An Improved Preisach Distribution Function Identification Method Considering the Reversible Magnetization

Long Chen, *Member*, *IEEE*, Lvsheng Cui, Tong Ben, and Libing Jing

Abstract—**This paper presents an identification method of the scalar Preisach model to consider the effect of reversible magnetization in the process of distribution function identification. By reconsidering the identification process by stripping the influence of reversible components from the measurement data, the Preisach distribution function is identified by the pure irreversible components. In this way, the simulation accuracy of both limiting hysteresis loops and the inner internal symmetrical small hysteresis loop is ensured. Furthermore, through a discrete Preisach plane with a hybrid discretization method, the irreversible magnetic flux density components are computed more efficiently through the improved Preisach model. Finally, the proposed method results are compared with the traditional method and the traditional method considering reversible magnetization and validated by the laboratory test for the B30P105 electrical steel by Epstein frame.**

Index Terms—**Magnetic material, Preisach distribution function, Reversible magnetization, Hybrid discretization method.**

I. Introduction

ACCURATE calculation of the hysteresis properties of the magnetic materials is of great significance for the loss prediction and efficient optimal design of electrical equipment [1]. The Preisach model and its modification are one of the most commonly used models for predicting the hysteresis behavior of electrical steels for its high simulation accuracy [2]-[4]. However, the identification process of the distribution function for this model is relatively difficult. Moreover, using the first-order reversal curve (FORC) requires a large amount of experimental data [5]-[6]. This fact may stem from its industrial applications.

To simplify this process, Biorci and Pescetti et al. proposed an improved Preisach–Néel model, which only uses the initial magnetization curve combined with a descending saturation hysteresis loop [7]. However, it can only ensure the simulation accuracy in describing the hysteresis loops under high flux density levels [8]. To improve the computing accuracy at lower flux densities, the reversible magnetization part versus magnetic field strength should be further considered [9]-[10]. In 2007, Fanny Beron proposed a method to consider reversible magnetization in the FORC diagram [11]. Nevertheless, this method is some grade cumbersome.

In recent years, the centered cycle (CC) methods for identifying the Preisach model have been commonly used as these methods use symmetric loops that can be easily obtained [12]-[14]. Reference [12] proposes an identification method base on the ΔH-fixed discrete approach (HFA) for the Preisach distribution function identification combined with the CC method. However, this method uses uniformly distributed C.C.s to discretize the Preisach plane, which decreases simulation accuracy. Then, MFA (ΔM-fixed approach) based on the CC method is proposed, which improves the simulation accuracy compared with HFA [13]. However, the calculation accuracy of the hysteresis loop near the knee joint is not correctly considered in that method. Therefore, a non-uniform discretization method based on the CC method is proposed, improving the simulation accuracy near the knee point [14].

However, these methods do not adequately consider the influence of reversible magnetization of the model. Therefore, to properly evaluate the effect of reversible components in the CC method. Reference [15] proposed a modified scalar Preisach model (MSPM), which correctly considers reversible magnetization in the CC method. However, the MAPM must resolve a bilinear equation system, resulting in an enormous computational burden. Further, Reference [16] proposed an identification method in which the Preisach distribution function is identified using the remanence curve obtained by the CC method. However, using the irreversible component to

Manuscript received February 22, 2023; revised April 04, 2023; accepted April 25, 2023. Date of publication December 25, 2023. Date of current version June 16, 2023.

This work was supported by the National Natural Science Foundation of China under Grant 52007102, 52207012, and by the State Key Laboratory of Reliability and Intelligence of Electrical Equipment under Grant EERIKF2021015. *(Corresponding author: Tong Ben)*

Long Chen is with College of Electrical Engineering and New Energy, China Three Gorges University, Yichang, 443002, China, and also with Hubei Provincial Engineering Technology Research Center for Power Transmission Line, China Three Gorges University, Yichang 443002, China (e-mail: chenlong@ctgu.edu.cn).

Lvsheng Cui and Libing Jing are with College of Electrical Engineering and New Energy, China Three Gorges University, Yichang 443002, China. (e-mail: cuils0635@163.com; jinglibing163@163.com)

Tong Ben is with College of Electrical Engineering and New Energy, China Three Gorges University, Yichang 443002, China, and also with Hebei University of Technology, Tianjin 300130, China (e-mail: bentong@ctgu.edu.cn).

