

Design and Analysis of an Interior Permanent Magnet Synchronous Motor with a Carbon Fiber-Reinforced Plastic Sleeve Based on Electromagnetic-Mechanical Coupled Analysis

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This paper presents the design and analysis of an interior permanent magnet synchronous motor (IPMSM) rotor with a carbon fiber-reinforced plastic (CFRP) sleeve, based on electromagnetic-mechanical coupled analysis. To address the stress issues arising from the increase in the rotor's maximum rotational speed, this study emphasizes the specific considerations necessary for its construction, which is complicated by the incorporation of the CFRP sleeve. This added complexity distinguishes the design of the rotor from that of conventional IPMSMs.

Index Terms—Electromagnetic analysis, finite element analysis, permanent magnet motors, traction motors.

I. INTRODUCTION

ELECTRIC vehicles (EVs) have attracted growing global interest, leading to extensive research efforts worldwide aimed at the development of high-performance EVs. High-performance electric vehicles require advanced battery technology with high voltage and efficiency, as increases in battery voltage directly impact the maximum rotational speed of the motor. Traction motor manufacturers aim to maximize output density by increasing the maximum rotational speed while minimizing the motor's volume. However, increasing the maximum rotational speed of conventionally designed motors may lead to issues where the stress on the rotor exceeds allowable limits. Therefore, to develop high-performance, high-power-density traction motors, it is essential to address the rotor stress issue and create a design capable of sustaining higher rotational speeds.

To address this issue, Tesla applied a carbon fiber-reinforced plastic (CFRP) sleeve to the rotor of the interior permanent magnet synchronous motor (IPMSM), which is primarily used as a traction motor, enabling the mass production of the Model S Plaid. By utilizing a lightweight, high-strength, and high-elasticity CFRP sleeve, the rotor stress issue can be effectively addressed [1], [2]. However, the increase in effective air gap length corresponding to the sleeve thickness results in a reduction in the magnetic flux passing through the stator. This reduction can be compensated by opening the ribs and bridge to block leakage flux paths [3]. Nevertheless, opening these components also increases the load on the sleeve. Therefore, it is essential to adopt a design approach that considers both the electromagnetic and mechanical characteristics, which are in a trade-off relationship.

Therefore, this paper employs the finite element method (FEM) to analyze the electromagnetic and mechanical properties of the rotor of an IPMSM with a CFRP sleeve,

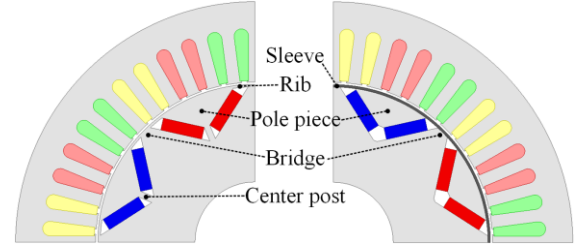


Fig. 1. Model configurations of conventional and wrapped interior permanent magnet synchronous motors.

TABLE I
REQUIREMENTS FOR TRACTION MOTOR

Parameters	Value	Unit
Number of pole / slots	8 / 48	-
Stator outer / inner diameter	200 / 133	mm
Rotor outer / inner diameter	131.2 / 50	mm
Axial length	156	mm
Length of air-gap	0.9	mm
Base speed	5,200	rpm
Maximum speed	20,000	rpm
Maximum torque	400	N·m
Maximum power	230	kW
Voltage limit	700	V _{dc}
Current density limit	30	A _{rms} /mm ²
Safety factor	1.2	-

aiming to efficiently design the rotor. Through this analysis, the study seeks to derive the optimal thickness of the CFRP sleeve and rotor configuration.

II. ELECTROMAGNETIC AND MECHANICAL CHARACTERISTICS ANALYSIS FOR INITIAL MODEL DESIGN

A. Design Requirements

Fig.1 illustrates the configuration of an 8-pole, 48-slot V-type conventional IPMSM (CIPMSM) and a wrapped IPMSM (WIPMSM) with a CFRP sleeve wrapped around the rotor. Table 1 shows the design requirements for the target traction motor. The maximum operating speed of the previously

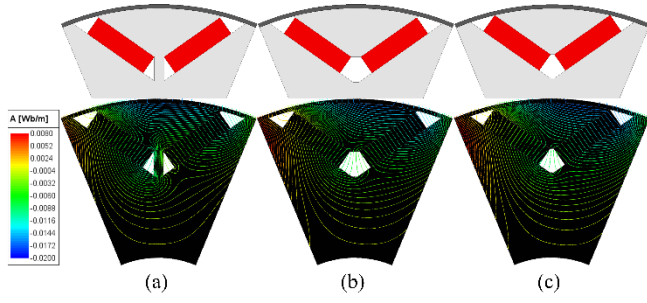


Fig. 2. Shapes and flux lines of (a) WIPMSM with a center post; (b) WIPMSM without a center post; (c) WIPMSM without a center post, with minimized gaps between magnets and between magnets and the sleeve.

