3-D Vector Magnetic Properties of SMC Material for Advanced Field Analysis of SMC Machine

Youguang Guo¹, Jianguo Zhu¹, Haiyan Lu¹, Zhiwei Lin¹, Shuhong Wang¹,², and Jianxun Jin³
¹Faculty of Engineering and Information Technology, University of Technology, Sydney, NSW 2007, Australia
²Faculty of Electrical Engineering, Xi’an Jiaotong University, Xi’an, 710049, China
³Center of Applied Superconductivity, University of Electronic Science and Technology of China, Chengdu, 610054, China

Abstract- In a rotating electrical machine or the T-joints of a multiphase transformer, the magnetic flux is basically three-dimensional (3-D) and rotational. This paper presents the 3-D vector magnetic properties of soft magnetic composite (SMC) materials for advanced field analysis of electromagnetic devices with SMC core, which is particularly developed for application of electrical machines with complex structure and 3-D flux. The 3-D magnetic reluctivity tensor is derived from the magnetic measurements on a cubic SMC sample by using a 3-D magnetic property tester. The tensor consists of both diagonal and off-diagonal terms and the latter account for the effect of rotating flux. Practical techniques for employing the vector magnetic properties in field analysis are reviewed and discussed.

I. INTRODUCTION

In rotating electrical machines and T-joints of multi-phase transformers, particularly those with complex structures and three-dimensional (3-D) magnetic flux paths, a typical flux density vector in the armature core rotates circularly or elliptically in the 3-D space. Therefore, 3-D vector magnetic properties of ferromagnetic materials should be properly determined and applied in the device design and analysis [1].

For a 3-D flux machine, the magnetic field in the armature has significant component along any direction, so the conventional laminated steels are not suitable for the core because the field component perpendicular to the lamination plane may cause excessive eddy current loss. For such a machine, soft magnetic composite (SMC) material can be an ideal candidate thanks to its unique properties such as magnetic isotropy and very low eddy current [2]. A lot of research has been conducted to investigate the application potential of SMC in electromagnetic devices in the past decade. Typical examples are claw pole and transverse flux potential of SMC in electromagnetic devices in the past decade. For such a machine, soft magnetic composite (SMC) material can be an ideal candidate thanks to its unique properties such as magnetic isotropy and very low eddy current [2]. A lot of research has been conducted to investigate the application potential of SMC in electromagnetic devices in the past decade. Typical examples are claw pole and transverse flux potential of SMC in electromagnetic devices in the past decade.

Conventional magnetic field analysis only employs the reluctivities or B (flux density) – H (field strength) curves along three orthogonal coordinates. The data are obtained by measuring scalar B and H along a specified direction by using the Epstein testing or the single strip testing. In order to determine the tensor reluctivity, the relations between vectors B and H with not only alternating field in arbitrary directions but also rotating field should be obtained using two-dimensional (2-D) or 3-D magnetic testers.

This paper presents the 3-D vector magnetic properties such as 3-D reluctivity tensor of SMC materials for advanced magnetic field analysis of SMC electromagnetic devices. Different approaches considering the vector properties for advanced magnetic field finite element analysis (FEA) are reviewed and discussed.

II. 3-D VECTOR MAGNETIC PROPERTIES

Fig. 1 shows the 3-D magnetic property tester and Fig. 2 shows the cubic SMC sample with its B and H sensing coils. By controlling the excitations of the X-, Y-, and Z-coils, the magnetic properties of SMC can be measured with various B loci, e.g. alternating (one-dimensional or 1-D), 2-D rotating, and even a loop in the 3-D space. These measurements provide necessary data for modeling the vector magnetic properties, e.g. the 3-D magnetic reluctivity tensor [4-5].

Under rotating flux excitation, even in an isotropic ferromagnetic material B and H are not parallel, so their relation has to be described as a tensor:

\[ H_i = \sum_{j=x,y,z} \nu_{ij} B_j \quad (i=x, y, z) \] (1)

It is known that any patterns of B or H can be transformed into a Fourier series, and each of the harmonics basically forms an elliptical locus with an axis ratio \( R_q \) between 0 and 1, including purely alternating \( (R_q=0) \) and circularly rotational \( (R_q=1) \) [6]. Therefore, it may be sufficient to investigate the vector magnetic properties only under the excitations of elliptical B vectors.

