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THEORY

A Higher-Order Loss-Separation Model for Fast Estimation of Core Loss in High-Frequency Transformers

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ABSTRACT The core loss calculation is essential for the design and performance evaluation of high-frequency transformers. It is related to the dimensions, temperature rises performance, and operating efficiency of transformer designs. Some scholars have examined the correlation between the characteristics of the core and losses, such as the core air gap length and the core structure; some investigations have also analyzed the effects of harmonics, distortion flux, and other factors on core losses. However, in reality, the core operating environment of high-frequency transformers is very complex, and achieving the required accuracy of loss model calculations is difficult. This paper discussed the insufficiency of the classical Bertotti loss separation model in estimating core loss under non-sinusoidal excitation of high-frequency transformers. Based on the derivation and modification of the classical loss model, the magnetic performance test platform of the nanocrystalline core material was established. In order to obtain a higher-order correction calculation method for the core loss of high-frequency transformers under trapezoidal wave excitation, the experimentally measured loss curves of nanocrystalline materials were further corrected. Finally, the accuracy of the correction model was verified by changing the loss results by varying the trapezoidal wave rise time constant.

INDEX TERMS High-frequency transformer, non-sinusoidal excitation, core loss, Bertotti loss separation model, hysteresis, eddy current.

I. INTRODUCTION

The rapidly developing new power system imposes higher performance requirements on electrical equipment. High-frequency transformers are gradually being used increasingly with their small size, light mass, high efficiency, and high power density [1], [2]. Reducing core and winding losses is a fundamental means of optimizing high-frequency transformers. The high-frequency operation causes more frequent flux flip-flops, resulting in more core losses, and the magnitude of core losses is closely related to the transformer core material, winding structure, and excitation characteristics [3]. Mathematical formulas and hysteresis modeling are two common methods used to evaluate core material losses. The advantage of the formula method is that it is simple, fast, and applicable to common core materials. However, there may be some limitations to the accuracy of this method, especially in the nonlinear and high-frequency ranges. Therefore, it is of great engineering significance to investigate the calculation method of core loss in high-frequency transformers under non-sinusoidal excitation conditions [4].

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In recent years, scholars have paid particular attention to studying core loss in high-frequency transformers. The hysteresis modeling method focuses on the magnetization mechanism of ferromagnetic materials [5], including purely mathematical models such as the Preisach model and physical models such as the Jiles-Atherton model. Reference [6] incorporated nonlinear core behavior into the finite element formulation using a vector hysteresis model with a magnetic difference tensor, and proposed a finite element model for analyzing the iron loss of three-phase transformers; Research in [7] developed an improved Preisach model for three-phase medium-frequency transformers. They analyzed the transformer core power losses by optimally identifying the parameters of the distribution function of the Preisach hysteresis model. In [5], the researchers estimated core power losses in magnetic components using a mathematical empirical hysteresis model. They proposed a new method of calculating core losses, taking into account geometrical and material parameters. Hysteresis models can more accurately describe the nonlinear magnetic behavior of materials and can provide more accurate loss estimates. However, the material hysteresis model used in loss calculation need to consider too many model parameters, which causes a complicated model and long calculation time [8].

The loss mathematical model provides a microscopic analysis of the magnetization process, focusing on the factors that influence losses, including the classical Steinmetz empirical equation and the Bertotti loss separation model. Reference [9] describes the equivalent electromagnetic parameters of multi-stage circular cross-section winding cores at different frequencies. The Bertotti loss separation model has fewer parameters and clearer physical significance. For high-frequency transformers operating mainly under non-sinusoidal excitation, many scholars have conducted optimization studies on the loss model parameters for a specific excitation case [10], [11]. However, in fact, the core operation environment of high-frequency transformers is very complex, and the accuracy of the classical loss model is difficult to meet the requirements, so it is necessary to derive new loss calculation methods [12], [13].

