Measurement and Computation of Rotational Core Loss Considering Higher Harmonic Components of Magnetic Flux Density Waveform

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Abstract—This paper presents a simplified method of calculating rotational loss of electrical steel sheet under distorted magnetic flux density condition, in which the non-sinusoidal magnetic flux density (*B*) waveform is expanded into fundamental and higher harmonic components using Fourier series expansion, and the trajectory of *B* vector tip is described as the overlap of several elliptical loci at different frequency. The total loss under distorted *B* is calculated from the sum of loss at different frequencies measured by a two-dimensional (2-D) magnetic property testing system. By comparing the simulation results with experimental test ones for a motor iron core model, the effectiveness of the proposed method is verified.

***Index Terms*—Magnetic Flux density, Magnetic loss, Harmonic analysis, Finite element analysis, Fourier series.**

I. Introduction

THE rotational loss computation is a key factor in design and analysis of electrical machine and transformers [1]. There have been foregoing researches to develop some permeability (or reluctivity) models to calculate core loss under alternating or rotating magnetic flux conditions by means of the two-dimensional (2-D) magnetic property measurement system [2-4]. However, the waveform of magnetic flux density (*B*) in electric machines and transformers is often distorted from sinusoidal one. A reluctivity model, hence, under distorted *B*-waveform was presented in [5] by estimating the magnetic field strength *H*-waveforms generated by the eddy currents induced by the higher harmonic components of the magnetic flux density. To calculate the rotational loss, this model was coupled with finite-element analysis (FEA) of magnetic field at the cost of large computation time.

This paper presents a method calculating core losses under distorted magnetic flux density with higher harmonic components for the purpose of simplifying the FEA, assisted by experimental data using a 2-D magnetic property tester. By comparing the simulation results with experimental test ones for a three-phase induction motor stator iron model, the effectiveness of the proposed method is verified.

II. Measurement and Computation of Rotational Loss

A. 2-D rotational loss measurement system

Fig. 1(a) shows a 2-D magnetic properties tester for the electric steel sheet, in which two groups of computer-controlled excitation coils are employed to generate various ***B*** loci, which is formed by ***B*** vector tip, within the sample of 60mm×60mm. The trajectory of a single flux density can be alternating or elliptically rotating, and can be described by B_{max}, α and θ, where B_{max} is maximum flux density, α is the ratio of minor to major axis, called axial ratio, and θ is the inclination angle of elliptical locus. Fig. 1(b) shows measured trajectory of the magnetic field strength *H* when θ=0°, α=1 and B_{max} with 0.9T, 1.1Tand 1.3T, respectively.

B. Measurement of Rotational loss under sinusoidal B

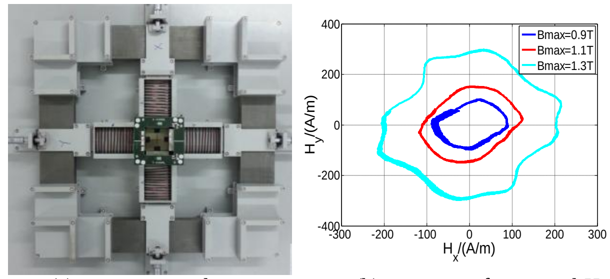
The total core loss calculation formula is expressed as

$$P = \frac{1}{\rho T}\int_T \left(H_x \frac{dB_x}{dt} + H_y \frac{dB_y}{dt} \right) dt \qquad (1)$$

where ρ is the density of the material, T is the excitation current period, and B_x, B_y, H_x and H_y are measured *B*-waveform and *H*-waveform along rolling direction (RD) and transverse direction (TD). When carrying out 2-D magnetic measurement, the calculated power losses from (1) are strongly dependent on the rotating direction of the flux density vector tip are different in clockwise (CW) and counterclockwise (CCW) direction [6]. The mean loss curve of the CW and CCW direction gives us a reasonable rotating loss values in higher magnetic flux excitations. Hence, in the paper, we will take the average of the both directions to obtain loss results.

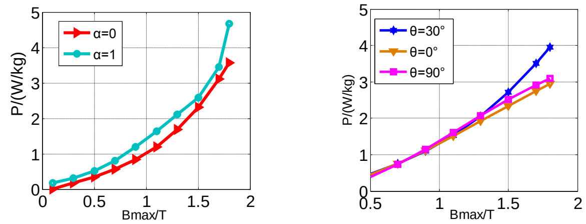
Fig.2 shows the measured loss curves of electrical steel sheet under different axis ratio and inclination angle with a sinusoidal B with 50Hz and various peak values. Fig.2 (a) illustrates that the rotational losses (α=0.5 or 1) are higher than alternating losses α =0 under the same exciting conditions. From Fig.2 (b), we can see that the rotational losses vary with the change of θ.

C. Computation of Rotational loss under distorted B



(a) measurement device (b) trajectory of measured *H*

Fig.1 2-D magnetic property measurement of electrical steel sheet.



(a) θ=0 °　　(b) α=0.5

Fig.2 Measurement results of loss when f= 50Hz

In practical application, the B-waveform in iron cores often covers higher harmonic components, and then B vector tip is a distorted ellipse as shown in Fig.3(a). However, experimental measurements under distorted ***B***-waveform condition are very difficult because of lack of the criterion for measurement.

