Magnet Skew in Cogging Torque Minimization of Axial Gap Permanent Magnet Motors

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Abstract – Several cogging torque minimization techniques exist for permanent magnet (PM) machines, and these are well documented in earlier studies. However, the majority are used to reduce the cogging torque in radial flux PM (RFPM) machines. In this paper, cogging torque minimization techniques for axial-flux PM (AFPM) disk machines are briefly reviewed, and one of the foremost cogging torque minimization method, magnet skew, is examined in detail. Various magnet skewing methods, types, and effects on the machine performance are also investigated. The results are compared with a reference AFPM machine, and the improvements are demonstrated.

I. INTRODUCTION

Permanent magnet (PM) AC and DC motors are widely used in many applications. For such motors, designers usually try to minimize the torque fluctuations that are the main source for vibrations, noise and speed fluctuations. These speed variations have two key components: torque ripple [1-5] and cogging torque. Torque ripple is caused by the fluctuations of the field distribution and the armature MMF while the cogging torque is caused by the interaction between the stator slot driven airgap permeance harmonics and magnet driven MMF harmonics. The main sources of torque ripple in PM machines are cogging, PWM current harmonics, non-ideal back-EMF waveforms, and converter related issues. Torque ripple is usually filtered out by the system inertia at high speed levels. However, at low speeds, torque ripple may result in undesirable speed variations, vibrations, and acoustic noise which in return may affect the machine performance significantly.

Minimization of cogging torque is often a significant concern during the design of PM machines, and it is one of the main sources of torque and speed fluctuations. As the minimization of cogging torque for RFPM machines has already been investigated, the focus of present investigation has been on AFPM machines. A variety of techniques exist for reducing the cogging torque of conventional RFPM machines [6-18], such as skewing the slots and/or magnets, displacing and shaping the magnets, employing dummy slots or teeth, optimizing the magnet pole-arc to pole-pitch ratio, employing a fractional number of slots per pole, and imparting a sinusoidal self-shielding magnetization distribution, etc. Some of the techniques can be applied directly to AFPM machines [20-25]. However, their impact on manufacturing cost may be high and therefore, alternative low cost cogging torque minimization techniques for AFPM machines are desirable.

In this paper, the utility of various cogging torque minimization techniques for AFPM machines is examined by 3-D finite element analysis. The cogging torque minimization methods are categorized in two main groups: Stator side modifications and rotor side modifications. The stator side modifications are briefly summarized in the paper. The rotor side modifications are also explained with the focus on magnet skew. Various skew techniques are reviewed and their effects on cogging torque are investigated. All cogging torque simulations are obtained by finite element analysis (FEA), and compared with the cogging of the reference machine.

II. AXIAL FLUX PM REFERENCE MACHINES

The analyses reported in this paper are based on a 24-slot 8-pole dual-rotor single-stator AFPM machine, as shown in Fig. 1. This type of axial flux machine is called slotted TORUS machine with back-to-back gramme-ring type winding. The stator comprises a tape wound core while the rotor comprises a mild-steel disc and fan-shaped surface-mounted magnets. The machine parameters are given in Table I. Parallel stator slot openings are employed to ease manufacturing, modeling and analysis. Reference AFPM motor has a peak cogging torque value of 8 Nm and cogging torque profile as a function of mechanical rotation or time as well as airgap magnet flux density is illustrated in Fig. 2.
### Table I. Parameters of Reference Axial-Flux PM Machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole number</td>
<td>8</td>
</tr>
<tr>
<td>Stator OD</td>
<td>89mm</td>
</tr>
<tr>
<td>Stator ID</td>
<td>50mm</td>
</tr>
<tr>
<td>Airgap</td>
<td>0.8mm</td>
</tr>
<tr>
<td>Number of slots</td>
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</tr>
<tr>
<td>Total axial length</td>
<td>38mm</td>
</tr>
<tr>
<td>Number of phases</td>
<td>3</td>
</tr>
<tr>
<td>Magnet thickness</td>
<td>7.2mm</td>
</tr>
</tbody>
</table>

Fig. 2. (a) Cogging torque profile of the reference dual-rotor single-stator AFPM motor and (b) airgap flux density of the reference machine obtained from 3D FEA.

### III. Cogging Torque Minimization Techniques for Axial Flux PM Machines

In general, cogging torque minimization in AFPM machines can be accomplished in two manners: Modifications from the stator side and rotor side. Classification of these techniques can be shown in Fig. 3. An important drawback of modifying the stator to minimize the cogging torque component is that it complicates the stator manufacturing and consequently increases the manufacturing cost of the machine. Therefore, modifications from the stator side are not practical in AFPM machines and usually not preferred.

One of most effective rotor side techniques is employing an appropriate magnet pole-arc to pole-pitch ratio. Since the cogging torque is produced by the interaction between the edges of the magnet poles and the stator slots, both the magnitude and shape of the cogging torque waveform depend on the magnet pole-arc. Reducing the magnet pole-arc to pole-pitch ratio reduces the magnet leakage flux, but it also reduces the magnet flux, and consequently, the average torque. Another method of reducing the cogging torque is to employ different magnet pole-arcs for adjacent magnets such that the phase difference between the associated cogging torques results in a smaller net cogging torque.

