Design criteria and experiments considering the mechanical characteristics of high-speed permanent magnet synchronous generator of 8kW and 40krpm class

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Jeong-In Lee, Kyung-Hun Shin, Gang-Hyeon Jang, Tae-Kyoung Bang, Dong-Wan Ryu, and Jang-Young Choi
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ABSTRACT

In this study, we designed, analyzed, and tested a permanent magnet synchronous generator by considering the mechanical characteristics required for a high-speed PMSG in a UAV. The feasibility of the design was then validated by comparing experimental data with those of the finite elements method (FEM).

I. INTRODUCTION

Interest in unmanned aerial vehicle (UAV) has recently increased worldwide. UAVs are largely classified according to their use, either military or civilian, and are widely used in a variety of fields, such as remote sensing and disaster prevention. However, the inclusion of various devices increases the weight of the UAV system. Therefore, motors and generators that are designed to be highly efficient and lightweight are required in order to increase overall efficiency. To meet these demands, high-speed devices that are directly connected to, and driven by, direct drivers or turbines are used. High-speed devices are used in various industrial applications because they are advantageous from the perspectives of system miniaturization, efficiency, and cost. However, a variety of electrical and mechanical problems have been identified, including mechanical stress of the rotor due to high-speed rotation, and core loss due to high-frequency operation, bearing technology, heat dissipation, and cooling.

In this paper, we report the design of a high-speed permanent magnet synchronous generator (PMSG) by considering the electromagnetic and mechanical characteristics required for a high-speed PMSG in a UAV. The feasibility of the design was then validated by comparing experimental data with those of the finite elements method (FEM).

II. ELECTROMAGNETIC DESIGN CONSIDERING MECHANICAL CHARACTERISTIC

A. Selection of rotor size

The PMSG designed in this study rotates at high-speed, is limited in size, and was chosen to be air-cooled on the basis of system...
TABLE I. Design restrictive condition.

| Parameter       | Value | Unit |
|-----------------|-------|------|
| Rated power     | 8     | kW   |
| Rated speed     | 40    | krpm |
| Current density | 5     | A/mm²|
| Limited stack length | 50  | mm   |
| Output Voltage  | 220   | V rms|

requirements. Table I lists the restrictions placed on the high-speed PMSG for UAV applications. In general, the rotor volume of an electric machine can be determined using the torque per rotor volume (TRV) method. However, the TRV value depends on the device design, the presence of a permanent magnet (PM), and the material that the PM is constructed of. Once the TRV value has been determined, the outer diameter ($D_{ro}$) and the stack length ($L_{stk}$) of the rotor can be calculated using equation (1):

$$TRV = \frac{T_e}{\left(\pi/4 \cdot D_{ro}^2 \cdot L_{stk}\right)}$$

The TRV value of the designed generator was chosen to be 50 because the PM used is composed of samarium cobalt. Fig. 1(a) shows how the outer radius of the rotor and the stack length are determined by considering the restrictive conditions of the PMSG and the tangential velocity of the rotor. An initial design that is highly efficient and produces higher power density at the selected rotor size was subsequently created using an analytical method that considers the ratio of the electrical loading to the magnetic loading. The analytical method has the advantage that it responds to design variables faster than FEM; hence, it is useful in the initial design stages where variables change frequently. Equation (2) expresses equation (1) in terms of electrical loading and magnetic loading, and was used to calculate the rational air-gap flux density of the rotor.

FIG. 1. (a) Rotor size selection using TRV method (b) air-gap magnetic flux density using analytical method.

FIG. 2. Stress analysis of rotor (a) prediction of von-Mises stress using (b) analytical results of von-mises stress according to interference length (c) analytical results of von-mises stress at interference length: 20µm (d) FEM result of von-mises stress.
high-speed PMSG.

\[ TRV = \frac{\pi}{\sqrt{2}} k_w A_{m} B_{g, \text{max}} \eta \cos \phi \]  

(2)

where \( k_w \) is the stator winding factor, \( \eta \) is the machine efficiency, \( \cos \phi \) is the power factor, \( B_{g, \text{max}} \) is the air-gap maximum magnetic flux density, and \( A_{m} \) is the maximum current density of the electric loading. The pore magnetic flux density calculated by equation (2) is about 0.6-0.7T. Fig. 1(b) compares the air-gap flux densities determined by the analytical method and FEM, which reveals a good match.

