International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 5, Number 6 (2012), pp. 783-790
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Comparative study of cogging torque for different tooth gap width and airgap flux of PMBLDC motor for motion control applications

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Abstract

This paper presents the comparative study of Permanent Magnet (PM) Brushless Direct Current motor (BLDC) meant for motion control applications. The motion control application normally needs high positioning accuracy, easy controllability, high torque to inertia ratio and minimum cogging torque. In low speed motion control applications the cogging torque is predominant and plays a major role in production of torque ripple. Hence it is considered and the various causes of it and ways by which it can be reduced/eliminated is discussed. FEM analysis is carried out for a surface mounted PM type BLDC motor used in slow speed applications. With solid model of the motor FE optimization is carried out and optimal slot width and air gap flux is presented.

Keywords: Cogging torque, Finite-element analysis, PM Brushless DC motor, tooth gap width (slot opening), Torque ripple reduction, optimization, Motion control application.

Introduction

Permanent Magnet Brushless PMBLDC motor uses permanent magnets on rotor for field excitation and electronically commutated winding on stator. Due to presence of high energy permanent magnet materials PMBLDC exhibits high efficiency with compact structure making it fit candidate for numerous applications [1]. Important features like high efficiency, high power /weight ratio, high torque/current ratio, robustness and excellent controllability have been reported in early literature and its suitability for replacing brushed motors are justified. Moreover as the rotor has only PM without any brushes and commutator rings it is robust and maintenance free [2].

Among the two variants of PMBLDC motors, the sinusoidally fed motor commonly known as Permanent Magnet Synchronous Motor (PMSM) has least ripple torque but due to complexity in drive of the motor it is not widely preferred. Trapezoidal type normally referred as PMBLDC is used in many applications with advantage of easy control and simple and compact drive. In PMBLDC machine constant torque is produced only when the rectangular current is feed in the flat portion of the trapezoidal ideal back-emf. Thus in this machine the commutation occurs at every 60 deg electrical [1], [2] & [6]. Section 2 deals with the torque ripple analysis followed with the design details in section 3. Cogging and FE torque analysis is dealt in section 4 and 5. Results are presented in section 6.

Torque Ripple Analysis

High performance motion control applications require smooth torque. The torque ripple may exist due to several reasons. It is produced due to cogging torque, emf waveform imperfections, supply current ripple resulting from inverters and the phase current commutation. Emf waveform imperfections can be reduced by modulating the dc link current. The supply current ripple can be sustained by various commutation techniques that are reported by previous researchers and these two causes for torque ripple are not dealt in this paper as it is out of view for this particular application. For high performance applications such as in robotics and motion control requires utmost accuracy and torque smoothness is essential. Hence it is very important to minimize the cogging torque thereby reducing the torque ripple [3].

Design details of PMBLDC motor

A slow speed PMBLDC motor is chosen for experimental study of cogging torque variation and to study the suitability of motor for particular application. After preliminary design the motor is modeled using FEA software and analysis is done for various airgap. In each airgap for various teeth gap width cogging torque is analyzed. The results are compared and optimum combination of airgap and tooth gap width without compromising torque density and efficiency is reported for the particular motor. Recent researchers published that elimination of cogging torque by Slotless technique. But in slotless technique reported requires smart fabrication techniques [5] and one has to be ready in spending for more PM material to compensate the loss in airgap flux arising due to increase in airgap length [4]. Hence here a slotted configuration is taken for analysis as it is easy for fabrication and winding. Surface mounted type PM rotor is preferred due to the various advantages in handling and fabrication reported earlier.

A preliminary design for number of slots, magnet/pole, stator and rotor dimensions with the coil assembling structures is made and presented in the forthcoming sections.

