An Improved Complex Reluctivity Model Considering 2D Magnetic Properties of Electrical Steel Sheet

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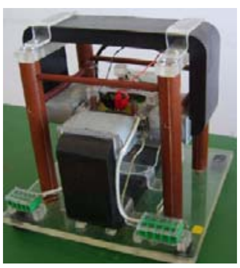
***Abstract*— This paper presents an improved complex reluctivity model considering 2D magnetic properties of electrical steel sheet from the viewpoint of saving computation time and guaranteeing the solution accuracy. In this model, the effective magnetic reluctivity coefficients are calculated according to the average magnetic energy density in one time period, and the effective magnetic hysteresis coefficients are computed from the magnetic hysteresis loss. To improve the modeling accuracy, the effects of higher harmonic terms besides the fundamental one of the magnetic field intensity waveform on the magnetic property are considered into this model. The effectiveness of the proposed model in comparison with experimental results is investigated.**

I. INTRODUCTION

As one of highly accurate methods to simulate two-dimensional (2D) vector magnetic properties of electric steel sheet, the E&S model has attracted more and more attentions. In this model, the magnetic anisotropy of electrical steel sheet under the alternating and rotating magnetic flux conditions is calculated from plenty of experimental data measured from a 2D magnetic property measurement system [1]. Very recently, in order to save the computation time of finite element analysis (FEA) considering E&S model, a complex E&S model is proposed with assumption that both magnetic flux density and magnetic field intensity vary sinusoidally with time [2]. It has mentioned in [2] that this model can only be used in low magnetic flux region because the magnetic field intensity will be gradually distorted from the purely sinusoidal waveform with the increase of magnetic flux density.

In this paper, an improved complex reluctivity model is proposed, in which the distorted waveform of magnetic field intensity at high magnetic flux density region is considered through the computation of the effective magnetic reluctivity and hysteresis coefficients. By comparing with the experimental results, it has demonstrated that the proposed model is time-saving and accurate.



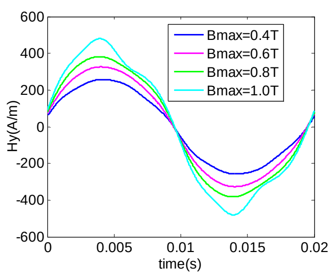


Fig.1(a) 2D magnetic property measurement device (b)measured H_y waveforms under several elliptical locus of ***B***

II. METHOD DESCRIPTION

A. Improved Complex Reluctivity Model

In order to describe 2D magnetic properties, the E&S reluctivity model based on the Chua-type model can be expressed as follows[1]:

$$H_k = \nu_{kr} B_k + \nu_{ki} \frac{\partial B_k}{\partial t} \quad (k = x, y) \tag{1}$$

where ν_{kr} and ν_{ki} are magnetic reluctivity and hysteresis coefficients, respectively, B is magnetic flux density, and H is magnetic field intensity. In this model, ν_{kr} and ν_{ki} are expressed as the function of time and the locus of magnetic flux density ***B*** in one time period, and the corresponding finite element analysis is transient. In order to save FEA computation time, the complex reluctivity model is expressed as follows [2]:

$$\dot{H}_k = \bar{\nu}_{kr} \dot{B}_k + j\omega \bar{\nu}_{ki} \dot{B}_k \tag{2}$$

where $\bar{\nu}_{kr}$ and $\bar{\nu}_{ki}$ are defined as the effective magnetic reluctivity and effective magnetic hysteresis coefficients, respectively, and calculated from the fundamental terms of measured B- and H-waveforms with 2D magnetic property measurement device. As mentioned above, these two coefficients in [2] only reflect the magnetic property resulted from undistorted H-waveforms.

By using a self-developed 2D magnetic properties measurement device of electric steel sheet in Fig.1(a), the measured magnetic field intensity waveforms are shown in Fig.1(b) when the controlled elliptical locus of magnetic flux density vary from 0.4T to 1.0T. From this figure, it can be seen that the H-waveform is distorted and includes high order harmonic terms when the B locus is 1.0T. Therefore, in order to improve the accuracy of complex model in (2), it is necessary that the definition of the effective magnetic reluctivity and hysteresis coefficients needs to take the high order harmonic terms of measured H-waveforms into account. In this paper, an improved complex reluctivity model is proposed, and the computation of $\bar{\nu}_{kr}$ and $\bar{\nu}_{ki}$ are derived in detail in the following contents.

