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Experiments and Design Criteria for a High-Speed Permanent Magnet Synchronous Generator with Magnetic Bearing Considering Mechanical Aspects

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Abstract

In this paper, the design and experiment of a high-speed permanent magnet synchronous generator (PMSG) using magnetic bearing without mechanical friction were performed. The rotor size was derived using TRV method and analytical method. Rotor structure analysis was performed to verify the validity of the selected sleeve and PM thickness. And, the magnetic bearing was designed considering the rotor weight and DN-factor of the generator. Then, the validity of the proposed design method was verified by the electromagnetic and mechanical analysis, design and comparison with experimental results of the high-speed PMSG of 124kW, 36krpm.

Design Requirement Conditions

Table I. Design Requirement Conditions

Parameter	Value	Unit
Rated Power	124	kW
Power generation voltage (L-L)	380	V_{rms}
Operating temperature	180	℃
Rated speed	36	krpm
Input aerodynamic force	670	N
PM material	Sm_2Co_{17} (YXG-32)	
Colling type	Liquid	

- ✓ The generator designed in this paper is used for mid and low temperature waste heat recovery power generation system using supercritical organic rankine cycle.
- ✓ As it is used in the waste heat recovery system, the force of input aerodynamic force is high, it rotates at high speed, and the operating temperature is very high.
- ✓ Table 1 shows the design requirements of the generator.
- ✓ Permanent magnet of the designed generator used samarium cobalt with excellent magnet properties even at high temperature.

Magnetic Bearing Design and Characteristic Analysis

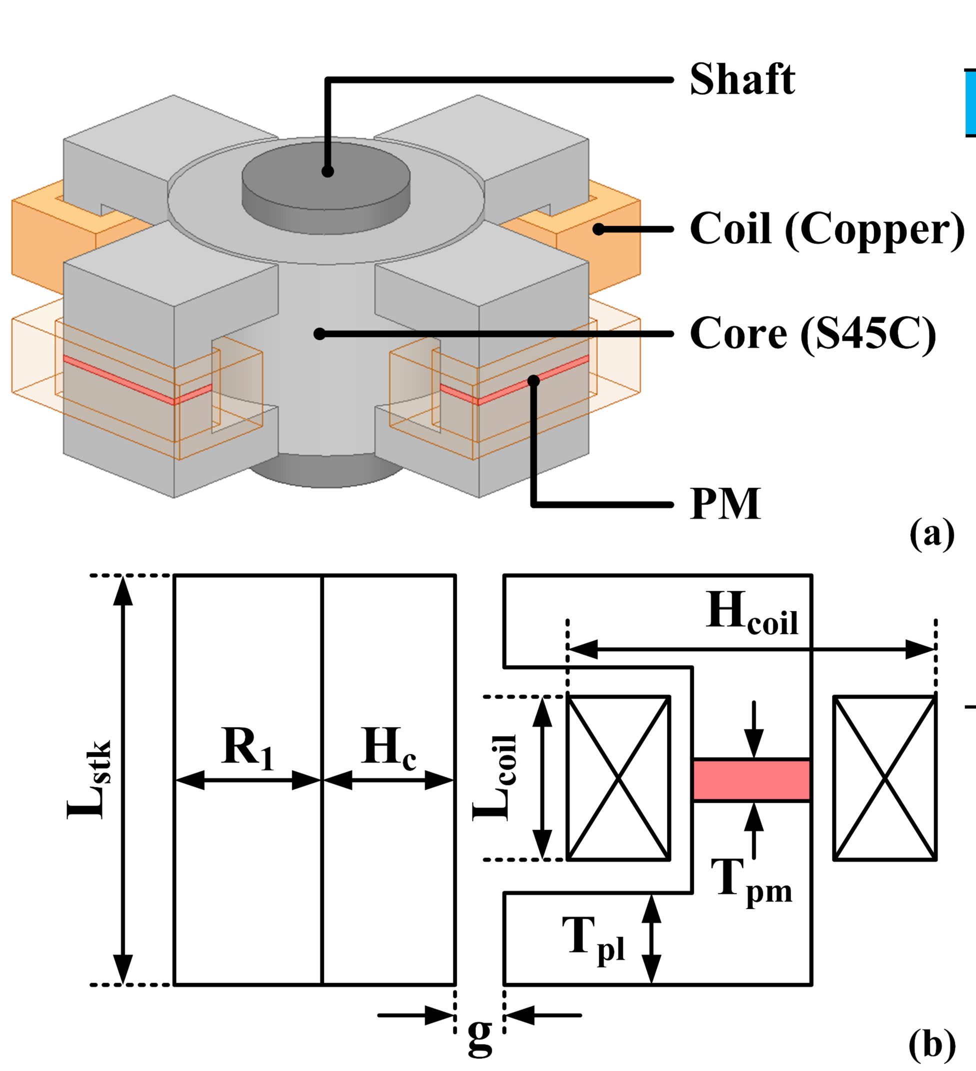

Fig. 1. (a) Structure of radial magnetic bearing (b) design variables of magnetic bearing

