DEVELOP HIGH TORQUE LOW SPEED COGGING LESS PERMANENT MAGNET SLOTLESS BLDC MOTOR USING ANSYS SOFTWARE

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Abstract **:***This paper presents the finest design of an exterior mountedPermanent Magnet Brushless DC motor meant for various applications. Some applications require the selection of a torques motor with elevated torque density, least cogging torque, enhanced positional stability and high torque to inertia ratio. The slotless type of halbach array develops zero cogging torque and high developed torque and to provide dramatic improvements in consistency, maintainability, supportability and cost as well as enhancements in different applications. Furthermore, the machine life forms coreless to provide high torque to inertia ratio and zero magnetostriction.*
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Keywords*:Slotless, Permanent Magnet Brushless Direct Current Motor, Halbach Array, Cogging Torque, Ansys Maxwell two dimensional.*

1. INTRODUCTION

BLDC Motor have advantages over brushed DC Motors and Induction Motor. They have better speed verses torque characteristics, high dynamic response, high efficiency, long operating life, noiseless operation, higher speed ranges, and rugged construction. Also, torque delivered to motor size is higher, making it useful in application where space and weight are critical factor. These motors are rapidly gaining popularity in the appliance, automotive, aerospace, consumer, medical and industrial automation industries. As a result of the absence of mechanical commutators and brushes and the permanent magnet rotor, brushless dc motors have many advantages over the brush dc and induction motor. Some of the advantages of brushless dc motors are [1]:

i) High power density, low inertia and high torque to inertia ratio and high dynamic response due to the small size, low weight and high flux density neodymium-iron-boron permanent magnet rotor.
ii.) High efficiency due to the low rotor losses as a result of the absence of current carrying conductors on the rotor and reduced friction and windage losses in the rotor.
iii) Long operating life and high reliability due to the absence of brushes and metallic commutators.
iv) Clean operation due to the absence of brushes, resulting in no brush dust during operation and allowing for clean room applications.
v) Low audible noise operation due to the absence of brushes, commutators and smooth low air resistance rotor.
vi) Low thermal resistance since most of the machine losses occur in the stationary stator, thereby allowing heat dissipation by the process of direst conduction.

Brushless direct current motors (BLDC) have been confirmed to be the superlativeversatile type of motors for various applications because of their extended life, high torque, high efficiency, and small heat indulgence because no brush and commutator and overall reduction of electromagnetic interference (EMI) with no windings on the rotor. The torque produced in a Slotted PMBLDC motor can be classified as Useful Torque and Cogging torque. Useful torque is formed due to the interaction of the permanent magnet in the stator conductors and Cogging Torque is caused by the disparity in the magnetic energy stored in the air gap, due to the PM flux with the angular position of the rotor [2-4].Basically it is due to the interaction between rotor magnetic flux and the variation on the stator.For high recital applications, torque smoothness is essential. Hence, it is awfully imperative to believe torque ripple minimization and its linked harmonics without disturbing 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 suitable applications require an ideal choice of machine that has high torque density, zero cogging torque, high positional stability, high torque to inertia ratio and zero magneticstiction. A slotless BLDC motor design however eliminates the tooth ripple element of cogging as fine as has slight slot harmonic effects thereby facilitating the requirement of smooth torque output essential for the application [5]. A slotless machine, nevertheless suffers from a usually lower magnetic flux crossing the motor air gap which outcome in a lower power output in the slotless design compared to an equivalent slotted design. This reduction in the magnetic flux crossing the air gap is remunerated by the use of halbach magnetized array having strong and uniform magnetic field[6-8].The advancement of a high speed and high density FPGA established processor is currently providing the greatest substitute to the ASIC and microprocessor based execution of intricate control algorithms. The upgraded and significant dynamic and steady state recital of BLDC motors appended with FPGA based controllers will make them proper for position control in machine tools, robotics and high accuracy servos aerospace, healthcare/biomedical apparatus, speed control, and torque control in several industrial drives and process control applications[9-10].

2.ANALYSISOF SLOTLESS PERMANENT MAGNET BRUSH LESS DC MOTOR

2.1 AnalyticalModeling

The outer diameter and axial length of the machine is selected as 220 mm and 75 mm respectively. A design is developed in accordance with the specifications.