In this study, an accurate calculation of iron core losses in high-frequency transformers under non-sinusoidal excitation was achieved by implementing a higher-order correction method for the core loss separation model. Firstly, the effect of the trapezoidal wave rise time constant on the core loss was considered, and the mathematical model of the core loss under non-sinusoidal excitation was derived. Then, the loss coefficients of the separation model were step-corrected with the magnetic induction strength as the independent variable, in order to establish the loss correction of the separation model under trapezoidal excitation. Finally, experiments were conducted to verify the accuracy and validity of the model proposed in this study, which provided guidance for optimizing the loss model under various non-sinusoidal excitation waveforms.

II. REVIEW OF CORE LOSS CALCULATIONS

A. STEINMETZ EMPIRICAL FORMULAE

Core losses are usually calculated by the model of hysteresis, the Steinmetz formula, and the loss separation model. The hysteresis model contains the Preisach model, the Jiles-Atherton model, and the Energetic model. These models have difficulties in distinguishing parameters during the calculation process and exhibit notable deficiencies in the field of high-frequency transformer research [14]. Core loss calculations for high-frequency transformers under various excitation conditions include the Steinmetz empirical formula and its optimization algorithm [15], [16]. The Steinmetz formula is used to characterize the transformer core loss under sinusoidal excitation, the empirical form is expressed as:

$$P_v = C_m \cdot f_s^{\alpha} \cdot B_m^{\beta} \tag{1}$$

where P_v refers to the total core loss, f_s is the frequency of the applied sinusoidal excitation voltage, B_m is the maximum flux density of the core, α and β are core coefficients, representing the nonlinearity of the core material. They both satisfy the conditions of $1 < \alpha < \beta < 3$ and $\beta \approx \alpha + 1$ [17].

However, this empirical formula is only applicable to the sinusoidal excitation case. In actual operating conditions of high-frequency transformers, there are more application scenarios with non-sinusoidal excitation than standard sinusoidal excitation. Therefore, scholars have made many efforts to optimize the formula for the calculation of non-sinusoidal excitation losses. C_m, α, and β in the Steinmetz formula are the main directions for optimizing other non-sinusoidal excitation core loss calculation methods [18]. For example, the non-sinusoidal excitation is considered as an equivalent superposition of a series of sinusoidal excitations [19], and the equivalent result is obtained by summing the sinusoidal excitations for each decomposition.

B. BERTOTTI LOSS SEPARATION MODEL

The loss separation model was found by Bertotti(the Italian scholar) after analyzing a large amount of experimental data. It divides the core loss into three parts: hysteresis loss, eddy current loss, and residual loss based on the mechanism of core loss composition.

1) HYSTERESIS LOSS

Under the influence of an alternating magnetic field, the domain walls between adjacent domains of the core are oriented and shifted from a relatively stable state. While some of the shifted domains can automatically return to their initial state upon removal of the power supply, other domains in the transformer core maintain their magnetization even when the alternating electromagnetic field changes. These domains undergo repeated magnetization and demagnetization, resulting in hysteresis losses. The calculation formula is:

$$P_{\mathrm{h}} = K_h f B_m^2 \tag{2}$$

where P_h is hysteresis loss, K_{h} is the hysteresis loss factor; f is the excitation voltage frequency in Hz; B_m is the peak magnetic flux density in T.

2) EDDY CURRENT LOSS

Iron core coils flow through the alternating current will produce rapid changes in the magnetic field, the electromagnetic field through the core to produce dynamic magnetic flux, and the core will produce a closed induced current, which is called eddy current. Its path around the initial flux rotating because the resistivity of the core material is not infinite, and the existence of a certain value of the resistance, the eddy current through the iron core will produce eddy current losses. The formula is:

$$P_e = K_e f^2 B_m^2 = \frac{\sigma d^2}{12\rho T'} \int_0^{T'} |\frac{dB(t)}{dt}|^2 dt \tag{3}$$

where P_e is eddy current loss, K_e is the eddy current loss factor; ε is the material conductivity, D is the core stack thickness, and P is the material density.

