Research on Stress Characteristics of Shunt Reactor Considering Magnetic and Magnetostrictive Anisotropy

Ben Tong[1], Yang Qingxin[1,2], Yan Rongge[1], Zhu Lihua[2], Zhang Changgeng[1]

[1] Province-Ministry Joint Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability, Hebei University of Technology, 300130, Tianjin, China yanrg@hebut.edu.cn

[2] Municipal Key Laboratory of Advanced Technology of Electrical Engineering and Energy, Tianjin Polytechnic University, 300387, Tianjin, China

In order to control and reduce the vibration of shunt reactors with air-gap core structure, accurate stress computation should be carried out. Stresses in reactor cores are generated from magnetostrictive deformation of silicon steel and electromagnetic force between the core discs. The ferromagnetic materials in reactor cores show magnetic and magnetostrictive anisotropy, which will largely affect the stress distribution of shunt reactor cores. However, non-oriented electrical steel in the shunt reactor cores were generally considered as magnetic and mechanic isotropy in the past studies on reactor stress. This paper tests magnetization and magnetostriction properties for non-oriented electrical steel sheet along the rolling direction (RD) and the transverse direction (TD) to support the computation. Based on the measured constitutive relations, an electromagneto-mechanical coupled numerical model for reactors is presented. Considering electromagnetic force effect and magnetostriction effect, reactor core vibrations including x direction and y direction are calculated. In order to study the influence of magnetic and magnetostrictive anisotropy on stress of shunt reactors, another model without considering magnetic and magnetostrictive anisotropy is calculated, too. From the computation results, it can be seen that the magnetic and magnetostrictive anisotropy greatly influences the peak value and distribution of reactor core stress.

***Index Terms*—Finite element analysis, magnetic anisotropy, magnetostriction, vibrations.**

I. Introduction

Shunt reactors are widely used in extra high voltage (EHV) power transmission system owing to their excellent working characteristics for reactive compensation. Due to their special core structure with air-gaps and core discs, shunt reactors have strong vibration and noise, which will become one of the restricting factors for their application and development [1].

It is generally believed that magnetostriction of silicon steel and electromagnetic force between reactor core discs are the major causes of the vibration of shunt reactors. Meanwhile, non-oriented silicon steel often shows magnetic and mechanic anisotropy [2]-[3], which will influence the magnetic field and stress distribution of reactor cores. However, previous research about reactor core vibration did not consider anisotropy of magnetic properties [1], which will affect the magnetic field and stress distribution of shunt reactors.

In this paper, an electromagneto-mechanical coupled numerical model considering magnetic and magnetostrictive anisotropy for shunt reactors is proposed to calculate electromagnetic force and magnetostrictive force. From the comparison between the computed results without considering and considering anisotropy, it can be seen that magnetic and magnetostrictive anisotropy has large effect on magnitude and distribution of reactor core stress.

II. Shunt Reactor Vibration Model

A. Analysis of magnetic and magnetostrictive anisotropy

Shunt reactors work in high magnetic flux density, thus this paper measures magnetic and magnetostrictive curves with the magnetic flux densities amplitude B_{max}=1.7T. Fig. 1 and Fig. 2 show the measurement device and the measured hysteresis loops of silicon steel sample along the RD and TD, respectively. As shown in Fig. 2, hysteresis loops are so slender that the hysteresis losses will be negligible. Thus, the single-value magnetization curves are measured and applied in stress computation of shunt reactors.

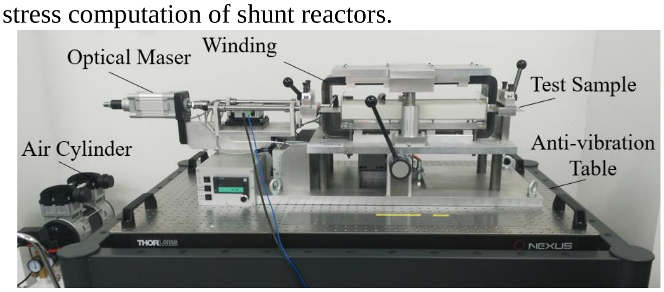

Fig. 1. Magnetization and magnetostriction measurement device.

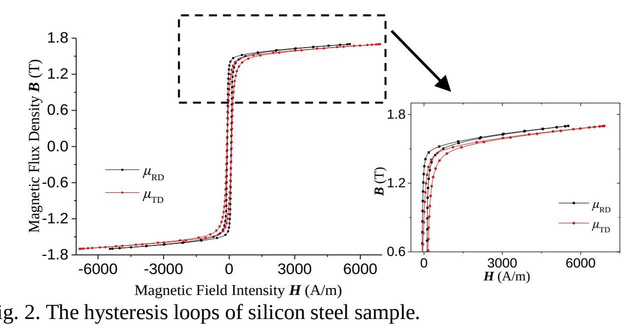

Fig. 2. The hysteresis loops of silicon steel sample.

