No-Load Magnetic Field Analysis of Permanent Magnet Canned Motors with Different Tooth Tip Structural Parameters Postprint

Authors: Ni Youyuan, Sun Miao

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Abstract

The finite element method offers high accuracy and is well-suited for solving magnetic field problems in motors with complex structures. Using the three-dimensional finite element method, a comparative analysis was conducted on the no-load magnetic field parameters of permanent magnet shielded motors featuring two magnetization directions (radial and parallel magnetization) and two structural configurations (with and without tooth tips). Building upon this, the influence of tooth tip structural parameters–including the average arc length of tooth tips, tooth tip thickness, and outer inclination angle–on the no-load magnetic field parameters of motors with the two magnetization directions was investigated. The computational results demonstrate that for both magnetization directions, permanent magnet shielded motors with tooth tip structures exhibit larger fundamental amplitude of no-load air-gap flux density, THD, and cogging torque, yet smaller induced electromotive force.

Full Text

No-Load Magnetic Field Analysis of a PM Canned Motor with Different Structure Parameters of Tooth Tips

Ni Youyuan, Sun Miao
School of Electrical Engineering and Automation, Hefei University of Technology, Hefei 230009, China

Ni Youyuan (male, born in 1976) is an associate professor and master' s supervisor. His research interests include motor design and control.
Sun Miao (male, born in 1990) is a master' s student. His research direction is motor design.

Abstract

The finite element method offers high computational accuracy and is well-suited for solving magnetic field problems in electric machines with complex structures. Using a three-dimensional finite element method, this paper compares and analyzes the no-load magnetic field parameters of permanent magnet canned motors with and without tooth tips for both radial and parallel magnetization directions. Building upon this foundation, the influence of tooth tip structural parameters—including average arc length, tooth tip thickness, and outer inclination angle—on the no-load magnetic field parameters of motors with both magnetization directions is examined. The computational results demonstrate that for both magnetization directions, motors with tooth tip structures exhibit larger fundamental amplitude and THD of no-load air gap flux density, as well as higher cogging torque, but lower induced electromotive force.

Keywords: PM canned motor, no-load magnetic field, tooth tips, three-dimensional finite element method

1 Introduction

Canned motors combined with pumps to form canned motor pumps are typically installed inside pipelines for transporting ordinary, highly toxic, corrosive, radioactive, and flammable liquids. Historically, early canned motors were primarily induction types, but their efficiency was limited by the fundamental principles of induction machines [1-5]. With continuous advances in permanent magnet materials research, permanent magnet canned motors have developed rapidly [6-8]. The application of permanent magnet canned motors not only reduces rotor losses and improves efficiency but also enables structural optimization, demonstrating broader application prospects. Therefore, research on permanent magnet canned motors holds both theoretical value and practical significance for social development.

Domestic and international research comparing the performance of motors with and without tooth tip structures remains scarce. References [9-10] employed analytical methods to analyze magnetic field parameters of radially magnetized permanent magnet motors with and without tooth tips. Due to their relatively simple motor structures, analytical methods were suitable; however, the influence of tooth tip structural parameters on motor performance was not investigated. The three-dimensional finite element method, owing to its high computational accuracy, is appropriate for solving magnetic field problems in complex motor structures. This paper first presents the structure of a permanent magnet canned motor and establishes a three-dimensional simulation model in Maxwell software. Subsequently, the no-load magnetic field of permanent magnet canned motors is analyzed for radial magnetization, parallel magnetization, and structures with and without tooth tips, providing the no-load air gap magnetic field parameters. Based on this analysis, the effects of tooth tip structural parameters—including average arc length, thickness, and outer inclination angle—on the no-load magnetic field parameters of motors with both magnetization directions are investigated, revealing the influence patterns of tooth tip structural parameters on the no-load parameters of permanent magnet canned motors.

2.1 Motor Structure and Materials

The permanent magnet canned motor analyzed in this paper has a rated speed of 3000 r/min and is used in a canned motor pump. The main structural parameters are listed in .

The stator core of the permanent magnet canned motor is constructed from 50W470 silicon steel laminations with a thickness of 0.5 mm. The permanent magnets are Y10T ferrite with a relative recoil permeability of 1.05, remanence of 0.2 T, coercivity of 150 kA/m, electrical conductivity of 2×10^6 S/m, and density of 4.5×10^3 kg/m³. The can serves to isolate the liquid and is made of 06Cr19Ni10 stainless steel with a resistivity of 7.3×10^{-5} $\Omega \cdot$cm and density of 7.93×10^3 kg/m³. The rotor shaft employs aluminum oxide ceramic material, which offers high mechanical strength, economic durability, and excellent friction and impact resistance, enabling long-term use without deformation. This component is omitted from the electromagnetic simulation analysis.

