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Cogging torque reduction of axial flux permanent magnet brushless DC motors for electric vehicle applications with magnet segmentation technique

Mıknatıs segmentasyon tekniği ile elektrikli araç uygulamaları için eksenel akılı sabit mıknatıslı fırçasız DC motorların cogging torkunun azaltılması

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Abstract

Axial flux permanent magnet brushless DC motors have many attractive features along with major disadvantage of high cogging torque. Cogging torque reduction is major challenges in permanent magnet motor design, specifically for electric vehicle applications. In order to lower the cogging torque of axial flux permanent magnet brushless motors for use in electric vehicle applications, this article proposes the magnet segmentation technique. To accomplish this, each permanent magnet mounted on the rotor core surface is separated into two identical sections. This work also considered the influence of segmentation on average torque, flux density profile, and back emf profile. A 250 W, 150 rpm axial flux permanent magnet brushless DC motor was simulated and analyzed using three-dimensional finite element analysis. It is observed that the suggested approach effectively reduces cogging torque.

Keywords: Cogging torque, PM motor, Design, FEA, Permanent magnet

Öz

Eksenel akılı sabit mıknatıslı fırçasız DC motorlar birçok cazip özelliğe sahip olmakla birlikte, en büyük dezavantajı yüksek vuruntu momenti. Sürekli mıknatıslı motor tasarımında özellikle elektrikli araç uygulamalarında karşılaşılan başlıca zorluklardan biri de vuruntu momenti azaltılmasıdır. Bu makalede, elektrikli araç uygulaması için eksenel akılı sabit mıknatıslı fırçasız motorların vuruntu momenti azaltmak için mıknatıs segmentasyonu yaklaşımı sunulmaktadır. Bunu başarmak için, rotor çekirdek yüzeyine monte edilen her bir sabit mıknatıs iki özdeş bölüme ayrılır. Bu çalışmada ayrıca segmentasyonun ortalama tork, akı yoğunluğu profili ve geri emf profili üzerindeki etkisi de değerlendirilmiştir. Üç boyutlu sonlu eleman analizi, 250 W, 150 rpm eksenel akılı sabit mıknatıslı fırçasız DC motorun simülasyonu ve analizi için gerçekleştirilmiştir. Önerilen yaklaşımın vuruntu momenti etkili bir şekilde azalttığı gözlemlenmiştir.

Anahtar kelimeler: Cogging torku, PM motor, Tasarım, FEA, Kalıcı mıknatıs

1 Introduction

Fossil fuels pose a threat to the ecosystem due to limited resources, CO_2 emission and environmental pollution. Gasoline and diesel-powered vehicles release harmful emissions that harm the general public's health over time. Electric automobiles emit much less pollution than gasoline or diesel vehicles. Approximately 60 % of the electrical energy from the grid can be converted by electric vehicles to power the wheels, but only 17 %–21 % of the energy in fossil fuel can be transferred by gasoline or diesel cars. Despite the fact that completely electric automobiles produce no emissions at all, even when power generation is taken into consideration, the average electric car releases almost one-third of carbon dioxide as that of gasoline or diesel vehicles. Use of renewable energy in electric vehicles results in to zero carbon emission. As a result, electric vehicles are the future of a sustainable and green revolution.

PMBLDC (Permanent Magnet Brushless DC) motors are gaining popularity in electric vehicle applications on account of better operational efficiency, compact size, fast dynamic response, wide speed range, compatibility with solar-powered sources, and flexibility in control [1-3]. Permanent magnet motors are the most suitable in the case of direct drive applications, viz. windmills, electric vehicles, robotics, CNC machines, elevators, etc. [4-5]. Radial flux motors and axial flux motors are two types into which permanent magnet brushless motors can be classified. As their names imply, the axial flux and radial flux machines differ in that the magnetic flux direction in the former is parallel to the machine's rotating axis while the latter is radial. Axial flux motors have shorter and more direct flux routes than the radial machine [6-7]. The magnetic field is strong over the shorter length, which helps to boost the axial flux PMBL motors' productivity and power density. The flat shape is the typical advantage of axial flux motors in applications like electric vehicles demanding a low aspect ratio [8]. The number of stators and rotors, as well as how they are arranged in relation to one another, are additional categories for axial flux motors. Single stator single rotor, dual rotor sandwiched stator, dual stator sandwiched rotor, and multi-stack are the various categories of axial flux BLDC motors. Sandwiched stator double rotor axial flux BLDC motor possesses a balanced, attractive force between stator and rotors [9]. It is very crucial to achieve low cogging torque axial flux PMBL motors for torque-sensitive applications like electric vehicles, robotics, submarines, elevators, etc. The major reason for the overall torque ripple, which has a negative impact on the performance of the motor, particularly in high-precision applications, is cogging torque. Therefore, it is crucial to

