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Cogging Torque Minimization Technique for Multiple-Rotor, Axial-Flux, Surface-Mounted-PM Motors: Alternating Magnet Pole-Arcs in Facing Rotors

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Cogging Torque Minimization Technique for Multiple-Rotor, Axial-Flux, Surface-Mounted-PM Motors: Alternating Magnet Pole-Arcs in Facing Rotors

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***Abstract* – A variety of techniques exist for reducing the cogging torque of conventional radial flux PM machines. Even though some of these techniques can be applied to axial flux machines, manufacturing cost is especially high due to the unique construction of the axial flux machine stator. Consequently, new low cost techniques are desirable for use with axial flux PM machines. This paper introduces a new cogging torque minimization technique for axial flux multiple rotor surface magnet PM motors. First, basic principles of the new technique are explored in this paper. A 3-kW, 8-pole axial flux surface-magnet disc type machine with double-rotor-single-stator is then designed and optimized in order to apply the proposed new method. Optimization of the adjacent magnet pole-arc which results in minimum cogging torque as well as assessment of the effect on the maximum available torque using 3D Finite Element Analysis (FEA) is investigated. The minimized cogging torque is compared with several existing actual machine data and some important conclusions are drawn.**

Keywords – Axial flux surface mounted PM machines, cogging torque, finite element analysis.

I. INTRODUCTION

Permanent magnet (PM) machines have been used in an increasing number of applications since the introduction of rare-earth magnets. The main reason for employing rare-earth magnets is that it introduces much higher flux densities than ferrite materials, which makes the resulting motors suitable for variable speed drive (VSD) applications.

Torque quality is a very decisive issue for VSDs. There exist two undesired pulsating torque components in PM machines which affect the machine performance, one of which is ripple torque arising from harmonic content of the machine voltage and current waveforms and the other is cogging torque caused by the attraction between the rotor magnetic field and angular variations of the stator reluctance. By definition, no excitation is involved in cogging torque production. Existence of these torque mechanisms is a foremost concern in the PM motor design due to the unwanted harmonics added to the motor output torque. These components not only affect the self-starting ability of the motor but also produce noise and mechanical vibrations.

Cogging torque is estimated by calculating the change of total energy stored in the airgap with respect to the rotor position and can be written as

$$T_{cog}(\theta_r) = -\frac{1}{2}\phi_g^2 \frac{dR}{d\theta_r} \tag{1}$$

where ϕ_g is the airgap flux, R is the airgap reluctance and θ_r is the angular rotor position. As the permanent magnet strength is increased, the cogging torque also increases due to the increased amount of flux in the airgap. However, the cogging torque fundamentally results from the non-uniform flux distribution in the airgap. As the teeth become saturated, the flux begins to distribute more evenly in the airgap and the cogging torque decreases. The cogging torque increases linearly while the stator steel behaves linearly, but levels off and then decreases as the stator steel begins to saturate.

Many techniques for cogging torque minimization are documented in the literature for PM machines due to the high demand on PM machines for high performance applications [1-6]. These techniques include magnet pole shape, skewing stator tooth or rotor magnets, magnet or pole shifting, pole-arc ratio and stator slot design, dummy slots on the stator tooth, varying the radial shoe depth and graded airgaps. Most of the techniques mentioned can be applied to axial flux machines. However, the high manufacturing cost of the axial flux machines will be even higher when these techniques are applied. For instance, skewing stator slots by one slot pitch or introducing dummy slots will not only boost the manufacturing cost of the axial flux machine stator but complicate the manufacturing process as well. A new, effective and cheap technique could help axial flux machines improve their performances without a high manufacturing cost and

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significant sacrifice of the output or peak torque of the machine.

In this paper, a new cogging torque minimization technique especially for axial flux PM machines structures called alternating magnet pole-arcs in facing rotors is proposed. Basic principles of the technique are explored in the first section. A double-rotor-single-stator axial flux permanent magnet (AFPM) machine is designed and used as an example machine in order to explain the principles and detailed analysis of the new method. Cogging torque variation and optimization, peak cogging torque and the effect on torque ripple of the new method using 3D FEA are explored in the third section. The effectiveness of this technique is also demonstrated by comparing the cogging torque with some actual machine data and it is shown that the new technique is very effective to minimize the cogging torque component in axial flux PM motors.

