The Iron Loss Analysis of Direct-driving External-rotor Motor with Cobalt-iron Alloy

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Abstract

In this paper, the iron loss characteristics of an External Rotor Permanent Magnet Synchronous Motor (ER-PMSM) for direct-driving of electric vehicle is analyzed in detail. As a kind of cobalt-iron alloy, whose saturation magnetic density is about 2.4 Tesla, is adopted to manufacture the iron core, the experimental platform has been established to test the B-H curve and the iron loss characteristics of the alloy, firstly. According to the characteristics of iron loss coefficient varying with frequency, a variable coefficient orthogonal decomposition iron loss model is proposed. Then, a magnetic loss calculation model based on cobalt-iron alloy is established. The empirical coefficient of iron loss is re-corrected, and the analysis model of the iron loss is obtained. Finally, the experimental platform is set and a prototype of ER-PMSM is manufactured. The iron loss of the stator with cobalt-iron alloy is tested. The experimental results agree well with the numerical results and the calculated results, which verify the correctness of the theoretical analysis.

Keywords: external-rotor motor, direct-driving motor, iron loss model, high efficiency motor.

1. Introduction

With the development of rare-earth permanent magnet material, high performance soft magnetic alloy, wide band semiconductor, the performance of permanent magnet motor has been greatly improved. The power density of permanent magnet motor is basically the same as that of traditional fuel engines and steam turbines. Due to the characteristics of high efficiency, smooth speed regulation, short transmission chain and convenient maintenance, the application of all-electric propulsion technology based on high-performance motor system is more and more extensive, such as electric vehicles, high-speed electric-power trains, all-electric ships with distributed propulsion system, etc. All electric propulsion technology is already an important direction for the future development of transportation\cite{1}.

High efficiency and high power density motor system is one of the core technologies of all electric propulsion system. For permanent magnet motors, the efficiency characteristic can not be improved without accurate calculation and control of the loss of each part. The loss of permanent magnet motor mainly includes copper loss and iron loss. The iron loss can also be divided into stator iron loss and rotor eddy current loss. In order to increase the power density of the motor, the flux density of the stator teeth and yoke will usually be designed relatively high, which could make full use of the magnetic material\cite{2}. Therefore, the loss of stator will account for a larger proportion of total motor losses. High performance soft magnetic alloys, such as cobalt-iron alloy produced by VAC, have very high saturation magnetic properties. Therefore, using cobalt-iron alloy as stator iron core to fabricate motor can greatly improve the output performance\cite{3-4}. However, the iron loss characteristic of cobalt-iron alloy is different from that of traditional silicon steels, which makes the loss characteristic of motors made of cobalt-iron alloy need to be further studied. In this respect, the magnetic permeability characteristics of cobalt-iron alloys have been studied in many literature, but the properties of motors made of cobalt-iron alloys, especially the loss characteristics, were researched relatively few.

In this paper, the losses of cobalt-iron alloy at different frequencies and different magnetic densities were measured, and the specific loss curves of cobalt-iron alloy at different frequencies were obtained. Then, the loss characteristics of stator core made of cobalt-iron alloy were analyzed in detail by finite element method. Finally, a test platform was built to measure the core loss of the stator. Many useful results have
been obtained, and the correctness of analysis and testing has been verified.

2. Research methodology

The iron loss characteristics of cobalt-iron(Co-Fe) alloys are different from those of silicon steels. The chemical composition of cobalt-iron alloys is Fe_{49}Co_{49}V_{2}. The content of Co/Fe in the alloy is about 49% typified by Permendur, shown in Tabel 1. This alloy is modified by Vanadium additions to improve ductility. The reason for the use of cobalt-iron alloy is that in this classic alloy, one obtains the maximum saturation magnetization, 23800 gauss(2.38Tesla) with annealing, with a square shaped hysteresis loop. Because of their higher strength, this alloy find application in top performance electrical machines where weight and size are at a premium and cost is of lower importance, such as the all electric propulsion system for electric vehicles. It can greatly reduce the volume and quality of the motor, and then improve the power density of the motor. Results show that different annealing processes often have great influence on the saturation magnetization and iron loss characteristics of cobalt-iron strip, so it is necessary to test the iron loss characteristics before use. The cobalt-iron alloy we used is produced by China NPA company, named 1J22.

| Table 1 products of cobalt-iron alloy |
|-----------------------------|-----------------|-----------------|------------|----------------------|
| Alloy Name | Co | Fe | V | Saturation Induction | Supplier |
| Permendur 49 | 49 | 49 | 2 | 2.34T | Telcon |
| Permendur 49 | 24 | 76 | - | 2.34T | Telcon |
| Rotelloy 3 | 49 | 49 | 2 | 2.34T | Telcon |
| AFK 524 | 52 | 4 | 44 | 2.0T | Imphy |
| AFK 4025P | 49 | 49 | 2 | 2.38T | Imphy |
| Vacoflux48 | 49 | 49 | 2 | 2.35T | VAC |
| 1J22 | 49 | 49 | 1 | 2.38T | NPA |

