Summary of calculation methods of PMSM iron loss based on finite element analysis

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Abstract. Since the birth of the motor, the accurate calculation of the iron loss of the motor has always been a big problem in the field of motor design. Too many factors affect the change of the iron loss of the motor, which is the main reason why it is difficult to accurately calculate the iron loss of the motor. The traditional magnetic circuit method and the finite element method are the two main ways to calculate the iron loss at present. In this paper, various iron loss calculation models in the finite element method are summarized and introduced, and the advantages of each model are compared.

1. Introduction

High efficiency and low cost have always been the goal of permanent magnet synchronous motor design. Therefore, the process of motor optimization design is usually the process of improving power density and reducing loss. The loss of the motor mainly includes copper loss, iron loss, additional loss, mechanical loss, etc., among which iron loss is caused by the change of the main magnetic field in the core of the motor, which is one of the main losses of the motor, generally accounting for a large proportion of the total loss, especially the high-speed motor [1]. When the motor is in high speed, the frequency of magnetic field change in the core of the motor is higher, and the iron consumption will increase sharply, which will eventually lead to the increase of temperature and the decrease of efficiency of the motor.

At present, there are generally two ways to study the iron loss of motor. One is the traditional magnetic circuit method: analyze the magnetic circuit of motor, calculate the average size of the fluctuating magnetic density in the core from the magnetomotive force and magnetic resistance, and then calculate the iron loss from the above calculation model. However, the magnetic circuit method can only calculate the total iron loss of the motor, and cannot analyze the distribution of the local loss of the core in detail, so it is difficult to provide a more accurate reference for the research of reducing loss measures such as structural optimization. The second is the finite element calculation method, which can easily get the internal magnetic field distribution of the motor, such as the waveform of any point on the motor core with the magnetic density changing with time, and the post-processing is convenient for the fast Fourier decomposition to get the harmonic iron loss, etc. This paper mainly introduces the finite element method to analyze the iron loss of the motor [3].

2. Basic calculation model of iron consumption

In 1892, Steinmetz proposed a calculation model of hysteresis loss for ferromagnetic materials. In 1924, Jordan divided ferromagnetic loss into hysteresis and eddy current. This model is also known as the two models of iron loss [3]. Up to now, this model is still widely used, as shown in formula (1).
\[ P_{Fe} = P_{h} + P_{e} = k_{h} fB^{\alpha} + k_{e} f^{2} B^{2} \]  

(1)

Among \( k_{h} \) and \( k_{e} \), hysteresis loss coefficient and eddy current loss coefficient are the attributes of the material itself, \( f \) is the frequency and \( B \) is the magnitude of magnetic density.

In 1988, Bertotti proposed a core loss model consisting of hysteresis loss, eddy current loss and additional loss in reference [5]. Based on rigorous physical derivation. The model is also widely used, as shown in formula (2).

\[ P_{Fe} = P_{h} + P_{e} + P_{a} = k_{h} fB^{\alpha} + k_{e} f^{2} B^{2} + k_{a} f^{1.5} B^{1.5} \]  

(2)

The above three term model is the most commonly used model to calculate the iron loss of motor by using finite element method. The applicability of the model is verified by studying the loss characteristics of eight kinds of ferromagnetic materials in reference [5]. At the same time, the comparison of measured and calculated loss of grain oriented three percent SIFE ferromagnetic materials is made. It is pointed out that when \( f \geq 50 \text{Hz} \) and \( B \) is near 1.5T, the error between calculated and measured loss is low. At the same time, Bertotti pointed out in reference [5] that the calculation error of this model for most silicon steel sheets is less than 10%, which is enough to describe the internal loss characteristics of motors.

Although the expressions of the three and two models are different, each loss coefficient of the two methods is obtained from the least square fitting of the magnetic density loss curve provided by the silicon steel sheet manufacturer. The corresponding hysteresis coefficient or eddy current coefficient of each model may be different, but the fitting curve with all losses must be similar to the original B-P curve. Therefore, which iron loss calculation model is adopted has little influence on the total loss calculation results, mainly depending on which model has better fitting effect [6].

