Analysis and optimization of temperature field of high-speed permanent magnet motor

Kai Hu\textsuperscript{1,2}, Guangming Zhang\textsuperscript{1} and Wenyi Zhang\textsuperscript{2}

Abstract
High-speed permanent magnet motor (HSPMM) has a wide application prospect in machinery, energy, and other industries. The temperature field of HSPMM was analyzed and optimized in order to reduce the operating temperature and improve the service life and efficiency. Two new methods were proposed to reduce the copper loss and iron loss. Response surface method was employed to improve permanent magnet parameters. The response surface results demonstrate that when factor A is 7.7 mm, factor B is 5.0 mm, and factor C is 134.9°, the core loss is minimum with 32.91 W. On the premise of comprehensively considering the thermal convection, conduction, and radiation effects, the equivalent thermal circuit model of HSPMM was creatively established. The theoretical analysis data show that the temperature of each position of the optimized motor is reduced by 8.2°C–10.2°C. In order to verify the correctness of the above theoretical analysis, a temperature measuring experiment was conducted. The temperature error between the measured data and the theoretical calculation data is acceptable, and the average error is only 4.01%. The research methods and conclusions can be widely extended to the temperature field optimization of other permanent magnet motors.

Keywords
High-speed permanent magnet motor, temperature field, equivalent thermal circuit model, response surface method, temperature measuring experiment

Introduction
High-speed motor is that whose rated rotational speed exceeds 10,000 rev/min. Compared with the conventional motor, the power density of the high-speed motor is higher, and its geometric size is much smaller. Permanent magnet motor is a motor in which the excitation magnetic field is established by permanent magnet. Since no winding is needed to form an exciting field, the amount of copper consumption and the resistance loss of the permanent magnet motor are greatly reduced. High-speed permanent magnet motor (HSPMM) takes the both advantages into account, and has a wide application prospect in many industries, such as machinery, energy, textile, and so on. High-speed permanent magnet motor has small volume and high-power density, so the loss per unit volume is increased, but the heat dissipation space is reduced. The changing frequency of the working current and magnetic field of the high-speed motor is

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very high, and the iron loss and copper loss of the motor are positively correlated with the frequency. With the increase of frequency, the skin effect and proximity effect of stator winding become obvious, and the hysteresis loss and eddy current loss of iron core also increase significantly. Excessive temperature will cause motor performance decline, and even lead to permanent magnet demagnetization for HSPMM. Statistics data show that the temperature rise of 10°C will reduce the insulation life by about 50%. What more, the temperature rise of 50°C will increase the resistance of copper windings by 20% and the temperature rise of 135°C will increase the resistance of copper windings by 53%. The service life and efficiency of the HSPMM will be significantly affected by the operating temperature. Therefore, it is of great significance to analyze and optimize the temperature field of HSPMM to decrease its operating temperature.

The analysis and optimization methods of temperature field of HSPMM have been deeply researched by scholars in previous study. Dong studied the influence of rotor structure of HSPMM on heat dissipation. Computational fluid dynamics (CFD) and finite element method were adopted to solve the fluid-solid coupling solution of the internal temperature field. The results show that the air velocity in the rotor cavity is lower when the rotor has no wind thorn and no hole. Under such working conditions, it is difficult for the rotor to dissipate heat, and the temperature rise of the permanent magnet is higher. However, this study only analyzed the temperature distribution by optimizing the rotor structure, and it may cause the electromagnetic performance loss. In a follow-up study, the skin effect and proximity effect under different frequency and phase current was studied by Kim. The mathematical model of windings loss was established, and its correctness was verified by experiments. Unfortunately, the accuracy of this mathematical model is not recognized at high-frequency current above 100 Hz. The current frequency is usually higher than 300 Hz for HSPMM, so the model may be difficult to apply Hruska et al. thoroughly analyzed the mechanism of copper consumption of HSPMM and proposed to restrain copper loss by deepening the depth of stator slot. The test data show that this method can reduce the copper consumption by 5% and 10%. However, the stator structure of the motor is changed, which may increase the volume or influence the electromagnetic performance. It can be said that the reduction of copper loss is at the expense of the performance decline. Park et al. optimized the temperature field of surface-mounted HSPMM. The influence of the structural parameters of the permanent magnet on the iron loss was analyzed, and the correctness of the theoretical analysis was verified by the CFD method. But the strength of the permanent magnet of the surface-mounted motor is difficult to withstand a large centrifugal force, which greatly limits its rotational speed. It further limits the popularization and application of surface-mounted HSPMM. One of the most cited studies is that of Sun et al. who conducted multiphysics design optimization of a switched reluctance motor for electric vehicle. The electromagnetic finite element model was introduced and the 3D transient lumped-parameter thermal model, considering both axial and radial heat transfer, was proposed. The simulation and experimental results show that the optimal solution exhibits lower temperature, higher torque, lower torque ripple, and less loss.