The measured relative permeability and magnetostrictive property curves of non-oriented silicon steel along the RD and TD are shown in Fig. 3. As shown in Fig. 3, the NO silicon steel is more easily magnetized along the RD than that along the TD. On the contrary, the magnetostrictive deformation along the TD is more serious than that along the RD.

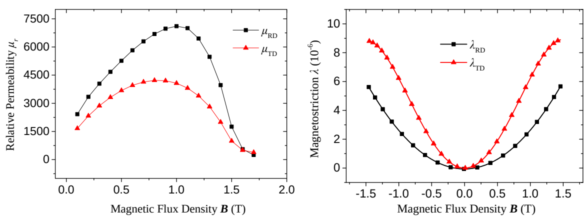

Fig. 3. Magnetic and magnetostrictive properties of non-oriented silicon steel along the RD and TD: (a) magnetic property; (b) magnetostrictive property.

B. Electromagneto-mechanical coupled model of shunt reactor

The total energy functional of shunt reactors can be expressed as follows:

$$I=\int_{\Omega_1}\left(\int_0^{\varepsilon}\sigma\cdot d\varepsilon\right)d\Omega-\int_{\Gamma_1}f^{\Gamma}\cdot u\,d\Gamma-\int_{\Omega_1}f^{\Omega}\cdot u\,d\Omega+\int_{\Omega_2}\left(\int_0^{H}H\cdot\mu\cdot dH\right)d\Omega-\int_{\Omega_2}\left(\int_0^{A}J\cdot dA\right)d\Omega+\int_{\Omega_1}(\sigma\cdot d\cdot H)d\Omega \quad (1)$$

where A is the magnetic vector potential. u is the mechanical displacement vector. σ and ε are the stress and strain tensor, respectively.

This paper adopts the Dirichlet boundary conditions (flux line boundary conditions), hence the potential energy of the magnetic field boundary is zero. $\mu=(\mu_x\ \ \mu_y)^{\mathrm{T}}$ and $d=(d_x\ \ d_y)^{\mathrm{T}}$, which are the permeability tensor and magnetostriction coefficient tensor, respectively, can obtain their parameters from measured results according the corresponding relations in different reactor core parts in Tab. 1.

TABLE I

THE CONSTITUTIVE RELATION ON DIFFERENT PARTS OF REACTOR CORES

Core Parts	Magnetic Permeability	Magnetostriction Coefficient
Iron Yoke	$\mu=\begin{bmatrix}\mu_{RD}(H_x) & 0\\ 0 & \mu_{TD}(H_y)\end{bmatrix}$	$\lambda=\begin{bmatrix}\lambda_{RD}(H_x) & 0\\ 0 & \lambda_{TD}(H_y)\end{bmatrix}$
Core Limb	$\mu=\begin{bmatrix}\mu_{TD}(H_x) & 0\\ 0 & \mu_{RD}(H_y)\end{bmatrix}$	$\lambda=\begin{bmatrix}\lambda_{TD}(H_x) & 0\\ 0 & \lambda_{RD}(H_y)\end{bmatrix}$

As for parallel plane field, the energy functional can be rewritten as:

$$\begin{aligned}I=&\int_{\Omega_1}\frac{1}{2}\left\{\frac{E}{1-\alpha^2}\left[\left(\frac{\partial u_x}{\partial x}\right)^2+\left(\frac{\partial u_y}{\partial y}\right)^2+2\left(\frac{\partial u_x}{\partial x}\right)\left(\frac{\partial u_y}{\partial y}\right)\right]+\frac{E}{2(1+\alpha)}\left[\left(\frac{\partial u_x}{\partial y}+\frac{\partial u_y}{\partial x}\right)^2\right]\right\}dxdy \quad (2)\\&+\int_{\Omega_2}\frac{1}{2}\left[\frac{1}{\mu_y}\left(\frac{\partial A}{\partial y}\right)^2+\frac{1}{\mu_x}\left(\frac{\partial A}{\partial x}\right)^2\right]dxdy-\int_{\Omega_2}JA\,dxdy\\&+\int_{\Omega_1}\left[d_y\frac{\partial A}{\partial y}\frac{E}{1-\alpha^2}\left(\frac{\partial u_x}{\partial x}+\alpha\frac{\partial u_y}{\partial y}\right)+d_x\frac{\partial A}{\partial x}\frac{E}{1-\alpha^2}\left(\frac{\partial u_y}{\partial y}+\alpha\frac{\partial u_x}{\partial x}\right)\right]dxdy,\end{aligned}$$

where E is the Young's modulus, α the Poisson ratio, ν the magnetic reluctivity.