Eddy current is derived from the law of electromagnetic induction and is directly related to the rate of change of magnetic induction strength. Therefore, the higher the frequency of the alternating magnetic field, the greater the eddy current generated, and the more eddy current loss is generated.

3) RESIDUAL LOSS

The residual loss is mainly induced by the relaxation effect and the magnetic hysteresis effect during the magnetization process. In the process of repeated magnetization of the core, the magnetization process of the transformer core lags behind the change of magnetic field strength, and the magnetization needs a process to reach the final state, which is the reason for the residual loss:

$$P_c = K_{\mathrm{c}} f^{1.5} B_{\mathrm{m}}^{1.5} = \sqrt{\sigma G S V_0} \frac{1}{T'} \int_0^{T'} |\frac{dB(t)}{dt}|^{1.5} dt \tag{4}$$

where P_c is residual loss, K_c is the residual loss coefficient, S is the core cross-sectional area, V_0 is the internal statistical parameter of the ferromagnetic material, T' is the magnetization period, and G is the dimensionless coefficient.

From the above-mentioned principles of various loss generation, it can be seen that core loss in an alternating magnetic field is affected by several factors such as material resistivity, excitation frequency, peak magnetic induction intensity, and others. Bertotti introduced the transient loss separation model based on the assumption of uniform distribution of magnetic induction intensity and the random statistical distribution characteristics of the magnetic domain structure:

$$\begin{aligned} P_{\mathrm{v}} &= P_h + P_e + P_c \\ &= K_{\mathrm{h}} f B_{\mathrm{m}}^2 + K_{\mathrm{e}} f^2 B_{\mathrm{m}}^2 + K_{\mathrm{c}} f^{1.5} B_{\mathrm{m}}^{1.5} \\ &= K_{\mathrm{h}} f B_{\mathrm{m}}^2 + \frac{\sigma d^2}{12\rho T'} \int_0^{T'} |\frac{dB(t)}{dt}|^2 dt \\ &\quad + \sqrt{\sigma G S V_0} \frac{1}{T'} \int_0^{T'} |\frac{dB(t)}{dt}|^{1.5} dt \end{aligned} \tag{5}$$

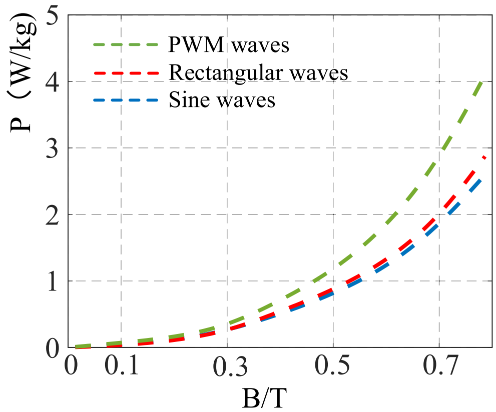

FIGURE 1. Loss curves for nanocrystalline materials under 2khz excitation.

C. COMPARISON OF ESTIMATION RESULTS OF CLASSICAL BERTOTTI LOSS SEPARATION MODEL

No-load experiments were conducted on the high-frequency transformer. The secondary side of the transformer was left open to visualize the differences in transformer losses under different excitation waveforms in high-frequency electromagnetic fields. The experiments also aimed to assess the errors between the classical loss separation model and the actual operating losses of high-frequency transformers. Through the adjustment of the frequency of the signal generator and the waveform, measurements of nanocrystalline materials were conducted at frequencies of 2kHz and 5kHz. The waveforms used for measurement were sinusoidal, rectangular, and PWM, respectively. The loss curves were obtained by observing the change in loss with the variation in magnetic induction intensity. These loss curves are depicted in Figure 1 and Figure 2:

