Comparison between Modeling Methods of Two-Dimensional Magnetic Properties in Magnetic Field Analysis of Synchronous Machines

Shingo Higuchi[1], Yasuhito Takahashi[1], Tadashi Tokumasu[2] and Koji Fujiwara[1]
[1] Department of Electrical Engineering, Doshisha University, Kyoto 610-0321, Japan
[2] Toshiba Mitsubishi-Electric Industrial Systems Corporation, Yokohama 230-0045, Japan
dum0309@mail4.doshisha.ac.jp

***Abstract*—This paper investigates a modeling method of two-dimensional magnetic properties based on magnetic energy. To verify the effectiveness, finite element analyses of a ring core by the proposed and other modeling methods of magnetic anisotropy is performed and their advantages and disadvantages are discussed from the standpoints of computational accuracy and cost. Additionally, we investigate the influence of magnetic anisotropy on the machine performance of synchronous machines.**

***Index Terms*— Magnetic anisotropy, Finite element methods, Computational modeling, Newton method, Magnetic energy, Non-oriented electrical steel sheet, Single sheet tester.**

I. Introduction

An effective modeling of two-dimensional (2-D) magnetic property is required to achieve high analysis accuracy because electrical steel sheets have magnetic anisotropy. Recently, some modeling methods have been reported [1]-[3] and we have proposed an anisotropic modeling method based on magnetic energy [4] using some one-dimensional (1-D) magnetic properties. However, the features of these methods in magnetic field analyses of practical electric machines have not been deeply discussed. In order to verify the effectiveness of the proposed method clearly, finite element analyses of a ring core are performed by using the proposed method and other modeling methods of magnetic anisotropy and their advantages and disadvantages are discussed from the standpoints of their computational accuracy and convergence properties. Furthermore, as a practical application, the interior permanent magnet (IPM) motor in consideration of 2-D magnetic property is analyzed and the influence of magnetic anisotropy on iron loss is investigated.

II. Modeling Method of 2-D Magnetic Properties

We compare the proposed method (Method (i)) with following three modeling methods.

Method (ii): direct modeling of $\partial\boldsymbol{H}/\partial\boldsymbol{B}$ ($\boldsymbol{H}$: field intensity, $\boldsymbol{B}$: flux density) based on measured data with a 2-D single sheet tester [3]

Method (iii): conventional method which uses only two magnetization curves in the rolling and transverse directions independently as following equations:

$$H_x(B_x) = H(B_x, \theta_B = 0), \quad H_y(B_y) = H(B_y, \theta_B = \pi/2). \tag{1}$$

Method (iv): isotropic modeling using an ordinary magnetization curve

A nonsymmetrical Jacobian matrix $\partial\boldsymbol{H}/\partial\boldsymbol{B}$ generally arises from magnetic anisotropy modeling with Method (ii). In Method (ii), the Jacobian matrix $\partial\boldsymbol{H}/\partial\boldsymbol{B}$ is often symmetrized as follows:

$$\frac{\partial Hx}{\partial By} = \frac{\partial Hy}{\partial Bx} \Leftarrow \frac{1}{2}\left(\frac{\partial Hx}{\partial By} + \frac{\partial Hy}{\partial Bx}\right). \tag{2}$$

This method is called Method (ii-a), and Method (ii) using nonsymmetric $\partial\boldsymbol{H}/\partial\boldsymbol{B}$ is called Method (ii-b). Although symmetrizing $\partial\boldsymbol{H}/\partial\boldsymbol{B}$ is one of the computational techniques to avoid unreasonable magnetic hysteresis in Method (ii) due to the nonsymmetric $\partial\boldsymbol{H}/\partial\boldsymbol{B}$. Method (ii-b) requires a linear iterative solver for nonsymmetric coefficient matrices. In this paper, we use the BiCGstab2 method [5].

III. Numerical Results

A. Ring Core Model

The ring core shown in Fig. 1 is analyzed for verification of the proposed method. The rolling direction (RD) and transverse direction (TD) are parallel to the *x*-axis and *y*-axis respectively. In this paper, we use the magnetic properties of non-oriented electrical steel sheets (JIS grade: 50A470). Fig. 2 shows distributions of magnetic flux density. The analysis results by the proposed method agree well with those by

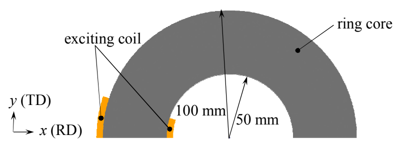


Fig. 1. Ring core.