3. Improved calculation model of iron consumption

3.1. Improved calculation model with constant coefficients

As the magnetic flux density and frequency are too high, the linearity of silicon steel sheet becomes poor, which leads to the increase of eddy current loss; with the increase of saturation degree, the hysteresis loop will produce local hysteresis loop, which leads to the increase of hysteresis loss, leading to the inaccuracy of the constant coefficient trinomial model calculation. In order to solve this problem, the high-order term of flux density is added to eddy current loss term in Bertotti's three constant coefficient model as compensation. A calculation model of iron loss with eddy current addition term is proposed as formula (3).

\[ P_{Fe} = a_{1} B^{\alpha} f + a_{2} B^{2} f^{2} \left( 1 + a_{3} B^{\alpha 4} \right) + a_{4} B^{1.5} f^{1.5} \]  

(3)

Among \( \left( 1 + a_{3} B^{\alpha 4} \right) \) the flux density term is used to account for the added value of eddy current loss caused by saturation factors, but each loss coefficient is constant, and the change of hysteresis loss caused by harmonic magnetic field is not considered, so the accuracy of the mode cannot be guaranteed when the frequency and flux density range span are large; the reference [7] considers the core loss caused by harmonic magnetic field on the basis of formula (3). The calculation model as shown in formula (4) is proposed.

\[ P'_{Fe} = a_{1} \sum_{n=0}^{\infty} \left( B_{n}^{\alpha} f_{n} \right) + a_{2} \sum_{n=0}^{\infty} \left( B_{n}^{2} f_{n}^{2} \right) + a_{3} \sum_{n=0}^{\infty} a_{n} B_{n}^{4+1.2} f^{2} + a_{4} \sum_{n=0}^{\infty} B_{n}^{1.5} f_{n}^{1.5} \]  

(4)

Although the influence of harmonic magnetic field is considered, no definite compensation term of hysteresis loss is proposed. In addition, the coefficients in formula (4) are all constant coefficients, which still can not guarantee the accuracy of the model when the frequency and flux density range span is large.

3.2. Improved calculation model with variable coefficient

Although the constant coefficient trinomial calculation model introduced above can reflect the actual iron consumption of the motor to a certain extent, its calculation error is relatively high under
some special circumstances. For example, reference [8] points out that the calculation error of the constant coefficient trinomial model may reach more than 30%. In order to solve the problem of calculation accuracy, it is found in reference [9, 10] that the coefficient in the calculation model of iron loss should be a function of magnetic field frequency $f$ and magnetic density $B$, and then a more accurate calculation model of variable coefficient iron loss is developed.

In reference [9, 10], a two term model with variable coefficients is proposed, as shown in formula (5). The loss of silicon steel sheet with thickness of 0.5mm, relative permeability of 3071, 3.16w/ib and density of 7800kg/m3 was measured by Epstein square circle, and the corresponding model was established to calculate the loss of silicon steel sheet. The error of comparison between the calculation and the actual measurement is within 3%, and the error of comparison between the calculation and the actual measurement is within 5% under other frequencies (the data under these frequencies are not used for model extraction).

$$P_{Fe} = P_h + P_e = k_a(f, B) f B^2 + k_a(f, B) f^2 B^2$$ (5)

At the same time, reference [9, 10] proposed a three term model of variable coefficient, as shown in formula (6). In reference [9], the error of the model is less than 5% according to the measured and calculated results of three kinds of silicon steel sheets by using the variable coefficient three term model; at the same time, taking a 6-pole built-in permanent magnet motor as an example, the measured and calculated results are compared, as shown in Figure 1. The results show that the calculated results of the variable coefficient three term model are more consistent with the actual test values.

$$P_{Fe} = P_h + P_e + P_{ce} = k_{ae}(f, B) f B^2 + k_{ae}(f, B) f^2 B^2 + k_{ae}(f, B) f^{1.5} B^{1.5}$$ (6)

![Figure 1. Calculation and measurement of no-load iron loss of built-in permanent magnet motor](image)

It should be noted that the premise of formulas (6) and (7) is the magnetic density of sinusoidal alternating current, which does not reflect that the rotating magnetic field will appear at some positions in the actual motor magnetic field, and the iron loss generated by rotating magnetization cannot apply the above formula. Because the loss coefficient of the variable coefficient model is expressed as a polynomial of frequency and flux density by numerical fitting method, which is affected by the ill conditioned characteristics of polynomial fitting, when the frequency and amplitude span is large, it will also lead to large errors.

