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An Improved Loss-Separation Method for Transformer Core Loss Calculation and Its Experimental Verification

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ABSTRACT The separation of core loss plays an important role in the transformer loss calculation. To obtain more accurate core loss, based on the comparison and analysis on two traditional loss separation methods, an improved loss separation method was proposed for the core loss calculation of the transformer in a wide magnetic flux density range. Firstly, through analysis the eddy current loss was obtained by direct calculation, while the hysteresis loss was obtained by performing the quasi-static magnetization process. And the coefficient corrections for the hysteresis loss and eddy current loss calculation were conducted by using the experimental data. The result comparison between the proposed method and traditional ones were made. Secondly, by setting up the Epstein frame platform, the total loss and static hysteresis loss of 14 types of industrial silicon steel were measured. In addition, the suggestive values and the corresponding value range of the loss coefficients of 14 kinds of industrial silicon steel were given. The results obtained by the proposed method were in good agreement with the measured data in the wide magnetic flux density range, while the suggestive values and the corresponding value range of 14 kinds of industrial silicon steel can provides an effective data support for the accurate core loss calculation.

INDEX TERMS Epstein frame platform, oriented silicon steel, transformer core loss separation, hysteresis, eddy current.

I. INTRODUCTION

The excitation characteristics and no-load loss of a transformer are important indicators to evaluate its performance. Due to the complicated magnetic material properties of the transformer core, it is difficult to build the core model and calculate the core loss, thus making the core loss prediction even harder [1]–[3]. Currently, the methods for core loss calculation of different silicon steel types in a wide magnetic flux density range still remain problematic, which makes the calculation of the iron loss an important issue under study [4].

In the Jiles-Atherton model, the magnetic hysteresis phenomena was studied according to macroscopic energy calculation [5], while in the Preisach model, the theoretical analysis on the model itself was made based on the statistics of magnetic domain movement in time and space. But they both relied on a large number of measurement data, which brought certain limitations to the research [6]. Steinmetz summarized an empirical formula for the per unit volume magnetic loss in 1982 which is simple in form and has few parameters [7] and is widely used in iron loss calculation of electromagnetic equipment such as transformers. As a matter of fact, it is also the basis of other iron loss calculation models. The idea of loss separation was proposed by Bertotti in 1988 [8]. According to the mechanism of the loss generated by ferromagnetic materials under the action of alternating magnetic field, the iron loss can be decomposed into three parts, named the hysteresis loss, the energy loss caused by the friction between the domains; eddy current loss, the joule loss caused by the induced current in ferromagnetic materials; abnormal loss respectively, caused by eddy currents in alternating leakage magnetic fields [9].

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Based on the Bertotti model, scholars has been trying to overcome the difficulty in separating the core loss [10]–[12]. In this article, multiple sets of commonly used silicon steels were studied. The results of the variational magnetic flux density method were in good agreement with the experimental ones in the low-magnetic flux density range. However, the calculation results become unreliable as the magnetic flux density increases gradually. Although by using frequency-variation method, the influence of the frequency on the hysteresis loss is inevitable, it still has a large calculation error [13]. At the same time, this method has higher requirements on the frequency data, and the selection of different frequency data has a great impact on the calculation results, which affects its practicability.

Therefore, the direct application of the Bertotti model or other improved method to certain types of silicon steels during the loss separation, and it works well in the low magnetic flux density range. However, due to the typical non-linear characteristics of the oriented silicon steel sheet, serious distortion emerges in the high magnetic flux density range (over 1.5 T) [14], resulting in a large calculation error of about 50%. Accordingly, the constant coefficient model cannot accurately describe the loss changes of ferromagnetic materials in various magnetic flux density ranges, nor can it take into account the influence of core oversaturation in high magnetic flux density range on the loss [15], which leads to the poor practicability and separation accuracy. In order to make up for the deficiency of the Bertotti model in describing the magnetic flux density saturation of the core, references [16] and [17] adopted the method by adding a compensation term to the original eddy current loss to solve the problem that the calculated value is smaller than the total loss. In fact, the thickness of oriented silicon steel used in transformers is much smaller than the skin depth under the operating frequency [18], thus the magnetic permeability in silicon steel sheet is almost uniform and the core eddy current loss can be directly obtained without any compensation [19].

