

Design Optimization of PMSM Considering Shaft-to-Frame Voltage Increase Due to Tapered Rotor

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A rotor shape with tapering is a widely adopted design technique that sinusoidalizes the air-gap flux to reduce back-electromotive force (B-EMF) total harmonic distortion (THD) and cogging torque. However, as the air-gap length distribution changes, the parasitic capacitance caused by the geometry of the motor also varies, which significantly affects the shaft-to-frame voltage, leading to motor lifespan degradation due to bearing currents. Therefore, this paper analyzes the changes in parasitic capacitance and shaft voltage caused by the rotor shape with tapering, and employs a theoretical model to investigate them. The trend of parasitic capacitance and its effect on shaft voltage, analyzed through the theoretical approach, are validated by electrostatic finite element analysis (FEA). The validation results show that applying a tapered rotor increases the shaft-to-frame voltage, confirming it as a factor to be considered in the design process. Therefore, the B-EMF THD, average torque, and shaft-to-frame voltage are set as objective functions, and an optimal design is performed using a machine learning-based niching genetic algorithm (NGA). Finally, prototypes of the initial and optimized model with a rotor tapered are manufactured, and the results are validated through no-load, load conditions, and shaft-to-frame voltage experiments.

Index Terms— back electromotive force, bearing current, cogging torque, electric erosion, optimization, shaft-to-frame voltage

I. INTRODUCTION

MOTOR design must consider various performance factors such as power density and efficiency, with recent emphasis on reducing vibration and noise, where back-electromotive force (B-EMF) and cogging torque are key factors. The B-EMF total harmonic distortion (THD) has a significant influence on torque ripple, harmonic current, and inverter capacity increase [1]. Additionally, cogging torque is generated by the interaction between the rotor and stator teeth and is a source of noise and vibration in the motor [2]. Therefore, design techniques such as rotor skewing, notching, and tapered rotors are being studied to mitigate B-EMF THD and cogging torque. However, the tapering method requires changes in the air-gap length distribution, leading to variations in the shaft-to-frame voltage. Therefore, when applying the tapering, it is necessary to consider not only B-EMF THD and cogging torque but also shaft-to-frame voltage.

The shaft-to-frame voltage is one of the factors that can cause bearing failure. In electric motors, bearing failures caused by shaft-to-frame voltage are a significant issue. The common mode voltage (CMV) generated by pulse width modulation inverters induces shaft-to-frame voltage through the parasitic capacitance caused by the motor geometry [3]. If this voltage exceeds the threshold of the bearing oil film, it causes insulation breakdown and electric discharge machining (EDM) currents. These lead to bearing surface damage and reduce the lifespan of the motor [4]. Therefore, this paper analyzes the effect of a tapered rotor on shaft-to-frame voltage, employing a theoretical model. This result confirms that a tapered rotor poses a risk of increasing shaft-to-frame voltage. Additionally, an optimal design is performed using a machine learning-based niching genetic algorithm (NGA) to find a compromise between shaft-to-frame voltage and electromagnetic characteristics. Finally, the initial model and the optimized model are manufactured, and the results are validated through experiments.

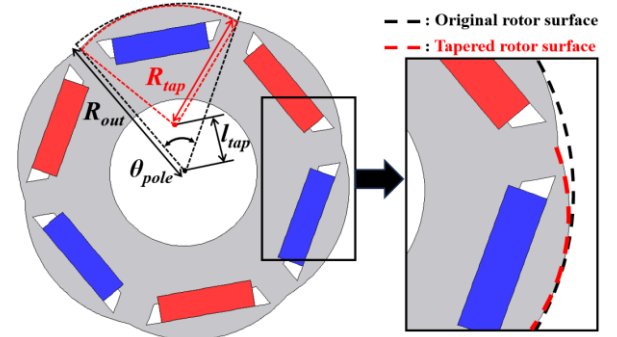


Fig. 1. Geometry and design variables of the tapered rotor

TABLE I
MOTOR REQUIREMENT AND SPECIFICATION

Specification	Value
Motor type	IPMSM
Pole / Slot	6 / 9
Rated torque	1.5 [Nm]
Rated power	300 [W]
Rated speed	2,000 [rpm]

II. THEORETICAL MODEL OF PARASITIC CAPACITANCE FOR A TAPERED ROTOR

The geometry and design variables of the tapered rotor for reducing B-EMF THD and cogging torque is illustrated in Fig. 1. The rotor is tapered by a circle with a radius of R_{tap} centered at a point located l_{tap} radially away from the origin. The R_{tap} is the value obtained by subtracting l_{tap} from R_{out} . The rotor surface is tapered, resulting in a non-uniform air-gap between the rotor and the stator. Such a non-uniform air-gap distribution causes variations in the parasitic capacitance, which is a key factor in the shaft-to-frame voltage.