2.1.1Assumption

i) The halbach array considered in this design is two segments per pole

ii) The machine dimensions provided arewith respect to the stator diameter and the axial length. The actual dimension of the machine including the casing will be additional and according to the factor ofsafety requirements

The following assumptions are made:

i) The magnet is responsive according to halbach magnetization and is fully magnetized in the direction of magnetization.

ii) The effect of infinite axial length is neglected.

iii) The back iron is infinitely permeable.

A code was developed based on the analytical representation developed for halbach array slotless PMBLDC motor. They are formulated in polar coordinating and relation for qualified recoil permeability of the magnets.

For a halbach magnetized machine the magnetic distribution M varies sinusoidally. In cylindrical coordinates it is given by,

$$M = M_r r + M_\theta \theta \quad (1)$$

Where, M - Magnetization vector

Hence for an Internal rotor halbach machine,

$$M = M \cos p\theta_r - M \sin p\theta_\theta \quad (2)$$

Where M is the amplitude of magnetization which is equal to Br/μ0, Br is the remanent flux density of the magnet, r and μ are the magnetic vectors in the radial and circumferential way in that order. The governing Laplacian(in air gap) and quasi Poissonian(in magnets) equations[2], in cylindrical co –ordinates are given by:

$$\nabla^2 \phi I = \frac{\partial^2 \phi I}{\partial r^2} + \frac{1}{r}\frac{\partial \phi I}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \phi I}{\partial \theta^2} = 0 \quad (3)$$

$$\nabla^2 \phi II = \frac{\partial^2 \phi II}{\partial r^2} + \frac{1}{r}\frac{\partial \phi II}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \phi II}{\partial \theta^2} = \frac{\mathrm{div} M}{\mu_r} \quad (4)$$

where ϕI and ϕII are the scalar magnetic potentials in the air gap and magnets respectively[2].The magnetization source is given as,

$$Div\ M = \frac{M_r}{r} + \frac{\partial M_r}{\partial r} + \frac{1}{r}\frac{\partial M_\theta}{\partial \theta} \quad (5)$$

$$H_{\Theta I}\ at\ (r=Rs) = 0 \quad (6)$$

$$H_{\Theta II} at (r=Rs) = 0 \quad (7)$$

$$BrI = BrIIat(r = Rm) \quad (8)$$

$$H\mu I = H\mu IIat(r = Rm) \quad (9)$$

The magnetic field intensity vector H can be related to the scalar magnetic potential by the expressions[2]

$$H = -grad\phi \quad (10)$$

$$H_r = -\frac{\partial \phi}{\partial r}\ ;\ H_\theta = -\frac{1}{r}\frac{\partial \phi}{\partial \theta} \qquad (11)$$

$$B_{rI} = \frac{-4Brp}{M_o(1+p)}(1+\mu_r)\times\left[1-\left(\frac{Rr}{Rm}\right)^{p+1}\right]$$

$$\times\left[\left(\frac{r}{Rs}\right)^{p-1}\left(\frac{Rm}{Rs}\right)^{p+1}+\left(\frac{Rm}{r}\right)^{p+1}\right]cosp\theta (12)$$

$$M_o = 2\left\{\begin{matrix}(1-\mu_r)\left(\frac{Rr}{Rm}\right)^{2p}\left[(1-\mu_r)+(1+\mu_r)\left(\frac{Rm}{Rs}\right)^{2p}\right] \\ -(1+\mu_r)\left[(1+\mu_r)+(1-\mu_r)\left(\frac{Rm}{Rs}\right)^{2p}\right]\end{matrix}\right\} (13)$$

where p is the pole pair number, μr is the relative recoil permeability of the magnet ϴ, 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

2.2Feasibility Analysis

We will perform an initial feasibility of the input and output using basic thumb rules before performing an in-depth analysis. The formula to calculate the output of the motor is as below.