In addition, scholars at home and abroad have attached great importance to the measurement method of magnetization properties of magnetic materials. At present, there are three kinds of measurement methods with high degree of recognition: the monolithic measurement method, the ring sample method and the Epstein frame method [20]–[22]. Among them, the Epstein frame measurement method is more traditional and is widely used as the main measurement method of electrical ferromagnetic materials in China. In standard IEC 60404-2:1996 and GB/T 3655-2088, the measuring condition and procedure of transformer core loss are given.

The rest of this article is organized as follows. The method overview was presented in Section II. In section III, the Epstein frame platform was introduced. Section IV gives the verification of improved loss separation method, followed by its application in Section V. In section VI, the conclusion is given.

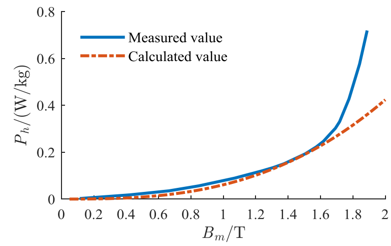


FIGURE 1. Comparison of calculated hysteresis loss and measured one for B27R095 by variational magnetic flux density method.

II. METHOD OVERVIEW

A. TRADITIONAL LOSS SEPARATION METHODS BASED ON BERTOTTI MODEL

The trinomial core loss separation model proposed by Bertotti in 1988 is the most commonly used loss separation model at present. The core loss can be expanded into the form shown in (1):

$$\begin{aligned} P_{\mathrm{tot}} &= P_{\mathrm{h}} + P_{\mathrm{e}} + P_{\mathrm{ex}} \\ &= k_{\mathrm{h}} B_{\mathrm{m}}^{\alpha} f + k_{\mathrm{e}} B_{\mathrm{m}}^{2} f^{2} + k_{\mathrm{ex}} B_{\mathrm{m}}^{1.5} f^{1.5} \end{aligned} \tag{1}$$

where P_{tot} is the total core specific loss per unit mass, W/kg; P_{h}, P_{e} and P_{ex} respectively represent the hysteresis loss per unit mass, eddy current loss per unit mass and abnormal loss per unit mass, W/kg; f is frequency, Hz; B_{m} is the amplitude of magnetic flux density, T; k_{h}, k_{e}, $k_{\mathrm{ex}}$and α are the coefficients related to the microstructure of ferromagnetic materials.

For better illustration, two traditional loss separation methods were analyzed in this part.

1) VARIATIONAL MAGNETIC FLUX DENSITY METHOD

For the method based on Bertotti model, the steps are as follows: by changing the excitation voltage, the loss under different magnetic flux density is obtained; then the regression equation is set up by a mathematical statistics method and the measured B_{m}-P_{tot} data are used for regression calculation according to the Bertotti model; after that, four coefficient, k_{h}, k_{e}, k_{ex} and α, are obtained and the three kinds of loss is successfully separated. Figure 1 shows the comparison between the calculated hysteresis loss and the measured value of the electrical steel sheet with type of B27R095 under the power frequency sinusoidal excitation.

As in Fig. 1, although the calculated results were in good agreement with the experimental ones in a low magnetic flux density range, they tended to deviate from the measured ones when the magnetic flux density increases to 1.7 T and the iron core approaches saturation. In fact, the calculated results are smaller, and the error increases with the increase of the magnetic flux density.

2) FREQUENCY-VARIATION METHOD

In addition, the frequency-variation method was adopted [23]. According to the fact that the hysteresis loss term is a linear function of f, equation (2) can be obtained by dividing both

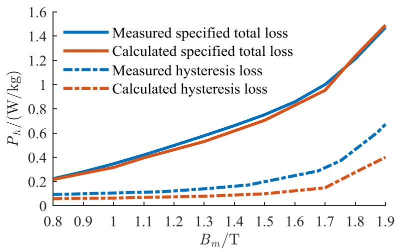


FIGURE 2. Comparisons between calculated hysteresis loss and measured one, and calculated specified total loss and measured one for 27ZH95 by frequency-variation method.

TABLE 1. Loss separation results of 27ZH95 by frequency-variation method.