The CMV and parasitic capacitance generate shaft voltage through electrical coupling, and the shaft voltage equation is determined by the equivalent circuit of the shaft voltage as follows [4] :

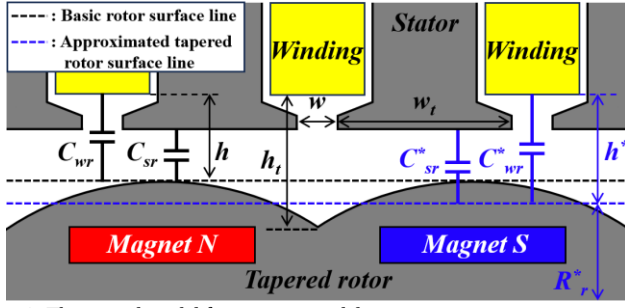


Fig. 2. Theoretical model for tapering model.

$$V_{\text{shaft}} = \frac{C_{wr}}{C_{wr} + C_{sr} + C_b} \times V_{CMV} \quad (1)$$

Here, C_{wr} is the winding-rotor capacitance, C_{sr} is the stator-rotor capacitance, C_b is the bearing capacitance, and V_{CMV} is the CMV. The conventional method for calculating C_{wr} assumes the winding and rotor as a parallel plate capacitor and the case of the C_{sr} , if the slot opening is neglected, the stator and rotor are assumed as a concentric cylindrical capacitor [4].

To explain the principle of shaft-to-frame voltage variation caused by changes in parasitic capacitance in the tapered rotor, this study derives an theoretical model by approximating the rotor surface based on the conventional method. The theoretical model requires two assumptions for simplification. First, the fringing effect is neglected. Second, because the air-gap varies along the tangential direction in the tapered rotor, it is approximated as a constant rotor surface, as shown in Fig. 2. Here, the approximated rotor surface is selected as the average of the minimum and maximum values of R_r . Based on these assumptions, the theoretical model for C_{wr} and C_{sr} are derived as follows :

$$C_{wr}^{equi} = N \frac{\epsilon_0 w L}{h^*}, \quad h^* = \frac{h + h_t}{2} \quad (2)$$

$$C_{sr}^{equi} = \frac{2\pi\epsilon_0 L}{\ln(R_s / R_r^*)} \times \frac{w_t}{w + w_t} \quad (3)$$

where, h^* is the distance between winding and approximated rotor surface, h_t is the distance between winding and minimum point of R_r , R_r^* is the approximated rotor outer radius, w_t is the thickness of the tooth.

The difference from conventional method is that h^* and R_r^* , which consider the approximated rotor, are replaced, and a second term is added to (3) to exclude the influence of the slot opening. When tapering is applied, h^* increases and R_r^* decreases, leading to a decrease in both C_{wr} and C_{sr} . However, typically, C_{sr} is significantly larger than C_{wr} , and the rate of decrease in C_{sr} due to changes in R_r^* which is included in logarithmic function is greater than the rate of decrease in C_{wr} due to changes in h^* . In other words, based on (1) considering C_{wr} and C_b , if C_{sr} decreases significantly, it may cause an increase in shaft voltage. These trends of parasitic capacitance will be validated through electrostatic FEA in the full paper. Therefore, when applying a tapered rotor, not only B-EMF and cogging torque but also shaft voltage must be considered.

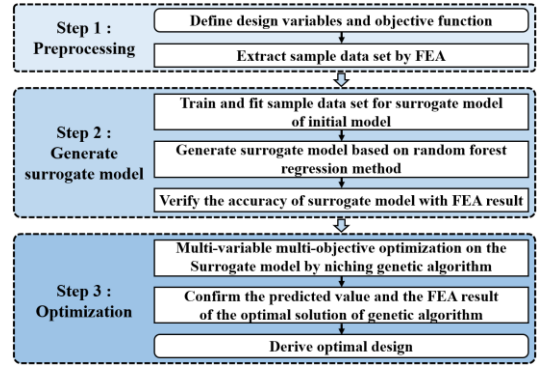


Fig. 3. Flow chart of the multi-objective optimization.

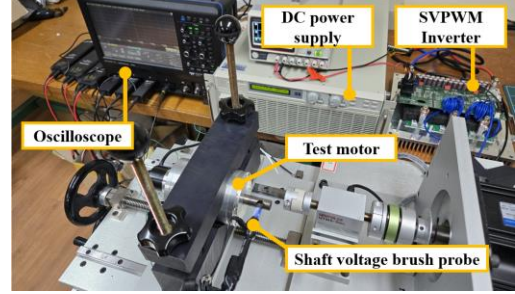


Fig. 4. Experimental setup to measure the shaft voltage.

III. DESIGN OPTIMIZATION AND EXPERIMENT VALIDATION

Based on the requirements tabulated in Table 1, an optimal design is performed using a machine learning-based NGA following the flow chart shown in Fig. 3. The design variables are set to 3, including the degree of tapering, and the objective functions are defined as B-EMF THD, average torque, and shaft-to-frame voltage. In the data sample extraction stage, B-EMF THD and average torque are analyzed using electromagnetic transient FEA, while the parasitic capacitance of the shaft-to-frame voltage is analyzed using electrostatic FEA. Finally, the initial model and the derived optimal design are manufactured and validated through experiments using the setup shown in Fig. 4. The detailed optimization results and experimental findings will be discussed in the full paper.

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