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minimize this parasitic torque while designing axial flux PMBL motors [10]. Cogging torque is the result of the interaction between the stator teeth and the magnetic flux created by PM [11]. As the flux always favors a path with the least amount of reluctance, PM flux has a tendency to pass through the stator teeth, which causes an undesirable torque to be generated. Particularly for low-speed applications, cogging torque produces speed and torque ripple, which causes vibration and acoustic noise [12]. The motor performs better overall when the cogging torque is reduced.

[R1-V, R2 VI] Magnet segmentation divides a large magnet into smaller pieces. Unlike other approaches for reducing cogging torque, the magnet segmentation method results in a simpler motor build. The fundamental concept in this approach is to regulate the airgap flux density by segmenting the magnet pole into multiple magnet blocks [13]. Because the magnets are in the same relative position with regard to the stator slots, their interactions have an additive effect. The magnet segmentation method involves breaking this cumulative effect. In reality, a compensatory effect may be obtained by segmenting each magnet pole into multiple identical elementary magnet blocks and mounting them on the rotor surface in regular intervals. The division of an arced magnet pole with radial magnetization into many arced magnet blocks with radial magnetization per pole may result in a large decrease in cogging torque. The amount of the cogging torque's lower harmonics may be lowered or avoided by properly positioning each magnet block. The segmentation approach may be used with any size of motor [14]. The partial magnet segmentation (PMS) approach is comparable to complete segmentation, except the penetration of the incision is less than 100 %. This process assures that the magnet remains in one piece throughout manufacturing. The second approach is known as double-sided partial magnet segmentation (DS-PMS). This method is similar to SS-PMS, with the exception that non-aligned cuts may be produced from either face of the magnet. This approach similarly assures that the magnet remains intact throughout the segmentation process, but it has the benefit of segmenting both sides of the magnet simultaneously. The partial magnet segmentation approach is simple to execute while also being successful in reducing magnet loss [15].

Many authors have suggested techniques to tackle this issue of cogging torque reduction. A few techniques are suitable for radial flux PMBL motors and axial flux PMBL motors. In general, reducing cogging torque may be achieved by altering the stator or rotor design. The choice of permanent magnet motors' pole and slot counts also affects cogging torque [16]. Skewing reduces the cogging torque of permanent magnet motors [17], but it has a limitation in terms of high axial thrust generation [18]. Magnet displacement is the technique applicable for cogging torque reduction of both radial flux and axial flux motors [19]. [20] proposed slot displacement technique for 5.0 kW 8-pole axial flux motors. It is analyzed that the slot opening displacement technique reduces cogging torque by almost 50 % but results in reduced useful torque, too. The displacement of the stator slot increases the motor's manufacturing cost and complexity [21]. The displaced slot opening method is effective in the reduction of cogging torque, but it complicates the motor laminations, hence resulting in high costs [22].

Many authors have recommended a comprehensive way of using design variables linking optimization methods for cogging torque reduction. The proper shape of the magnet has a significant influence on cogging torque. An integrated algorithm applicable to a wide range of problems is presented conducted to magnet shape optimization of a 3-phase radial flux PMBLDC motor with 6 poles-18 slots based on a reduced basis technique [23]. In order to achieve complete sensor-less control and low torque ripple, design factors are chosen with an eye on improving saliency. Simultaneously, taking into account the shapes of rotor & stator of the selected PMSM allowed for optimization [24]. Multi-objective cogging torque optimization of 550 W, 1500 rpm, 220 V motor is discussed and validated using FEA [25]. The Genetic Algorithm (GA) method is used to minimize cogging torque by optimizing three motor variables: PM thickness, PM shape, and PM embrace, which is the covering of the rotor by magnets or the magnet span. The GA traversed the whole space of possible solutions and discovered the most suitable of three design variables, which resulted in the global minimum of the optimization of cogging torque. Cogging torque is significantly reduced when these three parameters are optimized [26–27].

