An Improved Inverse Preisach Model for Hysteresis Modeling of Grain-Oriented Silicon Steel Based on Neural Networks

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In this paper, a generalized inverse Preisach model based on neural networks is proposed by characterizing an Everett function of the irreversible magnetization and taking magnetization-dependent hysteresis, as well as reversible magnetization part, into account, which not only ensures the simulation accuracy for both symmetric and asymmetric minor loops but also very easy to implement the model in the FEM. The model accuracy is verified by the experimental data of B30P105 grain oriented (GO) silicon steel under different magnetization conditions, and the computational efficiency is compared with the traditional model.

I. INTRODUCTION

The accurate modeling of the hysteresis performance in electrical steel sheets holds significant importance for magnetic field analysis and optimizing efficiency in electrical equipment, such as motors and transformers. Recognized for its high simulation accuracy, the Preisach model stands out in modeling techniques, while traditional models involve complex integration operations. To avoid this problem, the discrete Everett function with an analytic expression is introduced, which can be numerically computed directly[1].However, the Everett function obtained by this method has some problems in the simulation of hysteresis loops with high flux density. Deep neural networks, which is used to solving nonlinear problems are recently applied for modeling the hysteresis[2]. However, the direct combination of traditional neural network and Preisach model requires a large amount of experimental data, which leads to long calculation time and difficult training. To solve these problems, a generalized inverse Preisach model based on Convolutional Neural Network(CNN) is proposed.

In this paper, a generalized inverse Preisach model is established. A Everett function is used for modeling the irreversible magnetization.The reversible and magnetization-dependent hysteresis components are coupled in the inverse model by performing a time-step difference on the effective field. The accuracy and validity of the model are demonstrated by comparing the simulated hysteresis loops with the measured data of B30P105 grain- oriented (GO) silicon steel.

II. GENERALIZED INVERSE PREISACH MODEL

A. The Everett function in the forward Preisach model

The classic Preisach model can utilize a section of a gyration curve to obtain the Everett function, with the calculation method as follows:

$$E(\alpha,\beta)=\frac{M_{\alpha\alpha}-M_{\alpha\beta}}{2} \quad (1)$$

where Mαα is the maximum magnetic flux density of the concentric loop, and Mαβ corresponds to a point on the descending branch.

B. Generalized Inverse Preisach model in analytical form

In general, the magnetization can be separated into the irreversible magnetization component, and the reversible component, where the classical Preisach model can only be used to determine the irreversible part, and the reversible component is characterized by the reversible magnetic susceptibility:

$$M(H)=M_{\mathrm{irr}}(H)+M_{\mathrm{rev}}(H) \quad (6)$$

where M_{irr} is the irreversible magnetization, and M_{rev} is the reversible magnetization.

The reversible magnetization only depends on the current magnetization, and the reversible magnetization part can be characterized by reversible magnetic susceptibility. The slope of the hysteresis loop is different before and after the reversal point. The reason for the difference is that when the direction of the magnetic field change is changed, the magnetic field change in the system is completely reversible after the reversal point. Therefore, the reversible magnetic susceptibility χ_{rev} can be obtained by calculating the slope dM/dH at the reversal points of the concentric hysteresis loops. After calculated value of reversible magnetic susceptibility, the reversible magnetization can be written as:

$$M_{\mathrm{rev}}(H)=\int_0^H \chi_{\mathrm{rev}}(H)dH \quad (7)$$

According to the moving Preisach model, magnetization feedback needs to be considered to relax the limitations of congruence characteristics in the classical model. The magnetic field strength considering magnetization feedback can be expressed as:

$$H_{\mathrm{e}}=H+KM \quad (8)$$

where H_{e} is the effective magnetic field strength, and K is the feedback coefficient. The feedback coefficient can be obtained by the following formula [10]:

$$K=\frac{M_{\mathrm{e}}-M}{\chi M} \quad (9)$$

where the M_{e} and M are the magnetizations measured and calculated by the classical Preisach model, respectively, and χ is the magnetic susceptibility of the major hysteresis loop.

To obtain an efficient inverse form of the above model, a time-step difference on the magnetic field strength H is

employed for calculating the input from the output, with the following formulation:

$$H_{i+1} = H_i + \frac{B_{i+1} - B_i}{(\mathrm{d}B/\mathrm{d}H)_i} \tag{10}$$

where H_i is the current magnetic field strength value, H_{i+1} is the magnetic field strength value obtained at the next step, and $(\mathrm{d}B/\mathrm{d}H)_i$ is the derivative of magnetic flux density B_i concerning magnetic field strength H_i.