The reluctivity depends on three parameters including the maximum flux density, axis ratio and orientation [7]. The orientation is defined by the direction of major axis of B ellipse, which is given by the angles between the major axis and the three coordinate axes [8]. Theoretically, SMC materials are magnetically isotropic and their magnetic properties should be independent of the orientation of B vector. Hence, the terms of the reluctivity tensor are a function of the flux density magnitude and axis ratio only.

The magnetic properties of a cubic SMC sample has been systematically measured under a series of elliptical B vectors with different maximum magnitudes and axis ratios. From these data, the 3-D reluctivity tensor can be deduced [4-5]. Fig. 3 shows the measured magnetic reluctivity.

2008 Australasian Universities Power Engineering Conference (AUPEC'08) Paper P-079 page 1
III. MAGNETIC FIELD FEA WITH VECTOR PROPERTIES

A. General Formula

The reluctivity tensor can be incorporated in the magnetic field FEA of SMC motors as

\[ \mathbf{J} = \nabla \times (\mu \nabla \mathbf{A}) \]

(2)

where \( \mathbf{A} \) is the magnetic vector potential, \( \mathbf{J} \) the current density, which is nearly zero in SMC that has negligible eddy current.

In 3-D problems, (2) can be expanded as

\[
\begin{align*}
\frac{\partial}{\partial y} & \left[ V_{yz}(\frac{\partial A_y}{\partial z} - \frac{\partial A_z}{\partial y}) + V_{zy}(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}) \right] + \frac{\partial}{\partial z} \left[ V_{xz}(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}) + V_{zx}(\frac{\partial A_z}{\partial x} - \frac{\partial A_x}{\partial z}) \right] + V_{xx}(\frac{\partial A_x}{\partial x} - \frac{\partial A_x}{\partial x}) \\
- \frac{\partial}{\partial x} & \left[ V_{yx}(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}) + V_{xy}(\frac{\partial A_x}{\partial y} - \frac{\partial A_y}{\partial x}) \right] + V_{yy}(\frac{\partial A_y}{\partial y} - \frac{\partial A_y}{\partial y}) \\
= & \mathbf{J} \cdot \mathbf{n}_x + \mathbf{J} \cdot \mathbf{n}_y + \mathbf{J} \cdot \mathbf{n}_z
\end{align*}
\]

(3)

where \( \mathbf{n}_x \), \( \mathbf{n}_y \), and \( \mathbf{n}_z \) are the unit vectors along the X-, Y- and Z-axes, respectively.

The direct incorporation of (3) into 3-D FEA is quite complicated and time consuming, especially when the reluctivities are nonlinear. In this paper, different techniques are reviewed and discussed for practical use of the vector magnetic properties.
B. 2-D FEA with Vector Properties

The magnetic field FEA can be simplified into a 2-D problem as the magnetic flux basically flows within a plane. In this case, (3) can be rewritten as [9-10]

\[
\frac{\partial}{\partial x} \left( v_\nu \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left( v_\nu \frac{\partial A}{\partial y} \right) - \frac{\partial}{\partial y} \left( v_\nu \frac{\partial A}{\partial y} \right) - \frac{\partial}{\partial x} \left( v_\nu \frac{\partial A}{\partial x} \right) = -J_x
\]

(4)

where the magnetic flux flows in the XOY plane and only the Z-components of \( \mathbf{J} \) and \( \mathbf{A} \) exist.

Enokizono et al. conducted the finite element magnetic field analysis in a three-phase transformer core of oriented steel by using (4), in which the effects of anisotropy and rotating field are considered by the tensor reluctivity [11-12]. The authors concluded that with the tensor expression, the accuracy of approximation in arbitrary direction was higher than that with the conventional expressions. In [13], a new finite element formulation for considering the 2-D vector properties was proposed, aiming to improve the convergence of the numerical computation. The investigation on multi-phase transformers proposed, aiming to improve the convergence of the numerical computation. To overcome this defect, the ‘Enokizono and Soda (E&S)’ model was developed [17].