This work aims to investigate the magnet segmentation technique for axial flux PMBLDC motor cogging torque reduction. This research examines the structure of an axial flux PMBLDC motor for electric vehicles, specifically focusing on a twin rotor inner stator topology. Modification on the stator of the axial flux PMBLDC motor increases complexity further; hence, it is not usually preferred. The proposed technique is focused on rotor side modification; hence, it is practically viable and manufacturable. The novelty of the proposed technique is the reduction in permanent magnet (PM) usage due to segmentation and ease in the manufacturing process due to the transformation of the single poles into small slabs of PM. The eradication of eddy-current losses in the magnets, which are not taken into consideration in this article, is another benefit of pole magnet segmentation. This article is ordered as follows. Section 2 elucidates the design of an axial flux motor for electric vehicle applications. It is considered as the initial design and cogging torque profile; useful torque profile and field plot are presented. Magnet segmentation technique for cogging torque reduction is presented in section 3. Finite Element (FE) supported software is used for modeling and electromagnetic analysis. Section 4 presents the simulation results of the improved motor and its comparison with the initial motor. This paper is concluded in section 5.

2 Axial Flux BLDC Motor Design

Axial flux brushless DC motor, as shown in Figure1, is of double rotor single stator type designed for electric two-wheeler having laden weight 150 kg., rated speed 25 kmph, acceleration 0 to 25 km in 09 Sec. Double rotor single stator topology is the most suitable in direct drive vehicular applications. Motor rating of 250 W, 48 V calculated considering application needs and vehicular dynamics. Axial flux PMBLDC motor is designed for electric two-wheelers based on the assumption of various design variables like air-gap flux density, electric loading, current density, space factor, magnet fraction, core flux density, diametric ratio, etc. The selection of design variables significantly influences the performance of the axial flux BLDC motor [28]. The proper selection of design variables is crucial as it influences performance. The selection of design variables is carried out based on performance expectations and the availability of materials. Double rotor topology is selected as it offers stable operation because of net zero axial thrust.

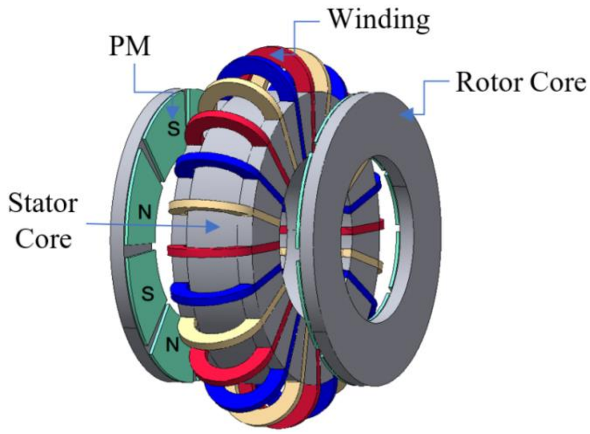


Figure 1. Double rotor axial flux PMBLDC motor.

The design information for the 250 W axial flux BLDC motor is shown in Table 1. NdFeB magnets have high remanence and energy product hence used to obtain higher power density and superior performance [29]. Each rotor has eight magnet poles whereas the stator has 24 slots on each side. The sandwiched stator comprises three-phase ring-type winding. The ferromagnetic material M19, which has a thickness of 29 Ga and high relative permeability, is used to make the stator core.

Table 1. Design Information.

Parameters	Symbol	Unit	Value
Stator phase	N_{ph}	-	3
Stator slots	N_s	-	48
Rotor poles	N_p	-	16
Outer dia.	D_o	mm	182
Stator bore dia.	D_i	mm	104
Magnet thickness	L_m	mm	2.7
Length of Air-gap	L_g	mm	0.5
Remanence	B_r	T	1.2
PM	-	Grade 50	NdFeB
Magnetization	-	-	Radial
Core material	-	-	M19

The interaction between a permanent magnet motor's PM and stator teeth produces cogging torque (CT). Another name for it is detent torque. Depending on the quantity of magnetic poles and stator teeth, it has a periodic character. Using FEA, the cogging torque at a given rotor position is determined. Until the desired rotor position is reached, this procedure is repeated. Figure 2 depicts the procedure chart for getting the CT profile of the AF-BLDC motor. Because of the structural symmetry of the motor, the CT variation is observed to be periodic. The CT profile and electromagnetic torque profiles are shown in Figure3 and Figure4, respectively. As shown in Figure 3, the max CT of 5.43 N.m. obtained in initially designed AF-BLDC motor. Initially designed axial flux BLDC motor has an average torque value of 15.06 N.m.