After the no-load experiment, the transformer operating conditions were kept unchanged, and finite element simulation was used to obtain the core loss calculated by the classical loss separation model under high-frequency sinusoidal wave conditions. The core loss in the finite element simulation (FEM) was estimated using the classical Bertotti loss separation model. The average value of core loss under different magnetic induction strengths was determined by taking 20 frequency values ranging from 1kHz to 10kHz. The resulting core loss area controlled by frequency and magnetic induction strength was obtained as shown in Figure 3:

From the values of losses in the above cases, it can be observed that the losses remain relatively stable at low

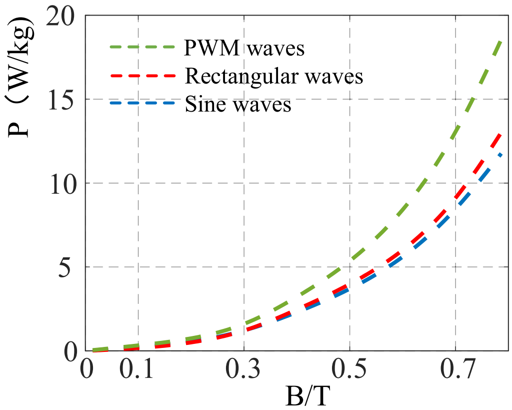

FIGURE 2. Loss curves for nanocrystalline materials under 5khz excitation.

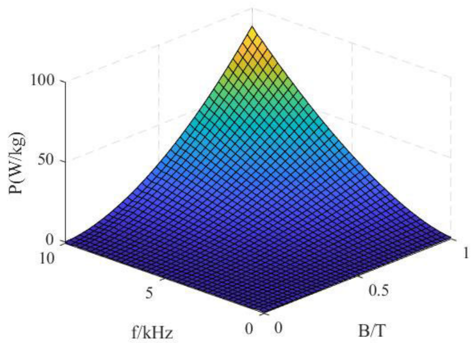

FIGURE 3. Nanocrystalline loss fitting surface.

TABLE 1. Comparison of measured core losses and classical loss separation modeling.

B/T		0.2	0.3	0.4	0.5	0.6	0.7
2kHz	Measured /(W/Kg)	0.088	0.243	0.486	0.779	1.249	1.862
	Simulation /(W/Kg)	0.080	0.220	0.429	0.691	1.106	1.614
	Errors/%	8.93	9.58	11.73	11.28	11.43	13.30
5kHz	Measured /(W/Kg)	0.451	1.023	2.204	3.584	5.274	8.385
	Simulation /(W/Kg)	0.410	0.918	1.914	3.131	4.595	7.167
	Errors/%	9.08	10.22	13.17	12.63	12.87	14.53

magnetic induction strengths. However, when the magnetic induction strength (B) exceeds 0.4T, the core losses increase exponentially, which is consistent with the results described by the loss separation model.

It can also be found that the traditional loss separation model may produce large errors in the analysis of losses due to the complex nature of losses generated by high-frequency transformers, and the error comparison by intercepting the characteristic points from the measured results and the simulation fitted surface is shown in Table 1. (All loss results are retained to 3 decimal places)

Obviously, a serious degradation in the computational accuracy of the classical loss separation model was caused by the increase in frequency. As a result, there is a need for a targeted improvement of the loss model.

