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

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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 motors, in which the flux density locus is complicated and basically rotational in 3-D space [3].

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].

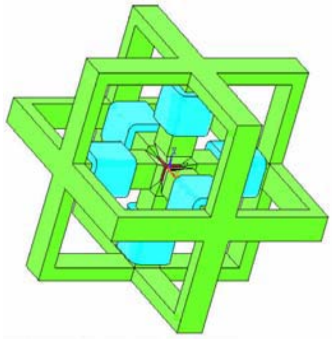
Under rotating flux excitation, even in an isotropic ferromagnetic material **B** and **H** are not parallel, so their relation has to be described as a tensor:

$$H_i = \sum_{j=x}^{z} \nu_{ij} B_j \quad (i = x, y, z) \tag{1}$$

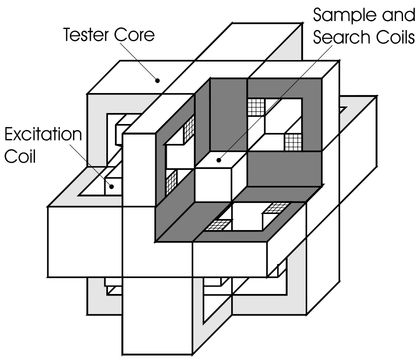
It is known that any patterns of **B** or **H** can be transformed into a Fourier series, and each of the harmonics basically forms an elliptical locus with an axis ratio R_B between 0 and 1, including purely alternating (R_B=0) and circularly rotational (R_B=1) [6]. Therefore, it may be sufficient to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



(a)



(b)

Figure 1. 3-D magnetic tester: (a) framework, and (b) cut away view

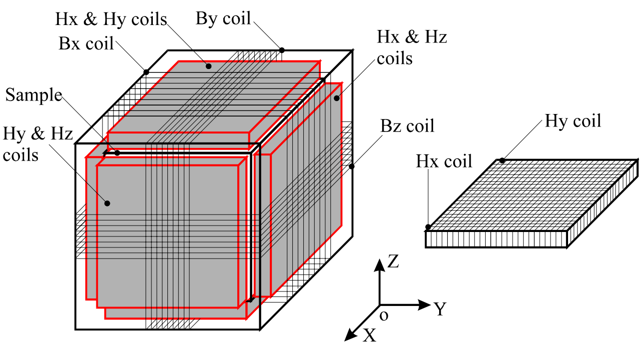
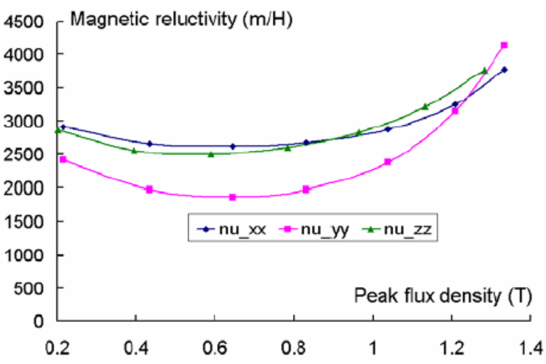
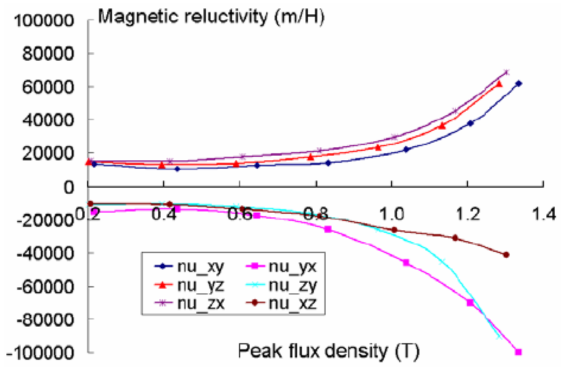


Figure 2. A cubic sample and its *B* and *H* sensing coils



(a)



(b)

