



Dual Skewing Technique for Cogging Torque Reduction of Double Rotor Single Stator Axial Flux Permanent Magnet Brushless DC Motor

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Abstract: Cogging torque arises in Permanent Magnet motors due to interaction between rotor permanent magnets and stator teeth. Cogging torque is undesirable as it induces noise and vibration. Design improvement is quite essential to reduce cogging torque of Axial Flux Permanent Magnet Brushless DC (PMBLDC) motor. This paper proposes dual skewing technique to reduce cogging torque of axial flux PMBLDC motor. Initially 250 W, 150 rpm Axial Flux PMBLDC motor is designed and its cogging torque profile is obtained. Cogging torque profile of improved design with dual skewed rotor magnets is obtained and its comparative analysis is carried out with initial cogging torque profile. Three dimensional finite element (FE) simulation and results are presented to validate proposed technique.

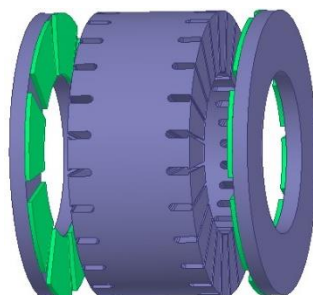
Keywords: Cogging Torque, Axial flux PMBLDC motor, FE Analysis, Dual Skewing

I. Introduction

The Permanent Magnet Brushless DC (BLDC) motors have been becoming popular in various industrial applications such as electric vehicle, robotics, process instrumentation, computer peripherals, satellite, air conditioners and blowers. They offer high efficiency and compact size compared to similar power rating induction motor [1]. Overall cost of Permanent Magnet motor drive has been decreasing due to advancement in the field of semiconductor devices and permanent magnet material technology.

Permanent Motors are classified according to direction of magnetic flux. In Axial Flux Permanent Magnet motors magnetic flux sets in axial direction and exciting current flows in radial direction [2]. Axial Flux motors have considerably small ratio of axial length to diameter hence they are usually named as 'flat' or 'disc' motors because of this aspect ratio. They develop high torque at low speed. Percentage of copper winding mass which generates no torque but still creates losses is lower in Axial Flux machines as they have more proportion of electromagnetically active material. Currently, Axial Flux Permanent Magnet machines are interest of many researchers. Varieties of structures are proposed considering application needs in comparison to Radial Flux Permanent Magnet machines. Figure 1 shows double rotor single stator Axial Flux Permanent Magnet (AFPM) motor suitable in direct drive applications. Axial Flux Permanent Magnet machines have attractive features of high efficiency, compactness, fast response and better utilization of winding material [3].

Figure 1 Dual rotor single stator Axial Flux PM motor



Unfortunately main demerit of AFPM motor is high cogging torque causing undesirable vibration and noise. Cogging torque is due to interaction between MMF of rotor PM and stator teeth. Cogging torque is inherent in machines having permanent magnets and slotted stator structure [4]. It exists even when stator is unexcited. Motor design must be improved to reduce cogging torque in turn to enhance overall performance of motor drive.

Skewing of stator slots, skewing of rotor magnets, modification in magnet shape, modification in stator tooth shape, displacing magnets, notching of stator tooth, notching of magnets, variation of magnet fraction, variation of slot opening, displacing slot openings, unequal width of stator teeth, unequal rotor pole arc etc. are various techniques to reduce cogging torque in Radial Flux PM machines. Applicability of these technique in AFPM machines is governed by manufacturability and cost implications. Manufacturable and low cost techniques are always desirable. In AFPM, stator side modifications are not practically viable as they increase complexity in manufacturing process and cost [5]. Cogging torque reduction with modification on rotor side is desirable because it is more practically viable and cost effective compared to stator side modification.

This paper is focused on reduction of cogging torque as torque quality is one of the important performance parameters of permanent magnet machines. Cogging torque originates due to variation of air-gap permeance and permanent magnet rotor MMF. Cogging torque exists even without any stator current. Cogging torque also affects self-starting capability of motor. Effect of cogging torque is more noticeable at low speed. Reduction of cogging torque during design process is indispensable task for motor designers. This paper addresses reduction of cogging torque of Axial Flux PM machines using dual skewing technique. A computer program has been developed to calculate dimensions and other performance parameters of Axial Flux PM motor considering various assumed design variables viz. average air gap flux density, slot loading, winding factor, stator conductor current density, magnet fraction, maximum allowable flux density in magnetic sections and diametric ratio.