Previous studies have the following limitations. Firstly, the electromagnetic performance of the HSPMM may be weakened by using the existing method of temperature field optimization. Secondly, the CFD and finite element method were adopted which not only need accurate mathematical models, but also have slow calculation speed. Thirdly, most research was aimed at the temperature field optimization of the surface-mounted HSPMM whose electromagnetic performance is poor. The limit rotational speed of surface-mounted HSPMM is greatly limited without adding the protective sleeve. The research methods and conclusions of this paper effectively solve the above problems.

The remaining parts of the paper are organized as follows. A new method to reduce copper loss was proposed and its correctness is verified by finite simulation in Section 2. In Section 3, the installation parameters of permanent magnet are optimized by response surface method (RSM). In Section 4, The equivalent thermal circuit model (ETCM) of HSPMM is creatively established and the simulation results show that it has high computational efficiency and accuracy. The temperature measuring experiment was conducted in Section 5. The three innovations of this paper and the future work are expounded in detail in Section 6. At last, the concluding remarks of this study were described in Section 7. The research methods and conclusions adopted in this paper can be extended to the analysis and optimization of the temperature field of other permanent magnet motor.

**Copper loss reduction method**

**Theoretical analysis**

When there is an alternating current or an alternating electromagnetic field in a conductor, the current in the conductor will be distributed unevenly. The current is concentrated on the surface of the conductor, and the current inside the conductor is actually small. This phenomenon is called the skin effect. When multiple adjacent conductors have alternating current or alternating electromagnetic fields, the electromagnetic fields...
generated between each other will affect the current inside the adjacent conductors. This phenomenon is called proximity effect. The skin effect and proximity effect will reduce the effective cross-sectional area of the conductor, thus increasing the conductor resistance. The current frequency of HSPMM is very high. As a result, the skin effect and proximity effect are more obvious, and the heat converted from copper loss is greater. It is very important to reduce copper loss of HSPMM effectively to reduce the operating temperature.

The solid conductor is placed in the slot. The ferromagnetic material is surrounded on three sides. When alternating current flows through the conductor, a certain intensity of magnetic field is generated in this area. Figure 1 shows the schematic diagram of the whole conductor placed in the slot. The leakage flux at the bottom of the conductor will be larger than that at the top. From the bottom to the top of the conductor, the conductor impedance decreases and the current density increases. Formula (4) can be derived by applying Ampere law to the area surrounded by path A (1–2–3–4–1) in Figure 1.

\[
\oint H dl = Hb - (H + \frac{\partial H}{\partial y} dy) b = J b_c dy
\]  
(1)

Formula (2) can be obtained by solving formula (1).

\[-\frac{\partial H}{\partial y} = \frac{b_c}{b} J \]  
(2)

\(H\) is the magnetic intensity produced by the current. \(J\) is the current density. \(b_c\) is the width of the conductor and \(b\) is the slot width. \(l\) is the depth of ferromagnetic material.

Formula (3) can be derived by applying Faraday law of electromagnetic induction to the area surrounded by path B (5–6–7–8–5) in Figure 1.

\[
\oint E dl = -El + \left(E + \frac{\partial E}{\partial y} dy\right) l = -\frac{\partial B}{\partial t} l dy
\]  
(3)

\(E\) is the electric field intensity. \(B\) is the magnetic flux through the closed path, and \(t\) denotes the time.

