Using vector stop hysteresis model for anisotropic magnetic material with finite element method

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***Abstract* –This paper presents an anisotropic vector stop model to represent the magnetic property of electrical steel sheet. The influence from this anisotropic hysteresis model on the distribution of flux density in electrical machines is analysed by finite element method (FEM). The vector stop model based on the second thermodynamic law has an analogy to the rheological elements for mechanics. The spring elements for elastic deformation are used in vector stop model representing the anhysteretic anisotropic characteristics. In our model, the anisotropic properties of magnetic material will be dealt with anhysteretic anisotropic model.**

I. INTRODUCTION

Commonly used hysteresis models are isotropic hysteresis models, which can be simplified to scalar hysteresis model by neglecting the anisotropy behaviour of soft magnetic materials [1]. Although an isotropic property is expected for non-oriented (NO) electrical steel sheets, the anisotropy effect can still be noticed. To represent the magnetic anisotropy in dependency to the amplitude and direction of the applied magnetic field, different vector hysteresis models are built. A simple model is given by superposition of scalar hysteresis models from different directions [2] [3]. The other option is to vectorised with play or stop operators directly, which has a thermodynamic consistency in the entire model [4] [5]. The Play or Stop models are constructed with rheological elements. In this way, the hysteresis model is splitt into a reversible and an irreversible part, modelled by a spring and a friction damper [6].

There are several approaches to represent the anisotropy anhysteretic properties. The anhysteretic model can be derived from measurements by interpolation between different excitation directions. Some of the models are based on the energy or coenergy density. The anisotropic anhysteretic behaviour is considered by the equal contours of the energy density [7] [8]. In this paper, the anhysteretic part of the model is implemented by the anisotropic anhysteretic surfaces $\vec{\boldsymbol{H}}_{\boldsymbol{x}}(\vec{\boldsymbol{B}}_{\boldsymbol{x}},\vec{\boldsymbol{B}}_{\boldsymbol{y}})$ and $\vec{\boldsymbol{H}}_{\boldsymbol{y}}(\vec{\boldsymbol{B}}_{\boldsymbol{x}},\vec{\boldsymbol{B}}_{\boldsymbol{y}})$. These surfaces are obtained by interpolation of ten alternating measurement data using a rotational single sheet tester (RSST). In the end, the Stop model with anisotropic characteristic is integrated into FEM solver to study the influence from hysteresis model on the distribution of magnetic flux density in electrical machines during FEM simulation.

II. MEASUREMENTS FROM RSST

In order to gain the amplitude relationship and phase shift between the magnetic field $\vec{\boldsymbol{H}}$ and magnetic flux density $\vec{\boldsymbol{B}}$, the sample with a thickness of 0.5 mm and a square shape of 60 × 60 mm is used to measure by the RSST. It is from the soft magnetic material M400 and is excited by flux densities from 0.1 T to 1.6 T with a step of 0.1 T. The excitation direction is along an angle from 0° to 90° in steps of 10°. To extract the anhysteretic characteristics from the measurements the major loops from each direction are used. As now without considering hysteresis part of the model, the Helmholtz free energy must be a convex surface to ensure the uniqueness of $\vec{\boldsymbol{H}}$, which means the reluctivity matrix must be positive definite [6]. According to this, the anhysteretic curves are smoothed and depicted in Fig. 1.

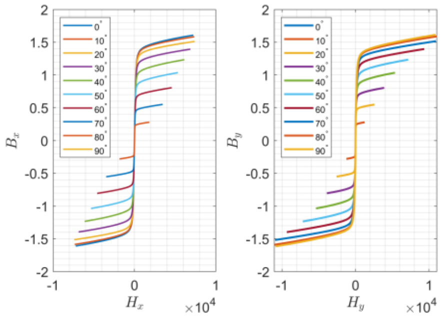


Fig. 1. Anhysteretic curves from measured major loop in the magnetization direction along 0° to 90°.

