Analysis of Load Loss Characteristics of FeCo Alloy High Speed Permanent Magnet Motor

Dajun Tao 1,2,3,* , Guifen Li 1,2, Peng Hou 3 and Gang Hu 1,2

1 State Key Laboratory of Hydro-Power Equipment, Harbin 150040, China
2 Harbin Electric Machinery Company Limited, Harbin 150040, China
3 School of Electrical and Electronic Engineering, Harbin University of Science and Technology, Harbin 150080, China

* Correspondence: taodj@hrbust.edu.cn

Abstract: In order to study the change law of loss and efficiency of high-speed permanent magnet motor (HSPMM) under load after using FeCo_B800 alloy material instead of silicon steel sheet DW310_35 material to make iron core, two FeCo_B800 stator materials with the same structure and size parameters were developed. HSPMM and HSPMM of silicon steel DW310_35 stator material. The loss and efficiency characteristics of the two motors under the same operating conditions were tested by the experimental method, and the losses of the two motors at different load rates were compared and analyzed by means of the finite element method. The research results show that at light load, the FeCo_B800 motor stator core loss is lower than the DW310_35 silicon steel sheet motor, and the efficiency advantage is very obvious; however, with the increase of the load rate, the FeCo_B800 motor stator core is seriously saturated, resulting in the distortion of the winding magnetomotive force waveform. The loss caused by the harmonics of the winding magnetomotive force is higher than that of the DW310_35 silicon steel sheet motor, and the efficiency advantage of the FeCo-B800 motor gradually decreases with the increase of the load rate.

Keywords: FeCo_B800 material; silicon steel DW310_35 material; HSPMM; load loss

1. Introduction

HSPMM has the advantages of compact structure, high efficiency and high power density, and is suitable for high-speed centrifuges, high-speed compressors, flywheel energy storage and other fields [1–3]. And with the development of material technology, FeCo alloy material is more and more used in HSPMM due to its excellent low loss performance. However, after using FeCo alloy material to replace silicon steel material to manufacture the motor stator core, the internal loss structure of the motor made of FeCo alloy material will also undergo serious changes. Therefore, it is of great significance to study the composition of FeCo HSPMM iron loss and its influence on the stator material for the design of FeCo motors.

Many scholars at home and abroad have studied alloy motors with different stator materials and made certain achievements. In ref. [4], the author has developed a 250 W alloy asynchronous motor. After the stator is made of alloy materials, iron loss is reduced by 80%. In ref. [5], a 4-pole, 500 W small asynchronous motor with alloy 2605SA1 as stator and silicon steel sheet M600 as rotor is used. Comparative analysis and no-load iron loss of silicon steel sheet motor at different frequencies show that the iron loss of alloy motor at different frequencies is half of that of silicon steel sheet motor. In ref. [6], A 7.5 kW, 1360 r/min motor is designed. The stator and rotor are made of alloy material, totally 47 kg, 5.44 kg less than M19 silicon steel core, and the motor efficiency reaches 92%. In refs. [7,8], the author has studied axial flux amorphous permanent magnet motors to improve efficiency and power density by optimizing stator structure. In ref. [9], taking a 20 kW and 2500 r/min permanent magnet motor for electric vehicle as an example, the
After optimization, the power density of amorphous alloy motor is 45% higher than that of silicon steel sheet motor. In ref. [10], taking a 3000 r/min permanent magnet motor as an example, the variation rule of motor loss after using amorphous alloy to replace silicon steel to make motor core is analyzed. The result shows that the loss of replaced amorphous alloy motor and core is reduced by 50%. A 60,000 r/min high speed amorphous permanent magnet motor was manufactured in [11]. The analysis results show that the efficiency of amorphous alloy motor is higher than 90% in a wide range of motor torque operation range after amorphous alloy material is used. In ref. [12], the author studied an axial flux amorphous permanent magnet motor with 7000 r/min. The result shows that the efficiency of the motor increases from 90% to 93.5% by using amorphous alloy material. In ref. [13], the author has studied a super-high speed amorphous alloy permanent magnet motor with a maximum speed of 120,000 r/min. The research shows that compared with silicon steel sheet, the rotor made of amorphous alloy can reduce the loss of rotor core material by 82%. In the process of analysis and calculation of the above documents, only the total iron loss value is calculated, but the change rule of iron loss distribution with load rate is lack of in-depth study.

