Rotor Configuration for Cogging Torque Minimization of the Open-Slot Structured Axial Flux Permanent Magnet Synchronous Motors

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Abstract **─** In this study, the rotor structure of the double rotor – single stator axial flux permanent magnet synchronous motor (AFPM) is optimized for minimizing the cogging torque without significantly changing the average torque of the motor. Three-dimensional (3-D) finite element analysis (FEA) is used for this optimization. Obtained results are compared with a base line reference axial flux synchronous motor.

Index Terms **─** AFPM motor, FEA, structural analysis, surface permanent magnet motor.

I. INTRODUCTION

After utilization of high energy density magnets, the AFPMs have been widely used in different industrial applications due to their advantages such as their high efficiency, simple structure, high power and torque densities, and low rotor losses [1]-[4]. AFPM machines can be single- or double-sided, with or without armature slots/core, have internal/external PM rotors, contain a surface-mounted or interior PM, and are single- or multi-stage [5].

AFPM machines have an inherent 3D electromagnetic structure. Indeed, most of authors use 3D finite element analysis (3D FEA) for its study [6-8].

Most of these applications require torque ripple minimization for ensuring the smooth operation of the motors [9]. While torque ripples can be filtered by the system inertia at high speed operations, torque ripples can cause undesired speed variations, vibrations, and acoustic noise at low speed operations [10]. One of the two fundamental reasons of the torque ripples is the harmonic distortions in the voltage and current waveforms and the latter is the cogging torque generated due to the magnetic interactions between the rotor magnets and the stator teeth [11]-[12].

The cogging torque of these motors is known to influence significantly the behavior of this type of machine. In general, techniques of minimizing cogging torque to improve torque quality can be classified into two major categories. The first one includes the technique for modifying motor design so that the pulsating torque component is minimized. Cogging torque can also be significantly reduced by optimal selection of slot and pole combinations [13] and stator tooth width and rotor magnet spacing [13], [14], [15]-[18]. Less common yet ingenious measures, such as stator teeth pairing [18], stator slot pairing [19], teeth notching [13], [17], [20], [21], magnet pairing [13], magnet segmentation [22], and magnet shifting [13], [23], have also been proposed [24].

The second way is based upon control schemes for modifying the stator excitation waveform to obtain smooth torque. There are various techniques for reducing the cogging torque in permanent magnet (PM) machines such as shoe of stator teeth, fractional pitch, change of PM magnetization shape and skewing. Previous research work has been made in order to reduce the cogging torque in PM synchronous machine and it was demonstrated that it is greatly affected by the configuration of the stator, and magnetization distribution. Cogging torque can be calculated accurately using the FEM [25], [26], [27].

In this study, to determine the rotor structure that minimizes the cogging torque in double rotor – single stator AFPM, the cogging torque variations are observed by relatively rotating one rotor with respect to the other rotor at various values of the

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magnet pole-arc and for different magnet structures. Furthermore, the effects of the applied techniques on the average torque are investigated. The 3-D finite element analysis method is used for this purpose. 3D FEA analysis was performed with Maxwell 3D. Obtained results are compared with a base line reference axial flux synchronous motor and experimental data.

II. COGGING TORQUE IN AXIAL GAP PM MOTORS

Cogging torque of a full-pole stepping becomes equal to zero when the thread centre and interpolar axes are in the same line, and/or centre of the grooves and interpolar axes are in the same line. However, magnet always tends to be located around the location, where maximum energy is stored. This position comes to a stable balance position when leakage flux path between poles is minimum, and corresponds to unstable balance position when leakage flux paths contain groove apertures. Positive and negative end points of knocking torque in the form of waves, approximately correspond to the position, in which interpolar axes and edges of the grooves are in the same line [17].

In axial flux synchronous motors, rotor discs are made of massive iron. On the surface of the rotor, magnets are glued with a special adhesive material or they are bolted as demonstrated in Fig. 1.

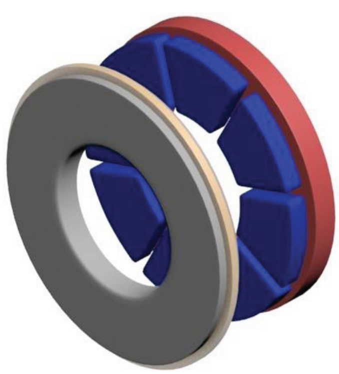


Fig. 1. Rotor with surface mounted magnet and stator.

The stator of the machine is formed by spirally winded laminated iron plaques. Different rotor and stator structures are presented in Fig. 2. Due to the ease of manufacturing and low cost and to provide the highest level of cogging torque minimization, the stator sluts in our study is designed to be totally open and they are winded in laminated structure. The rotor and stator structures are represented in more details for the configurations given in Fig. 2.

