Iron Loss Separation in High Frequency Using Numerical Techniques

Lei Liu[1], W. N. Fu[1], Shiyou Yang[2] and S. L. Ho[1]

[1]Department of Electrical Engineering, The Hong Kong Polytechnic University, Hong Kong, eewnfu@polyu.edu.hk
[2]College of Electrical Engineering, Zhejiang University, 310027 China

This paper proposes a tractable and robust numerical method to predict iron losses in electrical steel laminations subjected to high-frequency excitation. To achieve this goal, Preisach modeling and finite difference method (FDM) are firstly employed to simulate the hysteresis loss and the eddy current loss respectively. On this basis, a better approximation of the excess loss and its optimal parameter identification are achieved. All these efforts, with tolerable computational burden, reduces the errors between the estimated values and the measured ones, when compared to those obtained using conventional engineering models.

***Index Terms*— Excess loss, finite difference method, Lagrange multiplier, loss separation.**

I. Introduction

Due to the advent of power electronics, increased electrical apparatuses are working with high frequency supplies have distorted waveforms with rich high-order harmonic components. It is important to analyze and evaluate the iron losses of electrical steel lamination exposed to high frequency excitations. However, the classical engineering modeling of iron losses [1], derived from the statistical loss theory, has only been validated for low-frequency supplies. Attempts to extend the classical model are important, not only because the negligence of skin effects and magnetic nonlinearity in high frequency are unjustified, it is also because the origin and estimation accuracy of the excess losses are also controversial.

This paper employs validated computational methods, i.e., Preisach modeling and finite difference method, to predict hysteresis losses and eddy current losses accurately. On this basis, a robust parameter identification procedure and approximation of the original modeling of the excess losses are proposed. Numerical results demonstrate that the accuracy of the estimation of excess losses is improved. It can be shown that the proposed loss computation produces satisfactory results in various situations within tolerable computational burden.

II. Statistical Loss Theory

Bertotti reports that [1], in terms of the statistical property of Barkhausen effects, iron losses consist of the following components: the loss due to a single Barkhausen jump is referred to as the hysteresis loss P_h; the loss caused by independent Barkhausen jumps is the classical eddy current loss P_{ed} and the correlated Barkhausen jumps are responsible for the excess loss P_{ex}. Among all these components, P_h can be either segregated and interpolated via measurements or simulated by the famous Steinmetz model, $P_h = K_h B^{\alpha} f$, where the parameters K_h and α are obtained from experimental results. As for the eddy current loss, it is determined by the magnetic field distribution. Bertotti assumed that the lamination is electrically thin, the induced eddy currents will not significantly affect the external magnetic field distribution. The eddy current loss per unit volume can be computed from:

$$P_{ed} = \frac{\sigma d}{12}\frac{1}{T}\int_0^T \left(\frac{\partial B}{\partial t}\right)^2 dt \tag{1}$$

where σ is the conductivity of the lamination; d is the depth of the lamination; T is the time period of induction B. In the end, by the introduction of magnetic objects, i.e., virtual body with magnetization changed in a coherent way, whose related parameters are n and V, the excess loss modeling is simplified. If the cross-sectional area of the lamination is S, and with G denoting the magnetic object friction coefficient,

$$P_{ex}(t) = \frac{1}{T}\int_0^T \frac{nV}{2}\left|\frac{\partial B}{\partial t}\right|\left(\sqrt{1+\frac{4\sigma GSV}{n^2V^2}\left|\frac{\partial B}{\partial t}\right|}-1\right)dt \tag{2}$$

Since it is generally believed that $(4\sigma GSV/n^2V^2)|\partial B/\partial t| >> 1$, (3) can be approximated as

$$P_{ex}(t) = \frac{1}{T}\sqrt{\sigma GSV}\int_0^T \left|\frac{\partial B}{\partial t}\right|^{3/2} dt \tag{3}$$

In summary, for the Steinmetz model, (1) and (3) are the prevalent expressions of conventional engineering model of iron losses. Given the measurement of the total loss P_t under standard harmonic excitations at two different frequencies, the following separation of the hysteresis loss is prevalent. Firstly, $(P_h + P_{ex})/f$ can be obtained by subtracting the classical eddy current loss P_{ed} evaluated by (1) from the measured P_t. Since $(P_h + P_{ex})/f$ is a linear function of $f^{1/2}$, The P_h and V in (3), for any external induction B, can be estimated from the intercept and the slope of the fitted straight line. In this way the hysteresis loss P_h can be simply evaluated by interpolation.

III. Proposed Model

A. The Hysteresis Loss

Although the hysteresis modeling is still a challenge, scalar Preisach model is well-suited for engineering application. The comparison is conducted among the Preisach model and the other models depicted in the previous section, as shown in Fig. 1. It can be seen that the Steinmeiz model and the Preisach model do match fairly well, while there are oscillations for the prediction of the interpolating model, whose fidelity is doubtful. Compared with the identification procedure, the

Preisach modeling [2] is more straightforward and robust than the Steinmetz model.

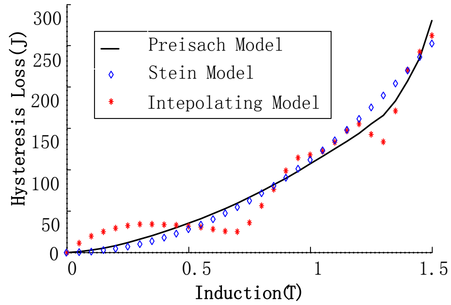

Fig. 1. Comparison among hysteresis losses given by different models.