Table 1. Specifications of BLDC motor

Parameter	Value	STATOR	
BLDC MOTOR			
Supply , V	15V	Skew	0
Rated current, I	10 Amps	Inner diameter, D_{is}	49.8 mm
Number of phases	3	Backiron depth L_{bi}	9.0087mm
Rated speed, N	1000rpm	Slot area, A_s	97.34mm
Number of poles	6	Slot depth D_s	10.99mm
Number of slots	18	Shank legth L_s	8.9mm
Motor outer diameter, S_{OD}	90mm	Tooth gap angle, θ_{tg}	5 deg
Airgap thickness	0.4mm	Tooth gap width,W_{tg}	1.25mm
Stack length	60mm	Tooth width W_t	5.7974
ROTOR		COIL WINDINGS	
Magnet	Samarium cobalt	Connection type	Wye(star connected)
Skew	0	Drive type	Six step
Number of magnets/Pole	1	Number of parallel paths	1
Inner diameter D_{ir}	8mm	Diode voltage drop V_d	0.6v
Outer diameter D_{or}	49mm	Swithch voltage drop, V_s	0.2v
Magnet angle θ_m	60	Current hysterysis, I_h	15
Magnet thickness T_m	5mm		
Magnet tip radius, D_{mt}	0		

Cogging Torque Analysis

The airgap variation and magnet shape forms the origin of cogging torque. This arises from the interaction of stator teeth with rotor permanent magnet. In simple it can be said that the attempt of of rotor PM to align with the position of maximum ferromagnetic material[6]. It is given by

$$t_{cog} = -\frac{1}{2}\Phi^2 \frac{dR}{d\theta} \tag{1}$$

where ∅ airgap magnetic flux , R is the reluctance through which flux passes. Cogging reduces with

(a) Minimizing slot opening width (for varying the reluctance).
(b) Increasing the airgap length relative to the slot opening
(c) If the slot opening are spread out over the surface area (skewing)

Skewing reduces cogging but at the same time increases the complexities in construction as well as loss in motor torque. One slot pitch skew normally reduces cogging[6] [7] it cannot be taken as such as it depends on the combination of number of slots and number of magnet poles. The minimum skew required to eliminate cogging is given by

$$S_m = \frac{N_s}{lcm(N_p, N_s)} \tag{2}$$

4.1 Number of magnet poles and number of stator slots

It is reported that the net cogging torque of a integral slot motor is equal to the product of cogging torque created by each magnet and number of magnetic poles. Thus Cogging torque simply adds to create the net effect. The cogging torques experienced by all stator teeth have the same shape, but are offset from each other in phase by the angular slot pitch. The fundamental frequency of the cogging torque is twice the fundamental electrical frequency whose period is one magnet pole pair as cogging torque is periodic and the south magnet poles creates the same cogging torque as the north magnet poles.[8] As a result, the cogging torque experienced by the n_{th} stator tooth T_{scn} can be written as

$$T_{scn}(\theta) = \sum_{n=-\infty}^{\infty} t_n e^{jn2(\theta - k\theta_s)} \tag{3}$$

Where t_n is number of slots and θ_s is angular slot pitch. The factor 2 in the exponent of the above equation reflects the fact that the fundamental cogging frequency is twice the electrical frequency. Since the cogging torque of each tooth adds to create the net cogging torque of the motor, the motor cogging torque can be written as

$$T_{mcog}(\theta) = \sum_{sc=0}^{N_s-1} T_{scn}(\theta) \tag{4}$$

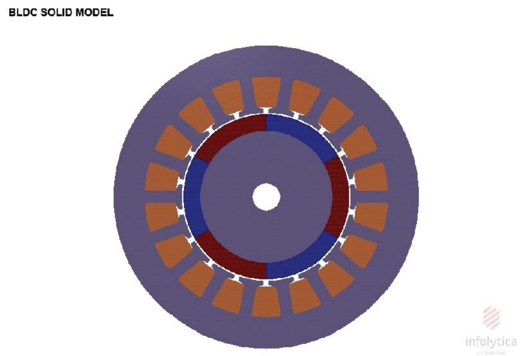
Substituting equation 4 in 3

$$T_{mcog}(\theta) = \sum_{n=-\infty}^{\infty} (t_n \theta_n S_{2n}) e^{jn2\theta} \tag{5}$$

Equation (4) clearly indicates that Fourier coefficient t_n is determined by the field gap distribution around each tooth, the air gap length and size of the slot opening between the teeth [10]. Hence various air gap values and the slot width variation is considered for study for reduction in cogging torque for a PMBLDC motor[8]. Comparing the results from the modeled analysis the optimal air gap and the slot width for the particular experimental motor is proposed for fabrication.