Hence, in this paper, the distorted ***B*** is, firstly, decomposed into several elliptical loci or alternating loci or both of them, as shown in Fig.3(b) and (c), by using the Fourier series expansion as follows:

$$\begin{aligned} B_x(\tau) &= B_{1x}\sin\tau + B_{3x}\sin 3\tau + B_{5x}\sin 5\tau \\ B_y(\tau) &= B_{1y}\sin\left(\tau+\frac{\pi}{2}\right) + B_{3y}\sin 3\tau + B_{5y}\sin 5\tau \end{aligned} \tag{2}$$

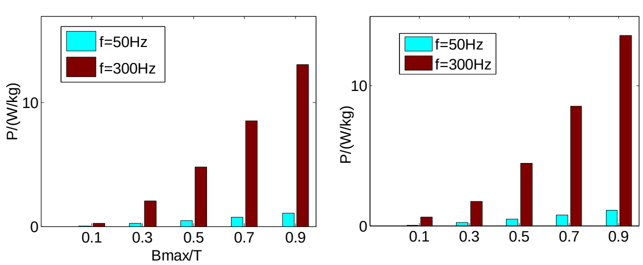
Then, we carry out measuring the harmonic loss of electrical steel sheet corresponding to each elliptical locus or alternating loci with different frequency, as shown in Fig.4. At last, the total loss is summarized by harmonic loss, and can be expressed as

$$P_t = \sum_{k=1}^{N} P_k = \sum_{k=1}^{N}\left[\frac{1}{\rho T}\int_T\left(H_{kx}\frac{dB_{kx}}{dt} + H_{ky}\frac{dB_{ky}}{dt}\right)dt\right] \tag{3}$$

where N is the number of harmonic components, and k=1 stands for the fundamental component at 50Hz. Fig. 5 shows measured trajectory of H under distorted ***B***, and measured loss is 3.12 W/kg in comparison with computed 2.98 W/kg from (3). The experimental verification and more discussions will be given in the version of full paper.

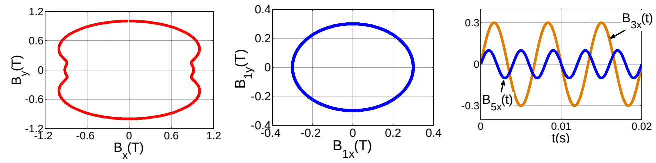
III. Calculation of Core Loss in Electrical Machines

Although the reluctivity model, such as E&S model, coupled with FEA can calculate the iron core accurately, the computation program is relatively complicated and wastes time. Based on the 2-D loss property measurement mentioned above, in this paper, a simplified computation method of core loss is presented as follows:



(a) θ=0 °　　(b) θ=60 °

Fig.4 Measurement results of loss when f= 50Hz and 300Hz, respectively



(a)　　(b)　　(c)

Fig. 3 Fourier analysis of distorted ***B***. (a) distorted ***B*** locus; (b) ***B*** locus of fundamental component; (c) higher harmonic components

Firstly, the transient FEA of electrical devices is carried out by employing two orthogonal (rolling direction and transverse direction) *B-H* curves to take the magnetic anisotropic property of silicon steel into account

Secondly, calculated magnetic flux density ***B*** waveform in each discretization element within one time period is decomposed by Fourier analysis, and the trajectory of ***B*** vector tip is overlapped with different elliptical ***B*** loci at different frequencies.

Finally, by searching the experimental data, the loss in each mesh element can be obtained by summing up measured fundamental and harmonic loss of elliptical ***B*** loci at different frequencies.

In the full paper, a 5.5kW three-phase induction motor model is taken as a simulation example, in which the pole number is 2, the stator slot number is 30 and rotor is 26. We will compare the computed loss in iron core by proposed method and one in [4], respectively with measured ones in order to examine the verification of proposed method.

IV. References

[1] A.J. Moses, "Importance of rotational losses in rotating machines and transformers," *Journal of* Materials *Engineering and Performance*," vol. 1, no. 2, pp. 235-244, Mar. 1992.

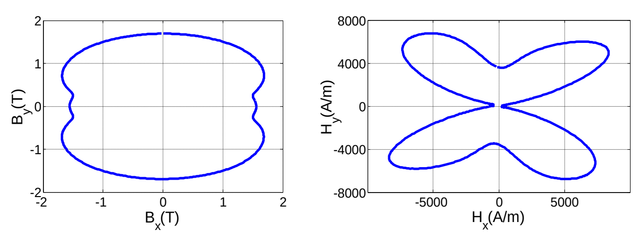
[2] M. Enokizono, "Loss evaluation of induction motor by using magnetic hysteresis E&S^2 model," *IEEE Trans. Magn.*, vol. 38, no. 5, pp. 2379-2381, Sep. 2002.

[3] H. Yoon, I. Kim, P. S. Shin, and C. S. Koh, "Finite element improvement of a generalized Chua-type vector hysteresis model and application to iron loss analysis of three-phase transformer," *IEEE Trans. Magn.*, vol. 47, no. 5, pp. 1122-1125, May 2011.

[4] Y. Zhang, Y. H. Eum, D. Xie, and C. S. Koh, "An improved engineering model of vector magnetic properties of grain-oriented electrical steels," *IEEE Trans. Magn.*, vol. 44, no. 11, pp. 3181-3184, Nov. 2008.

[5] S.a Urata, T. Todaka, M. Enokizono, etc., "Measurement of 2D vector magnetic properties under the distorted flux density *conditions*," *Journal of Magnetism and Magnetic Materials*, vol. 304, pp. 574-576, 2006.

[6] Y. Maeda, H. Shimoji, T. Todaka and M. Enokizono, "Study of the counterclockwise/clockwise (CCW/CW) rotational *losses* measured with a two-dimensional vector magnetic property measurement system", *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 3, pp. 222-228, 2008.



(a) distorted ***B*** locus　　(b) measured ***H***

Fig.5 Measurement results under distorted ***B***