2.2 Three-Dimensional Finite Element Model

A three-dimensional model of the permanent magnet canned motor with tooth tips was established in Maxwell 3D, featuring a 6-slot, 4-pole configuration as shown in [Figure 1: see original paper]. In Ansoft Maxwell 3D software, the three-dimensional geometric model of the permanent magnet synchronous canned motor is first created. Since Ansoft provides a powerful material library with extensive editing capabilities, appropriate material properties can be assigned to each component. Through proper meshing methods and accurate mesh refinement settings, all components within the solution region are discretized. Finally, boundary conditions and excitation sources are applied to the model for solution. Post-processing of the result data yields the required outcomes.

2.3 Structures With and Without Tooth Tips

The permanent magnet canned motors with and without tooth tips are illustrated in [Figure 2: see original paper]a and 2b, respectively. Compared with the structure without tooth tips, the tooth tip structure is more complex, resulting in different magnetic circuits and consequently different motor performance characteristics.

3 No-Load Magnetic Field Analysis of Radially Magnetized Permanent Magnet Canned Motor

Using the three-dimensional finite element method, the no-load magnetic field parameters of the radially magnetized permanent magnet canned motor were calculated. [Figure 3: see original paper]a and 3b show the no-load induced electromotive force (EMF) waveforms for radially magnetized permanent magnet canned motors with and without tooth tips. The results indicate that the RMS values of induced EMF are 15 V and 18.9 V for the structures with and without tooth tips, respectively.

[Figure 4: see original paper]a and 4b present the cogging torque waveforms for radially magnetized permanent magnet canned motors with and without tooth tips. The peak cogging torque values are 6.25 mN · m and 5.6 mN · m for the structures with and without tooth tips, respectively.

[Figure 5: see original paper]a and 5b illustrate the no-load air gap flux density waveforms for both motor structures. The results show that the air gap flux density amplitude is larger for the structure with tooth tips. Additionally, the air gap flux density was calculated at different axial cross-sections, revealing that the air gap flux density remains relatively stable near the symmetrical plane but decreases significantly at both ends. This indicates that the air gap flux density maintains a relatively constant value between the stator and rotor but diminishes noticeably near the end regions.

Fourier decomposition of the air gap flux density was performed to obtain the fundamental and harmonic components for both structures under radial magnetization, as shown in [Figure 6: see original paper]a and 6b. The fundamental amplitude and THD of the no-load air gap flux density for both structures are summarized in . The results demonstrate that the structure with tooth tips exhibits a larger fundamental amplitude of air gap flux density, indicating lower leakage flux. However, due to the more complex tooth tip structure, it also produces a higher proportion of harmonics.

3.1 Influence of Tooth Tip Structural Parameters on Motor No-Load Magnetic Field

[Figure 7: see original paper] illustrates the tooth tip structural parameters, which primarily include average arc length, thickness, and outer inclination angle. By varying only the average arc length of the tooth tips while keeping the tooth tip thickness, outer inclination angle, and other motor parameters constant, the no-load induced EMF and cogging torque were calculated as functions of different average arc lengths, as shown in [Figure 8: see original paper] and [Figure 9: see original paper], respectively. The results show that the induced EMF increases with increasing average arc length of the tooth tips. The cogging torque reaches its maximum at intermediate values of average arc length and becomes smaller at both shorter and longer arc lengths. The fundamental amplitude of air gap flux density shows a positive correlation with average arc length, though the change is less pronounced at very short or very long arc lengths.

The fundamental amplitude and THD of the radially magnetized air gap flux density for different average arc lengths are presented in . The results indicate that the induced EMF increases with increasing average arc length of the tooth tips. At shorter arc lengths, the fundamental amplitude of air gap flux density changes insignificantly, but it gradually increases as the average arc length grows.

By varying only the tooth tip thickness while keeping the average arc length, outer inclination angle, and other motor parameters constant, the no-load magnetic field parameters were calculated as shown in . The results reveal that the induced EMF remains essentially unchanged, indicating minimal influence from tooth tip thickness. However, the variation patterns of cogging torque, fundamental amplitude of air gap flux density, and THD with thickness change are not obvious. At certain thickness values such as 1.2 mm, 2.1 mm, and 3.0 mm, the air gap flux density amplitude, THD, and cogging torque calculations yield relatively superior results.