B_m(T)	P_h(W/kg)	P_e(W/kg)	P_{ex}(W/kg)
0.8	0.05760	0.05132	0.10945
1.0	0.06330	0.06913	0.18349
1.1	0.06870	0.07065	0.25561
1.3	0.07810	0.10743	0.34436
1.5	0.09835	0.14473	0.46174
1.7	0.14790	0.15080	0.65372
1.8	0.27570	0.17788	0.78064
1.9	0.48526	0.19201	0.87142

ends of (1) by f.

$$\frac{P_{tot}}{f} = \frac{P_h}{f} + \frac{P_e}{f} + \frac{P_{ex}}{f} = k_h B_m^h + k_e B_m^2 f + k_{ex} B_m^{1.5} f^{0.5} \tag{2}$$

As be seen from above, when B_m is fixed, the hysteresis loss in each cycle is a fixed value. The value of core loss at different frequencies can be obtained through experimental measurement and the f-P_{tot}/f curve can be plotted. In this way, the hysteresis loss can be obtained through curve intercept.

When using this method, a fixed value of the magnetic flux density B_m should be ensured. In this article, the high-quality silicon steel sheet with the type of 27ZH95 is selected as example. Six representative test points of the magnetic flux density, namely 0.8 T, 1.0 T, 1.1 T, 1.3 T, 1.5 T, 1.7 T, 1.8 T and 1.9 T, were measured and analyzed by the above method for loss separation. By calculating the loss coefficients under each of the magnetic flux density, the hysteresis loss, eddy current loss and abnormal loss of the selected steel sheet can be obtained.

Figure 2 shows the comparison between the results of specific total loss and hysteresis loss calculated by the frequency-variation method and the measured results of electrical steel sheet 27ZH95 under a sinusoidal power frequency excitation.

As shown in Fig. 2, although the error of specified total loss in calculated results was slight compared with the measured one, the hysteresis loss calculated by frequency-variation method was smaller than the measured one, and the error tended to increase with the increase of magnetic flux density.

Table 1 shows the loss separation results of 27ZH95 silicon steel sheet under sinusoidal excitation at the power frequency.

Generally, when the transformer works normally, the magnetic flux density B_m of the core is about 1.7 T. It has been pointed out in the transformer design principle that in high-quality silicon steel sheets, the hysteresis loss accounts for about 20%-30% in the whole core loss, the eddy current loss for about 20%-30%, and the abnormal loss accounts for about 40%-50%. In fact, for the loss separation results of silicon steel sheet 27ZH95 obtained by frequency-variation method, when $B_m = 1.7$ T, the hysteresis loss was 0.148 W/kg, accounting for 15.5% of the total loss; the eddy current loss was 0.1508 W/kg, accounting for 15.8%; the abnormal loss was 0.653W/kg, accounting for 68.7%. Obviously, they did not conform the transformer design principle, which means that the obtained results are not accurate.

B. IMPROVED LOSS SEPARATION METHOD

As analyzed above, the traditional Bertotti model performs well in the low magnetic flux density range of 0-1.5 T; however, it does not consider the non-linear characteristics of the core, nor does it take into account the influence of the core oversaturation on the loss in the high magnetic flux density range. As the magnetic flux density exceeds 1.5 T, the error of the separation result increases significantly. In the light of the limitation of traditional Bertotti core loss separation model, an improved loss separation method is proposed in this article. First, the eddy current loss is separated from the total core loss for it is easy to calculate; then, taking 1.5 T as the threshold, the value below 1.5 T named the low magnetic flux density range and the value above 1.5 T named the high magnetic flux density range. Then, according to the saturation degree of the steel, the fitting calculation and the correction of the coefficients are performed. In the low magnetic flux density range, the traditional separation loss calculation based on Bertotti model is performed to obtain k_h, k_{ex}, α and γ; while in the high magnetic flux density range, the hysteresis loss and eddy current loss are calculated by using the loss data of oversaturated magnetic flux density [24]. The details are as follows.

