Core Loss Calculation Based On Finite Element Method with Jiles–Atherton Dynamic Hysteresis Model

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For accurate computation of core losses, the Jiles-Atherton (J-A) dynamic hysteresis model accounting for hysteresis, eddy current, and excess losses is incorporated into the finite element method. The J-A dynamic hysteresis model is constructed by combining the traditional J-A hysteresis model with the models of instantaneous eddy current and excess losses. The J-A model parameters and dynamic loss coefficients are determined by fitting the models to the measurement data of a Single-Sheet Tester (SST 500). To find the robust best fit, the Particle Swarm Optimization (PSO) algorithm is employed. By using the proposed J-A dynamic hysteresis model and finite element analysis, the magnetic characteristics of a magnetic core is simulated and the core loss distribution within the core is obtained. Finally, the core loss calculation results are compared with the experimental results, and it is shown that the proposed model is accurate and effective.

***Index Terms*— J-A dynamic hysteresis model, Finite element method, Core losses**

I. INTRODUCTION

Core loss is a key and difficult component to calculate accurately in the design optimization of power transformers to achieve high efficiency and avoid the risk of local overheating [1].

In a magnetic core, the total core loss can be attributed to the magnetic hysteresis and eddy currents. Due to the existence of magnetic domains, the eddy current loss has two components due to the global and local eddy currents, known as the eddy current loss and excess loss, respectively. For core losses under sinusoidal excitations at different frequencies, the Bertotti loss separation formula has been used to separate the total core loss into three components corresponding to the hysteresis, eddy current and excess losses [2].

When the excitation is nonsinusoidal, however, a general dynamic model is required. In [3], the core loss is calculated by integrating the area of dynamic hysteresis loop. In [4], the hysteresis model and the finite element method (FEM) are coupled. Based on this, the FEM is employed for 3D eddy current analysis, and it was claimed that this method could improve greatly the accuracy of core loss calculation, but the influence of the excess loss was not considered, and there is still some discrepancy between the theoretical and experimental results [5]. In [6], the dynamic hysteresis model is derived to calculate the core loss, but the loss distribution of the transformer cannot be calculated, and thus the local overheating still remains a problem. A dynamic core loss model was proposed for loss distribution calculation [1, 7] based on the equivalent elliptical loop method, which is inaccurate to account for the magnetic hysteresis.

This paper proposes a new method to calculate the core loss and its distribution in a magnetic core by the FEM incorporated with the Jiles–Atherton (J-A) dynamic hysteresis model, which integrates the hysteresis, eddy current, and excess losses. To assess the calculation accuracy, the calculated core loss is compared with the experimental results obtained by both the single-sheet and Epstein frame testers.

II. THE J-A DYNAMIC HYSTERESIS MODEL

A. The J-A Dynamic Hysteresis Model

In order to consider the effects of eddy current and excess losses on the hysteresis loop, the traditional J-A hysteresis model is extended to the J-A dynamic hysteresis model.

The differential expression of the dynamic J-A model can be expressed as

$$\frac{dM}{dB}=\frac{M-M_{an}-\dfrac{ck\delta}{1-c}\dfrac{dM_{an}}{dH_e}+k_c\dfrac{dB}{dt}+k_c\delta\left|\dfrac{dB}{dt}\right|^{\frac{1}{2}}}{\mu_0(\alpha-1)(M_{an}-M+\dfrac{ck\delta}{1-c}\dfrac{dM_{an}}{dH_e})-\dfrac{\mu_0 k\delta}{1-c}} \tag{3}$$

where $k_c=e^2\sigma/2\beta$, $k_e=(GSV_0\sigma)^{1/2}$, e is the thickness of material, σ the conductivity, β a geometric coefficient, G a coupling constant, S the cross-sectional area of steel sheet, V_0 a statistical coupling field coefficient, M_{an} the anhysteretic magnetization, k the pinning coefficient, δ the direction coefficient, δ=1 for $dH/dt>0$, δ=-1 for $dH/dt<0$, α the local field parameter, and c the reversibility parameter.

By fitting the J-A dynamic hysteresis model to the experimental data by the PSO algorithm, 7 parameters of the model were determined. It was found that these parameters varied with the flux density, and the mathematical relationships between these parameters and the flux density were also determined. More details will be presented in full paper.

B. The FEM Considering Magnetic Hysteresis

The differential expression of FEM considering magnetic hysteresis can be written as

$$\left.\begin{aligned}&\Omega:\nabla\times\frac{1}{\mu}\nabla\times\mathbf{A}-\nabla\times\mathbf{M}=\mathbf{J}\\&\Gamma_1:\mathbf{A}=0\\&\Gamma_2:\frac{1}{\mu}\nabla\times\mathbf{A}\times\mathbf{n}=0\end{aligned}\right\} \tag{4}$$

where **A** is the vectorial magnetic potential, **M** the magnetization, **J** the excitation current density, μ the differential permeability, and **n** the unit normal vector.

III. CALCULATION AND VERIFICATION

A. *Single Sheet Test Simulation and Verification*

To verify the accuracy of proposed model, the calculated results are compared with measured data of SST. Fig. 1 shows the single sheet tester SST 500 used in the experimental characterization of silicon steel sheets. For this study, the B-H relationship and the corresponding core losses of non-oriented silicon steel sheets, 50ww470, were measured and calculated.

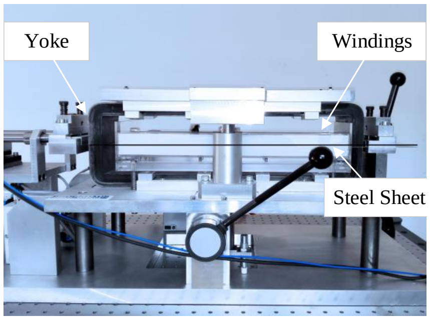

Fig. 1. Single-Sheet Tester (SST 500)

The core losses corresponding to different magnetic flux densities were simulated and compared with the experimental data, as shown in Fig.2 and Table I.

