

Enhanced Loss Model and Magnetostriction Model for Oriented Silicon Steel Sheets under Complex Operating Conditions

Huiqi Li¹, Feng Zhang¹, and Guang Ma², Yuru Liao¹, Guang Yang¹

¹Hebei Key Laboratory of Green and Efficient New Electrical Materials and Equipment,
North China Electric Power University, Baoding, 071003 China, huiqili@263.net

²State Key Laboratory of Advanced Power Transmission Technology,
China electric power research institute, Beijing, 100192 China

The magnetic characteristics of the oriented silicon steel used in transformer cores vary with material properties, external frequency, and mechanical stress. Adverse operating conditions can exacerbate the losses in oriented silicon steel sheets and enlarge the magnetostrictive strain, leading to noise issues. In this paper we present an enhanced loss separation model and a magnetostrictive model for oriented silicon steel sheets under complex operating conditions. These two models are established on the basis of Bertotti's traditional loss separation model and Sablik-Jiles' magnetostrictive model. Drawing upon ferromagnetism theories, such as excess loss, hysteresis loss, and stress-induced magnetostrictive strain, a series of experimental investigations have been carried out on the loss and magnetostriction characteristics of various models of oriented silicon steel sheets under varying stresses and frequencies. These experiments validate the effectiveness and accuracy of the enhanced loss separation model and magnetostriction model. Furthermore, by utilizing the enhanced model proposed in this article, the loss characteristics and magnetostriction variation of oriented silicon steel sheets under complex operating conditions are examined, thereby confirming the precision of the two models. The findings presented in this paper serve as a crucial theoretical foundation for the reduction of loss and noise in transformers.

Index Terms—magnetic losses, magnetostriction, mechanical stress, frequency

I. INTRODUCTION

The EU's Carbon Border Adjustment Mechanism (CBAM) and new battery regulations have expedited the necessity for industrial upgrades and low-carbon technologies in the power sector [1]–[2]. Transformers, which serve as critical components in power systems, suffer from increased losses and magnetostriction-induced noise due to mechanical stress, excitation frequency, and material properties. Investigating the loss and magnetostriction behavior of grain-oriented silicon steel (transformer core material) under different conditions provides a theoretical basis for energy-efficient transformer design. Although prior studies [3]–[4] experimentally analyzed stress effects on magnetic properties and established stress-loss correlations, they lacked in-depth modeling. Additionally, the study on Ferromagnetism [5] briefly discussed magnetostriction factors while omitting stress and material effects.

The study in this paper is primarily based on the Bertotti loss separation model and the magnetostrictive model proposed by Sablik-Jiles, combining the mechanisms of stress effects on the magnetic properties of oriented silicon steel in ferromagnetism. It presents an enhanced loss separation model and an enhanced magnetostrictive model that comprehensively considers stress, frequency, and material characteristics. Experimental validation of the enhanced models demonstrates their high level of accuracy.

II. ENHANCED LOSS MODEL AND MAGNETOSTRICTION MODEL UNDER COMPLEX WORKING CONDITIONS

A. Enhanced loss separation model

The iron losses P_s in ferromagnetic materials can be

classified into three categories: the hysteresis loss P_h , the eddy current loss P_e , and the excess loss P_e . Given that the traditional loss separation model fails to consider the influence of stress on losses, it is imperative to refine the traditional loss separation model.

The modification of the loss separation formula yields

$$\frac{P_s - P_e}{f} = \frac{P_h}{f} + \frac{P_e}{f} = W_h + 8\sqrt{\sigma GSV_0} B_m^{1.5} f^{0.5} \quad (1)$$

where, f is the excitation voltage frequency, measured in Hz, B_m is the peak magnetic flux density, measured in T, σ is the conductivity of grain-oriented silicon steel, measured in S/m, S is the cross-sectional area of the sample, measured in m², G is a constant equal to 0.1356, W_h is the hysteresis loss per cycle, measured in J/kg. The excess loss parameter V_0 is utilized to describe the influence of various microstructural features, such as grain size, grain texture, and residual stress[6]. Since the hysteresis loss and the excess loss parameter V_0 share the same stress correlation, in this paper the coefficients in excess loss and hysteresis loss are formulated as functions of stress and peak magnetic induction intensity.

$$V_0 = pB_m^\alpha (1 + \tau)^m \quad (2)$$

$$W_h = qB_m^\beta (1 + \tau)^n \quad (3)$$

where, τ represents the magnitude of the mechanical stress, in MPa, p and q represents the dimensionless coefficients, α and β represent the polynomials related to the peak magnetic induction intensity, m and n represents the polynomials related to stress.

