Postprint of Multi-Physics Coupled Analysis of Fractional-Slot Permanent Magnet Motors

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Date: 2019-03-05T00:00:00+00:00

Abstract

Since a motor’ s operating state and characteristics are directly related to its electrical, magnetic, thermal, and other physical fields, multi-physical field coupling analysis is essential for motors. This paper employs the three-dimensional finite element method to analyze and calculate the magnetic field distribution of a fractional-slot permanent magnet motor during operation. Based on the magnetic field analysis results, losses in various components are computed and subsequently used as heat sources during motor operation to conduct simulation analysis of the motor’ s temperature field, thereby obtaining the temperature distribution. Building upon this, experimental analysis is conducted on a prototype, with experimental results consistent with simulation results. This validates the effectiveness of the multi-physical field coupling analysis method for this motor and establishes a theoretical foundation for subsequent motor structural optimization.

Full Text

Preamble

Multi-Physics Field Coupling Analysis of Fractional Slot Permanent Magnet Machine

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Abstract

The operating status and characteristics of electric machines are directly related to their electrical, magnetic, thermal, and other physical fields, making multi-physics field coupling analysis essential. This paper employs three-dimensional finite element method (3D FEM) to analyze and calculate the magnetic field distribution of a fractional slot permanent magnet machine during operation. Based on the magnetic field analysis results, the losses in various components are computed and subsequently used as heat sources for thermal simulation of the motor, yielding the temperature distribution throughout the machine. Experimental analysis conducted on a prototype machine demonstrates good agreement between experimental and simulation results, thereby validating the effectiveness of the proposed multi-physics field coupling analysis method and establishing a theoretical foundation for subsequent motor structure optimization.

Keywords: Permanent magnet machine, fractional slot, loss, multi-physics field, finite element method

Supported by National Natural Science Foundation of China (51407094) and Natural Science Foundation of Jiangsu Province (BK20140785).

1 Introduction

Compared with traditional electrically excited machines, rare-earth permanent magnet motors offer numerous advantages including simple structure, reliable operation, compact size, light weight, low losses, high efficiency, and flexible design options in shape and dimensions. Consequently, they find widespread applications in aerospace, defense, industrial and agricultural production, and daily life. Magnetic field analysis and calculation constitute a critical aspect of motor design. However, temperature rise during operation significantly affects performance, potentially causing irreversible demagnetization of permanent magnets due to overheating. Therefore, thermal analysis and calculation are of paramount importance in permanent magnet motor design and analysis.

This paper investigates a 4-pole, 15-slot permanent magnet synchronous motor with a rated speed of 1500 r/min. The study employs 3D finite element method to compute the motor' s magnetic field, losses, and temperature field, and analyzes the magnetic and temperature fields under steady-state operation. Experimental validation using a prototype machine establishes a theoretical foundation for subsequent structural optimization design.

2 Magnetic Field Analysis of Permanent Magnet Motors

Accurate magnetic field calculation is crucial for studying permanent magnet motor performance. While the magnetic circuit method is commonly used for simplified calculations, its accuracy is limited and it cannot resolve all internal motor problems. Consequently, finite element method has become the standard approach for permanent magnet motor magnetic field analysis. For accurate loss analysis, 3D FEM serves as the primary computational tool. The magnetic and eddy current field analysis based on 3D FEM primarily utilizes the A- method, with fundamental equations given by:

$$\begin{cases} \nabla \times (\nu \nabla \times \mathbf{A}) = \mathbf{J}_0 - \sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \nabla \phi \right) \\ \nabla \cdot \left(-\sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \nabla \phi \right) \right) = 0 \end{cases}$$

where $\mathbf{A}$ is the magnetic vector potential, ϕ is the electric scalar potential, σ is the electrical conductivity, ν is the magnetic reluctivity, and $\mathbf{J}_0$ is the coil current density.

To calculate the temperature field within the motor, accurate computation of various component losses must first be performed to determine the heat sources. Permanent magnet motor losses primarily include iron losses, stator winding copper losses, mechanical losses, rotor eddy current losses, and other stray losses not accounted for in the aforementioned categories. These losses are converted into heat and removed by the motor’ s cooling system while simultaneously raising the temperature of various components. Therefore, precise loss calculation is essential for accurate temperature field analysis.