Total Output Power = Torque * RPM * 0.104
Total Output Power = 45 Nm * 800 RPM * 0.104
Total Output Power = 3769.2 watts

Assuming a conservative motor efficiency of 85%, the total input power of the motor would be

Total Input Power = Total Output Power / Efficiency
Total Input Power = 3769.2 / 0.85
Total Input Power = 4434 watts
Total Input Power = 4434 / 745.7
= 5.95 HP

The derived input power is slightly more than expected rating and can be adjusted by altering the torque and or RPM requirements of the machine.

Fig 1 shows the cross sectional view of Brushless Permanent magnet DC motor with all parts.

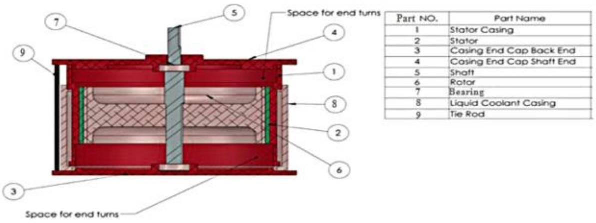


Fig. 1.Cross section of Brushless DC motor with Permanent Magnet

2.3 Analytical Discussion and Result

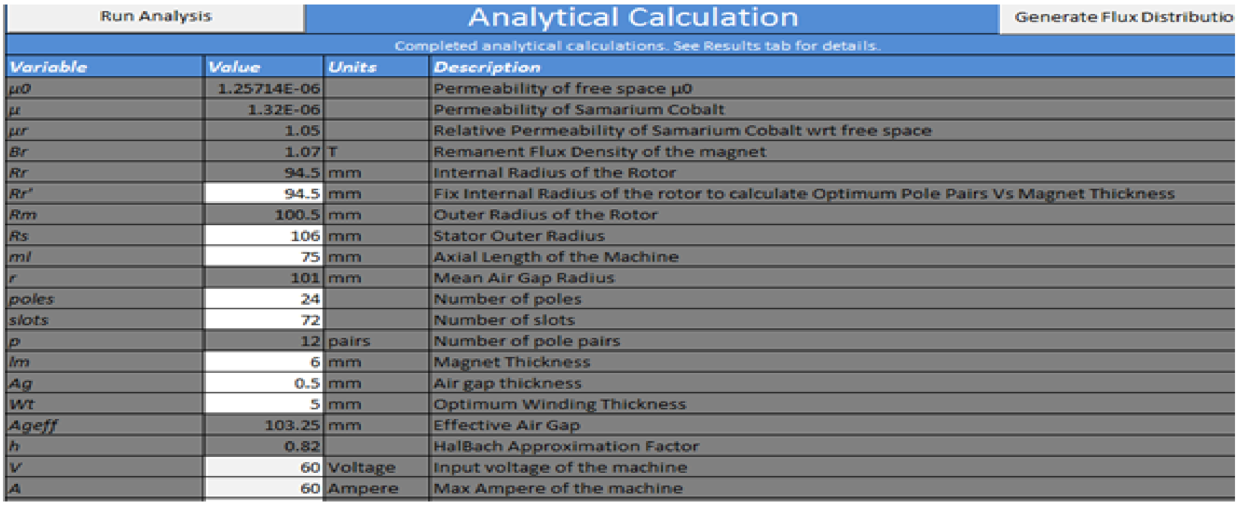
Anexcel based analytical model was built to facilitate the analysis. Since it would be difficult to perform an in-depth analysis of the design with so many open variables we will be fixing some of the parameters of the required motor as mentioned below and feeding them into the analytical model. The input parameters of the model can then be fine-tuned by altering them iteratively until the model provides the best possible output. The excel model was built to perform the following analytical calculations

i) Determine air gap flux density of mean effective air gap between the machine.
ii) Determine the optimum thickness of the magnet and the number of pole pairs to be used in the machine.
ii) Plot the Flux density of the machine.

The excel file was built to help perform the analytics. By varying the various input parameters the model's output can be studied and then the input tweaked until an optimum model is arrived. The excel file has 3 main tabs comprising of

i) Input
ii) Data
iii) Result

The input sheet is as below in fig.2 The input fields are marked in white and can be varied. The "Run Analysis" buttons at the top left corner can be used to invoke the analytical calculation macros. Interim data derived from the analytical calculation are stored in the "Data" sheet and graphical results drawn in the "Result" sheet. The macros apply the complete solution to the interior rotor halbach array zero cogging motor (obtained by the solution of Laplace's and quasi-Poisson's equation). The "Generate Flux Distribution" key at the top right corner plots the flux distribution of the machine.