Furthermore, by varying only the outer inclination angle of the tooth tips while keeping the average arc length, tooth tip thickness, and other motor parameters constant, the no-load magnetic field performance parameters were obtained as shown in . The results demonstrate that the outer inclination angle has minimal effect on the induced EMF and fundamental amplitude of air gap flux density. However, the variation patterns of cogging torque and THD of air gap flux density with changes in tooth tip thickness are not clearly defined.

4 No-Load Magnetic Field Analysis of Parallel Magnetized Permanent Magnet Canned Motor

After setting the magnetization direction of the rotor permanent magnets to parallel magnetization, three-dimensional no-load magnetic field analysis was performed on permanent magnet canned motors with and without tooth tips. [Figure 10: see original paper]a and 10b show the no-load induced EMF waveforms for parallel magnetized permanent magnet canned motors with both structures. The results indicate that the RMS values of induced EMF are 20.8 V and 26.7 V for the structures with and without tooth tips, respectively.

[Figure 11: see original paper]a and 11b present the cogging torque waveforms for parallel magnetized permanent magnet canned motors with both structures. The peak cogging torque values are 6.1 mN·m and 4.68 mN·m for the structures with and without tooth tips, respectively.

[Figure 12: see original paper]a and 12b illustrate the no-load air gap flux density waveforms for parallel magnetized permanent magnet canned motors with and without tooth tips. The results show that the air gap flux density amplitude is larger for the structure with tooth tips.

Fourier decomposition of the air gap flux density was performed to obtain the fundamental and harmonic components for both structures under parallel magnetization, as shown in [Figure 13: see original paper]a and 13b. The fundamental amplitude and THD of the no-load air gap flux density are summarized in . Evidently, the structure with tooth tips exhibits a larger fundamental amplitude of air gap flux density, indicating that leakage flux remains smaller in parallel magnetized permanent magnet canned motors with tooth tips. Similarly, for parallel magnetized permanent magnet canned motors, the more complex tooth tip structure results in a higher proportion of harmonics.

4.1 Influence of Tooth Tip Structural Parameters on Motor No-Load Magnetic Field

For parallel magnetized permanent magnet canned motors, by varying only the average arc length of the tooth tips while keeping the tooth tip thickness, outer inclination angle, and other motor parameters constant, the no-load induced EMF and cogging torque were calculated as functions of different average arc lengths, as shown in [Figure 14: see original paper] and [Figure 15: see original paper], respectively. Additionally, the fundamental amplitude and THD of the air gap flux density for different average arc lengths were obtained as shown in . The results show that the induced EMF increases with increasing average arc length of the tooth tips. The cogging torque is larger at intermediate values of average arc length and smaller at both shorter and longer arc lengths. The fundamental amplitude of air gap flux density is positively correlated with the average arc length, though the change is less pronounced at very short or very long arc lengths.

By varying only the tooth tip thickness while keeping the average arc length, outer inclination angle, and other motor parameters constant, the no-load magnetic field performance parameters of the parallel magnetized permanent magnet canned motor were calculated as shown in . The results indicate that tooth tip thickness has minimal effect on the induced EMF. However, the variation patterns of cogging torque, fundamental amplitude of air gap flux density, and THD with thickness change are not obvious. At certain thickness values such as 1.2 mm and 3.0 mm, the cogging torque, air gap flux density amplitude, and THD yield relatively superior results.

Furthermore, by varying only the outer inclination angle of the tooth tips while keeping the tooth tip thickness, average arc length, and other motor parameters constant, the no-load magnetic field performance parameters of the parallel magnetized permanent magnet canned motor were obtained as shown in . The results demonstrate that the outer inclination angle has minimal influence on the induced EMF and fundamental amplitude of air gap flux density. However, the variation patterns of cogging torque and THD of air gap flux density with changes in tooth tip thickness are not clearly defined.

6 Conclusion

For electric machines with complex structures, the finite element method is necessary to accurately calculate their performance. This paper employs a three-dimensional finite element method to compute the no-load magnetic field of permanent magnet canned motors under radial magnetization, parallel magnetization, and with and without tooth tip structures. The no-load air gap flux density waveforms, back EMF waveforms, and cogging torque waveforms were obtained, and Fourier decomposition was performed on the air gap flux density. The computational results indicate that for both magnetization directions, the tooth tip structure yields larger fundamental amplitude and THD of air gap flux density, as well as higher cogging torque, but lower induced EMF. The influence of tooth tip structural parameters—including average arc length, tooth tip thickness, and outer inclination angle—on the no-load magnetic field parameters of motors with both magnetization directions was analyzed, revealing the influence patterns of tooth tip parameters on no-load magnetic field characteristics. This study provides a theoretical reference for the structural optimization of permanent magnet motors and permanent magnet canned motors.

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