B. Sleeve thickness selection and mechanical structural analysis

A device that rotates at high-speed has a structure that encloses a PM with a shrinkage fitting sleeve in order to prevent scattering and breakage of the PM. The sleeve is mainly composed of non-magnetic materials; hence, the electromagnetic air-gap increases with increasing sleeve thickness, which may reduce generator performance. Therefore, the thickness of the sleeve should be determined by considering the required electromagnetic performance and mechanical properties. The most important factor in determining the thickness of the sleeve is the outer diameter of the rotor and the interference length. The interference forces in the tangential and radial directions generated in the PM are expressed in the same manner as equation (3), with the centrifugal forces in the tangential and radial directions of the PM and sleeve expressed by equations (6) and (7).

\[ \sigma_{\text{int}} = -p \frac{a^2}{(b^2 - a^2)} \frac{b^2}{r^2} \]  

(4)

\[ \sigma_{\text{ir}} = -p \frac{a^2}{(b^2 - a^2)} \frac{b^2}{r^2} + 1 \]  

(5)

where \( \rho \) is the mass density, \( r \) is the stress-analysis radius, \( \sigma_1 \) and \( \sigma_2 \) are the stress components of the PM and sleeve, respectively, which should be designed so as not to deviate from the yield stress of each material.

Fig. 2(b) and (c) show the stress-analysis results of the rotor as functions of interference and sleeve thickness. At this time,
interference lengths that do not exceed the yield stresses of the PM and the sleeve are revealed. The indentation amount was chosen to be 20 \( \mu m \) by considering a mechanical safety factor of 1.5. Fig. 2(d) shows the stress-analysis data of the rotor using the analytical method, which show that yield stresses do not deviate from those of the rotor materials. The results of the analysis method and the characteristics comparison with the FEM were verified to confirm their validity. Therefore, the shape and fabrication parts of the model, designed with high-speed PMSG requirements and electromagnetic and mechanical properties in mind, are shown in Fig. 3.

III. EXPERIMENT AND VERIFICATION

Fig. 4 shows the test bed used to evaluate the performance of the fabricated high-speed PMSG for UAV applications. The test method was to build a back-to-back method using a high-speed motor and PMSG. In order to drive the high-speed motor, the output characteristics of the PMSG were evaluated using a commercial inverter for control. Fig. 5 compares the characteristics of the PMSG obtained by FEM and experimental testing. Fig. 5(a) shows the back EMF of the PMSG at no load, while (b) shows the generated voltage and current characteristics as functions of the speed of the PMSG at load. At no load, back-EMF was measured at approximately 2740rpm for ease of experiment. The FEM and experimental load characteristics at the rated speed were compared, which revealed a voltage error rate of about 1.3% and a current error rate of about 1.8%. Therefore, the output performance of 9.06 kW was verified at the final design target of 40krpm.

IV. CONCLUSION

In this study, we designed an 8kW and 40krpm class high-speed PMSG for UAV applications by considering the required mechanical characteristics. During the initial PMSG design, the rotor size was selected by determining the air-gap flux density on the basis of the electrical and magnetic loading using the TRV method. The structure was then analyzed by selecting the interference length of the sleeve and by considering the required structural characteristics, which led to an optimum sleeve thickness devoid of structural problems. After confirming by structural analysis that the rotor was problem-free, the high-speed PMSG was manufactured and its performance verified against the design criteria presented in this paper. Performance testing confirmed the suitability of FEM, with error rates well within 2%.

Therefore, the design method presented in this paper is reliable and may also be applicable to various future high-speed PMSGs.

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