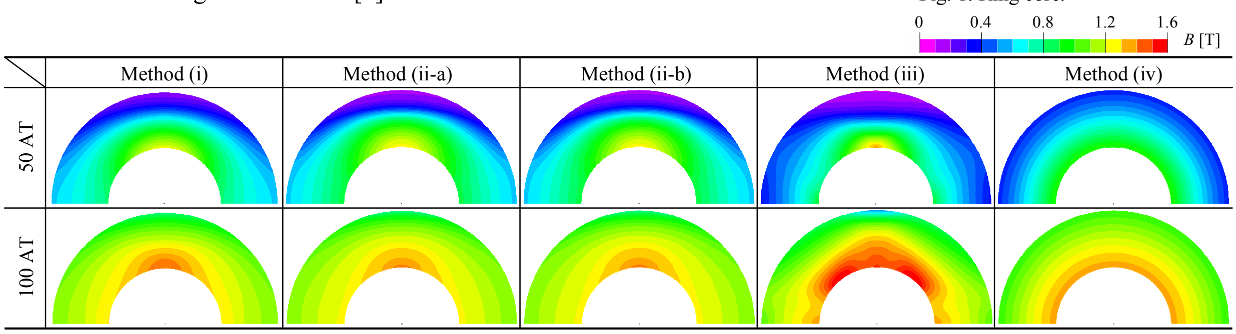


Fig. 2. Distributions of flux density in the ring core (50A470).

Methods (ii-a) and (ii-b). In the case of Method (iii), the unreasonable distribution of magnetic flux density occurs because of the reason mentioned in [6]. Naturally, in the case of Method (iv), the uniform distributions of magnetic flux density are obtained in a circumferential direction and are quite different from those obtained from the other anisotropic modeling methods.

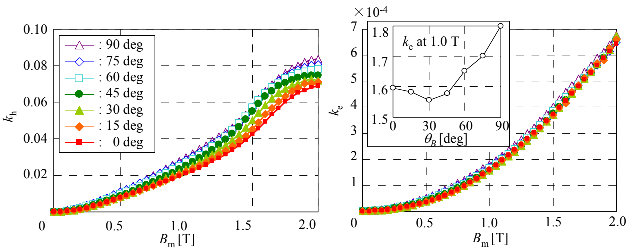
Table 1 lists the total number of ICCG or BiCGstab2 iterations, the number of NR iterations, the computation time required for calculating Jacobian matrices, the computation time required for solving a linear system of equations and the total computation time. The numbers of unknowns are 25,342. The exciting current is 50 AT. When the change of the flux density is less than 10^{-4} T for each element, the NR iteration is terminated. The convergence criterion for the ICCG and BiCGstab2 method is that the 2-norm of the relative residual is less than 10^{-3}. In the case of Method (iv), the computation time is the fastest and the number of iterations are least as is expected. Method (iii) achieves the second fastest computational time. These methods, however, cannot take account of magnetic anisotropy appropriately. Method (ii-b) needs the most calculation time because of the increase of computational burden for the matrix-vector product in the BiCGstab2 method. The proposed method achieves the best performance because its convergence property of the NR method is better than Method (ii-a). From the above results, the effectiveness of the proposed modeling method for 2-D magnetic properties based on magnetic energy can be confirmed from the standpoints of the availability of measurement results for identification of the model and the computational accuracy and costs in finite element analyses.

B. IPM motor with Concentrated windings

The loss analysis is performed by the proposed method considering anisotropic iron loss property. The hysteresis loss coefficient k_h and eddy current loss coefficient k_e of 50A470 are shown in Fig. 3. While k_h changes depending on inclination angle θ_B from the RD, k_e does not change significantly.

Table 1. Convergence characteristics (50 AT).

analysis method	number of iterations: ICCG / BiCGstab2	number of iterations: NR	computation time required for calculating Jacobian matrices [sec]	computation time required for solving linear system of equations [sec]	total computation time [sec]
Method (i)	1579	11	11.80	7.99	41.65
Method (ii-a)	3799	26	27.31	19.65	94.58
Method (ii-b)	2471	23	23.90	43.69	112.09
Method (iii)	1631	9	8.95	8.25	33.51
Method (iv)	1016	6	5.76	5.16	21.37



(c) k_h–B_m characteristic (d) k_e–B_m characteristic

Fig. 3. Iron loss coefficients (50A470).