This paper proposes dual skew technique for cogging torque reduction of Axial Flux Permanent Magnet Brushless DC (PMBLDC) motor. Manufacturability and cost effectiveness are main objectives of this work. 3-D finite element simulations and analysis is performed to examine effectiveness of proposed dual skewing technique as no analytical model for cogging torque in existence for Axial Flux PMBLDC motors. 3-D finite element analysis is also useful to check flux density spectrum in motor. Basics of cogging torque and associated equations are discussed in section II. Design information of reference machine is described in section III. Section IV elucidates dual skewing technique for cogging torque reduction and comparative analysis.

II. Cogging Torque

Following is the generalized equation of instantaneous electromagnetic torque developed by Permanent Magnet Machines without considering leakage and saturation of magnetic circuit [6].

$$T_e(t) = T_{avg} + \sum_{k=1}^{\infty} T_{6k} \cos(k6\omega t) + T_{cog} \quad (1)$$

where T_{avg} is average torque output, T_{6k} indicated harmonic torque components due to nonsinusoidal counter emf and exciting currents, T_{cog} is cogging torque and $k = 1, 2, \dots$

Cogging torque waveform determined analytically or by finite element analysis can be described by Fourier series.

$$T_{cog}(\theta_m) = \sum_{k=1}^{\infty} T_k \sin(kN_c \theta_m + \phi_k) \quad (2)$$

where T_k and ϕ_k are torque amplitude and phase of k^{th} harmonic component, θ_m rotor position, N_c is LCM between number of rotor poles $2p$ and number of slots N_s .

Cogging torque is intrinsically generated in Permanent Magnet machines due to interaction between excitation and air gap harmonic permeance. Permanent Magnet has tendency to align with the least reluctance path. It is also known as no current torque. Cogging torque has no net magnitude but it increases pulsations resulting in to vibration and noise. Cogging torque is proportional to product of air gap flux and reluctance variation as depicted in equation (1). Cogging torque can be lessen by reducing either air-gap flux or reluctance variation. Reduction in air-gap flux is not advisable as it will lead to reduced motor output. Decreasing reluctance variation with design improvement is only option for cogging torque reduction [7].

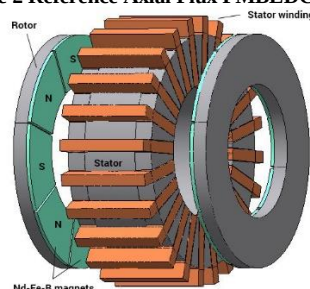
$$T_{cog} = -\frac{1}{2} \Phi_g^2 \frac{dR}{d\theta_m} \quad (3)$$

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

III. Reference AFPM Machine

Axial Flux PMBLDC motor of 48 stator slots and 16 rotor poles is designed initially and exercise is carried out to reduce cogging torque. Initially designed motor as shown in Fig.2 is considered as a reference motor in subsequent sections.

Figure 2 Reference Axial Flux PMBLDC Motor



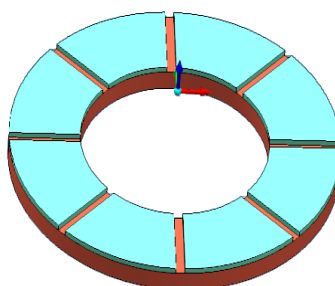
Slotted stator is made up of tape rolled thin laminations of silicon core material. Conductors are placed in back to back ring type fashion in stator slots to form stator winding. Rotor core is made up of mild steel. Neodymium iron borone (NdFeB) type permanent magnet material is the best choice to enhance efficiency and power density of motor. Rotor poles of fan type shaped NdFeB are affixed on rotor core plates. Short magnetic flux path reduces core losses. Machine is designed with $q=1$ where $q = \text{slot/pole/phase}$. No cogging torque reduction technique is applied to this reference motor. Design details of reference motor is given in Table I.

TABLE I Design information of Axial Flux PMBLDC Motor

Parameter	Value
Stator radius-outer	45.5 mm
Stator radius-inner	26 mm
Number of stator slots	48
Number of rotor poles	16
Slots/pole/phase	1
Outer to inner radius	1.73
Type of PM	NdFeB
Magnet thickness	2.7 mm
Air-gap length	0.5 mm
Stator core material	M19
Rotor core material	Mild steel