2.1 Experimental principle of iron loss with cobalt-iron alloy

Similar as silicon steel, the iron loss of cobalt-iron alloy can be divided into hysteresis loss, eddy current loss and additional loss[5-6]. The iron loss could be calculated by the function is as follows

\[ P_{Fe} = K_h f B_m^a + K_e \left( f B_m \right)^2 + K_o \left( f B_m \right)^{1.5} \]  

(1)

where \( K_h \) is the Hysteresis loss coefficient, \( \alpha \) is the Steinmuntz coefficient, \( K_e \) is the Eddy current loss coefficient, \( K_o \) is the Additional loss coefficient.

Therefore, the purpose of the test is to obtain the loss coefficient in the iron loss calculation model. The loss coefficients in the loss calculation model would be obtained by fitting the loss curves under different frequencies and magnetic induction intensities. The schematic diagram of the experimental test is shown in Figure 1.

![Figure 1 Test diagram of the Co-Fe alloy ring](image1)

As shown in Fig.1, the tested ring is made of annealed cobalt-iron alloy strip, wounded by a coil with a certain number of turns. The number of turns of the coil is designed according to the needs of the test to ensure that the magnetization inside the tested ring is within the range of 0.1-2.2T. The inner diameter of the ring is 32 mm, the outer diameter is 40 mm, the thickness is 5 mm, and the thickness of the Fe-Co alloy strip is 0.35 mm. The cobalt-iron alloy strip is annealed and oxidized on the surface, so the material strip is insulated.

According to Ampere's law, the relationship between the amper turns of the coil and the magnetic potential difference in the ring can be obtained by,

\[ NI = HL \]  

(2)

where \( N \) is the turns of coil, \( I \) is the current amplitude, \( H \) is the magnetization, \( L \) is the length of magnetic path.

The input power in the coil, \( P_i \), can be calculated by

\[ P_i = \frac{UI \cos \varphi}{2} \]  

(3)

Where is the he phase angle between the terminal voltage and the current in the coil.

By calculating the input power \( P_i \) and the copper loss \( P_{Cu} \) in the coil, the iron loss \( P_{Fe} \) can be obtained by

\[ P_{Fe} = P_i - P_{Cu} \]  

(4)

In order to calculate the loss ratio of the material, it is necessary to test the DC magnetization curve of the strip, firstly. The schematic diagram of B-H curve test for cobalt-iron alloy strip is shown in Fig. 2.

![Figure 2 Test diagram of the magnetization curve](image2)
A sinusoidal current, $I(f)$, with a certain frequency is introduced into the excitation coil, so that a sinusoidal magnetic field of the same frequency as the current, $B(f)$, is induced in the iron core of the ring. According to Faraday's principle, a sinusoidal alternating back EMF, $U_2(f)$, is induced in the induction coil with the same frequency of magnetic field. The induced EMF in the induction coil can be expressed in the following formula

$$u_2(f) = N_2 S \frac{dB(f)}{dt} \tag{5}$$

where $N_2$ is the turns of induction coil, $S$ is the equivalent cross-sectional area of the ring, $U_2(f)$ is the EMF in the induction coil.

The magnetic field intensity $H$ in the ring can be obtained by formula 2. By changing the voltage and current of the excitation coil, the magnetic induction intensity $B$ of different magnetic field intensity $H$ can be obtained, then the $B$-$H$ curve of cobalt-iron strip can be drawn[7].

2.2 Test results of iron loss characteristics of cobalt-iron alloy strip

The iron loss per unit mass (loss ratio) at different input currents with a given frequency is measured, then the iron loss coefficient at that frequency can be fitted according to the calculated magnetic induction intensity amplitude. The test platform is shown in Figure 3. Using the programmable AC power supply, SW10500 of Ametek Company, the excitation sinusoidal currents of different frequencies are introduced into the coil on the ring, and the induction voltage $U(f)$, and current, $I(f)$, are collected by oscilloscope[8].

![Programmable AC power supply](image1)

**Figure 3** The test platform of the cobalt-iron alloy

The DC magnetization curve of the cobalt-iron strip is shown in Fig.4. The iron loss ratio of the cobalt-iron strip at 60 Hz, 100 Hz, 150 Hz, 200 Hz and 300 Hz are measured respectively. The iron loss ratio curves are drawn as shown in Fig.5. Based on the principle of least square method, the iron loss coefficient of the cobalt-iron strip at different frequencies can be fitted. The curves of iron loss coefficient at different frequencies are shown in Fig.6. From the results of Fig.

6, it can be seen that the iron loss coefficient of the cobalt-iron strip is different at different frequencies. The hysteresis loss coefficient and eddy current loss coefficient first decrease and then increase with the frequency, while the additional loss coefficient first increases and then decreases. Therefore, when calculating the core loss of the motor, it is necessary to consider the influence of frequency on the loss coefficient, otherwise the calculation results will be inaccurate, and then affect the efficiency and temperature rise characteristics of the motor.