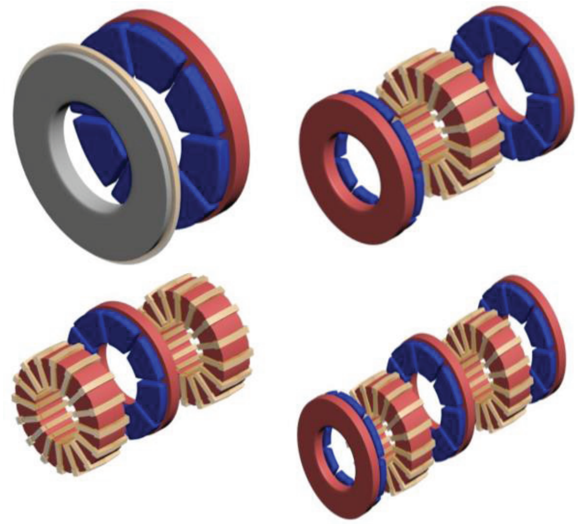


Fig. 2. Axial flux motors in various structures.

In permanent magnet motors, the cogging torque is generated due to the interactions between the magnets mounted within the rotor or rotor surface and the stator slots. Cogging torque has a negative effect on the average output torque and it is generated due to the movement of the rotor magnets because of the change in magnetic field [28].

If the amount of energy stored in the airgap is known, the cogging torque can be computed easily. If the electromagnetic system includes only the linear soft magnetic materials and linear permanent magnets, the system energy is simply the energy obtained from the magnets.

$$T_{cog}(\theta) = -\frac{dW}{d\theta}, \quad (1)$$

here, θ is the mechanical rotor angle.

In Fig. 3, the curve that connects the permanent magnet motor's operating point and the origin is known as the load curve. Load curve is defined by the airgap reluctance. In SM machines with salient or slotted stator structures, the operating point of the magnet changes as the rotor rotates. For each rotor position, the operating point of the permanent magnet is defined and the total energy stored in the system is obtained. Thereby, the cogging torque is computed, too.

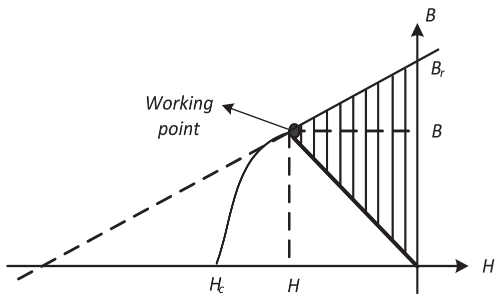


Fig. 3. B-H diagram and the energy density curve [29].

In this study, the cogging torque analysis is performed through the finite element method at the electromagnetic design process. The important advantage of the finite element analysis method is that its ability to calculate the torque ripples and cogging torque as the rotor position changes. In Fig. 4, one example of the mesh structures obtained with the 3-D FEA model is presented that is obtained by rotating one rotor relative to the other one. These analyses are completed with a computer with 3.16 GHz Intel Core 2 Quad processor and 3.49 GB of RAM. The number of total elements is 234745 and the total CPU processing time is 22 minutes.

In Fig. 5, the flux density of the AFPM motor's stator and no-load rotor is shown.

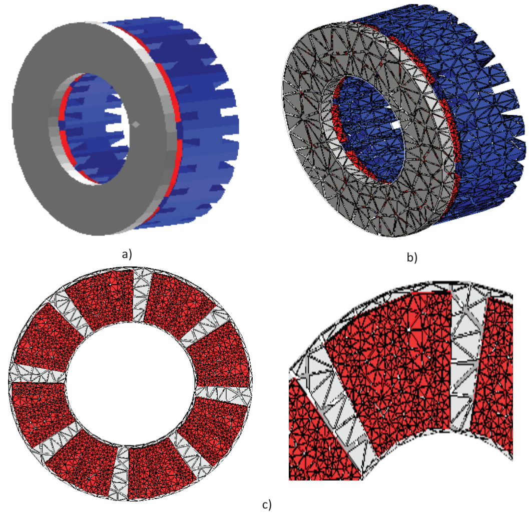


Fig. 4. AFPM motor's: (a) FEA model, (b) 3-D element structure, and (c) magnet element structure.

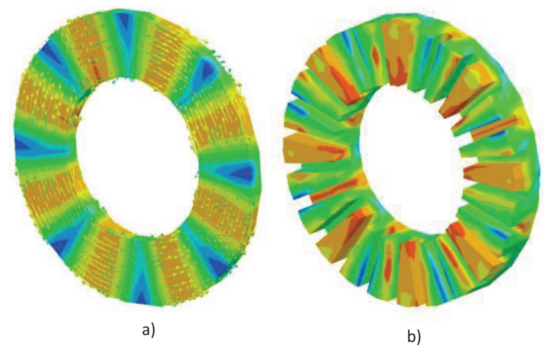


Fig. 5. Stator and no-load condition rotor flux density variations of the AFPM motor.