Table II. Design Parameters and Specification of Radial Magnetic Bearing

Parameter	Remark	Value
L_{stk}	Stack length	62 [mm]
R_1	Radius of shaft	18 [mm]
H_c	Core thickness	16 [mm]
L_{coil}	Coil length	24 [mm]
H_{coil}	Coil height	41.4 [mm]
g	Air-gap	0.4 [mm]
T_{pl}	Pole leg thickness	16 [mm]
T_{pm}	PM thickness	16 [mm]
θ	Pole angle	42 [deg.]
Max current		10 [A]
Turns		140

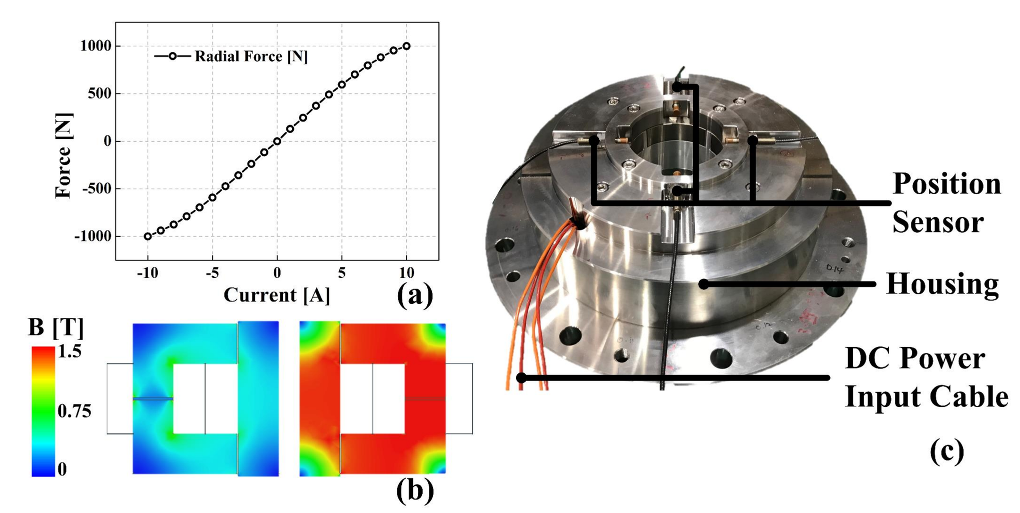

Fig. 2. (a) Radial force analysis result of radial magnetic bearing (b) radial magnetic bearing flux density (c) radial magnetic bearing prototype

- ✓ Magnetic bearing has a structure in which the rotor floats due to electromagnetic force when a current is applied to the coil.
- ✓ Magnetic bearings have the advantage of high speed rotation because they do not require physical friction and lubrication.
- ✓ Magnetic bearings must be designed with input aerodynamic forces in mind. Therefore, the radial magnetic force range of about 1,000N was selected in consideration of the safety factor 1.5 of the input aerodynamic force of about 670N applied to the bearing.
- ✓ Fig. 1 shows the structure and design parameters of a radial magnetic bearing designed for use in PMSG.
- ✓ Fig. 2 (a) and (b) show the results of the characteristic analysis of the designed radial magnetic bearings.

