

Calculation Method of Core Loss Under Intermediate Frequency Excitation

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Abstract: Based on Brockhaus magnetic measurement system, the magnetic properties of GT100 ultra-thin silicon steel under middle and high frequency sinusoidal excitation are measured. Based on the Preisach model, the static hysteresis and loss characteristics are simulated accurately. In addition, an improved loss model was proposed. The formula of eddy current loss was improved according to skin effect principle, and the statistical parameter V_0 of abnormal loss was adjusted by iterative algorithm. The simulation results of sinusoidal dynamic hysteresis loop and iron loss at different frequencies and different flux densities are compared with the measured results, which verifies the accuracy and versatility of the improved model. In addition, the influence of increasing frequency and flux density on total loss is also studied.

Keywords: GT100, Bertotti's conventional loss separation model, Hysteresis Model.

1. Introduction

In recent years, medium frequency transformer is widely used in the field of power, and the core as the largest component of volume and weight, core loss will directly affect the thermal analysis and insulation evaluation of equipment. There are two main types of core loss calculation methods, namely Steinmetz Equation and loss separation method.

Among them, Steinmetz Equation is relatively simple in form and involves few parameters. It is widely used in engineering practice and has been developed and perfected after constant modification by predecessors. The Original Steinmetz Equation (OSE) is only applicable to the calculation of core loss under sinusoidal excitation. It needs to be modified to apply OSE to the calculation of core loss under non-sinusoidal excitation. The OSE can be modified in the following four ways: Modified Steinmetz Equation (MSE), Generalized Steinmetz Equation (GSE), Improved Generalized Steinmetz Equation (IGSE) and Waveform-coefficient Steinmetz Equation (WcSE).

The emphases of these model updating methods based on OSE are different.

However, which method is more accurate and more suitable for the calculation of core loss under the excitation of non-sinusoidal waveform of medium frequency transformer needs further comparative study. Nonetheless, this method cannot be applied to all waveforms.

The loss separation method simplifies the analysis process of core loss, improves the calculation accuracy and is more universal in all waveforms after considering the extra loss.

In order to better fit the hysteresis loop and improve the prediction accuracy of loss and hysteresis characteristics, a dynamic hysteresis model in medium frequency is proposed by improving Bertotti's loss separation method.

2. Hysteresis Model under Sinusoidal Excitation

According to Bertotti's conventional loss separation model, the total power loss of the core can be divided into static

hysteresis loss, eddy current loss and abnormal loss.

$$\begin{aligned} P_t &= P_h + P_{cl} + P_{ex} \\ &= P_h + \frac{C_{cl}}{T} \int_0^T \left(\frac{dB}{dt} \right)^2 dt + \frac{C_{ex}}{T} \int_0^T \left| \frac{dB}{dt} \right|^{1.5} dB \end{aligned} \quad (1)$$

where B is the magnetic flux density under sinusoidal excitation, C_{cl} and C_{ex} is the coefficient of the classical eddy-current loss and the excess loss respectively.

In order to calculate and improve relevant parameters more directly through experiment, some scholars have carried out a series of deductions to transform the loss problem into the magnetic field strength problem, namely

$$H(t, B) = H_h(B) + H_{cl}(t, B) + H_{ex}(t, B) \quad (2)$$

where H , H_h , H_{cl} , and H_{ex} are the magnetic field intensity of the total loss P , hysteresis loss P_h , eddy-current loss P_{cl} and excess loss P_{ex} , respectively. The unit of loss of each part is W/kg .

2.1. Traditional Hysteresis Model

1) Static hysteresis model

Base on Preisach model, The static hysteresis characteristics were fitted. First, according to the limit hysteresis loop under sinusoidal excitation, the first-order gyration curve was obtained, and then the Everett function was generated based on FORCs. Finally, the Everett function E was used to simulate the curve to realize the model. Since the Preisach model based on variable H has great influence on the hysteresis loop close to the coercive field, the Preisach model based on variable B was adopted.