1) EDDY CURRENT LOSS OF SILICON STEEL

According to the thickness of the currently used laminated steel sheet (most of them is less than 0.3 mm or even 0.18 mm) which is far less than the skin depth, the magnetic flux density be assumed to uniform in the steel sheet [25]. Therefore, the eddy current loss can be directly obtained by calculation. By using (3) and (4), the eddy current loss of the steel sheet under different magnetic flux densities can be calculated, which directly reduces the number of terms to be separated in the traditional model.

$$P_e = k_e (f B_m)^2 \tag{3}$$

where k_e is the coefficient of eddy current loss

$$k_e = \frac{\pi^2}{6\rho\rho_{fe}} \Delta_{fe}^2 \tag{4}$$

where ρ is the electrical conductivity of silicon steel sheet, $\rho_{fe}$is the material density, and $\Delta_{fe}$is the sheet steel thickness.

2) COEFFICIENT CALCULATION OF LOW MAGNETIC FLUX DENSITY RANGE

Based on the Bertotti model, the coefficients in the low magnetic flux density range of 0 T-1.5 T are calculated by utilizing the measured loss data, and the values of hysteresis loss and abnormal loss are obtained. In addition to the eddy current loss, the hysteresis loss and abnormal loss in the low magnetic flux density range can be calculated by (5):

$$P_{tot}^{low} - P_e = P_h + P_{ex} = k_h B_m^{\alpha} f + k_{ex} (B_m f)^{1.5} \tag{5}$$

The mathematical method of replacing the fixed constants 1.5 by variable coefficient γ, is able to reduce the calculation error. Usually in the traditional Bertotti model, the power exponent of the abnormal loss is a fixed value, while in this article, γ is used to replace it and its value range is specified in the calculation which will be illustrated in the following.

The values of k_h, k_{ex}, α and γ are required for the coefficient calculation in the low magnetic flux density range. Through the calculation of multiple groups of experimental data, it is found that the three loss coefficients, k_h, k_e and k_{ex}, are all constants with the magnitude of about 10^{-3}, while the exponential coefficients α and γ are the variables between 1 and 2. Some attention should be paid to limiting the value range of each coefficient in calculation. The preliminary calculation equation is shown as follows:

$$P_{tot}^{low} - P_e = P_h + P_{ex} = k_h B_m^{\alpha} f + k_{ex} (B_m f)^{\gamma} \tag{6}$$

3) COEFFICIENT CORRECTION IN HIGH MAGNETIC FLUX DENSITY RANGE

When the magnetic flux density is within the range of 1.5 T-2.0 T the transformer core approaches to saturation. It can be seen from Fig. 1 that the hysteresis loss calculated by the Bertotti model is far less than the measured one. Therefore, the coefficient correction for the hysteresis loss and eddy current loss calculation should be studied. Since it is necessary to keep the functional characteristics of the original loss with respect to frequency unchanged, the compensation term is designed as a function of magnetic flux density, as shown in (7):

$$P_{tot}^{hi} = P_h \left(1 + k_1 B_m^{\alpha 1}\right) + P_e \left(1 + k_2 B_m^{\beta 1}\right) + P_{ex} \tag{7}$$

Among them, k_1, k_2, α_1 and β_1 are four variable correction coefficients whose values are basically stable in the same material with different magnetic flux density, but vary greatly in different materials.

In this article, the Marquardt method combined with the general global optimization algorithm is adopted in the coefficient calculation and correction process [26]–[28]. The advantage of this algorithm is that it can reduce the requirements for initial value, improve the self-adaptability of correction, and thus improve the accuracy of nonlinear calculation. The iteration process of the improved algorithm is described in (8):

$$\begin{cases} \boldsymbol{X}^{s+1} = \boldsymbol{X}^{s} + \boldsymbol{\Delta} \\ \boldsymbol{\Delta} = -(\boldsymbol{J}_f^T \boldsymbol{J}_f + \lambda \mathbf{I})^{-1} \boldsymbol{J}_f^T \boldsymbol{f} \end{cases} \tag{8}$$

where $\boldsymbol{X}$ represents the unknown coefficient to be fitted; $\boldsymbol{J}$ is the Jacobian matrix; $\boldsymbol{I}$ is the unit matrix; Δ is the iterative incremental; $\boldsymbol{f}$ represents the specific total loss vector whose dimension depends on the number of collection points.