Finite Element (FE) analysis

From the data obtained by preliminary design as per the requirement as shown in the table the BLDC motor is modeled using FE based software to obtain the air gap flux and cogging torque performance characteristics[8]. The model of the motor is shown in the figure (1a). The material properties are assigned to the modeled motor.



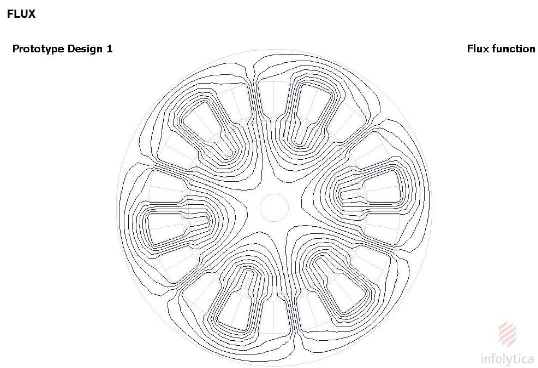
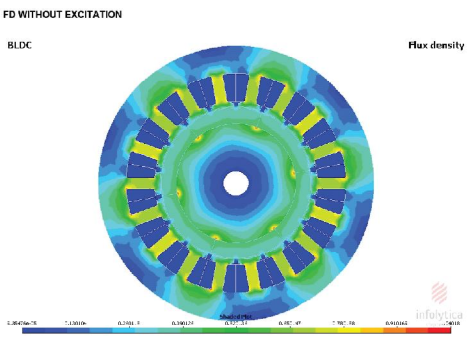


Fig. 1a FE model of BLDC motor Fig 1b Flux function plot

High energy density magnet Samarium cobalt with thickness of 5mm is chosen for PM rotor to have a better magnetic loading to the motor. The rotor is assumed to be with zero skew. M-19 silicon steel of 29 gauge is assigned to stator with back iron depth of 9mm and tooth gap width of 1.25mm. Coil connection is assumed to be star connected and six step drive is employed for excitation with single parallel path. In order to determine the geometric parameters of the motor for a given constraint on the overall dimension the air gap flux density distribution is obtained[9] from the FE analysis for various airgap of 0.4mm, 0.5mm and 0.3mm. The flux density varies from 0.8 to 1 tesla as shown in the fig (3 to 5). For each airgap tooth gap width is varied and the from the tabulated results 0.3mm airgap is found to be optimal for the required flux density.



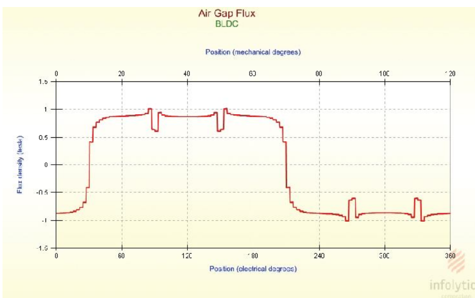
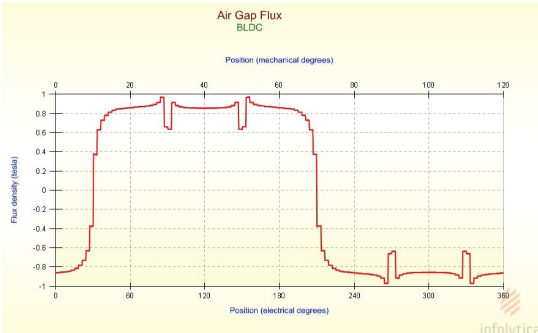


Fig. 1 Flux density without excitation Fig 2 Flux when airgap = 0.3mm

For each airgap value of 0.3, 0.4 and 0.5mm the slot width is varied say 0.75mm, 1mm,1.25mm and 1.5mm and for each combination flux density and cogging torque is studied. The values thus obtained are tabulated as shown in table 2.