In order to solve the problems of rotating magnetization and harmonics, a method of calculating the iron loss of permanent magnet synchronous motor (PMSM) based on the finite element analysis of electromagnetic field and Bertotti's iron loss calculation model is proposed in reference [11]. The main idea is to decompose the rotating magnetic flux vector into radial and tangential alternating components, i.e., rotating magnetization is converted into alternating magnetization to calculate the iron loss in radial and tangential directions. The hysteresis loss, eddy current loss and additional loss are calculated upward. At the same time, since the radial and tangential magnetic density change curves contain high-order harmonic components, the iron loss of each harmonic can be calculated respectively, and then the iron loss of each harmonic can be added. The corrected iron loss calculation model is as follows (7).
\[ P_{Fe} = P_h + P_e + P_s \]
\[ = \sum_{i=1}^{n} \left[ k_{hi} f_i \left( B_{hi}^+ + B_{hi}^- \right) \right] + \sum_{i=1}^{n} \left[ k_{ei} f_i \left( B_{ei}^+ + B_{ei}^- \right) \right] \]
\[ + \sum_{i=1}^{n} \left[ k_{ci} f_i \left( B_{ci}^{1.5} + B_{ci}^{1.5} \right) \right] \]
\[ \text{(7)} \]

In reference [12], based on the actual measurement of core loss of oriented electrical steel sheet at different frequencies and rolling directions, regression analysis was carried out on the experimental data to determine the hysteresis and eddy current loss coefficients in the calculation model of core loss. Through the finite element analysis, according to the change law of the magnetic field in different regions of the stator core and considering the influence of the alternating and rotating magnetic fields in the motor, a new calculation model of the iron loss of the permanent magnet synchronous motor is proposed. The main idea is that for the elliptical rotating magnetic field of the k-th harmonic, it can be decomposed into two orthogonal alternating magnetic fields with the flux density of the long axis of \( b_{k\max} \) and the flux density of the short axis of \( b_{k\min} \). The loss caused by the elliptical rotating magnetic field is equivalent to two orthogonal alternating loss modified iron loss calculation models as follows (8).

\[ P_{Fe} = P_h + P_e + P_s \]
\[ = \sum_{i=1}^{n} k_{hi} f_i \left( B_{hi}^+ + B_{hi}^- \right) + k \sum_{i=1}^{n} k^2 f^2 \left( B_{eih}^+ + B_{eih}^- \right) \]
\[ + k_e \frac{1}{T} \int \left| \frac{dB_i}{dt} \right|^2 dt + \int \left| \frac{dB_i}{dt} \right|^2 dt \]
\[ \text{(8)} \]

The iron loss of a high-speed permanent magnet motor with rated speed of 60000r / min is analyzed and calculated, and compared with the test results as shown in Figure 2. The results show that the core loss is closer to the actual measured value when considering the influence of rotating magnetic field and harmonic magnetic field component, which shows that the influence of rotating magnetization and harmonic magnetic field cannot be ignored in the calculation of iron loss of high-speed motor.

![Figure 2. Comparison between calculated and tested values of iron loss of high speed permanent magnet motor at different frequencies](image)

\[ \text{Figure 2. Comparison between calculated and tested values of iron loss of high speed permanent magnet motor at different frequencies} \]

On the basis of the problem of rotating magnetization and harmonic wave, considering the influence of the uneven distribution of eddy current on the lamination thickness on the core loss caused by the skin effect, reference [13] proposed that when the alternating frequency is high, the skin effect is obvious, so the skin effect must be considered. As a result of skin effect, the distribution of eddy current on the lamination thickness is uneven. At this time, \( \kappa \), the eddy current loss coefficient of silicon steel sheet is a function of alternating frequency, as shown in formula (9).
Because the magnetic field in the actual motor stator core is an irregular elliptical magnetic field, it can be decomposed into a series of elliptical harmonic magnetic density vectors with the help of harmonic analysis principle. For each elliptical harmonic magnetic field, two mutually orthogonal alternating magnetizations are used to be equivalent, and the skin effect at different harmonic frequencies is considered. The improved orthogonal decomposition model of variable loss coefficient is as follows (10).

\[
P_{Fe} = K_{h/f} \sum_{k=1}^{\infty} k \left( B_{k}^{2} + B_{k}^{0} \right) + f \sum_{j=1}^{\infty} K_{k} \left( k^{2} B_{k}^{2} + B_{k}^{0} \right)
\]

The proposed orthogonal decomposition model with variable coefficients and the traditional iron loss model are used to calculate the stator core loss at different frequencies. The comparison between the calculation results and the experimental results is shown in Figure 3. Compared with the traditional calculation model of constant coefficient iron loss, the variable coefficient orthogonal decomposition model proposed in this paper has higher calculation accuracy and is closer to the experimental results.