Run Analysis | Analytical Calculation | Generate Flux Distributio

Completed analytical calculations. See Results tab for details.

Variable	Value	Units	Description
µ0	1.25714E-06		Permeability of free space µ0
µ	1.32E-06		Permeability of Samarium Cobalt
µr	1.05		Relative Permeability of Samarium Cobalt wrt free space
Br	1.07	T	Remanent Flux Density of the magnet
Rr	94.5	mm	Internal Radius of the Rotor
Rr'	94.5	mm	Fix Internal Radius of the rotor to calculate Optimum Pole Pairs Vs Magnet Thickness
Rm	100.5	mm	Outer Radius of the Rotor
Rs	106	mm	Stator Outer Radius
ml	75	mm	Axial Length of the Machine
r	101	mm	Mean Air Gap Radius
poles	24		Number of poles
slots	72		Number of slots
p	12	pairs	Number of pole pairs
lm	6	mm	Magnet Thickness
Ag	0.5	mm	Air gap thickness
Wt	5	mm	Optimum Winding Thickness
Ageff	103.25	mm	Effective Air Gap
h	0.82		HalBach Approximation Factor
V	60	Voltage	Input voltage of the machine
A	60	Ampere	Max Ampere of the machine

Fig.2.Excel based Analytical

The output from the excel model referred in the research paper[1] as follows.Fig.3 shows the relation between the angular displacement (Mechanical Degrees) and the mean air gap flux density. One of the most important characteristics of the motor is air-gap flux density. So it was simulated to monitor the effect of air-gap variation in these characteristics.It shows the variation of mean airgap flux density under one pole pitch of the halbachSlotless PMBLDC motor The flux density wave form at the mean air gap of halbach array slotless motor is free from any harmonic content. This is due to the adoption of slotlesstopology. Also this design is free from of cogging torquecomponent as stator is having no teeth.

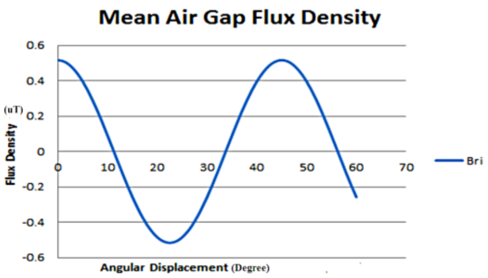


Fig.3. Angular displacement and flux density.

Fig.4shows the relationship between an electromagnetic torque developed and displacement angle from steady state position. The electromagnet torque acts ac on the stator causing rotation of a clockwise direction, provided the rotor magnet is prevented from moving and the stator is free to move.

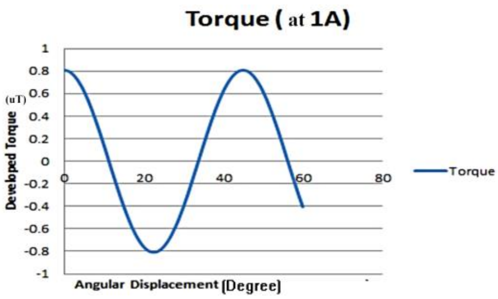


Fig.4. Torque developed and displacement angle

Fig.5shows the relations of peak flux density pole pairs and the thickness of rotor magnet.Although using an 8 mm magnet and 16 pole pairs provides the maximum flux density, 6mm magnet and 12 pole pairs has been selected considering the below mentioned factors

i) Electrical loading
ii) Space Constraints
iii) Cost
iii) Availability (Ease of procurement)

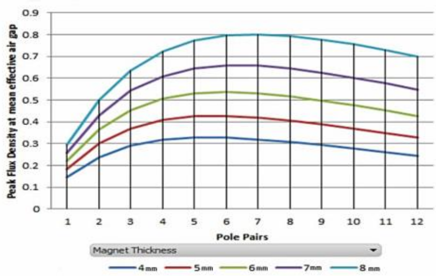


Fig.5. Flux Density and Pole Pair

The excel model was validated by feeding the data assume and comparing the results of the excel model with that of the results derived from the paper[1].The results were found to be an exact match. Based on the difference between analytical results and FE analysis in the research paper [1], a halbach approximation factor of 0.82 was used in the excel model.

