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The Influence of Stator Pole Shape and Its Arrangements on Cogging Torque for Double-sided AFPM Generator

Chang-Eob Kim *, Joong-Keun Jang *, and Sung-Jun Joo **

Abstract — In this paper, the cogging torques were calculated for 1kw double-sided axial flux permanent magnet (AFPM) generator with different stator core pole arrangements. The generator is composed of 18 stator pole and 24 rotating field magnets on each side. The cogging torques of the generator with three types of arrangements of stator poles were calculated using 3D finite element method and the optimum core shape was determined to minimize the cogging torque.

Keywords: AFPM generator, cogging torque, Stator core position, Different magnet pitch

1. Introduction

The axial flux permanent magnet (AFPM) machines have many advantages compared to the radial flux permanent magnet (RFPM) machines, including high power density, and better ventilation and cooling. The AFPM machine is generally the more suitable choice for high frequency or low speed operations because of its larger outer diameter than that of the RFPM machine [1]-[3]. However, there still remains the problem of the cogging torque, and many researches have been conducted in order to find ways to decrease it [4]-[6]. In this study, we present the influence of the shapes and arrangements of the stator core pole on cogging torque of a double-sided AFPM generator. Fig. 1 shows an analysis model of a double-sided AFPM generator, which is composed of 18 poles of stator cores, and 24 poles of rotor magnets. Here, we calculated the cogging torques of the generators with three types of arrangements of stator poles, using 3D finite element method. Also, the optimum core shape was utilized to minimize the cogging torque.

2. AFPM Generator and Cogging Torque

Fig. 2 shows the stator pole arrangements of AFPM generator with different positions of upper and lower pole, where τ_p, τ_α are pole pitch and pole difference, respectively. We investigated the influence of the stator pole and its arrangement on the cogging torque.

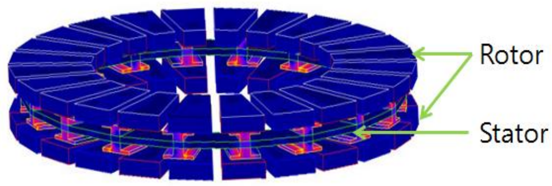
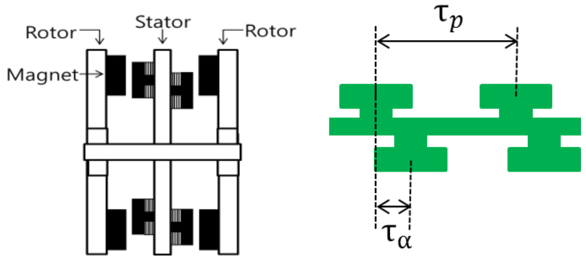


Fig. 1. Analysis model of 1kw AFPM generator.



(a) AFPM machine (b) Stator pole arrangement

Fig. 2. Stator pole arrangements of AFPM machine.

2.1 Cogging Torque

Cogging torque is produced by the reluctance difference between stator and rotor of generator when the stator current is not applied. The following is the cogging torque equation by the reluctance variation.

$$T_{cog} = -\frac{1}{2}\emptyset^2\frac{dR}{d\theta_R} \tag{1}$$

where, φ is magnetic flux, R air gap reluctance, and θ_R rotor angle.

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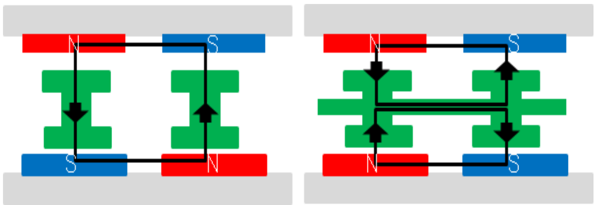
2.2 AFPM Generator

The proposed generator has a double-sided rotor with a magnet on each side. The type of magnet arrangement is divided into N-S and N-N as shown in Fig. 3. We adopted the N-N type of magnet arrangement for the generator in order to ensure the flux path in the center core as shown in Fig. 3 (b).



(a) N-S model (b) N-N model

Fig. 3. Two types of magnet arrangements.

The generator is composed of 24 poles of outer rotor, and 18 poles of stator. Table 1 shows the specifications of 1kw AFPM generator

Table 1. specification of AFPM generator

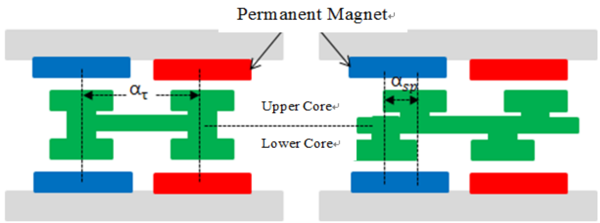
Design parameter		Values
Pole number / Phases Number of slots		24 / 3 18
Core length Air gap		59 mm 1mm
Stator	Outer Dia. / Inner Dia.	Ø395mm / Ø235mm
	Coil cross-section area	0.3 mm^2
	Coil turns	200 Turn
	Current density	3.75 A/ mm^2
	Core material	Cast iron
Rotor	Magnet	NdFeB Br 1.38[T]
	Core material	Cast iron

3. Cogging Torque for Stator Pole Arrangements

3.1 Stator Core Position

In order to reduce the cogging torque of generator, we investigated the influence of the variations of stator pole positions on the cogging torque. The stator poles are composed of upper and lower core as shown in Fig. 4.