II. Principle of Alternating Magnet Pole-arcs

Given that the overall cogging torque of an AFPM machine consists of several portions each of which is produced in one air gap, the overall cogging torque is reduced by two general approaches: Reducing the amplitude of each portions, similar to what conventional methods accomplish, and shifting the relative phase of the different components so that they can compensate each other. Consequently, the overall cogging torque will be much reduced at minimal incremental cost. One of the methods to shift the cogging torque phase is to vary the magnet pole-arc, as shown in Fig. 1. The consequent magnets in each rotor are designed with two different magnet pole-arc ratios: α_m and α_c. The two magnet pole-arc ratios of the next rotor are same as the previous ones, but in the reversed order, i.e. α_c and α_m, so that the cogging torque produced in each air gap has a phase shift relative to that produced in the consequent. Therefore, the overall cogging torque in any two consequent air gaps could be reduced. The amplitude of each portion can be reduced as well by optimizing the two arcs. In other words, the objective of this technique is to vary the cogging torque phase angle by alternatively using two magnet pole arcs and simultaneously to reduce the amplitude of each portion so that the superposition of the cogging torque variation of all airgap adds up to a very small value. The technique is applied to slotted double-rotor-single-stator North-North (NN) type AFPM machine and illustrated in Figs. 2 and 3.

It should also be mentioned that the definition of magnet pole-arc is given by the ratio of magnet pitch to rotor pole pitch, i.e.

$$\alpha_m = \frac{\tau_m}{\tau_p} = \frac{\tau_{gm}}{\tau_{gp}} \qquad (2)$$

and

$$\alpha_c = \frac{\tau_c}{\tau_p} = \frac{\tau_{gc}}{\tau_{gp}} \qquad (3)$$

where τ_m and τ_c are the magnet pitch and τ_p is the rotor pole pitch.

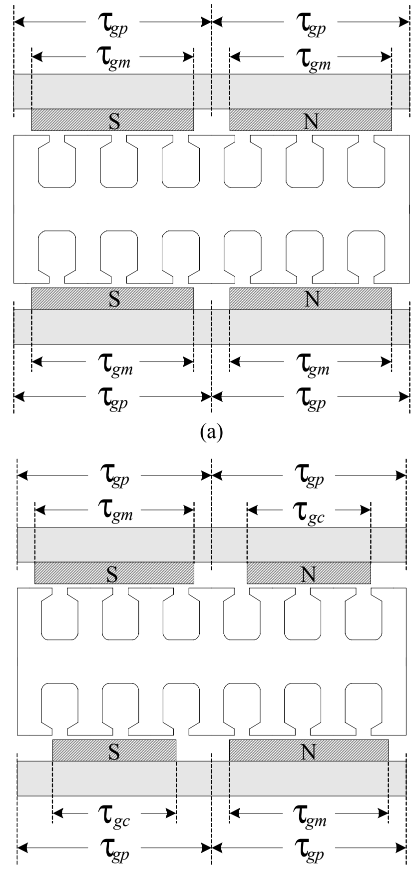

Figure 1. Two pole section of the (a) conventional double-rotor-single-stator AFPM machine with the same magnet pole-arc and (b) AFPM machine with alternating pole arcs for cogging torque minimization at the average diameter

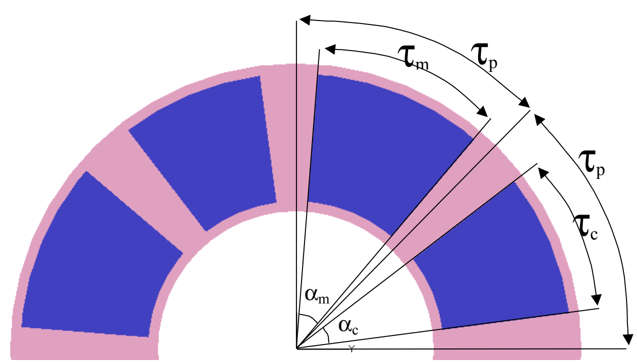

Figure 2. One of the AFPM machine rotors with alternating magnet pole-arcs. The other rotor disc is rotated by one mechanical pole.