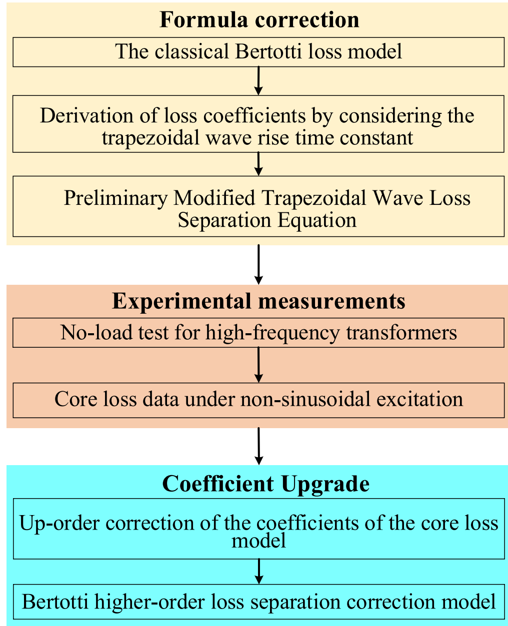

FIGURE 4. Schematic of the loss model correction process.

III. CORRECTIONS TO MODEL COEFFICIENTS FOR LOSS SEPARATION UNDER TRAPEZOIDAL WAVES

High-frequency transformers are subject to the combined effects of electromagnetic, temperature, and flow fields. The excitation waveforms of these transformers are generally non-sinusoidal, with a large number of harmonics added to the excitation. This presence of harmonics can significantly affect the quality of the power. Compared to low-frequency transformers, high-frequency transformers experience significant hysteresis losses and eddy current losses. These losses are fundamental factors that contribute to the reduction of insulation performance and the shortening of the transformer's life.

The flow diagram of the method used in this section is shown in Figure 4:

A. DERIVED EQUATION FOR CORE LOSS SEPARATION UNDER TRAPEZOIDAL WAVE EXCITATION

The trapezoidal waveform is the commonly used excitation waveform for high-frequency transformers. To accurately predict the iron consumption of high-frequency transformers under its action, the loss separation formula was corrected by combining it with the relationship between magnetic induction strength and voltage.

When the magnetic induction strength and frequency are determined, the hysteresis loss is not much related to the waveform, the main influence on the accuracy of the calculation is eddy current loss and residual loss. Barbiso derived the two parts of the original calculation formula as (6)

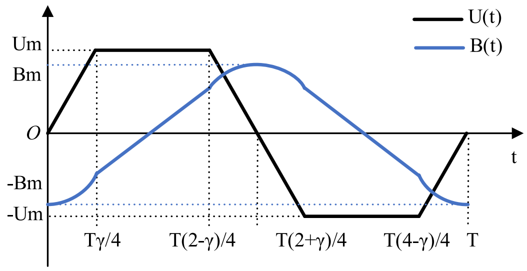

FIGURE 5. **The curve of voltage versus magnetic induction strength B for trapezoidal wave excitation.**

and (7) based on the loss separation model:

$$P_e = \frac{\sigma d^2}{12\rho T'} \int_0^{T'} |\frac{dB(t)}{dt}|^2 dt \tag{6}$$

$$P_c = \sqrt{\sigma GSV_0} \frac{1}{T'} \int_0^{T'} |\frac{dB(t)}{dt}|^{1.5} dt \tag{7}$$

where σ is the material conductivity, d is the core stack thickness, S is the core cross-sectional area, ρ is the material density, T' is the magnetization period, and G is the dimensionless factor.

The law of electromagnetic induction specifies the differential relationship between magnetic induction intensity and voltage. The relationship between the image of the voltage (U) and the magnetic induction intensity (B) in a period for rectangular and trapezoidal waves is as follows:

where γ is the rise time constant of the trapezoidal wave.

The integration of the excitation voltage wave over a period yields the following segmented expression for the magnetic induction under the action of a symmetrical trapezoidal wave:

$$B(t) = \begin{cases} B_\mathrm{m}(-1 + \dfrac{16}{\gamma T^2(2-\gamma)} t^2) & [0, \dfrac{T\gamma}{4}] \\ B_\mathrm{m}\left(\dfrac{8t}{T(2-\gamma)} + \dfrac{-2+4\gamma}{2-\gamma}\right) & [\dfrac{T\gamma}{4}, \dfrac{T}{4}] \end{cases} \tag{8}$$