First, the first-order gyration curve of the material should be obtained. How to obtain the first-order gyration curve and establish Everett function E is the key to realize parameter identification of hysteresis model. Using the limit static

hysteresis loop data ($B_m = 1.8T, f = 5Hz$) to generate the first-order gyration curve based on the zirka method. This method has better generalization ability and wider application scope and can be used to generate the first-order turning curves under different conditions, as shown in Figure 1.

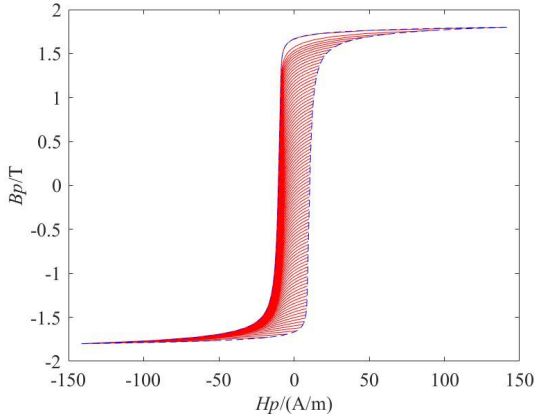


Figure 1. The first-order gyration curves

And then the E function can be founded. The inverse Everett function E value can be calculated as follows:

$$E(B, b) = \frac{1}{2} (H_{forc}(B, b) - H_{forc}(B)) \quad (3)$$

Take the first-order gyration curves starting from the ascending branch as an example, $H_{forc}(B)$ is the corresponding output value when the input value on the riser is B , and $H_{forc}(B, b)$ is the corresponding output value when the input decreases to point b , as shown in Figure 2.

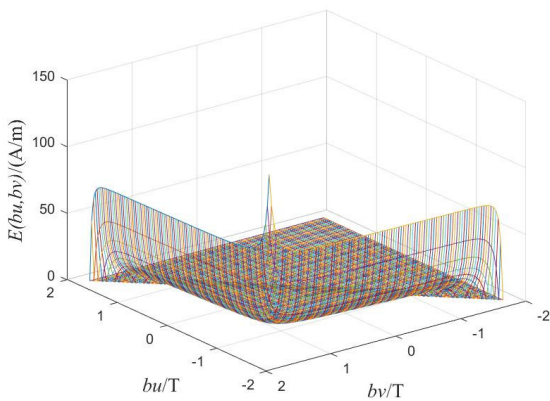


Figure 2. Everett function

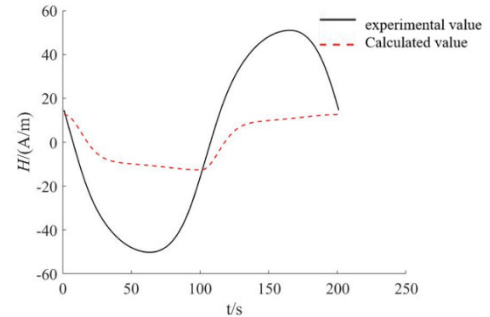
Combined with the basic theory of Preisach model, the static hysteresis loops under sinusoidal excitation in different conditions can be obtained, and then the static hysteresis losses can be obtained.

The output magnetic field intensity H can be expressed by the formula (4):

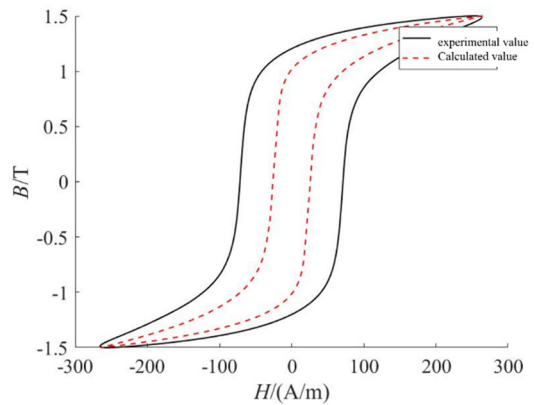
$$f(t) = -E(B_0, b_0) + 2 \sum_{k=1}^{n(t)} [E(B_k, b_{k-1}) - E(B_k, b_k)] \quad (4)$$