Firstly, the effective magnetic hysteresis coefficient $\bar{\nu}_{ki}$ is related to hysteresis loss of electric steel sheet. The total iron loss including both alternating loss and rotational loss can be calculated as follows[1]:

$$P_{loss} = \frac{1}{\rho T}\int_0^T \left(H_x \frac{\mathrm{d}B_x}{\mathrm{d}t} + H_y \frac{\mathrm{d}B_y}{\mathrm{d}t} \right) \mathrm{d}t \qquad \text{W/kg} \qquad (3)$$

By utilizing the measurement data of magnetic field intensity corresponding to different elliptical locus of magnetic flux density, the iron loss in (3) of the electric steel sheet can be measured. Obviously, the measured loss results include the high harmonic terms of H-waveform. On the other hand, during the course of measurement, the controlled B-waveform can be expressed as follows:

$$B_k = B_{mk} \sin(\omega t + \varphi_k) \quad (k = x, y) \qquad (4)$$

where B_{mk} is the amplitude of B_k. According to E&S model, the corresponding H-waveform can be deduced from (4) as follows:

$$H_k = \bar{\nu}_{kr} B_{mk} \sin(\omega t + \varphi_k) + \bar{\nu}_{ki} B_{mk} \omega \cos(\omega t + \varphi_k) \qquad (5)$$

Substituting (4) and (5) into (3), the calculated iron loss can be obtained. By considering the measured and calculated iron loss simultaneously, the effective magnetic hysteresis coefficients $\bar{\nu}_{ki}$ can be derived as follows:

$$\bar{\nu}_{ki} = \frac{2}{B_{mk}^2 \omega^2 T}\int_0^T H_k(t) \cdot \frac{\mathrm{d}B_k(t)}{\mathrm{d}t} \mathrm{d}t \qquad (6)$$

where $H_k(t)$, B_k(t) and B_{mk} are obtained from the 2D magnetic property measurement data. For a definite B locus described with three elliptical parameters: long axis length B_{max}, the inclination angle θ, and axis ratios α, the effective magnetic hysteresis coefficients $\bar{\nu}_{ki}$ are constant.

Secondly, the effective magnetic reluctivity coefficients $\bar{\nu}_{kr}$ are related to the average magnetic energy density in one time period. The average magnetic energy density can be calculated as follows:

$$W_e = \frac{1}{T}\int_0^T \frac{1}{2} H \cdot B \mathrm{d}t \qquad (7)$$

By applying the similar derivation course as the $\bar{\nu}_{ki}$ and taking account of both the measured energy density and the calculated one, the effective reluctivity coefficients $\bar{\nu}_{kr}$ can be calculated as follows:

$$\bar{\nu}_{kr} = \frac{2}{B_{mk}^2 T}\int_0^T H_k(t) \cdot B_k(\mathrm{t}) \mathrm{d}t \qquad (8)$$

Similarly, the effective magnetic reluctivity coefficients $\bar{\nu}_{kr}$ are also the function of B_{max}, α and θ.

In a word, the coefficients $\bar{\nu}_{ki}$ and $\bar{\nu}_{kr}$ in the complex reluctivity model, in this paper, are calculated from the viewpoint of measured iron loss and energy density in order to take the high order harmonic terms of measured H-waveforms into account. It can be seen that the proposed model has higher modeling accuracy. The detailed discussion for $\bar{\nu}_{ki}$ and $\bar{\nu}_{kr}$ will be given in the extended paper.

B. *Governing equation*

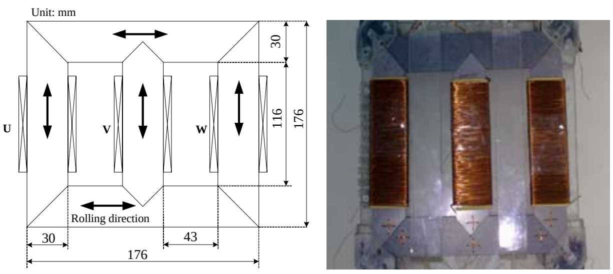
The governing equation under the consideration of the proposed complex reluctivity model can be expressed as follows:

$$\frac{\partial}{\partial x}\left(\bar{\nu}_{yr} \frac{\partial \dot{A}}{\partial x} + j\omega \bar{\nu}_{yi} \frac{\partial \dot{A}}{\partial x} \right) + \frac{\partial}{\partial y}\left(\bar{\nu}_{xr} \frac{\partial \dot{A}}{\partial y} + j\omega \bar{\nu}_{xi} \frac{\partial \dot{A}}{\partial y} \right) = -\dot{J} \qquad (9)$$

where $\dot{A}$ is complex magnetic vector potential, and $\dot{J}$ is the complex exciting current density. With the proposed complex reluctivity model, the efficiency of finite element analysis can be improved.

III. RESULTS

A three-phase transformer core model is taken as a numerical example, shown in Fig.2(a), to verify the effectiveness of the proposed method. The experimental model is shown in Fig.2(b). Fig.3 shows the locus of $\boldsymbol{B}$ vector in one time period at T-type part of the core. Fig.4 shows the iron loss distribution. More results and discussions will be given in the extended paper.



(a) numerical model (b) experimental model

Fig.2 Three-phase transformer core model.

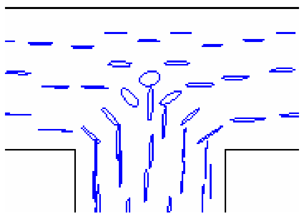


Fig.3 Distribution of **B** locus at T-type part of the core in one time period.

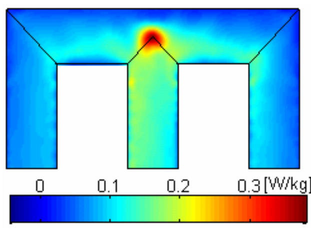


Fig.4 Iron loss distribution.

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