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Citation: AIP Advances **7**, 056651 (2017); doi: 10.1063/1.4976000
View online: https://doi.org/10.1063/1.4976000
View Table of Contents: http://aip.scitation.org/toc/adv/7/5
Published by the American Institute of Physics

AIP ADVANCES **7**, 056651 (2017)

Orthogonal decomposition of core loss along rolling and transverse directions of non-grain oriented silicon steels

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(Presented 2 November 2016; received 24 September 2016; accepted 30 November 2016; published online 6 February 2017)

Rotational core loss of the silicon steel laminations are measured under elliptical rotating excitation. The core loss decomposition model is very important in magnetic core design, in which the decomposition coefficients are calculated through the measurement data. By using the transformation of trigonometric function, the elliptical rotational magnetic flux can be decomposed into two parts along two directions. It is assumed that the rotating core loss is the sum of alternating core losses along rolling and transverse directions. The magnetic strength vector H of non-grain oriented (NGO) silicon steel 35WW270 along rolling and transverse directions is measured by a novel designed 3-D magnetic properties tester. Alternating core loss along the rolling, transverse directions and rotating core loss in the xoy-plane of this specimen in different frequencies such as 50 Hz, 100 Hz, and 200 Hz. Experimental results show that the core loss model is more accurate and useful to predict the total core loss. [http://dx.doi.org/10.1063/1.4976000]

I. INTRODUCTION

Silicon steel laminations are widely used in design and manufacture of power transformer and electrical machines. In order to increase efficiency of equipments, prediction of the core loss is a key factor in obtaining the optimum design of electrical machines.

As is known, it is not accurate enough to calculate the core loss only by considering the influence of alternating magnetization in one direction. The rotating core loss contributes up to 50% of the total core loss in rotating electrical machines, also occurs in the T-joints of three-phase power transformers. The increased loss may cause local overheating and consequently destruction of a transformer or a motor.[1] With increasing demand on high efficiency motors, the core loss calculation becomes more and more refined. Therefore, accurate properties measurement of magnetic materials is very important, especially under rotating excitation. The measurements by applying rotating excitation model have been attempted in the last decade. The methods of measurement under rotating magnetization are constantly improved. However, the precision of the experimental results rarely reaches the desired purpose for the magnetic core designers. Core loss calculation and prediction are limited through the relationship description of magnetic flux density $\boldsymbol{B}$ and magnetic field strength $\boldsymbol{H}$.

In this paper, magnetic properties of NGO silicon steels 35WW270 are measured by a novel 3-D magnetic properties tester in different frequencies.[2] As shown in Fig. 1, the 3-D excitation structure consists of three orthogonal C-shaped cores, six multilayer excitation coils which are wound around the core poles. A laminated silicon steel cubic specimen with surface-mounted sensing structure is placed in the center of the tester. Six thin pieces, named as homogeneous field core shoe, are fixed around the specimen to make the measured field more uniform at the surface of specimen.[3,4]

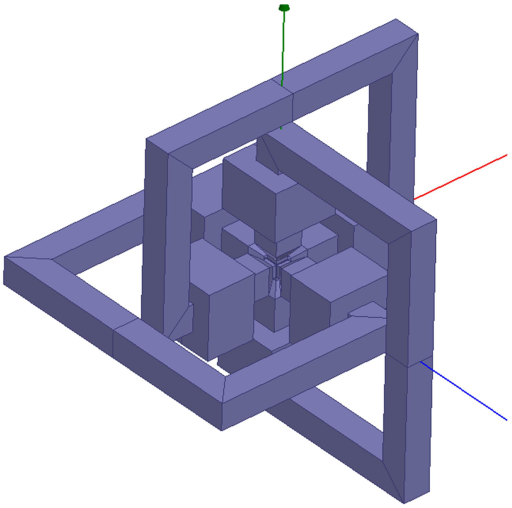


FIG. 1. Model of 3-D magnetic properties tester.

