# Design and Analysis of Zero Cogging Brushless DC Motor for Spacecraft Applications

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**ABSTRACT**

This paper presents the optimal design of a surface mounted permanent magnet Brushless DC motor (PMBLDC) meant for spacecraft applications. The spacecraft applications requires the choice of a torques motor with high torque density, minimum cogging torque, better positional stability and high torque to inertia ratio. Performance of two types of machine configurations viz Slotted PMBLDC and Slotless PMBLDC with halbach array are compared with the help of analytical and FE methods. It is found that unlike a Slotted PMBLDC motor, the Slotless type with halbach array develops zero cogging torque without reduction in the developed torque. Moreover, the machine being coreless provides high torque to inertia ratio and zero magnetic stiction.

**Keywords**: Brushless DC Motor, Slotted, Slotless, Halbach, Torque, Cogging, Space Application

## 1. INTRODUCTION

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 [1]. The torque produced in a Slotted PMBLDC motor can be classified as Alignment Torque (Useful Torque) and Cogging torque. Alignment torque is produced due to the interaction of the permanent magnet with the stator conductors and 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. Simply it is due to the interaction between the rotor magnetic flux and the variation of stator.

For high performance applications, torque smoothness is essential. Hence, it is very important to consider torque ripple minimization and its related harmonics without affecting the developed torque of the machine.

Cogging is one of the disadvantages faced in the slotted motor design, as it causes high ripple in the torque generated by the motor. The attitude control systems (ACS) for future spacecraft applications requires an ideal choice of motor that has high torque density, zero cogging torque, high positional stability, high torque to inertia ratio and zero magnetic stiction. Stepper motors, a special case of BLDC motors cannot be used for critical ACS applications because of its high ripple torque. Moreover the research work carried out by the authors [2], [3] clearly reveals the magnitude of the detent torque present in the stepper motor which is almost 13% of the developed torque. 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 in the slotless design compared to an equivalent slotted design [4],[5]. This reduction in the magnetic flux crossing the air gap is compensated by the use of Halbach magnetized array having strong and uniform magnetic field. As per the requirements of the spacecraft application the outer diameter and axial length of the machine is selected as 104 mm and 40 mm respectively. Hence a design is to be developed in accordance with the specifications for spacecraft applications.

## 2. ANALYSIS OF A SLOTTED PMBLDC MOTOR

### 2.1 Analytical Modeling

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 vector po-

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tentials derived from the solutions of Laplace's and Poisson's equations.

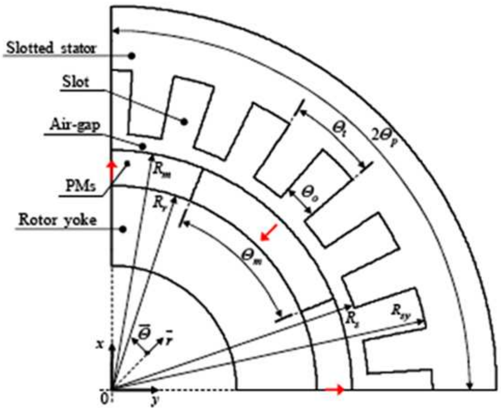


***Fig.1:*** *Cross section of a slotted PMBLDC Motor*

Fig.1. shows the cross section of a slotted PM-BLDC motor under one pole pitch and is used for the 2-D analytical solution of the no load magnetic flux density with the effect of slotting considered. The main parameters of this geometry are: the radius of the stator yoke surface, $R_{sy}$, the radius of the stator surface, Rs, the radius of the PMs surface, $R_m$, the radius of the rotor yoke surface, $R_r$, the mechanical angle of PMs, $\theta_m$, the mechanical angle of a stator slot-opening, $\theta_0$, the mechanical angle of a stator tooth-pitch, $\theta_t$, and the mechanical angle of a pole-pitch, $\theta_p$ .The following are the assumptions made for the analytical modeling:
i) End-effects are neglected; ii) The stator and rotor back-iron is infinitely permeable (i.e., the magnetic saturation is neglected); iii) The electrical conductivity of the PMs is assumed to be null to calculate the no-load magnetic vector potential; iv) The PMs are assumed to be non oriented, isotropic, and having a linear demagnetization characteristic (rare earth magnets); v) Radial slot faces on the stator.