Formula (4) can be obtained by solving formula (3).

\[\frac{\partial E}{\partial y} = -\frac{\partial B}{\partial t} = -\mu_0 \frac{\partial H}{\partial t} \]  
(4)

The value of vacuum permeability \((\mu_0)\) is \(4\pi \times 10^{-7} \text{ H/m}\). Formula (5) can be deduced according to Ohm law.

\[J = \sigma_c E \]  
(5)

\(\sigma_c\) is electric conductivity.

Formula (6) can be derived by differentiating the formula (5) in the \(y\) direction and substituting the result into formula (4).

\[\frac{\partial J}{\partial y} = -\mu_0 \sigma_c \frac{\partial H}{\partial t} \]  
(6)

When the current is sinusoidal, formulas (2), (4) and (6) can be transformed into plural forms. As results, formulas (7), (8) and (9) can be obtained.

\[-\frac{\partial H}{\partial y} = \frac{b_c}{b} J \]  
(7)

\[\frac{\partial E}{\partial y} = -j\omega \mu_0 H \]  
(8)

\[\frac{\partial J}{\partial y} = -j\omega \mu_0 \sigma_c H \]  
(9)

Formula (9) is differentiated first, and then formula (10) can be obtained in combination with formula (7).

\[\frac{\partial^2 J}{\partial y^2} - j\omega \mu_0 \sigma_c \frac{b_c}{b} J = 0 \]  
(10)

Formula (11) is the solution of formula (10).

\[J = C_1 e^{(1 + j\omega y)} + C_2 e^{-(1 + j\omega y)} \]  
(11)

In formula (10), \(\alpha\) can be expressed by formula (12).

\[\alpha = \sqrt{\frac{1}{2} \mu_0 \sigma_c \frac{b_c}{b}} \]  
(12)

The converted height of the conductor is a dimensionless number that can be defined by formula (13).

\[\delta = \alpha h_c = h_c \sqrt{\frac{1}{2} \mu_0 \sigma_c \frac{b_c}{b}} \]  
(13)
The ratio of AC resistance to DC resistance of a conductor is called resistance coefficient. For the conductor in Figure 1, its resistance coefficient can be calculated by formula (14)

\[
k_{Ru} = \frac{b^2}{I} \int_0^h y^2 dy
\]

\(k_{Ru}\) is resistance coefficient. \(I\) is internal current of conductor. \(h_c\) is the height of conductor.

The whole conductor structure shown in Figure 1 does not exist in the actual motor. The windings are arranged in the stator slots in the configuration shown in Figure 2.

According to the conclusion of the reference,25 the resistance coefficient of the kth layer conductor can be calculated by formula (15).26

\[
k_{Rk} = \varphi(\delta) + k(k - 1)\psi(\delta)
\]

In formula (15), the converted height of the conductor (\(\delta\)) can be defined by Formula.

\[
\delta = h_{c0} \sqrt{\frac{1}{2} \omega \mu_0 \sigma_c z_a b_{c0} \over b}
\]

\(h_{c0}\) is height of a single conductor. \(b_{c0}\) is width of a single conductor. \(\omega\) is current angular frequency. \(\sigma_c\) is electric conductivity. \(z_a\) is the number of conductor columns.

The expressions of functions \(\varphi(\delta)\) and \(\psi(\delta)\) are expressed by formulas (17) and (18) respectively.

\[
\psi(\delta) = \frac{2 \delta \sinh(\delta) - \sin(\delta)}{\cosh(\delta) + \cos(\delta)}
\]

The above formulas reveal that the resistance coefficient of the bottom layer in the stator slot is the smallest, while that of the top layer is the largest. This means that the contribution of the bottom conductor to the copper loss is smaller than that of the top layer. In order to obtain less copper loss, the number of conductor layers should be reduced.

