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An Improved Model for the Back-EMF and Cogging Torque Characteristics of a Novel Axial Flux Permanent Magnet Synchronous Machine With a Segmental Laminated Stator

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An improved model for the back-electromagnetic-force (back-EMF) and cogging torque characteristics of a novel axial flux permanent magnet (AFPM) synchronous machine with a segmental laminated stator is presented. Based on a 3-D finite-element analysis (FEA) modeling approach that takes into the anisotropic properties of the machine's laminated cores, the proposed model provides superior performance prediction to existing isotropic models, in which lamination effects are not considered. An anisotropic model has been developed to predict the back-EMF and cogging torque of an existing prototype AFPM machine with optimized rotor magnets. Experimental results of the AFPM machine are compared against the results from the FEA models based on anisotropic and isotropic modeling, respectively. The results show that anisotropic modeling provides more accurate performance prediction of the AFPM machine with laminated cores.

Index Terms—**Anisotropic modeling, axial flux permanent magnet(AFPM) machines, isotropic modeling, segmental laminated stator.**

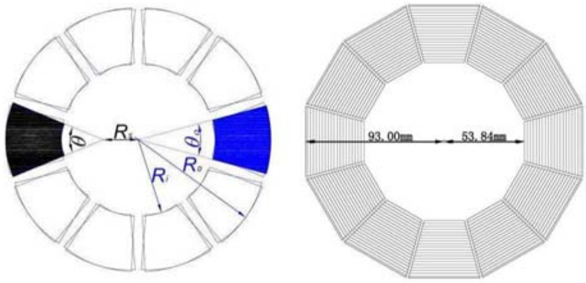
I. Introduction

AXIAL FLUX PERMANENT MAGNET (AFPM) machines, which have unique characteristics such as high aspect ratio, high torque density, and excellent efficiency, are becoming more popular in electric traction applications, particularly, as in-wheel direct-drive motors. One key reason for the increased popularity is the emergence of soft magnetic composite (SMC), which allows arbitrary flux distribution of moderate level to be developed within the magnetic cores of the machine, as an alternative to axially laminated steel cores. The isotropic characteristic of the SMC is of particular interest to the AFPM machine since, unlike its radial flux counterparts, the flux distribution tends to be more arbitrary due to more pronounced end effects. An SMC-based AFPM machine with a yokeless and segmented stator armature, is proposed as a high-efficiency in-wheel electric drive for electric vehicle propulsion [1], [2]. The machine benefits from simple fabrication of the SMC-cores compared with axially laminated steel cores, which normally cannot be easily made by stampings. However, the machine has lower air gap flux due to low permeability of SMC, and is generally more suitable for medium- and high-speed applications. Moreover, the material cost of SMC is much higher than conventional laminated steel. Recently, an AFPM machine with a novel segmental laminated steel stator has been proposed for low-speed in-wheel direct drive applications for lightweight electric vehicles [3]. The machine has higher flux, stronger mechanical structure, and less core losses than an SMC machine. In addition, as the machine's axial lamination can be made readily by stampings due to a novel stator topology, material and production costs would be significantly lower than that of a SMC machine. Thus, the machine possesses highly desirable features that are essential for rapid adoption of the technology in the in-wheel direct drive electric vehicle market. However, due to the omission of lamination effects of the existing modeling methods for AFPM machines with a laminated stator, a more accurate means of modeling the machine's performance is important, so that potential users of the machine can evaluate its benefits with confidence.

This paper focuses on an improved model for the AFPM machine with a segmental laminated stator previously studied comprehensively with both analytical and FEM models [3]. In general, the isotropic characteristic of the stator core is assumed in these models. For radial flux machines, magnetic flux distribution does not generally vary along the axis of rotation. Thus, it suffices to use a 2-D finite-element analysis (FEA) approach where the machine's magnetic core can be assumed to be isotropic. Thus, lamination effects can be ignored without affecting the prediction of flux distributions in these machines. For axial flux machines, however, the magnetic flux distribution generally varies along the axis of rotation. It is, therefore, always necessary to use 3-D FEA models. The effects of lamination on flux distribution will be more profound than in radial flux machines. Thus, a 3-D FEA model that accounts for the anisotropic property of the laminated stator is desirable. To date, there appears no research work on anisotropic modeling of the effects of lamination in axial flux machines in general, and in AFPM machines with a segmental laminated stator in particular.

