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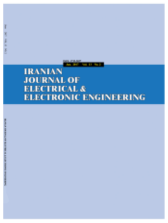

Double Layer Magnet Design Technique for Cogging Torque Reduction of Dual Rotor Single Stator Axial Flux Brushless DC Motor

A. N. Patel*$^{(C.A.)}$ and B. N. Suthar**

Abstract: Cogging torque is the major limitation of axial flux permanent magnet motors. The reduction of cogging torque during the design process is highly desirable to enhance the overall performance of axial flux permanent magnet motors. This paper presents a double-layer magnet design technique for cogging torque reduction of axial flux permanent magnet motor. Initially, 250 W, 150 rpm axial flux brushless dc (BLDC) motor is designed for electric vehicle application. Initially designed reference axial flux BLDC motor is designed considering 48 stator slots and 16 rotor poles of NdFeb type single layer permanent magnet. Three-dimensional finite element modeling and analysis have been performed to obtain cogging torque profile of reference motor. Additional layer of the permanent magnet is created keeping usage of permanent magnet same with an objective of cogging torque reduction. Three-dimensional finite element modeling and analysis have been performed to obtain cogging torque profile of improved axial flux BLDC motor with double layer permanent magnet design. It is analyzed that double-layer magnet design is an effective technique to reduce the cogging torque of axial flux BLDC motor.

Keywords: Cogging Torque, Axial Flux BLDC Motor, Finite Element Analysis, Double-Layer Magnet.

1 Introduction

ELECTRIC Vehicles (EV) are increasingly becoming popular due to its environment-friendly features and economic merits. Limited resources, uncertainty of supply and continuous increase in cost of fossil fuel motivated researchers to design and develop reliable and implementable systems for electric vehicle. Performance improvement of electric motors is highly indispensable for realisation of electric vehicles with improved performance parameters. Efficiency and compactness are two important performance parameters of electric motors for electric vehicle applications. Application of permanent magnet excitation in place of electromagnetic excitation significantly enhances performance of electric motors. Rare earth magnet materials like Neo-dymium Iron Borone and Samarium Cobalt have capabilities to set high flux density in magnetic circuit resulting into efficient and compact electrical motors. Permanent magnet (PM) motors have been progressively used in many emerging applications since introduction of rare earth magnets and semiconductor devices [1]. According to flux direction, PM motors can be classified into two kinds: (i) radial flux PM motors and (ii) axial flux PM motors. In radial flux motors, flux sets in radial direction and current flows in axial direction. Flux sets in axial direction and current flows in radial direction in axial flux motors [2]. The axial flux permanent magnet motors possess attractive features than radial flux permanent magnet motors like high torque density, high efficiency, better torque/current ratio, better winding utilization and flat shape [3]. Axial flux permanent magnet motors can be also classified according to placement of permanent magnets, type of slots, numbers and relative positions of

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stators–rotors and type of winding. Permanent magnets are fixed on rotor core in surface permanent magnet topology whereas PMs are inserted in rotor core in interior permanent topology. Axial flux permanent magnet motors are classified as slotted motors or slotless motors according to construction of stator core [4]. They are further classified based on relative position and number of stators and rotors respectively in four categories viz. single stator single rotor (SSSR), single stator double rotor (SSDR), double stator single rotor (DSSR) and multi-disc. Ring-type and drum type are two classifications according to armature winding pattern of axial flux permanent magnet motors. Double rotor single stator surface-mounted permanent magnet axial flux permanent magnet motors with ring-type winding are well suited in direct drive applications like electric vehicles, elevators and etc.

Torque quality assessment of axial flux permanent magnet motors is interesting assignment of motor designers as torque ripple is certainly considered as one of the important performance parameters along with torque density. High torque ripple increases vibration and noise. Generally, torque ripple is filtered out due to system moment of inertia at high speed but at low-speed torque ripple results into considerable vibration and noise resulting into inferior performance of permanent magnet motors [5]. Many researchers are actively involved in torque quality assessment and its improvement. Cogging torque, distorted stator current & counter emf waveforms, switching of phase excitation, fluctuation in delay time and fluctuation of inverter DC link voltage are the main causes of torque ripple. Cogging torque arises due to interaction between PM rotor magneto-motive harmonics and air-gap permeance harmonics. Even without stator current excitation, rotor demonstrates tendency to align in number of stable positions due to cogging torque [6]. Cogging torque also affects self-starting capability and dynamic performance of motor [7].