![Figure 4 B-H curve of the cobalt-iron strip](image2)

**Figure 4** B-H curve of the cobalt-iron strip

![Figure 5 Loss ratio curves of the cobalt-iron strip under different frequency magnetic field](image3)

**Figure 5** Loss ratio curves of the cobalt-iron strip under different frequency magnetic field

![Figure 6 Hysteresis loss coefficient $k_h$](image4)

**Figure 6** Hysteresis loss coefficient $k_h$
The accurate calculation of PMSM core loss is inseparable from the accurate solution of the stator flux density waveform. There will be a big error if the flux variation in stator is considered as sinusoidal variation. The finite element model of the external rotor permanent magnet synchronous motor is shown in Fig. 7. The main parameter of the motor is shown in Table 2. In order to describe the variation of magnetic density of stator core, six points of the same pair of teeth and yoke in the stator at different positions are selected according to the distribution of magnetic field lines. As shown in Fig.7, the variation of radial magnetic density ($B_r$) and tangential magnetic density ($B_θ$) of six selected points in an electric cycle is analyzed. The results of calculation and analysis are shown in Fig.8. For the external rotor motor, point a is located at the center of the tooth tip. The radial magnetic density and tangential magnetic density of the outer rotor relatively large in one electrical cycle, and the sinusoidal variation law is basically presented, but there are a certain number of high harmonics. The magnetic density map formed by radial magnetic density and tangential magnetic density is distributed according to elliptic law: Point b and point c are located in the upper part and the middle part of the tooth, and their radial magnetic density distribution is basically the same, with sinusoidal variation and less harmonic content, lower tangential magnetic density amplitude. The magnetic density map is a narrow ellipse in the form of a long X-axis short Y-axis; The d point is located at the root of the tooth, and its radial magnetic density and tangential magnetic density change are large, because the magnetic flux of the stator tooth portion is divided into two parts to the yoke portion; The e-point and the f-point are located in the yoke portion, and the radial magnetic density change is small, and the tangential magnetic density substantially exhibits a sinusoidal variation over a period of time. The magnetic density map presents a narrow ellipse with a short X-axis and a Y-axis.

3. Iron Loss Analysis of the ER-PMSM with cobalt-iron alloy strip

When the rotor of permanent magnet synchronous motor(PMSM) rotates relative to the stator, rotating flux and alternating flux are produced in the tooth and yoke parts of the stator core respectively. In addition, the influence of tooth harmonics is introduced after the stator teeth are grooved, so that the magnetic density waveform inside the stator core is no longer sinusoidal. 

*Figure 6* Loss coefficient of the Co-Fe strip under different magnetic field. (a)Hysteresis loss coefficient Kh. (b)Eddy-current loss coefficient Ke. (c)Additional loss coefficient Ke. (d)Steinmetz coefficient α.

*Figure 7* The finite element model of the ER-PMSM
Table 2 Main parameters of the ER-PMSM

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor outer diameter/mm</td>
<td>312</td>
<td>Stator outer diameter/mm</td>
<td>278</td>
</tr>
<tr>
<td>Rotor inner diameter/mm</td>
<td>280</td>
<td>Stator inner diameter/mm</td>
<td>130</td>
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<tr>
<td>Thickness of magnet/mm</td>
<td>10</td>
<td>Axial length/mm</td>
<td>170</td>
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<td>Pole/slot combination</td>
<td>22/24</td>
<td>Tooth width/mm</td>
<td>15</td>
</tr>
</tbody>
</table>

Figure 8 The magnetic density of the ER-PMSM varied with the time

4. Experimental Investigation on Iron Loss of the ER-PMSM with Cobalt-iron Alloy

The principle of the experimental platform is shown in Fig.9, and the prototype of stator core with cobalt-iron alloy is shown in Fig.10. During the experiment, the symmetrical three-phase sinusoidal current with adjustable amplitude and frequency is input into the A phase, B phase and C phase of the stator armature winding respectively. The line voltage, phase current and active power in the armature winding are measured by Yokogawa WT1600 power analyzer. Therefore, the measured active power minus the copper loss produced by the three-phase winding is the iron loss of the stator core.

Figure 9 The test diagram of the stator core loss
5. Conclusions

Compared with silicon steel strip, the electromagnetic and iron loss characteristics of cobalt-iron alloy strip are quite different. Under the same magnetic flux density and frequency, the specific loss of iron-cobalt alloy is more than 40% higher than that of silicon steel strip. The test results show that the iron loss coefficient of iron-cobalt alloy changes greatly at different frequencies. Based on the test results of loss coefficient of cobalt-iron alloy, the results of stator core loss are basically consistent with the calculation. With the increase of current frequency and amplitude, the deviation between experimental results and numerical results increases gradually.

Reference