At present, the theoretical research on the loss of FeCo stator material is still in its infancy, and there is no literature to study the loss of FeCo stator material, based on the above research status, this paper uses experiments to test the loss and efficiency of FeCo HSPMM and silicon steel HSPMM under the same operating conditions, and compares and analyzes the experimental results. Variation of wave loss. On this basis, the variation law of the loss of each part of the two motors with the load rate is deeply studied by means of the finite element method.

2. Performance Comparison of FeCo_B800 and Silicon Steel DW310_35 Cores

In the frame of this study, the FeCo motor stator core and the silicon steel motor stator core are made of FeCo_B800 and DW315_50 materials, respectively. The lamination coefficient of FeCo_B800 iron core is 0.88, and the lamination coefficient of silicon steel DW315_50 iron core is 0.97. In order to obtain the magnetization performance and loss performance of FeCo_B800, the magnetization performance and loss curve of FeCo_B800 iron core material at 300 Hz were measured experimentally in this paper. The experimental schematic diagram and circuit diagram are shown in Figures 1 and 2, respectively. The DW315_50 material was compared, and the results are shown in Figures 3–5. The thickness of silicon steel sheet DW315_50 is 0.5 mm, and the average thickness of FeCo_B800 is 0.28 mm.
It can be seen from the comparison of the magnetization curves in Figure 1 that the inflection point position and saturation magnetic density of FeCo_B800 iron core are lower than those of silicon steel sheet DW315_50 iron core. It can be seen from the relative magnetic permeability comparison in Figure 4 that the magnetic permeability of FeCo_B800 iron core is higher than that of silicon steel sheet DW315_50 iron core when the magnetic density is low, but within the magnetic density range of iron cores commonly used in motors, the magnetic permeability of FeCo_B800 iron core is lower than that of the silicon steel sheet DW315_50 core. Taking the magnetic flux density B of 1.0 T as an example, the magnetic permeability of the silicon steel sheet DW315_50 is 1.52 times that of the FeCo_B800 iron core. It can be seen from the comparison of loss density curves in Figure 5 that the FeCo_B800 core has a very obvious advantage in loss density. Moreover, taking the magnetic flux density B as 1.0 T as an example, the FeCo_B800 core loss density is only 43.1% of that of the silicon steel sheet DW315_50.

Figure 2. Experimental setup test.

Figure 3. Comparison of magnetization curves.

Figure 4. Comparison of relative permeability curves.
3. Comparison of Efficiency of FeCo Motor and Silicon Steel Motor

Using the above two iron core materials, two FeCo and silicon steel HSPMMs with the same structure and size parameters were fabricated, respectively. The motor adopts distributed short-distance winding, and the total length of permanent magnet is the axial length of the motor, 80 mm. The structure is shown in Figure 6, and the specific parameters of the motor are shown in Table 1.

![Figure 6. Structure of HSPMM.](image-url)
Table 1. Main parameters of HSPMM.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power/kW</td>
<td>100</td>
<td>Rotor out diameter/mm</td>
<td>94</td>
</tr>
<tr>
<td>Rated speed/rpm</td>
<td>18,000</td>
<td>PM thickness/mm</td>
<td>7</td>
</tr>
<tr>
<td>Rated voltage/V</td>
<td>380</td>
<td>Sleeve thickness/mm</td>
<td>5</td>
</tr>
<tr>
<td>Mechanical air gap/mm</td>
<td>2</td>
<td>Stator slot</td>
<td>24</td>
</tr>
<tr>
<td>Pole number</td>
<td>2</td>
<td>pole arc coefficient</td>
<td>1</td>
</tr>
<tr>
<td>PM</td>
<td>NdFeB</td>
<td>Length of PM/mm</td>
<td>80</td>
</tr>
</tbody>
</table>

In order to intuitively analyze the change of the loss and efficiency of the motor after the stator core is made of FeCo_B800 material, the thermal state of the two motors under the power supply of the PWM inverter was tested by the experimental method, and the speed was 18,000 r/min. Working characteristics, the experimental platform is shown in Figure 7, the experimental results are analyzed, and the loss and efficiency of the two motors at different load rates are compared, as shown in Figures 8 and 9.