In this paper, two 3-D FEA models of the AFPM machines are formed. One is based on isotropic modeling that does not take lamination into consideration, and the other is based on anisotropic modeling that accounts for lamination effects. Optimization of the rotor's magnet shape is performed to minimize machine's torque pulsations. Back-electromagnetic-force (back-EMF) and cogging torque analyses are then undertaken using the two 3-D FEA models. The simulation results from the models are validated against the experimental results of an existing prototype AFPM machine with a laminated stator [3]. The results confirm the validity of the anisotropic model, and as a more accurate tool in predicting the machine performance than the isotropic model, by accounting for the lamination effects.

Fig. 1. Exploded view of the AFPM segmental laminated machine.



(a) (b)

Fig. 2. Simplified 2-D diagrams of machine's rotor and stator. (a) Rotor magnet optimization. (b) Stator lamination arrangement.

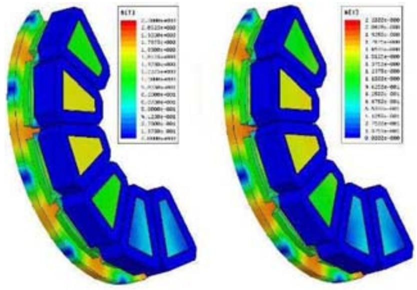
TABLE I
KEY DESIGN PARAMETERS OF THE PROPOSED MACHINE

Parameters	Values	Parameters	Values
Stator poles	12	Winding thickness	8.7mm
Magnet poles	10	Magnet axial length	5.0mm
Magnet outer radius	95.0mm	Air gap length	1.5mm
Magnet inner radius	55.0mm	Rated rotational speed	1200 rpm
Stator innermost layer	53.8mm	Rated torque	50 Nm
Stator outermost layer	93.0mm	Magnet span angle	30 degree
Winding axial length	39.0mm	Stator pole span angle	25.7degree

II. MACHINE AND FE MODELS

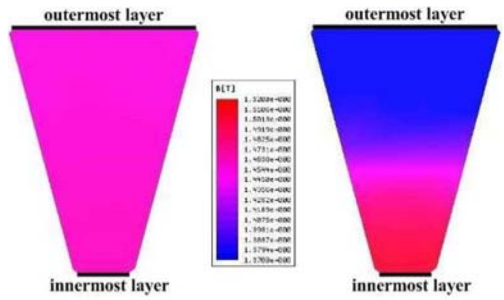
A. Proposed Machine

The AFPM machine under study is depicted in an exploded view in Fig. 1, which has a rotor–stator–rotor configuration, and comprises novel stator poles made of linearly proportionally sized laminated steel sheets stacked together to form a rigid laminated core. The simplified 2-D diagrams of the rotor magnets and stator lamination arrangements are shown in Fig. 2, and the key design parameters of the proposed machine are given in Table I. Each stator pole has concentrated windings and is individually joined by means of two high strength aluminum alloy ring holders, forming a yokeless magnetic core with maximum utilization of magnetic material. This structure thus possesses a number of merits typical of a yokeless segmental stator configuration [1], [2]: 1) shortened end windings leading to higher torque density and efficiency, 2) ease of winding process and high winding fill factor, 3) reduced mutual inductance between the machine phases resulting in good phase independency and fault tolerance, and 4) reduced stator core weight and stator core losses due to the absence of the stator yoke.



(a) (b)

Fig. 3. Open-circuit flux density distributions at *d*-axis rotor position. (a) Isotropic model. (b) Anisotropic model.



(a) (b)

Fig. 4. Enhanced shading of the flux density distributions in the middle cross section of a stator pole. (a) Isotropic model. (b) Anisotropic model.