Laplace's equation is used in the air-gap (i.e., concentric region: Region 2) and in the slots on the stator (i.e., non-concentric regions: Regions i) for the solution of no load magnetic flux density whereas Poisson's equations was used in the PMs (i.e., concentric region: Region 1) [see Fig. 1]. The magnetic vector potential and the magnetic flux density components at no-load (at I = 0 A) with I the RMS value of stator current) are expressed in the PMs (i.e., Region 1) by:

$$A_{z1} = B_{rm}.R_m.f_{z1n}(E_{1n}, G_{1n}, r, \theta_s) \tag{1}$$

in the air-gap (i.e., in Region 2) by:

$$A_{z2} = B_{rm}.R_m.f_{z2n}(E_{2n} \sim H_{2n}, r, \theta_s) \tag{2}$$

in the slots on the stator (i.e., Regions $i$) by:

$$A_{zi} = B_{rm}.R_s.f_{ziv}(F_{iv}, v, \theta_s) \tag{3}$$

where $r$ and $\theta_s$ are respectively the radial position and the mechanical angular position of the stator; $B_{rm}$ is the remanent flux density of PMs; $n$ and $v$ are respectively the spatial and the slotting harmonic orders; $f_{z1n}\sim f_{ziv}$ are the dimensionless functions in Fourier's series which depend respectively on the integration constants $E_{1n}$ &$G_{1n}$ in Region 1, $E_{2n} \sim H_{2n}$ in Region 2, and $F_{iv}$ in Regions i.

The integration constants in each region are determined by numerically solving the linear equations (i.e., the Cramer's system) for each $\theta_{rs}$ (with $\theta_{rs}$ the mechanical angular position between the rotor and the stator). This system for each $\theta_{rs}$ consists of $6(n_{max}+1) + Q_p\ (v_{max}+1)$ equations and unknowns with $n_{max}$ and $v_{max}$ terms in the Fourier's series for the computation of $A_{z1} \sim A_{zi}$. ($Q_p$ is the number of slots per pole) The linear Cramer's system for each $\theta$rs is expressed by:

$$[IC] = [Q]^{-1}.[K] \tag{4}$$

where the matrices $[IC]$, $[Q]$ and $[K]$ are given by the equations (5) and (6).

$$[IC] = \begin{pmatrix} E_{1n} \\ E_{2n} \\ F_{2n} \\ G_{1n} \\ G_{2n} \\ H_{2n} \\ F_{iv} \end{pmatrix} ; [K] = \begin{pmatrix} K_{1n} \\ K_{3n} \\ 0 \\ K_{2n} \\ K_{4n} \\ 0 \\ 0 \end{pmatrix} \tag{5}$$

$$[Q] = \begin{pmatrix} Q_A & 0 & Q_B \\ 0 & Q_A & Q_C \\ Q_D & Q_E & Q_F \end{pmatrix} \tag{6}$$

The elements of the matrics [Q] is given by equations (7)-(9)

$$Q_A = \begin{pmatrix} Q_{1nn} & Q_{0nn} & Q_{0nn} \\ Q_{2nn} & -Q_{0nn} & Q_{0nn} \\ 0 & Q_{3nn} & Q_{4nn} \end{pmatrix} \tag{7}$$

$$Q_B = \begin{pmatrix} 0 \\ 0 \\ Q_{5nv} \end{pmatrix} ; Q_C = \begin{pmatrix} 0 \\ 0 \\ Q_{6nv} \end{pmatrix} ; Q_F = (Q_{11vv}) \tag{8}$$