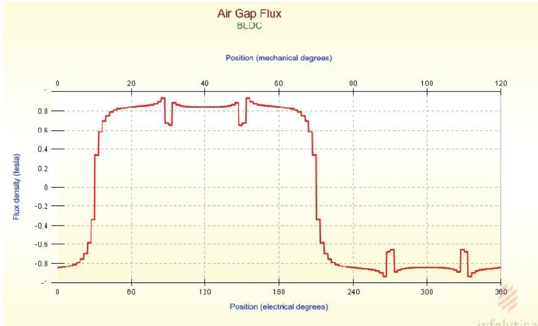


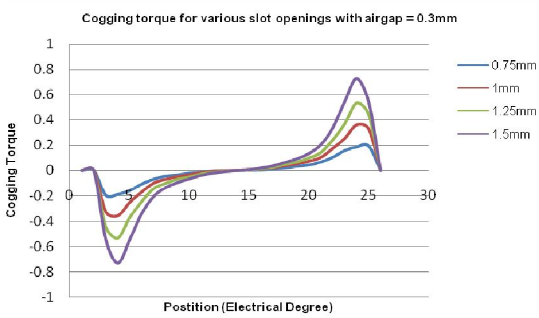
Fig 2 Flux when airgap = 0.4mm Fig. 3 Flux when airgap = 0.5mm

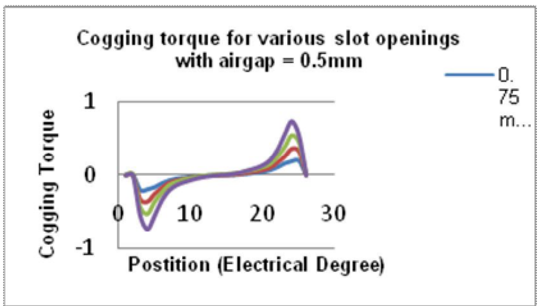
Table 2. Cogging torque at different toothgap and Airgap configurations

Airgap (mm)	Tooth gap width (mm)	Cogging torque (Nm)	Flux density (Tesla)
0.3	0.75	0.22	1
	1	0.38	
	1.25	0.56	
	1.5	0.71	
0.4	0.75	0.148	0.88
	1	0.35	
	1.25	0.486	
	1.5	0.72	
0.5	0.75	0.25	0.8
	1	0.32	
	1.25	0.48	
	1.5	0.65	

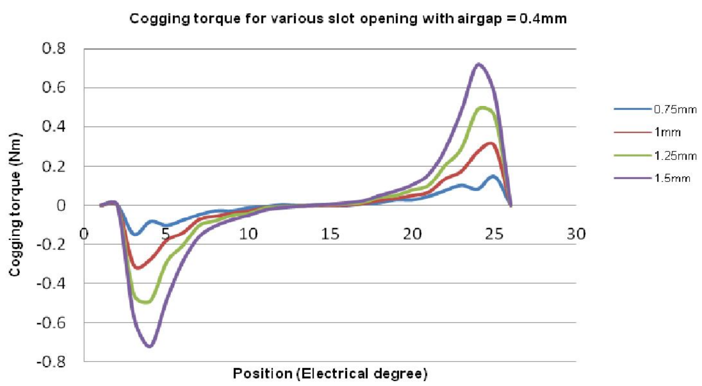
Results and discussion

For an airgap of 0.5mm and for a tooth gap width of 1.5mm the cogging torque is 0.71 Nm and the flux density distribution of 1tesla is obtained. If the airgap is reduced from 1.5mm to 1mm as expected the cogging torque reduces to 0.38Nm. In reducing further a value of 0.22Nm can be obtained with the tooth gap width of 0.75mm reducing the gap further will result in winding problems in the aspect of fabrication.





The modeled system is analyzed with 0.4mm airgap and 0.5mm airgap for various tooth gap widths refer to the waveforms presented below. Interestingly in the 0.4mm airgap profile it can be observed that for the tooth gap width of 0.75 the cogging torque is least say 0.148Nm. This is the best combination of airgap width and tooth gap width for this particular motor as for the same 0.75 tooth gap width with an airgap of 0.5mm the cogging torque again raises to 0.25Nm.



Conclusion

A method of obtaining optimal air-gap and tooth gap width by FEA method is suggested for an PMBLDC used in motion control application. The motor configuration is modeled and analyzed using FEA software for minimal cogging torque. Various tooth gap width and air gap combinations are investigated and the results are analysed. For the air gap of 0.4mm and tooth gap width of 0.75mm the cogging torque is 0.148Nm which is less than the other combinations. Hence by FE optimization optimal air gap length and teeth gap width can be obtained for attaining minimum cogging torque without sacrificing flux density in the air gap and is verified.

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