The segmented expressions for magnetic induction with rise time constants are brought into the original loss separation model to calculate eddy current losses and residual losses, and the expressions for eddy current losses and residual losses corresponding to trapezoidal waves are as follows:

$$\begin{cases} P_e = \dfrac{16\sigma d^2 \gamma}{9\rho(2-\gamma)^2} f^2 B_\mathrm{m}^2 \\ P_c = 8^{\frac{3}{2}} \sqrt{\dfrac{\sigma GSV_0}{2-\gamma}} f^{1.5} B_\mathrm{m}^{1.5} \end{cases} \tag{9}$$

B. FITTING OF HIGH-ORDER CORE LOSS SEPARATION EQUATION

In order to further correct the deduced separation model, the no-load experiments on the transformer are continued to obtain loss data. The trapezoidal wave excitation here specifies a rise time constant of 0.2, and when the frequency is taken to be 2 kHz, the loss measurement curves of nanocrystalline materials under different magnetic induction intensities are shown in Figure 6:

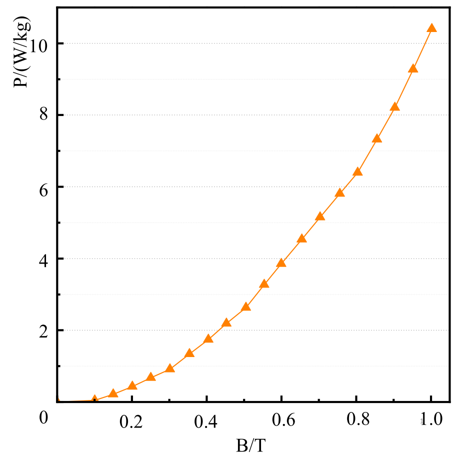

FIGURE 6. **Results of 2kHz core loss measurements.**

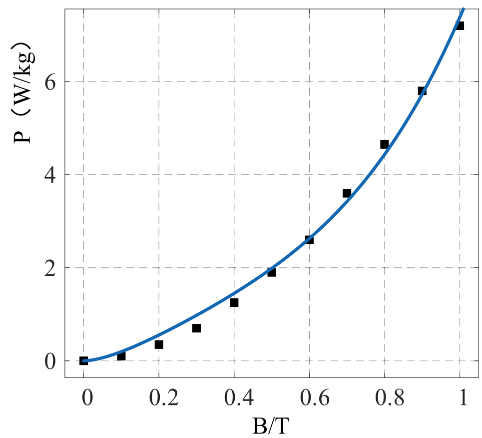

FIGURE 7. **The fitting curve for the core loss under trapezoidal wave excitation.**

According to the measured loss data, the coefficients of each part of the derived loss separation model are considered as polynomial functions. The magnetic induction strength (B) is considered as the independent variable, while the total loss is considered as the dependent variable for equation fitting. The fitting curve is shown in Figure 7 with a goodness of fit of 0.9952. Finally, the higher-order corrections are obtained for each loss coefficient. The corrected expression is:

$$\begin{aligned} P_\mathrm{v} = & (b_1 + b_2 B_\mathrm{m}) f B_\mathrm{m}^2 \\ & + \frac{(b_3 + b_4 B_\mathrm{m})\gamma}{(2-\gamma)^2} f^2 B_\mathrm{m}^2 \\ & + \frac{(b_5 + b_6 B_\mathrm{m})}{\sqrt{2-\gamma}} f^{1.5} B_\mathrm{m}^{1.5} \end{aligned} \tag{10}$$

where b_1, b_2, b_3, b_4, b_5 and b_6 are loss separation model correction factors.

