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Reduction of Cogging Torque of Radial Flux Permanent Magnet Brushless DC Motors with Application of Dual Permanent Magnet Materials

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Abstract**: *The cogging torque is a detrimental to the performance of radial flux permanent magnet brushless dc (PMBLDC) motor. It causes vibration and audible noises. This paper presents a design technique for cogging torque reduction of radial flux brushless dc motors. The 200 W, 1000 rpm radial flux BLDC motor is initially designed with NdFeB permanent magnet (PM) material on each rotor pole. Cogging torque profile of initially designed motor is obtained with finite element modelling and analysis. The design is improved with application of dual PM materials. NdFeB and Alnico are alternately placed on rotor pole. The influence of design improvement on cogging torque of radial flux BLDC motor is analyzed by conducting series of FE exercises. It is analyzed that peak cogging torque is reduced from 0.55 N.m. to 0.4 N.m. with application of dual PM material in improved designed motor.***

Index Terms**: *Cogging Torque, Dual PM Material, FE Analysis, Radial Flux BLDC Motor.***

I. INTRODUCTION

Permanent magnet brushless dc motors are gradually becoming popular in various industrial and domestic applications. They exhibit high efficiency, high power density, better dynamic response, wide speed range, high torque to current ratio. Use of PMs in electric motors increases motor's efficiency as magnetic flux is created in airgap without excitation windings and copper loss. Efficiency of PMBLDC motors are inherently better because of loss free excitation from PMs. There are various types of PMs currently used for PM motors like Alnicos, Ferrites and Rare Earth Magnets. Samarium-cobalt and neodymium-iron-boron are rare earth type PM materials. The NdFeB is the strongest among various PMs, having highest energy product which produces magnetic flux considerably higher than ferrites or alnicos. This reduces motor frame size for given rating in comparison with motors using ferrite or Alnico magnets. Other advantages of NdFeB are that they enhance the steady state performance, improves dynamic response and power density of the BLDC motors [1].

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In addition to motor's size and efficiency, the quality of motor torque is an important performance parameter. The good PM motor design not only produces desired torque but also produces better quality torque. High torque ripple causes vibration and undesirable audible noise in motor operation and even reduces dynamic performance of PM motor. It is essential to achieve low torque ripple for quality torque. High cogging torque and improper switching of exciting currents result into high torque ripple. Torque ripple can be reduced from reduction of cogging torque and/or improvement in switching of exciting currents. This paper emphasis on reduction in cogging torque with design improvement of radial flux PMBLDC motor. The interaction between air-gap reluctance variation and PM mmf creates cogging torque in PM motors. It exists even when the stator winding is unexcited. It does not contribute to production of average torque since its average value is zero. Rather, it superimposes on average torque of the PM motor and increases torque ripple. Cogging torque is inherent in PM machines having PMs and slotted stator structure. Cogging torque reduction is essential in various applications sensitive to torque ripple. Torque ripple is usually filtered out due to system moment of inertia at high speed but at low speed torque ripple results into unwanted vibration and noise. It is desirable to reduce it at the design stage. Various design techniques have been described in literature to reduce cogging torque of PM motors. The magnet shaping, skewing of magnets and/or stator, addition of dummy slots, fractional of slots per pole, step skew of PMs, slot opening shifting, notching of PM, notching of stator teeth, segmented stator laminations, unequal placement of rotor magnets, are some techniques to reduce cogging torque[2] – [7]. The magnet pole arc variation affects the desired mutual torque. Reduction of magnet pole arc to reduce cogging torque adversely affect motor performance under rated condition. Inclusion of dummy slot increases total number of slots thus increasing cost of production. It also increases manufacturing complexity. With inclusion of dummy slots, the stator area has to be increased which increases size and cost of the motor. Though fractional of slots per pole reduces cogging torque, it reduces average torque and increases radial magnetic forces. It also increases manufacturing complexities and cost. Although skewing PMs reduce cogging torque but it decreases the phase back emf and hence reduces the average torque.

