Research Report

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Optimal Rotor Design of Ultra-high Speed Axial Flux Permanent Magnet Motor for Cogging Torque and Torque Ripple Minimization

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코깅토크와 토크리플 저감을 위한 초고속 축방향 자속 영구자석 모터의 최적 로터 설계

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Optimal Rotor Design of Ultra-high Speed Axial Flux Permanent Magnet Motor for Cogging Torque and Torque Ripple Minimization

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Abstract - This paper introduces an ultra-high speed and small size axial flux permanent magnet (AFPM) machine for energy storage application. The target is to get sinusoidal back-EMF and reduce cogging torque and torque ripple of the machine. This is very important for the machine performance and smooth operation. The rotor magnet shape is used as a design variable and optimization is done through Kriging method and Genetic Algorithm (GA). Both no-load and full-load conditions are analyzed by 3-D Finite Element Method (FEM) and the results are then compared with the basic model.

1. Introduction

The use of small and very high speed electric machines has been an area of interest for certain applications such as aerospace flywheel energy storage systems in which the machine is required to operate at extremely high speed; i.e., of the order of hundreds of thousands of revolutions per minute (rpm) [1]. At such high speed, the machine performance should be carefully investigated such as cogging torque and torque ripple; to ensure its smooth operation. For these reasons, the machine should have sinusoidal back-EMF waveform since the cogging torque and torque ripple largely depends upon the harmonics present in the back-EMF waveform of the machine [2]. In this paper, the rotor pole shape is designed for a two-phase axial flux permanent magnet (AFPM) motor rotating at one million rpm to get sinusoidal back-EMF and minimize cogging torque.

2. Basic Model

The basic model is shown in Fig. 1, which is double-rotor and single-stator design. The stator consists of a slotless cylindrical ferrite core.

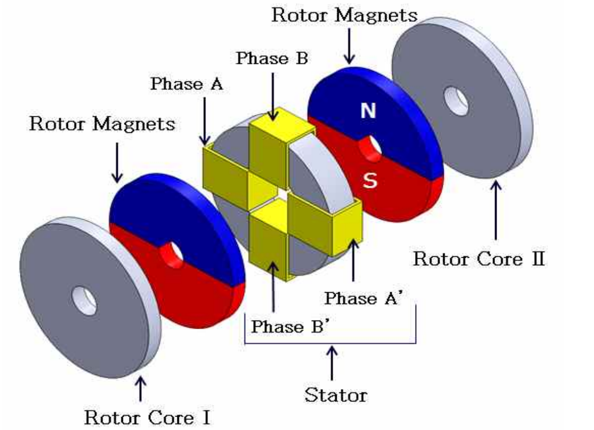

Fig. 1. Basic model showing different parts of the machine

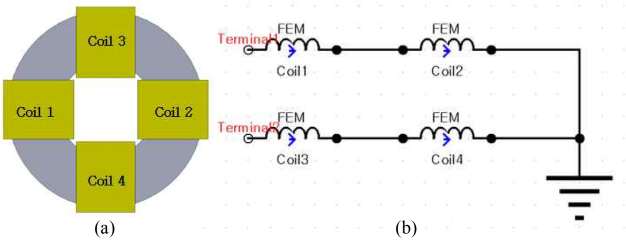

Fig. 2.(a) Stator core and coils (b) equivalent circuit diagram

The core is wound by four single turn copper coils forming two coils for each phase as shown in Fig. 2. The design comprises of two symmetrical rotors on both sides of the stator. Each rotor consists of one ferrite core and two permanent magnets as rotor poles. NdFeB (Hitachi Metals NEOMAX-42) is used as magnet material due to its high energy density [3]. In basic model, the magnets completely fill the rotor which makes the magnet shape a half circle. Table I shows the dimensions used in the machine design.

<Table I> Machine Dimensions

Item	Unit	Value
Stator Outer Diameter	mm	50
Stator Inner Diameter	mm	24
Rotor Outer Diameter	mm	52
Rotor Inner Diameter	mm	10
Air gap between rotor magnet and stator coil	mm	0.5
Rotor Core Thickness	mm	5
Magnet Thickness	mm	5
Stator Core Thickness	mm	10
Coil Thickness	mm	1
Coil Height	mm	18
Coil Width	mm	15
Clearance between Stator coil and Stator Core	mm	0.1
Number of Phases	-	2
Number of Turns per coil	-	1
Peak Current Density	A/mm^2	10
Rotor Angular Speed	rpm	1,000,000

3. Optimized Model

The basic criteria to optimize the rotor pole shape is to make a smooth magnet shape within the design domain to achieve the required target. Therefore, circular magnet shape is selected with radius of the circle 'R' as design variable. The center of the circle lies along the vertical axis as shown in Fig. 3. The circular arcs are always tangent to the rotor core boundary which is defined by R=26mm. The extra magnet part outside of the design domain is cut by the horizontal axis as shown. Linear samples are generated in this manner in design of experiments and no-load 3-D FEM simulation is carried out using JMAG® simulation software. Optimal value is selected based on Kriging method and genetic algorithm [4] using the design criteria shown below.