![Prototype experimental platform](image1)

**Figure 7.** Prototype experimental platform.

![Load loss comparison curve](image2)

**Figure 8.** Load loss comparison curve.
It can be clearly seen from Figures 8 and 9 that under different load rates, the loss of FeCo motor is lower than that of silicon steel sheet motor, and the efficiency of FeCo motor is higher than that of silicon steel motor. From the changing trends of the curves in Figures 8 and 9, it can be seen that the efficiency of the FeCo motor is significantly improved at light load, but with the increase of the load rate, the loss of the FeCo motor increases significantly faster than that of the silicon steel motor, and its efficiency advantage gradually increases. In order to analyze the reasons for this phenomenon, the motor loss separation method proposed in the literature [14] is used to compare and analyze the losses of each part of the two motors at different load rates.

4. Contrastive Analysis of FeCo Motor and Silicon Steel Motor Loss

4.1. Motor Loss Separation Method

Due to the relatively high frequency of high-speed motors, PWM inverters are generally used for power supply [14,15]. The prototype of this paper was tested experimentally, and the current waveform measured by the experiment was directly used for analysis. Figure 10 shows the FeCo motor at rated load. Line current waveform and its harmonic analysis.

The current waveform in Figure 10 is substituted into the finite element method as the excitation source to analyze the high-speed permanent magnet motor model, and the radial and tangential flux density change waveforms of the stator core teeth, yoke and the typical positions on the surface and inside of the permanent magnet are recorded, as shown in Figure 11. The high-speed permanent magnet motor in this study belongs to surface mounted rotor structure; therefore, the loss content in the rotor core is very small, which will be ignored. The harmonic components in the magnetic density waveform of the stator core and permanent magnet can be obtained by Fourier decomposition.

For the calculation of stator core loss, the harmonic magnetic densities derived from Fourier decomposition are substituted into Equation (1). Here it is necessary to specify, in particular, the $k_h$ in Equation (1). $\alpha$ and $k_e$ are obtained by non-linear fitting based on the core loss density test data of FeCo_B800 stator material and the loss density data of DW315_50 silicon steel. The specific values are shown in Table 2.

$$
\begin{align*}
P_{Fe} &= \int_{Stator} k_h \rho_s \sum_v (vf)(B^2_{vr} + B^2_{v\theta}) dV_s + \int_{Stator} k_e \rho_s \sum_v (vf)^2 (B^2_{vr} + B^2_{v\theta}) dV_s 
\end{align*}
$$

(1)
4. Contrastive Analysis of FeCo Motor and Silicon Steel Motor Loss

4.1. Motor Loss Separation Method

Due to the relatively high frequency of high-speed motors, PWM inverters are generally used for power supply [14,15]. The prototype of this paper was tested experimentally, and the current waveform measured by the experiment was directly used for analysis. Figure 10 shows the FeCo motor at rated load. Line current waveform and its harmonic analysis.

Table 2. Loss factor of stator core material.

<table>
<thead>
<tr>
<th>Core Material</th>
<th>$k_h$</th>
<th>$\alpha$</th>
<th>$k_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeCo_B800</td>
<td>0.0059</td>
<td>1.81</td>
<td>$5.65 \times 10^{-5}$</td>
</tr>
<tr>
<td>DW315_50</td>
<td>0.0213</td>
<td>2.03</td>
<td>$5.83 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

In the formula: $k_h$ and $\alpha$ are the hysteresis loss coefficients; $k_e$ is the eddy current loss coefficient; $\rho_s$ is the material density of the stator core; $\nu$ is the harmonic order of the magnetic density of the stator core; $f$ is the fundamental frequency; $B_{vr}$ is the $v$-th harmonic diameter; $B_{v\theta}$ is the tangential magnetic density component of the $v$-th harmonic; and $v_s$ is the volume of the stator core.

For the calculation of permanent magnet eddy current loss, according to Maxwell’s equations:

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{2}$$

$$\vec{J} = \sigma \vec{E} \tag{3}$$

The eddy current in the permanent magnet is solved as:

$$\vec{j}_v = -\sigma \frac{\partial B_{v\theta}}{\partial t} \tag{4}$$
The current waveform in Figure 10 is substituted into the finite element method as the excitation source to analyze the high-speed permanent magnet motor model, and the radial and tangential flux density change waveforms of the stator core teeth, yoke and the typical positions on the surface and inside of the permanent magnet are recorded, as shown in Figure 11. The high-speed permanent magnet motor in this study belongs to surface mounted rotor structure; therefore, the loss content in the rotor core is very small, which will be ignored. The harmonic components in the magnetic density waveform of the stator core and permanent magnet can be obtained by Fourier decomposition. (a) (b) (c) (d) Figure 11. Magnetic flux density waveforms at points (a–d) on the motor.