$$Q_D \begin{pmatrix} 0 & Q_{7vn} & Q_{8vn} \end{pmatrix} ; Q_E = \begin{pmatrix} 0 & Q_{9vn} & Q_{10vn} \end{pmatrix} \tag{9}$$

with $Q_{0nn}$ the unit matrix having $n_{max} \times n_{max}$ coefficients, $Q_{1nn} \sim Q_{1nn}$ the diagonal matrices having $n_{max} \times n_{max}$ coefficients, $Q_{5nv} \sim Q_{6nv}$ and $Q_{7nv} \sim Q_{10nv}$ respectively the matrices having $n_{max} \times v_{max}$ and $v_{max} \times n_{max}$ coefficients, $Q_{11vv}$ the diagonal matrix having $v_{max} \times v_{max}$ coefficients, and $K_{1n} \sim K_{4n}$ the matrices having $n_{max} \times 1$ coefficients which depend on $\theta$rs . The corresponding elements in the matrices and the details of the dimensionless functions in

(1) to (3) are derived in line with [6].Based on this analytical model a code was developed in MATHCAD for analyzing the no load air gap flux density of a slotted BLDC motor in all regions.

## 2.2 Analytical Results

The closed form solution derived in the previous section is used for designing an experimental radial magnetized Slotted PMBLDC Motor within the dimensional requirements of (104×40) mm for spacecraft applications. Table 1 shows the design details of the experimental slotted PMBLDC motor.

***Table 1:*** *Design Details of the experimental slotted PMBLDC Motor*

| Parameter | Value |
|---|---|
| Dimension | Φ(104×40)mm |
| Supply Voltage | 28 V |
| No. of Phases | 3 |
| No. of Poles | 12 |
| No. of Slots | 36 |
| Resistance/Phase | 3.37 Ω |
| Air gap thickness | 0.5mm |
| Permanent magnet | $Sm_2CO_{17}$ |
| Magnet thickness | 4 mm |
| Axial Length of magnets | 30mm |
| Radius of the stator yoke surface (Rsy) | 50.5mm |
| Radius of the stator surface (Rs) | 44.5mm |
| Radius of the PM's surface (Rm) | 44mm |
| Radius of the rotor yoke surface (Rr) | 40mm |

Fig.2. shows the no load magnet flux density variation of the experimental radial magnetized slotted PMBLDC motor under one pole pitch. The experimental slotted motor has 36 slot and teeth combination and the number of stator slots per pole is 3.From Fig.2 it is clear that significant amount of harmonics is present in the flux density waveform due to the effect of slotting. The basic design parameters obtained from the analytical model is used to model the machine in FE and optimization has to be carried out in FE in order to reduce the cogging component of torque to suit space applications.

## 2.3 FE Optimization and Results

There are lots of methods available in literature [7], [8] for the reduction of cogging torque in slotted motors. The most significant methods among them are: Skewing of the stator slots or permanent magnets, change in pole arc to pole pitch ratio, providing notches in stator teeth, shifting of permanent magnet pole pairs and adopting fractional slot pitch combination. The research done by the authors [9] clearly revealed the advantages of adopting fractional slot pitch configuration for reducing cogging torque in slotted BLDC motors.

