# Modeling and Validation of Magnetic Anisotropy Model Based on Energy for Silicon Steel Goss Structure

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**Grain-oriented silicon steel used as the core of power transformer has complex magnetic anisotropy characteristic. This paper proposes a magnetic anisotropy model of GO silicon steel Goss structure. Then the numerical method coupled the model and FEM is implemented in Matlab. At last, the engineering validation model is designed and built up. The comparison between the measurement and simulation proves the validation of the proposed model.**

***Index Terms*—Magnetic properties, magnetic anisotropy, finite element analysis, electro-magnetism.**

## I. Introduction

Grain-oriented(GO) silicon steel is widely used in power transformer. In order to improve the accuracy of electromagnetic finite element analysis of power transformer, the magnetic anisotropy model should be built up for GO silicon steel with Goss structure [1]. The permeability of GO silicon steel in transverse direction is much lower than that in the rolling direction. In the orthogonal magnetic anisotropy model, the rolling and transverse direction magnetic properties are independently calculated and then combined [2]. Furthermore, vector magnetic saturation is considered in elliptic magnetic anisotropy model. The two orthogonal *B-H* curves are interpolated into a two-dimensional plane [3, 4]. There is an important fact neglected in the orthogonal and elliptic magnetic anisotropy model. The permeability of Goss structure in the 55° with the rolling direction is lower than that of any of direction in the silicon steel plane. This simplification would cause calculation errors at the T-joints of power transformer. In this paper, a magnetic anisotropy model considering the 55° magnetic property is established, implemented and verified.

## II. Modeling of Magnetic Anisotropy

The primary goal in this modeling is to describe the magnetic properties in the 55° with the rolling direction. Thus, the modeling data must consist of at least three *B-H* curves which are measured along 0°, 55° and 90° with the rolling direction of GO silicon steel.

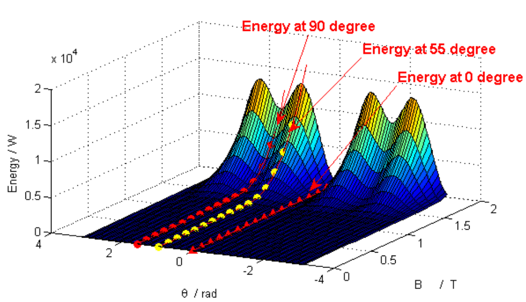



Fig. 1 Energy surface of GO silicon steel 18rk90.

Based on the work of magnetic field, the magnetic energy is expressed as

$$w(\boldsymbol{B}) = \int_0^{\boldsymbol{B}} H(\boldsymbol{B}) \cdot d\boldsymbol{B} \tag{1}$$

The three magnetic energy curves are integrated at 0°, 55° and 90° respectively. Then, the energy surface in polar coordinate system is interpolated by three energy curves by cubic spline method. Based on (1), the magnetic field strength is calculated by

$$\boldsymbol{H} = \frac{\partial w(\boldsymbol{B})}{\partial \boldsymbol{B}} \tag{2}$$

When the sample of GO silicon steel is excited by rotating magnetic flux density, the loci of magnetic strength field are plotted in Fig.2 based on (2).

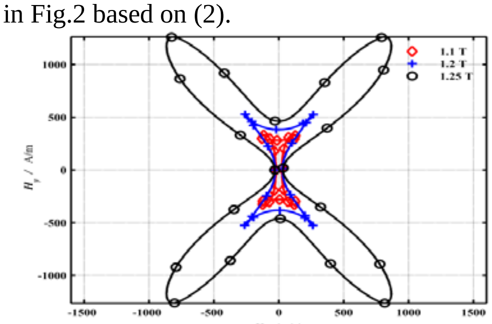



Fig. 2 The loci of magnetic field strength loci when the loci of rotational magnetic flux density range from 1.1T to 1.25T.

## III. Inclusion of Magnetic Anisotropy Model in FEM

The magnetic field distribution in power transformer and electrical machine is not coherent and homogenous, so electro-magnetism finite element method is developed using the proposed magnetic anisotropy model.

### A. FEM Approach

The numerical simulation equation in 2D is expressed as

$$\sigma \frac{\partial A_z}{\partial t} - \frac{1}{\mu_0} \nabla^2 A_z = J_z + \nabla \times \boldsymbol{M} \cdot i_z \tag{3}$$

where $\boldsymbol{A_z}$ is the magnetic vector potential and $J_z$ is the source current density. In the FEM based on $\boldsymbol{A}$, the magnetic flux density $\boldsymbol{B}$ is calculated at each time step. Then, the magnetic field strength $\boldsymbol{H}$ is determined by the magnetic anisotropy model of the laminated material.

$$\begin{cases} M_x = \dfrac{B_x}{\mu_0} - H_x \\ M_y = \dfrac{B_y}{\mu_0} - H_y \end{cases} \tag{4}$$

where $H_x$ and $H_y$ are calculated by the magnetic anisotropy model (e.g. elliptic model and the proposed energy model).