Where B and b respectively represent the local extreme

values of rising and falling magnetic induction intensity. $E(B_k, b_{k-1})$ is the inverse Everett function value corresponding to the local extreme values of rising when $k = 1, 2, \dots, n$, while $E(B_k, b_k)$ is the inverse Everett function value corresponding to the local extreme values of falling when $k = 1, 2, \dots, n$, the inverse Everett function value, $E(B_0, b_0)$ is the corresponding inverse Everett function value in the positive saturation state. Where, the inverse Everett function value can be calculated by formula (3), as shown in Figure 3.



a) $H - t$



b) $B - H$

Figure 3. Static hysteresis loop of $f = 400Hz$ under sinusoidal excitation a) $H - t$, b) $B - H$

2) Traditional Eddy-current Model

Suppose that the magnetic field distributes inside the material approximately evenly, H_{cl} can be obtained by the following equation based on Maxwell's equation:

$$H_{cl}(t, B) = \frac{\sigma d^2}{12} \cdot \frac{dB(t)}{dt} \quad (5)$$

Where σ refers to the electrical conductivity. d represents the thickness of the silicon steel lamination.

2.2. Extraction of Abnormal Loss Parameters

It can be obtained from the foregoing:

$$\begin{aligned} H(t, B) &= H_h(B) + H_{cl}(t, B) + H_{ex}(t, B) \\ &= H_h(B) + \frac{\sigma d^2}{12} \frac{dB(t)}{dt} + \sqrt{\sigma SGV_0} \delta \left| \frac{dB(t)}{dt} \right|^{0.5} \end{aligned} \quad (6)$$

The directional parameter $\delta = \text{sign}(dB/dt) = \pm 1$, is

controlled by the magnetic flux density, whether it is increasing or decreasing. σ is the conductivity of the material, d is the thickness of silicon steel sheet, G is the dimensionless coefficient, and the value is 0.1356. S is the cross-sectional area of the material, V_0 is a fitting coefficient related to magnetic field value, which is used to describe the microstructure characteristics of materials. The unit of loss of each part is W/kg .

H_h can be simulated by static hysteresis model, H_{ex} can be obtained according to the parameter formula about V_0 , as shown below:

$$H_{ex}(t, B) = \sqrt{\sigma S G V_0} \delta \left| \frac{dB(t)}{dt} \right|^{0.5} \quad (7)$$

Under sinusoidal excitation, $B = B_m \sin(\omega t)$ is substituted into (7) to obtain

$$H_{ex} = \delta_B \sqrt{2\pi f \sigma G S V_0} B_m \cdot (|\cos(\omega t)|)^{0.5} \quad (8)$$

Obviously, the size of H_{ex} is related to the excitation frequency.

The approximate value of the true permeability of ferromagnetic materials can be obtained by substituting this equation into $B = \mu H$.

$$\mu_{ex} = \sqrt{\frac{B_m}{2\pi f \sigma G S V_0}} \quad (9)$$

2.3. Improvement of Eddy Current Loss Calculation Formula

1) Derivation of eddy current loss considering skin effect

With the increase of working frequency, skin effect becomes more and more important. At this point, B is no longer evenly distributed in the material, so it is necessary to improve the classical loss separation model. The effect of skin effect on the loss separation model is mainly reflected in eddy current loss. By solving Maxwell's equations, the analytical expressions of eddy current losses with B_{max} and f as control variables can be obtained, as shown below:

$$P_{cl} = \frac{\sigma \pi^2 dB_m^2 f}{2\lambda} \cdot \frac{\sinh(d\lambda) - \sin(d\lambda)}{\cosh(d\lambda) - \cos(d\lambda)} \quad (10)$$

Where $\lambda = \sqrt{\pi f u \sigma}$

2) The expression of eddy current loss corresponding to field strength is improved

From the (1), we can know

$$W_{cl} = T P_{cl} = C_{cl} \int_0^T \left(\frac{dB}{dt} \right)^2 dt \quad (11)$$