III. PROPOSED TORUS NN-TYPE AXIAL FLUX PERMANENT MAGNET SYNCHRONOUS MOTOR STRUCTURE

In the analyses of this study, the permanent magnet motor of which the details are given in reference [30], is used as a base line. The reference motor is an axial flux motor with 24 slots, 8 poles, it has 2 rotors and 1 stator, its stator is siliceous laminated, and its rotor is a disc with surface mounted fan type magnets with 140° degrees of magnet pole-arc. No cogging torque reduction techniques are applied for this motor design. However for this study, differently from reference [30], an open stator slot structure is proposed. When the slot openings increased, the cogging torque increases about 2.5 times as compared to the previous structure as shown in Fig. 6. The reference motor parameters used in this study are given in Table 1.

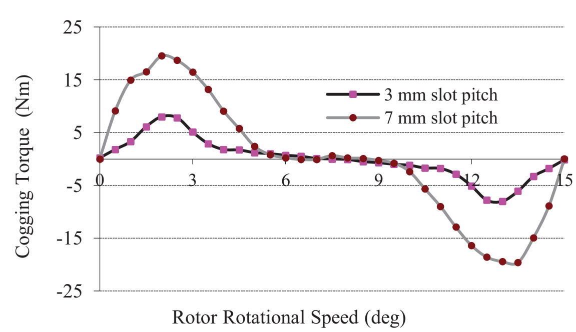


Fig. 6. Cogging moment variations with respect to the slot openness.

Table 1: AFPM reference motor parameters

Parameter	Value
Stator outer radius	89 mm
Stator inner radius	50 mm
Magnet thickness	7.2 mm
Stator axial length	22 mm
Slot/pole/phase	1
Airgap	0.8 mm
Phase number	3
Slot number	24
Slot pitch	7 mm

IV. COGGING TORQUE REDUCTION TECHNIQUES FOR AXIAL FLUX PERMANENT MAGNET MOTORS AND 3-D FINITE ELEMENT ANALYSIS STUDIES

In this study, first, the various values of the magnet pole-arc is investigated for the fan type magnets. Then, according to the best results among these magnet pole-arc (126° degrees), triangle and oval shifting techniques are applied while keeping the magnet surface the same.

Similar to the fan type magnets, the different values of the magnet pole-arc are studied for triangle and oval type magnets.

A. Varying the magnet pole-arc

One of the most common methods in cogging torque reduction of AFPM motors is changing the magnet pole-arc to an appropriate value. As known, cogging torque occurs due to the interactions between the magnet pole edges and the stator slots. Therefore, both the cogging torque waveform and its magnitude depend on the magnet pole-arc. Magnet leakage flux can be reduced by reducing the magnet pole-arc angle. However, reducing magnet flux reduces the average torque as well. Therefore, and appropriate magnet pole-arc angle should not cause a significant reduction in average torque while reducing the cogging torque.

In this study first of all, models are built in order to determine the most suitable structure of the conventional fan type magnets for reducing the cogging torque. Based on the obtained results, as can be seen in Table 2, 92.51% reduction is achieved in the fan type magnet structure with 126° degrees magnet pole-arc as compared to the 140° degrees magnet pole-arc. At this angle value, the cogging torque is measured as 1.426 Nm in the fan type magnet motor. In Fig. 7, the cogging torque magnitudes are graphically presented for the fan type magnet structures.

Table 2: Comparison of cogging torque values of fan type magnet structures with the reference motor

Magnet Pole-arc (deg)	Peak Cogging Torque [Nm]	Comparisons with the Reference Motor
100	24.802	27.06% rise
120	12.62	35.34% decrease
122	8,18	58,88% decrease
125	2,976	84,75% decrease
125.5	2,28	88,31% decrease
126	1,462	92,51% decrease
126.5	2,26	88,4% decrease
128	5.28	73.94% decrease
130	9.044	53.66% decrease
140	19.518	Reference motor

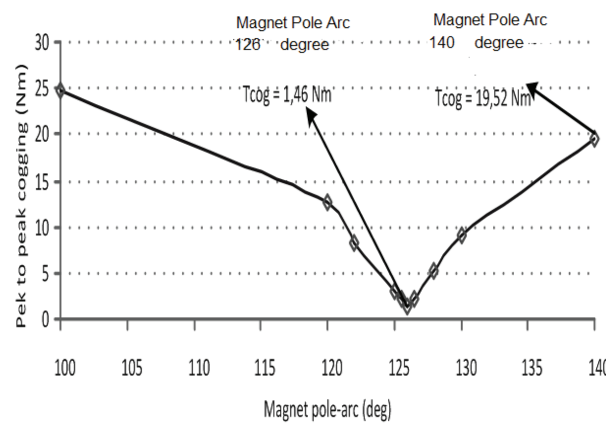


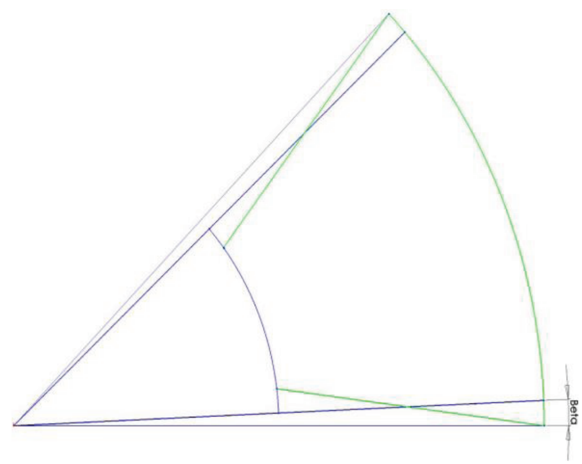
Fig. 7. Cogging torque peak values for the fan type magnet structures.