- ❖ Objective function
    - Minimize THD of Back EMF
    - Minimize Cogging Torque
- ❖ Design variable
    - Radius of the circle 'R'
- ❖ Constraints
    - 13mm 〈 R 〈 26mm
    - Magnet volume ≤ 5300 mm^3

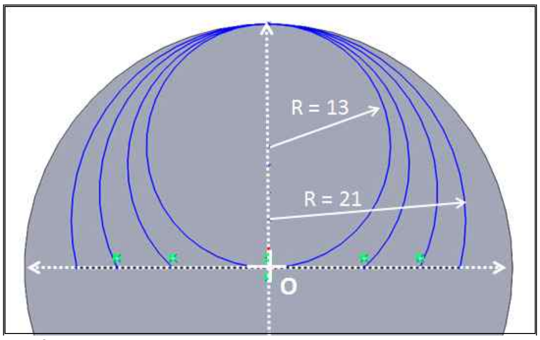

Fig. 3 Rotor showing various circular pole shapes in the design domain

4. Results

The optimal value of the circle radius found by this optimization is R = 20.953 mm. This value gives us the minimum value of back-EMF THD factor and cogging torque and finally the results are confirmed by 3-D FEM results. These results are plotted in Figs. 4-6. which clearly shows that machine performance has been greatly improved in terms of back-EMF, cogging torque and torque ripple.

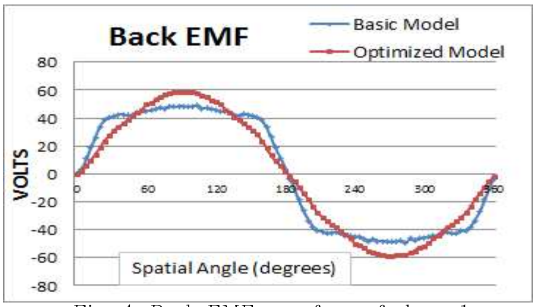

Fig. 4. Back-EMF waveform of phase-1

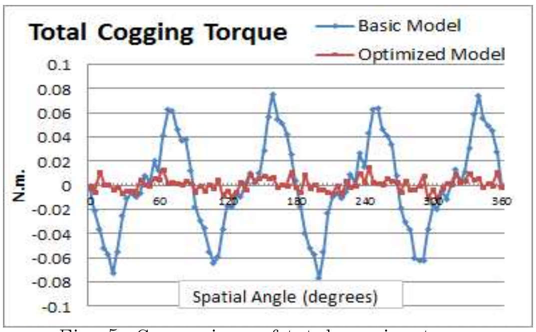

Fig. 5. Comparison of total cogging torque (Rotor-I torque + Rotor-II torque)

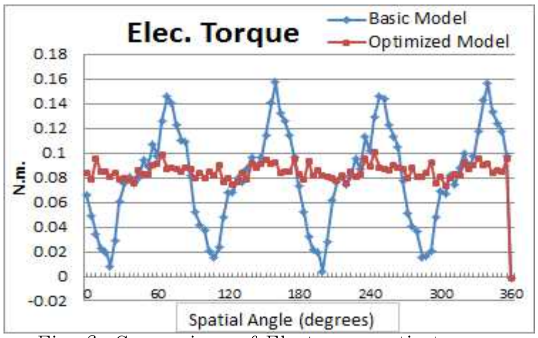

Fig. 6. Comparison of Electromagnetic torque (Rotor-I torque + Rotor-II torque)

Table II shows the performance comparison of all the models. The torque values are the sum of Rotor-I torque and Rotor-II torque.

〈Table II〉 Performance Comparison

Results	Unit	Basic Model	Optimized Model
Back-EMF (THD)	%	22.38	2.29
Back-EMF (RMS)	Volts	40.62	41.48
Cogging Torque (pk-pk)	Nm	0.1524	0.0259
Electromagnetic Torque (Average)	Nm	0.0803	0.0851
Torque Ripple	%	190.62	32.74

5. Conclusion

A small size and ultra-high speed AFPM motor has been introduced in this paper to improve its performance. The rotor magnet shape is used as a design domain to reduce the back-EMF THD and cogging torque of the machine. The 3-D FEM simulation results show that the optimized model has much lower values of back-EMF THD, cogging torque and torque ripple than the basic model. In future, more work will be done in terms of mechanical performance, loss and efficiency calculations.

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[References]

[1] Wensen Wang; Hofmann, H.; Bakis, C.E., "Ultrahigh Speed Permanent Magnet Motor/Generator for Aerospace Flywheel Energy Storage Applications," *Electric Machines and Drives, 2005 IEEE International Conference on* , vol., no., pp.1494,1500, 15-15 May 2005.

[2] Shah, S.Q.A.; Lipo, T.A.; Byung-il Kwon, "Modeling of Novel Permanent Magnet Pole Shape SPM Motor for Reducing Torque Pulsation," *Magnetics, IEEE Transactions on* , vol.48, no.11, pp.4626,4629, Nov. 2012

[3] Zheng, L.; Wu, T.X.; Sundaram, K.B.; Vaidya, J.; Zhao, L.; Acharya, D.; Ham, C.H.; Kapat, J.; Chow, L., "Analysis and Test of a High-Speed Axial Flux Permanent Magnet Synchronous Motor," *Electric Machines and Drives, 2005 IEEE International Conference on* , vol., no., pp.119,124, 15-15 May 2005.

[4] Jin-hee Lee; Byung-il Kwon, "Optimal Rotor Shape Design of a Concentrated Flux IPM-Type Motor for Improving Efficiency and Operation Range," *Magnetics, IEEE Transactions on* , vol.49, no.5, pp.2205,2208, May 2013.