**Copper loss calculation under different conductor arrangement**

In order to verify the correctness of the above theoretical analysis, the copper loss in the stator slot under different arrangement is simulated. In Figure 3(a), the conductors are arranged in seven layers. In Figure 3(b), the conductors are arranged into five layers. It should be noted that only the arrangement of conductors is changed, and the number of conductors and the space factor are exactly same for two different arrangements. The current with a frequency of 500 Hz and an amplitude of 10 A flows through the conductors. The cloud map of copper loss distribution is shown in Figure 3. The current distribution in the conductor is obviously affected by the skin effect and proximity effect, no matter how the conductors are arranged. The conductors near the stator notch have the largest copper loss, while the conductors in the middle have small copper loss.

It can be known by integrating the cross-sectional area of all conductors that the total copper loss of the all conductors with seven-layer arrangement is 135.43 W, and that with five-layer arrangement is 116.18 W. The total copper loss is decreased by 14.21%. The data show that the copper loss of all the conductors in the stator slot is effectively reduced by reducing the number of conductor layers.

**Iron loss reduction method**

**Iron loss calculation theory**

The core loss of motor can be divided into eddy current loss and hysteresis loss. The voltage will be induced under the action of alternating magnetic flux, and then some eddy current will be formed on the surface of the iron core. Hysteresis loss is the energy consumed by hysteresis phenomenon in the process of repeated magnetization of silicon steel sheet. The energy of eddy current loss and hysteresis loss will be converted into thermal energy, which increases the operating temperature and reduces the efficiency of the motor.
The eddy current loss and hysteresis loss of silicon steel sheet can be calculated according to formulas (19) and (20), respectively.

\[ P_{ed} = \frac{\pi \sigma_{Fe}}{6} f^2 d^2 m_{Fe} k_d \left(B_{tan,1}^a + B_{norm,1}^a \right) \]  \hspace{1cm} (19)

\[ P_{hy} = c_{hy} \frac{f}{100} m_{Fe} k_d \left(B_{tan,1}^a + B_{norm,1}^a \right) \]  \hspace{1cm} (20)

In the above formulas, \( k_d \) can be calculated by formula (21).

\[ k_d = 1 + \sum_{n=2}^{\infty} \frac{\left(B_{tan,n}^a + B_{norm,n}^a \right)}{\left(B_{tan,1}^a + B_{norm,1}^a \right)} \]  \hspace{1cm} (21)

\( P_{ed} \) is eddy current loss, \( \sigma_{Fe} \) and \( \rho_{Fe} \) are electrical conductivity and density of ferromagnetic material. \( f \) is alternating current frequency. \( d \) is thickness of ferromagnetic material. \( m_{Fe} \) is ferromagnetic material weight. Hysteresis coefficient \( (c_{hy}) \) is 1.2–2. \( B_{tan,n} \) is tangential component of the \( n \)th harmonic of magnetic flux. \( B_{norm,n} \) is normal component of the \( n \)th harmonic of magnetic flux.

The above formulas can accurately calculate the core loss of conventional speed motor, but for high-speed motor, the correction factor should be considered. If the above formulas are adopted directly, the iron loss error rate of HSPMM may be more than 20%. In addition, it is necessary to accurately obtain the magnetic induction intensity and each order harmonic component in the core to calculate the core loss according to formulas (19) and (20). It is often difficult to achieve for analytical calculation methods. Finite element method is often applied to calculate the iron loss.

**Optimization of installation parameters of permanent magnet**

The installation parameters of permanent magnet will affect the magnetic induction intensity and harmonic components of different positions in the iron core. The core loss can be effectively reduced by optimizing the installation parameters of permanent magnets. The finite element model of double-layer V-type HSPMM is established in electromagnetic software. Under the premise that the overall size of the motor and the length and width of the permanent magnet are not changed, the distance between the two layers of permanent magnets (factor A), the width of the magnetic isolation bridge (factor B), and the angle between the permanent magnets (factor C) are selected as the optimization parameters. The schematic diagram of the three factors is shown in Figure 4. It should be pointed out that factor B and factor C of the two-layer permanent magnet are equal. The constraint conditions of the three factors are shown in formula (22). RSM optimization analysis was carried out to minimize core loss. The RSM results are presented in Table 1.

