Improvement on Estimation Model of Hysteresis Loss in Induction Motor Core Considering Rotational Magnetization

Yajun Ren[1], Yanli Zhang[1], Dianhai Zhang[1], Linsuo Zeng[1], Dexin Xie[1], Chang Seop Koh[2]

[1]School of Electrical Engineering, Shenyang University of Technology, Liaoning 110870, China, zhangyanli_sy@hotmail.com
[2]School of Electrical and Computer Engineering, Chungbuk National University, Cheongju, Chungbuk 361- 763, KOREA

There is plenty of distortedly elliptical magnetic flux density *B* in rotational machine cores. The core loss computation considering rotational magnetization is significant for the optimum design of electrical machines. This paper performs the measurement of rotational power loss with elliptical *B* and distorted *B* by means of a two-dimensional magnetic property tester. To improve the computation accuracy of conventional hysteresis loss model, a rotational loss formulation where the loss coefficient is identified as the function of inclination angle and axis ratio of the *B* locus is proposed. We also carry out the measurement of loss distribution with a self-developed *B*-*H* sensor on the surface of a stator core. The effectiveness of the improved model is verified with the experimental results in the stator core.

***Index Terms*—Core loss, rotational magnetization, hysteresis loss, stator core.**

I. INTRODUCTION

THERE WIDELY exists rotational magnetic field in motor stator cores and T-joint part of transformer cores. It has been shown by a number of researchers that the hysteresis loss caused by rotational magnetic field can exceed the loss due to alternating one [1]. One way to calculate the rotational hysteresis loss is to construct a two-dimensional (2D) vector magnetic property model such as E&S model coupled with finite element analysis (FEA) [2-3] with high simulation accuracy, but complicated mathematical derivation due to use of great amount of experimental data. Another way is to employ a loss estimation model. For example, the specific power loss under an elliptically rotational ***B*** in a silicon steel sheet is estimated from circularly rotational and alternating core loss [4], or expressed as a resultant of alternating hysteresis loss along two orthogonal directions [5]. However, these approaches may be suitable in low flux density range or low ellipticity of rotational magnetic field which will be explained in this paper.

In this paper, we present an improved hysteresis loss estimation model by adding a variable coefficient to the hysteresis loss term. The loss coefficients are identified by measurement on a 2D tester. In order to verify its validity, a loss distribution on the surface of motor stator core is measured by using a self-developed loss sensor and compared with the computed ones from the proposed model.

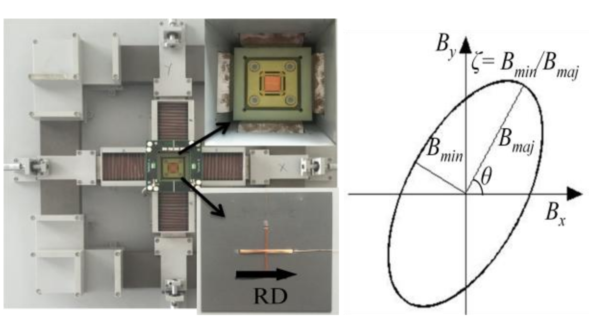


Fig.1 Measurement system and B locus

II. CORE LOSS MEASUREMENT AND IMPROVED LOSS MODEL

A. 2D magnetic Property Tester

A double-excitation type 2-D single sheet tester is developed in Fig. 1, in which two groups of orthogonally computer-controlled excitation coils are utilized to generate a specified elliptical ***B*** at different frequency, i.e. the locus of ***B*** vector tip in one time period forms an elliptical shape identified with three parameters, peak value B_{max} of major axis, axis ratio ζ of the minor axis to major one, and inclination angle θ between major axis and the rolling direction (RD). The power losses can be computed according to Poynting's theorem by

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

where ρ is density of the material, T is the excitation current period, and B_x, B_y, H_x, and H_y are measured B and H signals.

