Design and Analysis of a Novel Low-Speed and High-Torque Synchronous Motors with PM and Reluctance Hybrid Rotor

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Mon-Af-Po1. 22-11

MT26 International Conference on Magnet Technology Vancouver, Canada | 2019

Abstract

Low-speed and high-torque motors (LSHTMs) are widely used in many industrial fields. In order to make full use of the internal space of the motor, a double stator structure for LSHTM is proposed. In addition, a hybrid rotor is proposed to reduce the amount of permanent magnets (PMs). The proposed hybrid rotor structure is a combination of magnetic barrier reluctance rotor and PM rotor which are embedded on the inner and outer sides of magnetic isolation ring respectively. In this paper, the electromagnetic design of the proposed motor is carried out based on the connection of inner and outer stator windings in parallel. Secondly, the mechanical structure of the proposed novel motor is designed. Thirdly, the cooling system of the proposed motor is designed to reduce the temperature rise of the motor. Finally, the rationality of the proposed motor design and the correctness of theoretical analysis are verified by simulation analysis.

Electromagnetic Design of Proposed Motor

The schematic diagram of the proposed motor is shown in Fig. 1. As shown, the proposed motor consists of an outer stator, a hybrid rotor and an inner stator. In addition, the hybrid rotor is a combination of permanent magnet (PM), a magnetic barrier and magnetic isolation ring. The power of the proposed motor can be calculated by Eq. 1, and the equation also can be used to estimate the size of the motor. The specific design parameters of the motor are shown in Tab. 1, and the design flow is shown in Fig. 2.

Tab. 1 Specific design parameters of proposed motor

Name	Value	Name	Value
Rated power	50kW	Outside air gap	2.5 mm
Rated voltage	1140V	Inside air gap	0.8 mm
Number of poles	30	Outside diameter of outer stator	399 mm
Rated speed	90 r/min	Inside diameter of outer stator	305 mm
Stack length	350 mm	Height of PM	6 mm
Outside diameter of outer stator	740 mm	Width of PM	42.8 mm
Inside diameter of outer stator	550 mm	Number of magnetic layer	3

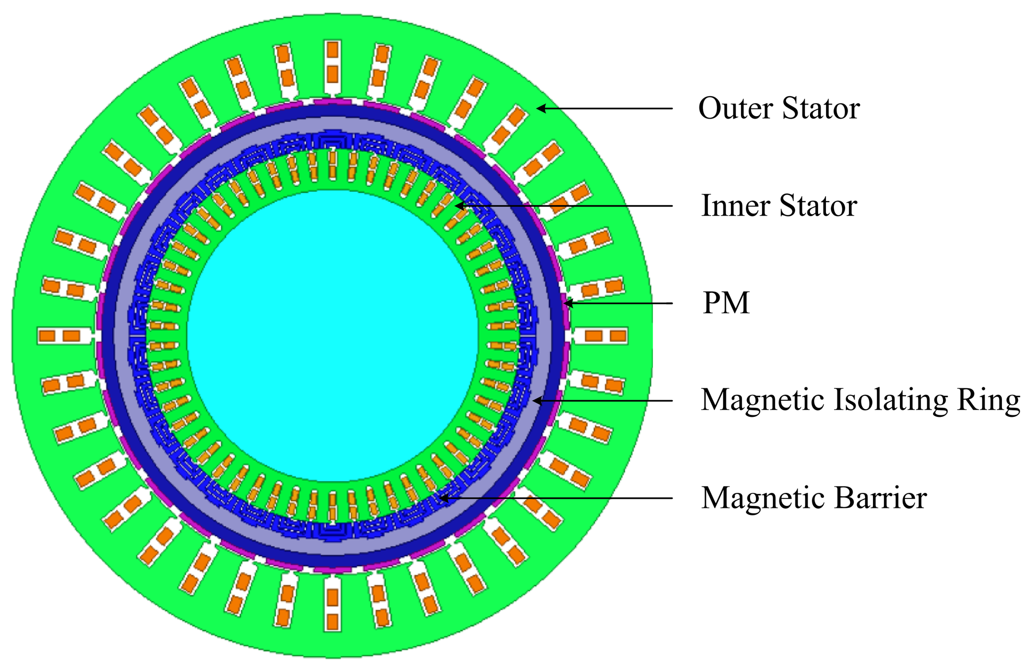

Fig. 1 Schematic diagram of proposed motor

$$P_{\text{out}}=\frac{\sqrt{2}\pi^2}{2}K_{\omega}\eta\left(\frac{f}{p}\right)l_{\text{ef}}\left(B_{\delta\text{o}}A_{\text{o}}D_{\text{o}}^2+B_{\delta\text{i}}A_{\text{i}}D_{\text{i}}^2\cos\alpha\right) \quad (1)$$