The calculational methods of the improved loss separation model under different magnetic flux density range are given above, and the suggested initial values of the coefficients are also given according to our practical experimental experiences. In this way, the deficiency of the original model in describing the nonlinear characteristics of the core is made up for and the calculation error is reduced significantly. In order to verify the effectiveness and accuracy of the improved loss separation method proposed in this article, the Epstein frame platform for loss measurement was built according to the international standard to measure the specific total loss of silicon steel sheet so as to verify the improved method.

III. EPSTEIN FRAME PLATFORM FOR CORE LOSS MEASUREMENT

In order to accurately obtain loss of the oriented silicon steel, according to the international standard IEC 60404-2:1996 and the national standard GB/T 3655-2008, a magnetic characteristic measurement platform based on a 25 cm square frame was built to measure the specific total loss of the silicon steel sheet [29].

A. MEASUREMENT PRINCIPLE

In terms of requirements for instruments in measuring circuits, IEC 60404-2:1996 and GB/T 3655-2008 specifies that the measuring precision of voltmeters shall be 0.2% or better; the precision of the actual power factor for the power meter should be ±0.5% or better. The precision of frequency meter should be ±0.1% or better; the power supply shall have a low internal resistance, the voltage shall be highly stable, the frequency error shall be kept within ±0.2%, and the waveform factor of the secondary voltage shall be kept within 1.111±1% when measuring the total loss. The circuit diagram of measurement is shown in Fig. 3.

In the measurement process, the P_m measured by the power meter also includes the instrument loss in the secondary loop, so the total loss power P_c of the silicon steel sheet should be calculated according to (9). The specific total loss $P_{tot}$is the ratio of the total loss P_c to the effective mass m of the sample.

$$P_c = \frac{N_1}{N_2} P_m - \frac{(1.111|\overline{U_2}|)^2}{R_i} \tag{9}$$

B. CONSTRUCTION OF MEASUREMENT SYSTEM

In this article, the Epstein frame measurement system was built according to the standard IEC 60404-2. A signal generator was used instead of traditional voltage regulator to

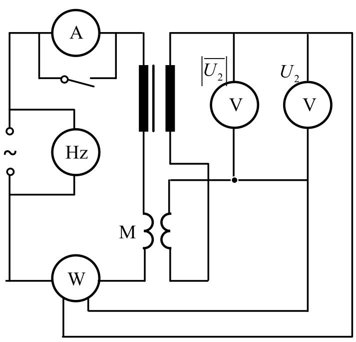


FIGURE 3. Circuit diagram of loss measurement.

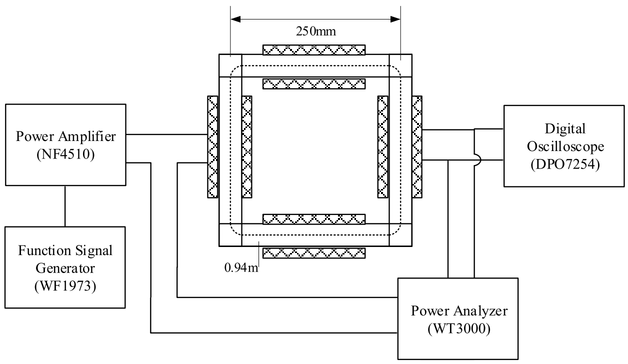


FIGURE 4. Epstein frame measurement system.

generate excitation of any frequency within DC-20KHz. The power analyzer was used to implement the measurement of voltage and current and calculate the power value directly. The basic precision is up to ±0.02% of the reading, higher than the measurement standard of 0.5%. Moreover, the apparent power and active power of the tested sample can also be measured. A digital oscilloscope was used to directly observe and record the signal waveform of the measured parameters. In this article, the measurement platform built based on the Epstein frame can be used to complete the measurement of the electrical quantity of the tested sample, such as the primary side voltage of the coil, secondary side current, core loss, etc. The schematic diagram of the measurement system and models of equipment are shown in Fig. 4.

Using the above method to build the Epstein frame measurement platform for oriented silicon steel, this article measured 14 kinds of common industrial silicon steel sheets. Figure 5 shows the measured results of specific total loss of 30ZH105 and B27R095 silicon steel plates, and the magnetic flux density range is 0 T to 2.0 T.