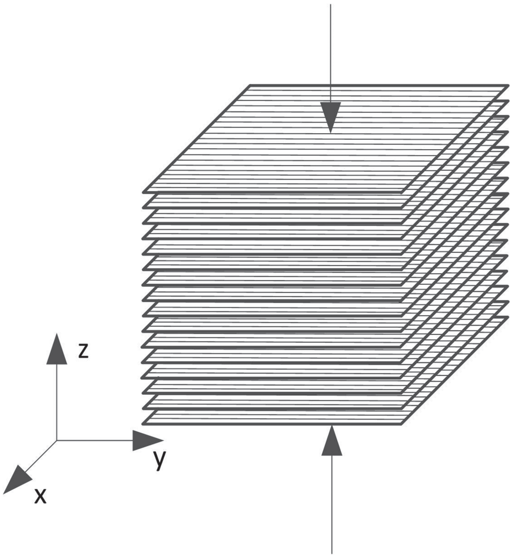


FIG. 2. The rolling direction (x axis) and transverse direction (y axis).

In order to calculate and analyze the core loss in detail, a series of B-H loops of the specimen have been measured systematically along the rolling and the transverse directions over wide frequency range, such as 50 Hz, 100 Hz, and 200 Hz. The rolling direction (x axis) and transverse direction (y axis) of the specimen are shown in Fig. 2, respectively.

II. CORE LOSS MODELS

The core loss plays an increasingly important role in the quality improvement of the electrical steels at the production stage. For correction and modification, a variety of core loss models, including orthogonal decomposition core loss model, are proposed in this section.

A. Three item model with constant coefficients

Based on Bertotti's core loss separation model, the alternating core loss can be expressed:

$$P_{\mathrm{al}} = k_{\mathrm{ha}} f B_{\mathrm{m}}^{\alpha} + k_{\mathrm{ca}}(fB_{\mathrm{m}})^2 + k_{\mathrm{ana}}(fB_{\mathrm{m}})^{1.5} \tag{1}$$

where, P_{al} represents the total core losses by applying a sinusoidal alternating magnetic field. k_{ha}, k_{ca}, and k_{ana} represent alternating hysteresis, eddy current, and anomalous loss coefficients, respectively.

Based on Eq. (1), the alternating core loss per cycle can be expressed as:

$$\begin{aligned} P_{\mathrm{al}}/f &= k_{\mathrm{ha}}B_{\mathrm{m}}^{\alpha} + k_{\mathrm{ca}}fB_{\mathrm{m}}^{2} + k_{\mathrm{ana}}f^{0.5}B_{\mathrm{m}}^{1.5} \\ &= k_{\mathrm{ha}}B_{\mathrm{m}}^{\alpha} + k_{\mathrm{ca}}(\sqrt{f})^{2}B_{\mathrm{m}}^{2} + k_{\mathrm{an}}\sqrt{f}B_{\mathrm{m}}^{1.5} \end{aligned} \tag{2}$$

The core loss data are used to plot curves of P_{al}/f *vs.* f for different values of flux density B_{m}. The curves should be straight lines, so the coefficients can be obtained by polynomial curve fitting. The core loss coefficients altered with different magnetic flux density $\boldsymbol{B}$ are obtained.

However, the above model ignores the skin effect. A large number of experimental results illustrate that the eddy current and anomalous loss coefficients k_{ca} and k_{an} should change with frequency and flux density because of the skin effect.[5]

B. Core loss model considering rotating magnetization

Due to lacking of rotating experimental data, traditional calculation methods only consider the alternating loss, which ignore the effect of rotating magnetic field and then through the experience coefficient correction method get the final result, which causes the inaccuracy of the core loss estimation.

The rotating core loss model also contains three components including hysteresis, eddy current, and anomalous losses, as expressed by the equation:

$$\begin{aligned} P_{\mathrm{r}} &= P_{\mathrm{hr}} + P_{\mathrm{er}} + P_{\mathrm{anr}} \\ &= P_{\mathrm{hr}} + k_{\mathrm{er}}(fB_{\mathrm{m}})^{2} + k_{\mathrm{anr}}(fB_{\mathrm{m}})^{1.5} \end{aligned} \tag{3}$$

where, P_{r} is the total core loss under rotating excitation. k_{er} and k_{anr} represent the coefficients of eddy current and anomalous losses, respectively.

Whereas, P_{hr} is the rotating hysteresis loss, it can be calculated by the below equation:[6]

$$\frac{P_{\mathrm{hr}}}{f} = a_1\left[\frac{1/s}{(a_2 + 1/s)^2} - \frac{1/(2-s)}{[a_2 + 1/(2-s)]^2 + a_3^2}\right] \tag{4}$$

$$s = 1 - \frac{M_{\mathrm{m}}}{M_{\mathrm{s}}}\sqrt{1 - \frac{1}{a_2^2 + a_3^2}} \tag{5}$$

where, a_1, a_2, and a_3 are constant coefficients; M_{s} is the saturation magnetization of ferromagnetic materials. All the coefficients can be obtained by fitting to the measurement losses, as the same to the separation of alternating core loss.

