# Availability of 2-Dimensional Vector Magnetic Property for High Flux Density Machines

**Masato Enokizono***

**Abstract** - The vector magnetic property is defined as the relationship between the magnetic field strength vector H and the magnetic flux density vector B. It is very important for the development of high efficiency and the high-density electric machines. The electrical steel sheet for the machine core shows the remarkable vector behavior by the high magnetic flux density level. In this paper, the magnetic characteristic analysis using E&S2 model is introduced as the useful technology for the design and development.

## 1. Introduction

Recently, simulation techniques such as the finite element method have rapidly spread with the development of the computer. The magnetic characteristics must be accurately introduced into this method, in which we intend to analyze electrical machinery and apparatus. On the other hand, actual magnetic materials such as the electrical sheet steel show magnetic anisotropy (rolling direction is "easy" direction) and magnetic hysteretic behavior even in the case of non-oriented electrical steel sheets. Therefore, the magnetic characteristics must be defined from the relationship between the magnetic field strength vector **H** and the magnetic flux density vector **B** [1]~[3]. It is impossible to express the relationship by using the physical constitutive equation **B**=μ**H**, because the vector **H** is not always parallel to the vector **B**. The vector **H** is parallel to the vector **B** only in the rolling direction or the transverse direction. This relationship cannot be measured by using the conventional standard measurement method like the Epstein tester or the single strip tester (SST), which was researched and surveyed [1][2].

The magnetic property at arbitrary directions is represented by the relationship between the locus of the vector **H** and the locus of the vector **B**, or by the $B_x$, $H_x$, $B_y$ and $H_y$ waveform. The magnetic property shows non-linearity not only in magnitude but also in the spatial phase angle $\theta_{BH}$ between the vector **H** and the vector **B**. We called the characteristic "vector magnetic property" or [3][4].

To express the relationship of the vector behavior, instead of the constitutive equation, we proposed the engineering "E&S$^2$ Model"[5]~[8]. In this paper, the formulation of this engineering model was described and applied to the numerical simulation of electrical machines [9]~[12].

* Faculty of Engineering, Oita University, 700 Dannohru, Oita 870-1192, Japan(enoki@cc.oita-u.ac.jp)
Received June 21, 2004 ; Accepted January 4, 2005

## 2. Vector Magnetic Property

In order to measure the two-dimensional vector magnetic property, the two-dimensional magnetic measurement method (Vector Magnetic Hysteresis Analyzer; **V-H** Analyzer) has been developed by the collaboration work between our laboratory and IWATSU Co.

### 2.1 E&S$^2$ model as the Engineering Model

We propose the engineering model for the expression of the two-dimensional vector magnetic property, which is to introduce the magnetic field analysis methods. Now let the suffix $k$=$x$, $y$, the E&S$^2$ model (Enokizono and Shimoji model, which is developed by improving the conventional E&S (Enokizono and Soda) model [13]. The model can be written as follows,

$$H_k = \nu_{kr}(B,\theta_B,\alpha,\tau)B_k + \nu_{ki}(B,\theta_B,\alpha,\tau)\int B_k d\tau \qquad (1)$$

$\nu_{kr}$ : magnetic reluctivity coefficient as a function of $B,\theta_B,\alpha$ and $\tau$

$\nu_{ki}$ : magnetic hysteresis coefficient as a function of $B,\theta_B,\alpha$ and $\tau$

where $B$ is magnitude of the vector **B** ($=\sqrt{B_x^2+B_y^2}$), $\theta_B$ is inclination angle from easy axis (rolling direction), $\alpha$ is the axis ratio of locus of the vector **B** ($=B_{short}/B_{long}$) and $\tau$ is period of one cycle. The $\nu_{kr}$, $\nu_{ki}$ show the relationship between the H-wave and B-wave. The magnetic measurement condition is set by the following relations:

$$B_k = B_{mk}\sin(\omega t+\varphi_k) = B_{mk}\sin(\tau+\varphi_k)$$
$$= R_{B_k}\cos\tau + I_{B_k}\sin\tau \qquad (2)$$

$$B_{mk} = \sqrt{R_{B_k}^2 + I_{B_k}^2}, \quad \tan\varphi_k = \frac{B_{B_k}}{I_{B_k}}, \quad R_{B_k} = B_{mk}\sin\varphi_k, \; I_{B_k} = B_{mk}\cos\varphi_k$$