Another effective rotor side technique to minimize the cogging torque is to displace adjacent magnets relative to each other. However, it should be noted that as the magnets are shifted from their symmetrical positions, the leakage flux increases on one side of each magnet and decreases on the other side.

The cogging torque in a double airgap AFPM machine results from the superposition of the cogging torque waveforms associated with each airgap. Using this principle, the resultant cogging torque can be reduced by circumferentially changing the relative phase of the two rotors or the two stators of the AFPM machine depending on the AFPM machine type.
IV. COGGING TORQUE MINIMIZATION WITH MAGNET SKEW

Magnet skew is an effective and simple cogging torque minimization technique used in PM machines frequently. Its use is even easier in AFPM machines than in RFPM machines due to their flat magnet surface and simpler magnet geometry. Some of the magnet skew techniques which will be covered here in this section are conventional skew, triangular skew, parallel-sided magnets, trapezoidal skew, circular magnets, dual-skew magnets, and are all illustrated in Fig. 4.

A. Unskewed (Fan-Shaped) Magnets

Since the cogging torque is produced by the interaction between the edges of the magnet poles and the stator slots, both the magnitude and shape of the cogging torque profile depend on the magnet pole-arc to pole-pitch ratio (See Fig. 4 (a)). Reducing the magnet pole-arc to pole-pitch ratio reduces the magnet leakage flux, but it also reduces the magnet flux, and, consequently, the average torque. Thus, a compromise is usually required during the design process. In addition, consideration needs to be given to the influence of the magnet pole-arc on the back-EMF related torque ripple [8].

A series of cogging torque simulations using 3D FEA are performed, and variation in the peak-to-peak amplitude for various magnet pole-arcs is shown in Fig. 8. The peak-to-peak cogging torque of the reference AFPM machine is also illustrated in the same figure. It can be seen that when the magnet pole-arc is 140°elec. (\(\alpha_p = 0.778\)), the peak cogging torque is ~51% of the rated torque, while the peak cogging torque is a minimum when the magnet pole-arc is 122.5°elec. (\(\alpha_p = 0.68\)), and is reduced to ~5% of the rated torque.

\[\text{Fig. 5. Variation of peak-to-peak cogging torque with magnet pole-arc}\]

B. Conventional Skew

Skewing is one of the simplest, most effective and common techniques to reduce the cogging torque in PM machines. It also reduces high order harmonics in the back-EMF waveform of brushless AC machines. Although it can be accomplished by skewing either the stator slots or the rotor magnets, skewing is only used in magnets in AFPM machines. It should be mentioned that skewing slots in either radial or axial gap machines increases leakage inductance and the copper losses, consequently, it has a negative effect on the efficiency. If the magnets are skewed by one slot-pitch, the cogging torque effectively becomes zero. However, whilst skewing the rotor magnets is relatively difficult in RFPM machines because of the complex shape, it is relatively easy to skew the magnets in AFPM machines. Fig. 4 (b) shows conventional skewed magnets on an AFPM machine rotor. As displayed in Fig. 6, fan-shaped magnet ABCD is skewed to ABC’D’, and the mechanical skew angle (\(\theta\)) is the angle between the edges of the fan-shaped magnet and the skewed magnet on the same side.

In general, as for RFPM machines [8], the peak cogging torque gradually reduces as the skew angle is increased. However, due to magnetic leakage at the inner and outer radii of the magnets in an AFPM machine, the optimal skew angle may not be exactly one slot-pitch, whilst the minimum cogging torque may be not zero. Fig. 7 shows the variation of the cogging torque waveform of the reference AFPM machine as

\[\text{Fig. 6. Definition of conventional magnet skew angle in AFPM machines. Fan-shaped magnet (ABCD), Skewed magnet (ABC’D’)}\]
the skew angle is varied from a \( \frac{1}{4} \) slot-pitch to \( \frac{3}{2} \) slot-pitches, whilst Fig. 8 shows the variation in the peak-to-peak amplitude of the cogging torque. As can be seen, the peak cogging torque reduces as the skew angle is increased and has a minimum at a skew angle of 18.75 mechanical degrees.

![Fig. 7. Variation of cogging torque waveform of the AFPM machine with various magnet skew angles](image)

![Fig. 8. Variation of peak-to-peak cogging torque with magnet skew angle](image)

**C. Triangular Skew**

Skew may be introduced by bringing the sides of the magnets at the rotor OD closer together whilst they are moved further apart at the rotor ID, as illustrated in Fig. 4 (c), thus resulting in a triangular shaped airspace between adjacent magnets. In other words, fan-shaped magnet (ABCD) is skewed to A'B'C'D' as given in Fig. 9. The cogging torque waveform for this kind of magnet shape has been determined for four different skew angles, \( \delta \) (See Fig. 9 for the definition of \( \delta \)), with the magnet surface area maintained constant at 0.778 or 140 electrical degrees to make a better comparison with the reference AFPM machine. As can be seen from Fig. 10, a significant reduction in the cogging torque can be achieved as the skew angle, \( \delta \), is increased, an 84.3% reduction in the peak cogging torque being achieved when \( \delta = 22.5 \) degree mech.

