Postprint: Analysis of Rotor Stress, Losses, and Temperature Field in High-Speed Permanent Magnet Brushless DC Motors with Two Rotor Structures

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Abstract

Motor design is a comprehensive multi-physics design. This paper designs a 10kW, 10,000r/min permanent magnet brushless DC high-speed motor. For the two rotor structures of surface-mounted and interior-mounted types, stress analysis, loss analysis, and temperature field analysis were conducted respectively for the interior-mounted rotor and the surface-mounted high-speed brushless DC motors with different retaining sleeves. Based on multi-physics field analysis and simulation, comprehensive design results satisfying rotor strength, losses, and temperature rise were obtained. The calculation process of losses and thermal field of brushless DC motors was analyzed, and the loss magnitude and temperature field distribution of the two motor structures were studied. The method proposed in this paper can not only accurately calculate the magnitude of internal losses in the motor, but also obtain the energy interaction process between internal losses and thermal field in the motor, to study the heating problem of the motor. Through comparison of simulation results, it was found that the surface-mounted structure exhibits more severe heating.

Full Text

Preamble

Loss and Temperature Field Analysis of Permanent Magnet Brushless DC High Speed Motor With Two Rotor Structures

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Abstract

Motor design is a comprehensive multi-physical field optimization process. This paper presents the design of a 10 kW, 10,000 r/min permanent magnet brushless DC high-speed motor, focusing on two distinct rotor configurations: surface-mounted and embedded. For each configuration, we conduct detailed analyses of mechanical stress, electromagnetic losses, and temperature distribution. Based on multi-physics analysis and simulation, we obtain comprehensive design results regarding rotor strength, loss characteristics, and temperature rise performance.

The calculation methodology for electromagnetic and thermal fields in brushless DC motors is systematically analyzed, with particular attention to loss magnitudes and temperature field distributions for both structural types. The proposed approach enables not only accurate quantification of internal losses but also reveals the energy interaction processes between losses and thermal fields, providing critical insights into motor heating phenomena. Comparative simulation results demonstrate that the surface-mounted configuration exhibits more severe heating issues, while the embedded structure suffers from magnetic flux leakage at magnet ends, which distorts current waveforms.

Keywords: High-speed brushless DC motor, different rotor structures, loss calculation, temperature field analysis

1 Introduction

Brushless DC motors offer numerous advantages including high efficiency, compact size, high reliability, excellent performance characteristics, convenient speed regulation, and simple structure, making them widely applicable in aerospace, marine engineering, and various industrial fields. The rotor structure of brushless DC motors is highly flexible, and based on permanent magnet placement, can be classified into embedded and surface-mounted types. These classifications can be further combined in various ways, creating many distinctive rotor magnetic circuit structures.

The magnetic field distribution in brushless DC motors is complex, and permanent magnets exhibit demagnetization as temperature increases, directly affecting magnetic field magnitude and distribution while causing performance fluctuations. Consequently, different rotor magnetic circuit structures significantly impact loss magnitude, heating levels, performance characteristics, manufacturing processes, and application suitability—representing a critical design consideration. Embedded rotor brushless DC motors offer greater structural flexibility and more design parameters, making them a current research focus both domestically and internationally.

2 Motor Structure and Basic Parameters

This paper designs three motor variants: an embedded rotor brushless DC motor, a surface-mounted rotor motor with an alloy retaining sleeve, and a surface-mounted rotor motor with a carbon fiber sleeve. All three are 4-pole, 3-phase permanent magnet brushless DC motors rated at 500 V, 10 kW, and 10,000 r/min. The initial structural configurations are illustrated in [Figure 1: see original paper], while summarizes the key design parameters.

3.1 Finite Element Analysis of Rotor Stress

Operating at 10,000 r/min, the permanent magnets on the rotor surface experience substantial centrifugal forces. Finite element analysis was employed to evaluate rotor stress distribution. The 2D rotor stress distributions for the three motor designs at 75°C operating temperature are presented in [Figure 2: see original paper].

The analysis reveals that at 10,000 r/min and elevated temperature (75°C), the equivalent rotor stresses are 34 MPa for the embedded design, 1.446 MPa for the alloy-sleeved surface-mounted design, and 0.75006 MPa for the carbon fiber-sleeved design, all satisfying the mechanical strength requirements for motor rotors.

3.2 Loss Analysis

High-speed permanent magnet embedded brushless DC motors offer advantages of high rotational speed, high power density, and compact size, but the increased core losses per unit volume inevitably cause temperature rise. Effectively reducing losses and minimizing heat generation represents a key challenge for embedded permanent magnet motors. While core losses can be neglected in low-speed motors, they become significant in high-speed applications due to high-frequency effects, impacting both efficiency and operating temperature. Accurate core loss calculation is therefore essential for temperature control and efficiency improvement.