Cogging torque reduction of axial flux permanent magnet motors must be crucial design consideration. This paper is concentrated on reduction of cogging torque of double rotor sandwiched stator axial flux BLDC motor. Surface-mounted slotted topology is selected in this work for simulation and analysis. Skewing of stator slots and/or rotor magnets, dual skewing, shifting of magnets, notching of magnets and/or stator tooths, unequal tooth width, variation of pole arc, and etc. are design techniques available in existing literature to decrease cogging torque in radial flux PM motors [8-14]. Few of these techniques are applicable in axial flux PM machines but manufacturability and cost of implementation are crucial issues. Manufacturable and cost-effective techniques for axial flux PM motors are desirable.

Cogging torque of axial flux PM motor is influenced by skewing of magnet and/or slots. Magnet skewing is effective technique to reduce cogging torque of axial flux permanent magnet motors [15]. Generation of unwanted axial thrust is drawback of magnet skewing technique [16]. Skewing of stator slots complicates manufacturing of axial flux permanent magnet motors. Dual skewing reduces axial thrust at cost of marginal reduction in average torque. Cogging torque of axial flux PM machine can be reduced with magnet pole arc variation. Variation of pole arc ratio for cogging torque reduction may adversely affect motor output and back emf waveform. Sinusoidally shaped magnets offer better torque quality compared to sector like magnets and cylindrical magnets with marginal penalty on torque/current ratio. Relative shifting of magnets reduces cogging torque. Leakage flux increases as magnets move from symmetrical position to unsymmetrical position [17]. Cogging torque of axial flux permanent magnet motors can be reduced with stator side modifications like slot opening shape variation and relative displacement of slot opening [18]. Cogging torque can be reduced with dual notched design of radial flux surface-mounted permanent magnet motor [19].

Stator side design modifications are not preferred in case of axial flux permanent magnet motors as it complicates stator core design & implementation. Cost of axial flux motors increases due to increased complexity of core. Rotor side design modifications for cogging torque reduction of axial flux permanent magnet motors are desirable because it is more practical and cost-effective in comparison to stator side modifications. The reduction in cogging torque of axial flux BLDC motors is major area of concern particularly for low-speed torque-sensitive applications. In this work, the authors have addressed this issue by proposing cost-effective and implementable magnet shaping technique called double-layer permanent magnet design technique. In proposed method usage of permanent magnet is kept same maintaining same volume of permanent magnet in initially designed motor and improved motor with dual-layer. Influence of the proposed double-layer magnet design technique on average torque and back emf waveforms are also presented. Thus, 3-D finite element analysis (FEA) technique is used to solve electromagnetic problem and to simulate technique. Basics of cogging torque and approaches for its reduction are explained in Section 2. A brief summary of the initially designed reference motor is presented in Section 3. Section 4 elucidates design improvement for cogging torque reduction of axial flux BLDC motor. Simulation and results are discussed in Section 5

2 Basics of Cogging Torque

Instantaneous electromagnetic torque developed by axial flux PM motors can be expressed as under.

$$T_e(t) = \frac{1}{\omega_m}\left[e_a(t)\,i_a(t) + e_b(t)\,i_b(t) + e_c(t)\,i_c(t)\right] + T_{cog} \quad (1)$$

The sum ($e_a i_a$+$e_b i_c$+$e_c i_c$) contains an average component and sixth order harmonics as the phase shifts between $e_a i_a$ and $e_b i_c$ and between $e_a i_a$ and $e_c i_c$ are -2π/3 and 2π/3, respectively. The other order harmonics are mutually canceled out and the instantaneous electromagnetic torque can be expressed as under based on the assumption of negligible flux leakage and core saturation [20].

