Loss Study of Dual Stator Low Speed High Torque Synchronous Motor with Hybrid Rotor

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Abstract. Low speed and high torque machines are widely used in industrial production, oilfield mining, wind power generation, etc. Low speed high torque motors have large internal space, in order to make full use of internal space this paper proposes a dual stator low speed high torque synchronous motor. The rotor adopts a surface-mounted permanent magnet rotor structure on one side, and a spliced reluctance rotor structure on the other side. A magnetic ring is added in the middle to make permanent magnet and magnetic resistance independent of each other. The motor has a special structure, and the loss distribution is different from that of a normal motor. The loss will affect the performance of the motor. This paper establishes the iron loss model considering the effects of alternating magnetic field, rotating magnetic field, and harmonics. Considering the influence of temperature on copper loss. Then establish a mathematical model of core loss and copper loss. Then studying the motor iron loss and copper loss distribution characteristics. Finally, the results are compared with the finite element method (FEM) to verify the effectiveness of the loss calculation in the paper.

1. Introduction

The dual stator low speed high torque synchronous motor with hybrid rotor has a special structure, and the loss distribution is different from that of a normal motor. The loss will affect the performance of the motor. Accurate analysis of the size and distribution characteristics of the loss of each part of the motor can provide a basis for further improving the design of the motor and reducing the loss. So it is very necessary to study the loss of this motor.

At present, the problem of motor loss is concerned by many scholars, and a variety of methods have been proposed to study loss. According to [1], the skin effect on the current distribution in the winding mechanism is elaborated, the relationship between penetration depth and current frequency, material resistance and other parameters is deduced, as the analytical calculation of AC winding loss provides the basis. Foreign scholars have thoroughly analysed the influence of factors such as frequency, wire diameter. And the calculation formula of AC loss considering the proximity effect and skin effect of various transformers and motor windings are deduced [2].

For the calculation of stator iron loss, the iron loss calculation model proposed by Bertotti is widely used. Now it is one of the most widely used and more accurate iron loss calculation methods. The core loss is decomposed into hysteresis loss, eddy current loss and additional loss[3]. Flux densities in motor yokes and transformer T-joints may be nonsinusoidal and sometimes contain dc components. Similarly to the previously presented loss separation methods, rotational losses are considered as another dynamic loss component[4]

According to[5],the magnitude and distribution of the loss caused by the current time harmonics of the inverter-powered permanent magnet synchronous motor are carefully studied. The coefficients can
be also considered as variables instead of constants to improve the accuracy of the iron loss model. Therefore in [6], an iron loss model is developed with the consideration of variable coefficients. This paper analyses the core loss and copper loss of a new type of dual stator motor, establishes a related mathematical model, and uses finite element analysis to verify the accuracy of the loss calculation.

2. Structure and parameters of dual stator low speed high torque synchronous motor with hybrid rotor

In this paper, the loss modelling for a 50kW, 90rpm dual stator low speed high torque synchronous motor is researched and studied. The rotor adopts a surface-mounted permanent magnet rotor structure on one side, and a spliced reluctance rotor structure on the other side. A magnetic ring is added in the middle to make permanent magnet and magnetic resistance independent of each other. The structure is shown in figure 1, and its detailed parameters are listed in Table 1.

![Figure 1 Motor structure diagram](image)

**Table 1.** Key data of the motor

| Item                              | Value |
|-----------------------------------|-------|
| Outer stator outside diameter/mm  | 740   |
| Outer stator inside diameter/mm   | 550   |
| Inner stator outside diameter/mm  | 253.8 |
| Inner stator inside diameter/mm   | 353.8 |
| Length/mm                        | 350   |
| PM thickness /mm                 | 6     |
| No. of outer poles               | 30/10 |
| No. of slots                     | 36/72 |
| Speed/rpm                       | 90    |
| Power /kW                       | 40/10 |

3. Analysis of loss of dual stator low speed high torque synchronous motor with hybrid rotor

3.1. Core loss of the motor

At present, the commonly used calculation model for solving motor iron loss is the Bertotti separation calculation model, which is composed of hysteresis, eddy current and additional loss as follows:

\[ P_{Fe} = P_h + P_c + P_e \] (1)

Where, \( P_{Fe} \) is total core loss, \( P_h \) is hysteresis loss, \( P_c \) is eddy current loss, \( P_e \) is additional loss.