This new technique has some advantages over the other cogging torque minimization techniques mentioned in the literature:

- Less cogging while the peak torque stays almost the same,
- Less magnet material and magnet cost for the same peak torque,
- Cheaper machine since the cost of the PM is more than the cost of iron or copper,
- Higher torque-to-weight, torque-to-material volume and torque-to-cost ratios for a particular magnet pole-arc

range since the torque has a flat region as the pole-arc changes,

- Little effect on total output torque for the cases between the same magnet pole arcs,
- Cost effective due to the low manufacturing cost compared to other cogging torque minimization techniques because of the simplicity of the new method.

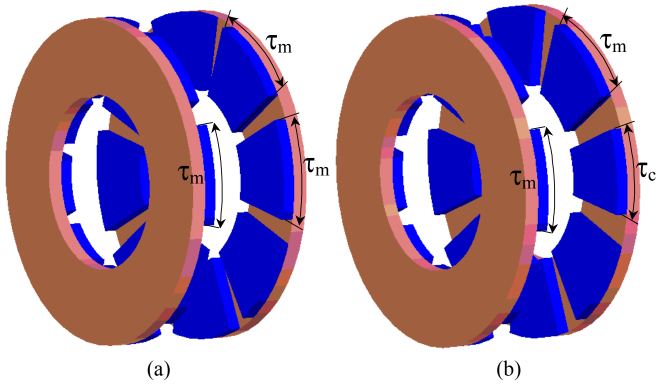

Figure 3. Double rotor single stator AFPM machine with (a) the same magnet pole-arcs and (b) alternating magnet pole-arcs for the purpose of cogging torque minimization

III. Design and Optimization of an AFPM Sample Machine for Cogging Torque Analysis

A 3-kW, 8-pole, 24-open-slot double-rotor-single-stator, NN type, AFPM machine is selected as a sample machine to apply the proposed alternating magnet pole arc technique to reduce the cogging torque component. The stator inner to outer diameter ratio, λ or (D_i/D_o), and airgap flux density are two important design parameters that affect the performance of the machine and should be optimized.

The machine power density is maximized during the optimization process by varying the diameter ratio and airgap flux density using the generalized sizing equations [8-9]. In order to do so, torque densities including torque-to-volume and torque-to-active material weight ratios are plotted in Fig. 4 as a function of the diameter ratio (λ) for the double-rotor AFPM machine. Based on Fig. 4, the diameter ratio of 0.58, which gives the maximum torque-to-volume, is chosen as the optimum design point for this machine. The main design parameters are summarized in Table I.

Table I
Optimization of the AFPM Machine for Maximum Power Density Point

Maximum power density (P_{max})	1.05 W/cm^3
Pole number	8
Airgap flux density (B_g)	0.86 T
Efficiency (η)	91.1%
Diameter ratio at MPD point (λ)	0.58
Electrical loading	270 A/cm
Outer machine diameter (D_o)	17.7 cm
Inner machine diameter (D_i)	10.3 cm
Total axial length (L_{tot})	8.8 cm

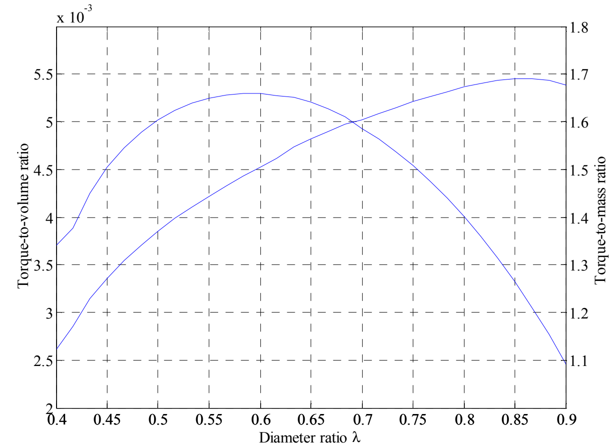

Figure 4. Torque density including torque-per-volume (Nm/cm^3) and torque-per-kilogram (Nm/kg) plots as a function of diameter ratio for 3kW, 8 pole, double-rotor-single-stator North-North (NN) type AFPM machine

IV. 3D NN Type AFPM Machine Models and Finite Element Analysis Results

Finite Element Analysis (FEA) software available in the market is extremely robust and accurate. It has been a great help for the engineers to solve electromagnetic field problems which are too complex to be solved using analytical techniques. Maxwell 3D by ANSOFT is used in this paper for all the FEA computations.

