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Cogging Torque Reduction of Sandwiched Stator Axial Flux Permanent Magnet Brushless DC Motor using Magnet Notching Technique

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ABSTRACT

Cogging torque reduction of axial flux permanent magnet brushless dc (PMBLDC) motor is an important issue which demands attention of machine designers during design process. This paper presents magnet notching technique to reduce cogging torque of axial flux PMBLDC motor designed for electric vehicle application. Reference axial flux PMBLDC motor of 250 W, 150 rpm is designed with 48 stator slots and 16 rotor poles of NdFeb type permanent magnet without notching. Three dimensional finite element modeling and analysis is performed to obtain cogging torque profile of initially designed reference machine. Notches are created on permanent magnets and its influence on cogging torque is analyzed with 3-D finite element modeling and analysis. It is analyzed that magnet notching is an effective technique to reduce cogging torque of axial flux PMBLDC motor.

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1. INTRODUCTION

Green vehicle like electric bicycle is widely used by city commuters due to its environment friendly features and economic merits. Permanent magnet (PM) motors have been increasingly used in electric vehicle applications since introduction of rare earth magnets [1]. Rare earth magnets have capabilities to establish higher flux density than other ferrites, which make final motor compact and suitable for variable speed applications. There are two types of PM motors; radial flux motors and axial flux motors. Flux travels radially and current travels axially in radial flux motors whereas flux travels axially and current travels radially in axial flux motors [2]. The axial flux motors have many advantages over a radial flux motors like high power density, high efficiency, high torque/current ratio and flat shape [3]. Axial flux motors can be classified according to numbers and relative positions of stators and rotors. Torque quality assessment of axial flux permanent magnet motors is a challenging assignment as torque ripple should also be considered along with torque density. Torque quality assessment and its improvement is current research interest of many researchers. Main sources of torque ripple are: (a) cogging torque (b) distorted stator current and counter emf waveforms (c) switching of phase excitation (d) fluctuation in delay time and dc link voltage of inverter. Usually torque ripple is filtered out due to system moment of inertia at high speed but at low speed torque ripple results in unaccepted vibration and noise [4]. Cogging torque originates due to interaction between air-gap permeance harmonics and PM rotor magneto motive harmonics. It demonstrates itself by the tendency of rotor to align in number of stable positions even without stator coil excitation. No excitation is involved in cogging torque generation. Air-gap permeance harmonics are inherent in slotted stator structure. Cogging torque also affects self-starting capability of motor.

This paper is focused on reduction of cogging torque as it must be important consideration in design of permanent magnet machines. Analysis carried out in this work is concentrated on axial flux PM machines. Skewing of stator slots and/or rotor magnets, displacement of magnets, magnet shaping, stator tooth

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shaping, notching tooth and/or magnet, dual notched design, variation of pole arc, and etc. are various techniques to reduce cogging torque in radial flux PM machines available in existing literature [5-11]. Few of these techniques are applicable in axial flux PM machines but manufacturability and cost are crucial considerations. Manufacturable and low cost techniques are desirable.

Cogging torque of axial flux PM machine is influenced by magnet pole arc. Optimum pole arc ratio for cogging torque may adversely affect motor output and back emf harmonics. Magnet skewing is an effective technique to reduce cogging torque of axial flux PM machine [12]. One drawback associated with magnet skewing is generation of undesirable axial thrust [13]. Sinusoidally shaped magnets offer better performance compared to sector like magnets and cylindrical magnets. Relative displacement of magnets reduce cogging torque. Leakgae flux increases as magnets move from symmetrical position to unsymetrical position [14]. Cogging torque of axial flux PM machine can be reduced with stator side modifications like slot opening shape variation, relative displacement of slot opening and skewed slot opeing [15]. Cogging torque is reduced with lesser amount of PM material with dual notched design of radial flux surface mounted permanent magnet motor [16].

Modification in stator design of axial flux PM machines is neither practical nor preferred as it complicates stator manufacturing process and results into increased manufacturing cost. Cogging torque reduction of axial flux PM machines with modification on rotor side is desirable because it is more practical and cost effective in comparison to stator side modification. The reduction in cogging torque of axial flux PMBLDC motor is major area of concern. In this work, We tried to address this issue with proposing a cost effective and implementable magnet notching technique. The proposed technique also results in saving of PM material. Influence of magnet notching on average torque and back emf waveform are also presented. Mathematical representation of design modifications to reduce cogging torque in 3-D becomes much complex. Thus 3-D finite element analysis (FEA) technique is used to solve electromagnetic problem and simulate technique. Basics of cogging torque and approaches for its reduction are explained in section II. Brief summary of reference machine is described in section III. Section IV elucidates technique for cogging torque reduction and simulation & results are discussed insection V.