Where, K_{ω} is winding factor, η is assumed efficiency, f is fundamental frequency, p is the number of pole pairs, B is the air gap flux density, A is electrical loading, l_{ef} is stack length, α is the angle between q-axis vector and stator current vector of reluctance motor, D is the inside diameter of stator, and the subscript o and i express the outer stator and inner stator respectively.

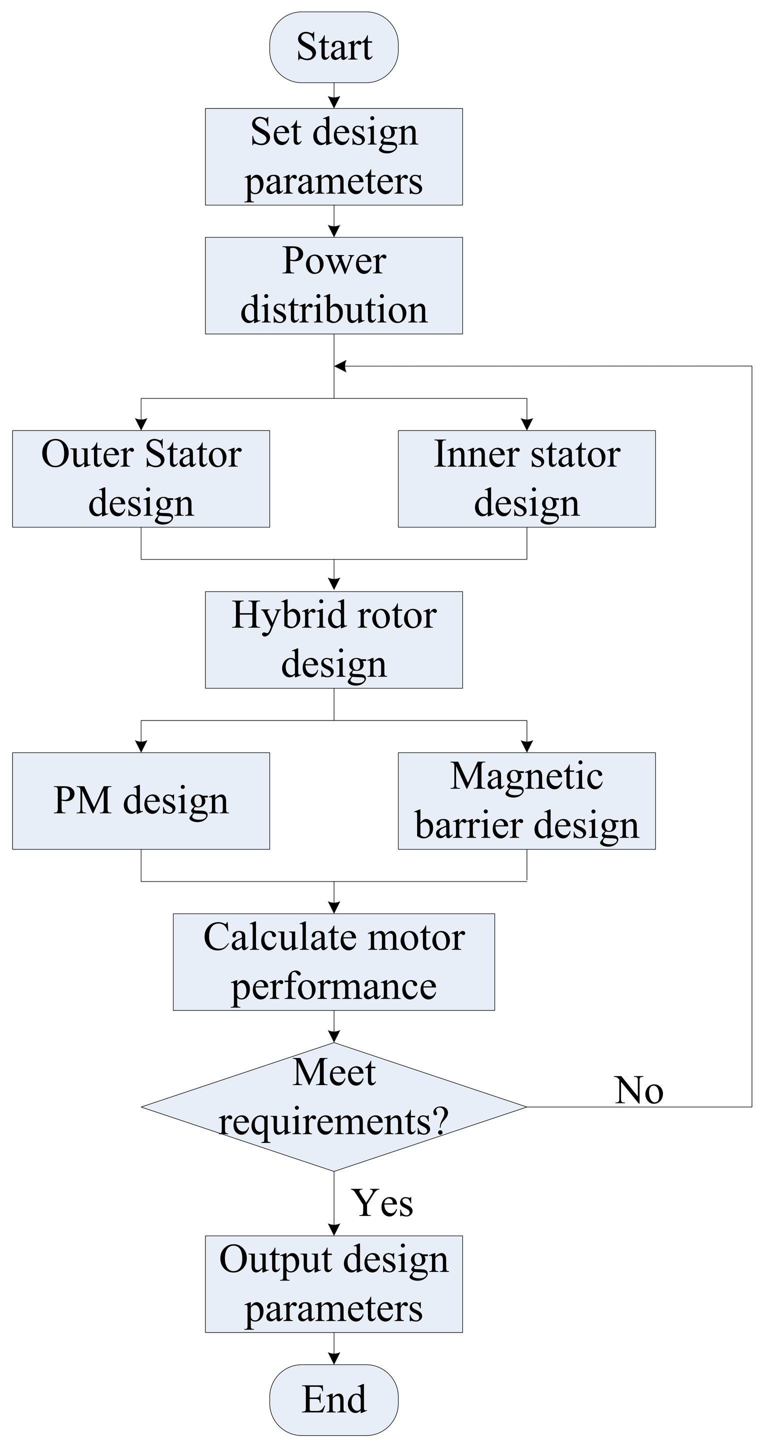

Fig. 2 Design flow chart of LSHTPMM

Mechanical Structure and Cooling System Design

According to the structural characteristics of the proposed motor, the mechanical structure and suitable assembly method for this kind of motor are designed. The overall structure is shown in Fig. 3. In addition, in order to facilitate the connection the windings of the inner stator, the stationary shaft adopts a hollow form. In order to reduce the temperature rise of the inner stator, the inner stator adopts a water-cooled cooling mode, and its schematic diagram is shown in Fig. 4.

1. front end cover
2. frame
3. outer stator
4. PM-reluctance rotor
5. inner stator
6. rear end cover
7. rotating shaft
8. bearing
9. fixing ring
10. dead axle
11. link lever
12. supporting seat