Under sinusoidal excitation, $B = B_m \sin(\omega t)$ and (10) are substituted into (11) to obtain

$$\begin{aligned} C_{cl} &= \frac{1}{2\pi^2 f^2 B_m^2} P_{cl} \\ &= \frac{\sigma d}{4\lambda f} \cdot \frac{\sinh(d\lambda) - \sin(d\lambda)}{\cosh(d\lambda) - \cos(d\lambda)} \cdot P_{cl} \end{aligned} \quad (12)$$

From the (6), we can know

$$H_{cl} = C_{cl} \frac{dB}{dt} \quad (13)$$

Where $\lambda = \sqrt{\pi f u \sigma}$

2.4. Improvement of Calculation Formula of Abnormal Loss

In the traditional loss separation model, Barbisio proposed the core loss algorithm suitable for sinusoidal excitation, and believed that there was a linear function relationship between $(W - W_{cl})$ and $f^{0.5}$, that is, the abnormal loss characteristic parameter V_0 is only related to magnetic flux density amplitude B_m , but has nothing to do with magnetization frequency f . However, with the increase of magnetization frequency f , the relationship between parameter V_0 and parameter B_m presents an obvious complex nonlinear relationship. Therefore, for abnormal loss, we extracted the corresponding parameters V_0 based on the experimental data of loss under single frequency sinusoidal excitation, analyzed the variation rule of parameter V_0 with B_m and f , and established the corresponding function relationship through numerical fitting method $V_0(B_m, f)$, so as to realize the fitting of abnormal loss of oriented silicon steel sheet under different single frequency sinusoidal excitation. Thus, the improvement of abnormal loss term is realized.

3. Measurement of Magnetic Properties of Ultra-thin Silicon Steel Under Sinusoidal Excitation

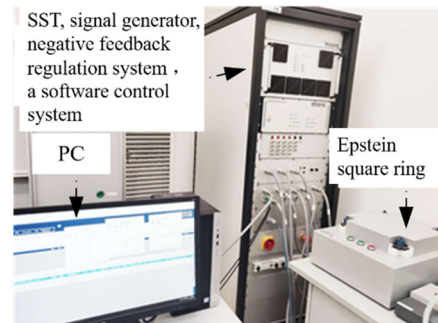


Figure 4. Schematic diagram of experimental device

The magnetic properties of Ordinary silicon steel sheet under sinusoidal excitation were measured by Brockhaus magnetic measurement system. The experimental platform including single-board tester (SST), signal generator, negative feedback regulation system and a software control system are shown in Fig.4. The given excitation is input at the

PC end and applied to the exciting winding of or ring sample through signal generator. The magnetic field intensity and flux density of silicon steel sheet can be measured based on amper law and Faraday's law of electromagnetic induction.

$$H(t) = \frac{Ni_1(t)}{l_m} \quad (14)$$

$$B(t) = \frac{1}{NS} \int_0^t u_2(t) dt \quad (15)$$

Where N is the number of turns per coil, $i_1(t)$ is the excitation current of the primary winding, l_m is equivalent magnetic circuit length; S is equivalent cross-sectional area of silicon steel sheet, $u_2(t)$ is the voltage at both ends of the secondary side winding.

4. Simulation Verification of Loss Separation Model and Loss Characteristics Under Single Frequency Sinusoidal Excitation