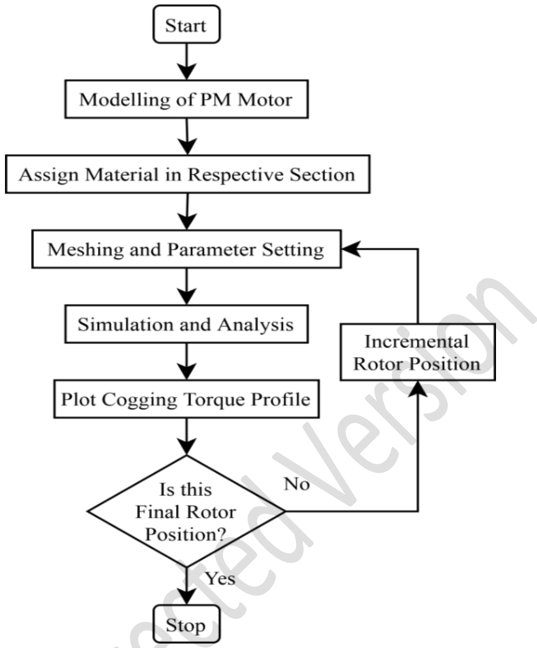


Figure 2. Flow diagram to obtain cogging torque.

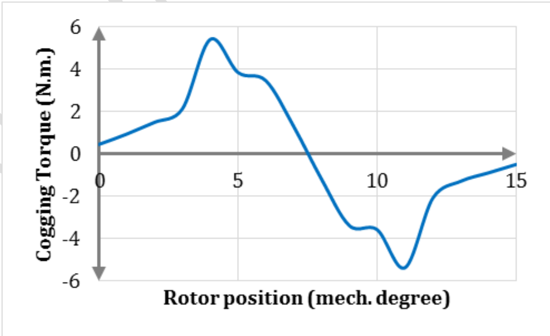


Figure 3. Cogging torque waveform of initial design.

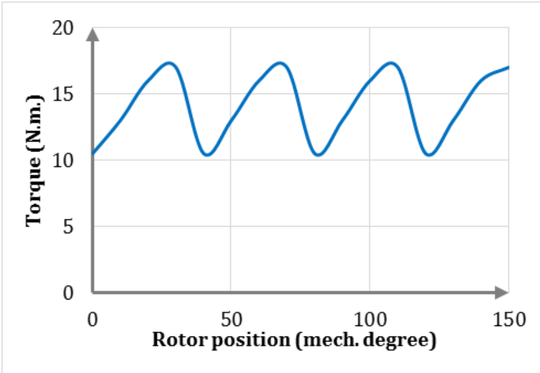


Figure 4. Torque waveform of initial design.

Design of permanent magnet machines necessitates the evaluation of field plot of motor. The evaluation of flux density in various parts of axial flux PMBLDC motor by FEA solves 3-D magneto-static field problem and by post processing the magnetic field solution to obtain magnetic field plot. As seen in Figure 5 the flux density in various parts is in line with assumed flux density respectively. The proximity between assumed flux density and actual flux density in respective section establishes the correctness of initial design of axial flux BLDC motor.