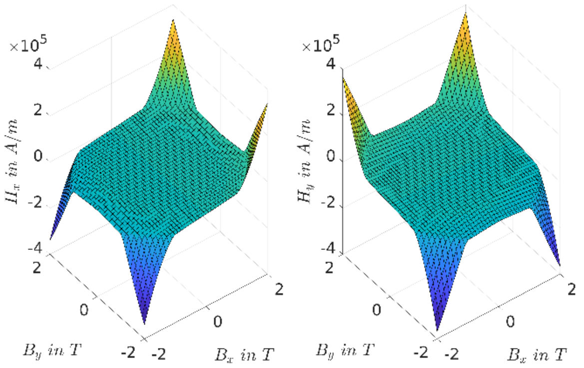
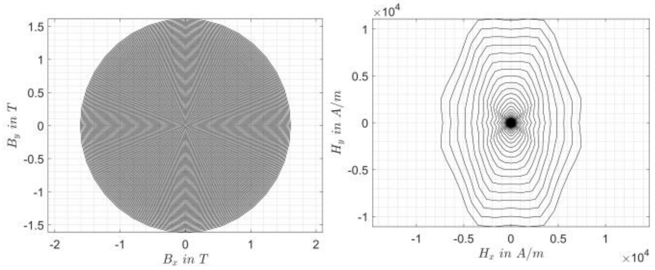
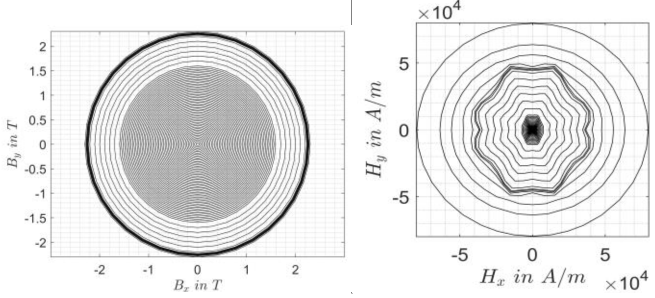


Fig. 2. Anhysteretic anisotropy surface in x and y direction by interpolation the anhysteretic curves.

The anhysteretic surfaces discribed in Fig. 2 are extracted by interpolation between anhysteretic $\vec{\boldsymbol{B}}\,(\vec{\boldsymbol{H}})$ curves from Fig. 1. The B-loci and H-loci obtained from this anhysteretic anisotropic model are illustrated in Fig. 3. As you can see, extrapolating the flux density up to 2.3 T, the materials tend to be isotropic. The H-loci tends to be more circular. This model is further used to represent the anisotropic anhysteretic properties by spring elements in Stop model.



a. magnetic flux density up to 1.6 T.



b. magnetic flux density extrapolated to 2.3 T.

Fig. 3. Extracted H-loci from anisotropic anhysteretic model.

III. ANISOTROPIC VECTOR STOP HYSTERESIS MODEL

The vector stop model can simulate the inverse relationship as $\vec{H}\,(\vec{B})$ directly, which is effecient by integrating into FE solver with vector potential fomulation.

The stop model is defined as [9],

$$\vec{H} = S(\vec{B}) = \int_0^{B_s} g\left(\eta, s_\eta(\vec{B})\right) d\eta \qquad (1)$$

where B_s is the saturation magnetic flux density, $s_\eta(\vec{B})$ the stop hysteron operator. $g\left(\eta, s_\eta(\vec{B})\right)$ is the shape function with η defining the hight of stop hysteron.

The shape function is then weighted with input dependent function $\omega(\vec{B})$ [9].

$$g\left(\eta, s_\eta, \vec{B}\right) = g_0(\eta, s_\eta)\,\omega(\vec{B}) \qquad (2)$$

As in stop model, the strain (analog as $\vec{B}$) is the input and the stress (analog as $\vec{H}$) is the output. One stop operator s_η is constructed with a spring in series connecting with a friction damper. Therefore, in each operator the stress on the spring is the same as the stress on the friction damper. So to evaluate the stress of one stop operator, only the stress on the spring is needed to be calculated. The shape function is aimed at representation the stress on the spring due to elastic deformation of it. The stop operators are then interconnected from each other with different weights $\omega(\vec{B})$.

In our model, in order to map the stress caused by the deformation of the spring, the shape function $g_0(\eta, s)$ is extracted from the anhysteretic anisotropic model. In this way the anisotropy of the hysteresis model is obtained directly.

Giving sinusoidal flux density excitations in x and y direction with maximal amplitude at 2 T into the vector stop model, the hysteresis curves from 0° to 90° obtained by this model are shown in Fig. 4. It is noticeable that the hysteresis curves obtained from this vector stop model is not a simple elliptical anisotropy. It can represent a hard magnetization direction between the excitation directions from 0° to 90°.

Furthermore, this vector stop model is applied into FE solver to simulate distribution of flux density in electrical machines.

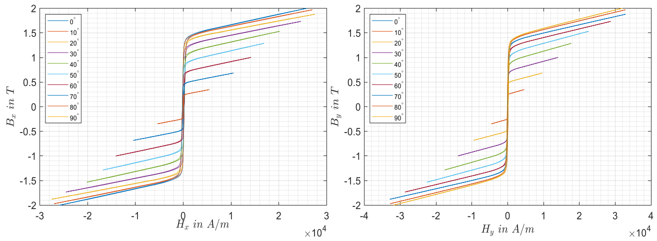


Fig. 4. Representation the anisotropic hysteresis obtained by stop model in the direction from 0° to 90°.

IV. CONCLUSIONS

By integrating the anisotropic anhysteretic vector surface into the shape function of the spring elements of the vector stop model the anisotropy can be represented. Furthermore, the FE simulation for electrical machines considering the hysteresis effects will be presented in the full paper.

V. ACKNOWLEDGMENT

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