In Fig. 4, α_τ is pole pitch and α_{sp} mechanical angle between upper and lower stator poles. For difference mechanical, the cogging torque was calculated. The cogging torque of a basic model with no mechanical was shown to be 8.99[N m]. The minimum value of the cogging torque was 2.09[N m] when the mechanical angle was 2.5 degree, which is about 77% less than that of the original shape. The simulation results for different mechanical angles are summarized in Table 2. Fig. 5 shows the cogging torque with the rotor position at different mechanical angles.



(a) $\alpha_{sp} = 0$ (b) $\alpha_{sp} \neq 0$

Fig. 4. Two types of stator core arrangements.

Table 2. Cogging torque with different mechanical angle

α_{sp}	0[°]	1[°]	2[°]	2.5[°]	3[°]	5[°]
τ_{DD} [N m]	8.99	8.11	6.71	2.09	4.63	13.5

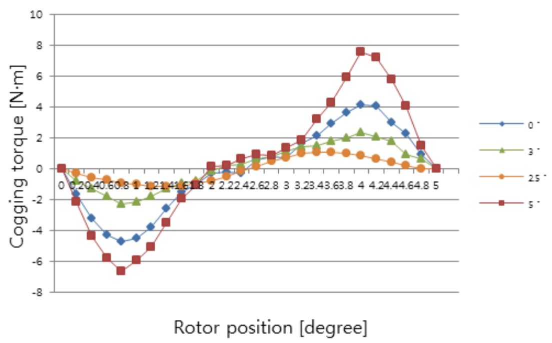
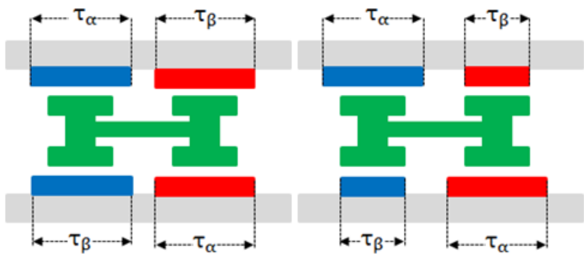


Fig. 5. Cogging torques with rotor position for different mechanical angles.

3.2 Different Magnet Pitch

Next, we investigated whether different magnet pitches had an influence on reducing the cogging torque of the generator. Fig. 6 shows the different magnet pitches.



(a) Same pitches (b) different pitches

Fig. 6. Two types of magnet pitches.

The simulation results for different magnet pitches are summarized in Table 3. Fig. 7 shows the cogging torques from different combinations of magnet pitches

Table 3. Cogging torque with different magnet pitch [N m]

τ_α \ τ_δ	43[mm]	40[mm]	38[mm]	37[mm]	34[mm]
43[mm]	5.16	4.48	2.64	1.8	2.48
40[mm]	4.48	5.04	2.88	1.52	2.18
38[mm]	2.64	2.88	4.14	4.35	2.8
37[mm]	1.8	1.52	4.35	5.2	4.33
34[mm]	2.48	2.18	2.8	4.33	4.26

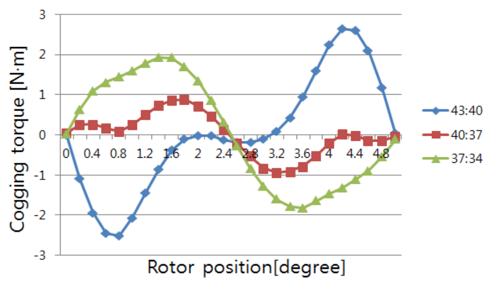


Fig. 7. Cogging torques with different combinations of magnet pitches.

4. Optimum Design of AFPM Generator Using Response Surface Method and FEM

4.1 Optimum Design of AFPM Generator

In this step, the stator pole arrangements and magnet pole pitches were applied as the design variables to reduce the cogging torque. In order to reduce the design experiments of calculation, response surface method was used. 3D finite element method was used for calculation at each design experiment. Fig. 8 is the flow chart of the optimum design using response surface method.

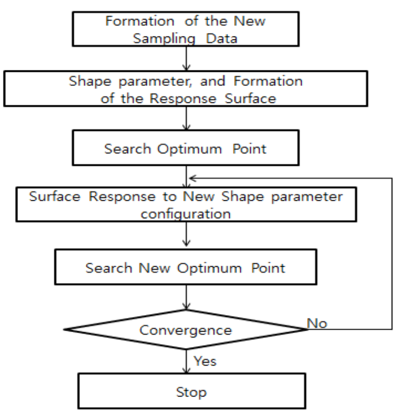


Fig. 8. Flow-chart of the optimum design algorithm.