B. Conventional Core Loss Formulation

The Bertotti three-term loss formula is

$$P = P_{hys} + P_{eddy} + P_{ex} \tag{2}$$

where the rotational hysteresis loss P_{hys} can be expressed in terms of the overlapping of the alternating loss along the RD and the transverse direction (TD) as [5]

$$P_{hys} = k_h \sum_{n=1}^{\infty} n\, f\,(B_{n\_maj}^{\alpha} + B_{n\_min}^{\alpha}) \tag{3}$$

The eddy-current loss P_{eddy} taking the effect of skin effect into account can be written as [6]

$$P_{eddy} = \frac{d\sigma\pi^2}{2\sqrt{\mu\sigma\pi}} \sum_{n=1}^{\infty} (nf)^{1.5} (B_{n\_maj}^2 + B_{n\_min}^2)\gamma(nf) \tag{4}$$

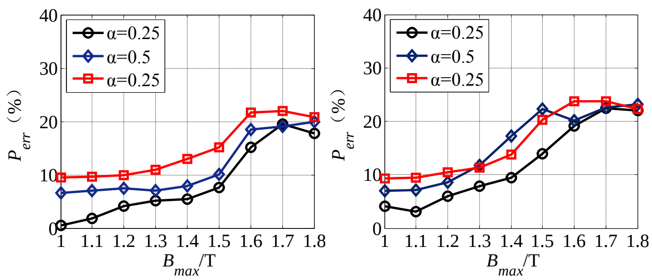
The excess loss P_{ex} is

$$P_{ex} = \frac{k_e}{(2\pi)^{1.5}} \frac{1}{T}\int_0^T \left[\left(\frac{dB_r}{dt}\right)^2 + \left(\frac{dB_t}{dt}\right)^2 \right]^{\frac{3}{4}} dt \tag{5}$$

In practice, $\gamma(nf)$ is the coefficient of skin effect, B_r and B_t are the RD and TD components of B, and the coefficients α, k_h

Table I Loss coefficients in (2) under alternating magnetizations

Inclination angle θ	k_h	α	k_e
0 °	0.0221	1.8667	0.0006
15 °	0.0234	1.8543	0.0005
30 °	0.0255	1.8583	0.0006
45 °	0.0268	1.8564	0.0005
60 °	0.0270	1.8544	0.0005
75 °	0.0266	1.8551	0.0005
90 °	0.0263	1.8543	0.0006



(a) $\theta = 30^{\circ}$ (b) $\theta = 75^{\circ}$

Fig. 2 Deviation of the calculated loss by (2) relative to the measured one with a 2D tester with specified elliptical ***B*** loci at 50 Hz

and k_e can be identified by measurement of alternating resis loss. Table I lists the coefficients α, k_e, and k_h when inclination angle θ varies from 0 °to 90 °with the step of 15 °.

Fig. 2 shows the error P_{err}(%) of specific loss caused by the discrepancy between the calculated loss from (2) to (5) and measured one with various elliptical ***B*** loci with B_{max} above 1T at 50 Hz. It can be seen that the bigger the flux density, the greater the error and the maximum error attains to 23.89% at B_{max}=1.6T, θ=75^{o} and ζ=0.75. It implies that when eq.(3) is employed to predict the rotational loss, the k_h interpolated from alternating case causes over 20% computation error especially at high *B* and high ζ.

C. Improved Rotational Hysteresis Losses

We calculate the variation of coefficient k_h with the trajectories of rotational magnetization, as shown in Fig. 3, by means of experimental data. It can be seen that the ellipticity ζ and magnetization direction θ of the *B* locus have a great influences of k_h. Thus, to improve the modeling accuracy, in this paper, the coefficient k_h in (2) is calculated by

$$k_h(\xi,\theta) = \sum_{i=0,\, j=0}^{i=2,\, j=5} C_{jk}\xi^i \sin^j(\theta) \qquad (6)$$