Taking the first-order derivative of (2), $\mathrm{d}B/\mathrm{d}H$ can be obtained:

$$\frac{\mathrm{d}B}{\mathrm{d}H} = \mu_0(1 + \frac{\mathrm{d}M}{\mathrm{d}H}) \tag{11}$$

Due to the consideration of the influence of magnetization feedback, the effective magnetic field strength is replaced by the magnetic field strength. $\mathrm{d}M/\mathrm{d}H$ requires the following transformation:

$$\frac{\mathrm{d}M}{\mathrm{d}H} = \frac{\mathrm{d}M}{\mathrm{d}H_e}\frac{\mathrm{d}H_e}{\mathrm{d}H} \tag{12}$$

Taking the first-order derivative of (8), $\mathrm{d}H_e/\mathrm{d}H$ can be obtained.

$$\frac{\mathrm{d}H_e}{\mathrm{d}H} = 1 + K\frac{\mathrm{d}M}{\mathrm{d}H} \tag{13}$$

By combining (11), (12), and (13), it can be obtained

$$\frac{\mathrm{d}B}{\mathrm{d}H} = \mu_0(1 + \frac{\frac{\mathrm{d}M}{\mathrm{d}H_e}}{1 - K\frac{\mathrm{d}M}{\mathrm{d}H_e}}) \tag{14}$$

Taking the first order derivative of (6), $\mathrm{d}M/\mathrm{d}H_e$ can be obtained by

$$\frac{\mathrm{d}M}{\mathrm{d}H_e} = \frac{\mathrm{d}M_{irr}}{\mathrm{d}H_e} + \frac{\mathrm{d}M_{rev}}{\mathrm{d}H_e} \tag{15}$$

The key lies in obtaining the irreversible magnetization Mir in Equation 15. In this paper, *M*ir is primarily calculated using a neural network that has been well-trained on the irreversible Everett function. Based on the obtained irreversible magnetization,the derivative of *M*ir with respect to the effective magnetic field *H*e is further computed.

Neural networks can introduce non-linear elements by incorporating activation functions, enabling them to approximate any complex non-linear function. The Everett function is a typical non-linear function, taking inputs α and β and producing an output M. By training the network to represent the Everett function, we can not only enhance computational speed but also conserve storage space.

The general idea of this model is to use neural networks to train Everett functions with irreversible components. By calculating the irreversible part of the hysteresis loop, the Everett function of the irreversible part is expressed. Give this part as input to the neural network, and the expected value of the output is the Everett function. This is used to train a network that can replace the analytic function. The Preisach model combined with neural network is shown in Fig1.

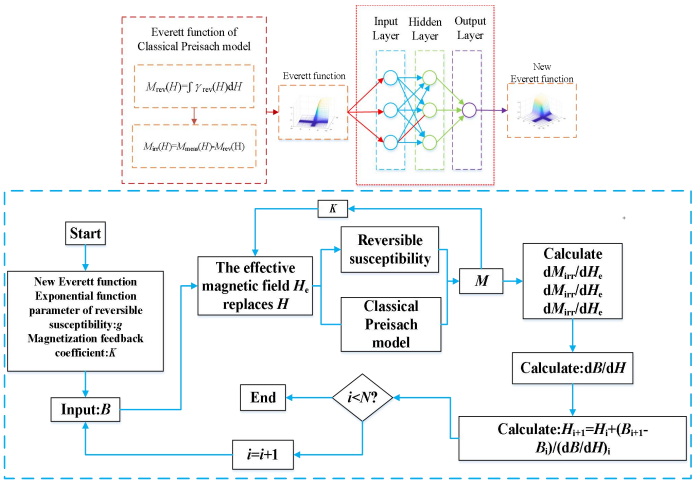


Fig. 1. Preisach algorithm based on neural network

III.RESULT AND DISCUSSION

To illustrate the validity of the proposed model, the calculated hysteresis loops of the improved model at differentCMP-403 4 peak magnetic densities are compared with the experiment data. The comparison of different magnetization conditions is shown in Fig 2.

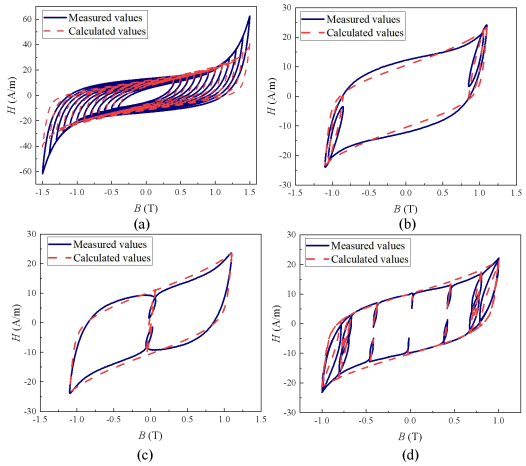


Fig.2. Comparison of the measured value and simulated value

IV. CONCLUSION

In this paper, a generalized inverse Preisach model based on neural networks is proposed by characterizing the irreversible magnetization component with a Everett function and considering magnetization-dependent hysteresis along with the reversible magnetization component. Obtained results demonstrate that the proposed model achieves relatively high accuracy for both sinusoidal and non-sinusoidal excitations. Moreover, it significantly reduces the average calculation time compared to traditional methods.

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