$$T_e(t) = T_{avg} + \sum_{k=1}^{\infty} T_{6k} \cos(k\,6\omega t) + T_{cog} \tag{2}$$

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

Following the Fourier series equation represents cogging torque waveform determined analytically or by finite element analysis [20].

$$T_{cog}(\theta_m) = \sum_{k=1}^{\infty} T_k \sin\left(kN_c\theta_m + \varphi_k\right) \tag{3}$$

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

Generation of cogging torque is inherent in PM motors on account of reluctance variation in air-gap due to slotted structure of stator. Cogging torque depends on flux in air-gap and air-gap reluctance variation as per Eq. (4). Air-gap flux and/or air-gap reluctance variation can be reduced for cogging torque reduction. Average torque of motor depends on air-gap flux hence any attempt to reduce air-gap flux will derate motor. Reduction of air-gap flux is not viable option for cogging torque reduction. Decreasing air-gap reluctance variation is the only option available for cogging torque reduction [20].

$$T_{cog} = -\frac{1}{2}\phi_g^2 \frac{dR}{d\theta_m} \tag{4}$$

where, ϕ_g, R and θ_m are air gap flux, air-gap reluctance, and rotor angle, respectively.

Authors have presented an analysis of cogging torque reduction technique using 3-D finite element modeling and analysis. 3-D finite element modeling and analysis remains relatively time-consuming but gives accurate results. To simplify the calculation, analytical technique may be combined with a finite element technique. Cogging torque can also be determined by calculating change of air-gap energy stored with respect to the rotor position. Due to strong permanent magnets and high flux density, the cogging torque is noticeable in PM motors. Conceptually, cogging torque is generated due to non-uniform flux distribution in air-gap. Each rotor magnet has the same position with reference to stator slots in integral slot machine where number of slots per pole is an integer. Thus, cogging torque components generated by all magnets are cophasal which results into considerable cogging torque.

3 Reference Design of Axial Flux BLDC Motor

The axial flux PM motor structure in the present study includes two exterior surface PM mounted rotors and sandwiched stator. The 250 W, 150 rpm initially designed reference motor considered in present work consists of 48 slots stator and two 8 poles rotor. Motor rating has been calculated based on vehicular dynamics and application requirements. The laden weight of vehicle 150 kg, maximum speed 25 kmph and attainment of top speed in 9 seconds are application requirements.

The stator is sandwiched between two surface mount rotors as shown in Fig. 1. The disc-shaped rotors carry axially magnetized magnets that are mounted axially on inner surface of rotor core. High grade Neo-dymium Iron Borone (NdFeB) permanent magnets are fixed on rotor core. NdFeB with high energy product is selected for better efficiency and compactness. Slotted stator is made of silicious core material of tape wound pattern. Core material possesses high relative permeability and low specific iron loss. The rotor core is made of mild steel. Motor is designed with an assumption of one slot/pole/phase. Diametric ratio of 1.73 is selected to obtain better power density [21]. The windings in radial direction are used for generation of torque. Two types of windings are feasible in axial flux PM motor i.e. drum winding or ring winding. End connections are kept circumferentially as shown in Fig. 2(a) in drum winding or tooth winding. Ring winding as shown in Fig. 2(b) popularly known as back to back or toroidal windings having axially kept end connections.

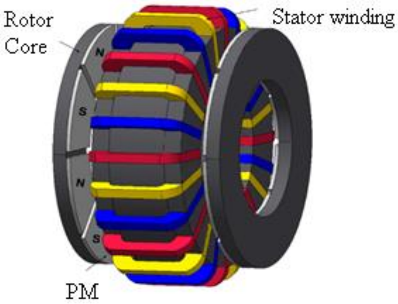


Fig. 1 Model of axial flux PMBLDC machine.