The enhanced excess loss parameters and hysteresis losses will be inserted into (1) to develop a refined loss separation

model under mechanical stress.

B. Enhanced magnetostriction model

In the field of ferromagnetism, the relationship between magnetostrictive strain and magnetic flux density is described as follows:

$$\lambda = kB^2 \quad (4)$$

where, k is the coefficient related to magnetostriction, which in ferromagnetism is associated with the stress experienced during the compressing process of magnetic domains. As the thickness of the silicon steel sheet increases, the magnetic elasticity contributed by individual closed domains increases accordingly, leading to a higher magnetostrictive strain. The thickness of oriented silicon steel sheets will affect the distribution of magnetic domains and the overall magnetomechanical performance. That implies that k_{yn} is affected, which can be expanded to the coupling coefficient associated with the thickness of oriented silicon steel sheets and the magnetic domain strain coefficient. In consideration of the effect of stress on the magnetization process, an enhanced model for the magnetostrictive behavior of oriented silicon steel sheets is presented regarding their thickness.

$$\lambda = (b_1 + \tanh(\frac{b_2 - \tau}{b_3})) \sum_{n=1}^{\infty} (c_{yn}d + k_{yn})B_y^{2n}f \quad (5)$$

where, c_{yn} is the fitting coefficient related to thickness, and k_{yn} is the fitting coefficient accounting for other factors. Here, b_1 , b_2 , and b_3 denote the fitting coefficients, reflecting the effect of stress on the magnetostrictive strain of oriented silicon steel. Different values of n lead to varying degrees of influence in polynomial expansion during the fitting calculation. For oriented silicon steel strips with a thickness of 0.20 mm, the root mean square error (RMSE) value attains saturation at $n = 4$.

III. EXPERIMENTAL VALIDATION

To verify the accuracy of the two enhanced models for loss separation and magnetostrictive effects, in this study we employ the BROCKHAUS magnetostrictive measurement system to experimentally measure the loss characteristics and magnetostrictive properties of various types of oriented silicon steel sheets. Measurements are conducted under both stress-free conditions and uniaxial stress applied along the rolling direction, across a range of frequencies. The measurement system is depicted in Figure 1.



Fig. 1. Magnetostriction measurement system

Taking the application of a 50Hz excitation as an example, Figure 2 displays the calculated values and experimental

measurements of loss and magnetostrictive for the 20SQGD065 grade (0.20mm thickness) grain-oriented silicon steel sheets at 50Hz. In the figure, compressive stress is represented by negative values following the implementation of the enhanced dissipation separation model.

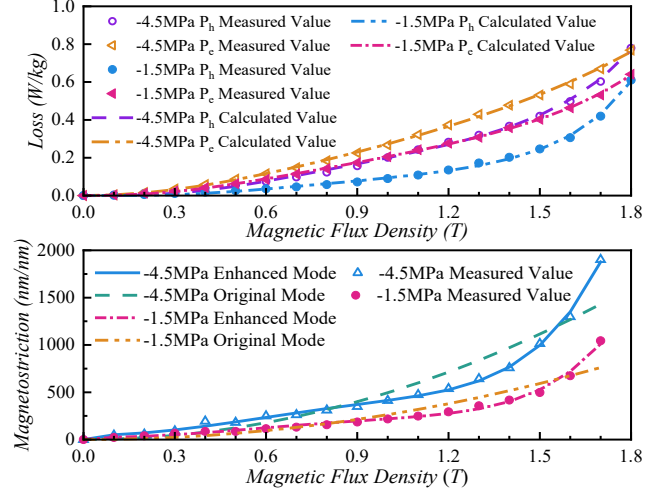


Fig. 2. Results of loss and magnetostriction

As shown in Figure 2, the calculated values of residual loss and hysteresis energy loss under different stresses, employing the enhanced loss separation model and magnetostriction model proposed in this paper, align well with the measured values within the permissible stress range of oriented silicon steel. The calculated curve reflects the experimental measurements quite well.

The updated model enables precise calculation of core losses and magnetostriction in oriented silicon steel sheets under varying stress and magnetic flux density conditions. It is applicable to silicon steel sheets of any frequency, grade, and thickness, with error reduced from 30.785% to 0.024%. It allows accurate prediction of magnetic properties under complex operating conditions, provides theoretical guidance for transformer core material selection, and quantitatively evaluates tensile/compressive stresses on silicon steel sheets to achieve precise assessment of core stress states.

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