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Skewing of PMs also generates small axial thrust to the rotor bearings. Skewing of stator slot increases length of conductors thus increases copper losses. Also winding becomes difficult to wind. Skewing of PMs and/or stator slots increases manufacturing complexity and production cost. Step skew of PMs also increases manufacturing complexity. With slot opening shift method, back emf is reduced slightly which may slightly reduce average torque of the motor. Individual segmented stators causes decrease of back emf and also increases manufacturing difficulties. Unequal placement of magnets offset center of mass of rotor from the rotating axis. The objective of this paper is to reduce cogging torque of radial flux brushless DC motor. The application of dual PM materials on performance of radial flux BLDC motor is analyzed. Intensive simulations using FE modelling and analysis are carried out to reach the conclusion. Introduction of cogging torque and related equations are presented in Section 2. Section 3 describes the reference radial flux BLDC motor model. Section 4 is devoted to explain the technique used to reduce cogging torque of reference radial flux BLDC motor. The simulation results are also presented and discussed in this section.

II. Cogging Torque

Cogging torque has been major limitation of PMBLDC motor. It increases torque ripple. It affects the average torque produced by the motor. The magnetic circuit gets completed by flux which travels from magnets and rotor, and then from air-gap and stator and returns in the same way. Cogging torque is produced due to variation in air-gap reluctance. As rotor changes its position the air-gap reluctance varies because the air-gap is non-uniform in PMBLDC motor and also stator and rotor materials are different. Hence, cogging torque is created by non-uniform air-gap reluctance resulting in the magnets constantly seeking the position of minimum reluctance [8]. The cogging torque can be expressed by,

$$T_{cog} = -\frac{1}{2}\phi_{pm}^{2}\frac{dR}{d\theta_m} \tag{1}$$

where Φ_{pm} is magnetic flux and $\frac{dR}{d\theta_m}$ is variation of air-gap reluctance with respect to rotor displacement.

Cogging torque is proportional to the square of PM flux and variation of air-gap reluctance w.r.t. rotor displacement. Cogging torque can be minimized by minimizing either air-gap flux or reluctance variation. Reduction of air-gap flux adversely affects the production of average torque of the motor. Hence, it is always desirable to reduce variation in air-gap reluctance w.r.t. rotor position.

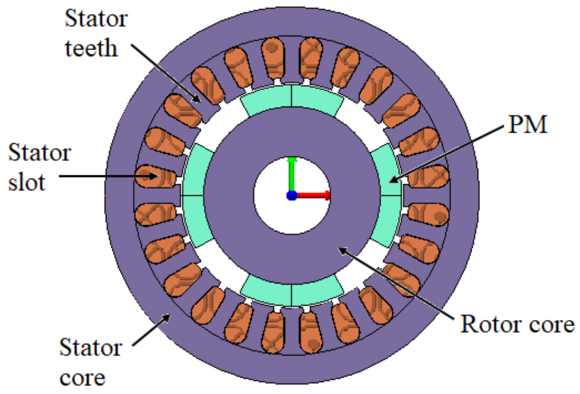
III. Reference Radial Flux PMBLDC Motor

The 200 W, 1000 rpm radial flux BLDC motor is initially designed and is considered as reference motor for the analysis. The reference radial flux PMBLDC motor is designed by assuming various design parameters i.e. specific magnetic and electric loadings, flux densities in stator and rotor, slot fill factor, winding factor, stacking factor, current density, etc. The details of design of reference BLDC motor is illustrated in Table I.

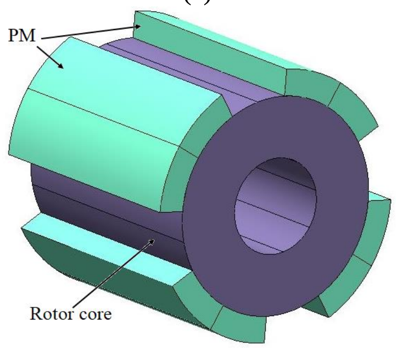
TABLE I Design details of Radial Flux BLDC Motor

Design Parameter	Value
Outer dia. of stator	87 mm
Outer dia. Of rotor	51 mm
Stack length	50 mm
Stator inner dia.	52 mm
No. of slot	24
No. of phases	3
No. of poles	4
No. of slots/pole/phase	2
Magnet thickness	5 mm
Air-gap length	3 mm
Type of PM	NdFeB
Stator core material	M19
Rotor core material	M19

The stator core and rotor core are made of laminated M19 steel material. Sectional view of motor is illustrated in Fig. 1(a). The rotor poles are made of NdFeB permanent magnet material. 3-D view of rotor of initially designed motor is shown in Fig. 1(b).



