Influence of *B-H* Curve Extrapolation Method on Transformer Characteristics under GIC condition

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This paper investigates the influence of *B-H* extrapolation methods on the transformer characteristics under GIC conditions. Four commonly used *B-H* extrapolation methods are applied, and their effects on the magnetic properties of grain-oriented electrical steel sheets in the saturation region are explained. Considering these magnetic properties, the magnetic and thermal characteristics of the transformer are evaluated using 3D finite element method. Through numerical estimations applying various extrapolation methods, this study demonstrates that the choice of B-H curve extrapolation method is a crucial factor in predicting transformer characteristics under GIC conditions.

***Index Terms*—Extrapolation method, Finite element method, Geomagnetically induced current, Transformer**

I. Introduction

POWER TRANSFORMER experiences geomagnetically induced currents (GIC) due to geomagnetic field disturbances. This current is induced in the transmission lines and flows into the transformer windings through the neutral point of the Y-connection. This current causes half-cycle saturation of the transformer core, which is made of grain-oriented electrical steel sheets. As saturation intensifies, the leakage flux from the core flows into nearby steel structures such as the tie-plate and end-frame, leading to eddy current losses and subsequent local temperature rise in these structures. Therefore, transformer manufacturers assess the health of transformers by evaluating these conditions in advance.

Numerous studies have been conducted to predict the temperature rise in transformers due to GIC. These studies have primarily focused on numerical methods such as the reluctance network model, duality-based equivalent circuit model, and the finite element method (FEM), as well as experimental studies conducted through laboratory and field tests [1]-[3]. Additionally, research has been done on the estimation of heat transfer coefficient which directly affects temperature rise in transformer structures [4].

From a different perspective than previous studies, this paper aims to investigate the impact of the *B-H* curve extrapolation method for grain-oriented electrical steel sheets used in the transformer core on temperature rise prediction under GIC condition. Since transformers exposed to GIC condition operate in an abnormal state with a saturated core, the extrapolation method of the *B-H* curve becomes a crucial issue. This is because the degree of extrapolation influences the amount of flux leakage from the saturated core.

This paper compares the magnetic characteristics of anisotropic electrical steel sheets based on different extrapolation methods and examines their impact on the magnetic and thermal characteristics of transformers under GIC condition. To evaluate magnetic and thermal characteristics of the transformer, transient non-linear magnetic analysis and coupled static-thermal analysis using 3D FEM are performed by ANSYS on a three-phase five-limbed power transformer, which is strongly influenced by GIC condition.

II. *B-H* Curve Extrapolation Method

A. Extrapolation methods

During the investigation, four commonly used models of the *B-H* curve extrapolation method were applied in this paper [5].

The linear extrapolation method (LE) uses a linear function with the last two data points (n) and (n-1) to extrapolate the saturation region. The differential permeability (D_n) is defined as follows:

$$D_n = \frac{1}{\mu_0} \cdot \frac{B_n - B_{n-1}}{H_n - H_{n-1}} \tag{1}$$

The law of approach to saturation method (LAS), widely discussed in scientific literature, is expressed as follows:

$$M = M_s \left(1 - \frac{b}{H^2}\right) \tag{2}$$

M and M_s represent magnetization and saturation magnetization in A/m, respectively. The coefficient b can be calculated analytically at the last data point n.

The simultaneous exponential extrapolation method (SEE) represents the saturation region using an exponential function of $B(H)$ as follows:

$$B = J_s(1 - ue^{-vH}) + \mu_0 H \tag{3}$$

J_s is the saturation induction in T. The coefficients u, v can be calculated analytically at the last data point n. J_s can be estimated from the resistivity ρ of the electrical steel sheet as follows:

$$J_s = 2.2041 - 0.003726 \cdot \rho \tag{4}$$

The quadratic extrapolation method (QE) is represented by two regions as shown in Eq. 5. Before the saturation region, it is expressed using a quadratic function where the differential permeability (D) is greater than 1, and after the saturation region, it is expressed using a linear function where D is equal to 1.

$$H = a_2 B^2 + a_1 B + a_0, \qquad D_n \le D < 1 \tag{5-1}$$

$$H = (B - J_s)/\mu_0, \qquad D = 1 \tag{5-2}$$

The coefficients a_2, a_1 and a_0 can be calculated analytically using boundary conditions and the last data point n.

B. Comparison of saturation region of B-H curve

Fig. 1 and 2 compare the *B-H* characteristics and differential permeability in the saturation region calculated using the four extrapolation methods. The *B-H* curve was measured up to 1.9 T for the anisotropic electrical steel sheet 30PH105 by an Epstein Frame Tester.