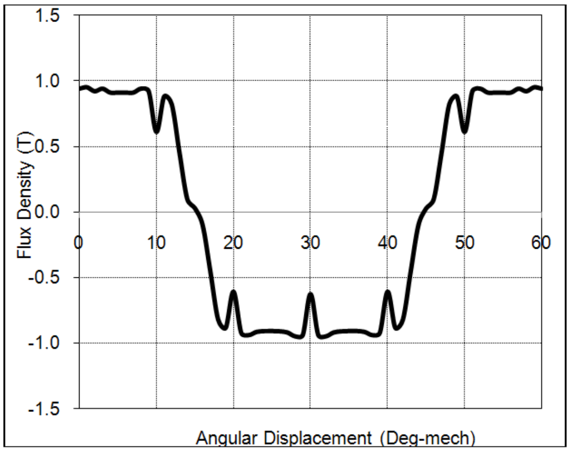


***Fig.2:*** *Variation of the no load magnetic flux density at the air gap under one pole pitch (Analytical Results)*

The number of cogging cycles in one complete mechanical rotation is given by the least common multiple of the Number of stator slots, Ns and Number of poles, Np. When the frequency of the cycle increases, the peak amplitude of the cogging torque comes down. Based on this strategy, the 12- pole, 36 slot experimental motor designed analytically is analysed using FE with stator of different slot numbers.

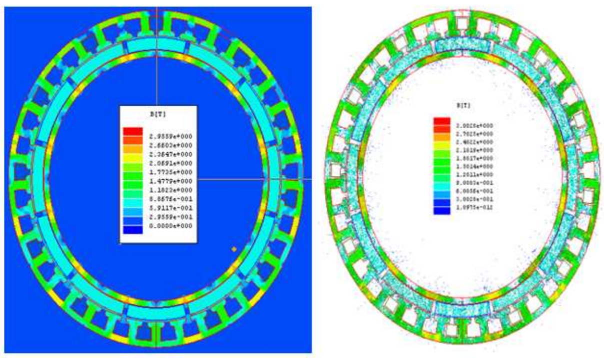

***Fig.3:*** *Flux Distribution of the optimized 37 slot, 12 pole PMBLDC machine (FE Results)*

From the FE analysis it was clear that the cogging torque reduces drastically once 37 slots was selected in the stator instead of 36.Fig.4 shows a comparison of the developed torque pattern under one pole pitch for a 36 slot and 37 slot radial magnetized PMBLDC motor. The torque pulsation in the developed torque is very high for a 36 slot combination which is detrimental for the positional stability for precise space applications. But the developed torque pattern has the least torque pulsations when a 37 slot combination is adopted. Fig.5 shows the cogging torque pattern of a