Table 4. Cogging torque for design experiments

No.	Design variables			Cogging torque [N m]
	α_{sp} [°]	τ_α [mm]	τ_δ [mm]	
1	2.4	34	38.5	3.92
2	2.85	38.5	38.5	2.15
3	3.3	38.5	43	7.04
4	2.4	38.5	43	5.57
5	2.4	38.5	34	4.75
6	3.3	34	38.5	5.29
7	2.85	38.5	38.5	2.15
8	2.85	34	43	7.32
9	3.3	43	38.5	5.29
10	2.85	38.5	38.5	2.15
11	3.3	38.5	34	5.27
12	2.85	43	43	2.87
13	2.4	43	38.5	6.42
14	2.85	34	34	5.54
15	2.85	43	34	9.45

For three design variables, 15 experiments of design were btained using the Box-Benhken method as shown in Table 4.

4.2 Result and Discussion

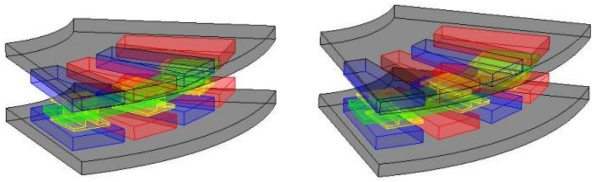
Table 5 shows a summary of the optimum values, which gives the minimum cogging torque at 1.42[N m] when the design variables were as follows: α_{sp} 2.79 °, τ_α 38.18mm and τ_δ 38.64mm.

Table 5. Cogging torques for different design models

Model \ Result	Design variable			Cogging torque [N m]	Decrease [%]
	α_{sp} [°]	τ_α [mm]	τ_δ [mm]		
Basic	0	43	43	8.99	-
Stator pole position	2.5	43	43	2.21	77%
Magnet pitch	0	37	40	1.52	82%
Optimum model	2.97	38.18	38.64	1.42	85%

In sum, the cogging torque was reduced by 85%

compared to that of the basic model. Fig. 9 shows the cogging torques of the basic and optimum models.



(a) Basic model geometry (b) Optimum model geometry

Fig. 9. AFPM machine geometry.

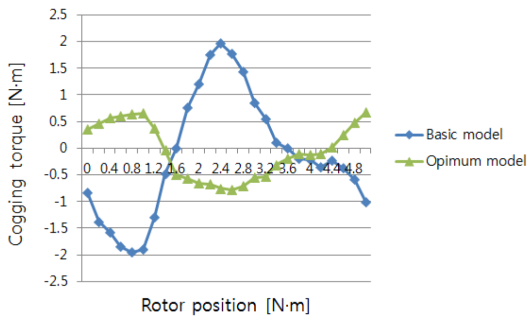


Fig. 10. Cogging torques of basic and optimum model.

5. Conclusion

We investigated the influence of stator pole arrangements on the cogging torque of 1kw double-sided AFPM generator. The optimum design was obtained using response surface method and 3D finite element method for three design variables – stator core position, magnet pole pitch, and the combination of the two. The cogging torque was reduced by 85% compared to that of the basic model. Future researches should be aimed to study the optimum design in consideration of the characteristics of the generator.

References

[1] J. F. Gieras, R. J. Wang, and M. J. Kamper, "Axial flux permanent magnet brushless machines," 2nd ed., Springer, pp. 1-19, 2008.

[2] F. Profumo, Z. Zhang, and A. Tenconi, "Axial flux Machines drives: a new viable solution for electric cars," *IEEE Trans. on Industrial Electronics*, vol.44, no.1, pp. 39-45, 1997.

[3] Z. Zhang, F. Profumo, and A. Tenconi, "Design of an axial flux Iinterior PM synchronous motor with a wide speed range," *Proceedings of International Conference on Electrical Machines*, vol.III, pp. 273-278, 1996.

[4] M. Aydin and M. Gulec, "Reduction of cogging torque in double-rotor axial-flux permanent-magnet disk motors: a review of cost-effective magnet-skewing techniques with experimental verification," *IEEE Trans. on Industrial Electronics*, vol.61, no.9, pp. 5025-5034, 2014.

[5] Gyeong-Chan Lee and Tae-Uk Jung, "Optimal cogging torque reduction design of dual stator radial flux permanent magnet generator," *15th European Conference on Power Electronics and Applications* (EPE), pp. 1-9, 2013.

[6] A. Mahmoudi, S. Kahourzade, N. A. Rahim, H. W. Ping, and M. N. Uddin, "Design and prototyping of an optimized axial-flux permanent-magnet synchronous machine," *Electric Power Applications*, vol.7, no.5, pp. 338-349, 349, 2013.

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