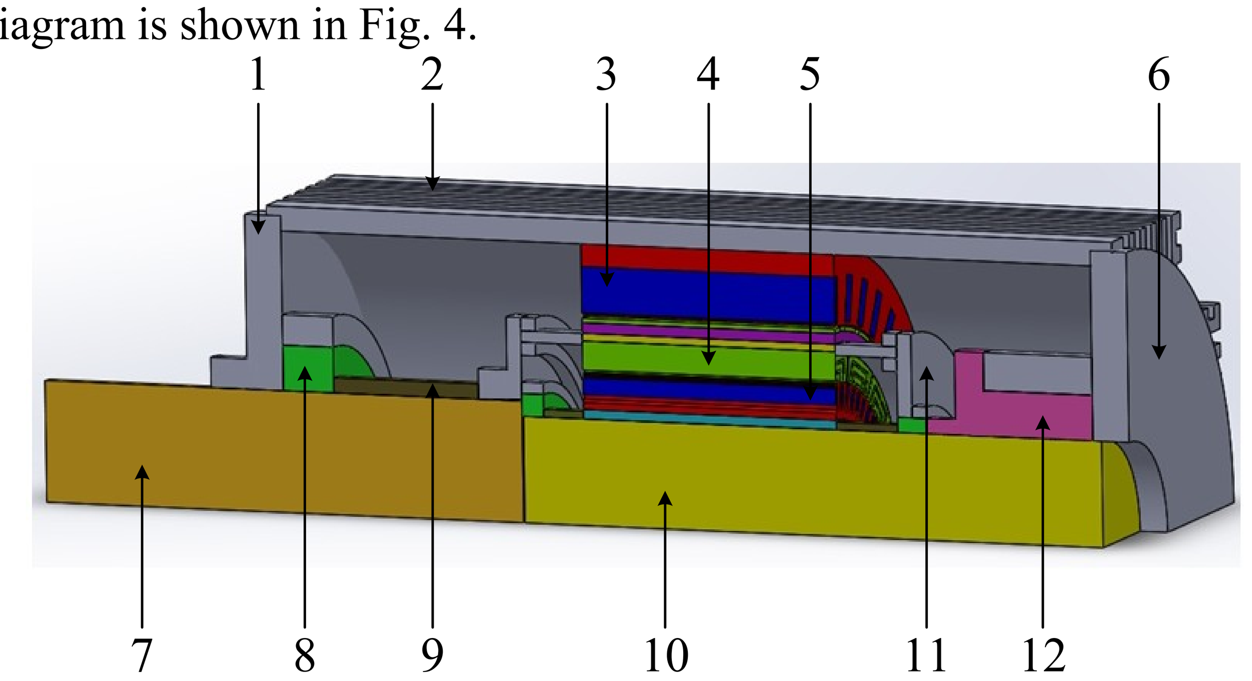

Fig. 3 Mechanical structure

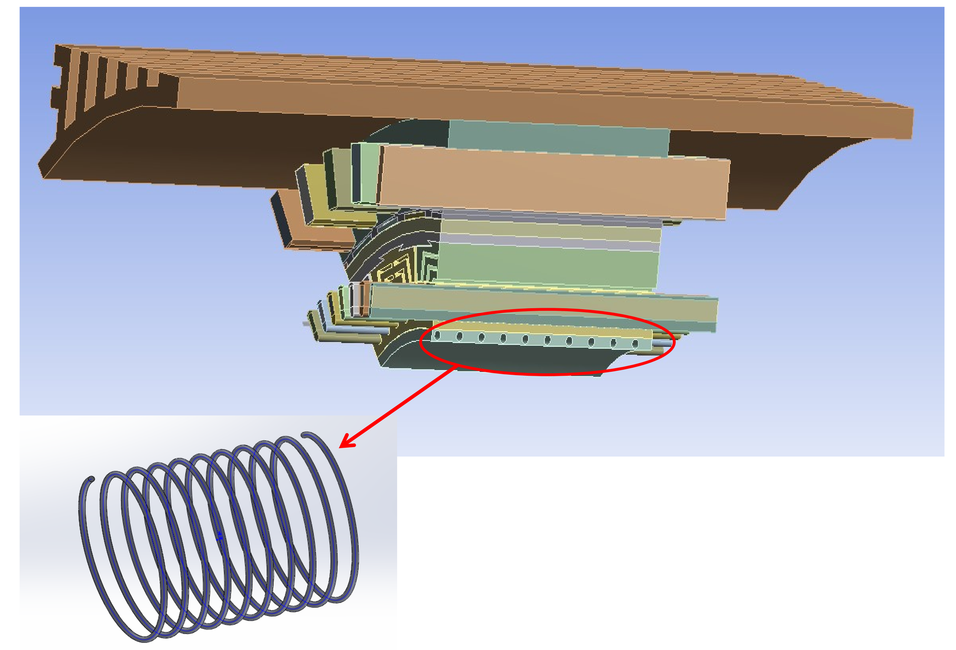

Fig. 4 Cooling system of inner stator

Simulation Results and Discussion

The back EMF waveforms under mo-load condition are shown in Fig. 5. It can be seen that both of the back EMF of the outer and inner stator windings can reach the rated value and the sinusoidal property is better. This also proves the rationality of the electromagnetic design of the proposed motor. The temperature distribution of the motor is studied and the results are shown in Fig. 6. It can be seen from the results that the maximum temperature rise of the motor is mainly concentrated in the rotor and the inner stator. The maximum temperature rise can reach 180° C without cooling system. However, when the water cooling system is used internally, the temperature rise of the motor drops significantly, and the maximum value is 60° C. This fully demonstrates the effectiveness of the proposed cooling structure. The deformation of the shaft was analyzed and the results are shown in Fig. 7. It can be seen from the results that the deformation range of the rotating shaft is 0~5.9e-4mm, which can satisfy the stable operation of the motor. In addition, the deformation is mainly concentrated on the rotor link lever.