To minimize the functional for unconstrained vertex A and u, we can obtain the matrix equation

$$\boldsymbol{KX}=\boldsymbol{F}, \quad (3)$$

where $\boldsymbol{X}$ is the unknown column matrix including the nodal magnetic vector potential A and displacement vector u , and $\boldsymbol{F}$ the known current column matrix, $\boldsymbol{K}$ the magnetic and mechanical stiffness matrix.

III. Vibration Calculation of Shunt Reactor

The peak value and frequency of the applied voltage are 50V and 50Hz, respectively. The calculated results without considering anisotropy are compared with those considering anisotropy under the same excitation, which is shown in Fig.4.

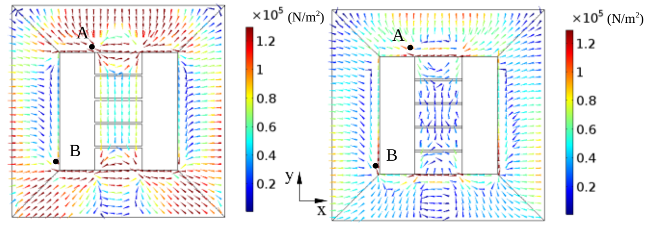

Fig. 4. The stress distribution of reactor core at t=0.015s: (a) without considering anisotropy; (b) considering anisotropy.

As shown in Fig.4, the magnetic and magnetostrictive anisotropy has effect on the distribution of reactor core stress. The two points A and B are chosen to analyze the stress magnitude variation during the running of the shunt reactor, which are shown in Fig. 5 and Fig. 6, respectively.

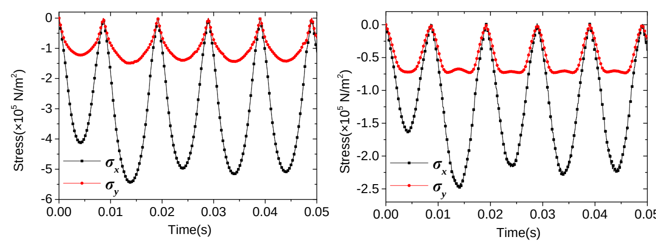

Fig. 5. The relationships between stresses and time at point A: (a) without considering anisotropy; (b) considering anisotropy.

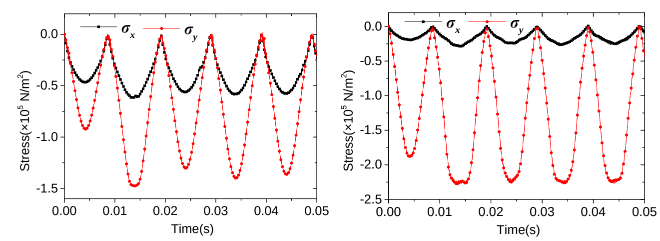

Fig. 6. The relationships between stresses and time at point B: (a) without considering anisotropy; (b) considering anisotropy.

As shown in Fig. 5 and Fig. 6, the stress peak value on reactor core without the consideration of anisotropic properties is bigger than that considering anisotropic properties. However, at the area of cores between air-gaps and the in-wall of core limbs (e.g. at point B), the conclusion is opposite from it.

Thus, we should adopt different vibration dampings at different locations to make the vibration reduction of shunt reactors more effective.

References

[1] R. Yan, X. Gao, L. Zhu, Q. Yang, T. Ben, Y. Li and W. Yang, "Research on three-dimensional stress distribution of reactor core," *IEEE Trans. Appl.*, vol. 26, no. 4, pp. 1-4, Jun. 2016.

[2] Y. Zhang, J. Wang, and X. Sun, et al, "Measurement and modeling of anisotropic magnetostriction characteristic of grain-oriented silicon steel sheet under DC bias," *IEEE Trans. Magn.*, vol. 50, no. 2, pp. 361-364, Feb. 2014.

[3] Y. Kai, Y. Tsuchida, and T. Todaka, et al, "Measurement of the two-dimensional magnetostriction and the vector magnetic property for a non-oriented electrical steel sheet under stress," *J. Appl. Phys*, vol. 111, no. 7, pp. 07E320 - 07E320-3, Apr. 2012.