Optimization of port size of high power density permanent magnet synchronous motor

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Abstract. The application of high power density motors is increasingly widespread, but the motor power density has been limited by the thermal load and the performance of the electromagnetic material. In order to reduce the thermal load of the motor, the relationship between the size of the motor Hs0 and Bs0 and the core loss of the motor is studied in this paper. It is found that the decrease of Hs0 and the increase of Hs0 can reduce the core loss of the motor. Meanwhile, with the increase of Bs0, the output torque of the motor increases first and then decreases. As the Hs0 increases, the output torque of the motor increases gradually. According to the above conclusions, the size of the notch of a high power density permanent magnet synchronous motor is optimized, and the core loss of the motor is reduced without affecting the output torque of the motor.

1. Introduction

Today, high-power density motors are being used in various industrial fields, such as drive motors for bionic robots, helicopter tail rotors and cars. In order to improve the product quality, high power density motor is required for these applications. Therefore, how to improve the power density of the motor is gradually becoming a key issue in the field of motor research.

Researchers have proposed many methods to increase the power density of the motor. And the methods are mainly divided into three types [1-2]: (1) improving the motor speed; (2) optimizing the motor structure; (3) using high-performance materials.

However, the increase of motor power density also faces two major problems: First, the problem of insufficient performance of existing materials (such as insufficient performance of magnetically conductive materials, and permanent magnet material remanence is not high enough). Second, the motor has insufficient heat dissipation capability (under the prior art conditions, the heat dissipation capability of a certain volume of motor has a rough upper limit). Therefore, increasing the armature current to increase the motor power density can cause the motor to overheat, insulation breakdown or affect the equipment around the motor.

At this stage, in order to solve the problem of insufficient heat dissipation capability of the motor, researchers mainly use those two kinds of methods: one is to find ways to reduce the heat production of the motor[3], and the other is to find ways to improve the heat dissipation capability of the motor[4-5]. In order to reduce the heat loss of high power density permanent magnet synchronous motor, this paper studies the relationship between stator slot width, slot height and motor core loss, and use the conclusion to optimize a motor. The method of optimizing notch size reduces the core loss of the...
motor, and provides a method for reducing the thermal load of the high power density motor. At the same time, because the change of the stator slot sizes changes the magnetic field of the motor, the motor output torque is also verified in this paper.

2. Calculation method of motor core loss

2.1 Influence of the shape of the slot on the magnetic field of the motor

When using the analytical method to solve the electromagnetic field of the motor and then solve the electromagnetic torque of the motor, the researchers often use the method of ignoring the specific groove shape of the motor to make the motor slot equivalent to an infinitely deep groove, and adopt mathematical methods such as conformal transformation (figure 1). The slot model of the motor is transformed into a slotless model, and then the electromagnetic torque can be solved easily. The calculated final result of output torque is in good agreement with the experimental results[6-10].

![Figure 1. Conformal transformation process](image)

The above research shows that the electromagnetic torque of the motor can be calculated accurately by ignoring the specific size of the motor slot, indicating that the specific slot size of the motor has little effect on the actual output torque of the motor, so the impact of output performance which caused by the change of the shape of the motor slot can be neglected.

2.2 Core loss calculation method

Regarding the calculation of the core loss of the motor, researchers at this stage generally adopt the core loss solving model proposed by Bertotti in 1988. According to the model, the core loss of the ferromagnetic material can be expressed as:

\[
P_{\text{Fe}} = P_h + P_n + P_{\text{ex}}
\]

\[
P_n = K_n f B_n^b
\]

\[
P_e = K_e f^{1.2} \int_0^{2\pi} \left( \frac{dB(\theta)}{d\theta} \right)^2 d\theta
\]

\[
P_{\text{ex}} = K_{\text{ex}} f^{1.5} \int_0^{2\pi} \left| \frac{dB(\theta)}{d\theta} \right|^{1.5} d\theta
\]

(1)

It can be seen from the above equations: Since the magnetic field frequency of each point of the AC motor is the same, the distribution of the core loss of the motor depends on the distribution of the magnetic density of the stator of the motor; and according to the above model of the core loss of the motor, core loss is proportional to the square of the magnetic density, so the core loss at different positions of the motor will vary greatly depending on the magnetic density.

Based on our laboratory experience, the highest magnetic density of the motor lies in the notch part, so the core loss of the notch part will be larger than other positions. And by 2.1, the shape of the motor slot has little effect on the output performance of the motor. Therefore, it is possible to reduce the core loss of the motor without affecting the output performance of the motor by optimizing the sizes of the slot, thereby reducing the thermal load of the motor.