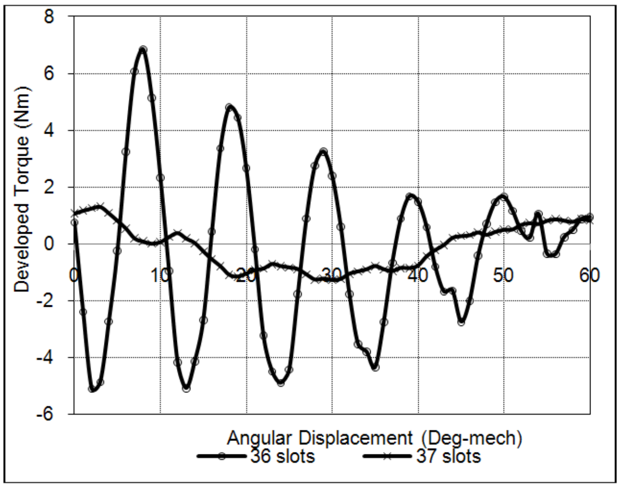


***Fig.4:*** *Comparison of the developed torque patterns of 36 slots and 37 slots PMBLDC machine (FE Results)*

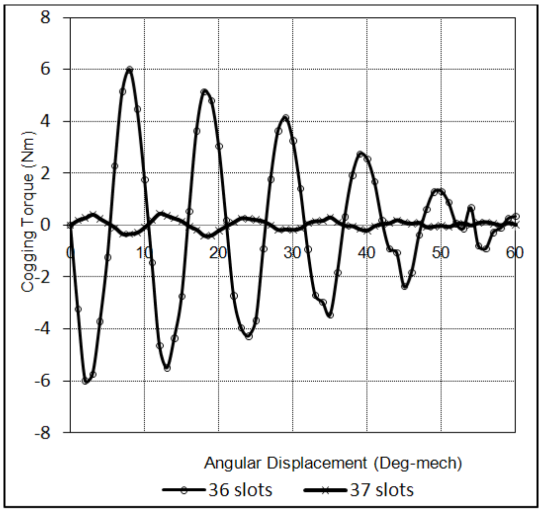


***Fig.5:*** *Comparison of the cogging torque patterns of 36 slots and 37 slots PMBLDC machine (FE Results)*

36 slot and 37 slot combinations. The magnitude of the cogging torque is very much reduced in a 37 slot combination when compared to a 36 slot PMBLDC motor. The machine is found to develop a peak developed torque of 1.3 Nm and an average torque of 0.723 Nm.But the magnitude of cogging torque even in the optimized model (37 slots, 12 pole) is found to be 20% of the developed torque which is higher than that of a hybrid stepper motor of compatible size. Hence in order to suit the spacecraft application requirements another class of PMBLDC motors,, i.e a Slotless PMBLDC configuration is investigated. The use of ferromagnetic material on the rotor can be avoided in a halbach machine unlike that of radial and parallel magnetization thereby reducing the core losses and permitting high torque to inertia ratio. Hence slotless halbach air core PMBLDC machine is considered for further analysis.

## 3. ANALYSIS OF A SLOTLESS PMBLDC MOTOR

### 3.1 Analytical Modeling

For deriving the analytical model of a slotless halbach magnetized PMBLDC motor, scalar magnetic potentials derived from the solutions of Laplace's and Poisson's equations is used.Inorder to obtain analytical solution for the

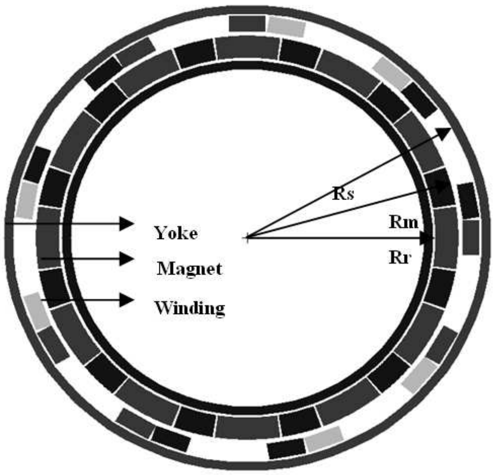


***Fig.6:*** *Zero Cogging PMBLDC Motor with Halbach array*

field distribution produced in a multi pole 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.

The Fig.6. shows a Zero Cogging permanent magnet BLDC motor with Halbach array. Unlike that of conventional slotted type PMBLDC motors the zero cogging BLDC motor employs slotless stator winding. Concentrated type of winding is employed as it gives less end winding and avoids overlapping of phase windings. The inherent self shielding property of Halbach machines over radial and parallel magnetized machines makes it an ideal choice for employing coreless configuration [10], [11].

From the schematic diagram of the machine shown in Fig.6 the region inside the Halbach array is considered as air as coreless machine configuration is considered which suits space requirements.

The field vectors B and H are coupled by,

$$\mathbf{B} = \mu_0 \mathbf{H}, \text{in airspace} \quad (10)$$

$$\mathbf{B} = \mu r \mu_0 \mathbf{H} + \mu_0 \mathbf{M} \text{ in the permanent magnet} \quad (11)$$

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

$$\mathbf{M} = \mathbf{M_r r} + \mathbf{M}_\theta \theta \tag{12}$$

Hence for an Internal rotor halbach machine,

$$\mathbf{M} = \mathrm{M}\cos \mathrm{p}\theta \boldsymbol{r} - \mathrm{M}\sin \mathrm{p}\theta \boldsymbol{\theta} \tag{13}$$

where 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 $\theta$ 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:

$$\nabla^2 \phi I = \frac{\partial^2 \phi I}{\partial r^2} + \frac{1}{r}\frac{\partial \phi I}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \phi I}{\partial \theta^2} = 0$$