B. 3-D FE Models

The analytical and 3-D FEA models based on an isotropic stator have been developed and validated by previous studies [3], [4]. Here, in addition to a 3-D FEA model based on an isotropic stator, another 3-D FEA model based on an anisotropic stator is developed to account for the lamination effects. It employs six local coordinates to implement the anisotropic property of the stator pole. By exploiting the periodicity and symmetry of the machine's structure and boundary conditions, only one fourth of the machine is modeled for computational efficiency. The open-circuit flux density distributions at the *d*-axis rotor position by the two models are shown in Fig. 3. Close examination shows that the flux distributions differ appreciably in the two models, as illustrated in Fig. 4, which uses enhanced shading to highlight the difference of flux distributions within a stator pole. In Fig. 4(a), the isotropic model clearly shows that the flux density is uniformly distributed at about 1.45 T in the whole cross section of the pole, where lamination effects are ignored. However, in Fig. 4(b), the anisotropic model shows variations of flux density with the consideration of lamination effects. The flux density decreases steadily from the highest level of ≈1.52 T in the innermost lamination layer (at position 53.8 mm from the center), to the lowest level of ≈1.37 T in the outermost lamination layer (position 93.0 mm), which represents a variation of over 10%. The results in Fig. 4 clearly show that the anisotropic model gives a more realistic prediction of the actual flux distribution in the laminated cores than the isotropic model. The anisotropic model is used to provide further optimization study for the machine's back-EMF and torque ripples.

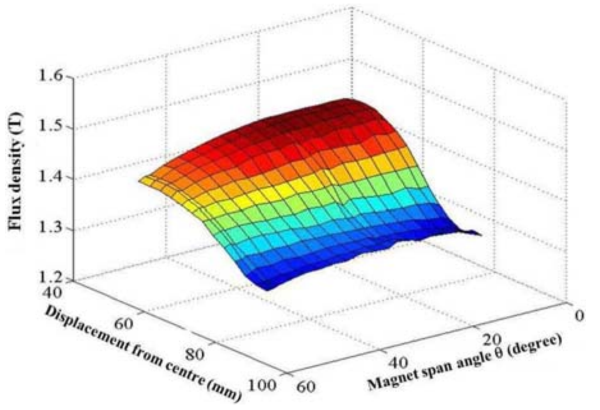


Fig. 5. Variation of flux density of stator pole (in the middle cross section) at different positions and magnet span angles.

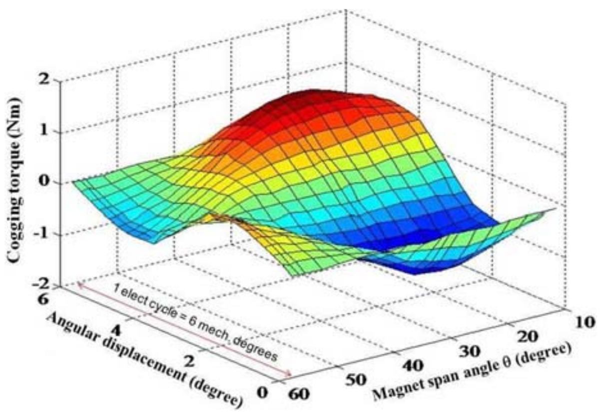


Fig. 6. Variation of cogging torque over a cycle (6 mechanical degrees) with different magnet span angles.

III. Magnet Shape Optimization

For in-wheel direct-drive electric vehicle applications, it is important to minimize torque ripples generated by the machine as there is no reduction gear to minimize and absorb the adverse effects. One main source of torque ripples is the load-independent cogging torque which is inherent with the machine's magnetic structure. Several simple yet effective cogging torque reduction techniques have been proposed for the AFPM machine with segmental stators [4]. Here, a rotor magnet shape optimization technique is employed to suppress both the belt harmonics in the back-EMF and cogging torque. To avoid extra manufacture complexity of the prototype without compromising the validity of the study, the machines with the same stator but differently shaped and positioned rotor magnets are investigated. Also, the volume of permanent magnets is maintained constant. Fig. 2(a) shows some details of the rotor magnet optimization. In the existing design, the original magnet shape and arrangement is defined by θ_o, with a value of 30°. The proposed annulus sectors of the magnet are defined by θ and R_s as shown. The correlations of the annulus parameters and the inner and outer radii R_i and R_o of the magnets can be obtained as