\[
\text{constraint conditions} \begin{cases} 
\text{factor A} & \in [5.0 \text{mm}, 10.0 \text{mm}] \\
\text{factor B} & \in [3.0 \text{mm}, 5.0 \text{mm}] \\
\text{factor C} & \in [125.0^\circ, 135.0^\circ]
\end{cases}
\]  \hspace{1cm} (22)

In the fourth group, when factor A is 7.5 mm, factor B is 5.0 mm, and factor C is 135°, the core loss is minimum with 33.36 W. In the 13th group, when factor A is 10.0 mm, factor B is 4.0 mm, and factor C is 125°, the core loss is maximum with 62.77 W. \( p \)-Value is a statistical parameter which is often used to evaluate the influence degree of a factor. According to statistical theory,
if the $p$-value is not greater than 0.05, it indicates that this factor has a significant impact on the target parameter. If the $p$ value is not greater than 0.01, it indicates that this factor has a very significant effect.\(^{27}\) The statistical analysis of each parameter is listed in Table 2. The influence degree of factor C on iron core loss is extremely significant. The influence degree of factor A is more significant, and the influence degree of factor B is small. The interactive influence of factor A–C is the most significant, while the interaction influence of factor A–B is the least significant.

The regression equation of iron core loss shown in formula (23) is fitted by quadratic regression analysis. The fitting accuracy of the regression equation of iron core loss is 91.08%. The fitting determination coefficient is 0.9552, indicating that the regression equation has good accuracy and meets the optimization requirements of the next step.

\[
\text{Core loss}(W) = 20.757A + 101.4775B - 38.163C
\]
\[
- 0.073AB - 0.2734AC - 0.5345BC
\]
\[
+ 1.0682A^2 - 3.86375B^2 - 0.15825C^2
\]
\[
+ 2314.47625
\]

The response surface variation of each factor to the core loss is shown in Figure 5.

As is shown in Figure 5(a), iron core loss decreases first and then increases with the increase of factor A. The iron core loss reaches the minimum when factor A is about 7.6 mm. In the process of factor C increasing from 125\(^{\circ}\) to 133\(^{\circ}\), the core loss becomes smaller and smaller. The core loss is likely to remain steady with the increase of factor C when factor C is more than 133\(^{\circ}\). The iron core loss changes sharply along the direction of factor A and slowly along the direction of factor C. This shows that factor A has a greater influence on iron core loss. Figure 5(a) and (b) demonstrate that, the iron core loss increases first and then decreases with the increase of factor B. The iron core loss reaches the minimum when factor B is about 4.1 mm. The change range

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**Table 1.** RSM optimization results.

| Group | Factor A/mm | Factor B/mm | Factor C/° | Core loss/W |
|-------|-------------|-------------|------------|-------------|
| 1     | 10          | 5           | 130        | 45.73       |
| 2     | 5           | 3           | 130        | 41.27       |
| 3     | 5           | 5           | 130        | 40.92       |
| 4     | 7.5         | 5           | 135        | 33.36       |
| 5     | 7.5         | 3           | 125        | 43.22       |
| 6     | 7.5         | 4           | 130        | 40.87       |
| 7     | 7.5         | 3           | 135        | 35.85       |
| 8     | 5           | 4           | 125        | 51.65       |
| 9     | 10          | 3           | 130        | 46.81       |
| 10    | 7.5         | 5           | 125        | 51.42       |
| 11    | 10          | 4           | 135        | 44.52       |
| 12    | 5           | 4           | 135        | 47.07       |
| 13    | 10          | 4           | 125        | 62.77       |

**Table 2.** Statistical analysis of each parameter.

| Factor | A   | B   | C   | A–B | A–C | B–C |
|--------|-----|-----|-----|-----|-----|-----|
| p-Value| 0.0246 | 0.4123 | 0.0017 | 0.8335 | 0.0233 | 0.0439 |

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**Figure 4.** The schematic diagram of the three factors.