where the coefficients C_{jk} can be determined by fitting k_h over

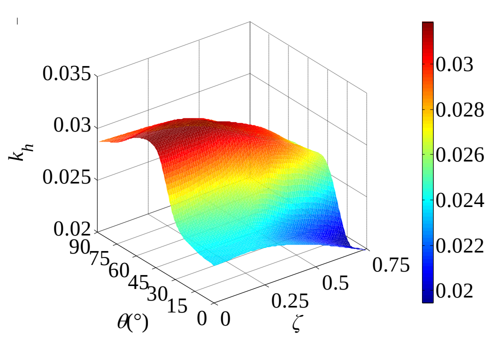


Fig. 3 Variation of the hysteresis loss coefficients k_h with the trajectory of rotational magnetization

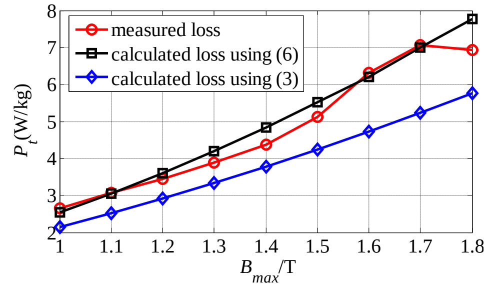


Fig. 4 Comparison between calculated losses using (6) and (3) and measured ones when θ=60^{o} and α=0.75.

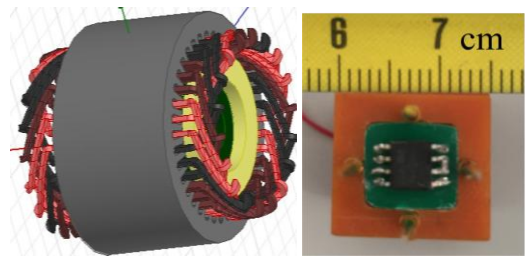


Fig. 5 *B-H* sensor and stator core

a range of ζ and θ in Fig. 3, and the results are C_{00}= 0.0229, C_{01}=0.0066, C_{02}=-0.0139, etc.

Taking an array of elliptical ***B*** with θ=75^{o} and ζ=0.75 as an example where the error P_{err}(%) attains to the maximum of 23.89% at B_{max}=1.6T, Fig. 4 compares the calculated loss using proposed formulation in (6) and conventional model in (3). It is apparent that the computed loss using (6) has better agreement with the measured one at different B_{max} and the maximum absolute error P_{err} (%) is reduced from 23.89% to 1.61%.

III. Verification and Application

To verify the validity of modeling method mentioned above, we carry out the measurement of loss distribution with a self-developed *B-H* sensor on the surface of a stator core as shown in Fig.5. The estimated loss distribution using proposed model is compared with the measured ones, and its validation is verified, which will be given in extended paper.

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, Feb. 1992.

[2] 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. on Magn.*, vol. 47, no. 5, pp. 1122- 1125, May 2011.

[3] Y. Zhang, Y. Liu, Y. Li, D. Xie, and B. Bai, “A complex-valued rotating magnetic property model and its application to iron core loss calculation,” *IEEE Trans. on Magn.*, vol. 50, no. 2, pp. 7009704, Feb. 2011.

[4] J. Zhu and V. S. Ramsden, “Improved formulation for rotational core losses in rotating electrical machines,” *IEEE Trans. Magn.*, vol. 34, no. 4, pp. 2234-2242, Jul. 1998.

[5] B. Stumberger, A. Hamler. “Accuracy of iron loss estimation in induction motors by using different iron loss models,” *Journal of Magnetism and Magnetic Material*, pp. 272-276(S1), E1723-E1725, 2004.

[6] M. T. Kakhki, J. Cros and P. Viarouge, “New approach for accurate prediction of eddy current losses in laminated material in the presence of skin effect with 2-d FEA,” *IEEE Trans. Magn.*, vol. 52, no. 3, pp. 6300604, Mar. 2016.