Study of 3-D Tensor Magnetic Reluctivity Properties of Soft Magnetic Composite Materials

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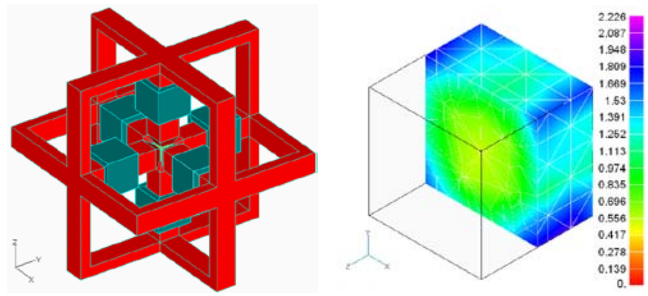
Abstract —In rotating electric machines, magnetic material shows complex three-dimensional (3-D) properties due to rotational domains. In order to comprehensively analyze the magnetic field distribution in rotating flux machines, a 3-D magnetic properties testing system fitting for cubic specimen has been constructed and modeled. This paper emphatically studies the tensor magnetic reluctivity properties based on measurement of soft magnetic composite materials in alternating and 3-D magnetization conditions. By means of the experiential data, 3-D reluctivity tensor is calculated and analyzed.

I. INTRODUCTION

Soft magnetic composite (SMC) materials are widely applied in electrical machines, especially in 3-D magnetic flux machines. While some complex properties such as anisotropy and nonlinearity are found out in rotational magnetized conditions. By using measurement apparatus, measurements of the magnetic properties have been done under rotating field excitations [1]. Enokizono *et al.* calculated and applied the 2-D magnetic tensor reluctivity to 2-D FEM of the rotating magnetic field [2]. However, modeling and analysis of the 3-D magnetic properties considering the reluctivity tensor is rarely reported. Magnetic reluctivity tensor, which is associated with the 3-D magnetic properties measurement, can be calculated to be a full rank matrix. By using the 3-D tester, this paper presents the tensor magnetic properties of a SMC material, SOMALOY™ 500 when the magnetic flux density **B** loci are controlled to be ellipses. These measurements can provide the necessary data for modeling the reluctivity tensor considering the maximum flux density, orientation, and axis ratio of the elliptical **B** locus.

II. MODELING OF 3-D TESTER

The 3-D magnetic property tester consists of 3-D yokes, six excitation windings which are wound around the three pairs of orthogonal poles. Yokes and poles are laminated structure with a grain-oriented material of HiB. A cubic SMC specimen is placed in the center of the tester and impinged by the six core-poles. Fig. 1 shows the model of the 3-D tester and the magnetic flux distributions in the SMC specimen. It can be seen that the area of the center of the core are relatively weak flux density areas. Therefore, the strongest field area of the cubic sample is distributed at the edges. In real measurement, in order to detect the relatively uniform field, a guarding piece with the same material of the specimen is mounted on top of the thin sensing coil which is attached to the surface of the cubic specimen.



(a) (b)

Fig. 1. Modeling of the 3-D tester: (a) Simulated 3-D tester structure, (b) Magnetized flux density distributions of the SMC specimen.

III. 3-D MAGNETIC PROPERTIES MEASUREMENT

By using the 3-D magnetic tester, the magnetic properties of an SMC specimen have been systematically measured.

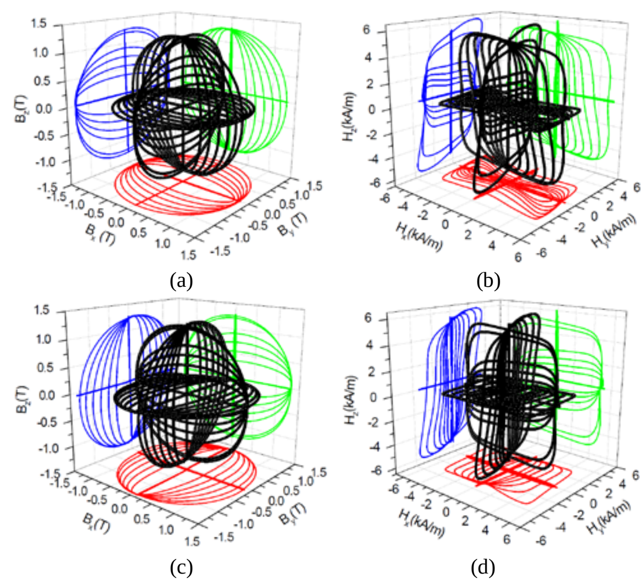


Fig. 2. Elliptical **B** loci and corresponding **H** loci in *xoy*-, *yoz*-, *zox*-plane and projections: (a) Elliptical **B** loci (the axis ratio ε = 0, 0.35, 0.48, 0.62, 0.75, 0.89, 1), the major axis is *x*, *y*, and *z* respectively; (b) Corresponding **H** loci; (c) **B** loci (the major axis is *y*, *z*, and *x* respectively); (d) Corresponding **H** loci.