2.3.1 ITERATION 1(16 Poles)

Table 1.Machine Data for 16 Poles

Motor Type	Slot-less using halBach array
Rotor Type	Internal with shaft output
Rated Power (Fixed)	5 HP / 3600 Watts
Output Power	3060
RPM (Rated Max)	800 RPM
Torque (Rated)*	45 Nm
Voltage (Fixed)	60V
Amp (Fixed)	60A
Stator Outer Dimension (Fixed)	220 mm OD
Axial Length (Fixed)	75 mm
Winding Thickness (Fixed)	5 mm
Stator Inner Diameter (Derived from above)	210 mm
Air Gap Thickness (Standard)	0.5 mm
Magnet Thickness (Fixed)	6 mm
Rotor Outer Diameter (Derived from above)	209 mm
Rotor Inner Diameter (Derived from above)	197 mm
Magnet Material (Standard based on ampere selection)	Samarium Cobalt
No of Slots (Fixed)	12 slots
No of Poles (Fixed)	16 poles
Permeability of Samarium Cobalt (Constant)	1.32E-06
Relative Permeability of Samarium Cobalt wrt free space (Constant)	1.05
Remanant Flux Density of the magnet (Constant)	0.96 T
Winding Method	Distributed

By fixing some of the input parameters as mentioned above and applying them in the excel model we arrived at the following outputs.

Fig.6 shows that the magnitude of flux density produced in the airgap is 0.507 web/m^2

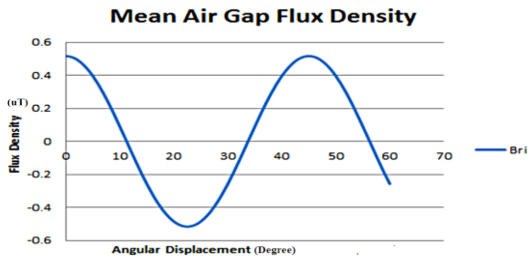


Fig.6. Angular displacement and flux density.

Fig.7 shows the magnitude of developed torque is 0.793 Nm at1A.for 16 Poles

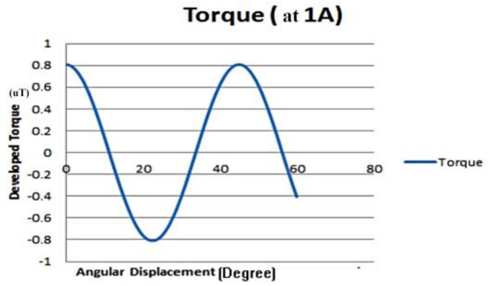


Fig.7. Torque developed and displacement angle

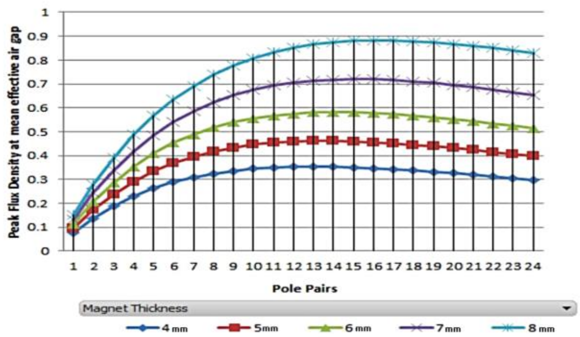


Fig.8. Flux Density and Pole Pair

Note that the above Fig.8 was obtained by constraining the internal radius of rotor to 98.5 mm. From the above figure it is clear that the optimum pole pairs are as follows.Here 6mm magnet and 12 pole pairs has been selected.