2. COGGING TORQUE

Following is the generalized equation of instantaneous electromagnetic torque developed by Permanent Magnet machines without considering leakage and saturation of magnetic circuit [17].

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

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,….

Following Fourier series equation describes cogging torque waveform determined analytically or by finite element analysis [17].

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

where, T_k and φ_k are torque amplitude and phase of kth harmonic component, θ_m is rotor position, N_c is LCM between number of rotor poles (P) and number of slots (N_s).

Cogging torque is inherent in permanent magnet machines because of reluctance variation in air-gap due to slotted stator. Equation (3) indicates that cogging torque depends on air-gap flux and reluctance variation. Cogging torque can be reduced by reducing either air-gap flux or reluctance variation. Reduction in air-gap flux will reduce motor output hence it is not advisable. Decreasing reluctance variation is only available option for cogging torque reduction [17].

$$T_{cog} = -\frac{1}{2}\phi_g^2 \frac{dR}{d\theta_m} \tag{3}$$

where, ϕ_g is air-gap flux, R is air-gap reluctance and θ is the rotor angle.

This paper includes analysis of cogging torque reduction technique using 3-D finite element analysis. 3-D finite element modeling and analysis remain relatively time consuming. To simplify calculation, analytical technique may be combined with 3-D finite element analysis. Cogging torque is also estimated by calculating change of air-gap energy stored with respect to rotor position. Due to strong permanent magnets and increased amount of flux in magnetic circuit the cogging torque is increased. Fundamentally cogging torque is generated due to non-uniform air gap flux distribution. Each rotor magnets have same position with regard to slots in integral slot machine where number of slots per pole is an integer. Therefore, cogging torque components produced by all magnets are in phase which results in considerable cogging torque.

2. REFERENCE AFPM MACHINE

The presented work is based on reference machine of 48 slot stator sandwiched between two 8-pole rotors as illustrated in Figure 1.

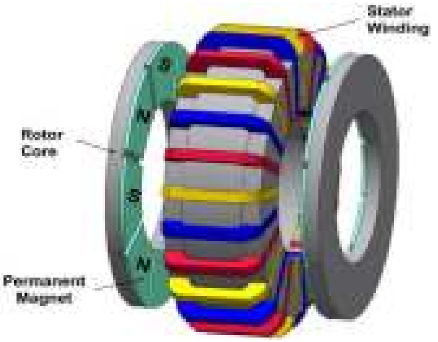

Figure 1. Model Axial Flux PMBLDC machine

Slotted stator is of tape wound siliceous core material and back to back ring type winding while two disc type rotors are of mild steel and surface mounted permanent magnets. Machine is designed with q=1 slot/pole/phase. No cogging torque reduction technique is applied to this reference motor. Reference motor parameters are given in Table I.

TABLE 1. Design details of Axial Flux PMBLDC motor

Design Parameter	Value
Outer diameter	91 mm
Inner diameter	52 mm
Number of phases	3
Number of poles	8
Number of slots/pole/phase	1
Number of slots	48
Diametric ratio	1.73
Magnet thickness	2.7 mm
Air-gap length	0.5 mm
Stator yoke thickness	35 mm
Rotor yoke thickness	9.2 mm
Permanent Magnet material	NdFeb
Core material	M19

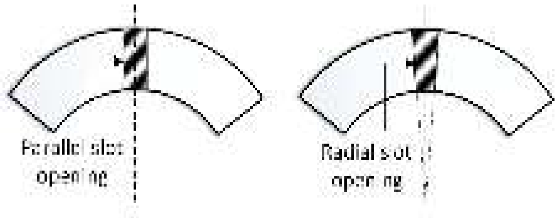

Figure 2. Slot openings of Axial Flux PM motor

For ease of manufacturing parallel slot opening is preferred over radial slot opening. In case of parallel slot, ratio of slot width to slot pitch does not remain constant while in radial slot ratio of slot opening to slot pitch remains constant [14]. 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. Simulation is carried out using commercially available finitie element (FE) software for electromagnetic analysis. Model is prepared as per calculated dimensions and appropriate materials are assigned. Meshing is done with tetrahedral elements and boundary conditions are assigned. Cogging torque is obtained with FEA at specific rotor position. This process is repeated for each incremental rotor position till final rotor position. Results of cogging torque are recorded to plot cogging torque profile. Flow chart for this series of simulation exercise is shown in Figure 4. This reference axial flux PM motor has peak to peak cogging torque of 10.6 N.m. The waveform of cogging torque is shown in Figure 5.