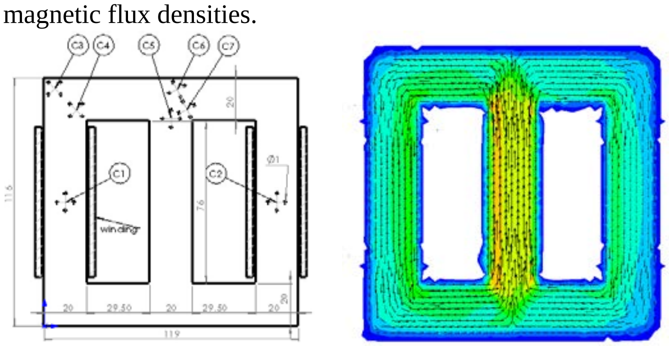
### B. *Solvers of FEM*

When the traditional magnetic anisotropy model,(e.g. elliptic model and two axis orthogonal model), is coupled with FEM, the nonlinear system is global convex and differentiable. As a result, the solver can be chosen as Newton-Raphson algorithm. However, when the energy anisotropy model based on three curves is coupled with FEM, local extreme points would be generated and fixed-point method must be used in order to guarantee the convergence and stability.

## IV. Experimental Validation

### A. *Validation model of magnetic anisotropy*

To validate the proposed magnetic anisotropy method, a three-limb laminated core is designed as shown in Fig. 3(a). The GO silicon steel 18rk90 is cut into a single part without air gap. The vertical direction is the rolling direction of the silicon steel, while the horizon direction is the transverse direction. The model is not as efficient as the real power transformer made up by the overlapped silicon steel which flux path is always along the rolling direction of silicon steel. However, the validation model can diminish the leakage flux effect as far as possible focusing on the magnetic anisotropy properties. The two windings are supplied by two independent excitation circuits. The cross pick-up coils (C1-C7) of 5 turns are drilled at different places to measure the local vector magnetic flux densities.




(a) (b)

Fig. 3 Experimental validation model of magnetic anisotropy modeling (unit: mm).

### B. *Control Mode*

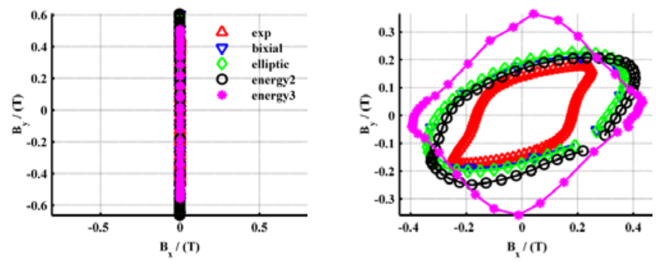
In all cases, both left and right windings are supplied by power amplifiers (MC E90), which magnitude of excitation voltage are the same and which phase difference is different listed in Table.1. The Case 1 and Case 2 simulated the alternating magnetization at the limb and yoke. And the Case 3 simulated the rotational magnetization at the T-joint. In the experiments, open loop excitation signal cannot make sure the exact voltage phase relation of both winding. Consequently, an adaptive digital feedback algorithm is applied to the validation model to guarantee the desired phase difference and magnitude of flux density [6].

Table. 1 Different excitation cases for validation model

| | Case 1 | Case 2 | Case 3 |
|---|---|---|---|
| $\Phi(U_1\text{-}U_2)$ | 180° | 0° | 90° |
| *Mode* | Strength alternating | Weaken alternating | Rotational excitation |

### C. *Comparison between experiments and simulations*

Fig.3(b) shows the distribution of magnetic flux density plotted by Tecplot™. And Fig.4 illustrates the comparison between of experiments and FEM simulation which proves the validation of the proposed magnetic anisotropy model. More details and analysis are presented in the full paper.




(a) (b)

Fig. 4 Comparison of different loci of vector magnetic flux density. (a) coil C1 (b) coil C5. exp: experiment, bixial: two axis orthogonal model, elliptic: elliptic model, energy2: energy model based on two *B-H* curves, energy3: energy model based on three *B-H* curves.

## V. Conclusion

The proposed magnetic anisotropy model describes the Goss structure of GO silicon steel. Compared with the traditional model, the proposed model takes into account the magnetic properties along the 55° magnetic hard axis. Furthermore, the improved FEM coupling algorithm guarantees the convergence of the FEM simulation.

## Acknowledgment

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