In air gap, i.e.(Rm<r<Rs) (14a)

$$\nabla^2 \phi II = \frac{\partial^2 \phi II}{\partial r^2} + \frac{1}{r}\frac{\partial \phi II}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \phi II}{\partial \theta^2} = \frac{div\boldsymbol{M}}{\mu_r}$$

In the Magnets, i.e. (Rr<r<Rm) (14b)

where $\phi I$ and $\phi II$ are the scalar magnetic potentials in the air gap and magnets respectively. The magnetization source for (14b) is given as,

$$div\boldsymbol{M} = \frac{M_r}{r} + \frac{\partial M_r}{\partial r} + \frac{1}{r}\frac{\partial M_\theta}{\partial \theta} \tag{15}$$

The boundary conditions to solve the above governing equations are defined by equations (16) to (19):

$$H_{\theta I} \ at \ (r = Rs) = 0 \tag{16}$$
$$H_{\theta II} \ at \ (r = Rs) = 0 \tag{17}$$
$$B_{rl} = B_{rll} at (r = R_m) \tag{18}$$
$$H_{\theta I} = H_{\theta II} at (r = R_m) \tag{19}$$

The magnetic field intensity vector $\boldsymbol{H}$ can be related to the scalar magnetic potential by the expressions (20), (21).

$$\boldsymbol{H} = -grad\phi \tag{20}$$
$$H_r = -\frac{\partial \phi}{\partial r};\ H_\theta = -\frac{1}{r}\frac{\partial \phi}{\partial \theta} \tag{21}$$

Hence the complete solution for the internal rotor Halbach array zero cogging motor under study is obtained by the solution of Laplace's and quasi-Poisson's equation given by (14a),(14b) and by the application of boundary conditions (16)to(19). The analytical equations are derived in line with [12]. For an internal rotor zero cogging halbach array motor, the radial flux density at the air gap, $\mathrm{B_{rI}}$ is

$$\begin{aligned} B_{rl} &= \frac{-4Brp}{M_0(1+p)}(1+\mu r) \times \left[1 - \left(\frac{Rr}{Rm}\right)^{p+1}\right] \\ &\times \left[\left(\frac{r}{Rs}\right)^{p-1}\left(\frac{Rm}{Rs}\right)^{p+1} + \left(\frac{Rm}{r}\right)^{p+1}\right]\cos p\theta \end{aligned} \tag{22}$$

where $\mathrm{M_0}$ is given by (5)

$$\begin{aligned} M_0 = 2 \Bigg\{ &(1-\mu r)\left(\frac{Rr}{Rm}\right)^{2p}\left[(1-\mu r) + (1+\mu r)\left(\frac{Rm}{Rs}\right)^{2p}\right] \\ &- (1+\mu r)\left[(1+\mu e) + (1-\mu r)\left(\frac{Rm}{Rs}\right)^{2p}\right]\Bigg\} \end{aligned} \tag{23}$$

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, Rr is the internal radius of the magnet, Rm is the magnet outer radius, Rs is the stator outer bore radius and r is the mean air gap radius where the flux density has to be calculated. A code was developed in MATLAB based on the analytical model developed for Halbach array slotless PMBLDC motor. They are formulated in polar coordinates and account for relative recoil permeability of the magnets.

### 3.2 Analytical Results and Discussion

The analytical expressions given in (22) and (23) is used for computing the radial component of the mean air gap flux density ($\mathrm{B}_{rI}$) for a Halbach slotless Internal rotor PMBLDC motor with the required specifications of (104×40) mm. Fig.7.shown below gives the variation of peak air gap flux density at mean air gap radius with pole pair number of the halbach slotless air core PMBLDC machine 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) [13]. It can be seen from Fig.7 that the optimum flux density is obtained when the total number of rotor poles is selected as 12. 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 12 respectively. Fig.8 shows variation of the mean air gap flux density under one pole pitch of the halbach slotless