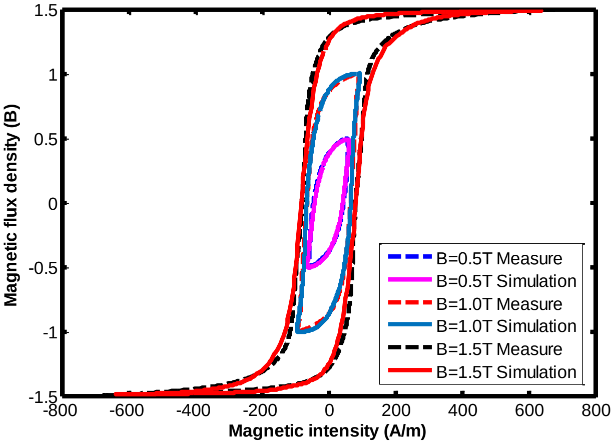

Fig. 2. Dynamic hysteresis loops of different magnetic flux densities at 50 Hz

TABLE I

COMPARISON OF CALCULATED RESULTS WITH SINGLE SHEET TESTS AT 50HZ

B (T)	Calculated Core loss (W/kg)	Measured Core loss (W/kg)	Error (%)	Eddy current loss (W/kg)	Excess loss (W/kg)
0.5	0.4681	0.4632	-1.1	0.0859	0.0405
1.0	1.4669	1.4759	0.6	0.5792	0.1505
1.5	3.2834	3.2787	-0.1	0.8889	0.2209

B. *Epstein Frame Test Simulation and Verification*

To further confirm the accuracy of the proposed model, the experimental results of Epstein Frame tests are used to compare with the theoretical results. Fig.3 shows the Epstein Frame test system, and Table II tabulates the calculated and measured results. As shown, the proposed model is sufficiently accurate for engineering applications.

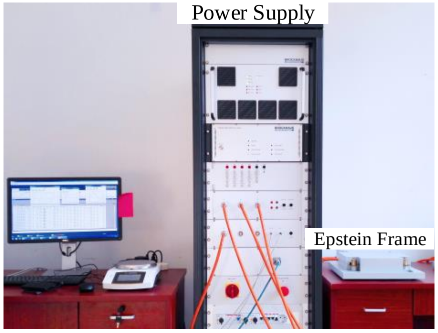

Fig. 3. Epstein Frame test system.

TABLE II

COMPARISON OF CALCULATED RESULTS WITH EPSTEIN FRAME TESTS AT 50HZ

B (T)	Calculated Core loss (W/kg)	Measured Core loss (W/kg)	Error (%)	Eddy current loss (W/kg)	Excess loss (W/kg)
0.5	0.5323	0.5423	1.8	0.1474	0.0536
1.0	1.7921	1.7082	-4.9	0.5200	0.1394
1.5	3.5464	3.6335	2.4	0.8727	0.1754

Fig.4 shows the core loss distribution in the test sample of the Epstein Frame when the flux density is 1.5T. As shown, the core loss distribution is reasonably uniform except at the four corners, confirming the validity of the Epstein Frame tests.

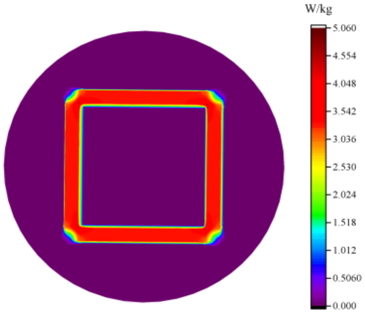

Fig. 4. Epstein Frame core loss distribution.

To test the implementation of the calculated model under the influence of harmonics, minor loops simulation and verification will presented in full paper.

IV. REFERENCES

[1] Lin Cao, JInliang He, and Bo Zhang, "Dynamic Hysteresis Loss Model of Power Transformer Under DC Current Biasing and Its Verification". *Proceedings of the CSEE*, Vol. 28, No. 24, pp. 141-146, 2008.

[2] G. Bertotti, "General properties of power losses in soft ferromagnetic materials". *IEEE Transactions on Magnetics*, Vol. 24, No. 1, pp. 621-630, 1988.

[3] Jianguo Zhu, *Numerical Modelling of Magnetic Materials for Computer Aided Design of Electromagnetic Devices*, PH.D. Thesis, University of Technology, Sydney, Sydney, 1994.

[4] Fugui Liu, Qingxin Yang, and Weili Yan, "Magnetic field numerical calculation method considering hysteresis characteristic". *Journal of North China Electric Power University*, Vol. sup, No. 32, pp. 59-61.

[5] Fugui Liu, *the Computation of Magnetic Field Taking in Account Hysteresis and the Measurement Techniques of Magnetization Properties*, PH.D Thesis, Hebei University of Technology, Tianjin, 2001.

[6] Yang Wang, and Zhizhen Liu, "Estimation Model of Core Loss Under DC Bias". *IEEE Transactions on Applied Superconductivity*, Vol. 26, No. 7, pp. 1-5, 2016.

[7] D. Lin, P. Zhou, W. N. Fu, Z. Badics, and Z. J. Cendes, "A Dynamic Core Loss Model for Soft Ferromagnetic and Power Ferrite Materials in Transient Finite Element Analysis". *IEEE Transactions on Magnetics*, Vol. 40, No. 2, pp. 1318-1321, 2004.