The core loss is related to the magnetic density amplitude of the motor tooth and yoke. Then the loss density of the tooth and yoke under a specific magnetic density can be obtained, and the basic iron loss can be obtained by multiplying by the weight. But the method does not consider the influence of rotational magnetic field and harmonics on the iron loss of the motor.
The magnetic field in the motor core changes with time and space. The classical loss separation model generally does not consider the influence of the local hysteresis loop. It is believed that the loss due to the hysteresis phenomenon is only related to the amplitude and frequency of the magnetic field. And the eddy current loss is not only proportional to the frequency and amplitude of the magnetic field of the stator and rotor cores, and is also closely related to its waveform. Different positions of the stator and rotor have different magnetization model, including alternating magnetic field and rotational magnetic field. Compared with alternating magnetization, rotating magnetic field not only changes the size of the magnetic field with time, but also the direction of the magnetic field. In fact, the magnetization method in the stator and rotor cores of the motor is neither a single alternating magnetic field nor a single rotating magnetic field, but an elliptical rotating magnetization.

Using the orthogonal decomposition loss model to calculate the iron loss of the motor can not only consider the two magnetization model at the same time, but also this method is relatively simple to implement and can ensure the loss calculation accuracy.

For this reason, when considering the effects of alternating magnetization, rotating magnetization and harmonics, the iron loss can be calculated as follows:

$$p_{Fe} = \sum_{v} k_h (v f) (B_{vr}^a + B_{vi}^a) + \sum_{v} k_c (v f)^{2} (B_{vr}^2 + B_{vi}^2) + \sum_{v} k_e (v f)^{1.5} (B_{vr}^{1.5} + B_{vi}^{1.5})$$  \hspace{1cm} (2)

Where, $v$ is the harmonic order, $B_{vr}$ is the radial flux density, and $B_{vi}$ is the tangential flux density. $k_h$ is hysteresis loss coefficient. $k_c$ is eddy current loss coefficient. $k_e$ is additional loss coefficient.

Iron loss of the $j$ unit can be calculated as follows:

$$p_j = p_{hj} + p_{ej} + p_{ij}$$ \hspace{1cm} (3)

The total loss of the stator core is equal to the sum of the iron loss of each continuous small unit on the stator core:

$$p_{Fe} = L \sum_{j=1}^{n} p_j \rho S_j$$ \hspace{1cm} (4)

Where, $n$ is the number of units of the entire iron core, $L$ is the length of the stator iron core (m), $\rho$ is the density of the silicon steel sheet (kg/m$^3$). $S_j$ is the area of the $j$ unit (m$^2$). $p_j$ is the $j$ Core loss per unit mass of the unit (W/kg)

The magnetization mode inside the motor core is divided into alternating magnetic field and rotational magnetic field, and the magnetization modes of different parts of the stator core are also different. Select special points on the motor as the research object, and each point represents a specific area, and then calculate the iron loss of the area to make the calculation more accurate. Calculate the radial magnetic density and tangential magnetic density at each point. Figure 2 shows the key points of flux density at the model.

![Figure2](image_url)  
**Figure2.** The selected regions

Due to the symmetry of the motor's magnetic barrier rotor structure, only one side is selected as the research object. The points of the inner and outer stators are similar, and only the points of the outer
stator and rotor are studied. Among them, Points P1-P11 are the research objects. The radial and tangential magnetic density of each point are as shown in figure 3.

![Figure 3](image1.png)

**Figure 3.** Flux density waveforms at different point (P1), (P4), (P5), (P10).

Analyze the selected points. Taking points P1, P4, P5, and P10 as examples, the magnetic field of the above points are shown in figure 4.

![Figure 4](image2.png)

**Figure 4.** The rotational magnetic flux waveforms of (P1), (P4), (P5), (P10).

From the Figure 4, it can be seen that each point is a magnetic field formed by the combined action of an alternating magnetic field and a rotational magnetic field. The alternating magnetic field at point P1 is stronger than the rotational magnetic field; the rotational magnetic field at point P4 is stronger than the alternating magnetization, and the alternating magnetic field and rotational magnetic field at
point P5 and P10 are both strong. However, not only the iron loss produced by the alternating magnetic field but also the iron loss produced by the rotational magnetic field should be considered in the calculation of the motor core loss. And contains a lot of harmonics. Harmonic analysis is performed on the rotational magnetic field of points P1, P4, P5, and P10, and the rotational magnetic field under different harmonics are obtained as shown in figure 5.