A. FEA Models and Cases Studied

Sixty six 3D-FEA models were created in order to investigate the cogging torque characteristics of the machine analyzed in this study. One of the FEA models of the machine analyzed with magnet pitch of τ_m=110^o and τ_c=140^o (electrical) is illustrated in Fig. 5. Both magnet pitches (τ_m and τ_c) of the facing rotors are used as variables not only to attain the minimum cogging torque for the designed dimensions and pole numbers but to prove the feasibility of the proposed technique as well. The cases investigated in this paper are tabulated in Table II. Both magnet pitches are varied in a large range from 60^o to 180^o. Fig. 6 shows the typical 3D FEA mesh for one of the FEA models illustrating the magnet case of τ_m=110^o and τ_c=140^o.

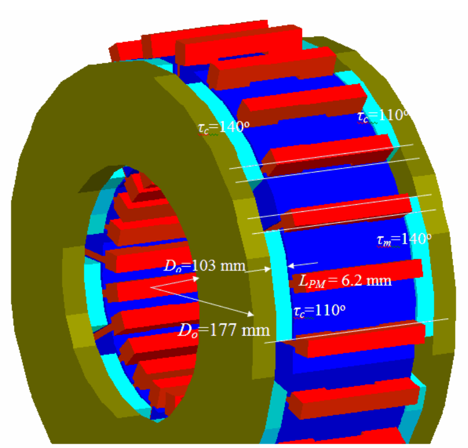

Figure 5. One of the 8-pole 24-slot double-rotor-single-stator AFPM motor models used in the cogging torque analyses (Case: τ_m=110^o and τ_c=140^o)

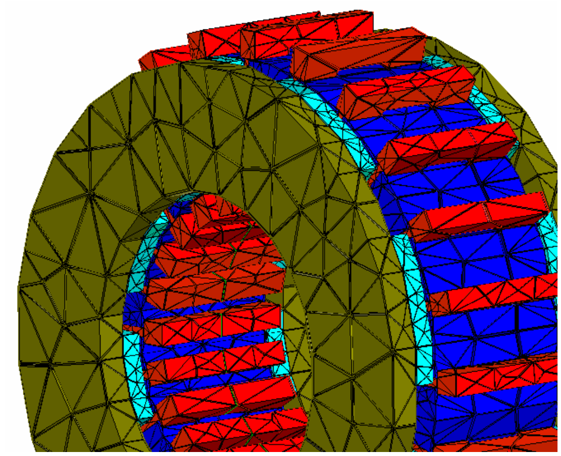

Figure 6. Typical 3D finite element mesh for one of the AFPM motor models analyzed (Case: τ_m=110^o and τ_c=140^o)
(Number of elements: 140186 Tetrahedras, Total CPU time: 84 minutes, Computer used: P4-1.8MHz PC)

TABLE II
CASES USED IN THE FINITE ELEMENT ANALYSIS

	τ_m										
τ_c	60	80	90	100	110	120	130	140	150	160	180
60	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
80		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
90			✓	✓	✓	✓	✓	✓	✓	✓	✓
100				✓	✓	✓	✓	✓	✓	✓	✓
110					✓	✓	✓	✓	✓	✓	✓
120						✓	✓	✓	✓	✓	✓
130							✓	✓	✓	✓	✓
140								✓	✓	✓	✓
150									✓	✓	✓
160										✓	✓
180											✓

✓ Cases analyzed

B. Cogging Torque Calculation using FEA

In these analyses, the pitch of the every other magnet is kept the same at a fixed magnet pitch while the others are varied from 60 to 180 electrical degrees with 10 degree increments. In other words, the magnet pole-arc ratios are varied from 0.333 to 1.000 in order to find the magnet pole-arc which gives the minimum cogging. The cogging torque plots are obtained for each of those cases in order to find the optimum magnet pole-arc for this motor. First, pole-arcs of the adjacent magnets are kept the same so as to see the amplitude of the cogging torque waveform of the same pole-arcs, which is plotted in Fig. 7. It is seen that the cogging torque is maximum around the magnet pitch of 140 electrical degrees while it is minimum at 120 electrical degrees. For the pitch of 140 degrees (or magnet pole-arc of 0.778), peak machine cogging is nearly 51% of the rated torque. However, even with the magnet pitch of 120 electrical degrees (or magnet pole-arc of 0.667), the peak cogging torque is about 19% of the machine rated torque.