$$\frac{\theta}{\theta_o} = \frac{R_o + R_i}{R_o + R_i - 2R_s}. \quad (1)$$

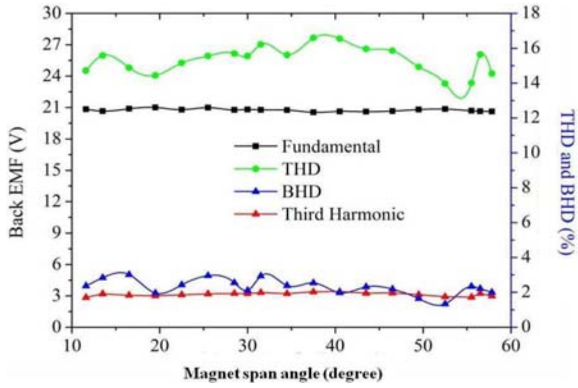


Fig. 7. Phase back-EMF characteristics for different magnet span angles.

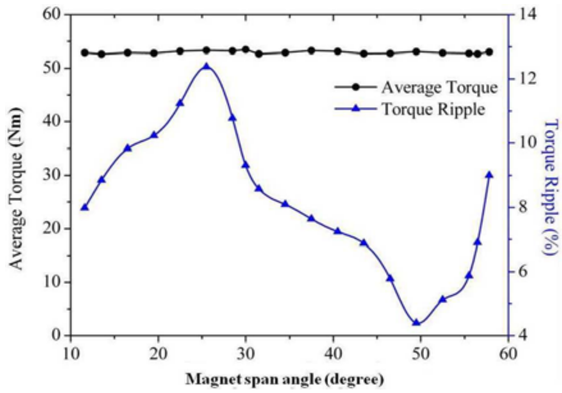


Fig. 8. Torque characteristics for different magnet span angles.

The flux densities in the middle cross section of stator pole at full alignment with the rotor magnet pole are evaluated by the 3-D magnetostatic model for different magnet shapes and positions, which is from innermost layer (53.8 mm) to outermost layer (93.0 mm) as shown in Fig. 2(b). Fig. 5 shows the predicted flux density variations. It can be seen that the flux density is generally higher at inner side than at outer side, similar to those in Fig. 4(b). The difference between inner and outer side flux densities gets smaller with increasing magnet angle θ. The variations of the cogging torque with different rotor magnets are predicted by the 3-D magnetostatic FEA model at different rotor positions, as shown in Fig. 6. The results show that magnet shape has a high impact on the cogging torque. The cogging torque can be greatly suppressed by selecting magnet angle θ close to 46°.

The phase back-EMF characteristics are evaluated by the 3-D magneto–transient FEA and shown in Fig. 7. The fundamental is almost unchanged because the same amount of magnet is used. The total harmonics distortions (THDs) in the back-EMF are relatively large due to high third harmonic components, which nonetheless will be eradicated internally in three phase machines. The belt harmonics distortion (BHD) is fairly small. The optimal machine back-EMF with the smallest BHD can be found when the magnet angle is near 52°. Due to limitation of the FE tools, simulation errors might incur, especially in the back-EMF harmonics. In Fig. 7, the correlations between the BHD/THD and magnet angle θ are not as distinct as those between the cogging torque and magnet angle θ. The 3-D magnetostatic FEA is resorted to evaluate the machine torque ripples at rated loads, as shown in Fig. 8. It can be seen that the

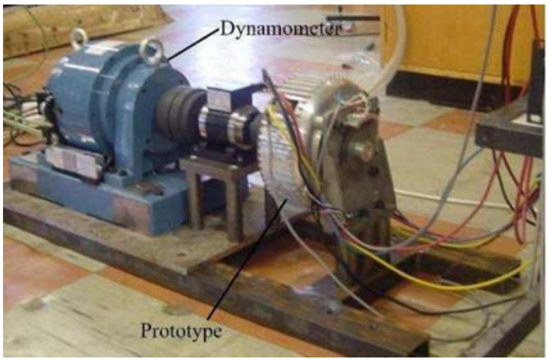


Fig. 9. Prototype AFPM machine and experimental setup.