C. Core loss model under elliptical flux density

Due to the existence of harmonics and magnetic flux saturation *et al*, the elliptical rotating magnetic field model is established in the electrical machines, generally.

After a great deal of literature researches are analyzed, the rotating magnetic flux can be decomposed into alternating flux along the rolling and transverse directions by using the transformation of trigonometric function. The angle between alternating magnetic flux vectors is 90 degrees, and it is not certain that the magnitudes of $\boldsymbol{B}_x$ waveform and $\boldsymbol{B}_y$ waveform are equal.

$$B = \sqrt{B_x^2 + B_y^2} \tag{6}$$

where, $B_x = B_{m1}\cos\omega t$, $B_y = B_{m2}\sin\omega t$. When $B_{m1} = B_{m2}$, it means that the synthesized magnetic field is circular; when $B_{m1} \neq B_{m2}$, the synthetized magnetic field is elliptical.

By controlling the waveform of the $\boldsymbol{B}$ signal, the rolling direction of the specimen along any angle can be obtained, which can be controlled by the following Eq. (7):

$$\begin{cases} B_x = B_{\mathrm{maj}}\cos\omega t \\ B_y = B_{\mathrm{min}}\sin\omega t \end{cases} \tag{7}$$

where, B_{maj} and B_{min} are the amplitudes of the flux density, ω is angular frequency.

From Eq. (7), we can define the measurable data according to experimental measurement. It is suitable for calculating the hysteresis loss or total core loss. It can be expressed as following:[7]

$$P_{\mathrm{t}} = R_B P_{\mathrm{r}} + (1 - R_B)^2 P_{\mathrm{al}} \tag{8}$$

where, P_{t} is total core loss, P_{r} is the rotating hysteresis loss, P_{al} is the alternating hysteresis loss.

D. Orthogonal decomposition core loss model with constant coefficients

Two mutually orthogonal magnetic flux field can be used to describe elliptical rotating magnetic field and replace the rotating loss data. The total losses under the elliptical flux is the summation of alternating core losses flux along rolling and transverse directions.[8] It can be written as:

$$\begin{aligned} P_{\mathrm{t}} = k_{\mathrm{h}} &\sum_{k=1}^{N} (kf)(B_{kmx}^2 + B_{kmy}^2) \\ +k_{\mathrm{e}} &\sum_{k=1}^{N} (kf)^2(B_{kmx}^2 + B_{kmy}^2) \\ +k_{\mathrm{an}} &\sum_{k=1}^{N} (kf)^{1.5}(B_{kmx}^{1.5} + B_{kmy}^{1.5}) \end{aligned} \tag{9}$$

where, B_{kmx} and B_{kmy} are the k^{th} harmonics amplitude of the components of the flux density along rolling direction (x axis) and transverse direction (y axis), respectively. Referring to Classical Bertotti's core loss model, the characteristic of the magnetic flux density waveform in the complex magnetization conditions are taken into account comprehensively. Eq. (9) reflects the connection and difference between the rotating core loss model established by the method of core loss separation and the alternating core loss model.

III. ANALYSIS OF EXPERIMENTAL RESULTS

Due to lacking of rotating hysteresis loss data of the material, traditional calculation methods only considered the alternating loss, and ignored the effect of rotating magnetic field. Then the extensive application in high efficiency motors is limited. 3-D magnetic properties experiment provides a large amount of data for the research of loss separation model. The relationship between vector $\boldsymbol{B}$ and vector $\boldsymbol{H}$ is analyzed when the $\boldsymbol{B}$ locus are well controlled to be circles or ellipses in xoy-plane of the specimen. For the analysis and calculation of core loss, the definition of the loss coefficients based on the original loss data or curves provided by the silicon steel laminations becomes essential.