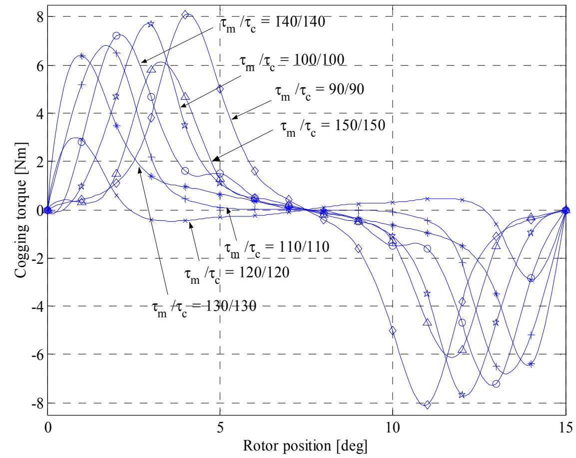

Figure 7. One cycle of cogging torque versus magnet rotor position for different values of magnet pole-arc (one cycle)

When the new proposed technique is applied for various magnet pole-arcs, a great reduction on cogging torque can be observed. Some of the cogging torque plots with small peak cogging torque for different pole-arc combinations are displayed in Fig. 8. The plots show that different combinations of τ_m/τ_c ratio offer reasonable small cogging torque compared to the case where both pole-arcs are the same. It illustrates that the cogging torque can be reduced by optimizing the pole-arc ratio. Fig. 9 displays the variation of cogging for a fixed τ_m and varying τ_c around the critical pole-arc region, which is in between 100 and 150 degrees for a fixed τ_m. When the τ_m is fixed at 110 electrical degrees and τ_c is varied, it was found out that the peak cogging of the machine is reduced to 1.4 Nm which is only 8.7% of that found in Fig. 7.

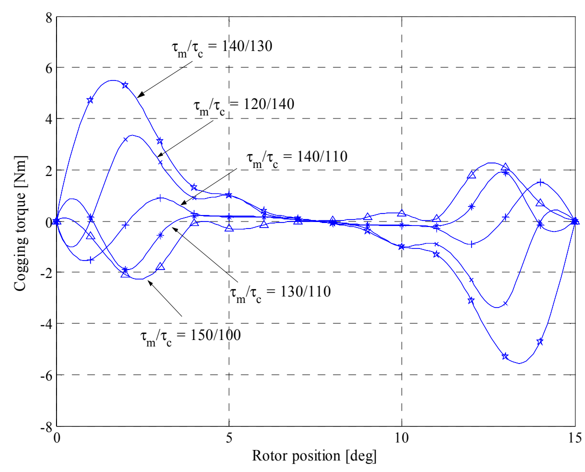

Figure 8. Cogging torque plots for different combinations of magnet pitch (in Nm)

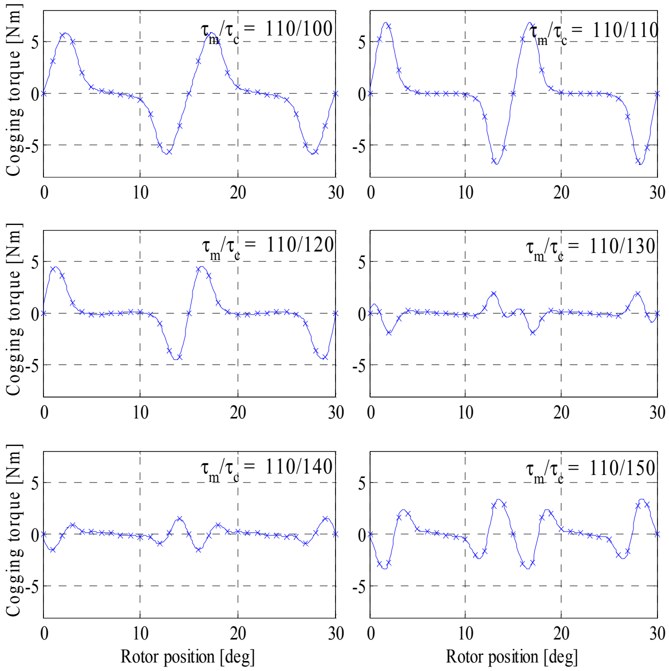

Figure 9. Cogging torque versus rotor position for different magnet pole arcs for a fixed τ_m and varying τ_c (in Nm s). First magnet pitch (τ_m) is fixed at 110 electrical degrees and the second magnet pitch (τ_c) is varied