After obtaining the optimum structure for the fan type magnets, triangle and oval shaped magnet models are also studied while keeping the same magnet surface area.

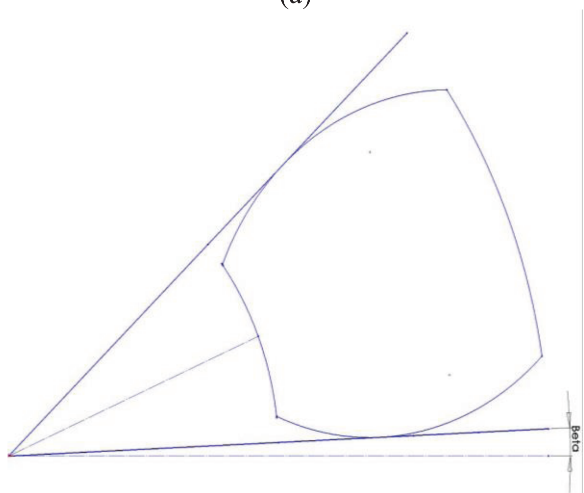
All the triangle and oval skewed structures have the same magnet surface area with the fan type magnet structure with 126° degrees of magnet pole-arc. In other words, the magnet pole-arc angles are all defined for the same magnet surface areas for the triangle and oval skewed structures such that, $A_{126fan}=A_{triangle\_skew}=A_{oval\_skew}$.

The example drawings are illustrated in Fig. 8

that are used for determining the triangle and oval skew angles.



(a)



(b)

Fig. 8. Definition of the skew angle: (a) oval skew, and (b) triangle skew.

The cogging torque values obtained for these structures are given in Tables 3 and 4. According to the obtained results, the triangle type magnet model with 162° degrees magnet pole-arc has the maximum cogging torque reduction of 85.3% among the other triangle type models. At this magnet pole-arc angle of the triangle skewed type magnet motor, the cogging toque is obtained as 2.868 Nm. In Fig. 9, the cogging torque peak values are graphically represented for the triangle skew magnet structures.

Table 3: Comparison of cogging torque values of the triangle skew magnet structures with the reference motor

Magnet Pole-arc (deg)	Peak Cogging Torque [Nm]	Comparisons with the Reference Motor
152	3.622	81.44% decrease
156	3.056	84.34% decrease
160	2.934	84.96% decrease
162	2.868	85.3% decrease
164	3.104	84.09% decrease
168	3.32	82.99% decrease
170	3.514	81.99% decrease
172	3.964	79.69% decrease
176	4.576	76.55% decrease
180	5.206	73.32% decrease

Table 4: Comparison of cogging torque values of the oval type magnet structure with the reference motor

Magnet Pole-arc (deg)	Peak Cogging Torque [Nm]	Comparisons with the Reference Motor
130	8.538	81.44% decrease
135	3.1	84.34% decrease
137	2.044	84.96% decrease
138	2.736	85.3% decrease
139	2.738	84.09% decrease
141	3.926	82.99% decrease
154	7.628	81.99% decrease
140	19.518	Reference motor

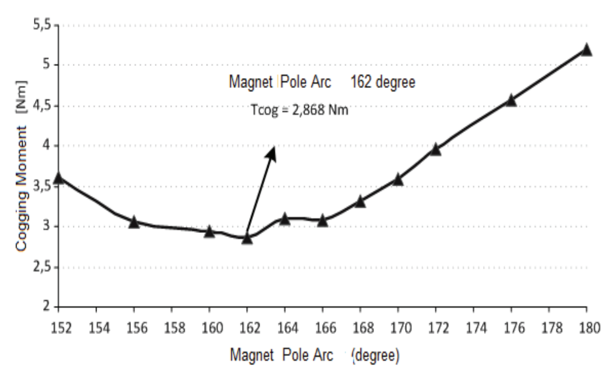


Fig. 9. Cogging torque peak values for the triangle skew magnet structures.

In Fig. 10, cogging torque peak values are graphically represented for the oval skew magnet structures.

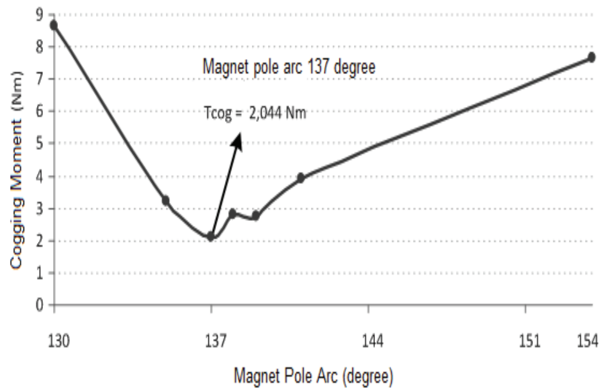


Fig. 10. Cogging torque peak values for the oval skew magnet structures.