3 Temperature Field Analysis of Permanent Magnet Motors

3.1 Theoretical Analysis of Temperature Field

According to fundamental heat transfer theory, steady-state temperature field solution within a motor in Cartesian coordinates can be formulated as the following boundary value problem:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right) + q_V = 0$$

with boundary conditions: - Heat generation boundary: $-\lambda \frac{\partial T}{\partial n} = q$ - Heat dissipation boundary: $-\lambda \frac{\partial T}{\partial n} = \alpha (T - T_f)$ - Insulation boundary: $\frac{\partial T}{\partial n} = 0$

where λ_x, λ_y, and λ_z are thermal conductivities in the x, y, and z directions, respectively; q_V is the heat source density representing losses generated per unit volume in each motor component; α is the convective heat transfer coefficient; and T_f is the ambient fluid temperature.

Based on variational principles, the equivalent variational form of equation (1) is:

$$J(T) = \int_V \left[\frac{1}{2} \left(\lambda_x \left(\frac{\partial T}{\partial x} \right)^2 + \lambda_y \left(\frac{\partial T}{\partial y} \right)^2 + \lambda_z \left(\frac{\partial T}{\partial z} \right)^2 \right) - q_V T \right] dV + \int_S \left(\frac{1}{2} \alpha T^2 - \alpha T_f T \right) dS = \min$$

After discretization, the 3D temperature field finite element equation is obtained:

$$\mathbf{KT} = \mathbf{F}$$

where $\mathbf{T}$ is the temperature array formed by all nodal temperatures in the solution domain, and $\mathbf{K}$ and $\mathbf{F}$ are the global coefficient matrix and global right-hand vector, respectively. Solving this equation yields the temperature at all nodes in the solution domain.

3.2 Analysis of Motor Heat Sources

The primary heat sources in the stator core are winding copper losses and core losses. Magnetic field distribution in the motor iron core can be obtained through electromagnetic calculation, with iron loss computed using:

$$W_{\text{loss}} = \sum_{i=1}^{n_{\text{elem}}} \left(W_{hi}(B, f) + W_{ei}(B, f) \right)$$

where $W_{hi}(B)$ is the hysteresis loss and $W_{ei}(B)$ is the eddy current loss in each element. As shown in equation (5), iron losses are divided into hysteresis and eddy current components. The accuracy of flux density distribution in various iron core parts significantly influences iron loss calculation accuracy. Since eddy current losses in permanent magnets are relatively small compared to other motor losses, they are neglected in the calculation, along with iron losses generated in the rotor core.

3.3 Thermal Conductivity and Boundary Conditions of Motor Components

Heat transfer within motors occurs primarily through thermal conduction and convection—an integrated process of conduction and convection. This process is directly related to the thermal conductivity of the medium and the surface heat transfer coefficient. According to Fourier’ s law, thermal conductivity is the amount of heat transferred per unit time through a unit area when the temperature gradient is 1. Thermal conductivity depends on material properties and varies with temperature, pressure, porosity, and uniformity, with temperature being the decisive factor. For most materials, before reaching melting or vaporization temperatures, thermal conductivity can be approximated as varying linearly: $\lambda = \lambda_0(1 + bt)$, where λ_0 is the thermal conductivity at zero temperature and b is an experimentally determined constant. The thermal conductivities of main materials used in this permanent magnet motor are listed in Table 1 .

Special treatment is required for the air gap when calculating the temperature field throughout the stator and rotor. The convective heat transfer effect in the air gap can be equivalently represented using an effective thermal conductivity. Assuming smooth cylindrical surfaces for the stator inner surface and rotor outer surface, the Reynolds number in the air gap can be expressed as:

$$\mathrm{Re} = \frac{\omega_{\phi 1}\delta}{\varepsilon}$$

where $\omega_{\phi 1}$ is the rotor circumferential velocity, δ is the air gap length, and ε is the kinematic viscosity of air.

The critical Reynolds number is:

$$\mathrm{Re}_{cr} = 41.2\frac{\delta}{R_i}$$

where R_i is the stator inner diameter.