A. Calculation of core loss

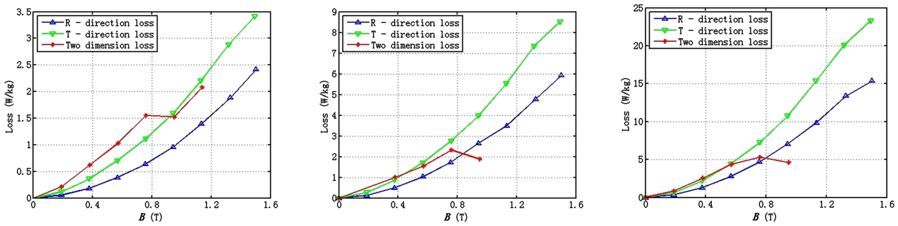
The core losses under different magnetization conditions can be directly calculated by the experimental data of H_x, H_y, B_x, and B_y waveforms. The B–H loops can be measured under alternating magnetization separately for the rolling and transverse directions. Whereas, since the alternating excitation is fundamentally different, the data are of course not interchangeable with the measured under rotational magnetization. Similar distinction can be made if the excitation is applied when the rotational B or H loci are controlled to be circular.

In terms of Poynting vector theorem, the total elliptical rotation core loss can be expressed:[9]

$$P_t = \frac{1}{\rho T} \int_0^T (H_x(t)\frac{dB_x(t)}{dt} + H_y(t)\frac{dB_y(t)}{dt})dt \tag{10}$$

where, T is the time period, ρ is the material mass density.

The comparison of core loss at 50 Hz, 100 Hz, and 200 Hz under the conditions of alternating excitation and rotating excitation is shown in Fig. 3. Compared with the core loss along the rolling direction, it is slightly larger than that along the transverse direction. It can be observed that the rotating core loss increases to peak value until the magnitude of $\boldsymbol{B}$ reaches to about 0.8 T. When the flux density further increases, the rotating hysteresis loss drops quickly and vanishes when the flux



(a) (b) (c)

FIG. 3. Alternating core loss in the rolling, transverse directions and rotating core loss in the *xoy*-plane. (a) $f = 50$ Hz. (b) $f = 100$ Hz. (c) $f = 200$ Hz.

density reaches the saturation value, whereas the alternating hysteresis loss continues to increase. Synthetically, the total rotating core loss presents downward trend. Thus, the rotating core loss may be smaller than the alternating core loss. It can be seen that loss data in rolling direction are in accordance with the manufacture's data. This can also verify the accuracy of the 3-D magnetic properties measurement.[10,11]

The domain wall theory can be used to explain the core loss better. There are two aspects of effect including alternating and rotating domain wall motion magnetization. By applying a rotating field, domain wall rotation mainly occurs. With the increase of the magnetic flux density, the domain walls evolve gradually into the irreversible changes from the reversible changes. The domain wall displacement vanishes and the domain rotation increase, gradually. The relevant studies show that the irreversible change of domain wall displacement contain discrepancy along different directions of the magnetic field under the rotating excitation, not as alternating magnetization material magnetic domain rotate. The magnetization process of the domain wall rotation are influenced by the magnitude and direction of applied magnetic field.

B. Separation of the core loss

The separation method of alternating core loss is not fit for core loss analysis under rotating excitation.

$$B(t) = B_0 + \sum_{k=1}^{\infty} B_k \sin(k\,\omega t + \varphi_k) \tag{11}$$

where, k is the order of magnetic flux density B.

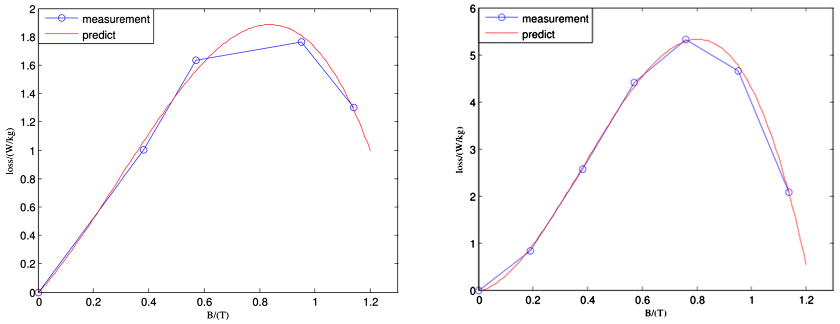
According to Eq (9), P_t is a function of B and f. The measured B_{mx} and B_{my} signals in different frequencies are Fourier transformed, respectively, as shown in Eq (11). The value of k is determined by the accuracy of the measurement. The high order harmonics of flux density influence slightly the total core loss. The loss coefficients k_h, k_e, and k_{an} of the model are derived from the measured rotating loss under various frequencies and various peak flux densities.