Digital Object Identifier 10.30941/CESTEMS.2023.00038

identify the reversible magnetization part is some grade complex [16].

To explore a more efficient identification method for the Preisach distribution function considering the effect of the reversible magnetization component of the CC method, this paper proposes an improved centered cycle method, in which the reversible components are characterized by reversible relative permeability, and the Preisach plane of irreversible components is discretized by the hybrid discretization method. The proposed method's results are compared with the traditional method [12] and the traditional method considering reversible magnetization and validated by the laboratory test for B30P105 electrical steel at 5 Hz.

II. Traditional Centered Cycle Method

The classical Preisach model assumes that magnetic materials are composed of countless rectangular hysteresis operators. The hysteresis effect of magnetic materials is expressed as the superposition of all hysteresis operators, and the magnetic flux density can be computed as:

$$B(t) = B_{\mathrm{m}} \iint_{\alpha \geq \beta} \mu(\alpha,\beta)\gamma_{\alpha\beta}[H(t)]d\alpha d\beta \tag{1}$$

where the magnetic flux density $B(t)$ is the output, and the magnetic field strength H(t) is the input of the model. B_{m} is the corresponding value when the input H reaches the maximum value. $\gamma_{\alpha\beta}[H(t)]$ is the elementary hysteresis operator of the model, which is represented by the rectangular loops with α and β as switching values ($\alpha > \beta$) and distributed in the Preisach triangle. $\mu(\alpha, \beta)$ is the distribution function of the hysteresis operator.

Among them, the distribution function satisfies the following conditions on the Preisach plane:

$$\iint_{\alpha \geq \beta} \mu(\alpha,\beta)d\alpha d\beta = 1, -H_{\mathrm{m}} \leq \alpha \leq H_{\mathrm{m}} \tag{2}$$

where H_{m} is the maximum value of the input magnetic field strength.

According to the geometric description of the model, the Preisach triangle corresponds to the experimental-centered cycles described in Fig. 1. The Preisach plane would be discretized to $n(2n+1)$ cells by n experimental-centered cycles. Assume that the value of the distribution function within each small cell is a constant. And the distribution function $\mu(\alpha, \beta)$ in the cell is symmetric along the $\alpha = -\beta$ axis. Therefore, only $n(n+1)$ cells need to be determined.

Using $2k + 1$ values of B in the ascending branch of the kth loop, $2k$ linearly independent equations can be established. So, there would be exactly $n(n+1)$ equations to solve $n(n+1)$ unknowns for n loops. As an example, the equation of the second loop can be given by:

$$B_2(H_6) - B_2(H_5) = 2B_{\mathrm{m}} \times \sum_{i=2}^{5} \mu_{(i,j=2)} \tag{3}$$

where B_2 represents the 2th loop. When H changes from H_6 to H_5, the amount of change of $S+$ and $S-$ in the Preisach triangle is $\mu_{(i,j)}$, $S+$ increases by $\mu_{(i,j)}$, and $S-$ decreases by $\mu_{(i,j)}$, so the total change is $2\mu_{(i,j)}$.

Through the above method, $n(n+1)$ equations are created to

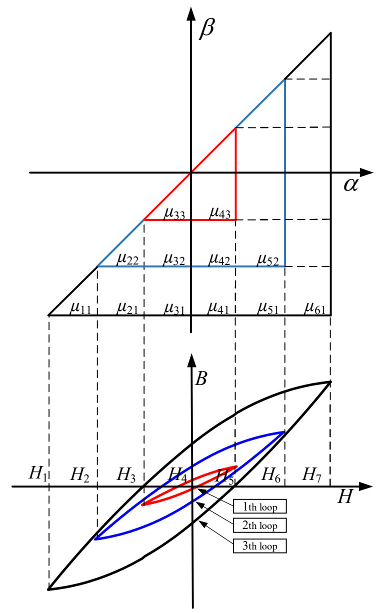


Fig. 1. Correspondence between the Preisach triangle and the hysteresis loops.

solve for the discrete distribution function values. Then the hysteresis loop of the silicon steel sheet at different magnetic flux densities is calculated by (4).

$$B = B_{\mathrm{m}} \sum_{i=1}^{2n} \sum_{j=1}^{i} p_{ij} \cdot \mu_{ij} \tag{4}$$

where p_{ij} represents the area in which the cell is located. If the cell is in the $S+$ region, p_{ij}=1. If the cell is in the $S-$ region, p_{ij} =−1. If it is in between, p_{ij} is the ratio of the difference between the area of the $S+$ region and the area of the $S-$ region in the cell to the whole cell.