After numerical fitting, the values of each parameter in the expression(10) are shown in Table 2:

TABLE 2. Values of parameters in the correction formula.

b_1	b_2	b_3
0.9090	-0.6829	-0.0072
b_4	b_5	b_6
0.00563	0.00004	-0.00072

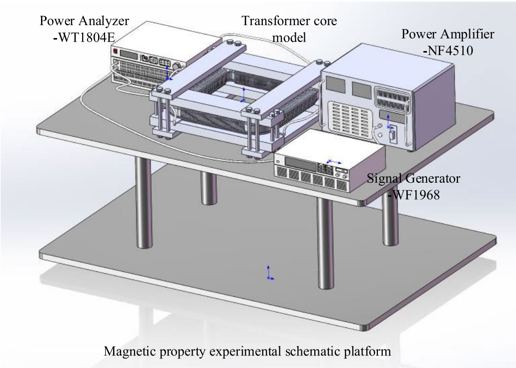

FIGURE 8. Magnetic property test bench for nanocrystalline iron cores.

TABLE 3. Comparison of core loss error before and after correction factor.

B/T	γ =0.3		γ =0.4	
	Errors before correction	Errors after correction	Errors before correction	Errors after correction
0.2	10.21%	4.69%	12.43%	3.99%
0.4	13.53%	8.24%	9.27%	4.96%
0.6	12.46%	5.47%	13.63%	6.03%
0.8	12.71%	5.77%	13.22%	6.41%
1.0	14.87%	6.64%	12.96%	5.95%

IV. EXPERIMENTAL VALIDATION OF A HIGHER-ORDER LOSS SEPARATION MODEL

To verify the correctness of the correction coefficients proposed in Section III and the accuracy of the correction model. The loss of the nanocrystalline core was calculated according to the equation (10) which was considered the trapezoidal waveform rise time coefficients and the experimental measurements were analyzed by comparing them with the calculated results.

In this section, a nanocrystalline magnetic performance test platform (shown in Figure 8) was built for obtaining the core loss data of high-frequency transformers in actual operation. The loss results can be obtained on the experimental platform by changing the input conditions such as waveform, frequency, amplitude, phase, and other parameters in real time. This facilitates the validation of the calibration model. The experiments were carried out when the trapezoidal waveform frequency was 2 kHz and the rise time constants γ were 0.3 and 0.4. The experimental measurement results of different magnetic induction strengths were compared with the measurement errors before and after the correction coefficients, and the comparison results are shown in Table 3. (All results are retained to 2 decimal places)

By comparing the calculation and measurement results, it becomes clear that the loss calculation error can be controlled by around 5% after the trapezoidal wave correction. This error percentage is 5% to 7% lower than the error percentage prior to the correction. The corrected results align more closely with the actual measurement results, meeting the accuracy requirements for the calculation process. The corrected values align more closely with the actual measurement results, meeting the accuracy requirements of the calculation process. Consequently, this correction factor provides a convenient and effective method for accurately calculating the core loss of high-frequency transformers.

V. CONCLUSION

In this paper, a transformer loss calculation method based on the Bertotti loss separation model was analyzed. The traditional loss separation model cannot accurately calculate the core loss of high-frequency transformers when exposed to non-sinusoidal excitation. To address this issue, the rising time constant of the trapezoidal wave and the relationship between trapezoidal excitation and magnetic induction strength were taken into account. The model was then preliminarily corrected. By analyzing the measured core loss data, a step-up loss coefficient was introduced, which considers magnetic induction strength as the independent variable. A new higher-order correction method was proposed for the Bertotti loss model. The calculation error of the modified model is significantly smaller than that of the classical model, and the proposed method provided theoretical support for the prediction of core loss of high-frequency transformers under non-sinusoidal excitation, transformer design, and core selection.

It should be noted that the non-sinusoidal excitation also includes PWM wave, rectangular wave, delta wave, etc. The actual operating conditions of high-frequency transformers are highly intricate. Factors such as frequency, winding arrangement, magnetic leakage, and core structure can significantly influence magnetic induction strength and loss. Therefore, considering the real operating conditions of high-frequency transformers and achieving more accurate loss calculations requires further research.

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