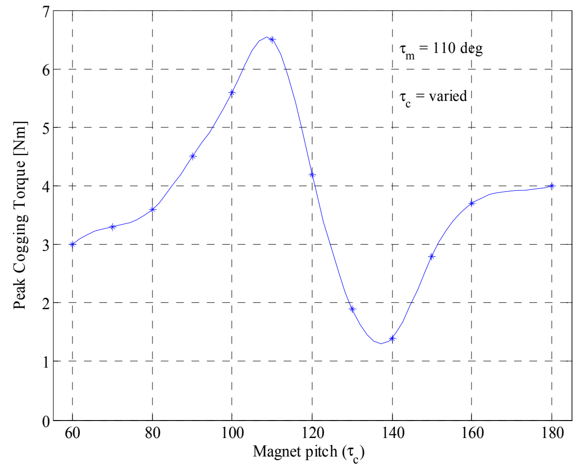

Figure 10. Peak cogging torque variation for various magnet pitch values with one of the magnet pitch is fixed at τ_m = 110 electrical degrees

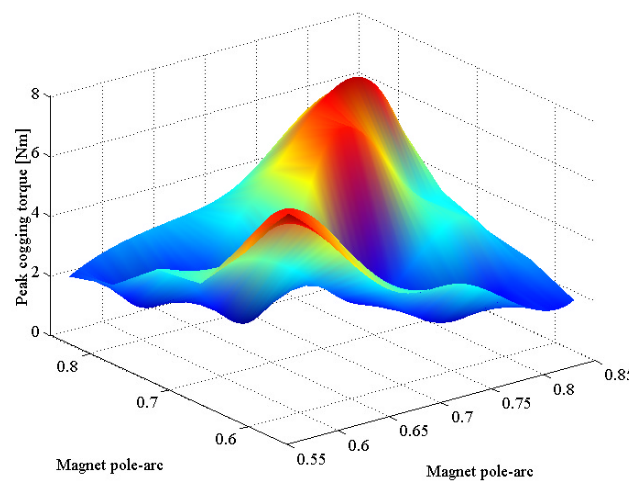

Figure 11. Peak cogging torque variation of the double-rotor-single-stator AFPM motor using finite element analysis as both adjacent magnet pole-arcs (α_m and α_c) are varied

One can observe from Fig. 10 that the peak cogging torque of the AFPM machine for the investigated case has a maximum value at the magnet pole-arc value of 0.611. In other words, the cogging torque is the maximum for the same values of pole-arcs (τ_m = τ_c =110 degrees) in the adjacent magnets while the peak cogging torque is less in all the other cases. The optimum value of the magnet pitch is also seen from the same figure. The cogging torque reaches a minimum value around the pole-arc of 0.778. It is very interesting to notice that the cogging torque of the analyzed axial flux machine decreases by about 83% as the magnet pitch of the every other magnet is changed from 110 degrees to 140 degrees. It also decreases by almost 53% of the rated torque when the pitch (τ_c) is modified from 120 to 140 degrees. After the cogging torque reaches a minimum value around 140 electrical degrees or magnet pole-arc of 0.778, it starts to ramp up again until all the available space for one rotor pole is fully utilized.

Similar trend can also be seen for other variations of adjacent pole-arcs as both τ_m and τ_c are used as variables. The region where the cogging reaches its maximum and minimum values is chosen as the critical region and finite element analyses are focused on that area. A 3D-plot obtained from 3D-FEA shows the peak cogging torque as variables of α_m and α_c which is illustrated in Fig. 11. The tendency of cogging torque as a function of τ_m and τ_c can easily be seen from this plot. For the same adjacent pole-arcs, cogging torque starts from a high value, reaches a minimum at 120^o and starts increasing as adjacent pole-arcs are increased. As both τ_m and τ_c are varied, minimum cogging torque for each pole-arc set can be found. The plots in 2D are also shown in Fig. 12. Detailed 3D FEA results are also summarized in Table III.