**Figure 5.** Response surface variation of each factor: (a) factor A–factor C (the value of factor B is 4 mm), (b) factor A–factor B (the value of factor C is 130\(^{\circ}\)), and (c) factor B–factor C (the value of factor A is 7.5 mm).
of core loss with the change of factor B is the smallest, indicating that the influence degree of factor B is not significant.

Taking three factors as optimization variables, the solution of the minimum core loss is obtained. The constraint conditions of the three factors are consistent with formula (22). The optimization results show that when factor A is 7.7 mm, factor B is 5.0 mm, and factor C is 134.9°, the core loss is minimum with 32.91 W.

### Rotor strength check

The rotor of HSPMM are subjected to large centrifugal force. The silicon steel sheet of the rotor needs to be punched in order to embed the permanent magnet. This will further reduce the yield strength and tensile strength of the rotor. The strength check of the optimized rotor silicon steel sheet is conducted by using finite element method. The cloud map of the rotor stress distribution is shown in Figure 6.

The maximum stress appears at the sharp angle of the magnetic isolation bridge of the outer permanent magnet. This is because the high linear velocity of the outer permanent magnet and the sharp positions are prone to stress concentration. The maximum stress of the rotor is 117.75 MPa, which is much less than the yield strength with 246 MPa of this silicon steel sheet. The optimized rotor meets the strength requirements.

### Establishment of equivalent thermal circuit model

In order to verify the correctness of the above theoretical analysis, the ETCM (Figure 7) of permanent magnet motor was established. In established model, the thermal convection, conduction, and radiation effect between different positions of the motor are comprehensively considered. The thermal conductivity, specific heat capacity, density, resistivity, and other parameters of silicon steel sheet, permanent magnet, rotating shaft, housing, and other materials are determined. The temperature field of the optimized motor and the contrastive motor was compared and analyzed. The two motor parameters are shown in Table 3. It should be pointed out that, except for the parameters in the table, the rest parameters are consistent. The steady-state thermal field was calculated under the condition of rated speed 12000 rpm of the two motors. The temperature distribution of the optimized motor and the comparative reference motor is illustrated in Figure 8.

As can be known from Figure 8, compared with the contrastive motor, the temperature of the stator tooth and stator yoke of the optimized motor is reduced by 8.3°C. The temperature of permanent magnet, winding, rotor surface, rotor end and shaft decreased by 10.1°C, 8.2°C, 10.2°C, 10°C, and 9.6°C, respectively. The results show that the method of reducing copper loss and core loss is feasible and effective. The steady-state operating temperature of HSPMM is decreased without changing the cooling mode and structure parameters.

### Experiment

A HSPMM with rated speed of 12,000 rpm was designed and manufactured according to the optimized parameters. The main parameters are listed in Table 4. And then the temperature measurement experiment was conducted. In the experiment process, the motor operates at rated power (500 W) and speed (12,000 rpm) and the experimental load torque is 0.398 N.m. The ambient temperature is 20.4°C. Platinum thermal resistances were employed to measure the temperature of the stator dynamically and a contactless temperature sensor was used to measure the temperature of the...
rotating shaft. It is difficult to measure the temperature directly for high-speed rotating rotor and permanent magnets. So, the steady-state temperature of the rotor and permanent magnet was measured. When the rising temperature is lower than 0.5°C in 10 min, the temperature field is considered to reach a steady state. The experimental site is presented in Figure 9. As results, the continuous temperature curves of the stator and shaft was drawn in Figure 10. The sampling time is 120 s. The steady-state measuring data and calculation data obtained by the ETCM are given in Table 5.

It is apparent from Figure 10 that he temperature of the stator yoke and shaft rise quickly at first, and the temperature of stator yoke is always higher than that of the shaft. The temperature variation curves of the stator and shaft enter stable states after 2400 and 2280 s, respectively. The temperature error between the measured data and the theoretical calculation data is

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**Table 4. Main parameters.**

| Parameter name                | Value    |
|------------------------------|----------|
| Rated power                  | 500 W    |
| Rated rotational speed       | 12,000 rev/min |
| Axial length of armature     | 75 mm    |
| Number of poles              | 4        |
| Length of air gap            | 1.2 mm   |

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**Figure 7.** Equivalent thermal circuit model of HSPMM.