In the process of data processing, we found that the

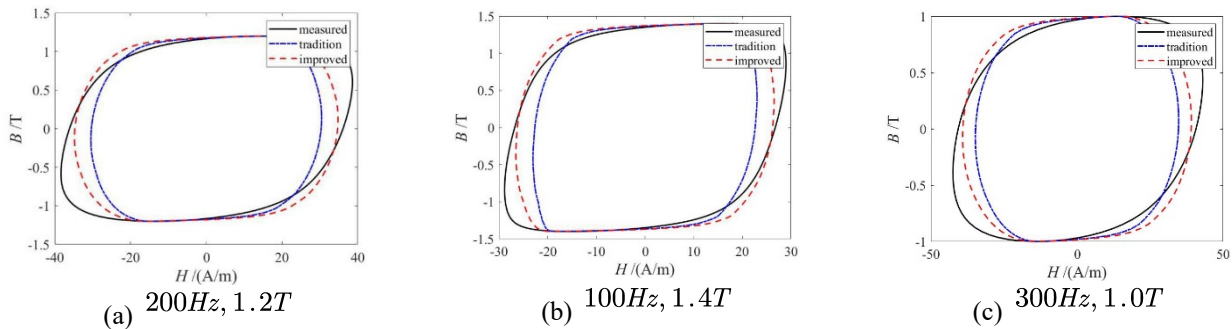


Figure 5. Simulates the dynamic hysteresis loop of Ordinary silicon steel sheet under sinusoidal excitation of $F = 200$ HZ, 100HZ, 300HZ and $B_m = 1.2T, 1.4T, 1.0T$

4.2. Dynamic Hysteresis Model Under Intermediate Frequency

In the case of mid-frequency sinusoidal excitation, the skin effect should be considered, and an improved loss separation model is used to simulate the magnetic characteristics of sample under single-frequency sinusoidal excitation. Firstly,

performance of the improved formula was different under low frequency and middle frequency, and the reason was that skin effect played a gradually significant role in the process of frequency increase. Therefore, we will fit hysteresis models under low and medium frequency excitation respectively.

4.1. Dynamic Hysteresis Model at Low Frequency

Under low frequency sinusoidal excitation, we simulate the magnetic properties of the sample under single frequency sinusoidal excitation based on the quasi-static hysteresis loop ($f = 5Hz$) measured in the experiment, without considering the skin effect. As shown in FIG. 5, the simulation and measurement results of dynamic hysteresis loops under sinusoidal excitation with different frequencies and different AMPLITUDE of AC magnetic density were selected based on the improved algorithm, and compared with the simulation results of the traditional algorithm. The relative errors of the total loss calculation of the simulated curve and the measured curve of the improved loss separation model are controlled below 5%, which is significantly improved compared with the fitting results of the traditional algorithm, and the calculation accuracy is increased by more than 10%, which confirms the accuracy of the improved loss separation algorithm.

statistical parameter V_0 is iterated. Table 1 is the value of V_0 under different B_m and f obtained through iteration algorithm. The value of V_0 is used to fit the value of abnormal loss and eddy current loss, and the dynamic hysteresis loop is drawn.

Table 1. The parameter V_0 extracted under sinusoidal excitations

f/Hz B_m/T	1000	1200	1400	1600	1800	2000
0.3	0.00671	0.00631	0.00607	0.00608	0.00579	0.00595
0.5	0.00636	0.00604	0.00574	0.00557	0.00543	0.00543
0.8	0.00646	0.00624	0.00604	0.00596	0.00551	0.00558
1.0	0.00709	0.00697	0.00664	0.00630	0.00638	0.00681
1.1	0.00766	0.00732	0.00705	0.00716	0.00735	0.00780
1.2	0.00805	0.00794	0.00811	0.00837	0.00870	0.00928
1.3	0.00891	0.00924	0.00960	0.01010	0.01070	0.01150
1.4	0.01040	0.01100	0.01170	0.01240	0.01320	0.01430
1.6	0.01520	0.01652	0.01790	0.01943	0.02090	0.02239

Then the dynamic hysteresis model under sine excitation of

intermediate frequency can be obtained.

As shown in FIG. 6, simulation and measurement results of dynamic hysteresis loops under three intermediate frequency sinusoidal excitation with different frequency and different amplitude of AC magnetic density were selected based on the improved loss separation model, and compared with the simulation results of traditional algorithm. The relative error

of total loss calculation of simulated curve and measured curve is controlled below 5%, which is significantly improved compared with the fitting result of traditional algorithm, and the calculation accuracy is increased by more than 10%, which confirms the accuracy of the improved loss separation model.