According to the obtained results, the oval type magnet model with 137° degrees magnet pole-arc has the maximum cogging torque reduction of 89.527% among the other oval type models. At this magnet pole-arc angle of the oval skewed type magnet motor, the cogging toque is obtained as 2.044 Nm.

According to the analyses performed so far, the rotor with fan type magnets with 126° degrees of magnet pole-arc, the rotor with triangle skew type magnets with 162° degrees of magnet pole-arc, and the rotor with oval type skew magnets with 137° degrees of magnet pole-arc have resulted in the optimal designs among their categories. For all three types of magnet structures, the fan type magnet structure with 126° degrees of magnet pole-arc achieved the minimal cogging torque value.

B. Rotating one rotor relatively to the other one

In AFPM motors with two airgaps, the total cogging torque equals to the vector sum of the cogging torque at each airgaps. Therefore, if one of the rotors is rotated relatively to the other one, the vector summation of the cogging torques, hence the total cogging torque can be reduced. With this respect, this technique is applied on the fan, triangle skewed, and the oval skewed magnet structures and the graphs shown in Figs. 11 to 13 are obtained. According to these results, the triangle skew magnet structure with 156° degrees of magnet pole-arc angle achieves the best results in terms of cogging torque reduction when one of the rotors is rotated with 4° degrees with respect to the other rotor. In this case, the peak value of the cogging torque is reduced to 0.475 Nm. When compared to the reference motor, this means 97.56% reduction in cogging torque.

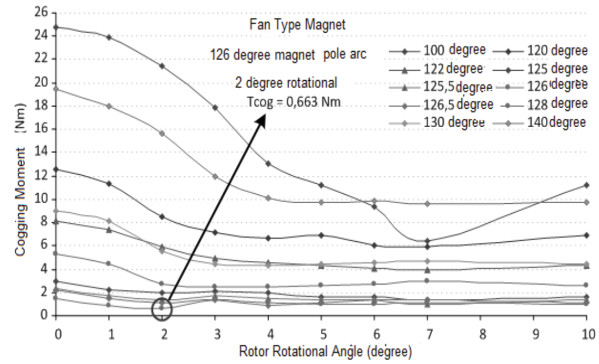


Fig. 11. Rotor rotation technique results for the fan type magnet structures.

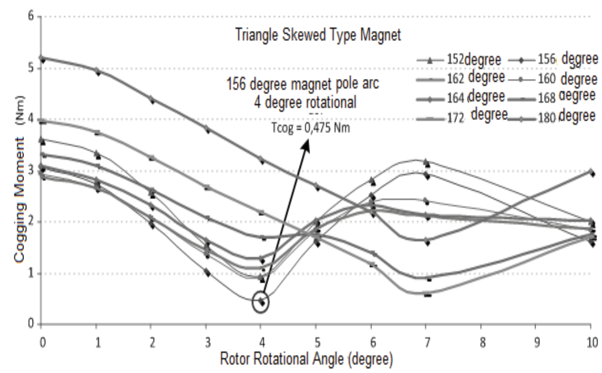


Fig. 12. Rotor rotation technique results for the triangle skewed type magnet structures.

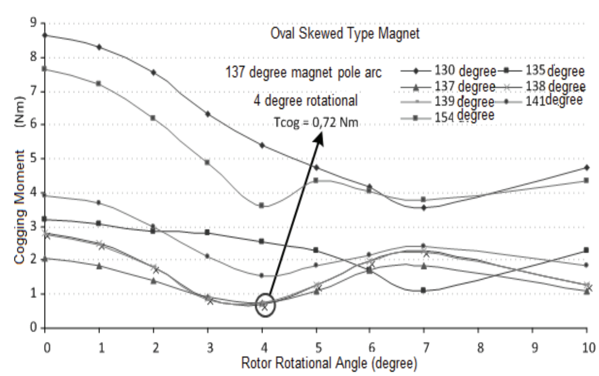


Fig. 13. Rotor rotation technique results for the oval skewed type magnet structures.

According to the analyses performed with the rotor rotation technique, when one rotor is rotated 2° degrees with respect to the other one, 0.663 Nm value is obtained for the fan type magnet structure with 126° degrees of magnet pole-arc angle. Similarly, when one rotor is rotated 4° degrees with respect to the other one, 0.475 Nm value is obtained for the triangle skewed type magnet structure with 156° degrees of magnet pole-arc angle. Consequently, when one rotor is rotated 4° degrees with respect to the other one, 0.72 Nm value is obtained for the oval skewed type magnet structure with 137° degrees of magnet pole-arc angle. The techniques that achieved best results for different motor structures are altogether presented in Table 5.

