compensating much with the flux density of the machine. Hence the optimum number of the rotor pole pairs for the machine to be designed is selected as 8. With the increase in length of the magnet even though the mean air gap flux density increases the space available for accommodating the stator windings decreases. Hence based on the tradeoff between electrical and magnetic loading optimized values of length of magnet and pole pairs are chosen as 6mm and 8 respectively.

Fig.4 shows and the magnetic field variation along the air gap radius of an ideal halfbach magnetized enclosed rotor motor configuration where an equal proportion between the main magnet and flux focusing magnet is adopted. From Fig.4. it is clear that the average value of peak air gap flux density along the length of air gap of the designed motor is 0.68T which is very high as compared to a conventional slotless machines employing single rotor configuration. The flux density along the length of air gap is almost constant and hence eliminates the possibility of circulating currents in stator conductors, thereby reducing torque ripple. Fig.5 shows the mean air gap flux density variation under one pole pitch of the Ideal Enclosed Rotor Zero Cogging Halfbach array PMLDC Motor investigated. A brief design data of the Enclosed Rotor machine developed is given in Table 1.

TABLE I  
DESIGN DETAILS DEVELOPED FOR THE MACHINE

Parameter	Value
Dimension	$\Phi(123-77)\times 40$ mm
Supply Voltage	28 V
No. of Phases	3
No. of Poles	16
No. of Stator coils	12
Resistance/Phase	4.5 $\Omega$
Air gap thickness	0.5 + 0.5 mm
Permanent magnet	$\text{Sm}_2\text{CO}_{17}$
No. of magnets	16 + 16 + 32
Axial Length of magnets	30mm
Position sensor	Hall element
Torque constant	1.59Nm/A
Power for 1 Nm at 50 rpm	8 watts
Torque Capability	6 Nm

## V. FE MODELING AND ANALYSIS OF THE MACHINE

### A. FE Modeling and Analysis

The basic design parameters obtained from the analytical results of an ideal Enclosed Rotor Halbach Array PMLDC motor such as the length of the magnet and the number of pole pairs are used to model the machine in FE. The optimization of the machine is carried out using Maxwell FE software package. Two dimensional FE analysis is carried out as the machine is axisymmetric.

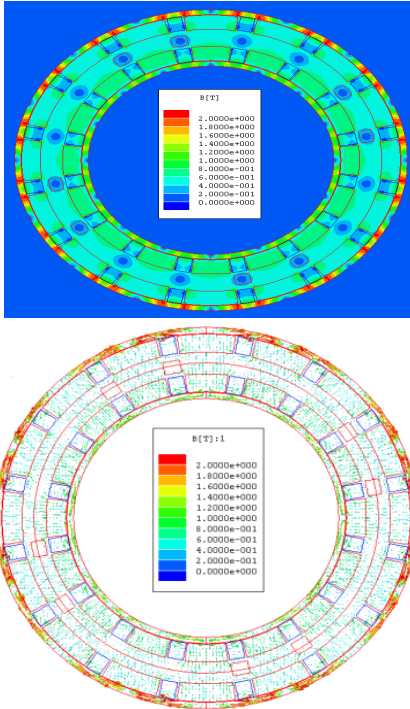


Figure 6. Flux Distribution of the machine (FE Results)

From the flux pattern, it is clear that flux focusing magnet acts as a path for flux between adjacent poles and reduces the flux in the back iron. The effect will be clearer with the increase in proportion between flux focusing and the main magnet.

### B. FE Optimization of Enclosed Rotor Halbach PMLDC Motor

The variation of the developed torque pattern with the change in proportion of flux focusing magnet and the main magnet is shown in Fig.7. Here, it is observed that with the increase in proportion of flux focusing magnet to the main magnet, the pattern becomes more sinusoidal with increase in peak torque. The ripple increases (i.e. more sinusoidal) with the increase in proportion of flux focusing magnet to the main magnet, which will be more suitable for sine-cosine drives. The variation of peak torque, average torque and ripple with this change is tabulated in Table 4. Based on these results an optimum configuration of 30-70 is chosen.

Fig.8. shows the developed torque pattern of the optimized Enclosed Rotor Halbach Array PMLDC Motor designed for spacecraft applications. The designed motor is found to deliver 1.59 Nm at 1A excitation. The developed torque pattern is near trapezoidal because of the increase in proportion of the main magnet to the flux focusing magnet.