When $\mathrm{Re} < \mathrm{Re}_{cr}$, air flow in the air gap is laminar and the effective thermal conductivity λ_{eff} equals the air thermal conductivity. When $\mathrm{Re} > \mathrm{Re}_{cr}$, the flow becomes turbulent. Calculations yield $\mathrm{Re} = 1325 > \mathrm{Re}_{cr} = 839.2$, indicating turbulent flow. The effective thermal conductivity is then:

$$\lambda_{\mathrm{eff}} = 0.0019\eta^{2.9084}\mathrm{Re}^{0.4614}\ln(3.33361\eta)$$

where $\eta = r_o/R_i$, with r_o being the rotor outer diameter and R_i the stator inner diameter. The calculated effective thermal conductivity of the air gap is 0.103 W/(m · K).

4 Model Establishment and Meshing

The electromagnetic field analysis process consists of three stages: pre-processing, solving, and post-processing. Pre-processing includes establishing analysis models (motor magnetic field FEM model and power converter circuit model), setting material properties, boundary conditions, simulation parameters, and mesh generation. In post-processing, magnetic field data from each element or node in the motor magnetic field FEM model and current/voltage data from the circuit model can be extracted for analysis.

The fractional slot permanent magnet motor model and mesh generation studied in this paper are shown in Figure 1 [Figure 1: see original paper] and Figure 2 [Figure 2: see original paper], respectively. Figure 3 [Figure 3: see original paper] illustrates the external circuit model of the motor.

5 Magnetic Field Simulation Results

The no-load electromotive force and cogging torque waveforms are shown in Figure 4 [Figure 4: see original paper] and Figure 5 [Figure 5: see original paper], respectively. Due to the open-slot design, the no-load electromotive force exhibits significant slot harmonics. Cogging torque arises from the interaction between permanent magnets and iron core when unpowered, caused by fluctuations in the tangential component of the interaction force between permanent magnets and armature teeth. Cogging torque leads to torque ripple, affecting system control precision and generating vibration and noise.

Figure 6 [Figure 6: see original paper] shows the overall flux density distribution, revealing partial saturation in the rotor. The average flux density in the stator core is 0.87 T, while that in the rotor core is 0.95 T. Figure 7 [Figure 7: see original paper] presents the magnetic vector diagram, enabling analysis of leakage flux distribution. Based on this magnetic field analysis, the motor’ s copper loss and iron loss are determined to be 34 W and 5.77 W, respectively.

Figure 8 [Figure 8: see original paper] shows the output torque at rated load. The motor produces 3.5 $\mathrm{N \cdot m}$ output torque with torque pulsation caused by cogging torque and control method, amounting to approximately 8% of the average torque.

6 Analysis of Permanent Magnet Motor Temperature Field Results

Using the losses obtained from magnetic field analysis as heat sources, temperature field simulation results are shown in Figure 9 [Figure 9: see original paper] and Figure 10 [Figure 10: see original paper]. The highest temperature occurs in the stator teeth, reaching approximately 83.8°C. This is attributed to the low thermal conductivity of winding insulation and insulating media, combined with the coil windings being a significant heat source. Detailed temperature rises for various components are provided in Table 2 .

All motor heating originates from its losses. The stator and windings function as both heat generation and heat transfer components, while other components serve as heat transfer elements. As motor temperature increases, the temperature difference with the surrounding medium gradually increases, leading to more heat dissipation to the ambient environment while the rate of temperature rise slows. Eventually, all generated heat is transferred to the surroundings, achieving thermal stability—typically defined as when the temperature change is less than 1°C per hour. Figure 11 [Figure 11: see original paper] shows the simulated temperature variation curve of the motor stator, indicating the maximum temperature reaches 84°C after extended operation.

Figure 12 [Figure 12: see original paper] presents the prototype motor model. Experimental measurements from the prototype show that after 70 minutes of operation, the average temperature in the stator core reaches 88°C, after which it remains essentially constant, demonstrating good agreement with the calculated results.

7 Conclusion

This paper analyzes and calculates the magnetic field of a fractional slot permanent magnet motor using 3D finite element method, derives the loss distribution based on magnetic field calculations, and performs magnetic-thermal coupling analysis using component losses as heat sources. Experimental measurements on a prototype machine demonstrate that the temperature distribution trends in various motor parts are consistent with the calculated data, establishing a theoretical foundation for subsequent motor structural optimization design.

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

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