where $\tau$ is ωt and from 0 to 2π. On the other hand, the H wave is distorted and is therefore expressed by the following equation:

$$H_k = \sum_{n=1}^{N} H_{mkn}\sin\{(2n-1)\tau\}$$
$$= \sum_{n=1}^{N}\left[R_{(2n-1)H_k}\cos\{(2n-1)\tau\} + I_{(2n-1)H_k}\sin\{(2n-1)\tau\}\right] \qquad (3)$$

$$H_k = (\nu_{kr}R_{B_k} + \nu_{ki}I_{B_k})\cos\tau + (\nu_{kr}I_{Bk} - \nu_{ki}R_{B_k})\sin\tau \qquad (4)$$

On the other hand, the H wave is distorted and is therefore expressed by the following equation:

$$\nu_{kr} = \frac{\sum_{n=1}^{N}\left[R_{(2n-1)H_k}\cos\{(2n-1)\tau\}\right]}{\cos\tau}\left(\frac{R_{B_k}}{R_{B_k}^2 + I_{B_k}^2}\right) + \frac{\sum_{n=1}^{N}\left[I_{(2n-1)H_k}\sin\{(2n-1)\tau\}\right]}{\sin\tau}\left(\frac{I_{B_k}}{R_{B_k}^2 + I_{B_k}^2}\right) \qquad (5)$$

$$\nu_{ki} = \frac{\sum_{n=1}^{N}\left[R_{(2n-1)H_k}\cos\{(2n-1)\tau\}\right]}{\cos\tau}\left(\frac{I_{B_k}}{R_{B_k}^2 + I_{B_k}^2}\right) - \frac{\sum_{n=1}^{N}\left[I_{(2n-1)H_k}\sin\{(2n-1)\tau\}\right]}{\sin\tau}\left(\frac{R_{B_k}}{R_{B_k}^2 + I_{B_k}^2}\right) \qquad (6)$$

Fig. 1 shows the waveform of the coefficient of the E&S$^2$ model between the B-wave and H-wave.

The coefficient of E&S$^2$ model can be expressed as a distorted wave form and as a function of the inclination angle of the vector **B** from the rolling direction. The volume size of stored memory is about more than 100MB.

Let us rearrange by substituting Eq. (1) into *rot***H=J** From Eq.(2) we get:

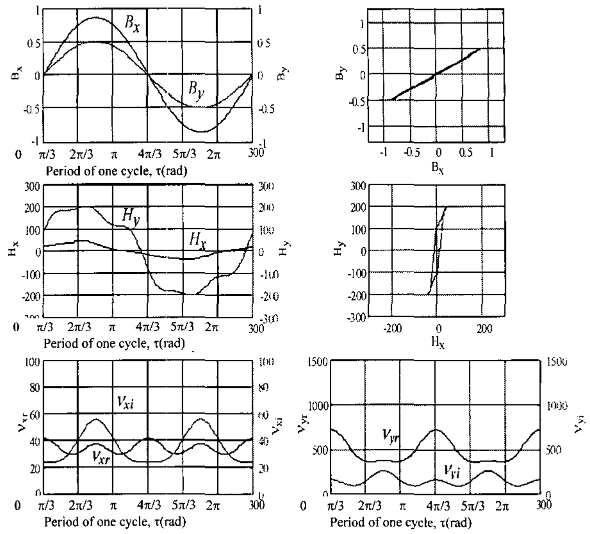


**Fig. 1** Coefficient function of E&S$^2$ model

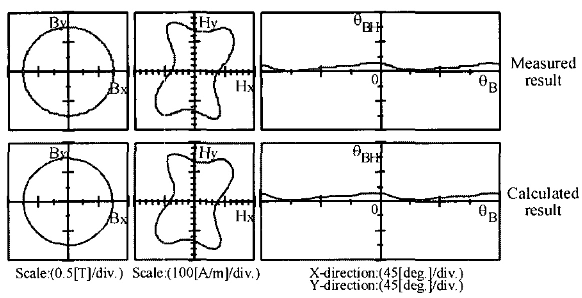
$$\frac{\partial}{\partial x}\left(\nu_{yr}B_y + \nu_{yi}\int B_y d\tau\right) - \frac{\partial}{\partial y}\left(\nu_{xr}B_x + \nu_{xi}\int B_x d\tau\right) = J_0 \qquad (7)$$

By substituting **B**=*rot***A** into Eq. (6), the following fundamental equation is obtained.