The traditional centered cycle method can easily identify the Preisach distribution function, but this method also has some drawbacks. Firstly, the traditional method can only identify the irreversible distribution function due to the rectangular characteristics of the hysteresis operators of the classical Preisach model, the influence of reversible magnetization is not considered correctly, and the error is significant when predicting the inner symmetrical minor loops. Secondly, the traditional method uses uniformly distributed centered cycles to discretize the Preisach plane, which requires more centered cycles to identify the distribution function to ensure the simulation's accuracy, resulting in an enormous computational burden.

III. Improved Distribution Function Identification Method

To solve the shortcomings of the traditional centered cycle method, an improved Preisach distribution function identification method is proposed considering the effect of reversible magnetization. The basic idea is to divide the magnetization process into reversible and irreversible components, with the reversible components characterized by reversible relative permeability. Then, the Preisach plane of irreversible components is discretized by the hybrid discretization method.

By analyzing the measurement data of the hysteresis loop, it can be found that the slope of the hysteresis loop is different before and after the turning point. The difference is that the change in magnetization before the turning point is attributed to reversible and irreversible magnetization. And the instantaneous magnetization after the turning point only has the reversible component contributing to the magnetization process. Therefore, the reversible relative permeability can be obtained by calculating the slope dB/dH at the turning point on the centered cycles [17]. Then the reversible components can be obtained:

$$B_{\text{rev}} = \mu_0 \int_0^H \mu_{\text{rev}}(H) dH \tag{5}$$

To ensure the calculation accuracy of the reversible relative permeability, the hysteresis loops are experimentally measured with appropriate measurement steps to keep the measurement data smooth. At the same time, to only consider the hysteresis properties of the material itself, it is essential to eliminate the influence of dynamic effects on the hysteresis loop, so the hysteresis loops of the B30P105 electrical steel at 5 Hz under sinusoidal excitation were measured. Then the reversible relative permeability was calculated, as shown in Fig. 2.

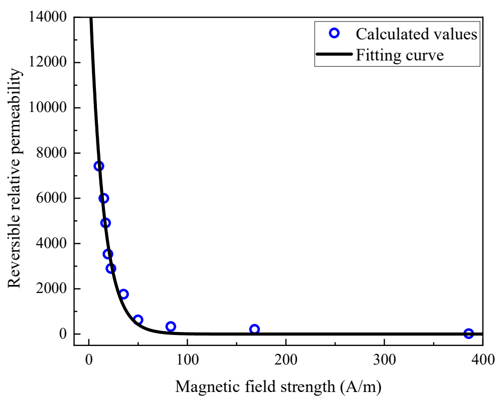


Fig. 2. Reversible relative permeability curve of the B30P105 electrical steel sheet.

By analyzing the calculated values of reversible relative permeability in Fig. 2, it can be observed that the calculated value changes sharply at low magnetic field strength. Therefore, an exponential function with parameters is constructed to describe the reversible relative permeability:

$$\mu_{\text{rev}} = a_1 e^{a_2 H} \tag{6}$$

where a_1 and a_2 are the parameters to be determined.

To get the unknown parameters of (6), the curve fitting method is used for the calculated reversible relative permeability, and the optimized parameters are tabulated in Table I. As a result, the reversible relative permeability characterization equation can realize the effective simulation of the reversible relative permeability of electrical steel B30P105, as shown in Fig. 2.

TABLE I
REVERSIBLE RELATIVE PERMEABILITY FUNCTION PARAMETER OF THE B30P105 ELECTRICAL STEEL

Parameters	a_1	a_2
Values	16360	-0.073

The irreversible component is expressed as (7):

$$B_{\text{irr}} = B_{\text{sm}} \iint_{\alpha \geq \beta} \mu_{\text{irr}}(\alpha, \beta) \gamma_{\alpha\beta}[H(t)] d\alpha d\beta \tag{7}$$

where B_{sm} is the corresponding irreversible component value when input H reaches the maximum value, μ_{irr} is an irreversible distribution function.