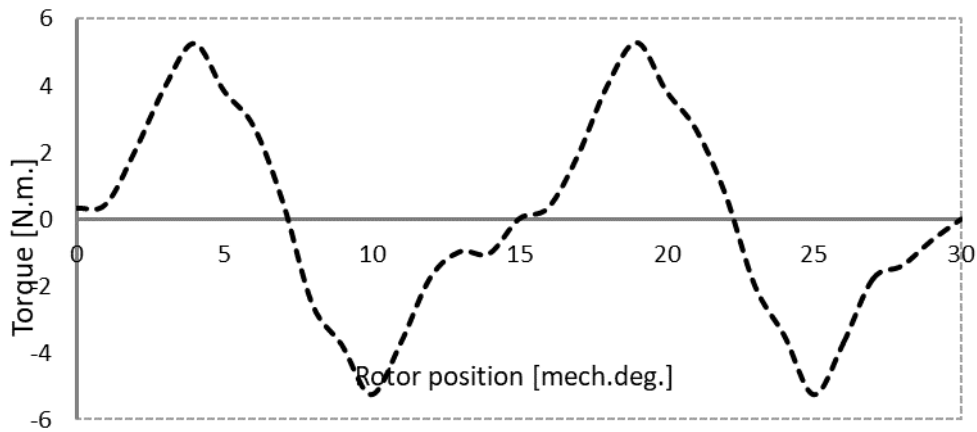
Parallel slot opening is preferred over radial slot opening considering manufacturability of stator. In case of radial slot opening ratio of slot opening to slot pitch remains constant where as in parallel slot opening ratio of slot width to slot pitch does not remain constant.

Figure 3 Initially designed rotor disc of Axial Flux PM Motor



Initially designed rotor disc comprising eight poles made up of NdFeB type permanent magnet material is shown in Figure 3. Initially designed Axial Flux PM Motor is considered as reference for comparison with improved designed motor. Usually two dimensional (2-D) analysis is used because of less time requirement and simplified modelling. 2-D analysis is used where geometrical and physical quantity in z direction are constant [8]. 3-D analysis is required in Axial Flux PM motor due to its geometry. In this work, 3-D FEA is performed to determine cogging torque profile of reference machine. In Figure 4, evaluation of cogging torque for 30° mechanical rotor displacement is shown. This reference Axial Flux PM Motor has peak cogging torque of 5.3 N.m.

Figure 4 Cogging torque profile of initially designed motor



IV. Dual Skewing of Permanent Magnet

Various techniques to reduce cogging torque of Radial Flux PM motors are available in literature. Orientation in this paper is to reduce cogging torque of Axial Flux PM motor. Modification on stator of Axial Flux motors is not feasible as it increases complexity of stator manufacturing process. Shaping of permanent magnet is considered here because it is cost effective and implementable technique. Conventional permanent magnet skewing technique is already explained in earlier studies. This paper is focused on reduction of cogging torque with dual skewing of rotor poles. Additional advantage of dual skew compared to conventional skew is less axial force. Rotor magnets are dual skewed and assessment of cogging torque is carried out. Skewed rotor permanent magnet pole shown in Figure 5.

Figure 5 Improved rotor design with dual skewed PM

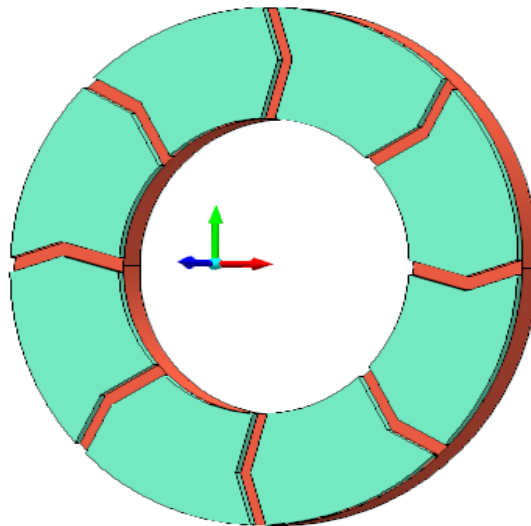
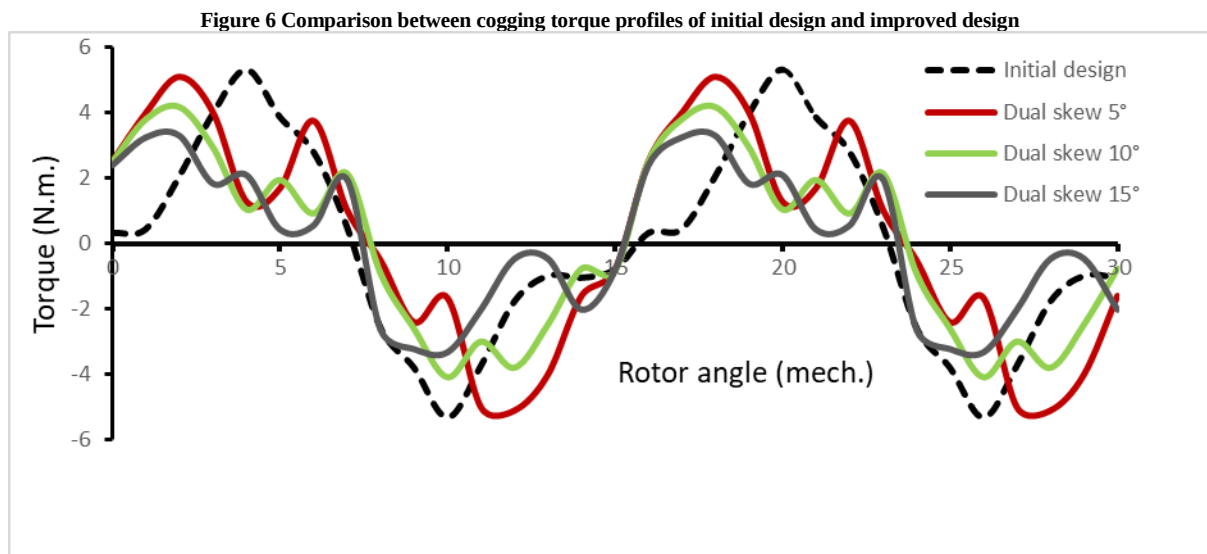