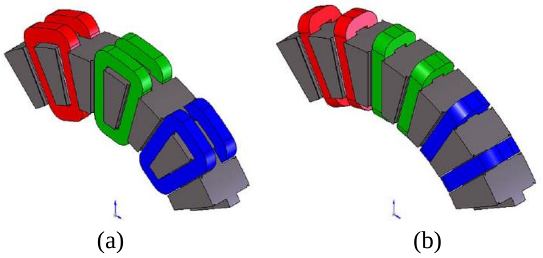
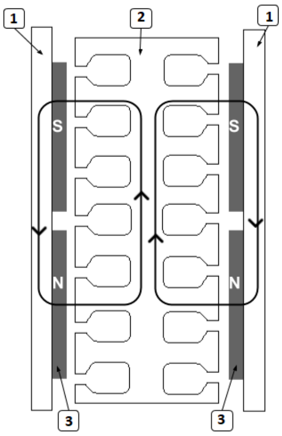

(a) (b)

Fig. 2 Types of windings: a) drum type, and b) ring type.

Ring type winding has better copper utilization due to short over hang with respect to active conductor length [22]. Short over hang results into reduced copper losses. In the present study, axial flux PM motor with ring type winding is considered. Double rotor single stator axial flux permanent magnet motors can be further classified as NN or NS according to polarity of opposite magnets. NN type topology has two opposite magnets of the same polarity while NS topology has two opposite magnets of opposite polarity. In this research work NN type topology is considered as shown in Fig. 3. As shown in Fig. 3 flux emanates from permanent magnet and crosses the air-gap and travels through stator core and closes path to opposite polarity permanent magnet.

The reference axial flux PM motor is designed without application of any cogging torque reduction technique. Design information of reference motor is given in Table 1.



^{1} Rotor core, ^{2} Stator core, ^{3} Permanent magnet

Fig. 3 Flux path in NN type axial flux PM motor.

Table 1 Design data of axial flux PMBLDC motor.

Design Parameter	Value
Outer radius	91 [mm]
Inner radius	45.5 [mm]
No. of phases	3
No. of poles	16
No. of slots/pole/phase	1
No. of slots	48
PM thickness	2.7 [mm]
Air-gap length	0.5 [mm]
Stator back iron thickness	35 [mm]
Rotor back iron thickness	9.2 [mm]
Permanent magnet material	NdFeb
Core material	M19

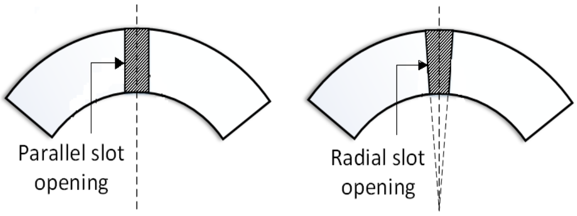


Fig. 4 Slot openings of axial flux PM motor.

Parallel slot opening is preferred over radial slot opening for the simplicity of manufacturing. The ratio of slot width to slot pitch does not remain constant in case of parallel slot opening whereas ratio of slot width to slot pitch remains constant in radial slot opening [17]. The reference motor is designed with a parallel slot opening as illustrated in Fig.4. Rotor disc comprising eight poles made up of NdFeb type permanent magnet material is illustrated in Fig. 5. Initially designed axial flux permanent magnet motor is considered as reference for comparison with improved designed motor with an objective of cogging torque reduction.

Simulation and analysis are carried out using commercially available finite element (FE) software for electromagnetic analysis. The model is prepared based on design information and appropriate materials are assigned. Meshing is done with tetrahedral elements and boundary conditions are assigned. Cogging torque is obtained with FEA at a specific rotor position. This process is repeated precisely for each incremental rotor position until the final rotor position.

Results of cogging torques are recorded to plot cogging torque profile. Flow chart for this series of simulation exercise is shown in Fig. 6. This reference

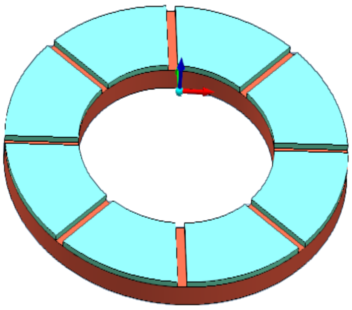


Fig. 5 Initially designed rotor disc of axial flux PM motor.