(a)



(b)

Fig. 1 Reference radial flux PMBLDC Motor (a) cross sectional view (b) 3-D view of rotor core

FE analysis has been performed to determine cogging torque profile of reference radial flux BLDC motor. The model of reference motor is prepared using FE software according to the dimensions and materials are assigned to various parts of the motor. The stator winding is not energized and the rotor is rotated in step of 1° mechanical upto 15°. The value of torque is noted for each degree of rotation.

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The curve obtained between the instantaneous torque and rotor positions is cogging torque profile as shown in Fig. 2. It is observed that reference BLDC Motor has cogging torque (peak) of 0.55 N.m.

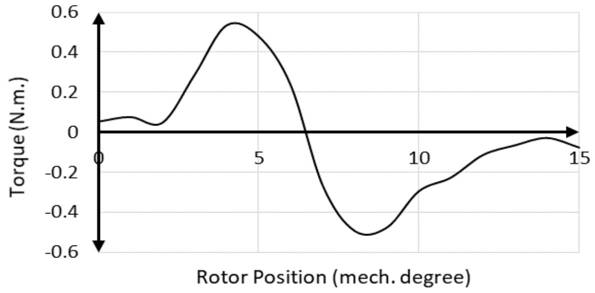

Fig. 2 Cogging torque profile of initial design

The motor is operated at rated speed of 1000 rpm and the stator windings are energized by appropriate switching of inverter switches. The values of torque at various rotor positions are obtained. The torque profile thus obtained is shown in Fig. 3. It is analyzed that motor generates average torque of 1.91 N.m.

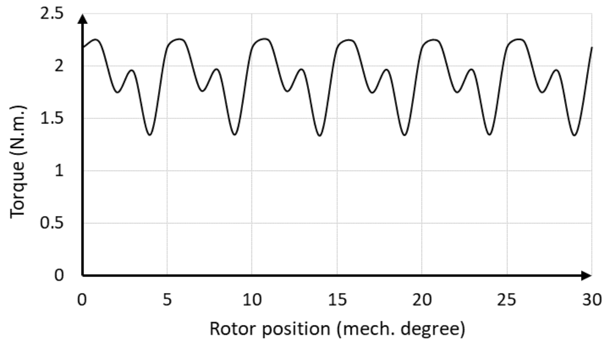

Fig. 3 Torque profile of initial design

IV. APPLICATION OF DUAL PM MATERIAL

This section discusses cogging torque reduction technique for radial flux BLDC motor. The reference design is improved with application of dual PM material i.e. NdFeB and Alnico on rotor core. The 3-D view of improved rotor design using dual type of PM materials is shown in Fig. 4.

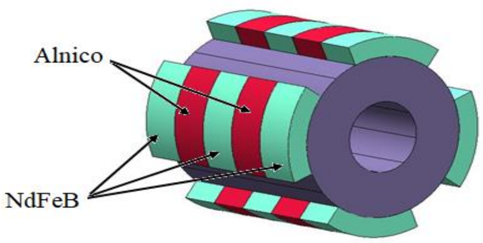

Fig. 4 3-D view of the rotor of improved design

The series of simulation exercises have been performed and cogging torque profile is obtained for improved design of radial flux BLDC motor. Fig. 5 shows relative comparison between cogging torque profiles of initial design and improved design of motor model.

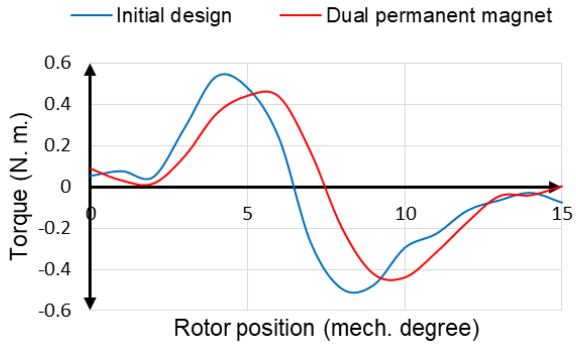

Fig. 5 Comparison between cogging torque profiles of initial design and improved design

Table II shows comparison between initial design and improved design of radial flux BLDC motor. It is observed that the initial design has peak cogging torque of 0.55 N.m. The improved design with magnet poles divided into five equal parts has cogging torque (peak) of 0.4 N.m.