In the process of distribution function identification for the irreversible component, it is necessary to modify the measured hysteresis loop to obtain the irreversible hysteresis loop, as shown in Fig. 3. The modification can be realized by:

$$B_{\text{irr}}(H) = B_{\text{mea}}(H) - B_{\text{rev}}(H) \tag{8}$$

where B_{mea} is the experimental values of magnetic field sampling points.

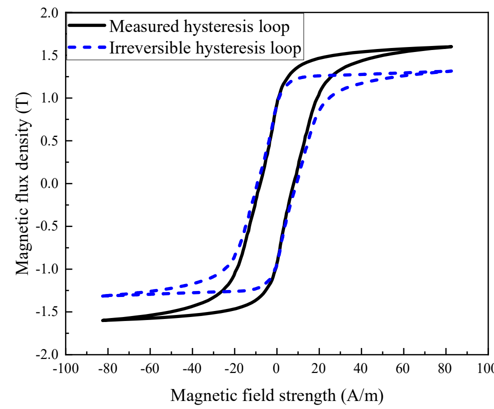


Fig. 3. Measured hysteresis loop and irreversible hysteresis loop.

To solve the problem of the large computational burden of traditional methods, a hybrid discretization method is proposed to improve the computational efficiency of the distribution function identification process. The remanence curve, which can represent the properties of the irreversible magnetization component of magnetic materials, is used in the identification process. It is derived from the measurement center cycle by taking each small center cycle and plotting zero field magnetization as a function of the maximum positive magnetic field strength, shown in Fig. 4 [16]. The method's main idea is that the derivative of the remanence curve determines the partition of the Preisach plane. MFA is used to discretize the Preisach plane in the region where irreversible magnetization changes rapidly, and HFA is used to discretize the Preisach plane where irreversible magnetization changes slowly.

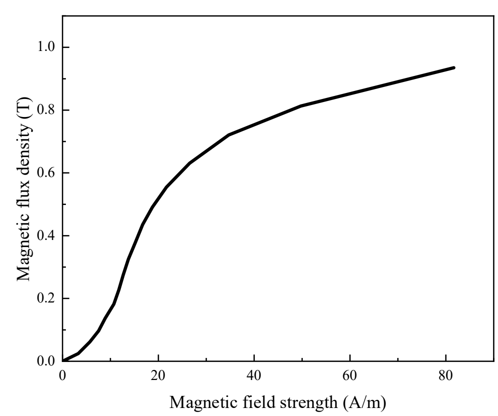


Fig. 4. The Remanence curve of B30P105 steel.

The derivative of the remanence curve is defined as:

$$k = \left| \frac{\mathrm{d}B}{\mathrm{d}H} \right| \tag{9}$$

Taking the derivative of the remanence curve, we can get the derivative of the remanence curve shown in Fig. 5. The maximum value of the derivative is defined as k_m. The (H_d, 0.4 k_m) to the right of the maximum derivative is selected as the boundary point in the region where the remanence changes rapidly. S_1 and S_2 represent regions corresponding to rapid and slow changes in the remanence curve.

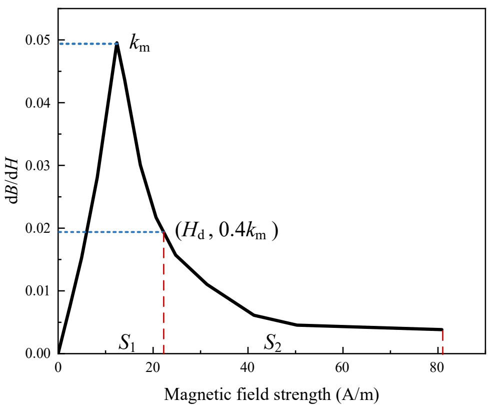


Fig. 5. Derivative of remanence curve of B30P105 steel.

After the partitioning strategy, it is necessary to determine the number of required centered cycles for each region, which is expressed as:

$$n_i = \begin{cases} n - n_2, & i = 1 \\ n\left\langle \dfrac{\int_{H_\mathrm{d}}^{H_\mathrm{m}} k\mathrm{d}H}{\int_0^{H_\mathrm{m}} k\mathrm{d}H} \right\rangle, & i = 2 \end{cases} \tag{10}$$

Where n_1 and n_2 are the number of centered cycles corresponding to S_1 and S_2 regions, n is the total number of centered cycles, $\langle x \rangle$ denotes the rounding operation, and H_d is the magnetic field strength corresponding to the boundary point.