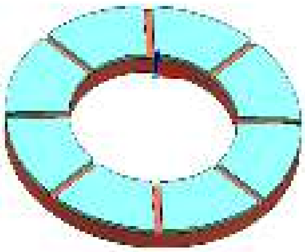

Figure 3. Initially designed rotor disc of Axial Flux PM motor

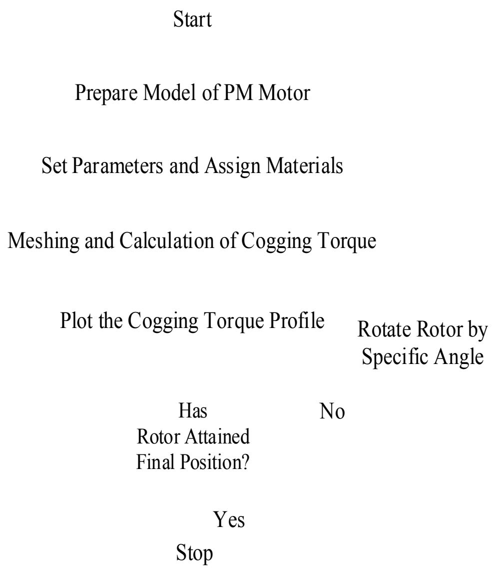

Figure 4. Flow chart of simulation process to obtain cogging torque profile

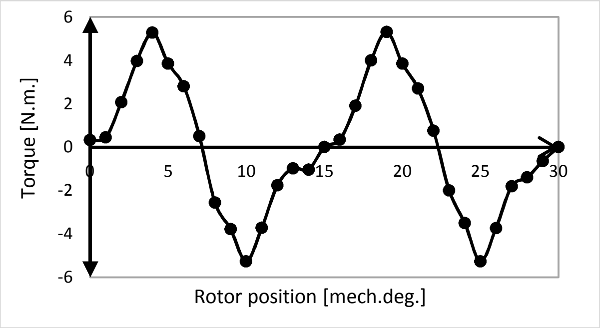

Figure 5. Cogging torque profile of initially designed motor

4. MAGNET NOTCHING TECHNIQUE

Various techniques are well documented to reduce cogging torque of radial flux PM motors. This section describes the technique to reduce cogging torque of axial flux PM motor. As discussed in introduction section, modifications on stator of axial flux motors are not recommended as it increases manufacturing cost and complexity. Therefore a cost effective magnet shaping technique is considered in this work. Conventional permanent magnet skewing technique is already explained in earlier studies. In conventional permanent magnet skewing, undesirable axial thrust is produced. Dual skewing technique has feature of low axial thrust. In slotted motor, cogging torque is generated due to interaction between magnet flux and slot reluctance variation. Cogging torque can be reduced by reduction of air gap reluctance variation. Peak cogging torque as well as cogging torque profile shape depend on magnet pole shape and geometry of magnet pole.

An eight pole surface mounted rotor without notched PM is shown in Figure 3. Improved rotor with notched PMs is shown in Figure 6 for reduction of cogging torque.

Two notches are created on one pole. Each notch has width of 1 mm and depth of 1 mm. Theoretically infinite combinations are possible between number of notches and its variants according to dimensions. Note that, mechanical strength and magnetic flux reduce with higher number of notches of large dimensions. Moreover, Peak cogging torque reduces with more number of notches. It is also observed that peak cogging torque further reduces at cost of less average torque when depth of notch is increased. Series of simulation exercises for different combinations are performed with 3-D finite element analysis to assess cogging torque and average torque. Finally, Number of notches and its dimensions are selected considering mimimum affect on cost and flux desnity distribution.

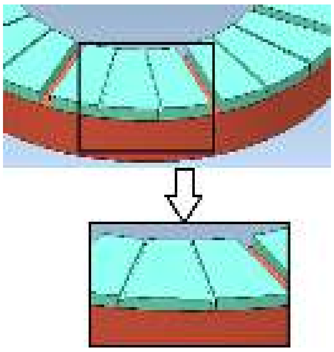

Figure 6. Improved design with notches on permanent magnets

5. SIMULATION and RESULTS

Figure 7 shows simulation results of cogging torque response on account of magnet notching on Permanent Magnet rotor poles and its comparison with cogging torque profile of initially designed reference machine.

Table 2 shows that initially designed reference axial flux PMBLDC motor has peak to peak cogging torque of 10.6 N.m. and improved design with magnet notching has peak to peak cogging toque of 6.59 N.m. Peak to peak cogging torque is reduced from 10.60 N.m. to 6.59 N.m.due to magnet notching.