Table 2.Magnetic thickness and pole pairs

Magnet Thickness	Optimum Pole Pair Range
6 mm	12 to 16 pole pairs
7 mm	14 to 16 pole pairs
8 mm	15 to 17 pole pairs

2.3.2 ITERATION 2(24 Poles)

We achieved the following output when the poles are 24.Fig.9 shows that the magnitude of flux density is 0.579 web/m^2 for the poles 24.

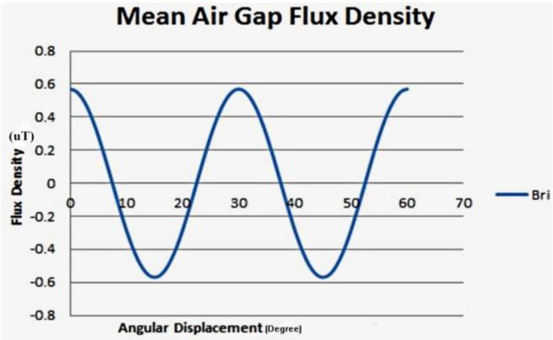


Fig. 9.Angular displacement and flux density.

Fig.10 clear that the developed torque is 0.906 Nm at 1A for 24 poles.

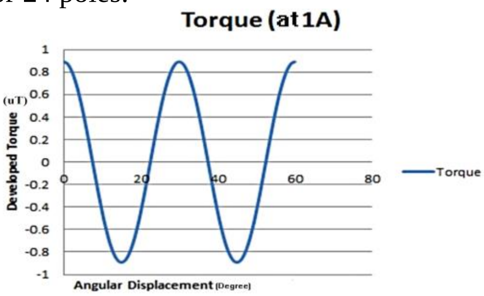


Fig. 10. Torque developed and displacement angle

2.3.3 COMPARISION OF ITERATION 1 AND 2

The magnitude of both flux density and developed torque is more in 24 poles when compared to 16 poles. The outputs are as shown in the Table .3. Here the peak flux density and peak Torque at 1A for 16 poles is 0.507Web/m^2 and 0.793Nm.And also the peak flux density and peak Torque at 1A for 24 poles is 0.579Web/m^2 and 0.906Nm.

Table 3.Comparision

Output Parameter	Iteration 1 Result	Iteration 2 Result
Peak Flux Density	0.507	0.579
Peak Torque at 1A	0.793 Nm at1A	0.906Nm at 1A

2.3.4. ITERATION 3(24 Poles , 72 slots)

Table 4. Machine Data

No of slots	72
Voltage	72V
Ampere	50 A
Rated speed of the machine in radians per second	1100 RPM
Length of the rectangular wire	4 mm
Width of the rectangular wire in mm	2 mm
Total number of parallel wires used to support the required input amps of the machine	2
Stator Outer Radius	106 mm
Magnet Ratio	0.7

We had arrived at the number of slots as 72 using the below calculation

Total perimeter at airgap radius of 101 mm

= 2*22/7*101 = 634.85mm

Total numbers of feasible virtual slots

= 634.85 / (4 mm * 2) = 78Nos

Considering packing factor and space requirements for glue / resin we have selected the number of slots as 72. Please note that the outer radius of the stator can be tweaked to arrive at a feasible number of virtual slots. The excel model will calculate the number of turns required to achieve a rated voltage of 72V at rated speed. Tweak the machine dimensions and machine speeds such that we arrive at a value of 1 turn per virtual slot. The excel model calculates the halbach Magnet dimensions as below.

Table 5.Size of Halbach Magnet

Halbach Magnet Dimensions - output		
Arc Length of a single halbach array	24.740	mm
Arc Length of the main magnet	17.318	mm
Arc Length of the flux concentrating halbach magnet	7.422	mm

2.3.5ITERATION 4(Magnets)

Alter the magnet ratio of the Halbach array such that the magnet dimensions are in multiples of 6. In our case use a ratio of 75:25 to arrive at the below dimensions.

