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Research paper

Characteristic Analysis of 8kW Class High-Speed Permanent Magnet Synchronous Motor

Tae-Kyoung Bang[1], Kyung-Hun Shin[2], Jeong-In Lee[3], Hoon-Ki Lee[4], Han-Wook Cho[5], Pan-Gun Park[6], Jang-Young Choi [*7]

[1 2 3 4] Dept. of Electrical Engineering, Chung-nam National University, 99, Dae-hak-ro, Yusung-gu, Daejeon, 34134, Republic of Korea
[5]Dept. of Electric, Electronic & Communication Eng. Edu. Chung-nam National University, 99, Dae-hak-ro, Yusung-gu, Daejeon, 34134, Republic of Korea
[6]Dept. of Radio and Information and Communication Engineering, Chung-nam National University, 99, Dae-hak-ro, Yusung-gu, Daejeon, 34134, Republic of Korea
[7]Dept. of Electrical Engineering, Chung-nam National University, 99, Dae-hak-ro, Yusung-gu, Daejeon, 34134, Republic of Korea
Corresponding author E mail: choi_jy@cnu.ac.kr

Abstract

Background/Objectives: This paper deals with characteristic analysis of High-Speed Permanent Magnet Synchronous Machine (High-Speed PMSM) for air-blower by using FEM (Finite Element Method) S/W tools and analytical method.
Methods/Statistical analysis: The High-Speed PMSM need the protective tube with non-magnetic materials that protect the scattering of permanent magnet, for preventing the damage of the High-Speed PMSM, it is necessary that analyzed about mechanical analysis.
Findings: The results of the stress analytical method are compared with the results of FEM analysis that validated the analytical method of stress analysis. Based on the results of the analysis, an analytical model was fabricated. Through the experiments, the presence of rotor breakage was examined and the performance was measured.
Improvements/Applications: The analysis methods presented in this paper could be applied to characteristic analysis of the high-speed permanent magnet machine.

Keywords: *mechanical stress analysis, interference fit, analytical method, high-speed PMSM, electromagnetic analysis, characteristic analysis*

1. Introduction

To build a high-performance pump and blower system, it is important to increase the speed and accuracy of electrical equipment. In addition to increasing the efficiency of the system, high output and high efficiency of the electric device are required, and the technology and research of the high-speed motor using the permanent magnet are developing. PMSM is adopted as a permanent magnet motor for high-speed operation. The IPM is not only difficult to control due to the generation of reluctance torque but also has a disadvantage in that it is complicated in structure and difficult to manufacture because permanent magnets are built in the rotor. On the other hand, the SPM is very easy to manufacture and control, but have the disadvantage that the performance range of field weakening is narrow. However, the structure is simple and suitable for high-speed operation [1]. For the design of a high-speed permanent magnet machines, the initial size was derived through the TRV equation. Through the initial size, mechanical stress analysis was performed and designed to the rotor and sleeve size[2]-[6]. The electromagnetic characteristics analysis of the high - speed permanent magnet machines was analyzed.

2. The Characteristic Analysis of High Speed PMSM

The design process of high-speed permanent magnet machines should be designed to minimize the damage of the machines system by mechanical breakage at high speed[7]-[10]. To prevent the damage of the system, mechanical and electromagnetic analysis of the rotor must be performed at initial design stage. Therefore, in this paper, the design range of the rotor size is derived using the TRV method and it is selected within the safe range through the stress analysis of the rotor. Through the experiment, the manufactured model validate the analysis method. Fig. 1 shows the design parameters according to the design requirements.

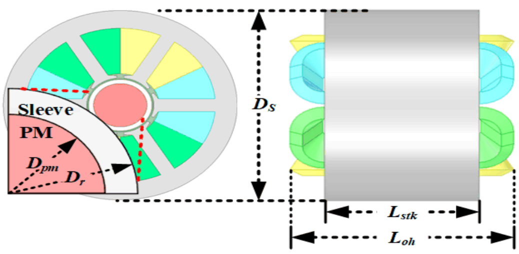


Figure 1: The design variable according to the following design requirement

Table 1: The TRV range of Machines type[10]