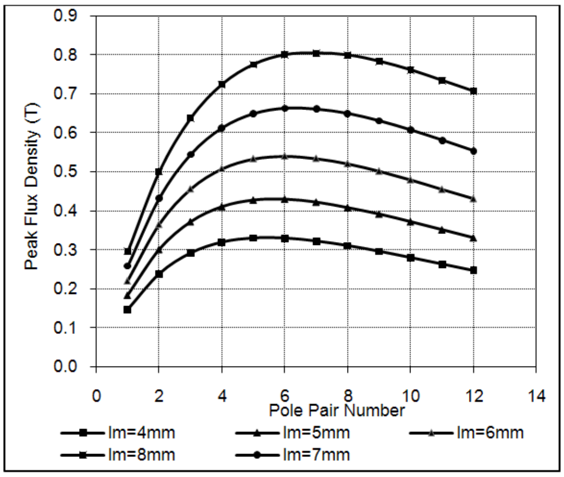


*Fig.7: Variation of peak Br1 with change in length of magnet and pole pairs (Analytical Results)*

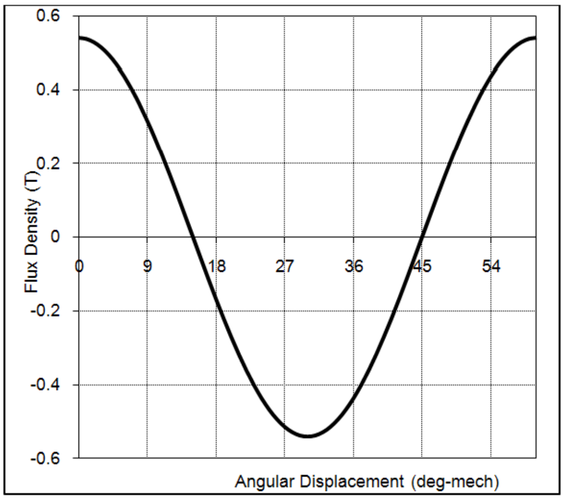


*Fig.8: Variation of mean air gap flux density under one polepitch (Analytical Results)*

air core PMBLDC designed. Unlike that of a slotted PMBLDC motor configuration, the flux density waveform at the mean air gap of a halbach array slotless motor is free of any harmonic content .This is due to the adoption of slotless topology. Also this design is free of the cogging torque component as stator is having no teeth. Hence a zero cogging halbach array PMBLDC motor is designed which largely suits spacecraft applications.

A brief design data of the developed Zero Cogging Halbach Array PMBLDC motor is given in Table 2.

### 3.3 FE Results and Discussion

The basic design parameters obtained from the analytical results of a slotless permanent magnet BLDC motor with Halbach array, such as the length of the magnet and the number of pole pairs is used to model the machine in FE. Two dimensional FE analysis is carried out as the machine is axisymmetric. Commercial FE Software package, Maxwell 2D is used for the analysis. Fig.9.shows the flux density plot and the magnetic vector plot of the designed zero cogging halbach machine. From the flux pattern, it is clear that flux focusing magnet acts as a path for flux between adjacent poles and hence reduces the flux in the back iron. Fig.10. gives a comparison of the torque developed by the machine at 1A excitation obtained from analytical and FE results. FE results are found to be in close agreement to that obtained from analytical results. The slight discrepancy between the results can be attributed to the realization of the halbach array using discrete magnet segments.