Table.6 Size of Halbach Magnet

Halbach Magnet Dimensions - output	
Arc Length of a single halbach array	24.740mm
Arc Length of the main magnet	18.555mm
Arc Length of the flux concentrating halbach magnet	6.185mm

To simplify; the main magnet can be split into 3 segments of 6mm magnets. Thus by using magnets for dimensions 6mm x 6 mm x 75 mm we can fulfill our requirement of both main magnets and the flux concentrating halbach magnets. The 75 mm length can be further subdivided into 25 mm x 3 Nos. The total number of magnets required therefore will be:-

Total number of magnets required

= Number of poles * 4 * 3 (of dimension 6 mm x 6 mm x 25 mm)

Total number of magnets required

= 24 * 4 * 3 = 288 Numbers / machine

2.3.6. FINAL ITERATION

The torque of the machine can be increased by the following changes in final iteration.

i)Decreased the voltage from 72V to 60V

ii) Increased the current rating from 50A to 60A

iii) Reduce the speed from 1100rpm to 800rpm

The above changes resulted in increase of torque from an earlier value of 26.5NM to 36.5Nm. A brief design data of the developed slotless halbach array PMBLDC Motor is given in Table7.

Table 7.Machine data

Motor Type	Slot-less using HalBach array
Rotor Type	Internal with shaft output
Rated Power (Fixed)	5 HP / 3600 Watts
Output Power	3060
RPM (Rated Max)	800 RPM
Torque (Rated)*	45 Nm
Voltage (Fixed)	60V
Amp (Fixed)	60A
Stator Outer Diameter(Fixed)	220 mm
Axial Length (Fixed)	75 mm
Winding Thickness (Fixed)	5 mm
Stator Inner Diameter (Derived from above)	210 mm
Air Gap Thickness (Standard)	0.5 mm
Magnet Thickness (Fixed)	6 mm
Rotor Outer Diameter (Derived from above)	209 mm
Rotor Inner Diameter (Derived from above)	197 mm
Magnet Material (Standard based on ampere selection)	Samarium Cobalt
No of Slots (Fixed)	12 slots
No of Poles (Fixed)	16 poles
Permeability of Samarium Cobalt (Constant)	1.32E-06
Relative Permeability of Samarium Cobalt wrt free space (Constant)	1.05
Remanant Flux Density of the magnet (Constant)	0.96 T
Winding Method	Distributed

3. MAGNETIC FLUX DISTRIBUTION

Figure.10 shows that the uniform magnetic flux distribution of machine

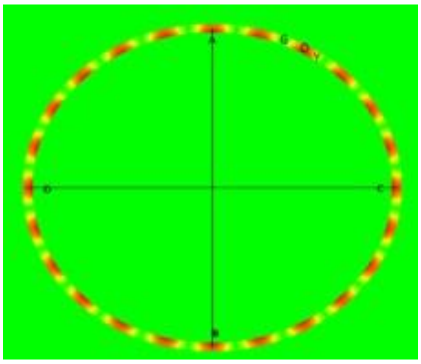


Fig. 11.Magnetic Flux distribution

Table.8 Level of Magnetic Flux distribution

	O	MORE FLUX
	Y	LESS FLUX
	G	ZERO FLUX

It shows the flux density plot and the magnetic vector plot of the designed slotless zero cogging halbach PMBLDC Motor. From the flux pattern, it is clear that flux focusing permanent magnet acts as a path for flux between adjacent poles and hence reduces the flux in the back iron. In vertical axis the flux distribution in the points A & B is 0.579 and in the horizontal axis in the points C & D is 0.579.The Table.8 denotes the magnitude of flux distribution

4.FE ANALYSIS DISCUSSION AND RESULTS

The analytical expressions given in (12) and (13) is used for computing the radial component of the mean airgap flux density of a halbach slotless Internal rotor PMBLDC motor with the required specifications of (220×75) mm.The length of the magnetic flux path of 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. With the increase in length of the magnet even though the mean airgap flux density increases the space available for accommodating the stator windings decreases.
Figure.12 shows the Maxwell two dimensional model for the performance analysis of Permanent Magnet Brush Less Direct Current Motor using Ansys RMxprt software. Simulation results for the model are shown in Fig 13 and Fig 14.