Type of the Machine	TRV (kNm/m^3)
Small totally-enclosed machines (Ferrite)	7 – 14
Totally-enclosed machines (Sintered Rare Earth or NdFeB)	14 – 42
Totally-enclosed machines (Bonded NdFeB)	21
Integral-hp industrial machines	7 – 30
High-performance servo machines	15 – 50
Aerospace machines	30 – 75
Large liquid-cooled machines	100 - 250

2.1. Selection of Rotor Size

For choosing the rotor size of machines, typical method employed by using TRV. TRV means torque per rotor volumes that is related endurable stress on the surface of rotor. Using the rotor volumes, it is composed the equation and it is derived rotor diameter and axial length by using TRV equation as follow equation (1) [10].

$$TRV = \frac{Torque}{\pi \cdot D_{ro}^2 \cdot L_{stk}} (1)$$

Here, the D_{ro} is the rotor diameter, L_{stk} is the effective axial length. The table 1 is shown the range of TRV value by considering the materials of PM. The analysis model of the HS-PMSM choose the TRV values of the high performance servomotors and it is necessary that need the high-performance for using air-blower, the range of the TRV value chosen the 15-50.

Figure 2.is shown the graph of the rotor and axial stack length size based on TRV value and the shape of design model. In the graph, design range is selected according to the following design specification. The table 2.is shown as the design specification of the high speed PMSM.

2.2. Mechanical Stress Analysis of Rotor

Operating the PMSM safely at rated speed, mechanical stress analysis result should be considered that the rotor of PMSM manufactured by employing the shrinkage fitting and varies with the PM and sleeve diameter by cylindrical interference of shrink fit. Mechanically, if the stress of the rotor is not considered in initial stage, the stress occurs over the yield strength of the rotor material that generate damage of the machines systems. Therefore, it is necessary that choose the suitable design variable parameter for operating safely with operation range, in order that choose the design parameter, it is necessary that the analysis results of stress are derived by using analytical method [2].

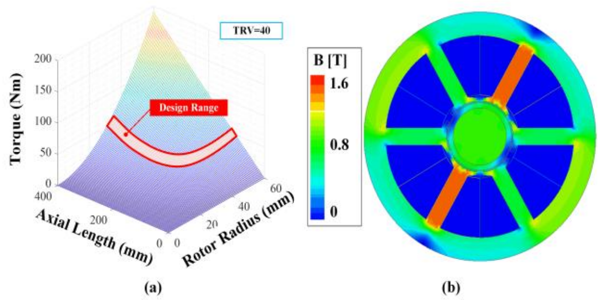


Figure 2: The Design Variable Range according to the following Design Specifications: (a) the design variable range (b) design model shape

Table 2: The Design Specification

Parameter	Value	Parameter	Value
Max Power	9.5 [kW]	Rotor Diameter Limits	30[mm]
Rated Torque	1.25 [Nm]	Axial Length Limits	125 [mm]
Max Speed	65000 [rpm]	Permanent Magnet	Sm_2Co_{17}

The equations of the mechanical stress by shrinkage fitting are described as follow equation (2) – (5). The stress of the rotor is influenced by occurring the compressive force due to the interference fit length. Therefore, it should be derived by according to interference fit length. The compressive force could be derived by using equation (2) [2],[3].

$$p = \frac{\delta}{b[\frac{1}{E_o}\left(\frac{c^2+b_o^2}{c^2-b_o^2}+v_o\right)+\frac{1}{E_i}\left(\frac{b_i^2}{b_i^2}\right)+v_i]} \quad (2)$$

Here, δ is the interference length, c is the rotor diameter, b_o is the sleeve diameter by interference force, b_i is the PM diameter by interference force, E_o is the young's modulus of the sleeve, E_i is the young's modulus of the PM, v_o is the poisson's ratio of sleeve, v_i is the poisson's ratio of PM, p is the compressive pressure on PM.

Derived the interference force, it used the equation of the mechanical stress as follow [2]

$$\sigma_{iw} = \frac{3+v_i}{8}\rho\omega^2[b^2 - r^2] \quad (3)$$

$$\sigma_{ow} = \frac{3+v_i}{8}\rho\omega^2\left[b^2 - \frac{1+3v_i}{3+v_i}r^2\right] \quad (4)$$

$$\sigma_{von-mises} = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2} \quad (5)$$

Here, ρ is the mass density of the each material ω is angular speed of the machines, r is the radius of the rotor, σ_1, σ_2 are the each stress of the rotor.