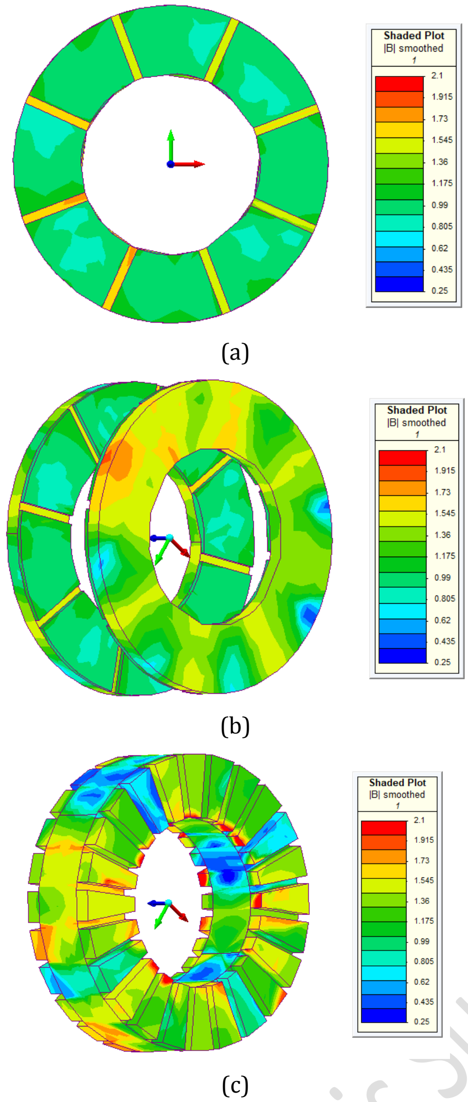


Figure 5. Flux density plot (a) initial rotor (b) initial dual rotor (c) initial motor.

3 Magnet Segmentation Technique

The inherent property of cogging torque results from the reluctance variation in the air gap caused by the stator's slotted structure and the permanent magnets present in permanent magnet motors. Equation 1 states that cogging torque is dependent on air-gap flux and air-gap reluctance variation. It is most visible at low speed, with the symptom of jerks & noise. At high speed the moment of inertia of motor filters out jerks and vibration due to cogging torque.

The following formula may be used to specify the cogging torque in detail:

$$T_{cog} = -\frac{1}{2}\varphi_g^2\frac{dR}{d\theta_m} \qquad (1)$$

where, φ_g = flux in air gap, R = reluctance in air gap and θ= Rotor angle. Reducing reluctance variation or air-gap flux will both lower cogging torque. The only alternative for reducing cogging torque is to decrease air-gap reluctance variation because reducing air-gap flux derates the motor and is therefore not preferred.

$$T_{cog}(\alpha) = \frac{L_{st}\pi\left(R_{st}^2 - R_{pm}^2\right)}{4\mu_0}\sum_{n=0}^{\infty} nLG_nB_n sin(nL\alpha) \qquad (2)$$

Equation 2 represents CT as Fourier series where α is the rotor angular position, μ_0 is air-gap permeability, L_{st} is stack length of stator core, R_{st} is radius of stator, and R_{pm} is radius of rotor PM. The Fourier coefficients of air-gap permeance function and air-gap flux density function are G_n and B_n respectively. L is the LCM of N_p and N_s where N_p number of poles and N_s number of stator slots. As per Equation 2 cogging torque is influenced by L, G_n and B_n. This paper investigates the cogging torque reduction with modifying coefficient B_n using magnet segmentation technique.

Magnets are in an identical relative position with regard to the slots hence the interactions between the magnets and the stator slots are additive. Figure 6 (a) shows the initially designed rotor without magnet segmentation.

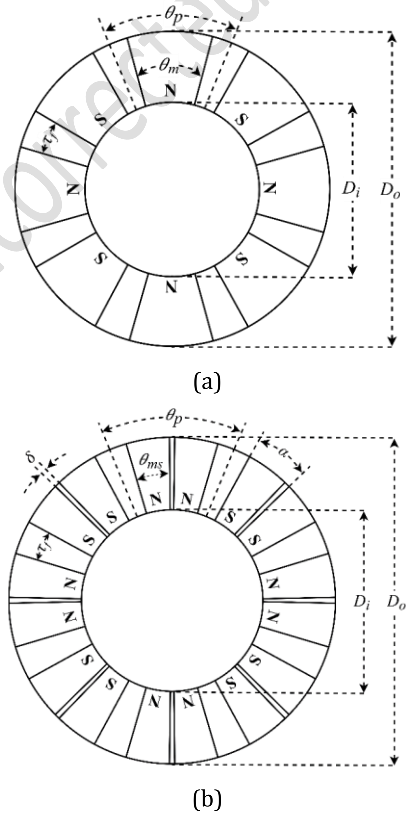


Figure 6. Rotor design (a) initial design (b) improved design with magnet segmentation.

