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Postprint: Analysis of High-Speed Permanent Magnet Machines with Different Rotor Sleeves

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Abstract

This paper presents the design of a 300kW, 15,000 r/min high-speed permanent magnet synchronous motor. For surface-mounted rotor structures, loss analysis and temperature field analysis are conducted on high-speed permanent magnet synchronous motors with carbon fiber and alloy steel sleeves, respectively. A high-power high-speed permanent magnet motor is designed, and its parameters are introduced. The motor is simulated using finite element analysis software to obtain iron loss data and other relevant data for analysis. Simulation results indicate that the motor with an alloy steel sleeve exhibits more severe heating.

Full Text

Analysis of High-Speed Permanent Magnet Motors with Different Rotor Sheaths

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Abstract: This paper presents the design of a 300 kW, 15,000 r/min high-speed permanent magnet synchronous motor. For surface-mounted rotor structures, loss analysis and temperature field analysis are conducted for high-speed permanent magnet synchronous motors with carbon fiber and alloy steel sheaths. A high-power, high-speed permanent magnet motor is designed with parameter specifications. Finite element analysis software is used to simulate the motor, obtaining and analyzing data such as iron losses. Simulation results demonstrate that motors with alloy steel sheaths exhibit more severe heating.

Keywords: Permanent magnet synchronous motor, temperature field, loss analysis, sheath, carbon fiber, alloy steel

1 Introduction

High-speed motors exhibit three primary characteristics: high rotor speed, high-frequency stator winding currents and flux in the iron core, and relatively high power density and loss density [1]. These features determine the unique key technologies of high-speed motors that differ from conventional machines. In recent years, high-speed motors have demonstrated broad application prospects in industrial and aerospace fields. Compared with traditional motors of the same power rating, high-speed motors offer smaller volume [2], higher power density, and effective material savings. Due to their low rotational inertia, high-speed motors provide fast dynamic response. They can be directly connected to prime movers or high-speed loads, eliminating traditional mechanical transmission devices, which not only reduces noise but also significantly improves system transmission efficiency [3]. Research and application of high-speed motors align with economic development needs for energy conservation and emission reduction, making them a current international research hotspot in electrical engineering. Based on these advantages, high-speed motors are widely used in high-speed grinding machines, air cycle refrigeration systems, energy storage flywheels, fuel cells, natural gas transmission high-speed centrifugal compressors, and distributed power generation systems for aircraft or shipboard power supplies. In particular, high-speed permanent magnet motors are most extensively applied in medium and small high-speed applications due to their simple structure, high power density, absence of excitation losses, and high efficiency. Given these advantages and extensive industrial applications, the design and research of high-speed permanent magnet motors hold significant importance for overall industrial development [4].

2 Motor Structure and Basic Parameters

The motor structure is shown in Figure 1 [Figure 1: see original paper], with basic parameters listed in Table 1. The slot dimensions are: Hs0: 8 mm; Hs1: 1 mm; Hs2: 42 mm; Bs0: 3.5 mm; Bs1: 10 mm; Bs2: 13.6 mm; Rs: 0 mm.

3 Loss Analysis and Comparison of Motors with Different Sheaths

3.1 Iron Loss Analysis

The Bertotti separation model is widely adopted for calculating and analyzing iron losses in high-speed permanent magnet motors. This model divides iron losses into hysteresis loss, eddy current loss, and anomalous loss based on their formation principles [5]:

$$P_{Fe} = K_h f B_m^h + K_c (f B_m)^2 + K_a (f B_m)^{1.5}$$

where K_h , K_c , and K_a are the respective loss coefficients, generally constants

obtained by fitting measured iron loss values under different flux densities and frequencies; B_m and f are the flux density amplitude and frequency of sinusoidal alternating fields, respectively. Using the finite element method to obtain the magnetic flux density variation waveform in each element of the motor, the corresponding iron core loss values can be derived from the above equation and summed to obtain the total motor losses [6]. The stator core loss curves under alloy steel and carbon fiber sheaths are shown in Figures 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper], respectively.

3.2 Eddy Current Loss Analysis

Rotor eddy current losses can be calculated using either analytical methods or finite element methods. For surface-mounted high-speed motors, the analytical method commonly neglects slotting effects, assumes infinite iron core permeability, replaces slot conductors with current sheets distributed at the slot openings, and simplifies the motor into a multi-layer concentric circle model. Maxwell's equations are then solved using the separation of variables method to obtain the magnetic vector potential A in each region [7].

For conductive regions: $A = c_1 I_p (j^{0.5} r) + c_2 K_p (j^{0.5} r)$

For non-conductive regions: $A = c_3 r^p + c_4 r^{-p}$

The loss calculation formula for eddy current regions is: $\text{Re}(E \times H^*) ds$

Simulation results for eddy current loss curves are shown in Figures 4 [Figure 4: see original paper] through 7 [Figure 7: see original paper]. Table 2 presents the loss comparison, indicating that under rated load, the motor with an alloy steel sheath exhibits the highest losses.

3.3 Copper Loss Calculation

Copper loss is calculated by first determining the resistivity of copper (ρ) and then computing the resistance based on the enameled wire's cross-sectional area (S) and length (l) [8]:

$$R = \rho \frac{l}{S}$$

4 High-Speed Motor Temperature Rise Analysis

Based on a 300 kW, 15,000 r/min permanent magnet synchronous motor, this paper analyzes the temperature rise characteristics of different sheath materials using finite element analysis. The boundary conditions for temperature field calculations are established according to fluid flow and heat transfer conditions inside the motor [9] as follows:

1. The ventilation path employs a fluid-solid coupling model set as turbulent flow, with an inlet velocity of 10 m/s and ambient temperature of 315 K specified.
2. Stator slot insulation is treated with equivalent thermal properties.
3. Corresponding temperatures are applied as heat sources to the stator, windings, sheath, and permanent magnets.
4. Rotor components are assigned rotational speeds to simulate actual motor operation.

Temperature rise analysis results for different sheath configurations are shown in Figures 8 [Figure 8: see original paper] through 13 [Figure 13: see original paper]. As indicated by Figures 10 through 13 and Table 3, the permanent magnet temperatures remain within safe limits for all sheath types. The highest temperatures occur in the permanent magnets and sheaths because the carbon fiber protective layer surrounding the permanent magnets has low thermal conductivity, impeding heat dissipation.

5 Conclusion

The NdFeB permanent magnet material employed in this study can withstand a maximum temperature of approximately 453 K [10]. When permanent magnet temperature exceeds this value, irreversible demagnetization may occur, severely affecting motor reliability. Therefore, permanent magnets should be maintained below 423 K during motor design. Temperature field and loss analyses demonstrate that the carbon fiber sheath performs better, with permanent magnet maximum temperatures remaining below 423 K in both configurations.

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