The table 3.is shown as the material parameter data of the PM and sleeve for analytical method, since, the yield strength of PM and sleeve is 35 and 1100 MPa, the maximum point of the mechanical stress should be designed to be lower than the yield strength to prevent the damage of the electrical machines [2].

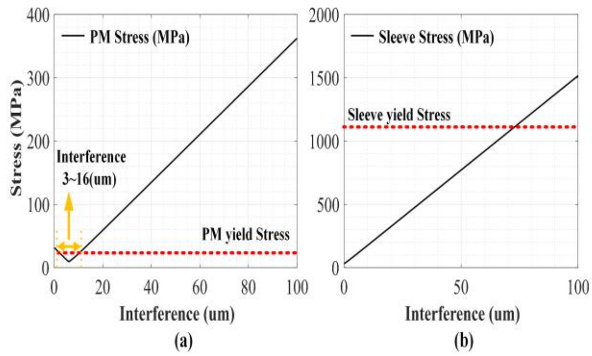


Figure 3: The analytical results of von - mises stress according to interference length: (a) PM stress (b) Sleeve stress

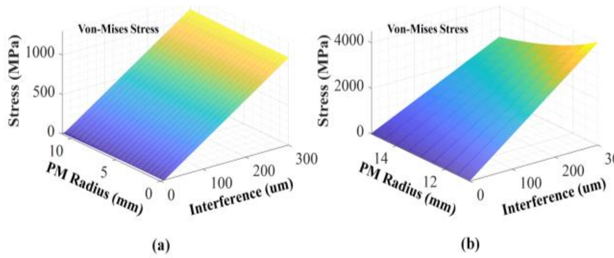
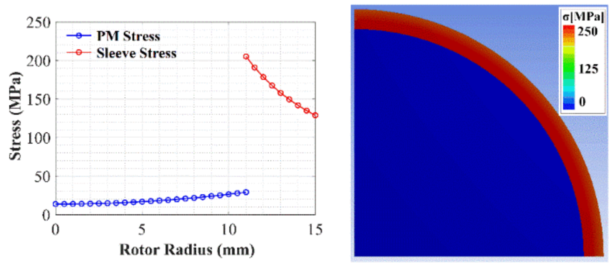


Figure 4: The analytical results of von - mises stress according to interference length and rotor Radius: (a) PM stress (b) Sleeve stress

Table 3: The material parameter data of the PM an Sleeve

Parameter	PM	Parameter	Sleeve
Poisson's ratio	0.24	Poisson's ratio	0.284
Young's modulus	120 [MPa]	Young's modulus	205 [MPa]
Density	8300 [kg/m^3]	Density	8190 [kg/m^3]
Yield Strength	35 [MPa]	Yield Strength	1100 [MPa]



(a) (b)

Figure 5: The analytical results of von - mises stress at interference length 13um: (a) PM stress (b) Sleeve stress

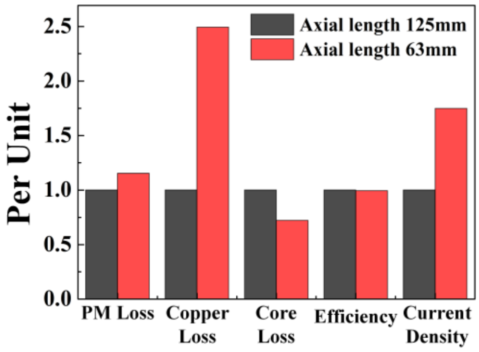


Figure 7: The comparison of the characteristic analysis results according to the D-L ratio

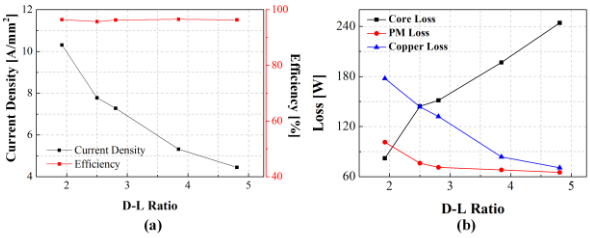


Figure 6: The results of the analysis on the D-L ratio (a) current density and efficiency (b) Loss

The analytical results of the mechanical stress by the shrinkage fit are shown as Fig. 3. and Fig. 4.. According to analytical results, the design range of PM and sleeve interference fit length are derived between 3 and 16um by comparing yield strength. Therefore, to consider the mechanical stress results occurring between the PM and Sleeve, the interference length is chosen 13um. Fig. 5(a) shown the results of the analytical method that employ the derived interference fit length. The Fig. 5 (a) and (b) are shown the validity of the analytical method of the mechanical stress. The maximum point of the stress of PM and Sleeve is about 25Mpa and 215MPa thus, it is considered that there is no the problem of the strength due to the stress of rotor.