![Fig. 9. Definition of \( \delta \) in triangular magnet skew](image)

![Fig. 10. Variation of cogging torque waveform with angle \( \delta \).](image)

**D. Parallel-Sided Magnet Skew**

Another skewing method is paralleling the adjacent sides of the magnets as illustrated in Fig. 4 (d). It should be noted that the influence of employing parallel sided magnets in reducing the cogging torque will be more significant in AFPM machines with a low pole number than those with a high pole number, because as the pole number increases, the magnet sides and slot openings become parallel giving rise to smaller skew angle which result in less reduction in cogging torque.

Fig. 11 shows cogging torque waveforms for parallel-sided magnets for various ratios of magnet area to pole area. Fig. 12, on the other hand, shows peak-to-peak cogging torque variation for both fan-shaped magnets and parallel sided magnets for various pole-arcs. It can be seen from both plots that the peak cogging torque can be reduced by 37.5% by employing parallel-sided magnets for the pole-arc ratio of 0.778. This reduction is even larger in other magnet pole-arc values.

![Fig. 11. Cogging torque waveforms for various magnet area / pole area](image)
E. Trapezoidal Skew

Another way of realizing skew in AFPM machines is illustrated in Fig. 4 (e) in which the magnets are shaped such that their inner edges are closer than the outer edges, so that the ratio of the magnet pole-arc to pole-pitch at the inner radius is higher than that at the outer radius. This results in a reduction of about 62% in the cogging torque, as shown in Fig. 13. However, one drawback is the fact that the leakage flux at the inner radius of the magnets then increases, which compromises the average torque. It should be mentioned that the extreme case for the trapezoidal skew is square shaped magnets. The results for the square magnets will also be given in the conclusions.

F. Circular Magnets

Round or circular magnets are also an effective means of introducing skewing in AFPM machines (See Fig. 4 (f)). In order to reveal the effectiveness of this method, the cogging torque of the reference AFPM machine has been simulated when the rotor is equipped with the round magnets for a range of the ratio of magnet area to pole area (This can also be considered as equivalent to pole-arc ratios in fan-shaped magnets). Seven different diameters of magnet have been considered in FEA. Their cross-sectional areas are equivalent to magnets having a pole-arc/pole-pitch ratio from 0.444 to 0.778. As can be seen from Fig. 14, a very significant reduction in the cogging torque can be attained by employing circular magnets. A 62.5% reduction in peak-to-peak cogging torque is achieved for the magnet pole ratio (or magnet pole-arc ratio) of 0.778. This reduction is 32.2% for magnet pole ratio of 0.667 (or 120 degree electrical).

G. Dual Skew

Dual skewed magnets have been successfully employed to reduce the cogging torque in RFPM machines [29] and to eliminate the axial force which generally results in skew. They can readily be employed in AFPM machines, as illustrated in Fig. 4 (g). Nevertheless, the most likely drawback is the additional complexity and manufacturing cost of such magnets, although the cost of magnets for AFPM machines is usually lower than that for RFPM machines, which are usually radially oriented arc-segments.

The cogging torque, which is obtained when the inner and outer skew angles are identical and the magnet cross-sectional area is the same as that of the magnets in the reference machine, is shown in Fig. 15, for a skew angle of ½ slot-pitch. Again, a significant reduction in the cogging torque is achieved.

V. CONCLUSIONS

In this paper, various cogging torque minimization techniques for AFPM machines have been studied. Effectiveness of the techniques has been examined by 3-D...
finite element analysis and the results are compared with a double-rotor, single-stator AFPM reference machine.

It has been shown that, there exist various techniques to minimize the cogging torque component in AFPM machines. Due to the complexity and cost of stator manufacturing, the focus was on rotor side minimization techniques. As shown in the paper, skewing is one of the effective rotor side techniques in minimizing the cogging torque component in AFPM machines and can be achieved in several ways. It was also proven that some of the skewing techniques offer significant reduction in cogging torque component. Comparison of different magnet skew methods as well as unskewed fan-shaped magnets is displayed in Fig. 16 for various pole-arcs or the ratio of magnet area to pole area. For example, a 37.5% reduction in parallel sided magnets and 62.5% reduction in round magnets are observed as opposed to fan-shaped magnets for the pole-arc ratio of 0.778.

![Graph showing cogging torque comparison](image)

**Fig. 16.** Comparison of peak-to-peak cogging torque variation for both fan-shaped, parallel sided, round and square magnets.

**ACKNOWLEDGMENT**

The author is indebted to TUBITAK (The Scientific and Technological Research Council of Turkey) for providing the financial support of this project.

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