As shown in Fig. 5, the specific total loss increased with the increase of magnetic flux density. Under normal working conditions, the saturation magnetic flux density of the transformer core is around 1.7 T, and the loss data measured by this system can meet the requirements.

IV. VERIFICATION OF IMPROVED SEPARATION METHOD

Taking the steel sheet B27R095 and 27ZDKH95 as two examples, the specific total loss of this kind of steel sheet

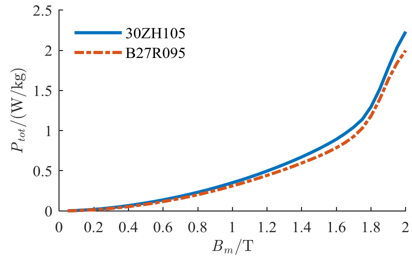


FIGURE 5. Measured results of specific total loss for 30ZH105 and B27R095.

TABLE 2. Calculated results of coefficients for B27R095 and 27ZDKH95.

Coefficient	B27R095	27ZDKH95
k_h	0.00100	0.00122
k_{ex}	0.00047	0.00051
α	3.0510	2.7954
γ	1.4743	1.4894

TABLE 3. Calculated results of the compensation coefficients for B27R095 and 27ZDKH95.

Coefficient	B27R095	27ZDKH95
k_1	0.00268	0.00105
k_2	1.57021×10-5	1.43207×10-5
α_1	10.413	10.321
β_1	10.673	10.508

under sinusoidal alternating voltage of power frequency and magnetic flux density of 0T-2.0 T were analyzed.

A. PRELIMINARY CALCULATION

The eddy current loss coefficient k_e and the eddy current loss P_e were calculated by (4) and (5), and the relevant parameters of B27R095 and 27ZDKH95 are acquired, k_e of B27R095 is 3.27424×10^{-5} and k_e of 27ZDKH95 is 3.24474×10^{-5}.

After the total loss minus the eddy current loss P_e, the specific total loss at 0 T-1.5 T were used to calculate k_h, k_{ex}, α and γ according to (6). The numerical results are listed in Table 2.

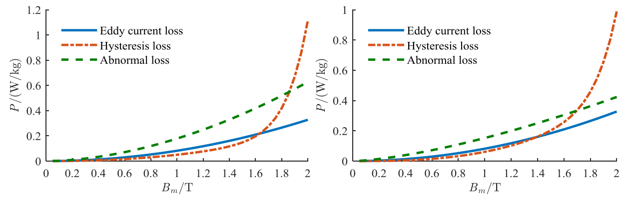
B. COEFFICIENT CORRECTION

The specific total loss data in the magnetic flux density range of 1.5 T-2.0 T were used to modify the initial calculated hysteresis loss and eddy current loss. The values of the four compensation coefficients were calculated by using (7), as listed in Table 3.

The basic coefficients in Table 2 and Table 3 can be substituted into (7) to calculate the loss. Figure 6 shows the calculation results of the hysteresis loss, eddy current loss and abnormal loss of B27R095 and 27ZDKH95 silicon steel plates by the improved method.

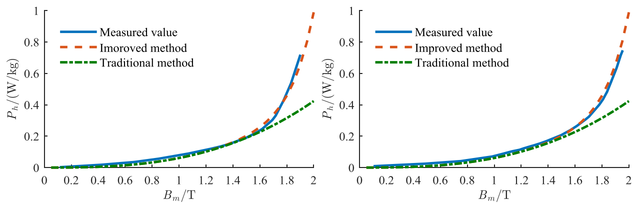
C. HYSTERESIS LOSS MEASUREMENT

In order to verify the accuracy of the method in this article, the hysteresis losses of two types of silicon steel plates, B27R095 and 27ZDKH95, were obtained by performing the quasi-static magnetization process with low-frequency



(a) B27R095 (b) 27ZDKH95

FIGURE 6. Final results of iron loss separation of B27R095 and 27ZDKH95.