Fig. 2 shows a series of **B**, **H** loci and corresponding projections when **B** loci are controlled to be ellipses, whose axis ratio of the minor axis to the major axis, ε, are increased up to 1 at 50 Hz in the *xoy*-, *yoz*-, and *zox*-plane, respectively. It can be seen that **B** and **H** loci lie in the same magnetization planes when the **B** loci are well controlled. The **H** loci evolve from figure-of-eight to saddle-like when the major axis is *x* in *xoy*-plane, while the evolution is from elliptic to rectangular when the major axis is *y*. This phenomenon is due to different magnetization process and the easy magnetization direction along *y*-axis. It may imply that the particles are much closer along the *y*-axis (the compaction direction) than along the *x*- and *z*-axis, that is, high mass density and weak demagnetization field along the *y*-axis [3].

IV. NUMERICAL ANALYSIS OF 3-D RELUCTIVITY TENSOR

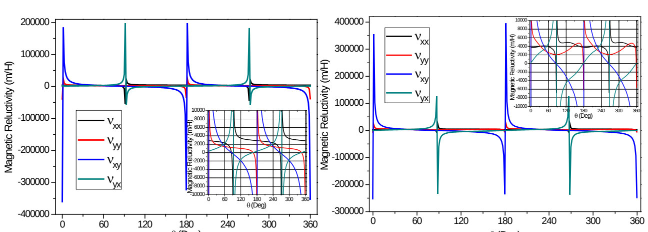
To analyze the magnetic field distribution in 3-D condition, a numerical model is built. **H** and **B** vectors are related by a tensor reluctivity. The components of **H** and **B** can be expressed as:

$$\begin{cases} H_x = \nu_{xx}B_x + \nu_{xy}B_y + \nu_{xz}B_z \\ H_y = \nu_{yx}B_x + \nu_{yy}B_y + \nu_{yz}B_z \\ H_z = \nu_{zx}B_x + \nu_{zy}B_y + \nu_{zz}B_z \end{cases} \tag{1}$$

where ν is the magnetic reluctivity tensor which can be expressed by a 3×3 full rank matrix :

$$\nu = \begin{bmatrix} \nu_{xx} & \nu_{xy} & \nu_{xz} \\ \nu_{yx} & \nu_{yy} & \nu_{yz} \\ \nu_{zx} & \nu_{zy} & \nu_{zz} \end{bmatrix} \tag{2}$$

In 3-D flux rotating electrical machine, when the rotor rotates, **B** and **H** loci at different positions in the magnetic core may take very different patterns, because any types of **B** or **H** locus can be transformed into a *Fourier* series, where each of the harmonics basically forms a circular or elliptical locus [4]. It might be enough to investigate the magnetic properties of ferromagnetic materials under the excitations of elliptical **B** vectors. Maximum flux density, orientation, and axis ratio of the elliptical **B** locus are composed to define the tensor magnetic properties. The orientation is defined by the inclination angles of **B**, *i.e.* the angles between the major axis and the three coordinate axes.



(a) (b)

Fig. 3. Magnetic reluctivity tensor of one cycle in *xoy* -plane when **B** is round rotating (the axis ratio is equal to 1). (a) B_r=0.22T, (b) B_r=1.32T.

Fig. 3 illustrates the one cycle magnetic reluctivity curves in *xoy*-plane when the ratio of **B** locus is 1. It displays that the change of ν_{xx} and ν_{xy} is smaller than that of ν_{yy} and ν_{yx} when the magnitude of round **B** increases from 0.22 T to 1.32 T in *xoy*-plane. It denotes that *y*-axis is the easy direction for magnetization, which is in accord with the conclusion of hysteresis measurement.

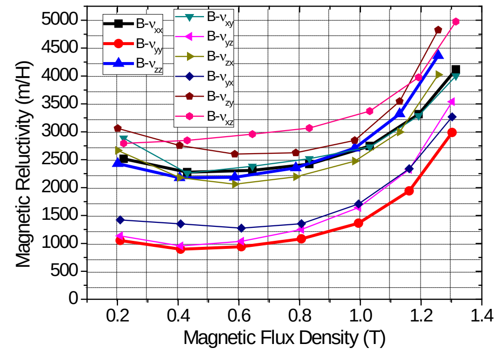


Fig. 4. Magnetic reluctivity tensor against the magnitude of the maximum round rotating **B**.

Fig. 4 shows the reluctivity calculated from **B** and **H** vectors at different magnitude of **B** vector. The values of diagonal elements ν_{xx}, ν_{yy} and ν_{zz} decrease with increasing magnitude of **B** up to 0.6 T. Then, they increase after 0.6 T. the value of ν_{yy} is smaller than that of ν_{xx} and ν_{zz}. It is also consistent with the previous conclusion of easy magnetized direction lying in *y*-axis. A group of off-diagonal elements of the 3-D reluctivity tensor ν_{xy}, ν_{yz}, ν_{zx}, ν_{yx}, ν_{zy} and ν_{xz} in condition of the axis ratio of elliptical **B** locus is 1, *i.e.* a round **B** locus, and the phase angle θ = 45°. Following increasing magnitude of **B**, the values of off-diagonal elements decrease to a minimum, then increase. The change becomes rapid when **B** is approaching saturation value. ν_{yx} and ν_{yz} are smaller than others because that the y direction is easy to be magnetized.

V. CONCLUSION

Under 3-D vector excitations, ***H*** and ***B*** vectors are related by magnetic reluctivity tensor which is a full matrix with off-diagonal elements due to the rotating magnetic flux. The tensor magnetic property demonstrates that the rotational magnetization is a complicated coupling interaction among different magnetization directions. More detailed analysis of the magnetic reluctivity model will be presented in the full paper.

VI. REFERENCES

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