**Figure 8.** Temperature distribution: (a) reference motor and (b) optimized motor.
acceptable, and the average error is only 4.01%. The temperature error at the end of the rotor is the largest with 5.89%. The temperature error of stator yoke is the smallest with 2.73%. The experimental results suggest that the established ETCM has high calculation accuracy and the calculated results are reliable.

Discussion

In this paper, the temperature field of HSPMM was analyzed and optimized. Two new methods for reducing copper and iron loss were proposed and the ETCM was established. At last, the correctness and feasibility of the theoretical analysis were verified by experiments. Compared with previous studies, there are three innovations in this research. Firstly, other researchers often reduce the operating temperature of HSPMM by changing the stator or rotor structure and optimizing the cooling mode. It may affect the electromagnetic performance or increase the manufacturing cost. The temperature field optimization method adopted in this paper does not change the structural parameters. The temperature is reduced only by changing the installation parameters of the permanent magnet and the number of the winding layers. Secondly, in the past, CFD or finite element method is usually used to calculate the temperature distribution of HSPMM. These methods need to construct an accurate motor model. Although large computer workstations are used, it will still take a lot of time to obtain reliable results. In addition, compared with other ETCM models, the established ETCM focuses on the heat generated by eddy current effect, which is one of the main heat sources of HSPMM. In this way, the ETCM established in this study has better accuracy to calculate HSPMM temperature field. The proposed ETCM has faster solution speed, without reducing the calculation accuracy. This means that the proposed method has a broad application prospect with the above two advantages. Thirdly, double V-type embedded HSPMM is taken as the research object in this paper, the previous research is mostly aimed at the surface-mounted HSPMM. The former has better electromagnetic performance and efficiency, and does not have to add a protective sleeve for the permanent magnet.

Conclusions

The temperature field of HSPMM was investigated in this paper. The method of reducing copper loss by decreasing the number of conductor layers was proposed based on theoretical analysis. The simulation results show that the total copper loss of the conductors with five-layer arrangement is 14.21% lower than that with seven-layer arrangement. The installation parameters of permanent magnet are optimized by RSM to reduce iron loss. The influence of three factors

Table 5. Measurement data and calculation data of HSPMM temperature.

| Position          | Calculation data/°C | Measurement data/°C | Error rate/% |
|-------------------|----------------------|---------------------|--------------|
| Stator yoke       | 98.9                 | 101.6               | 2.73         |
| Rotor end         | 89.9                 | 95.2                | 5.89         |
| Permanent magnet  | 90.5                 | 93.3                | 3.09         |
| Shaft             | 87.5                 | 91.3                | 4.34         |
| Average error rate|                      |                     | 4.01         |

Figure 9. HSPMM temperature experiment.

Figure 10. Temperature variation curves of stator yoke and shaft.
on iron loss was analyzed. When factor A is 7.7 mm, factor B is 5.0 mm, and factor C is 134.9°, the core loss is minimum with 32.91 W. In addition, the rotor strength was checked. The maximum stress of the rotor is 117.75 MPa, which is much less than the yield strength with 246 MPa of this silicon steel sheet. The optimized rotor meets the strength requirements. The ETCM of HSPMM was established creatively, and the theoretical analysis data demonstrate that the temperature of each position of the optimized motor is reduced by 8.2°C–10.2°C. Then the optimized motor was designed and manufactured to verify the correctness of the above theoretical analysis. The temperature error between the measured data and the theoretical calculation data is acceptable, and the average error is only 4.01%. The temperature error of the stator yoke is minimum with 2.73%. The accuracy and effectiveness of the temperature optimization method and ETCM of HSPMM proposed in this paper were fully proved. More importantly, these methods and conclusions can be widely extended to the temperature field analysis and optimization of other permanent magnet motors.

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