Torque characteristic of initially designed motor and improved motor is shown in Figure 8. It is observed that quality of torque is enahnced with marginal penalty on average torque of improved motor design with magnet notches.

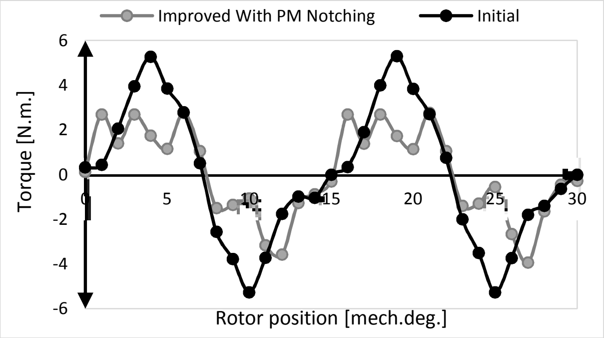

Figure 7. Comparison between cogging torque profiles of initial design and improved design

TABLE 2. Comparison between initial and modified design of Axial Flux Motor

Sr. No.	Performance Parameters	Initial Design	Improved Design with PM Notching
1.	Cogging Torque	10.60 N.m.	6.59 N.m.
2.	Average Torque	15.85 N.m.	14.45 N.m.

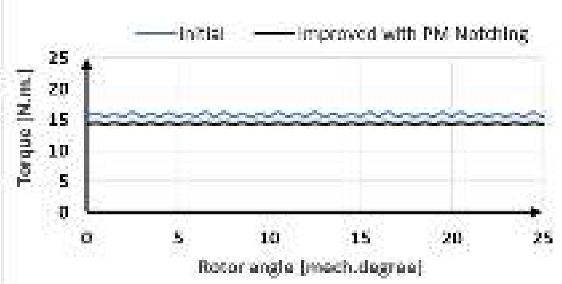

Figure 8. Torque versus time characteristics of both motors

Maxwell's fundamental governing equations describing magnetic field are as below.

$$\nabla . \boldsymbol{B} = 0 \tag{4}$$

$$\nabla \times \boldsymbol{E} = -(\partial \boldsymbol{B})/\partial t \tag{5}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} \tag{6}$$

Vector magnetic potential formulation is required to solve above equations. The magnetic flux density vector (B) is expressed using vector magnetic potential (A) as:

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \tag{7}$$

Magnetic field intensity (H) and magnetic flux density vectors are correlated as:

$$\boldsymbol{B} = \mu \boldsymbol{H} \tag{8}$$

Vector magnetic potential equation for magnetic field calculations is obtained by substituting equations (7) and (8) in equation (6).

$$\nabla \times (1/\mu \, \nabla \times \boldsymbol{A}) = \boldsymbol{J} \tag{9}$$

Finite Element method is used to solve this equation for flux density calculation.

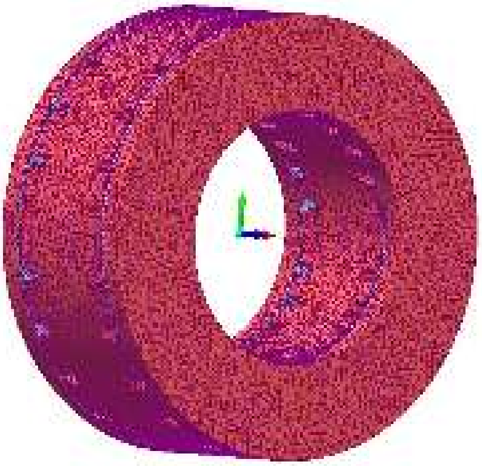

Figure 9. Three dimensional automesh generation

Figure 9 shows generation of 3-D automesh comprising tetrahedral elements. Densed automesh is generated with 4 mm element size. Number of elements are 105000 and one step computational time is 14.5 minutes. The simulations were carried out on Intel CPU core 5, I5-650 @ 3.2 GHz with 8 GB RAM.

The established flux density in various parts of Permanent Magnet motor is one of the important design parameter. This parameter influences core losses and overall performance hence comparative assessment between assumed flux densities and actual flux densities in various parts is very essential [18]. If actual flux density exceeds maximum permissible flux density, motor operates in saturation and efficiency reduces.

Figure 10 shows rotor section of FEA model of improved axial flux PMBLDC motor. Flux density distribution is shown on surface of PM and rotor core. Figure 11 shows flux density distribution in stator core of improved axial flux PMBLDC motor. It is analyzed that flux densities established in stator and rotor are near to assumed flux densities. Assumed flux desnities are 1.8 T and 1.5 T in stator teeth and back iron respectively based on property of magnetic material. Close agreement between assumed and actual flux densities in various sections of motor validates sizing of magnetic sections.