According to the Poynting vector, the eddy current loss in the permanent magnet is:

$$P_{PM} = \int_{P_{PM}} \sigma E^2 dV_m = \int_{P_{PM}} \frac{j^2}{2\sigma} dV_m$$

In the formula: $\sigma$ is the conductivity of the permanent magnet; $V_m$ is the volume of the permanent magnet.

4.2. Validation and Analysis of Loss Calculation Results

In this paper, the losses of each part of the FeCo motor and the silicon steel motor at multiple load rates are calculated, respectively. Figure 12 shows the loss of each part of the FeCo motor and the silicon steel motor when the load rate is 0.2 and their comparison with their respective experimental test values. In the figure, $P_{pm1}$, $P_{pm2}$ and $P_{pm3}$ are the permanent magnet loss caused by the harmonic current, the permanent magnet loss caused by the harmonic magnetomotive force of the winding, and the permanent magnet loss caused by the permeance harmonic, respectively; in the figure, $P_{stator1}$, $P_{stator2}$, $P_{stator3}$ and $P_{test}$ are the experimental values of the stator core loss caused by the fundamental wave, the stator core loss caused by the armature reaction magnetomotive force harmonics, the stator core loss caused by the harmonic current, and the motor loss, respectively. It should be explained that the loss experimental test value in Figure 12 is minus the winding copper loss, air friction loss, carbon fiber sleeve loss and mechanical loss.
It can be clearly seen from Figure 12 that the calculated loss values of the two motors are in good agreement with the experimental test values, which indirectly proves the correctness of the motor loss separation method. The excellent loss characteristics make the loss value in the FeCo motor stator core only 32.95% of that of the silicon steel motor, which is why the FeCo motor has an obvious advantage in efficiency at 0.2 times the load. However, the losses caused by harmonics in FeCo motors are significantly higher than those in silicon steel motors, especially the eddy current losses in permanent magnets. The main reason is that the magnetic permeability of FeCo_B800 material in the common magnetic density section of the motor is lower than that of the silicon steel sheet DW315_50 material, as shown in Figure 4. Since the inductance of the FeCo motor is lower than that of the silicon steel motor, when the PWM inverter is used for power supply, the blocking effect of the winding on the high-order carrier harmonic current is obviously weaker than that of the silicon steel motor, which directly leads to a higher harmonic content in the current waveform than the silicon steel motor. This also limits the efficiency advantage of FeCo motors to a certain extent. Further research shows that with the increase of the motor load rate, the loss of each part of the two motors presents a new change law. Figures 13 and 14 show the loss histograms of FeCo motors and silicon steel motors at different load rates.

It can be seen from Figures 13 and 14 that with the increase of motor load rate, \( P_{\text{stator1}} \), \( P_{\text{stator3}} \), \( P_{\text{pm1}} \) and \( P_{\text{pm3}} \) in FeCo motor and silicon steel motor remain basically unchanged, and the significant loss is caused by the harmonics of the armature reaction magnetomotive force. The stator core losses \( P_{\text{stator2}} \) and the permanent magnet losses \( P_{\text{pm2}} \) due to the harmonics of the winding magnetomotive force. Comparing Figures 13 and 14, it can be seen that the above two losses of FeCo motor increase with the increase of load rate much larger than that of silicon steel motor, especially the permanent magnet loss \( P_{\text{pm2}} \) caused by the harmonics of winding magnetomotive force. From 0.2 times the load to 1.2 times the load, the \( P_{\text{pm2}} \) of the FeCo motor increased from 18 W to 252 W, an increase of 14 times, while the \( P_{\text{pm2}} \) of the silicon steel motor increased from 11.55 W to 69.3 W, an increase of six times, the \( P_{\text{stator2}} \) of the FeCo motor increased from 14 W to 90 W, and the total loss of the FeCo motor increased to 310 W, the \( P_{\text{stator2}} \) of the silicon steel motor increased from 65 W to 120 W, the total loss of silicon steel motor increased by 112.75 W.
It can be seen from Figures 13 and 14 that with the increase of motor load rate, $p_{stator1}$, $p_{stator3}$, $p_{pm1}$ and $p_{pm3}$ in FeCo motor and silicon steel motor remain basically unchanged, and the significant loss is caused by the harmonics of the armature reaction magnetomotive force. The stator core losses $p_{stator2}$ and the permanent magnet losses $p_{pm2}$ due to the harmonics of the winding magnetomotive force. Comparing Figures 13 and 14, it can be seen that the above two losses of FeCo motor increase with the increase of load rate much larger than that of silicon steel motor, especially the permanent magnet loss $p_{pm2}$ caused by the harmonics of winding magnetomotive force. From 0.2 times the load to 1.2 times the load, the $p_{pm2}$ of the FeCo motor increased from 18 W to 252 W, an increase of 14 times, while the $p_{pm2}$ of the silicon steel motor increased from 11.55 W to 69.3 W, an increase of six times, the $p_{stator2}$ of the FeCo motor increased from 14 W to 90 W, and the total loss of the FeCo motor increased to 310 W, the $p_{stator2}$ of the silicon steel motor increased from 65 W to 120 W, the total loss of silicon steel motor increased by 112.75 W.