Table 5: Best results achieved with the applied techniques

Applied Technique	T_{cog} Peak Value [Nm]	Comparisons with the Reference
Fan type magnet structure with 126° degrees of magnet pole-arc angle	1.462	92.51% reduction
Triangle type skewed magnet structure with 162° degrees of magnet pole-arc angle	2.868	85.3% reduction
Oval type skewed magnet structure with 137° degrees of magnet pole-arc angle	2.044	89.527% reduction
When one rotor is 4° degrees with respect to the other one, the triangle skewed type magnet structure with 156° degrees of magnet pole-arc angle	0.475	97.56% reduction
Fan type magnet structure with 140° degrees of magnet pole-arc angle	19.518	Reference structure

V. EXPERIMENTAL RESULT

Magnet structures, from which the best results are obtained in terms of cogging torque as a result of the analyses performed, are shown in Table 6.

Table 6: Rotor structure, cogging torques of which will be analysed in laboratory

Magnet Structure	Magnet Type	Description
Fan type 140° degrees	NdFeB	Reference structure
Fan type 126° degrees	NdFeB	Fan structure with the lowest T_{cog} value
Triangular type 156° degrees	NdFeb	Triangular structure with the lowest T_{cog} value

Drawings of magnet types, FEA analysis of which have been performed, and optimum rotor structures of which are determined in Table 6, and magnet drawings used in production process are shown in Figs. 14, 15 and 16. Rotor disk of EASM motor, a prototype of which has been manufactured, can be made of standard steel and they can be produced as one-piece rotor discs, which will be used in this study, are designed specially for reducing cogging torque. The feature of these discs is that one can be turned in desired angles according to the other. In this way, knocking value of rotors, which are in different positions according to each other, will be analysed easily. In Fig. 17, drawings of rotor structure are given; in Fig. 18, pictures of special design rotor disc of motor and structure of turning gear operation are shown. In Fig. 19, phases of stator production are shown.

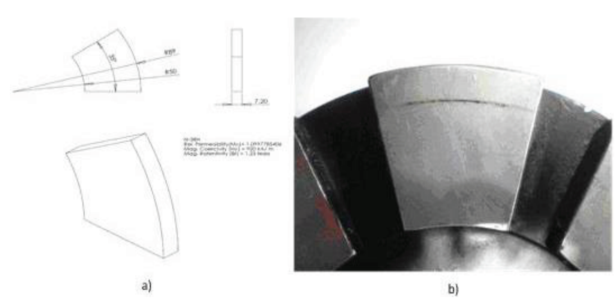


Fig. 14. Fan type 140° degree magnet.

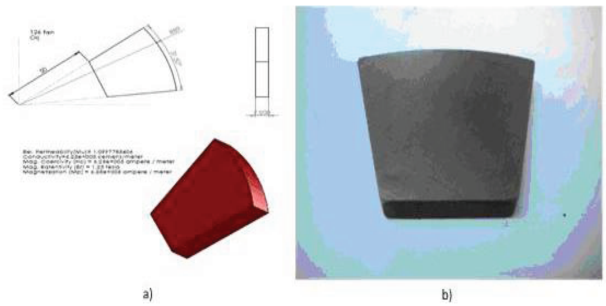


Fig. 15. Fan type 126° degree magnet.

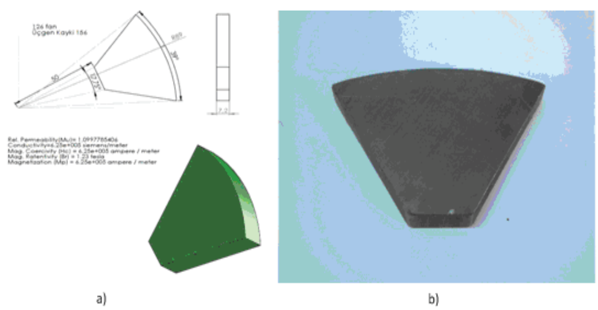


Fig. 16. Triangular skew 156° degree magnet.

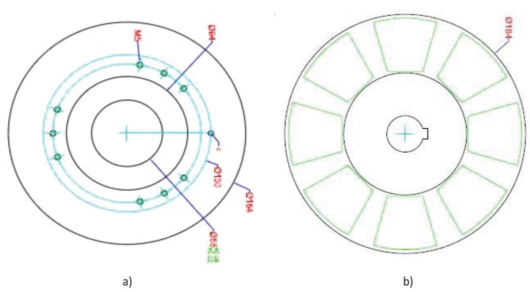
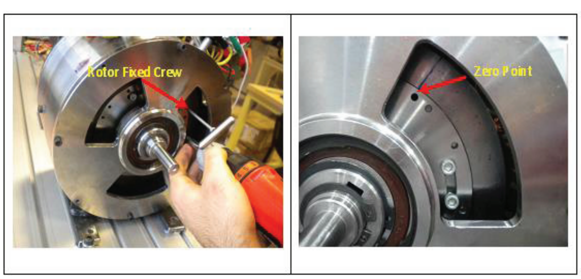


Fig. 17. (a) Moving disc, and (b) rotor drawings of EASM motor.



(a) (b)

Fig. 18. (a) Rotation of rotor for EASM motors, and (b) specially designed rotor disc.

Fig. 19. Production phases of EASM disc motor stator.