Figure 3. Reluctivity tensor: (a) diagonal terms; (b) off-diagonal terms

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

$$\nabla\times(\nu\nabla\times\mathbf{A})=\mathbf{J}_\mathbf{s} \qquad (2)$$

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

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

$$\begin{aligned}
&\{\frac{\partial}{\partial y}[\nu_{zx}(\frac{\partial A_z}{\partial y}-\frac{\partial A_y}{\partial z})+\nu_{zy}(\frac{\partial A_x}{\partial z}-\frac{\partial A_z}{\partial x})+\nu_{zz}(\frac{\partial A_y}{\partial x}-\frac{\partial A_x}{\partial y})]\\
&-\frac{\partial}{\partial z}[\nu_{yx}(\frac{\partial A_z}{\partial y}-\frac{\partial A_y}{\partial z})+\nu_{yy}(\frac{\partial A_x}{\partial z}-\frac{\partial A_z}{\partial x})+\nu_{yz}(\frac{\partial A_y}{\partial x}-\frac{\partial A_x}{\partial y})]\}\mathbf{n_x}\\
&+\{\frac{\partial}{\partial z}[\nu_{xx}(\frac{\partial A_z}{\partial y}-\frac{\partial A_y}{\partial z})+\nu_{xy}(\frac{\partial A_x}{\partial z}-\frac{\partial A_z}{\partial x})+\nu_{xz}(\frac{\partial A_y}{\partial x}-\frac{\partial A_x}{\partial y})]\\
&-\frac{\partial}{\partial x}[\nu_{zx}(\frac{\partial A_z}{\partial y}-\frac{\partial A_y}{\partial z})+\nu_{zy}(\frac{\partial A_x}{\partial z}-\frac{\partial A_z}{\partial x})+\nu_{zz}(\frac{\partial A_y}{\partial x}-\frac{\partial A_x}{\partial y})]\}\mathbf{n_y}\\
&+\{\frac{\partial}{\partial x}[\nu_{yx}(\frac{\partial A_z}{\partial y}-\frac{\partial A_y}{\partial z})+\nu_{yy}(\frac{\partial A_x}{\partial z}-\frac{\partial A_z}{\partial x})+\nu_{yz}(\frac{\partial A_y}{\partial x}-\frac{\partial A_x}{\partial y})]\\
&-\frac{\partial}{\partial y}[\nu_{xx}(\frac{\partial A_z}{\partial y}-\frac{\partial A_y}{\partial z})+\nu_{xy}(\frac{\partial A_x}{\partial z}-\frac{\partial A_z}{\partial x})+\nu_{xz}(\frac{\partial A_y}{\partial x}-\frac{\partial A_x}{\partial y})]\}\mathbf{n_z}\\
&=J_{sx}\mathbf{n_x}+J_{sy}\mathbf{n_y}+J_{sz}\mathbf{n_z} \qquad (3)
\end{aligned}$$

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]

$$\frac{\partial}{\partial x}\left(\nu_{yy}\frac{\partial A_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu_{xx}\frac{\partial A_z}{\partial y}\right)-\frac{\partial}{\partial x}\left(\nu_{yx}\frac{\partial A_z}{\partial y}\right)-\frac{\partial}{\partial y}\left(\nu_{xy}\frac{\partial A_z}{\partial x}\right)=-J_{sz} \quad (4)$$

where the magnetic flux flows in the XOY plane and only the Z-components of $\mathbf{J}_s$ 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 by using reluctivity tensor was also reported in [14].

In [15], 2-D magnetic permeability tensor was used to describe the material property of the hysteresis ring in a hysteresis motor. It was assumed that the torque in the hysteresis motor is caused by the angle difference between **H** and **B** vectors, so a tensor expression of magnetic property is necessary in the magnetic field FEA for torque computation.

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 magnetostriction, which is one of the major causes of noise and vibration.

C. E&S model

Enokizono and his team have long been involved in the study on 2-D magnetic vector properties of magnetic properties and have proposed several models to account for the vector properties in the magnetic field FEA. One is so-called the 'Enokizono and Soda (E&S)' model, defined as [17]

$$H_j=\nu_{jr}B_j+\nu_{ji}\frac{\partial B_j}{\partial t} \ (j=x, y) \quad (5)$$

$$\nu_{jr}=k_{jr1}+k_{jr2}B_j^2+k_{jr3}B_j\left(\frac{\partial B_j}{\partial t}\right)+k_{jr4}\left(\frac{\partial B_j}{\partial t}\right)^2 \quad (6)$$

$$\nu_{ji}=k_{ji1}+k_{ji2}B_j^2+k_{ji3}B_j\left(\frac{\partial B_j}{\partial t}\right)+k_{ji4}\left(\frac{\partial B_j}{\partial t}\right)^2 \quad (7)$$