By this method, the Preisach plane can be discretized only by fewer and more representative hysteresis loops. Therefore, five groups of symmetrical hysteresis loops are selected in this paper. The number of centered cycles corresponding to each region n_1=3, n_2 =2 is determined by (10). To obtain the distribution of centered cycles in each region, the hysteresis loop with a magnetic field strength of H_d is selected, and B_d is the maximum magnetic flux density of the loop. In this paper, H_d=22.5 A/m, B_d=1.2 T, and H_m=81.6 A/m. In the S_1 region, the distribution of the centered cycle is B_p=B_d/3, 2B_d/3, B_d; In the S_2 region, the distribution of the centered cycle is H_p=(H_d+H_m)/2, H_m. The discrete Preisach plane is shown in Fig. 6.

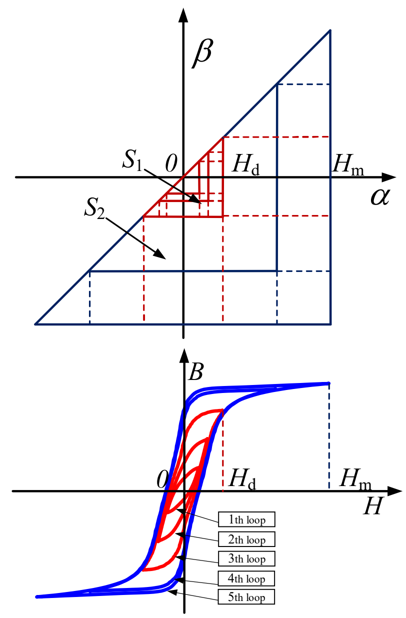


Fig. 6. Correspondence between the Preisach triangle and the irreversible hysteresis loops.

In identifying the irreversible distribution function, the distribution function of the two regions needs to be calculated separately. In the S_1 region, the identification of the irreversible distribution function requires n_1 centered cycles based on MFA distribution. The n_1(n_1+1) order matrix is constructed through n_1(n_1+1) equations to calculate the discrete cell value. The discrete cell of the S_2 area is shown in Fig. 7. In the S_2 region, the identification of the irreversible distribution function requires n_2+1 centered cycles based on HFA distribution. Since the irreversible distribution function in the S_1 region is known, it only needs to construct a matrix of (n_2+1)(n_2+2)-2 order through (n_2+1)(n_2+2)-2 equations to calculate the discrete cell value. The matrix of the S_2 region is as follows:

$$\begin{bmatrix} 100000000000 \\ 010000100000 \\ 001000010010 \\ 000100001011 \\ 000010111100 \\ 111111000000 \\ 000000100000 \\ 000000010010 \\ 000000001011 \\ 000000111100 \end{bmatrix} \cdot \begin{bmatrix} \mu_{11} \\ \mu_{21} \\ \mu_{31} \\ \mu_{41} \\ \mu_{51} \\ \mu_{61} \\ \mu_{22} \\ \mu_{32} \\ \mu_{42} \\ \mu_{52} \end{bmatrix} = \frac{1}{2B_\mathrm{sm}} \begin{bmatrix} B_5(-H_2) - B_5(-H_3) \\ B_5(-H_1) - B_5(H_2) \\ B_5(0) - B_5(-H_1) \\ B_5(H_1) - B_5(0) \\ B_5(H_2) - B_5(H_1) \\ B_5(H_3) - B_5(H_2) \\ B_4(-H_1) - B_4(-H_2) \\ B_4(0) - B_4(-H_1) \\ B_4(H_1) - B_4(0) \\ B_4(H_2) - B_4(H_1) \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ \mu_{33} \\ \mu_{33} + \mu_{43} \\ 0 \\ 0 \\ 0 \\ \mu_{33} \\ \mu_{33} + \mu_{43} \\ 0 \end{bmatrix} \tag{11}$$

Therefore, the proposed method reduces the number of constructed equations compared to the traditional centered cycle method:

$$\Delta n = 2n_2(n_1 - 1) \tag{12}$$

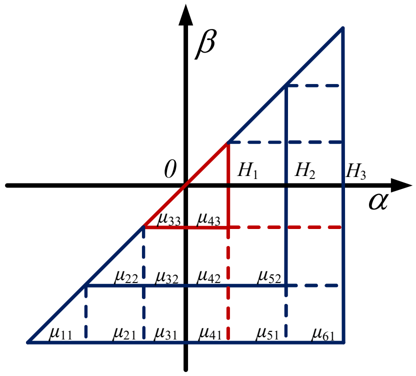


Fig. 7. The discrete Preisach plane for identifying the S_2 region.