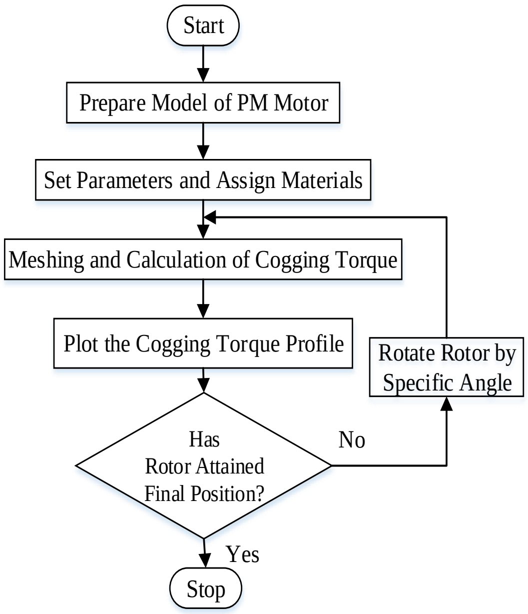


Fig. 6 Flow chart of simulation process to obtain cogging torque profile.

axial flux PM motor has peak to peak cogging torque of 10.6 N.m. The cogging torque profile of reference motor is shown in Fig. 7.

4 Double Layer Magnet Design

Various design techniques for cogging torque reduction of radial flux PM motors are well documented. This section presents design technique to reduce cogging torque of axial flux permanent magnet motor. As discussed in introduction section, stator side modifications of axial flux motors are not recommended as it increases manufacturing cost and complexity. Therefore a practically implementable 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 decreasing air-gap reluctance variation. Amplitude of cogging torque, as well as shape of cogging torque profile, depend on shape of permanent magnet pole fixed on rotor core.

An eight-pole surface mounted rotor without magnet shaping is illustrated in Fig. 5. Improved double-layer PM rotor is illustrated in Fig. 8 for reduction of cogging torque.

Fig. 9 illustrates single layer initial PM pole and Fig. 10 illustrates improved double layer PM pole. The volume of PM is kept same in both cases i.e. initial single layer PM pole and improved double layer PM pole.

The thickness of the second layer of PM can be determined from the following equation considering same usage of PM.

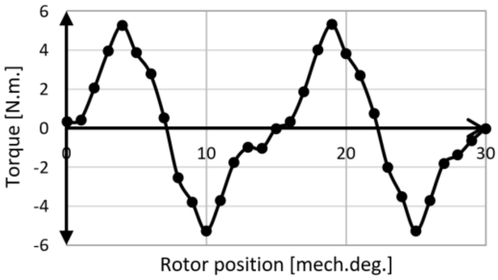


Fig. 7 Cogging torque profile of reference motor.

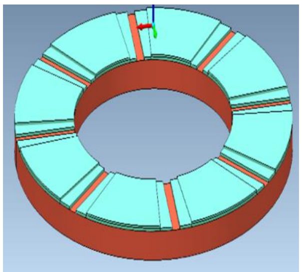


Fig. 8 Improved rotor with two layers of PM.

$$t_{pm2} = \frac{1 - x\, t_{sp}\left(t_{pm} - t_{pm_1}\right)}{1 - x\left(t_{sp} - 2w_1\right)} \tag{5}$$

where $x = \dfrac{P}{\pi\left(R_o + R_i\right)}$

where R_o is outer radius, R_i is inner radius, t_{sp} is width of spacer, t_{pm} is thickness of initial single layer PM, t_{pm1} is thickness of first layer of PM and w_1 is offset between second layer and first layer.