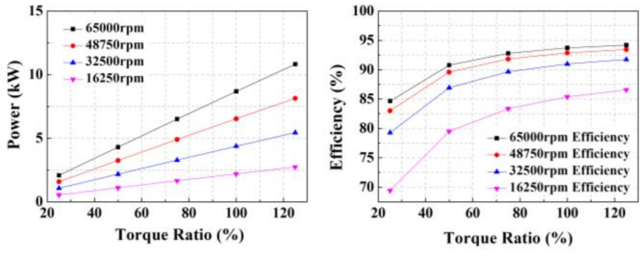
2.3. Electromagnetic Characteristic Analysis of PMSM

2.3.1. Characteristic Analysis of PMSM According to D-L Ratio

The design model was designed according to the D-L ratio that satisfies the target output as the design aimed at the minimum axial length within the mechanical limit. The results of the analysis on the D-L ratio at this time are shown in Fig. 6. The analysis results show that the current density decreases and the loss increases according to the D-L ratio. The analysis results show that the design specification limits is satisfied when the D-L ratio is larger than 2.4, therefore, the optimal axial length 63 mm was derived. Fig. 7 shows the comparison of the analysis results according to the axial length.

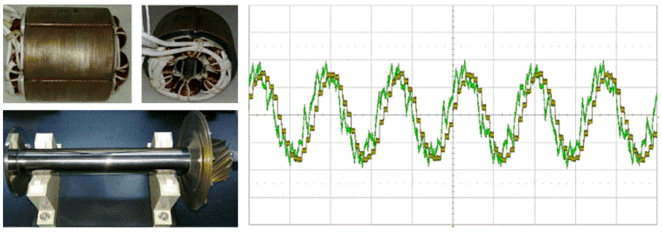
2.3.2. Characteristic Analysis of PMSM

For the design that satisfies the output and efficiency according to the speed, the output and efficiency analysis according to the speed-torque are performed and the graph is shown in Fig.8. The characteristic analysis result of rated operation point is shown as table 4. The torque ripple satisfied the requirements with 6%. The characteristic satisfied the requirements design point. The rated torque is 1.25Nm, the efficiency of electromagnetic is 96.8%. The current density is suitably less than 10 for the design model. Since, this model is less than 8, there is no thermal problem of the machines.



(a) (b)

Figure 8: The comparison of the characteristics analysis results of high speed PMSM : (a) Power (b) Efficiency



(a) (b)

Figure 9: (a) the manufactured model of high speed PMSM for air blower, (b) the measurement results of manufactured model

Table 4: The analysis results of the high speed PMSM at rated power

Parameter	Value	Parameter	Value
Torque	1.36 [Nm]	Input Current	19.27 [A_{rms}]
Back-EMF	271[V_{rms}]	Core Loss	156.55[W]
Cogging Torque	6.74 [mNm]	PM Loss	75.12 [W]
Current density	7.78[A/mm^2]	Copper Loss	176.14[W]

3. Results and Discussion

The manufactured model of the HS-PMSM that based on stress analytical method and characteristic analysis is shown the Fig. 9 (a). The rotor of PMSM is made of shrink fit with interference length 13um. Fig. 9 (b).is shown as the results of input current waveform measurement and on load back-emf. According to the results of mechanical stress analysis, the rotor of PMSM has not fracture. Therefore, the analysis results of the high-speed PMSM has a validity.

4. Conclusion

This paper deals with the characteristic analysis of the HS-PMSM for air blower using the analytical results of the mechanical stress analytical method and electromagnetic finite element analysis. By using the analytical method, the size of the rotor is derived, then designed the motor by comparing the results and analyzed the electromagnetic characteristics. Based on analysis results, the manufacture model was constructed and verified through experiments.

Acknowledgment

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