Therefore, in this paper, k_h is treated as a function of B_m and θ_B and k_e is a function of B_m.

The IPM motor with typical concentrated winding [7] shown in Fig. 4 is analyzed. Figs. 5(a) and 5(b) show the distributions of hysteresis loss density in the case of isotropic and anisotropic iron loss property, respectively, and Fig. 5(c) indicates the difference between (a) and (b). The great change of hysteresis loss distribution does not occur if anisotropic iron loss property is considered. However, hysteresis loss decreases in the stator teeth where the flux mainly passes through the RD, and increase in the region where the flux passes through near the TD.

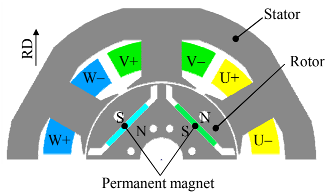
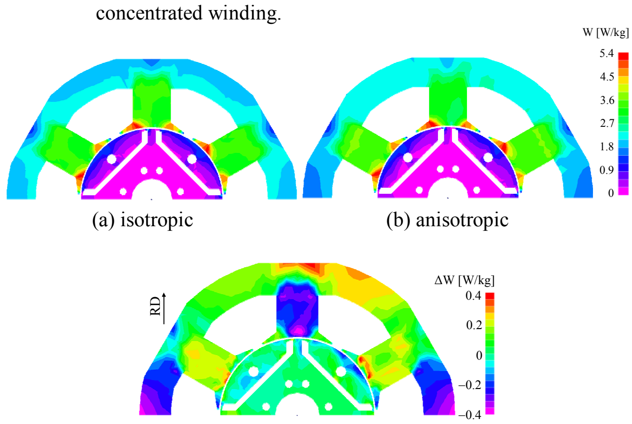


Fig. 4. IPM motor of typical concentrated winding.

Table 2. Analysis condition.

Material of core	50A470
Stack length [mm]	60
Number of turns [turn/slot]	125
Phase current [I]	4.4
current phase [deg]	200
Frequency [Hz]	50
Magnetization of magnet [T]	1.25



(a) isotropic (b) anisotropic

(c) difference (b–a)

Fig. 5. Distribution of hysteresis loss.

REFERENCES

[1] 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 (2002).

[2] M. Enokizono and N. Soda, “Finite Element Analysis of Transformer Model Core with Measured Reluctivity Tensor,” *IEEE Trans. Magn.*, vol. 33, no. 5, pp. 4110-4112 (1997).

[3] A. Kameari and K. Fujiwara, “FEM Computation of Magnetic Fields in Anisotropic Magnetic Materials,” *IEEJ Trans.*, vol. 126-B, no. 2, pp. 141-146 (2006).

[4] S. Higuchi, T. Nakao, Y. Takahashi, T. Tokumasu, K. Fujiwara, and Y. Ishihara, "Modeling of Two-Dimensional Magnetic Properties Based on One-Dimensional Magnetic Measurements," *IEEE Trans. Magn.*, vol. 48, no. 11, pp. 3486–3489 (2012).

[5] M. H. Gutknecht, “Variants of Bi-CGSTAB for Matrices with Complex Spectrum,” *SIAM J. Sci. Comput.*, vol. 14, no. 5, pp. 1020-1033 (1993).

[6] T. Nakata, K. Fujiwara, N. Takahashi M. Nakano, and M. Okamoto, “An Improved Numerical Analysis of Flux Distributions in Anisotropic Materials,” *IEEE Trans. Magn.*, vol. 30, no. 5, pp. 3395-3398 (1994).

[7] H. Kaimori, Y. Kawase, A. Yamagiwa, D. Higuchi, Y, Takahashi, K. Akatsu, T. Yamada, S. Nishita, K. Yamazaki and N. Takahashi, “Electromagnetic Field Analysis of IEEJ Benchmark IPM Motor with Concentrated Windings,” *The Papers of Joint Technical Meeting on Static Apparatus and Rotating Machinery of IEE Japan*, no. SA-13-028, RM-13-028 (2013) (in Japanese).