TABLE III
COGGING TORQUE SUMMARY OF THE AFPM MACHINE FOR VARIOUS POLE-ARCS AROUND THE CRITICAL REGION

		τ_m					
		100	**110**	**120**	**130**	**140**	**150**
τ_c	**100**	7.6	5.6	3.9	3.7	2.5	*2.1*
	110	5.6	6.5	4.2	1.9	*1.4*	2.8
	120	3.9	4.2	2.9	*1.7*	3.2	3.1
	130	3.7	1.9	*1.7*	6.4	5.3	3.7
	140	2.5	*1.4*	3.2	5.3	7.2	5.3
	150	*2.1*	2.8	3.1	3.7	5.3	5.8

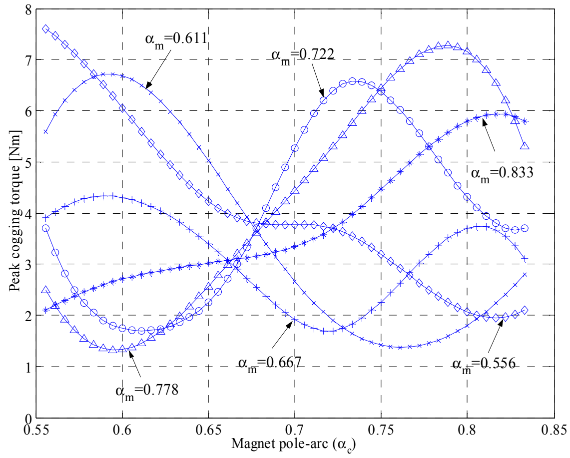

Figure 12. Peak cogging torque for various magnet pole-arcs around the focused critical magnet pole-arc region

C. Investigation of Peak Torque and Pulsating Torque Calculations for Various Magnet Pole-Arcs

In previous sections, minimization of the cogging torque using different pole-arcs in facing rotors has been investigated. It was shown that the new technique is truly effective and provides significant reduction in cogging torque. However, some other FEA calculations should be carried out in order to see the effect of this technique on peak torque and ripple torque.

In order to investigate the peak torque variation of each magnet pole-arc case and compare the torque values, 3D FEA models are set for different pole-arcs. The pole-arc values where the minimum cogging torque occurs are again chosen as a sample case for the torque calculation. Torque versus rotor position plot is obtained around the maximum torque region and the peak torque variation for various pole-arcs is illustrated in Fig. 13.

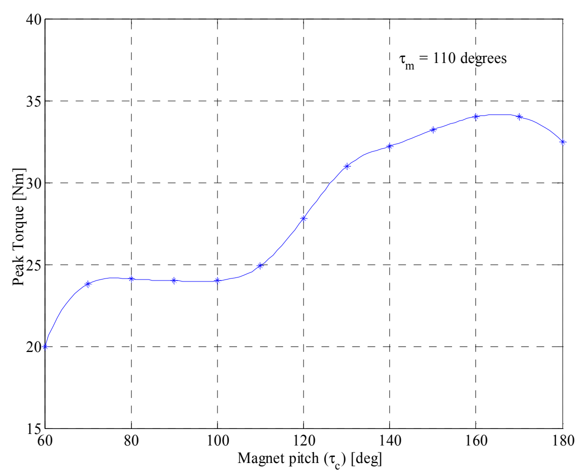

Figure 13. Peak torque versus magnet pole-arc for the AFPM machine for a fixed τ_m (=110 degrees) and varying τ_m

It can be seen that the machine peak torque increases as the magnet pitch increases up to the pitch of 70 degrees and then it remains the same until the magnet pitch of nearly 110 degrees. In other words, even if the magnet pitch (τ_c) is increased from 70 to 110 degrees, the machine peak torque remains almost the same while the cogging torque doubles and reaches a maximum value at 110 degrees or at the pole-arc of 0.611. If the machine pole-arc (α_c) is chosen greater than the adjacent magnet pole-arc (α_m) value, the peak torque goes up while the machine cogging goes down. Choosing the pole-arc (α_c) less than the α_m indicates that the machine torque-to-weight ratio and material cost go up as the magnet pitch decreases from the critical pitch value which is 110 degrees for this case. After the minimum cogging torque value, the peak torque as well as cogging torque increases until the magnet pole-arc reaches unity. Moreover, a large magnet pole-arc results in very high magnet leakage flux which also reduces the peak torque of the machine.