Test system, which is designed for measuring the cogging torque after production process is completed, is shown in Fig. 20. In the measuring system, there are excitation oriented step motor and its driver and a torque sensor in order to retrieve data related to torque values. Motor was rotated at a low speed (1 rpm) in order to obtain more accurate results in knocking torque measurement.

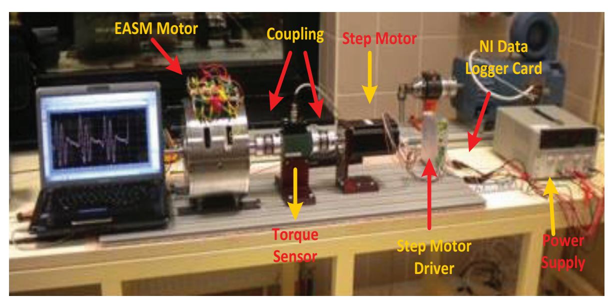


Fig. 20. Test system of EASM motor.

Experimental studies were conducted for axial flux machines with fan and triangular skew type rotor, and results of comparing each rotor structure with 3D FEA analysis were obtained as shown in Figs. 21 and 22. As shown in the results, FEA analyses of cogging torque and experimental results are compatible with each other.

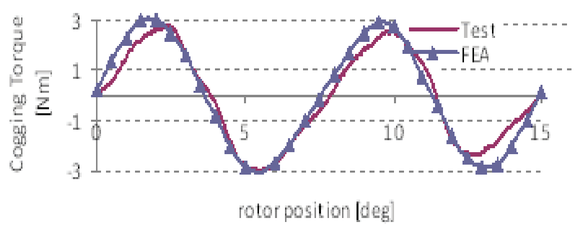


Fig. 21. A graphical comparison of FEA simulation of triangular skew (156° degree with magnet stepping) structure and cogging torque of experimental study.

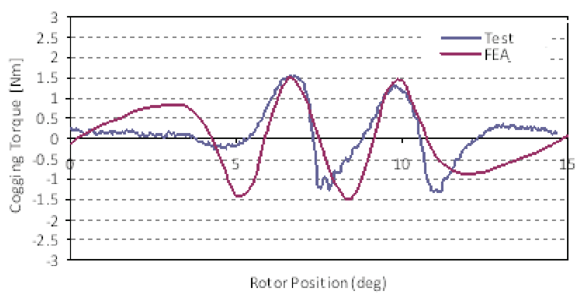


Fig. 22. A graphical comparison of FEA simulation of fan type (126° degree with magnet stepping) structure and cogging torque of experimental study.

VI. RESULTS OF THE TORQUE ANALYSIS

In this section, the techniques achieved the better results for cogging torque reduction for the fan, triangle skewed, and oval skewed magnet structures are compared in terms of average torque analyses and the torque ripples. It is observed from the obtained results that that the methods proposed for the cogging torque reduction did not cause any significant reduction in the average torque (Fig. 23).

Furthermore, it is seen that the proposed structures and dimensions for the fan, triangle skewed and oval skewed magnets that achieved the best results in cogging torque reductions also significantly reduced the torque ripples as compared to the reference motor, according to Fig. 24. Since the reference motor is designed to have the maximum cogging torque, its torque ripples are also the maximum.

Among the fan type magnet structures, at 126° degrees of magnet pole-arc angle, the lowest cogging torque value and the smallest torque ripples are obtained. Similarly, among the triangle skewed type structures, at 156° degrees of magnet pole-arc angle, lowest cogging torque and lowest torque ripples are obtained when the rotor rotation technique is applied.

Thus, when the rotor rotations are applied too, the triangle skewed type magnet structure with 156° degrees of magnet pole-arc angle becomes the most optimal structure in terms of both the average torque and the torque ripples.

In this article, cogging torque reduction methodologies are discusses for the AFPM motors and a double rotor – single stator AFPM with open slot structure is designed in order to have a reference motor with the maximum cogging torque. Then, several techniques are applied to the motor to reduce the cogging torque and the motor is analyzed with the 3-D finite element analysis method in order to test the effectiveness of the proposed methods.