3. Optimization of motor slot shape

3.1 Internal magnetic field of the motor
The basic parameters of the high power density permanent magnet synchronous motor which is optimized in this paper are as follows:

| Parameter       | Value   |
|-----------------|---------|
| Rated power     | 8 kW    |
| Rated speed     | 9000 rpm|
| Stator material | DW 540-50|
| Voltage         | AC 380V |
| Outer diameter  | 94 mm   |
| Axial length    | 70 mm   |
| Number of slots | 12      |
| Number of poles | 10      |

Maxwell was used to model the motor, and the method adopted by maxwell software is the core loss solution method mentioned in 2.1. The motor magnetic density cloud diagram is shown in figure 2:

As shown in figure 2, the highest part of the motor magnetic density is the motor slot portion. In addition, the method of taking points in each part of the stator of the motor accurately calculates the time variation of the magnetic density of the points at different positions in the stator. And the result is shown in figure 3: for the main parts of the magnetic circuit and the stator teeth, the magnetic density is substantially sinusoidal, and the peak of the magnetic density is 1.0-1.2T; but for the points of the notch, the peak of the magnetic density is 1.7-2.5T. In addition, since the magnetic permeability of the notch portion is severely saturated, the waveform of the magnetic density changes with time is distorted and is no longer a sine wave. This magnetically dense waveform brings high harmonics and further increases the core loss of the stator of the point motor.
3.2 Stator slot optimization

Figure 4 shows the shape of the motor slot, and the dimensions indicated in the figure are the variable dimensions of the motor slot. As mentioned in 2.1, changing the size of the motor slot, in other words, changing the size of $H_{s0}$ and $B_{s0}$ has little effect on the motor output performance; and the magnetic density of the region which is determined by these two sizes is much higher than it in other areas. This means that the core loss per unit volume in that area will be much higher than it of other areas, so the two sizes $H_{s0}$ and $B_{s0}$ are selected as the main optimization objects.

The design dimensions at the notches are $H_{s0} = 1.5$ mm and $B_{s0} = 6.5$ mm. The slot optimization is based on the finite element method. For $H_{s0}$, the step size is 0.1 mm, and for $B_{s0}$, the step size is 0.5 mm. Because of the limitation of assembly conditions, $H_{s0}$ should not be taken too small, and $B_{s0}$ should not be too large. Therefore, from the actual assembly situation, $H_{s0}$ takes the range of 0.3 mm - 1.1 mm, and $B_{s0}$ ranges from 1 mm to 5 mm. The results are shown in figure 5 and figure 6.

![Figure 4. Motor groove shape and size](image)

As shown in figure 5, the size of both $H_{s0}$ and $B_{s0}$ can affect the motor core loss: the motor core loss improves with the decrease of $B_{s0}$ and the increase of $H_{s0}$. For the motor designed in this project, the groove shape of $H_{s0} = 0.7$ mm and $B_{s0} = 4$ mm is finally adopted. At this time, the motor core loss is reduced to 88% of the original.

3.3 Motor output torque

Although the dimensional change at the motor slot has little effect on the main magnetic circuit of the motor, the change in size still affects the internal magnetic field of and thus affects the output torque of the motor. As shown in Figure 6: As the $B_{s0}$ increases, the motor output torque increases first and then decreases, but the increase of $H_{s0}$ can contribute the output torque of the motor. For the optimized size $H_{s0} = 0.7$ mm, $B_{s0} = 4$ mm, the output torque of the motor becomes 98.6% of the original size.
Although the output torque of the motor also varies with the two dimensions of Hs0 and Bs0, as shown in Figure 7, the influence of these two sizes on the output torque of the motor is much lower than the influence on the motor core loss, therefore, optimizing these two dimensions has little effect on the motor output torque.

![Figure 7. Change of L1, L2 with groove deformation (L1 = the core losses of the motor when using different size combinations/ the core loss of the motor when using the design size, L2 = The output torques of the motor when different sizes/ the output torque of the motor when using the design size)](image)

4. Conclusion
In this paper, the influence of the groove size change of high power density permanent magnet synchronous motor on the core loss and output torque of the motor is studied. At the same time, the groove size of the motor is optimized for the purpose of reducing the core loss of the motor. It is found that:

1. The size of the permanent magnet synchronous motor slot has an effect on the motor core loss and output torque. However, the influence of the motor slot size on the output torque is much smaller than its influence on the core loss.

2. Both the decrease of Hs0 and the increase of Hs0 can reduce the core loss of the motor;

3. With the increase of Bs0, the output torque of the motor increases first and then decreases. And the output torque of the motor increases gradually when the Hs0 increases.

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