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

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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]

<table>
<thead>
<tr>
<th>Type of the Machine</th>
<th>TRV (kNm/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small totally-enclosed machines (Ferrite)</td>
<td>7 – 14</td>
</tr>
<tr>
<td>Totally-enclosed machines (Sintered Rare Earth or NdFeB)</td>
<td>14 – 42</td>
</tr>
<tr>
<td>Totally-enclosed machines (Bonded NdFeB)</td>
<td>21</td>
</tr>
<tr>
<td>Integral-hp industrial machines</td>
<td>7 – 30</td>
</tr>
<tr>
<td>High-performance servo machines</td>
<td>15 – 50</td>
</tr>
<tr>
<td>Aerospace machines</td>
<td>30 – 75</td>
</tr>
<tr>
<td>Large liquid-cooled machines</td>
<td>100 – 250</td>
</tr>
</tbody>
</table>

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 to the design variable range on the surface of rotor. Using the volume, it is composed the equation and it is derived rotor diameter and axial length by using TRV equation as follow equation (1) [10].

\[
TRV = \frac{\text{Torque}}{\pi D_w L_{nk}} (1)
\]

Here, \(D_w\) is the rotor diameter, \(L_{nk}\) 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 specify 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].

\[
p = \frac{3\pi \sigma \omega^2}{8} \left[ \frac{b^2}{L_{nk}^2} - \frac{r^2}{L_{nk}^2} \right]
\]

Here, \(\delta\) is the interference length, \(c\) is the rotor diameter, \(b\) is the sleeve diameter by interference force, \(b\) is PM diameter by interference force, \(E_i\) is the young’s modulus of the sleeve, \(E_r\) is the young’s modulus of the PM, \(\nu_i\) is the poisson’s ratio of sleeve, \(\nu_r\) 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]

\[
\sigma_{iw} = \frac{3\pi \nu \rho \omega^2}{8} \left[ \frac{b^2}{L_{nk}^2} - \frac{r^2}{L_{nk}^2} \right]
\]

\[
\sigma_{ow} = \frac{3\pi \nu \rho \omega^2}{8} \left[ \frac{b^2}{L_{nk}^2} - \frac{1 + 3\nu_r}{3} \nu_r \right]
\]

\[
\sigma_{von-mises} = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}
\]

Figure 3 is shown 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].

![Image](image-url)

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

![Image](image-url)

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Power</td>
<td>9.5 [kW]</td>
<td>Rotor Diameter Limits</td>
<td>30 [mm]</td>
</tr>
<tr>
<td>Rated Torque</td>
<td>1.25 [Nm]</td>
<td>Axial Limits</td>
<td>125 [mm]</td>
</tr>
<tr>
<td>Max Speed</td>
<td>65000 [rpm]</td>
<td>Permanent Magnet</td>
<td>SmCo17</td>
</tr>
</tbody>
</table>

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].

![Image](image-url)

Table 2: The Design Specification

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![Image](image-url)

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

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson’s ratio</td>
<td>0.24</td>
<td>Poisson’s ratio</td>
<td>0.284</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>120 [MPa]</td>
<td>Young’s modulus</td>
<td>205 [MPa]</td>
</tr>
<tr>
<td>Density</td>
<td>8300 [kg/m³]</td>
<td>Density</td>
<td>8190 [kg/m³]</td>
</tr>
</tbody>
</table>
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.

### 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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References