Initial Design Using Analytical Method and TRV

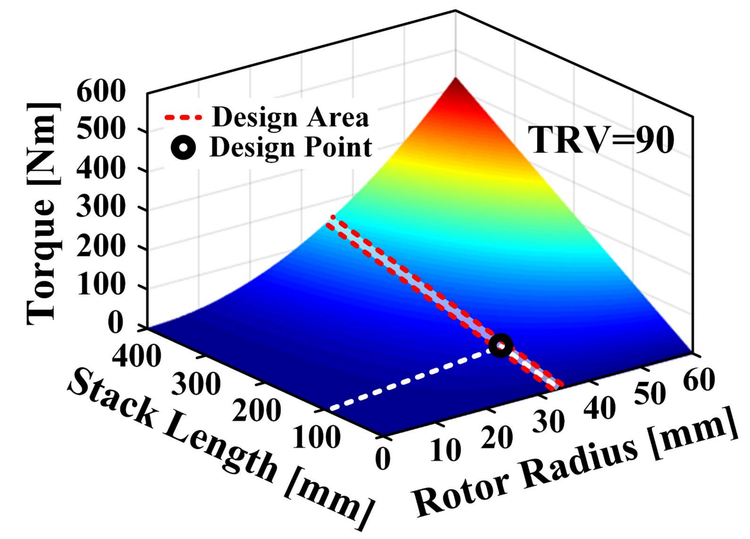

Fig. 3. Result of rotor size selection using TRV

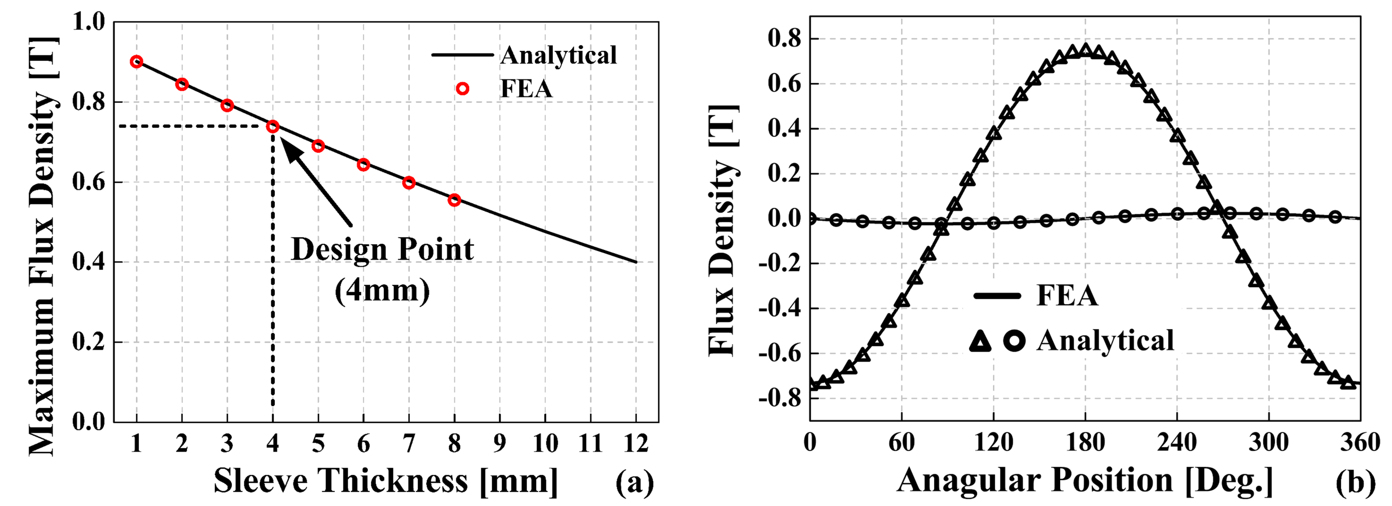

Fig. 4. (a) Air-gap magnetic flux density using FEA and analytical method (b) maximum air-gap magnetic flux density by sleeve thickness using FEA and analytical method (○: normal component B_r, △: tangential component B_{th})

- ✓ In this paper, the validity was verified through TRV method considering the selected rotor size 68mm during the magnetic bearing design.
- ✓ Fig. 4 (a) shows the change of maximum magnetic flux density of air-gap according to sleeve thickness by using FEA and analytical method through loading separation.
- ✓ Fig. 4 (b) shows the magnetic flux density distribution of air-gap derived by FEA and analytical method based on selected sleeve and PM size.