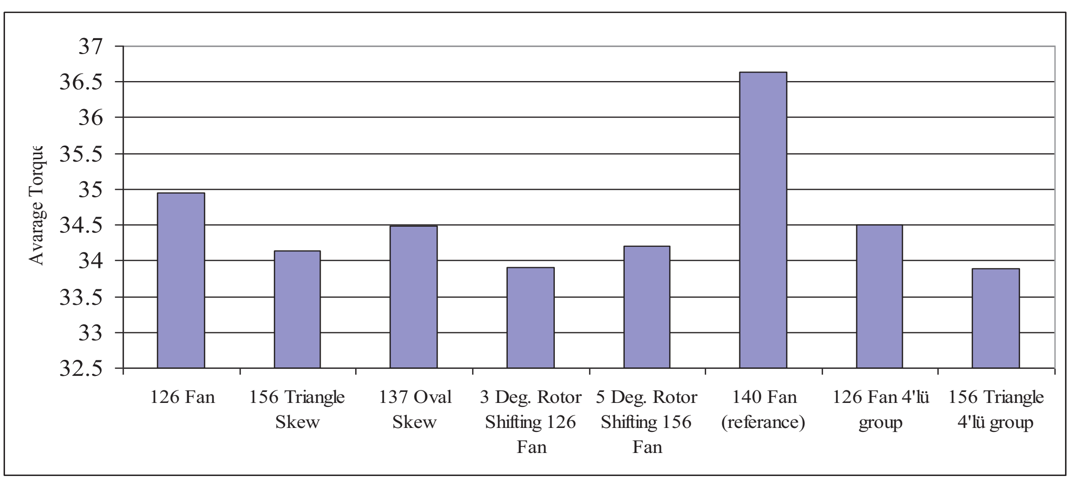


Fig. 23. Average torque comparisons.

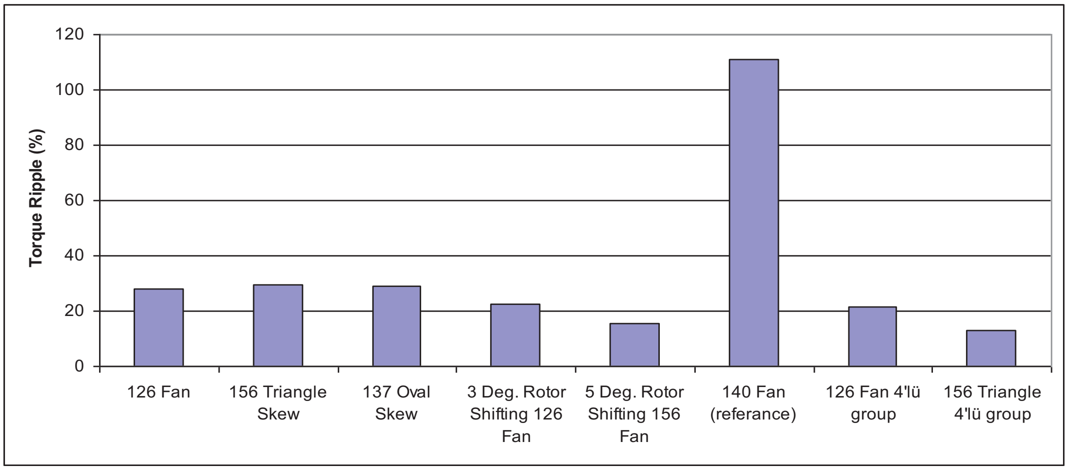


Fig. 24. Torque ripple comparisons.

The magnet skew method applied on the rotor site is a very functional method due to the manufacturing advantages introduced for the disc motors. Therefore, rotor side configuration adjustments are discussed in the proceeding sections of the article. Varying the magnet pole-arc angle on the rotor side and rotating one rotor relatively to the other rotor techniques are used.

According to the first studies performed to reduce the cogging torque, the maximum cogging torque reduction is observed at the fan type magnet structure with 126° degrees of magnet pole-arc angle as compared to the reference motor with 140° degrees of magnet pole-arc angle. At this angle value, the cogging torque is obtained as 1.462 Nm.

Once the optimal structure is obtained for the fan type magnet structure, magnet models with triangle skewed and oval skewed structures with the same surface area are studied. Accordingly, the motor with the triangle skewed magnet structure with 162° degrees of magnet pole-arc angle resulted in 58.3% maximum reduction as compared to the reference motor and the cogging torque value is obtained as 2.868 Nm. Similarly, the motor with the oval skewed magnet structure with 137° degrees of magnet pole-arc angle resulted in 89.527% maximum reduction as compared to the reference motor and the cogging torque value is obtained as 2.044 Nm.

The other technique used for the cogging toque reduction is that rotating one rotor relatively to the other one. According to the obtained results, the best cogging torque reduction is achieved when one rotor is 4° degrees rotated with respect to the other rotor in the triangle skewed structure with 156° degrees of magnet pole-arc angle. The peak value of the cogging torque is reduced to 0.475 Nm in this structure. Thus, 97.56% reduction is accomplished as compared to the reference motor.

In the last section of our study, the cogging torque reduction techniques applied on the rotor side are compared in terms of their effects on the average torque and the torque ripples. According to the analyses results, it is observed that the techniques that significantly reduce the cogging torque do not considerably reduce the average torque and they quite successfully reduce the torque ripples as compared to the reference motor.

VII. CONCLUSION

In this study, analyses were performed on different magnet structures of rotor in order to decrease the cogging torque of axial flux permanent magnet synchronous machines and a prototype motor was produced by using magnet models in optimal structures, which were obtained as a result of FEM analyses. Experimental measurements were made by using the apparatus of the performed experiment, and relevant data were authenticated by comparison with simulation results. As a result of the experimental study for AFPM's, it was observed that in fan type structure with 126° degree magnet stepping, torque ripple decreased by

74.9% according to the reference structure, and in triangular skew structure with 156° degree magnet stepping, torque rippled decreased by according to the reference structure.

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