IV. Results and Discussions

A. Experimental Platform

To verify the method's validity, the quasi-static hysteresis loop of B30P105 electrical steel was measured. In addition, a one-dimensional magnetic properties measurement system was established according to the IEC60404-2, including the AE7224 broadband power amplifier, the Epstein frame, two SR560 voltage preamplifiers, the NI-PXI6124 data acquisition card, and the LabVIEW software control system, as shown in Fig. 8.

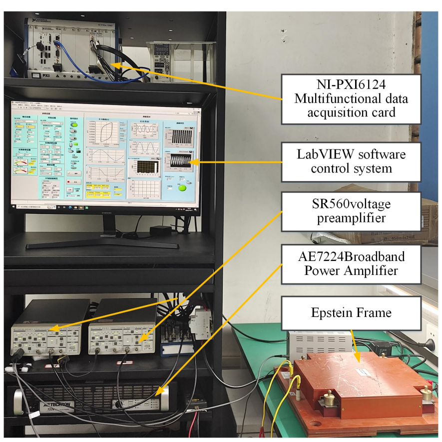


Fig. 8. Hysteresis loops measurement system for B30P105 steel.

The quasi-static (f=5 Hz) hysteresis loops under different peak flux densities of the B30P105 electrical steel are measured and presented in Fig. 9.

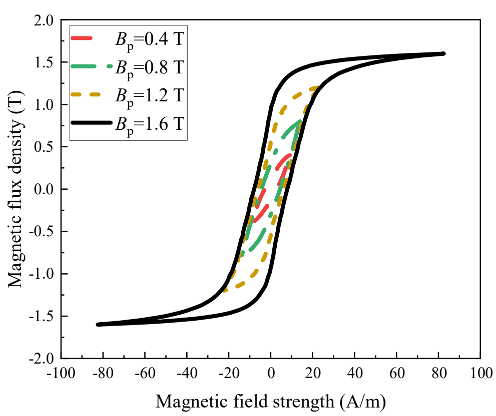


Fig. 9. The quasi-static hysteresis loops of silicon steel B30P150.

B. Verification of Calculation Results

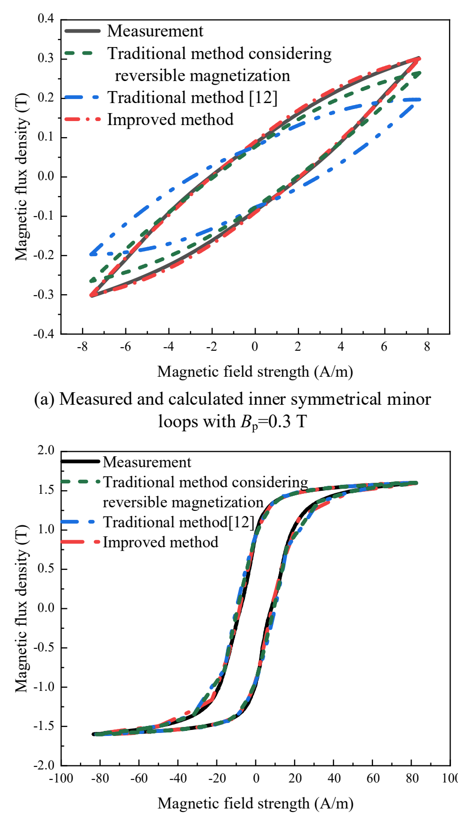
To illustrate the effectiveness of the proposed method, the hysteresis loops calculated by the traditional centered cycle method and the traditional method considering reversible magnetization and the proposed method are compared with the measured loops when at B_p=0.3 T and 1.6 T, as shown in Fig. 10.