Mechanical Characteristics

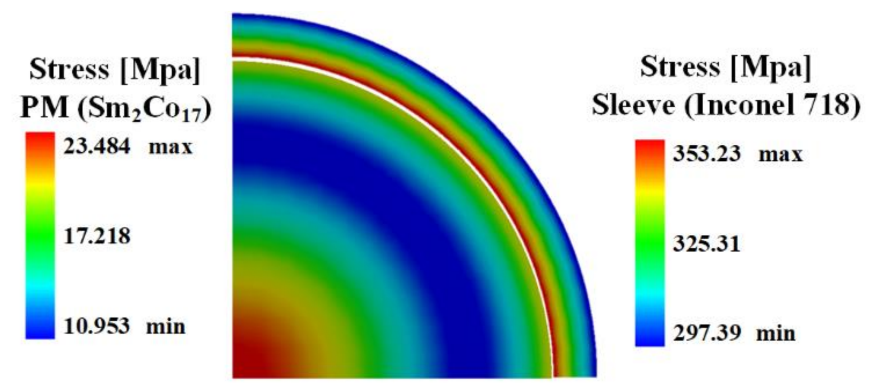

Fig. 5. Result of stress analysis of sleeve and PM

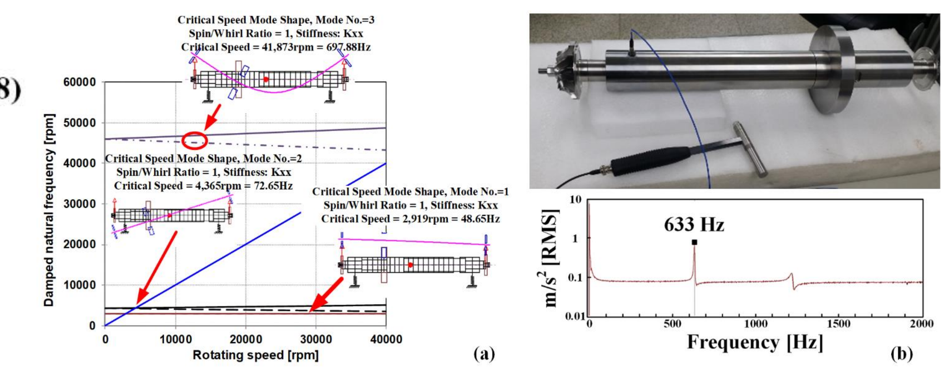

Fig. 6. Result of critical speed (a) FEA (b) experiment

Table III. Design specifications of PMSG

Parameter	Value
Outer diameter of rotor	68 [mm]
Outer diameter of stator	200 [mm]
Inner diameter of stator	72 [mm]
Stack length	97 [mm]
Sleeve thickness	4 [mm]
Air-gap	2 [mm]
Turns	3
Number of slots	24

- ✓ A machines that rotate at high-speeds involve various structural problems due to the centrifugal force of the rotor. In this paper, the mechanical characteristics of the designed high-speed PMSG rotor are analyzed.
- ✓ Fig. 5 shows the stress analysis results for the permanent mag-net and sleeve material of the selected size. The analysis results showed that each material does not deviate from the yield stress and has no structural problems.
- ✓ Fig. 6 (a) shows the analysis results of critical speed characteristics of the rotor using FEA.
- ✓ It was confirmed that there was no problem with the rotor de-signed as there were no points of intersection with the critical speed and bending frequency at the rated speed (36,000 rpm).

Conclusion

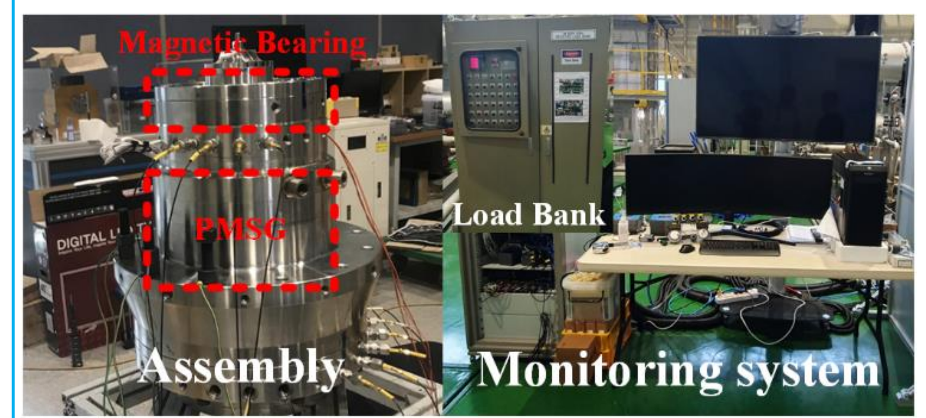

Fig. 7. Experimental evaluation test bed

Table IV. Comparison of FEA and experimental results

Parameter	FEA	Experiment
Phase resistance [Ω]	16.08	16.2
L-L Inductance [μH]	773.9	774.8
Output power [kW]	125.27	124.98
L-L voltage [V_{rms}]	391.42	389.94
Efficiency [%]	97.08	69.02

- ✓ In the high-speed rotation of the rotor, we have overcome the mechanical disadvantages and design the magnetic bearing to meet the requirements.
- ✓ The designed PMSG was fabricated and the results were satisfied to the requirements of the performance evaluation and the experiment and the validity and reliability of the design method were verified.