Cogging torque depends on air-gap reluctance variation as expressed in (3). Air-gap reluctance variation is inherent in slotted permanent magnet motors. Air-gap reluctance variation decreases due to additional layer of permanent magnet on rotor pole hence cogging torque reduces subsequently. Along with reduction of air-gap reluctance variation the air-gap flux density distribution and the shape of back emf wave form also improve with additional permanent magnet layer on rotor pole. In radial flux surface mount motors arc type permanent magnets are used but in axial flux motors flat permanent magnets are used. It is fairly easy to implement layer technique in flat type permanent magnets. Theoretically, any numbers of layers of permanent magnet are possible but it is worth to note that, mechanical strength reduces and manufacturing complexity increases with more numbers of layers. Peak cogging torque reduces with more number of layers of permanent magnet. As usage of permanent magnet is same in both initially designed reference motor and improved motor, the slight increase in cost of improved motor is due to additional cost of shaping of permanent magnet only. The slight increment in cost of improved motor is justifiable on account of improvement in torque quality and better overall performance of motor. Torque quality is one of the important performance parameters in torque-sensitive applications. Mathematical representation of design modifications of axial flux motors to reduce cogging torque in three dimensional (3-D) becomes much complex. Series of simulation

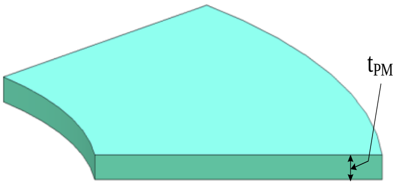


Fig. 9 Initial single layer rotor PM pole.

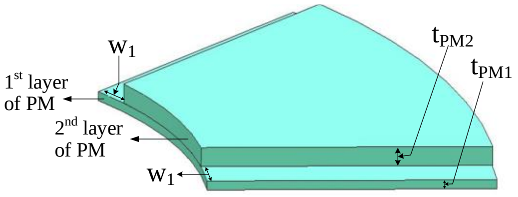


Fig. 10 Improved double-layer rotor PM poles.

exercises for different combinations are performed with 3-D finite element analysis to assess cogging torque profile and average torque profile. Finally, number of layers and its dimensions are selected considering minimum effect on cost and mechanical strength. In present analysis two layers with bottom layer of 1.2 mm thickness and top layer of 1.7 mm thickness are considered.

5 Simulation and Results

Cogging torque profile of improved motor with double magnet layers and its comparison with cogging torque profile of reference motor have been illustrated in Fig. 11.

Table 2 shows that initially designed reference axial flux BLDC motor has peak to peak cogging torque of 10.60 N.m. and improved design with layer magnet has peak to peak cogging toque of 2.20 N.m. Peak to peak cogging torque has been reduced from 10.60 N.m. to 2.20 N.m. with the application of layer magnet design. Reduction in peak to peak cogging torque is considerable in comparison to marginal reduction in average torque.

Torque characteristic of initially designed motor and improved motor are shown in Fig. 12. It is observed that torque quality is enhanced with marginal penalty on average torque of improved motor design with double layer magnets.

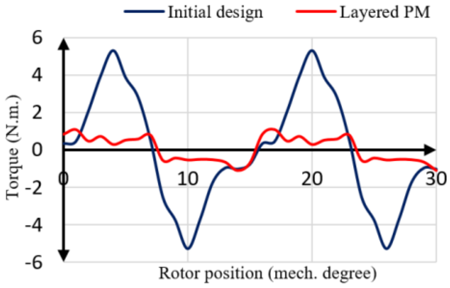


Fig. 11 Comparison between cogging torque profiles of initial design and improved design.

Table 2 Comparison between initial and improved design of axial flux motor.

Sr. No.	Performance parameters	Initial design	Improved design with PM notching
1.	Cogging Torque	10.60 N.m.	2.20 N.m.
2.	Average Torque	15.85 N.m.	14.05 N.m.

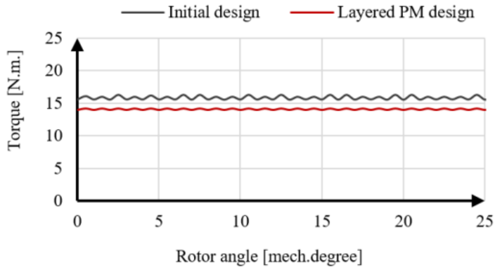


Fig. 12 Torque vs. time characteristics of both motors.

Axial flux permanent magnet motor represents 3-D electromagnetic problem according to its geometry. 3-D FEA results are very accurate but require more time and memory space.