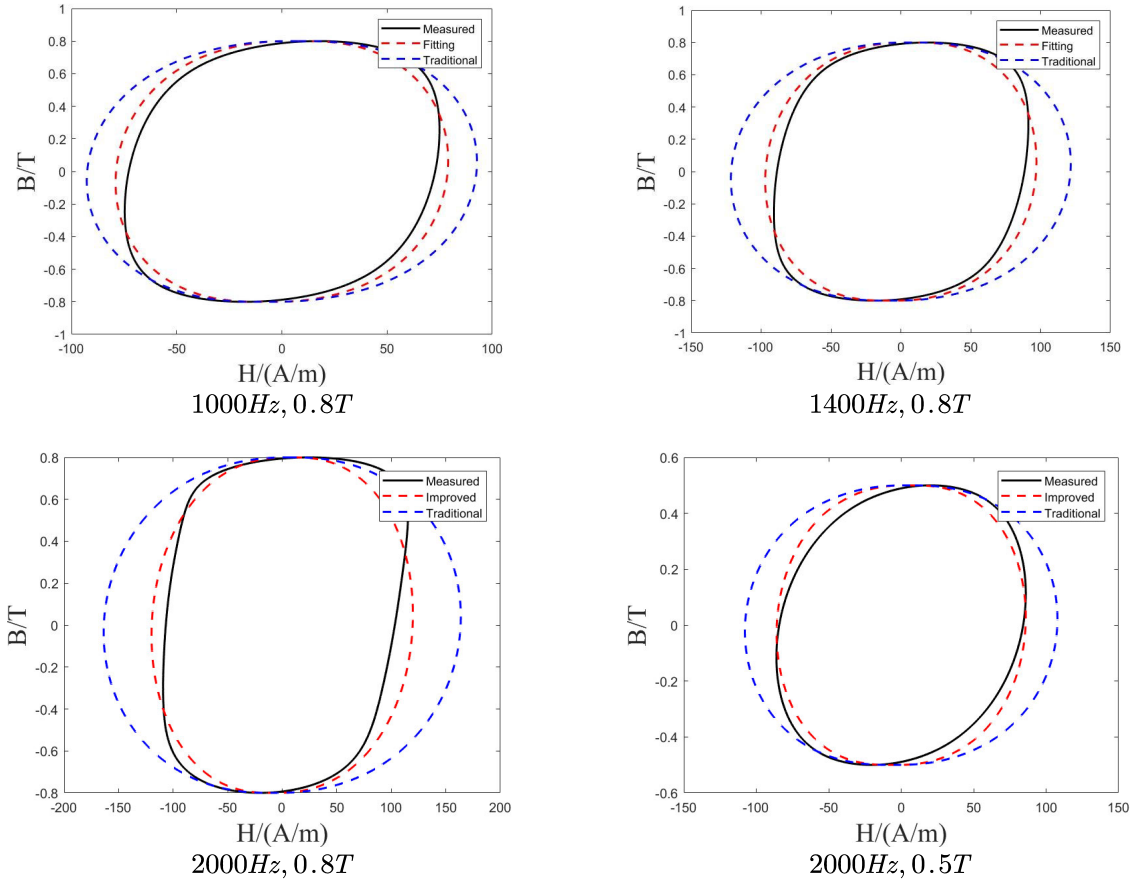


Figure 6. Simulates the dynamic hysteresis loop of Ordinary silicon steel sheet under sinusoidal excitation of $F = 1000$ HZ, 1400 HZ, 200 HZ and $B_m = 0.8$ T, 0.5 T

5. Conclusions

The losses of ultra-thin silicon steel at medium and high frequencies were measured using an improved Brockhaus experimental platform. Based on the static hysteresis simulation of Preisach model, a dynamic hysteresis model is proposed by improving the statistical parameters of abnormal losses. The model takes into account the effects of high frequency and skin effect on iron loss and achieves accurate simulation of dynamic hysteresis and loss characteristics.

Compared with the traditional model, the loss and hysteresis characteristics are greatly improved, especially the loss characteristics. The area of the image formed by the theoretical data fitted by MATLAB and the experimental data is roughly similar, and the shape of the hysteresis loop also has a high consistency. The simulation results are in good agreement with the measured values.

It can be seen from the loss fitting curves under different conditions that the total core loss increases with the increase of frequency F and magnetic induction intensity B_m , which is closely related to the principle of skin effect.

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