Mohammed et al. applied the reluctivity tensor in magnetic field FEA to consider the anisotropic properties of magnetic material [16]. The generalized 2-D tensor finite element model can compute all the force components in an electrical machine, including those caused by magnetostriiction, which is one of the major causes of noise and vibration.

C. E&S model

Enokizono and Soda and Shimoji (E&S2) model was developed [18]. The new model contains an extra parameter called the ‘Enokizono and Soda (E&S)’ model, defined as [17]

\[
H_j = v_{jx}B_j + v_{jy} \frac{\partial B_j}{\partial t} \quad (j=x, y)
\]

(5)

This model can be easily extended to 3-D case by defining \( j=x, y, z \). The coefficients \( k_{jx} \) and \( k_{jy} \) \((n=1, 2, 3, 4)\) are obtained by curve-fitting the measurements on samples.

The magnetic property can be nonlinear with respect to any of the following parameters: the maximum value of \( B \), axis ratio of \( B \) ellipse, and inclination angle of \( B \). Therefore, it is very difficult to express the vector magnetic properties by a general hysteresis model such as the Preisach model. Alternative models like the E&S model have to be employed. The E&S model can be easily extended to 3-D case by defining \( j=x, y, z \). The coefficients \( k_{jx} \) and \( k_{jy} \) \((n=1, 2, 3, 4)\) are obtained by curve-fitting the measurements on samples.

The magnetic property can be nonlinear with respect to any of the following parameters: the maximum value of \( B \), axis ratio of \( B \) ellipse, and inclination angle of \( B \). Therefore, it is very difficult to express the vector magnetic properties by a general hysteresis model such as the Preisach model. Alternative models like the E&S model have to be employed. The E&S model can be easily extended to 3-D case by defining \( j=x, y, z \). The coefficients \( k_{jx} \) and \( k_{jy} \) \((n=1, 2, 3, 4)\) are obtained by curve-fitting the measurements on samples.

The magnetic property can be nonlinear with respect to any of the following parameters: the maximum value of \( B \), axis ratio of \( B \) ellipse, and inclination angle of \( B \). Therefore, it is very difficult to express the vector magnetic properties by a general hysteresis model such as the Preisach model. Alternative models like the E&S model have to be employed. The E&S model can be easily extended to 3-D case by defining \( j=x, y, z \). The coefficients \( k_{jx} \) and \( k_{jy} \) \((n=1, 2, 3, 4)\) are obtained by curve-fitting the measurements on samples.

The magnetic property can be nonlinear with respect to any of the following parameters: the maximum value of \( B \), axis ratio of \( B \) ellipse, and inclination angle of \( B \). Therefore, it is very difficult to express the vector magnetic properties by a general hysteresis model such as the Preisach model. Alternative models like the E&S model have to be employed. The E&S model can be easily extended to 3-D case by defining \( j=x, y, z \). The coefficients \( k_{jx} \) and \( k_{jy} \) \((n=1, 2, 3, 4)\) are obtained by curve-fitting the measurements on samples.
This improved model has been applied in the FEA of magnetic fields in a number of electromagnetic devices such as transformers [22-25] and rotating motors [24-28].

IV. CONCLUSION AND DISCUSSION

For advanced magnetic field analysis of electromagnetic devices, the vector properties of magnetic materials under rotating field excitations should be properly determined and applied. This paper presents the determination of 3-D reluctivity tensor of SMC by using a 3-D magnetic property tester, and the application of the reluctivity tensor in advanced field analysis of SMC electromagnetic devices.

Various existing techniques for applying the vector magnetic properties in finite element analysis are reviewed and discussed. It is expected that magnetic field FEA considering vector properties will become a key tool for development of advanced electromagnetic devices. With the advance of computational speed and numerical techniques, direct application of the 3-D tensor reluctivity in FEA would be applicable for engineering practice in the future.

REFERENCES