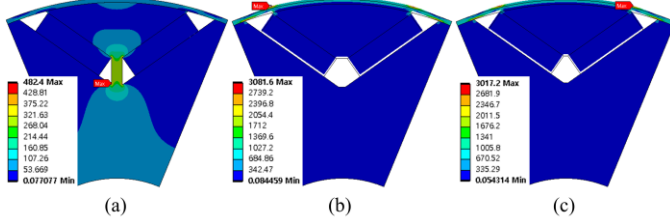


Fig. 3. Stress analysis results of the rotor at maximum speed: (a) WIPMSM with a center post; (b) WIPMSM without a center post; (c) WIPMSM without a center post, with minimized gaps between magnets and between magnets and the sleeve.

designed CIPMSM is 16,000rpm. Therefore, in this study, I designed a WIPMSM using a CFRP sleeve to increase the maximum operating speed to 20,000rpm.

B. Initial Model Design

Fig. 2 and 3 show the flux line distribution and stress analysis results based on the rotor geometry of the WIPMSM. In all three models, the sleeve thickness is 1mm, and the ribs of the CIPMSM were removed to apply the sleeve. Among the different models, model (c) in Fig.2 exhibits the lowest leakage flux, indicating the best electromagnetic performance. When comparing the mechanical properties, it was observed that the model with the center post experiences maximum stress at the center post, while the model without the center post experiences maximum stress at the sleeve. None of the three configurations satisfy the required safety factor in the initial models. However, since the stress that the CFRP sleeve used in this study can withstand is more than six times greater than the stress the core can endure, model (c), which exhibits the best electromagnetic performance, is selected as the initial model. Further stress improvements will be made through detailed rotor design.

III. DETAILED ROTOR DESIGN AND ANALYSIS FOR SATISFYING THE DESIGN REQUIREMENTS

A. Detailed Rotor Design Considering the Trade-off Relationship

In this chapter, detailed rotor design was performed considering the trade-off relationships between electromagnetic and mechanical properties. The analysis of the permanent magnet angle showed that torque reaches its maximum at a specific angle depending on the rotor shape, while maximum stress tends to decrease as the permanent magnet angle increases. The barrier angle affects leakage flux, and as the

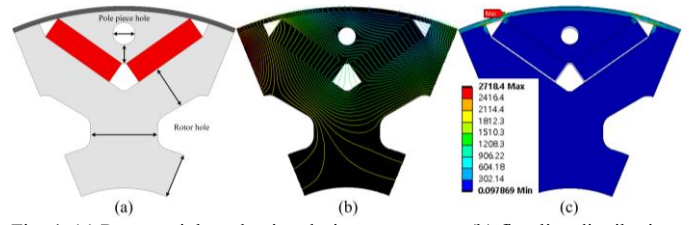


Fig. 4. (a) Rotor weight reduction design parameters, (b) flux line distribution with the application of hole structure, (c) stress analysis results with the application of hole structure.

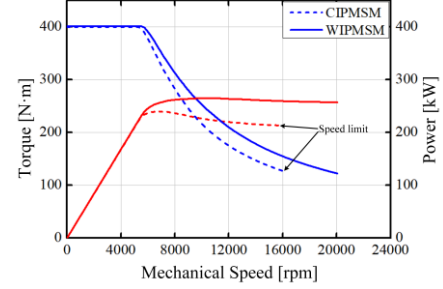


Fig. 5. Torque-speed and output-speed curve of CIPMSM and WIPMSM.

barrier angle increases, the area where the core contacts the sleeve increases, thereby reducing the stress on the sleeve.

B. Rotor Weight Reduction Design

Fig. 4 (a) rotor weight reduction design parameters, (b) flux line distribution with the application of hole structure, and (c) stress analysis results with the application of hole structure. To improve the mechanical stability that was not satisfied in the initial design, rotor weight reduction was performed without obstructing the flux flow, and it was confirmed that the safety factor now meets the required standards.

C. Comparison of CIPMSM and WIPMSM

Fig. 5 shows the torque-speed and output-speed curves of the CIPMSM and WIPMSM. The maximum operating speed of the designed WIPMSM increased by 4,000rpm, and the maximum output also improved.

IV. CONCLUSION

In this study, the design and analysis of a WIPMSM were carried out to overcome the limitations of the CIPMSM. By employing a CFRP sleeve, the stress issues at high speeds were addressed, leading to a 4,000rpm increase in maximum operating speed compared to the CIPMSM. Additionally, the WIPMSM demonstrated improved maximum output while meeting all design specifications. Detailed design parameters and analysis result will be presented in the full paper.

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