Figure 3. Comparison of calculation and experimental results of different iron loss models

According to the above analysis, in order to calculate the iron loss accurately in a wide range of frequency and flux density, and to make a refined analysis of the loss, the new model should meet the following conditions: 1) based on the nonlinear characteristics of ferromagnetic materials, systematically study the change rule of iron loss with flux density and frequency, and separately compensate the eddy current and hysteresis loss, and the compensation item The coefficient should change with the change of flux density or frequency; 2) the larger the change of flux density and frequency, the more serious the ill conditioned characteristic of fitting. In order to avoid this problem, it can be segmented according to the size of frequency or flux density, and the different coefficient of compensation term can be used in each flux density or frequency segment to compensate the hysteresis and eddy current loss.

Although reference [14] is the analysis and test of iron loss of induction motor, the analysis of the principle of iron loss and the process of establishing the calculation model of iron loss in this literature are of some enlightening significance to the analysis of iron loss of permanent magnet synchronous motor. In the literature, the added value of eddy current and hysteresis loss caused by nonlinear factors of ferromagnetic materials and high-order harmonic magnetic field is considered by using different additional flux density terms in different flux density and frequency range. Combined with the finite element method, the calculation model of sectional variable coefficient iron loss is proposed as follows (11).
In formula (11), $j$ is the $j$th element in the finite element model of the motor; $A_j$ is the area of the $j$-th unit; $l_n$ is the effective length of the motor core material; $f_n$ is the frequency of the $n$th harmonic of the Fourier decomposition of the flux density; $B_{a}$ is the amplitude of the $N$th harmonic of the flux density; $k_1$, $k_2$, $k_3$, $\alpha$ is the constant coefficient.

According to the difference of flux density and frequency, the flux density and frequency are divided into several intervals in different positions of stator and rotor cores. The parameters $a$ and $B$ in formula (11) are determined by $C$; the eddy current loss caused by saturation is taken into account by adding the flux density term $E$ in the eddy current loss term, which is called the eddy current loss additional flux density high-order term due to the large value of $F$; the change value of the hysteresis loss caused by the local hysteresis loop is taken into account by adding the flux density term $g$ in the hysteresis loss term, which is called the additional flux of the hysteresis loss due to the small value of $H$. Density low degree term.

At the same time, the coefficient $K_r$ of rotational magnetization loss is introduced to account for the increase of hysteresis loss caused by rotational magnetization. The calculation model changes as follows (12).

$$
P_{j}=k_1\sum_{j}A_j\left[\sum_{n}B_{a}^{n}f_{n}\left(k_1B_{a}^{n}\right)\right]+k_2\sum_{j}A_j\left[\sum_{n}B_{a}^{n}f_{n}^{2}\left(1+k_3B_{a}^{n}\right)\right]
$$

$$
+k_3\sum_{j}A_j\left[\sum_{n}B_{a}^{n}f_{n}^{1.5}\right]
$$

Compared with formula(11), formula(12) only increases the compensation coefficient $K_r$ of rotational magnetization in the hysteresis loss term, which size is determined by the ellipticity $\delta$, and the eddy current loss caused by rotational magnetization is not considered.

The model proposed in reference [14] does not change the Bertotti model loss coefficient, but ensures the applicability of the model by studying the physical nature of the influence of the nonlinearity of harmonic magnetic field and ferromagnetic material on the hysteresis and eddy current loss, and introducing compensation coefficient in different magnetic flux density or frequency range. Since the loss coefficient of Bertotti model has not been changed, the influence of harmonic magnetic field and nonlinearity of ferromagnetic materials on hysteresis and eddy current loss can be obtained directly through the model proposed in the literature. The method of solving the loss coefficient of the model is simpler, and the ill conditioned characteristic of polynomial fitting is avoided at the same time.

4. Conclusion

Although the calculation method of iron loss based on the finite element method has been widely used, there are many models at present, so there is still a need for further study in the comparison of calculation models, calculation accuracy and practicability. First of all, it is about the comparative study of different models. There are many calculation models of iron loss based on the finite element method, so the comparative study of different models should be carried out. Secondly, the actuarial accuracy. In some special applications, the calculation accuracy of constant coefficient model is low, so the research of variable coefficient model with high accuracy is the inevitable trend of using finite element method to calculate motor iron loss. Finally, it is practical, so a more suitable finite element calculation model should be established. The models introduced in this paper need to fit the measured loss data of materials, and the data processing process is cumbersome and the calculation amount is large. The practical model with simple and quick calculation method is needed in the project, so the research on the practical model of iron consumption calculation based on the finite element method is also the key work in the future.
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