As can be seen from Fig 10, the improved method considers the effects of reversible magnetization and the hybrid discretization method, which has higher accuracy than the traditional method in calculating the inner symmetrical minor loop. To further verify the accuracy of the improved method, the error of the hysteresis loops obtained by the three methods is calculated using the mean absolute percentage error formula of (13). The calculation results are shown in Fig. 11.

$$\sigma=\frac{1}{N}\sum_{i=1}^{N}\left|\frac{B_{\mathrm{mea}}-B_{\mathrm{cal}}}{B_{\mathrm{mea}}}\right|\times 100\% \tag{13}$$

Where B_{cal} is the calculated values of magnetic field sampling points, and N is the number of magnetic field strength sampling points in one magnetization cycle.

It can be seen from Fig. 11 that the maximum error of the hysteresis loop obtained by the improved method does not exceed 15%. In comparison, the maximum error of the traditional method considering reversible magnetization exceeds 25% and the traditional method exceeds 45%, which means that the proposed method not only ensures the simulation accuracy in higher flux density levels but also has higher accuracy in predicting hysteresis loops under low flux density levels.



(a) Measured and calculated inner symmetrical minor loops with B_p=0.3 T

(b) Measured and calculated limiting hysteresis loops with B_p=1.6 T

Fig. 10. Comparison between simulated and measured hysteresis.

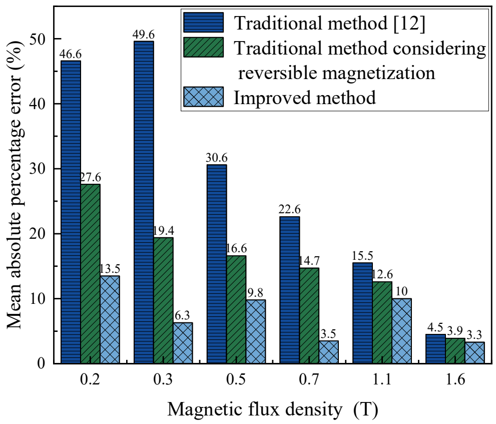


Fig. 11. Comparing the calculation errors of the three methods.

V. Conclusion

This paper proposes an identification method of the scalar Preisach model to consider the effect of reversible magnetization in the distribution function identification process. By reconsidering the identification process by stripping the influence of reversible components from the measurement data, the Preisach plane of irreversible components is discretized by five groups of CC selected by a hybrid discretization method, which reduces the computational burden of the identification process. Obtained results show that the calculation error of the hysteresis loop obtained by the improved method does not exceed 15%, which has higher calculation accuracy than the traditional method, which is essential for the optimal design of electrical equipment when using the finite element method.

References

[1] Y. Li, J. G. Zhu, and Y. J. Li *et al*, "A Hybrid Jiles–atherton and Preisach Model of Dynamic Magnetic Hysteresis Based on Backpropagation Neural Networks," *J. Magn. Magn. Mater.*, vol. 544, Feb, 2022.

[2] F. Preisach, "Über die Magnetische Nachwirkung," *Z Phys.*, vol. 94, no. 5, pp. 277-302, May, 1935.

[3] R. Zeinali, D. C. J. Krop, and E. A. Lomonova, "Comparison of Preisach and Congruency-based Static Hysteresis Models Applied to Non-oriented Steels," *IEEE Trans. Magn.*, vol. 56, no. 1, pp. 1-4, Jan, 2020.

[4] X. J. Zhao, X. N. Liu, and Z. G Zhao *et al*, "Measurement and Modeling of Hysteresis Characteristics in Ferromagnetic Materials under D.C. Magnetizations," *AIP Adv.*, vol. 9, no. 2, Feb, 2019.

[5] Z. Szabó and J. Füzi, "Implementation and identification of Preisach type hysteresis models with Everett Function in Closed Form," *J. Magn. Magn. Mater.*, vol. 406, pp. 251-258, May, 2016.

[6] M. Novak, J. Eichler, and M. Kosek, "Difficulty in Identification of Preisach Hysteresis Model Weighting Function Using First Order Reversal Curves Method in Soft Magnetic Materials," *Appl. Math. Comput.*, vol. 319, pp. 469-485, Feb, 2018.

[7] G. Biorci and D. Pescetti, "Analytical theory of the Behaviour of Ferromagnetic Materials," *Nuovo Cim.*, vol. 7, no. 6, pp. 829-842, Mar, 1958.