This model can be easily extended to 3-D case by defining j=x, y, z. The coefficients k_{jrn} and k_{jin} (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 is convenient to determine the core loss distribution under both alternating and rotating field excitations and it is generally applicable to anisotropic problems considering the hysteresis phenomena [17-18]. The three components of **B** and **H** and their derivatives with respect to time have been readily obtained by FEA, so the core loss in each element can be obtained by the Poynting theorem as

$$P_t=\frac{1}{\rho T}\int_0^T\left(H_x\frac{dB_x}{dt}+H_y\frac{dB_y}{dt}+H_z\frac{dB_z}{dt}\right)dt \ \text{(W/kg)} \quad (8)$$

and the total core loss is

$$P_{total}=\rho\sum_{e=1}^{N_e}P_{te}V_e \ \text{(W)} \quad (9)$$

where ρ is the mass density of core material, T the time period of magnetization, V_e the volume of the e-th element, and N_e the total number of elements.

This model has been applied in the design and analysis of high efficient electromagnetic devices such as three-phase transformer [19], permanent magnet motor [20], and induction motor [21].

D. E&S² model

The E&S model has the difficulty in convergence of numerical computation. To overcome this defect, the 'Enokizono, Soda and Shimoji (E&S^2)' model was developed with an integration term instead of a differential term. The 2-D vector magnetic property is then expressed by [22-23]

$$H_j=\nu_{jr}B_j+\nu_{ji}\int B_j d\omega t \ (j=x, y) \quad (10)$$

The flux density and field strength are approximated with the following equations expressed by Fourier transformation:

$$B_j=A_{B_j1}\cos\omega t-B_{B_j1}\sin\omega t \ (j=x, y) \quad (11)$$

$$H_j=\sum_{n=1}^{2}\left(A_{H_j(2n-1)}\cos\omega t-B_{H_j(2n-1)}\sin\omega t\right) \ (j=x, y) \quad (12)$$

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

[1] Y. G. Guo, J. G. Zhu, Z. W. Lin, and J. J. Zhong, "3D vector magnetic properties of soft magnetic composite material," *J. Magnetism and Magnetic Materials*, vol. 302, no.2, pp. 511-516, July 2006.

[2] "The latest development in soft magnetic composite technology," SMC Update, Reports of Höganäs AB, Sweden, 1997-2008. Available at http://www.hoganas.com/, see News then SMC Update.

[3] Y. G. Guo, J. G. Zhu, P. A. Watterson, and W. Wu, "Comparative study of 3-D flux electrical machines with soft magnetic composite core," *IEEE Trans. Ind. Appl.*, vol. 39, no. 6, pp. 1696-1703, Nov. 2003.

[4] Y. G. Guo, J. G. Zhu, Z. W. Lin, J. J. Zhong, H. Y. Lu, and S. H. Wang, "3D magnetic reluctivity tensor of soft magnetic composite materials," in *Digest Book of the 12th IEEE Conf. on Electromagnetic Field Computation*, Miami, Florida, USA, 30 April – 3 May 2006.

[5] Y. G. Guo, J. G. Zhu, Z. W. Lin, J. J. Zhong, H. Y. Lu, and S. H. Wang, "Determination of 3-D magnetic reluctivity tensor of soft magnetic composite materials," *J. Magnetic Materials and Magnetism*, vol. 312, pp. 458-463, May 2007.

[6] Y. G. Guo, J. G. Zhu, Z. W. Lin, and J. J. Zhong, "Measurement and modeling of core losses of soft magnetic composites under 3D magnetic excitations in rotating motors," *IEEE Trans. Magn.,* vol. 41, no. 10, pp. 3925-3927, Oct. 2005.

[7] S. Urata, M. Enokizono, T. Todaka, and H. Shimoji, "Magnetic characteristic analysis of the motor considering 2-D vector magnetic property," *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 615-618, Apr. 2006.

[8] Y. G. Guo, J. G. Zhu, Z. W. Lin, J. J. Zhong, H. W. Lu, and S. H. Wang, "Calibration of sensing coils of a three-dimensional magnetic property tester," *IEEE Trans. Magn.*, vol. 42, no. 10, pp. 3243-3245, Oct. 2006.

[9] M. Enokizono and K. Yuki, "Constitutive equation of magnetic materials and magnetic field analysis," *IEEE Trans. Magn.*, vol. 29, no. 2, pp. 1538-1541, Mar. 1993.

[10] M. Enokizono, K. Yuki, and S. Kanao, "Magnetic field analysis by finite element method taking rotational hysteresis into account," *IEEE Trans. Magn.*, vol. 30, no. 5, pp. 3375-3378, Sep. 1994.