TABLE II Comparison between initial and modified design of Axial Flux Motor

Sr. No.	Design Details		Cogging Torque (peak)
1.	Initial Design		5.30 N.m.
2.	Improved Design	Dual skew 5°	5.10 N.m.
3.		Dual skew 10°	4.17 N.m.
4.		Dual skew 15°	3.30 N.m.

Figure 6 shows simulation results of cogging response on account of magnet dual skewing. The initially designed reference machine has peak cogging torque of 5.3 N.m. Table II shows reduction in peak cogging torque with variation in skew angle. The improved design with 15° dual skew magnet has peak cogging torque of 3.3 N.m. With dual skewing peak cogging torque is reduced from 5.3 N.m. to 3.3 N.m. with marginal reduction in average torque.



The evaluation of established flux density in various parts of permanent magnet motor is one of the important design requirement. Comparative analysis between assumed flux density and established flux density in various sections of motor is necessary to avoid saturation of magnetic circuit [9]. Core losses and overall performance is influenced by flux density. Nonlinear magnetization characteristic makes this analysis complex. FEA is carried out to calculate flux density in various sections of motor. Rotor flux density spectrum and stator flux density spectrum of dual skewed improved design are shown in Figure 7 and Figure 8 respectively. It is analyzed that flux densities established in stator and rotor are near to assumed flux densities. Close agreement between assumed and actual flux densities in various sections of motor validates sizing of magnetic sections.

Figure 7 Rotor Flux density spectrum

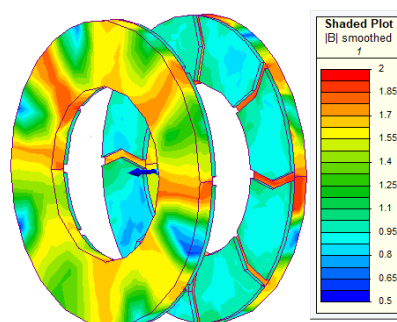
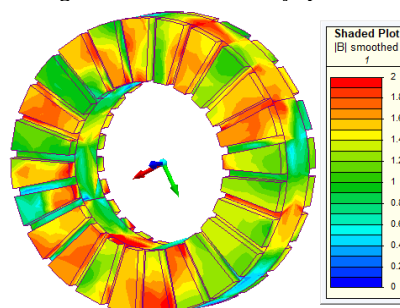


Figure 8 Stator Flux density spectrum



V. Conclusion

Shaping of Permanent Magnet is considered for performance enhancement by reduction of cogging torque of double rotor single stator Axial Flux PMBLDC motor for electrical vehicle application. Double rotor single stator is the most suited topology in direct drive application. Effectiveness of dual skew technique is assessed with 3-D finite element analysis. Comparison is made between cogging torque profiles of initially designed reference motor and improved design motor with dual skew technique. As discussed in paper, skew angle is varied in step of 5° from 0° to 15° . It is analyzed that minimum peak cogging torque of 3.3 N.m. is obtained at 15° skew angle. Peak cogging torque of 5.30 N.m. is reduced to 3.3 N.m. (37.73 % reduction) with marginal compromise in initial cost and complexity.

VI. References

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