Since the LE method uses the measured data of differential permeability at the last point, it maintains a differential permeability of about 100 even at high flux densities, which deviates from physical phenomena. This indicates that the LE method is not suitable for GIC analysis dealing with issues in the saturation region. For the LAS, SEE and QE methods, which use quadratic and exponential functions, it can be seen the differential permeability approaches almost 1 above 2.1 T. However, between 1.9 T and 2.1 T, the change trends vary depending on the extrapolation method, and at 2.0 T, the differential permeability is high in the order of SEE, QE, and LAS. Additionally, while LAS and QE show relatively smooth changes in differential permeability in the saturation region, SEE exhibits a rapid variation in permeability.

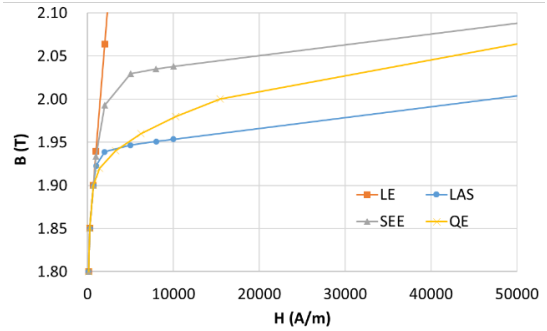


Fig. 1. Comparison of *B-H* curves according to extrapolation methods.

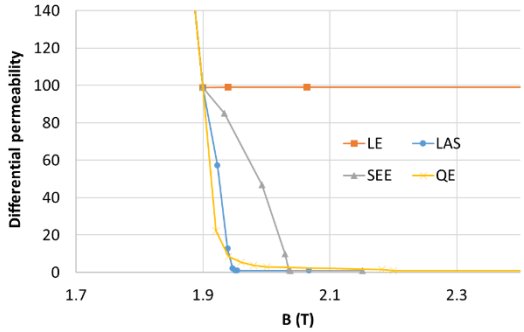
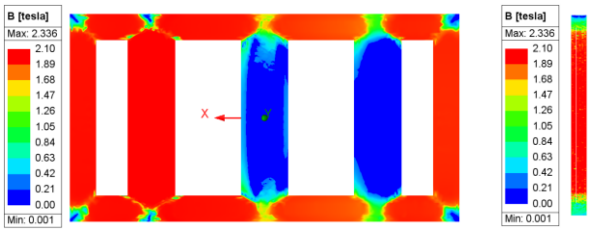


Fig. 2. Comparison of differential permeability curves.

III. Analysis of Transformer

The 3D finite element analysis is performed for 690 MVA three-phase five-limbed transformer which the rated voltages and connection are 345/18.05/18.05kV and YNd1d1. The analysis is performed under no-load conditions, and an GIC of 50 A_{dc} per phase is applied through the neutral point of the high-voltage winding.

Fig. 3 shows the flux density distribution in the transformer core and tie-plate with GIC. Due to GIC, the core becomes fully saturated, and a significant amount of flux leakage due to this saturation is observed to enter the tie-plate. Therefore, it implies that the saturation degree of the core, as well as the leakage flux and resultant eddy current loss in the tie-plate, are likely to be affected by the extrapolation method used in the saturation region of the electrical steel sheets.



(a) core (b) tie-plate

Fig. 3. Magnetic flux density distribution in core and tie-plate under GIC

Table I compares the flux density in the core and eddy current loss in the tie-plate according to the extrapolation method when GIC is applied. The eddy current losses in the tie-plate vary depending on the extrapolation method because the magnitude of the leakage flux in the tie-plate changes according to the extrapolation method. Hence, the choice of extrapolation method becomes a key point when dealing with core saturation and structural losses and temperature rise due to GIC.

TABLE I
FLUX DENSITIES IN CORE AND EDDY CURRENT LOSSES IN TIE-PLATE ACCORDING TO EXTRAPOLATION METHODS

Method	Flux density in core [T]	Eddy current loss in tie-plate [W]
LE	1.900	4932
LAS	1.934	4452
SEE	2.010	3777
QE	1.980	4261

IV. Conclusion

This paper shows that differences in *B-H* curve extrapolation methods influence the core saturation level and eddy current loss in the plates near the core. It demonstrates that the choice of extrapolation method is a key factor affecting the prediction of transformer characteristics under GIC conditions. In the full version of the paper, both the magnetic and thermal properties of the transformer will be explained under various GIC conditions in more detail.

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