The suggested strategy involves disabling this cumulative effect. In reality, a compensatory effect can be attained by dividing each magnet pole into a number of identical elementary magnet blocks that are routinely positioned on the rotor surface. In the scenario depicted in Figure 6 (b), each magnet pole is divided into two magnet blocks with angular gaps (δ) between adjacent blocks. The Fourier coefficient of magnetic flux density can be expresses by Equation (3) where, θ_{ms} is the span of segmented unit magnet block. Equation 3 suggests that θ_{ms} influence magnetic flux density function and subsequently cogging torque of axial flux BLDC motor. Following relations are applied as per Figure 6(b) of improved rotor design with magnet segmentation.

$$B_n \approx \frac{B_0^2}{\pi nL/p} sin(nL\, \theta_{ms}/2) \sum_{i=0}^{N-1} cos\left(niL\, \theta_{sp}\right) \qquad (3)$$

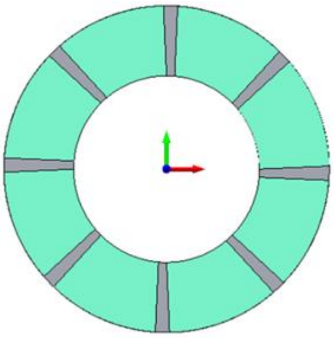
Segment pitch (θ_{sp}), segmented unit magnet block span (θ_{ms}), and displacement between magnet segments (δ) are interrelated as per Equation 5. Overall magnet span (θ_m) and segmented unit magnet block span (θ_{ms}) are interrelated as per Equation 5 where N stands for number of segmented magnet blocks.

$$\theta_{ms} = \theta_{sp} - \delta \qquad (4)$$

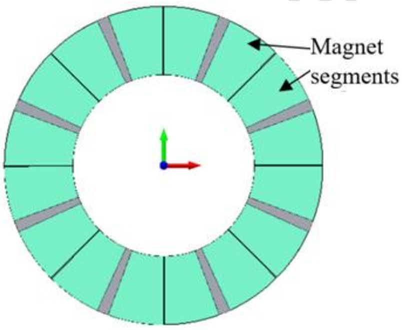
$$\theta_m = N\theta_{ms} + (N-1)\delta \qquad (5)$$

4 Simulation and Results

Initial rotor FE model with complete rotor poles known as non-segmented rotor poles is depicted in Figure 7 (a) and improved rotor FE model with segmented rotor poles is depicted in Figure 7(b). In improved rotor model each magnet pole is divided into two magnet segments with 0.5°angular gap between adjacent magnet blocks. It is important to note that the magnet thickness is kept same in initial as well as improved design. Except magnet segmentation all other design parameters are kept same as initial design.



(a)



(b)

Figure 7. Rotor model (a) Initial (b) improved with magnet segmentation.

Three dimensional (3-D) finite element analysis has been carried out to determine CT profile and average torque profile of improved axial flux BLDC motor with magnet segmentation. Cogging torque profile and average torque profile of improved motor are illustrated in Figure 8 and Figure9 correspondingly. It is analysed that magnet segmentation effectively weaken the cogging torque.

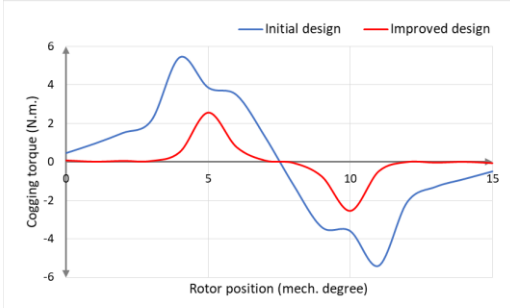


Figure 8. Comparison of CT profile.

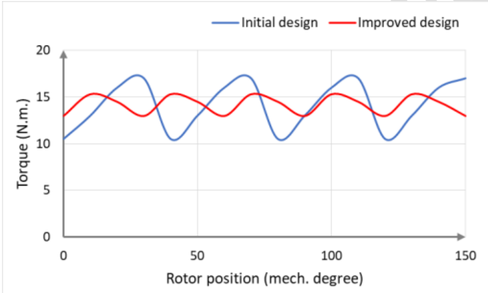


Figure 9. Comparison of useful torque profile.

Table II compares the performance of the original motor design with the modified motor. Peak CT is shown to be decreased from 5.43 N.m. to 2.56 N.m., while average torque is seen to be slightly decreased from 15.06 N.m. to 14.18 N.m. As can be observed, the cogging torque has effectively been reduced, resulting in a marginally lower average output torque value and a significantly lower torque ripple.

Table 2. Performance Comparison

Sr. No	Parameters	Unit	Initial motor	Improved motor with magnet segmentation
1	Cogging Torque (peak)	N.m.	5.43	2.56
2	Average Torque	N.m.	15.06	14.18
3	Torque Ripple	---	43.16 %	16.22 %
4	Efficiency	---	88.15 %	87.78 %

Back emf waveforms of initial design and improved design at no-load determined from FEA may be visualized in Figure 10. This illustration represents the scenario where the back emf waveform of segmented pole design is slightly improved.