(a) B27R095 (b) 27ZDKH95

FIGURE 7. Comparison of calculated hysteresis loss of B27R095 and 27ZDKH95.

excitation voltage [30]–[33]. In this experiment, the excitation voltage frequency was 0.005 Hz, and the core loss of a single period can be expressed as (10).

$$P_{ts} = P_{hs} + k_{es}B_m^2 f + k_{cxs}B_m^{\lambda} f^{\lambda-1} \quad (10)$$

where P_{ts} represents the specific total loss per unit mass in a single period; P_{hs} represents the hysteresis loss per unit mass in a single period; $k_{es}$and k_{exs} are the coefficients related to the material.

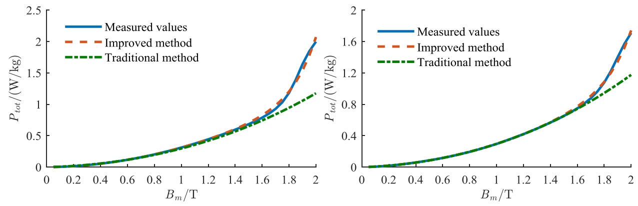
According to (10), in the excitation process, the hysteresis loss is independent of the frequency. Therefore, at this extremely low frequency, the eddy current loss and abnormal loss can be ignored compared with the hysteresis loss. That is, the hysteresis loop obtained in this way can exclude the influence of other loss terms, and the area of the hysteresis loop reflects the energy loss in one magnetization cycle. Therefore, the hysteresis loss at 50 Hz can be calculated by f multiplying the integral of hysteresis loop area, as shown in (11):

$$P_h = f \oint H \mathrm{d}B \quad (11)$$

where H represents the magnetic field strength and B represents the magnetic flux density.

Figure 7 shows the comparison of the calculated data of B27R095 and 27ZDKH95 silicon steel plates based on the traditional Bertotti method and the improved method and the measured hysteresis loss data.

As can be seen from Fig. 7, although at the low B_m (below 1.5 T), the results of the traditional Bertotti model were in good agreement with the experimental measurement ones. The calculated results were significantly smaller than the measured ones when the magnetic flux density reached saturation, and the error expanded with the increase of the magnetic flux density. By contrast, the calculated hysteresis loss obtained by the improved method in this article was in good agreement with the measured one in the whole magnetic flux density range, which resolves the problem of the nonlinear variation of core ratio loss.

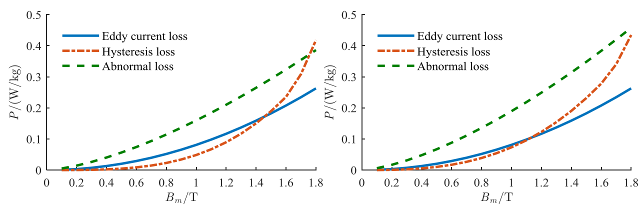


(a) B27R095 (b) 27ZDKH95

FIGURE 8. Comparison of specified total loss of B27R095 and 27ZDKH95.

TABLE 4. Suggested value of hysteresis loss model coefficients.

Type	k_h (×10^{-3})	α	k_1 (×10^{-3})	α_1
27PHD090	1.3619	2.2244	0.1918	13.802
27RK090	1.8343	1.6596	0.0269	17.052
27ZDKH90	1.6307	2.5185	0.0185	16.109
27PHD095	1.6015	2.4083	2.7104	12.886
27ZDKH95	1.2205	2.7954	1.0541	10.321
B27R095	1.0000	3.0510	2.6794	10.413
27ZH95	1.9121	2.4076	0.7545	11.241
27ZH100	1.8027	2.2513	3.2012	9.0460
30RK100	0.9921	2.7631	0.3613	12.115
30PH100	1.1339	1.4669	1.0000	12.438
30PH105	1.7421	2.6349	3.4122	8.9656
30ZH105	2.0564	1.6381	0.2134	13.747
B30P105	1.5511	1.6511	0.0465	16.023
30Q120	0.7190	1.9269	1.0018	10.320



(a) 27ZDKH95 (b) 27ZH95

FIGURE 9. Loss separation result for laminated core of 27ZDKH95 and 27ZH95 by improved loss separation method.