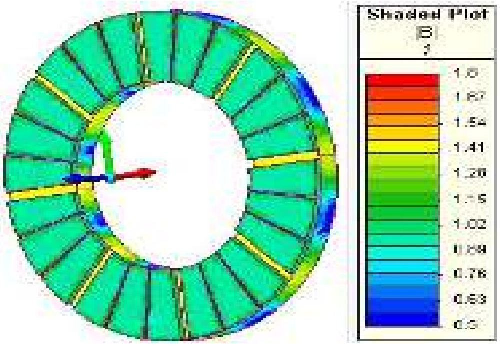

Figure 10. Rotor Flux density plot of improved motor

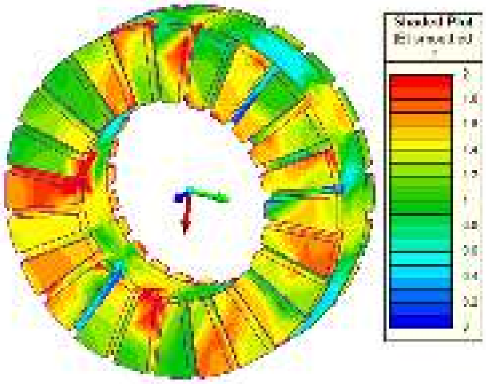

Figure 11. Stator flux density plot of improved motor

It is necessary to analyze back emf waveform of initial motor and improved motor [19]. Figure 12 illustrates back emf waveforms. Amplitude of back emf remains the same as surface area of magnet is unchanged. Minor dips are observed in back emf wave forms on account of notches of improved design.

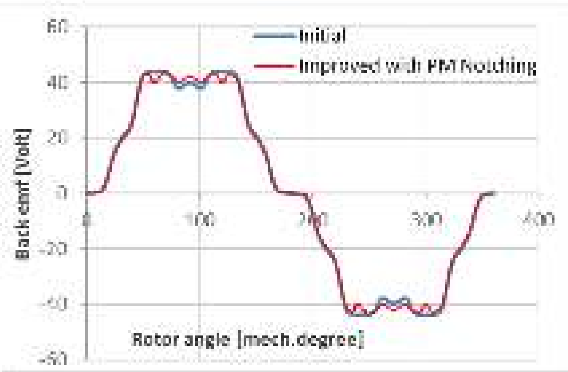

Figure 12. Back emf wave forms of both motors

6. CONCLUSION

Influence of magnet notching on cogging torque of axial flux PM motor is investigated. Selected topology of axial flux PM motor is double rotor single stator considering application in electric vehicle. 3-D finite element analysis is performed to obtain cogging torque profiles. Comparative analysis is done to assess effectiveness of magnet notching technique for reduction of cogging torque. As presented in paper, magnet notching is effective technique in cogging torque reduction of axial flux PM motor. Peak to peak cogging torque is reduced from 10.60 N.m. to 6.59 N.m. (37.65 % reduction) with marginal reduction in average torque.

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Cogging Torque Reduction of Sandwiched Stator Axial Flux Permanent Magnet Brushless DC Motor using Magnet Notching Technique

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چکیده

کاهش گشتاور گیر موتور های مغناطیس دائمی (PMBLDC) DC با شار محوری بدون جاروبکموضوع مهمی است که توجه طراحان ماشین را طی فرآیند طراحی می طلبد. این مقاله روش دندانه دار کردن مغناطیس را ارائه می دهد. تا گشتاور گیر مربوط به شار محوری موتورPMBLDC را که برای خودرو برقی طراحی شده است کاهش دهد. موتور مرجعPMBLDC با شار محوری با٢٥٠W، ١٥٠rpm، ٤٨شکاف استاتور، ١٦قطب روتوراز نوعNdFeb مغناطیس دائمی بدون دندانه طراحی شده است. مدل سازی سه بعدیاجزای محدود و تحلیل مساله انجام شده است تا پروفایل گشتاور گیر ماشین طرح شده اولیه بدست آید. دندانه ها روی مغناطیس دائم ایجاد شده اند و اثر آن ها بر گشتاور گیر با مدل سازی سه بعدی اجزای محدود و تحلیل صورت گرفته است. تحلیل حاصل نمایشگر آن است که دندانه دار کردن مغناطیس روشی موثر در کاهش گشتاور گیر موتور PMBLDC با شار محوری می باشد.

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