Loss analysis was performed using Ansoft software, generating the loss curves shown in [Figure 3: see original paper] through [Figure 5: see original paper]. Two-dimensional finite element methods, RMxprt, and Ansoft were employed to analyze the three motor designs, calculating stator core losses, rotor core losses, permanent magnet eddy current losses, and armature copper losses.

Under rated load conditions, the embedded rotor motor exhibits stator core losses of 184.1 W, rotor core losses of 19.585 W, permanent magnet losses of 62.265 W, and armature copper losses of 100.694 W, yielding total losses of 366.641 W. The alloy-sleeved surface-mounted rotor motor shows stator core losses of 137.3 W, rotor core losses of 1.7523 W, permanent magnet losses of 84.525 W, armature copper losses of 87.3161 W, and sleeve losses of 436.1 W, with total losses reaching 746.9934 W. The carbon fiber-sleeved surface-mounted rotor motor demonstrates stator core losses of 133.4 W, rotor core losses of 1.9032 W, permanent magnet losses of 62.265 W, armature copper losses of 87.3161 W, and sleeve losses of 271.2 W, totaling 556.0843 W.

These results indicate that under rated load, the embedded rotor motor achieves the lowest losses, while surface-mounted configurations exhibit substantially higher losses, with the alloy-sleeved design showing the greatest loss magnitude.

4 Temperature Field Analysis

High-speed motors feature compact dimensions and high power density, resulting in significant losses per unit volume. During operation, these motors experience severe heating and difficult heat dissipation, leading to elevated temperature rise. Since permanent magnet material performance is highly temperature-sensitive, excessive temperature rise may cause irreversible demagnetization and motor failure, making thermal analysis critically important.

The internal electromagnetic field distribution in brushless DC motors is extremely complex, with non-uniform heating across components and varying heat dissipation conditions. Heat exchange occurs between different heat sources, complicating internal thermal field analysis. Motor heat originates from losses in various components, transferring through conduction from internal regions to surfaces, then dissipating via convection and radiation to the surrounding medium.

Appropriate boundary conditions for the temperature field were established based on internal fluid flow and heat transfer characteristics: (1) fluid-solid coupling for the ventilation path with specified inlet temperature of 25°C, air velocity of 15 m/s, and outlet pressure; (2) equivalent insulation treatment for stator slot interiors; (3) temperature loading on stator, windings, sleeves, and permanent magnets as heat sources; and (4) rotational speed specification for rotor components to simulate actual operating conditions.

The solution domain models for both rotor structures are shown in [Figure 6: see original paper]. Temperature field analysis was conducted using the CFX module in ANSYS software, yielding steady-state temperature distributions presented in [Figure 7: see original paper]. Figures 7a through 7c illustrate the temperature fields for the embedded rotor motor, alloy-sleeved surface-mounted rotor motor, and carbon fiber-sleeved surface-mounted rotor motor, respectively. Axial and radial temperature distributions are depicted in [Figure 8: see original paper] and [Figure 9: see original paper], with axial position 0 representing the motor' s axial midpoint, and radial temperature data extracted from the axial centerline.

The NdFeB permanent magnet material employed in this study can withstand maximum temperatures of 180°C; exceeding this threshold causes irreversible demagnetization, severely compromising reliable operation. Forced air cooling is implemented with inlet temperature of 25°C, air velocity of 15 m/s, and pressure of approximately 300 Pa to maintain permanent magnet temperatures within safe limits.

presents the maximum temperatures for each component across the three motor designs. The data demonstrates that under identical power and speed conditions, the embedded rotor brushless DC motor operates at lower temperatures than surface-mounted designs, with the alloy-sleeved surface-mounted rotor exhibiting higher temperatures than its carbon fiber-sleeved counterpart.

5 Conclusion

This paper designs a 10 kW, 10,000 r/min permanent magnet high-speed DC motor with two rotor structures—embedded and surface-mounted—and analyzes both alloy and carbon fiber sleeves for the surface-mounted configuration. Finite element analysis using Ansoft software generated loss curves for all three motor designs, while ANSYS static analysis confirmed the structural integrity of the design.

Three-dimensional solution domain models for both rotor structures were developed using the CFX module in ANSYS. Appropriate boundary conditions were applied based on internal fluid flow and heat transfer characteristics, enabling calculation of temperature distributions for all three motor configurations.

Comparative analysis of the resulting data demonstrates that under the specified design parameters, the embedded permanent magnet synchronous brushless DC high-speed motor achieves lower losses, while surface-mounted configurations exhibit higher losses and more severe heating, potentially causing rubbing between components. The embedded structure avoids localized overheating but suffers from significant magnetic flux leakage at magnet ends, inducing circulating currents that distort current waveforms. Each rotor structure presents distinct advantages and disadvantages, and selection should be based on specific application requirements and technical specifications.

Note: Figure translations are in progress. See original paper for figures.