Furthermore, total torque profile of the AFPM machine with different pole-arcs has been investigated and the results are displayed in Fig.14. The magnet pole-arcs for the adjacent poles are both kept the same in the first case at 120 electrical degrees and the pole-arcs are modified for the next case where minimum cogging occurs. As can be seen from the total torque plots, the pulsating torque components for both cases are about the same as the pole-arc ratios are changed to the minimum cogging torque case. The analysis basically shows that the proposed technique does not degrade the torque pulsations but helps reduce the cogging torque component.

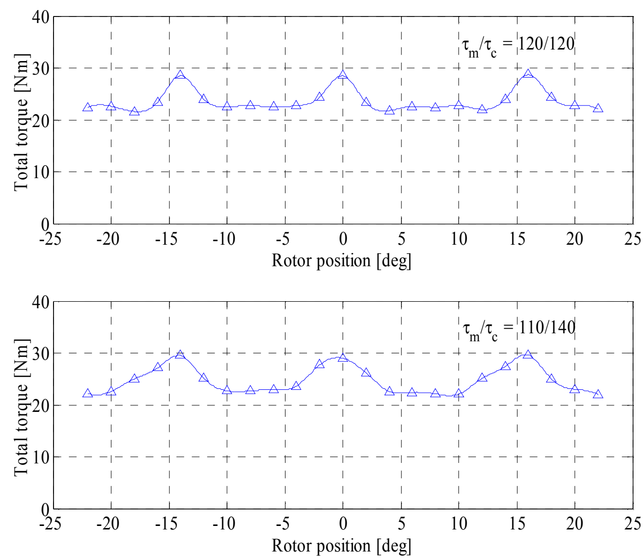

Figure 14. Total torque variation for two cases of magnet pole-arcs: (Case1: τ_m/τ_c = 120/120 and Case2: τ_m/τ_c = 110/140)

V. NORMALIZED COGGING TORQUE COMPARISON BETWEEN THE NEW TECHNIQUE AND EXISTING MACHINES

The cogging torque obtained from this technique is compared with some of the actual machine data and the comparison is given in Table IV. It can be observed that the proposed technique results in reasonably small cogging torque value for the axial flux PM machine analyzed in this work. This value can be reduced further with the help of other techniques mentioned in the literature. It should be mentioned that this technique is a cost effective technique compared to other cogging torque minimization methods used and/or covered in the literature.

TABLE IV
COGGING TORQUE COMPARISON BETWEEN ALTERNATING MAGNET POLE-ARCS TECHNIQUE AND DATA FROM ACTUAL MACHINES

	RFTPM(1)	SPM(2)	AFPM(3)	AFPM(4)
Rated Power (kW)	2.24	5	8	3
Rated Torque (Nm)	11.9	13.5	170	15.9
Cogging torque (Nm)	1	2.7	20	1.4
Normalized cogging torque (T_{cog}/T_{Rated}) (%)	8.4	20	11.8	8.8

(1) Ronghai Qu's design (8 poles) [2]
(2) Li and Slemon's design (4 poles) [5]
(3) Di Napoli, Honorati and et. Design (24 poles) [7]
(4) New technique proposed in this paper (8 poles)

VI. CONCLUSIONS

A new technique to minimize cogging torque for multiple rotor axial flux PM motors has been proposed and the analysis of this technique as applied to an 8-pole 24-slot double-rotor axial flux motor has been carried out using 3D FEA software. The analyses show that peak cogging torque components can be reduced greatly with careful and precise calculation of magnet pole-arcs in multiple-rotor machines. Besides the simplicity and cost-effective features of this technique, the results show that the new technique effectively reduces the cogging torque component without any sacrifice on the peak torque and pulsating torque components. It should also be mentioned that if some other techniques such as skewing, magnet shift or shifting one of the rotors are used besides the proposed technique, cogging torque components of the multiple-rotor AFPM machines can be reduced further. However, an analytical model of this technique combined with other available techniques applicable to AFPM machines would be helpful for precise and faster optimization and this will be the subject of a future paper.

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