B. The Eddy Current Loss

As mentioned, at high frequency, the skin effect, as well as magnetic nonlinearity, cannot be ignored. A simple modification is to multiply the skin effect factor by P_{ed} formulated in (1). However, this is an ambiguous expression on the application of effective permeability, as illustrated in Fig. 2. In this paper, a pair of coupled one dimensional FDM is employed to determine the classical eddy current loss [3]. Holding the same geometrical assumption for (1), the distribution of magnetic induction in the lamination can be determined by solving the following boundary value problem:

$$\frac{\partial^2 H}{\partial z^2} = \sigma\mu\frac{\partial H}{\partial t}\ ,\quad \frac{\partial H}{\partial z}\Big|_{z=d/2} = \frac{\sigma}{2}\frac{d\phi}{dt}\ ,\quad \frac{\partial H}{\partial z}\Big|_{z=0} = 0 \tag{4}$$

where φ is the external flux applied to the lamination; the z-coordinate is assumed to be perpendicular to the laminated plate. FDM is used to solve (4).

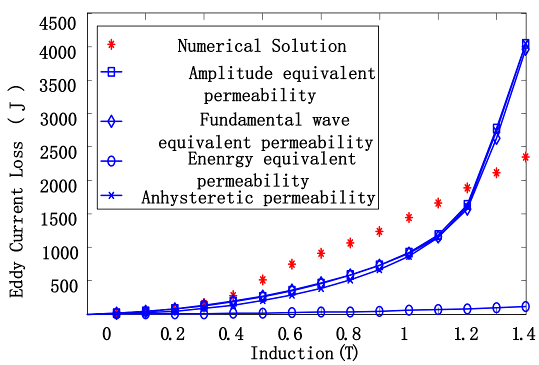

Fig. 2. Comparison among eddy current losses computed using different methods.

At low frequency (50 Hz and 60 Hz), the numerical results are identical to the approximate analytical solution in (1). As the operating frequency increases, there are significant differences between the numerical and analytical solutions, even with the modification of skin effect. For instance, Fig. 2 shows there are large differences in the evaluations of eddy current loss in the lamination with an operating frequency of 5000 Hz.

C. The Excess Loss

This paper finds that the postulation of (3) is doubtful. To avoid numerical integration of (2), the following approximation is employed.

$$\sqrt{1+x} = \begin{cases} 1+\dfrac{x}{2}-\dfrac{x^2}{8} & x \le 1.2 \\ \sqrt{x}+\dfrac{1}{2\sqrt{x}} & otherwise \end{cases} \tag{5}$$

The errors arisen from the approximation in (5) is less than 5%. Let x be $(4\sigma GS/n^2V)|\partial B/\partial t|$, the analytical excess loss can be obtained. For this analytical model, the linear regression is not applicable any more. Instead, this paper proposes an optimization approach to formulate the identification problem based on the least square view point:

$$\min\sum_{i=1}^{N}(P_d^i - P_{exc}(B_m^i, f^i, n_0, V_0))^2 \qquad s.t.\ n_0 \ge 0, V_0 \ge 0 \tag{8}$$

where N is the number of measurement data. P_d is the residual of the total iron loss removing the hysteresis loss and eddy current loss, which are evaluated by means of the Preisach model and FDM respectively. The induction B and frequency f in P_{exc} are known in *a priori*. The necessary condition of the optimum results in two polynomial algebraic equations which can be automatically solved by commercial software packages.

As mentioned earlier, different identifications provide different hysteresis loss and excess loss. To establish a fair comparison, FDM approach to eddy current loss is used throughout the comparisons among different identifications. The comparisons are illustrated in Fig. 3. Only the proposed method, which consists of Preisach modeling of hysteresis loss, FDM modeling of eddy current loss and the optimal model of excess loss, can agree fairly well with the measurements when compared to all other methods being reported.

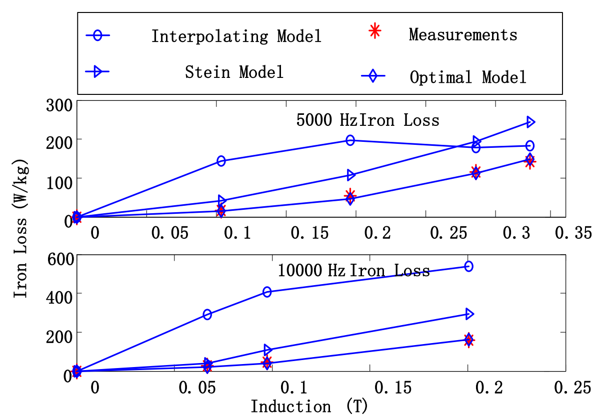

Fig. 3. Comparison among the iron losses computed using different methods and the measured loss curve of silicon steel 35ww270

IV. References

[1] G. Bertotti, "Spacetime correlation properties of the magnetization process and eddy current losses: Theory," *J. Appl. Phys.*, vol. 54, no. 9, pp. 5293-5305, 1983.

[2] S. Y. R. Hui, J. Zhu, "Numerical modelling and simulation of hysteresis effects in magnetic cores using transmission line modelling and preisach theory," *IEEE Proc. Electric Power Applications*, vol. 142, no. 1, pp. 57-62, 1995.

[3] R. M. Del Vecchio, "The calculation of eddy current losses associated with rotating machine fields in thin laminations," *IEEE Trans. Magn.*, vol. 18, no. 6, pp. 1707-1709, 1982.