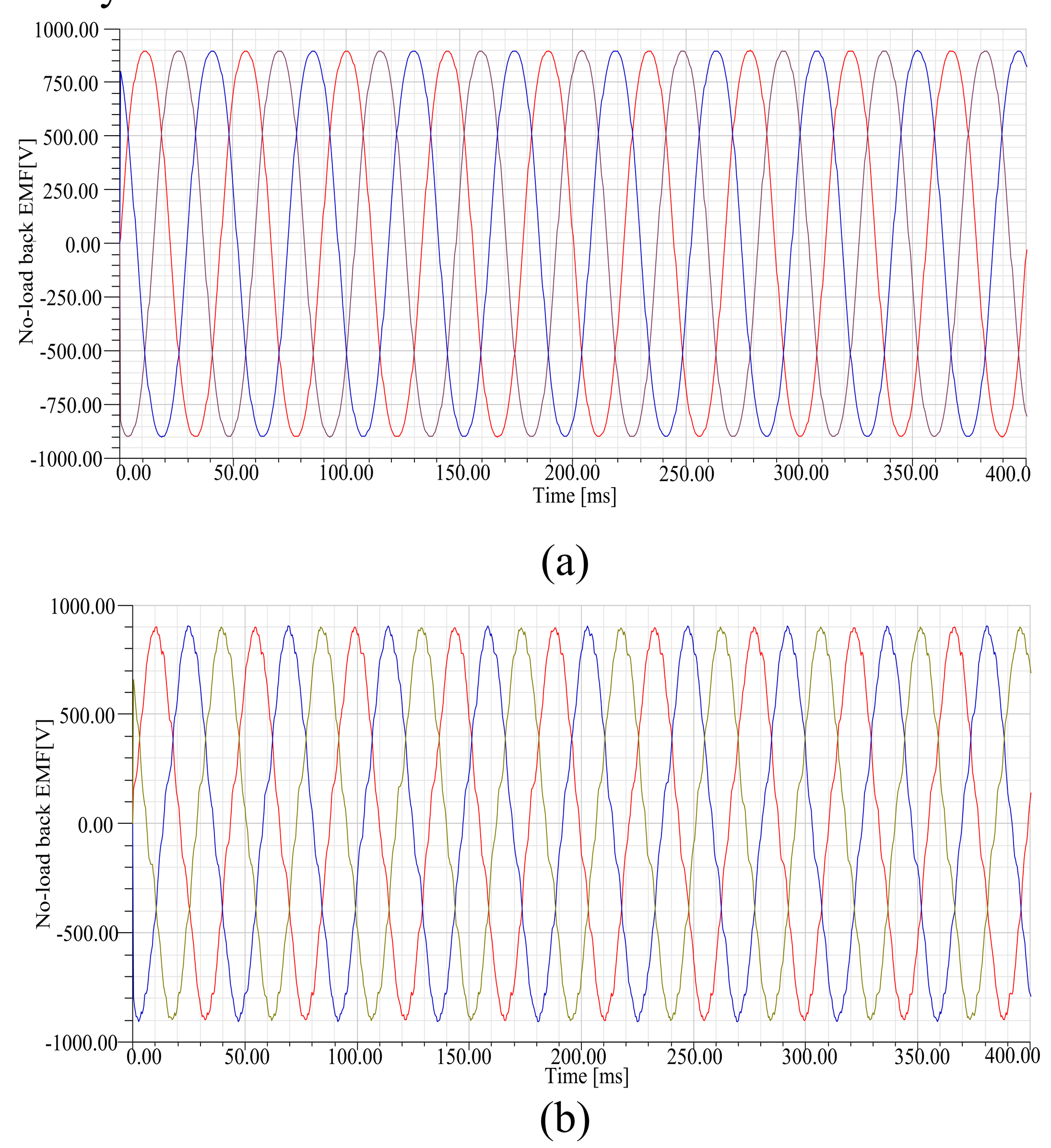

Fig. 5 Back EMF waveforms (a) outer stator (b) inner stator

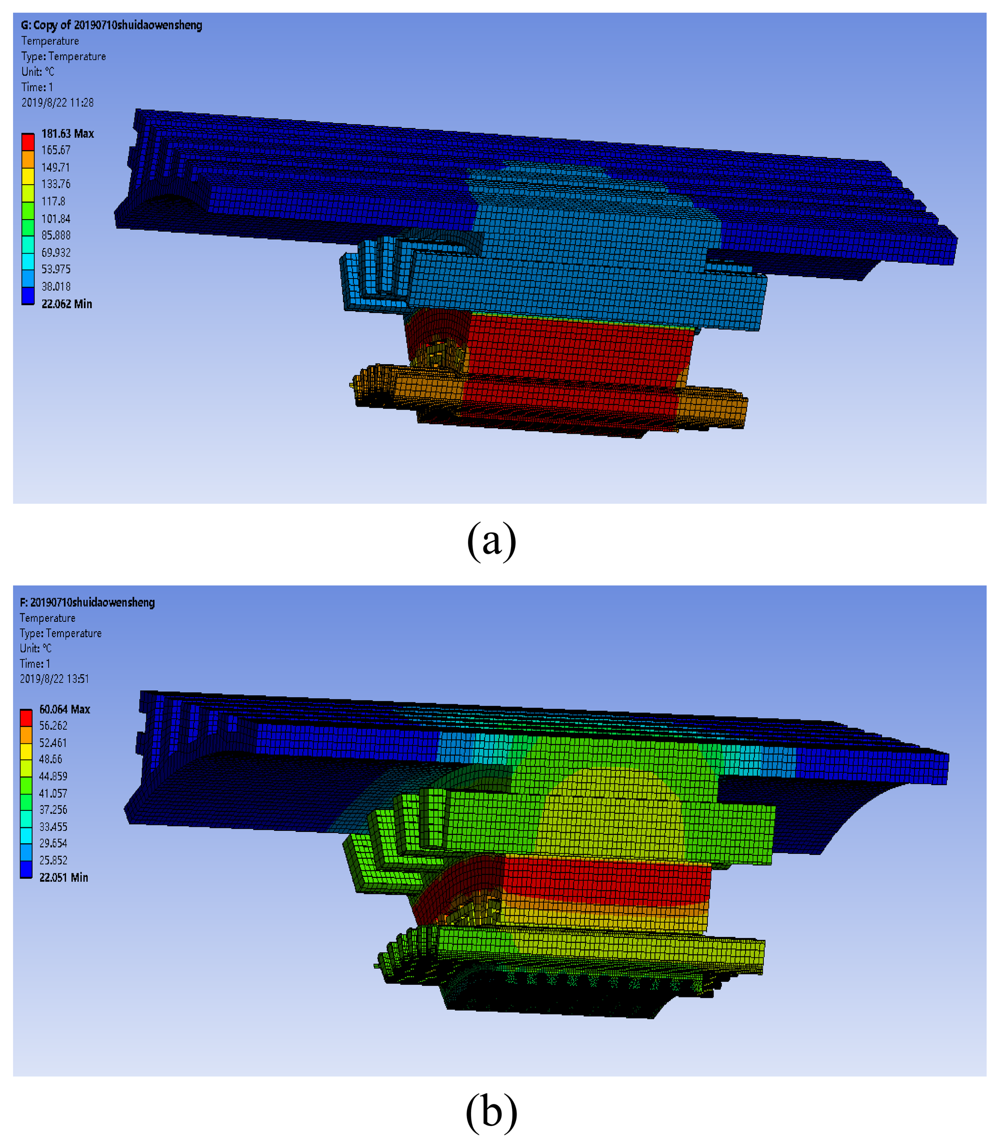

Fig. 6 Temperature distribution
(a) without cooling system (b) with cooling system

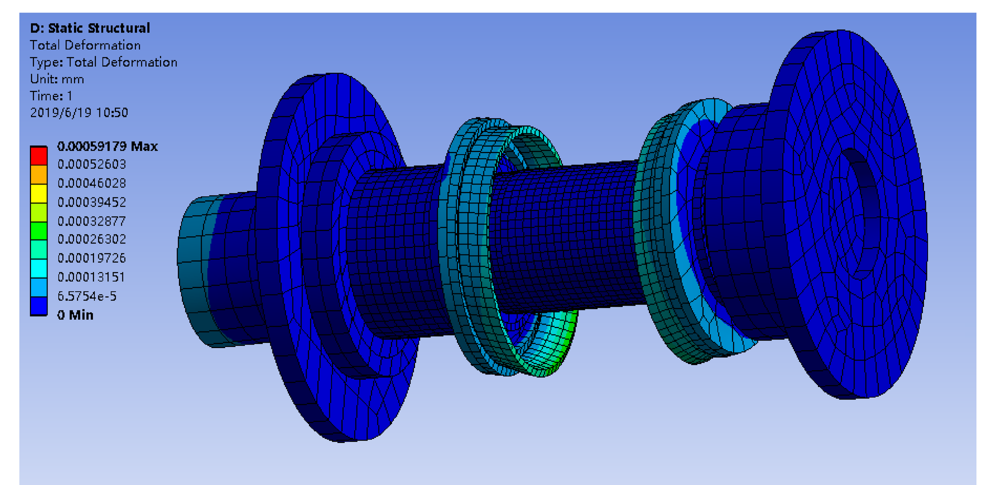

Fig. 7 Analysis of rotor deformation

Conclusion

In this paper, a low-speed and high-torque motor with double stator is proposed. A PM-reluctance rotor structure is adopted for the proposed to reduce the PM. The electromagnetic design method is studied and the special mechanical structures is proposed. In addition, the cooling system is designed to reduce the temperature rise. The electromagnetic performance, mechanical properties and temperature rise of the motor are analyzed by simulation. The simulation results proved the correctness of the motor design.