Figures 15 and 16 compare the distribution of magnetic densities of FeCo motor and silicon steel motor at 0.2 times load and 1.2 times load.

Figure 13. Loss separation of FeCo motors with different load rates.

Figure 14. Loss separation of silicon steel motor at different load rates.

Figures 15 and 16 compare the distribution of magnetic densities of FeCo motor and silicon steel motor at 0.2 times load and 1.2 times load.
It can be seen from Figures 15 and 16 that since the lamination coefficient of the FeCo motor iron core is lower than that of the silicon steel motor iron core, the magnetic density of the FeCo motor stator core is much higher than that of the silicon steel motor at 0.2 times the load. Furthermore, the saturation magnetic density of FeCo motor iron core is lower than that of silicon steel motor (Figure 3); therefore, with the increase of load rate, the saturation degree of FeCo motor stator iron core is much higher than that of silicon steel motor, and the FeCo motor winding magnetomotive force waveform distortion is more serious, due to the resulting increase of $p_{\text{stator2}}$ and $p_{\text{pm2}}$ with the increase of load rate is larger than that of silicon steel motor, which indirectly causes the FeCo motor’s efficiency advantage to become smaller and smaller with the increase of load.

Figure 15. Comparison of magnetic density at 0.2 times the load.
5. Conclusions

In this paper, the magnetic properties and loss coefficient of FeCo_B800 stator core material are tested by the method of experimental test, and the experimental results are compared with the material of silicon steel sheet DW315_50. The load loss and efficiency characteristics of two FeCo motors and silicon steel sheet motors with the same structural size are tested. The finite element simulation method is used to analyze the variation law of the loss of each part of the two motors with the load rate, and the following conclusions are drawn:

(1) The saturation magnetic density of FeCo_B800 stator material and the magnetic permeability in the common range of iron core are lower than those of silicon steel DW315_50 stator material, but FeCo_B800 stator iron core has a very obvious advantage of low loss density.

(2) Due to the excellent loss characteristics of FeCo_B800 stator core, the loss of FeCo_B800 stator core is significantly lower than that of silicon steel DW315_50 core at light load, and the efficiency advantage is obvious.

(3) With the increase of the load rate, the FeCo_B800 stator iron core is seriously saturated, and the loss caused by the winding magnetomotive force and armature reaction harmonics is higher than that of the silicon steel motor, which leads to the FeCo motor efficiency advantage gradually decreases with the increase of the load rate.

Figure 16. Comparison of magnetic density at 1.2 times the load.
Author Contributions: Conceptualization, G.L. and G.H.; software, D.T.; formal analysis, D.T. and G.L.; data curation, D.T.; writing—original draft preparation, D.T.; writing—review and editing, P.H. and D.T.; supervision, D.T. and G.H.; funding acquisition, D.T. and G.L. All authors have read and agreed to the published version of the manuscript.

Funding: Open Project of State Key Laboratory of Hydro-power Equipment (SKLHE-ORF-202002).

Institutional Review Board Statement: The study did not involve humans or animals.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Conflicts of Interest: The authors declare no conflict of interest.

References
1. Hou, P.; Ge, B.; Tao, D.; Pan, B.; Wang, Y. Rotor Strength Analysis of FeCo-Based Permanent Magnet High Speed Motor. *Machines* 2022, 10, 462. [CrossRef]