[11] M. Enokizono, K. Yuki, and S. Kawana, "An improved magnetic field analysis in oriented steel sheet by finite element method considering tensor reluctivity," *IEEE Trans. Magn.*, vol. 31, no. 3, pp. 1797-1800, May 1995.

[12] M. Enokizono and N. Soda, "Finite element analysis of transformer model core with measured reluctivity tensor," *IEEE Trans. Magn.*, vol. 33, no. 3, pp. 4110-4112, May 1997.

[13] K. Fujiwara, T. Adachi, and N. Takahashi, "A proposal of finite-element analysis considering two-dimensional magnetic properties," *IEEE Trans. Magn.*, vol. 38, no. 2, pp. 889-892, Mar. 2002.

[14] H. V. Sande, T. Boonen, I. Podoleanu, F. Henrotte, and K. Hameyer, "Simulation of a three-phase transformer using an improved anisotropy model," *IEEE Trans. Magn.*, vol. 40, no. 2, pp. 850-855, Mar. 2004.

[15] H. Y. Lee and S. Y. Hahn, "Torque computation of hysteresis motor using finite element analysis with asymmetric two dimensional magnetic permeability tensor," *IEEE Trans. Magn.*, vol. 34, no. 5, pp. 3032-3035, Sep. 1998.

[16] O. A. Mohammed, T. Calvert, and R. McConnell, "Coupled magnetoelastic finite element formulation including anisotropic reluctivity tensor and magnetostriction effects for machinery applications," *IEEE Trans. Magn.*, vol. 37, no. 5, pp. 3388-3392, Sep. 2001.

[17] N. Soda and M. Enokizono, "E&S hysteresis model for two-dimensional magnetic properties," *J. Magnetic Materials and Magnetism*, vols. 215-216, pp. 626-628, 2000.

[18] M. Enokizono and N. Soda, "Core loss analysis of transformers by improved FEA," *J. Magnetic Materials and Magnetism*, vols. 196-197, pp. 910-912, 1999.

[19] N. Soda and M. Enokizono, "Improvement of T-joint part constructions in three-phase transformer cores by using direct loss analysis with E&S model," *IEEE Trans. Magn.*, vol. 36, no. 4, pp. 1285-1288, July 2000.

[20] H. Shimoji, M. Enokizono, and T. Todaka, "Iron loss and magnetic fields analysis of permanent magnet motors by improved finite element method with E&S model," *IEEE Trans. Magn.*, vol. 37, no. 5, pp. 3526-3529, Sep. 2001.

[21] M. Enokizono and K. Okamato, "Designing a low-loss induction motor considering the vector magnetic properties," *IEEE Trans. Magn.*, vol. 38, no. 2, pp. 877-880, Mar. 2002.

[22] H. Shimoji, M. Enokizono, T. Todaka, and T. Honda, "A new modeling of the vector magnetic property," *IEEE Trans. Magn.*, vol. 38, no. 2, pp. 861-864, Mar. 2002.

[23] H. Shimoji and M. Enokizono, "E&S^2 model for vector magnetic hysteresis property," *J. Magnetic Materials and Magnetism*, vols. 254-255, pp. 290-292, 2003.

[24] M. Enokizono, H. Shimoji, and T. Horibe, "Loss evaluation of induction motor by using magnetic hysteresis E&S^2 model," *IEEE Trans. Magn.*, vol. 38, no. 5, pp. 2379-2381, Sep. 2002.

[25] S. Urata, M. Enokizono, T. Todaka, and H. Shimoji, "The calculation considered two-dimensional vector magnetic properties depending on frequency of transformers," *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 687-690, Apr. 2006.

[26] Enokizono, H. Shimoji, A. Ikariga, S. Urata, and M. Ohoto, "Vector magnetic characteristic analysis of electrical machines," *IEEE Trans. Magn.*, vol. 41, no. 5, pp. 2032-2035, May 2005.

[27] M. Enokizono, "Vector magneto-hysteresis E&S model and magnetic characteristic analysis," *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 915-918, Apr. 2006.

[28] S. Urata, M. Enokizono, T. Todaka, and H. Shimoji, "Magnetic characteristic analysis of the motor considering 2-D vector magnetic property," *IEEE Trans. Magn.*, vol. 42, no. 4, pp. 615-618, Apr. 2006.