*Table 2: Design Details of the Halbach array slotted PMBLDC Machine*

| **Parameter** | **Value** |
|---|---|
| Dimension | $\Phi(104\times40)$mm |
| Supply Voltage | 28V |
| No. of Phases | 3 |
| No. of Poles | 12 |
| No. of Stator coils | 9 |
| Resistance/Phase | $3.37\Omega$ |
| Air gap thickness | 0.5mm |
| Permanent magnet | $Sm_2CO_{17}$ |
| No. of magnets | 12+12 |
| Axial Length of magnets | 30mm |
| Position sensor | Hall element |
| Magnet Thickness | 6mm |
| Internal radius of the magnet (Rr) | 38mm |
| Magnet outer radius (Rm) | 44mm |
| Stator outer radius (Rs) | 50mm |

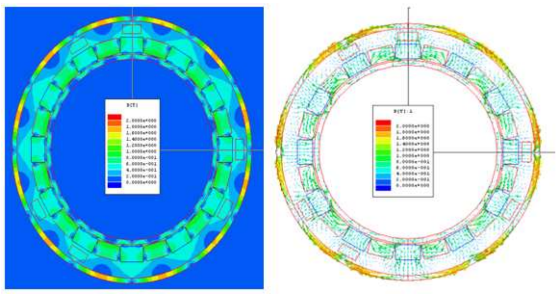

*Fig.9: Flux Distribution of the machine (FE Results)*

The zero cogging halbach array PMBLDC motor designed is found to develop a peak torque of 0.84 Nm at 1A excitation and an average torque of 0.55Nm under one pole pitch.

## 4. COMPARISON OF SLOTTED AND SLOTLESS PMBLDC MACHINE CONFIGURATIONS

Two different types of surface mounted PMBLDC machine configurations such as a radial magnetized

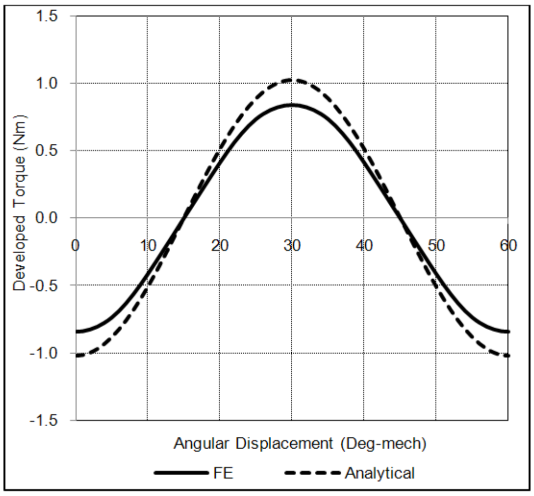


***Fig.10:*** *Comparison of the developed torque patterns obtained from analytical and FE Results*

slotted PMBLDC machine and Halbach magnetized slotless PMBLDC machine of same dimensions are analysed using FE and analytical results. Table 3 gives a comparison of the torque developed in the machines and it is found that slotless topology eliminates the cogging component of the torque completely without much reduction the developed torque component. Hence a Slotless Halbach Array PMBLDC motor topology is found to be the best topology to cater the needs for precise spacecraft applications.

***Table 3:*** *Comparison of PMBLDC Machine Configurations*

| Configuration | Torque (Nm) | Peak Torque (Nm) | Cogging Torque (%) |
|---|---|---|---|
| Slotted PMBLDC Motor | 0.72 | 1.3 | 20 |
| Slotless Halbach Array PMBLDC Motor | 0.55 | 0.84 | 0 |

## 5. CONCLUSION

The optimal design of a surface mounted PMBLDC meant for spacecraft applications is carried out. Two types of machine configurations such as Slotted PMBLDC and Slotless PMBLDC with halbach array were compared with analytical and FE results. It is found that unlike that of Slotted PMBLDC motor a Slotless PMBLDC motor with halbach array develops zero cogging torque without much reduction in the developed torque. Moreover the use of halbach array helps in achieving high Torque to inertia ratio and reduces core losses. The machine being coreless has zero magnetic stiction. The optimal design of Slotless Halbach Array PMBLDC machine is found to develop a peak torque of 0.84 Nm at 1A excitation and meet the required design requirements for spacecraft applications.

## 6. ACKNOWLEDGMENT

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