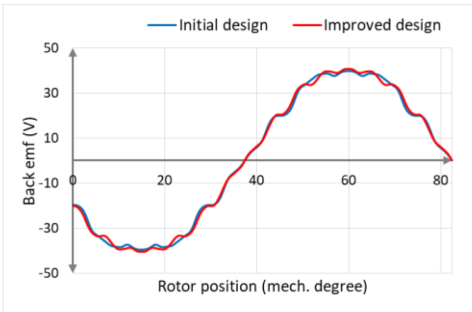


Figure 10. Back emf profile comparison.

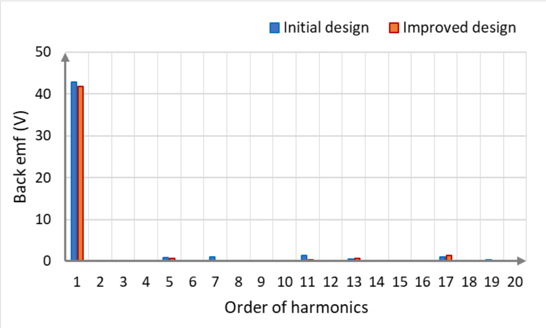
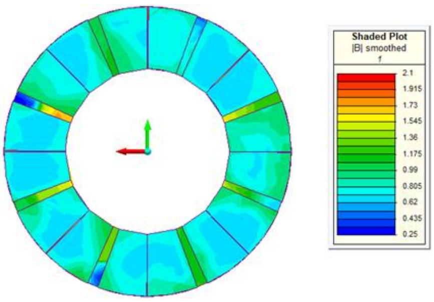
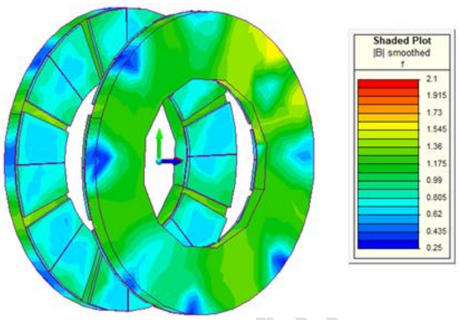


Figure 11. Back emf harmonic analysis.

Back emf waveforms of initial design and improved design are compared and harmonic analysis is illustrated in Figure11. It is observed that the fundamental amplitude is slightly reduced in improved design. The amount of the lower harmonics of the back emf waveform are decreased by segmentation of magnets. Flux density plots of improved motor can be seen in Figure12. Real flux density is found to be close to respective assumed flux density in various motor sections.



(a)



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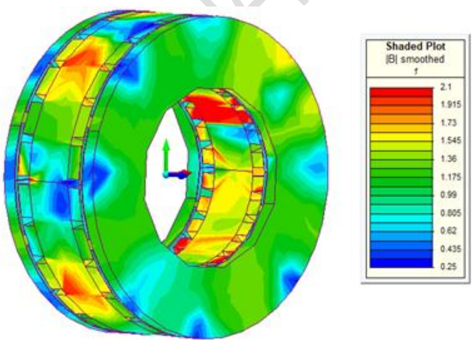

(c)

Figure 12. Flux density plot (a) segmented rotor (b) segmented dual rotor (b) improved motor.

5 Conclusion

Cogging torque is detrimental hence its reduction is highly desirable for overall performance improvement of axial flux PMBL motors for electric vehicle application. The CT can be significantly reduced by segmenting the PM poles. AF-PMBL motor for electric vehicle application is initially designed without magnet segmentation and 3-D simulation & analysis has been carried out. Improved axial flux PMBL motor is designed with magnet segmented into two blocks and its performance is compared with initially designed reference motor. Peak cogging torque is lowered by 52.85 %, while average torque is marginally reduced by 5.84 %. It has been observed that the magnet segmentation approach works well for CT AF-BLDC motors. The suggested method may also be used with other permanent magnet motor topologies.

6 Author contribution statement

Within the scope of this study, Author contributed to the design of axial flux PMBL motor, formation of the idea for cogging torque reduction, literature review, simulation exercise, results comparison, and writing of the article.

7 Ethics committee approval and conflict of interest statement

“There is no need to obtain permission from the ethics committee for the article prepared”

"There is no conflict of interest with any person / institution in the article prepared"

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