![Harmonic analysis](image)

**Figure 5.** Harmonics rotational magnetic flux density waveforms of (P1), (P4), (P5), (P10).

Each harmonic rotational magnetic flux can be decomposed into two orthogonal elliptical magnetic fields of the long-axis magnetic flux density and the short-axis magnetic flux density, and use them as the magnetic density of the radial and tangential components.

Through formulas (2), (3), and (4), the core loss when considering the influence of alternating magnetic field, rotational magnetic field and harmonics can be obtained. The core loss finite element analysis results are shown in Figure 6.

![FEM analysis](image)

**Figure 6.** FEM analysis

The calculated results and the FEM analysis are shown in Table 2

| Item            | Calculated | FEM    |
|-----------------|------------|--------|
| Outer stator    | 160.2W     | 146.9W |
| Inner stator    | 45.1W      | 41W    |
| Rotor           | 21.5W      | 19.1W  |

Table 2 presents the core loss of the outer stator is larger than that of the inner stator, because the frequency of the inner stator is lower than that of the outer stator. The core loss of each part calculated by the analytical method is larger than that of the FEM. This is because the FEM does not consider the
core loss under the action of rotating magnetization. The total iron loss calculated by the analytical method is 226.8W, and the total core loss calculated by the finite element method is 207W. For this reason, the influence of rotating magnetization on iron loss should be considered when calculating core loss.

### 3.2. Analysis of copper loss considering temperature

The skin effect and proximity effect cause the effective area of the wire to decrease, and the equivalent thermal resistance becomes larger, resulting in loss increased. The motor studied in this paper is in the low speed range, and the additional loss caused by the skin effect and proximity effect of the winding is small, and can be approximately ignored in the analysis.

The temperature characteristic of the copper resistance of the motor is mainly reflected in the electrical resistivity of the copper conductor that changes with temperature. This law will actually be more obvious in the internal high temperature during motor operation.

\[
R_T = \rho_T \frac{2Nl_0}{A_0a_1},
\]

\[
\rho_T = \rho_{20} \left[1 + \alpha(T - 20)\right],
\]

\[
p_{cu} = mI^2R_T
\]

\[
p_{cu} = mI^2R_t = m\rho_{20} \left[1 + \alpha(T - 20)\right] \frac{2Nl_0}{A_0a_1} I^2
\]

Among them, \(\alpha\) is the temperature coefficient of the conductor, which means the temperature coefficient of resistance \(1/^\circ\text{C}\). As for copper, it generally takes 0.004. \(\rho_{20}\) is the resistivity at 20 degrees, for copper 0.0175Ω•mm²/m. \(T\) is the conductor temperature \(^\circ\text{C}\). \(R_T\) is the resistivity when the temperature is \(T\). \(N_l\) is the number of series turns per phase. \(l_0\) is the average length of the half-turn of the coil. \(A_0\) is the cross-sectional area of the conductor. \(a_1\) is the number of parallel branches of the phase winding. \(m\) is phase number. \(I\) is current.

The copper loss of the outer stator winding at different temperatures can be obtained as shown in Figure 7.

**Figure 7.** The loss of copper. (a)Resistance of outer stator winding at different temperatures. (b)Copper loss of outer stator winding at different temperatures.

The outer motor rated current is 23.3A. It can be seen from the figure that the copper loss of the outer stator winding is 3017W when the temperature is 80 °C, the copper consumption is 3212W when the temperature is 100 °C. The relative error of outer winding copper loss is 6%. In the same way, the copper loss of the inner stator winding at 80 °C is 3365W, and the copper loss at 100 °C is 3542W. The relative error of inner winding copper loss is 5%. The copper loss of the inner motor is larger than that of the outer stator motor, which will cause a greater temperature rise. Therefore, temperature changes have a greater impact on the copper loss of the motor.

### 4. Conclusion
This paper analyses the core loss and copper loss of a new type of dual stator low speed high torque synchronous motor with hybrid rotor and draws the following conclusions:

Considering the iron loss caused by the alternating magnetic field, rotating magnetic field, and harmonics, and then comparing with the finite element analysis, the results show the accuracy of the iron loss calculation model. Considering the copper consumption at different temperatures, the results show that temperature has a great influence on copper consumption, and the influence of temperature should be considered when calculating copper consumption.

5. References

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Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant 51877139, the Liaoning Bai Qian Wan Talents Program, China, the Young and Middle-aged Scientific and Technological Innovation Talent Program of Shenyang City, Liaoning Province, China, under Grant RC190377 and the Key R&D Program Project of Liaoning Province, China, under Grant 2018106003.