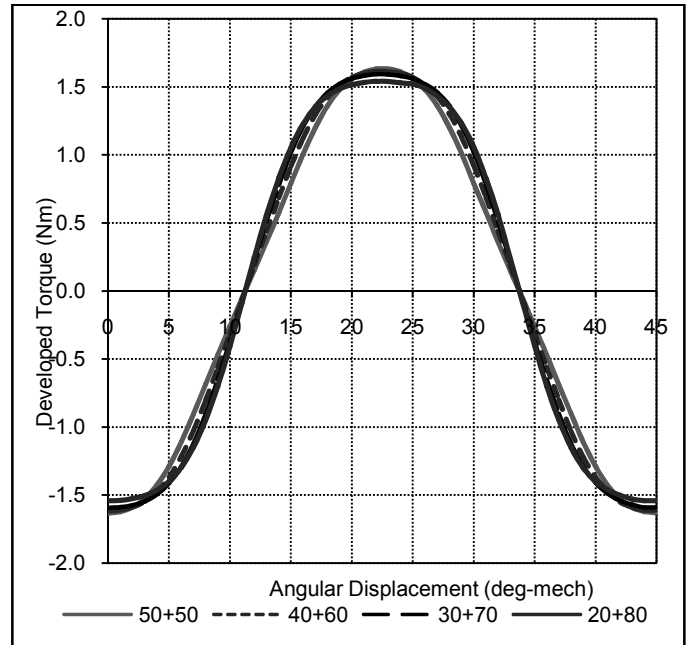


Figure 7. Developed Torque pattern with change in proportion of flux focusing and main magnet (FE Results)

TABLE II  
VARIATION OF PERFORMANCE PARAMETERS WITH THE CHANGE IN FLUX FOCUSING MAGNET PROPORTION

Main magnet (%)	Flux focusing magnet (%)	Average Torque (Nm)	Peak Torque (Nm)	Torque Ripple (%)
50	50	1.06	1.63	22.56
60	40	1.11	1.61	16.67
70	30	1.14	1.59	12.77
80	20	1.13	1.54	10.79

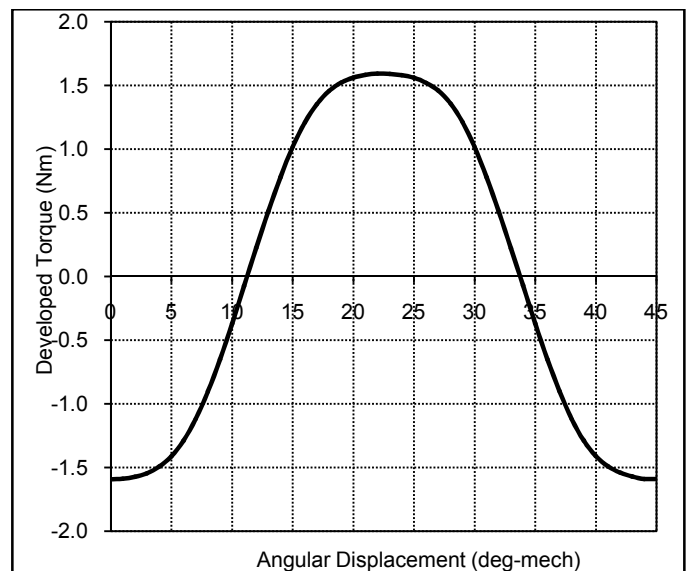


Figure 8. Developed torque pattern of the optimized Enclosed Rotor Halbach Array Motor (FE Results)

## VI. CONCLUSION

A novel design methodology for an Enclosed Rotor Zero Cogging Halbach Array PMBLDC motor for spacecraft applications is discussed in the paper. Analytical model of the machine have been developed for the initial design and the selection of basic design parameters. The optimization of the machine is carried out in FE. The Enclosed Rotor configuration helps in achieving high torque density and uniform flux density along the air gap of the machine thereby reducing torque ripple. Moreover the use of halbach array helps in achieving high Torque to inertia ratio and reduced core losses. The presence of cogging torque and magnetic stiction are also eliminated by employing coreless configuration. For further validation and as an extension of the present work it is proposed to fabricate Enclosed Rotor Halbach Array PMBLDC Motor with the specification obtained as per the design discussed in this paper and obtain experimental results. The work in this direction is already underway. The machine is found to develop a peak torque of 1.59 Nm at 1A excitation and meet the required design requirements for low speed spacecraft applications.

## VII. ACKNOWLEDGMENT

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## IX. BIOGRAPHIES

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