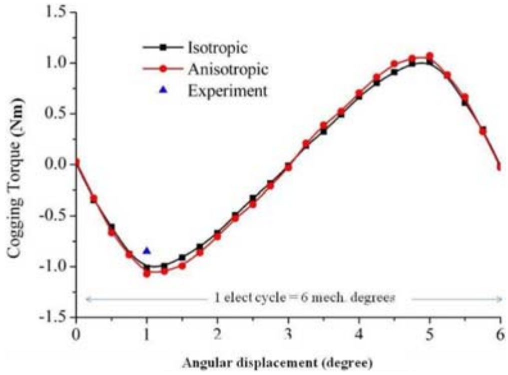


Fig. 10. Cogging torque of the prototype machine over one cycle.

average torque outputs remain at around 1% due to unchanged fundamental back-EMF. Torque ripples, however, vary from nearly 4% to more than 12%. Although 50° is not the optimal angle for cogging torque or back-EMF, it gives optimal overall torque ripple of 4.2%, which is lower than 9.3% found in the original magnet of 30°.

IV. Experimental Validation

Fig. 9 shows the prototype machine with original magnet shape under test, with a 5-kW dynamometer as the load. In the cogging torque test, due to mechanical tolerance in the experimental setup, only the peak cogging torque has been measured, as smaller measurements would incur excessive experimental errors. Fig. 10 shows the comparisons of the experimental cogging torque against the predicted cogging torques from the isotropic and anisotropic models, which are in close agreements. However, due to scarcity of experimental measurements, it can only be concluded that the cogging torques from both models yield similar results, and are in agreement with the measured one at the peak value. For the back-EMF analysis, the predicted back-EMFs at rated rotational speed by both models are compared against the experimental ones in both spatial and frequency domains, as shown in Figs. 11 and 12, respectively. It can be seen that the anisotropic model gives close agreements with the tested results with less than 1% discrepancy, whereas the isotropic model shows a larger discrepancy of about 6%, which represents an improvement in accuracy by 5%.

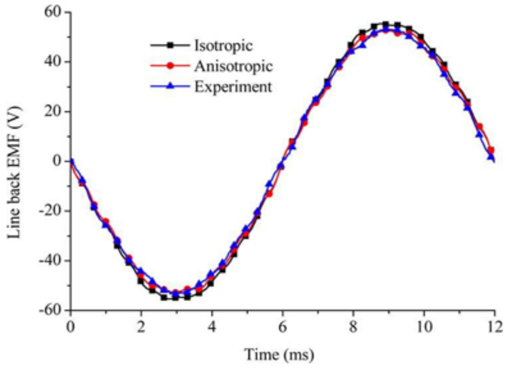


Fig. 11. Line back-EMF against time measured at rated speed of 1200 r/min.

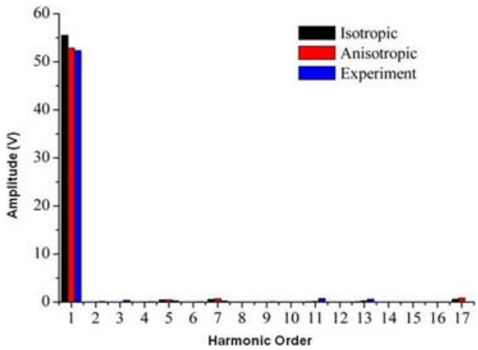


Fig. 12. Amplitude of the harmonics of line back-EMF at rated speed.

V. Conclusion

An improved model for the AFPM machine with a segmental laminated stator based on the anisotropic property of the stator core is proposed. The model gives a more realistic prediction of flux distribution by considering the lamination effects. Experimental results of the machine's back-EMF confirm that the anisotropic model is more accurate in predicting machine performance than the isotropic model, with an improvement of 5% in the study. However, the results of the machine's cogging torque are less conclusive, mainly due to the scarcity of accurate measurements obtainable. Although the study is concerned with only a specific AFPM machine, it shows that other axial flux machines with laminated stators can also benefit from adopting an anisotropic model for more accurate performance prediction.

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