D. RESULTS OF SPECIFIED TOTAL LOSS CALCULATION

Figure 8 shows the specific total loss of B27R095 and ZDKH95 silicon steel plates obtained by the improved method, traditional method and experimental measurement. It can be seen that the calculated specified losses by the improved method of the three items agreed well with the measured ones. It effectively solves the problem that the Bertotti model cannot fully describe the nonlinear characteristics in the high magnetic flux density range. On the contrary, it can be seen that the improved loss separation method proposed in this article is more accurate than the traditional ones.

In addition, the basic parameters of 14 common industrial silicon steel sheets were obtained, and the specific total loss was measured according to the measurement platform set up in Section 2. The hysteresis loss was measured by performing the process of quasi-static magnetization with low-frequency excitation voltage. Based on the improved method in this article, the suggested values of model coefficients of 14 kinds of

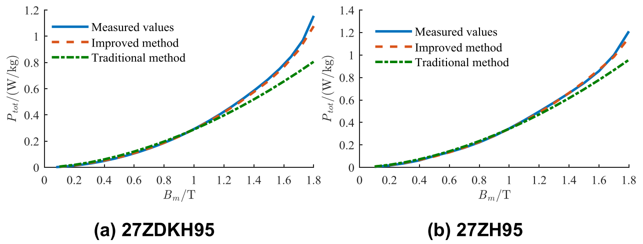


FIGURE 10. Specified total loss for laminated core of 27ZDKH95 and 27ZH95 when using different methods.

industrial silicon steel sheets in the calculation of hysteresis loss are presented in Table 4, which have reference value for the selection of initial values of other types of industrial silicon steel sheets. For the convenience of comparison, five significant digits are taken for the data. The reader can use the improved loss separation method to obtain the approximate values of hysteresis loss, eddy current loss and specific loss of other types of silicon steel according to the verification process in part IV.

V. APPLICATION

At present, the transformer core is mainly composed of oriented silicon steel sheet which is laminated by step lap. In this article, two industrial oriented silicon steel plates, 27ZDKH95 and 27ZH95, were selected to build a production-level transformer core model according to the actual industrial design standards, and the application and universality of the improved method proposed in this article were verified on these two core models. It should be pointed out that the size of the production-level transformer core model is close to the first-level size of an actual distribution transformer core in the power system, so it is considered that the main characteristics of actual transformer cores can be effectively reflected.

According to the improved loss separation method, the loss separation of the production-level laminated core model of 27ZDKH95 and 27ZH95 were studied. The calculated results of the eddy current loss, hysteresis loss and abnormal loss of the two types of silicon steel plates are shown in Fig. 9.

Figure 10 shows the comparison of the calculated results of specific total loss by the improved method and Bertotti method and the measured data of the laminated core model made of 27ZDKH95 and 27ZH95 silicon steel under sinusoidal excitation of power frequency.

As shown in Fig. 10, when the loss separation calculation was applied, the difference between the calculated value of specific total loss obtained by the Bertotti method and the experimental value became larger with the increase of magnetic flux density, while the results obtained by the improved method proposed in this article were in good agreement with the measured ones in the whole magnetic flux density range. Therefore, through the calculation and verification of the production-level laminated core model, the improved method is proved to have the ability of describing the nonlinear characteristics of the core better and maintaining high accuracy in both low and high magnetic flux density ranges.

VI. CONCLUSION

In this article, two traditional loss separation methods based on the Bertotti model were analyzed, and the calculated values of the traditional models had a large deviation from the experimental ones. By comparison and analysis, it was found that the influence of core oversaturation in high magnetic flux density range on the loss should be taken into account. In view of this, we proposed an improved loss separation method for core loss separation based on the traditional Bertotti model. In addition, by using the Epstein frame experiment platform, 14 types of commonly used industrial silicon steel plates were measured to obtain the experimental data of total loss and hysteresis loss. Through case verification, the effectivity of the improved method was proved which performed well in a wide magnetic flux density range for the core loss separation. In addition, the superiority in precision over traditional methods was confirmed by result comparison. Furthermore, the improved method was also applied on a product-level laminated core, and the results further verified our method. Moreover, the suggested coefficient values of 14 kinds of common industrial silicon steel as well as the value range of the proposed initial fitting value were given, which provides a reference for the loss prediction of other types of steel sheet, and also provides reliable data support for the accurate calculation of core loss for the transformer material selection.

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