The rotating core loss is measured by the 3-D tester at the frequencies of 100 Hz and 200 Hz. And then the coefficients of Eq. (9) are obtained by numerical treatment from the experimental data, as shown in Table I.

Curve fitting method is used to obtain the curve of rotating loss P versus B_m. Then, each part of rotating core loss can be obtained at arbitrary amplitude of the flux density from 0 to 1.2 T. As shown in Fig. 4, in the process of silicon steel laminations reaching saturation state, the calculation from the orthogonal decomposition core loss model have good agreement with the original loss data at the

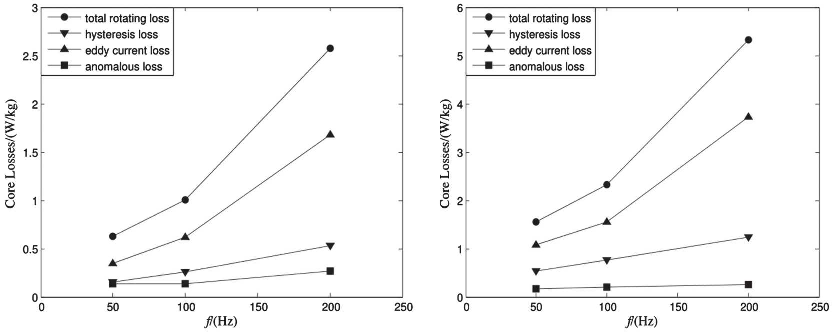
TABLE I. The rotating loss (W/kg) at the frequencies of 100 Hz and 200 Hz.

	0.38 T	0.57 T	0.76 T	0.95 T	1.14 T
100 Hz	1.004	1.543	2.319	1.879	1.300
200 Hz	2.579	4.351	5.330	4.606	2.084



(a) (b)

FIG. 4. Rotating core loss comparison of measurement and calculation: (a) f = 100 Hz; (b) f = 200 Hz.



(a) (b)

FIG. 5. Separation of rotating core loss for NGO silicon steel 35WW270: (a) B = 0.38 T; (b) B = 0.76 T.

lower flux densities.[12] This reveals that the orthogonal decomposition core loss model is effective in practical engineering.

In order to verify the accuracy of the orthogonal decomposition model, the core losses of silicon steel sheets along the rolling and transverse directions in different frequencies are fitted, and the loss coefficients of the model are obtained. The rotating hysteresis, eddy current, and anomalous losses are calculated, respectively, as shown in Fig. 5. The total rotating core loss and its component losses increase with rotating excitation frequency increasing. In the low frequency region, the rotating hysteresis loss is the dominant of the total core loss. Whereas, with the increase of rotating excitation frequency, due to the skin effect that only appears at high frequency, the proportion of the eddy current loss increases in the total core losses, and rotating anomalous loss decreases, relatively.[13]

According to the above analysis, the agreement between calculation and the experimental loss is acceptable.

A three-phase induction motor model is analyzed by using the improved finite-element method considering the vector magnetic properties. From analyzed results, the core loss distribution in the motor core from the relation between ***H*** vector and ***B*** vector can be calculated, directly. Comparison shows that this method is very useful in designing the motors with properties of low loss and high efficiency.[14,15]

IV. CONCLUSION

The core loss properties of NGO silicon steel 35WW270 along rolling and transverse directions are measured. The orthogonal decomposition core loss model is presented and analyzed, using the theory of domain wall and the comparison of measured data and calculated data. The experiment provides comprehensive data for deriving the coefficients of core loss models, which can be applied to calculate the total core loss and its each component loss in rotating electrical machines. The error between the calculated and measured core loss is reduced. Compared with the traditional model only considering the alternating core loss, the orthogonal decomposition model is more accurate and more close to the engineering practice. It is important to design low loss machines for saving energy. The experiment provides a large number of useful data for the engineering applications.

ACKNOWLEDGMENTS

This work was supported in part by the Key Project of National Natural Science Foundation of China, under Grant 51237005, the National Key Basic Research Program of China (973 Project) under Grant 2015CB251000, the Natural Science Foundation of Hebei (Youth Foundation), China, under Grant E2014202137, State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, under Grant LAPS16002.

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