Finite Element method is used to solve this equation for flux density calculation. Three-dimensional auto mesh generated with tetrahedral elements is illustrated in Fig. 13. Densed auto mesh is generated with 4 mm element size. Number of elements is 112000 and one step computational time is 17.1 minutes. The simulations were carried out on Intel CPU core 5, I5-650 @ 3.2 GHz with 8 GB RAM.

The assessment of flux densities established in various parts of permanent magnet motor is important as it influences core losses and torque ability. This parameter influences core losses and overall performance. Comparative analysis between assumed flux densities and actual flux densities in respective part is indispensable. Permanent magnet motor operates in saturation and performance deteriorates if actual flux density exceeds maximum permissible flux density in respective section

Fig. 14 indicates rotor section of FEA model of improved axial flux motor. Flux density spectrum is shown on surface of PM and rotor core. Flux density spectrum of stator core of improved axial flux motor is shown in Fig. 15. 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.

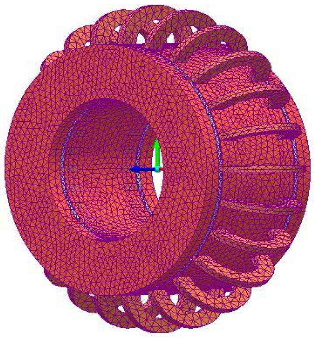


Fig. 13 Three dimensional auto mesh generation.

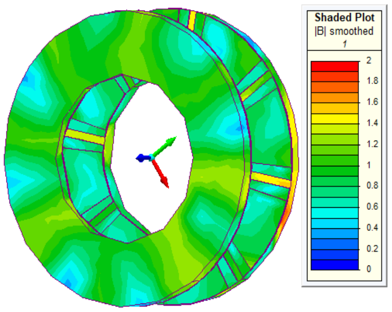


Fig. 14 Rotor Flux density plot of improved motor.

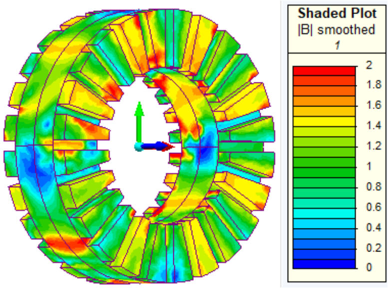


Fig. 15 Stator flux density plot of improved motor.

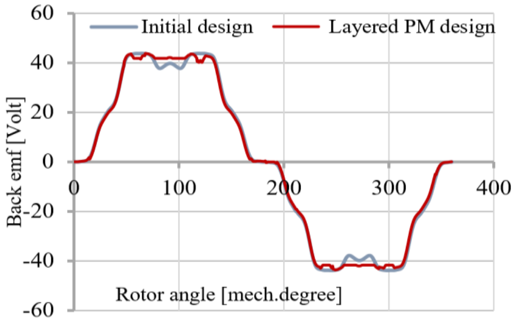


Fig. 16 Back emf wave forms of both motors.

It is important to analyze back emf waveform of initial motor and improved motor [24]. Back emf waveform of improved motor and its comparison with back emf waveform of initial motor is illustrated in Fig. 16. It is analyzed that back emf waveform of improved design is of better shape with reduced dips.

6 Conclusion

Double rotor single stator (DRSS) axial flux BLDC motor designed for direct drive electric vehicle application is considered as reference motor in this research work. DRSS axial flux BLDC motor is the best compatible motor in direct drive applications. Magnet shaping is performed with introduction of additional layer and its influence on cogging torque of axial flux permanent magnet motor is analyzed. Three-dimensional finite element modeling and analysis is performed to obtain cogging torque profiles of reference motor and improved motor with double-layer design of magnets. For the assessment of effectiveness of magnet layer design with an objective of cogging torque reduction, comparative analysis is carried out. Peak cogging torque with double-layer magnet is reduced from 10.6 N.m. to 2.2 N.m. with borderline reduction in average torque. It is analyzed that double-layered magnet design technique is effective and implementable technique also in cogging torque reduction of axial flux PM motor.

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