[8] L. Zegadi, J. J. Rousseau, and B. Allard *et al*, "Model of Power Soft MnZn Ferrites, Including Temperature Effects," *IEEE Trans. Magn.*, vol. 36, no. 4, pp. 2022-2032, Jul, 2000.

[9] L. Stoleriu, I. Bodale, and A. Apetrei *et al*, "Realistic Reversible Magnetization Component in Preisach-type Models," *IEEE Trans. Magn.*, vol. 46, no. 6, pp. 2341-2344, Jun, 2010

[10] P. C. Sarker, Y. G. Guo, and H. Y. Lu *et al*, "A generalized Inverse Preisach Dynamic Hysteresis Model of Fe-based Amorphous Magnetic Materials," *J. Magn. Magn. Mater.*, vol. 514, Nov., 2020.

[11] F. Béron, L. Clime, and M. Ciureanu *et al*, "Reversible and Quasireversible Information in First-order Reversal Curve Diagrams," *J. Appl. Phys.*, vol. 101, pp. 09J1071-09J1074, May, 2007.

[12] Y. Bernard, E. Mendes, and Z. Ren, "Determination of the Distribution Function of Preisach's Model Using Centred Cycles," *COMPEL-Int. J. Comput. Math. Electr. Electron. Eng.*, vol. 19, no. 4, pp. 997-1006, Dec, 2000.

[13] G. Consolo, G. Finocchio, and M. Carpentieri *et al*, "About Identification of Scalar Preisach Functions of Soft Magnetic Materials," *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 923-926, Apr, 2006.

[14] D. X. Peng, W. X. Sima, and M. Yang *et al*, "An Improved Centered Cycle Method for Identifying the Preisach Distribution Function," *IEEE Trans. Magn.*, vol. 54, no. 11, pp. 1-5, Nov, 2018.

[15] E. Cardelli, E. Della Torre, and G. Ban, "Experimental determination of Preisach Distribution Functions in Magnetic Cores," *Phys B.*, vol. 275, no. 1, pp. 262-269, Jan, 2000.

[16] E. Cardelli, E. D. Torre, and E. Pinzaglia, "Identifying the Preisach Function for Soft Magnetic Materials," *IEEE Trans. Magn.*, vol. 39, no. 3, pp. 1341-1344, May, 2003.

[17] Z. Birčáková, P. Kollár, and M. Jakubčin, *et al*, "Reversible and Irreversible Magnetization Processes Along DC Hysteresis Loops of Fe-based Composite Materials," *J. Magn. Magn. Mater.*, vol. 483, pp. 183-190, Aug, 2019.

Long Chen received a B.Eng. degree from the Hebei Normal University of Science & Technology, Qinhuangdao, China, in 2012 and a Ph.D. in electrical engineering from the Hebei University of Technology, Tianjin, China, in 2018.

He has been a Lecturer at the College of Electrical Engineering and New Energy, China Three Gorges University. His research interest includes measuring the magnetic properties of soft magnetic materials, hysteresis modeling, and wireless power transfer.

Lvsheng Cui received a B.Eng. degree from the Shandong University of Technology, Zi Bo, China, in 2017.

He is pursuing an M.S. degree with the College of Electrical Engineering and New Energy from the China Three Gorges University, Yichang, China. His research direction is hysteresis modeling.

Tong Ben received a B.Eng. and Ph.D. in electrical engineering from the Hebei University of Technology, Tianjin, China, in 2013 and 2018, respectively. Since 2022, she has been an associate professor in the College of Electrical Engineering and New Energy China Three Gorges University.

Her research interest includes stress and vibration analysis considering magnetostriction and Maxwell electromagnetic stress of transformers and motors.

Libing Jing received a B.S. degree from Zhongyuan University of Technology in 2006 and a Ph.D. from Shanghai University in 2013.

From October 2016 to November 2018, he worked as a postdoctoral student at Huazhong University of Science and Technology, Wuhan, China. Since July 2016, He has been an associate professor in the College of Electrical Engineering and New Energy China Three Gorges University. Dr. Jing has authored over 80 published technical papers and holds over ten patents/patent applications. In addition, he was a recipient of the Best Poster Presentation Award from the 4th International Conference on Intelligent Green Building and Smart Grid (IGBSG 2019). His research activities are related to designing, modeling, and analyzing electrical machines.