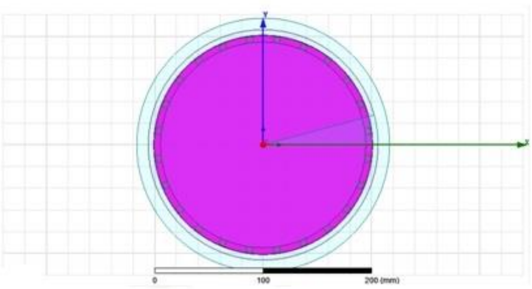


Fig. 12.Maxwell 2D Model

RMxprt gives simple motor design and performance based on given input dimensions. In order to check performance of motor thoroughly, it is necessary to run a finite element simulation in software like Maxwell 2D. The geometry prepared for RMxprt is taken into Maxwell 2D environment. The software itself creates meshing which is necessary for FEA; also it automatically chooses boundary conditions in which geometry is to be solved. Winding excitations is also assigned automatically.The basic designparameters obtained from the analytical results of slotless PMBLDC motor with halbach array, such as the length of the PM and the number of pole pairs is used to model the machine in FE for further optimization. The Maxwell 2-DFE analysis is carried out. Fig 13 shows the magnitude of air gap flux density produced by the machine at 1A excitation obtainedfrom FE results.

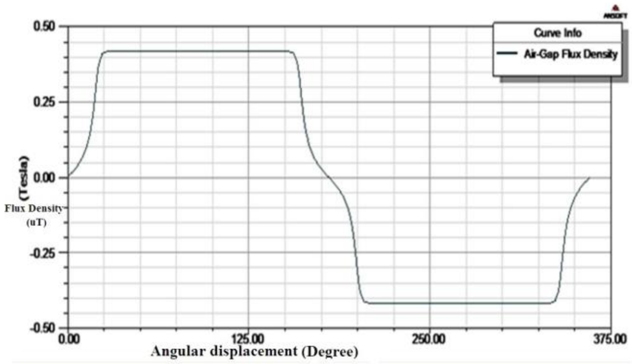


Fig.13. Angular displacement and flux density

Fig 14 shows the analytical results are found to be in good agreement with the 2-D FE results. Therefore, the analytical results for the magnetic torque are validated extensively by the corresponding 2-D FE results, and the magnitude of the torque developed by the machine at 1A excitation obtained from FE results.

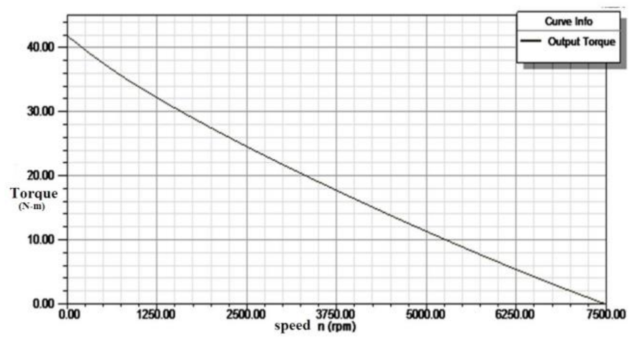


Fig. 14. Torque developed and speed of the motor

5. COMPARISION

According to the torque developed in Permanent Magnet Brushless Direct Current Motor by both analytical and finite element analysis is comparatively much closed values and it is proved by performing various iterations. Finally the torque developed by analytical method is 0.906Nm and for finite element analysis is 0.84Nm as shown in Table.9.

Table. 9 Comparison of the developed torque patterns obtained from Analytical and FE results

S.No	Patterns	Torque
1	Analytical	0.906 Nm
2	FE	0.84 Nm

6.CONCLUSION

The finest design of an exterior mounted Slotless PM-BLDC Motor meant for some applications is conceded. A Slotless PMBLDC with halbach array was designed and the performance is checked with, EXCEL and ANSYS- MAXWELL 2D.It is originated that unlike that of a Slotless PMBLDC motor with halbach array develops zero cogging torque without much drop in the developed torque. In addition thatthe use of halbach array helps in achieving high Torque to inertia ratioand reduces core losses. The machine being coreless has zero magnetostriction. The optimal design of Slotless halbach Array PMBLDC machine is foundto develop a peak torque of 0.906 Nm at 1A excitation and meet the required design requirements for some applications.

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