TABLE II. Comparison between initial and improved design of Radial Flux BLDC Motor

Sr. No.	Performance Parameters	Initial Design	Improved Design with Application of Dual PM Material
1.	Peak Cogging Torque	0.55 N.m.	0.4 N.m.
2.	Average Torque	1.9 N.m.	1.8 N.m.

Comparison between average torque of reference design and improved design with application of dual PM material is shown in Fig. 6. The average torque of improved design is 1.8 N.m. compared to 1.9 N.m. of initial design. Hence, average torque of the motor reduces marginally while cogging torque is reduced to 27.2 % in improved design.

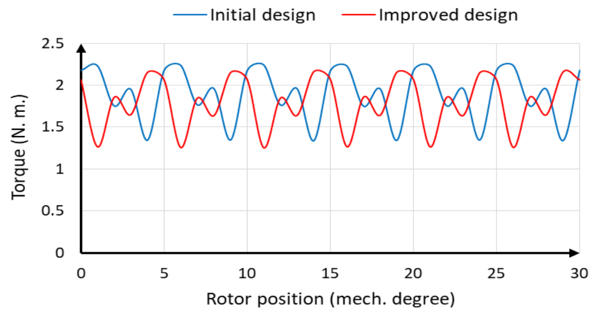

Fig. 6 Comparison between average torque profiles of initial design and improved design

The electromagnetic field analysis using FE software helps to evaluate performance parameters of motor. The flux densities in various parts of the motor is required to be assessed for performance evaluation. If the established flux densities are higher than assumed respective flux densities, the motor operates in saturation leading to higher core losses and deteriorating performance of the motor.

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The FE analysis is carried out for initial design and improved design and flux densities in various parts of the motor is evaluated. The flux density plot of initial design and improved design is shown in Fig. 7 and Fig. 8 respectively. It is analyzed that actual flux densities in various parts of the motor is very close to the respective assumed flux densities. Hence, both initial and improved designs are validated.

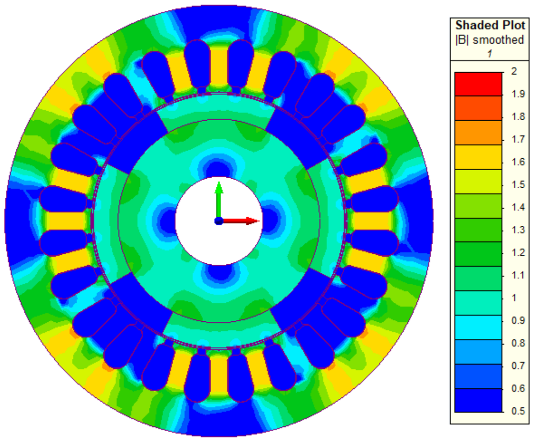

Fig. 7 Field plot of initial design

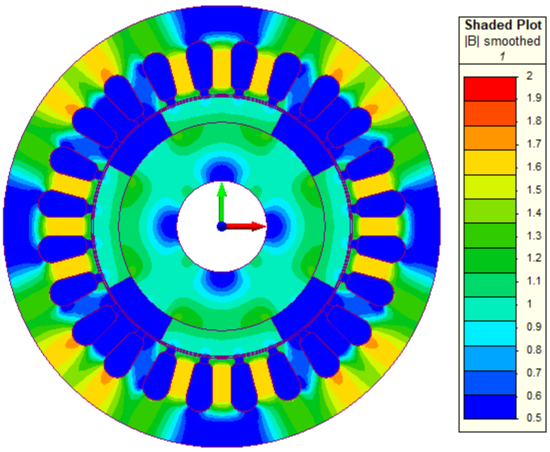

Fig. 8 Field plot of improved design

V. CONCLUSION

This paper proposes application of dual permanent magnet pole for reducing cogging torque of 200 W, 1000 rpm radial flux BLDC motor. The radial flux PMBLDC motor is designed initially with four magnet poles. The poles are assigned NdFeB permanent magnet material. The design is improved with application of dual permanent magnet material. FE analysis is carried out to obtain cogging torque profiles of both initial and improved designs. It is observed that cogging torque (peak) is reduced from 0.55 N.m. to 0.4 N.m. with marginal reduction in average torque.

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