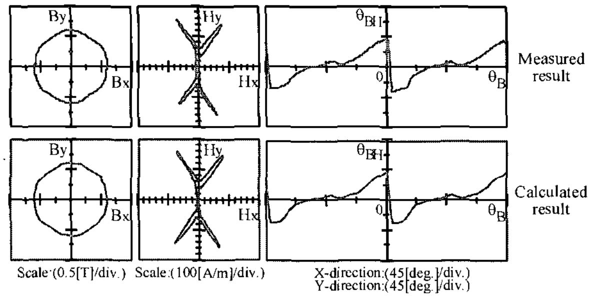
$$\frac{\partial}{\partial x}\left(\nu_{yr}\frac{\partial A}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{xr}\frac{\partial A}{\partial y}\right) + \frac{\partial}{\partial x}\left(\nu_{yi}\int\frac{\partial A}{\partial x}d\tau\right) + \frac{\partial}{\partial y}\left(\nu_{xi}\int\frac{\partial A}{\partial y}d\tau\right) = -J_0 \qquad (8)$$

### 2.2 Comparison Between Ccalculated Results and Measured Results

The calculation result according to the E&S$^2$ model is compared with the measurement result in order to check the validity of the model. Fig.s 2(a) and (b) show the comparative results on various kinds of electrical steel sheet under purely rotating flux condition. It can be seen that the calculated results are in good agreement by using the E&S$^2$ model with the measurement results.



(a) Non-oriented electrical steel sheet




(b) Grain-oriented electrical steel sheet

**Fig. 2** Comparison between measured results and calculated results by E&S$^2$ model under purely rotating flux condition, (axis ratio $\alpha = 1.0$).

## 3. Magnetic Characteristic Analysis of Electrical Machines and Apparatus

This numerical method introduced by the E&S$^2$ model has the typical benefit, that it can analyze the total magnetic power loss directly without the loss data. The specific total magnetic power loss can be from the following equation,

$$W_i = \frac{1}{\rho T}\int_0^T \left( H_x \frac{\partial B_x}{\partial \tau} + H_y \frac{\partial B_y}{\partial \tau} \right) d\tau \tag{9}$$

where $\rho$ is the density, T the period. By using this method, we can obtain not only the distribution of the locus of the vector **B** but also that of the vector **H**. From these results the iron loss can be directly calculated by using Eq. (9).
This analytical method can clarify the behavior of the model core is rotating machines with a complicated iron core structure. Various magnetic behaviors are observed in each iron core part. Fig. 3 shows the distribution of iron loss in the single-phase induction motor. Though the used electrical sheet is a non-oriented, it shows anisotropy, i.e. the rolling direction is a clear "easy" direction. Fig. 4 shows the load characteristics, torque, efficiency and iron loss, of the three-phase induction motor. The behavior of torque and efficiency is well known. It was newly found that the iron loss increases with decreasing the slip. Iron loss of the motor can be obtained as following equation:

$$P_{total} = \rho \cdot D_p \cdot N_{os} \cdot \sum_{i=1}^{N_{es}} P_{ti} \cdot S_i \text{ , [w]} \tag{10}$$

where $\rho$ is the density, $D_p$ the thickness of steel sheet, $N_{os}$ the number of steel sheet, $P_{total}$ the magnetic power loss of element, $S_i$ the area of element, $N_{es}$ the number of element.

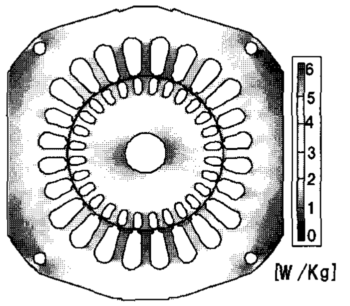



**Fig. 3** Distribution of total iron loss on single-phase induction motor obtained by the E&S$^2$ analysis.

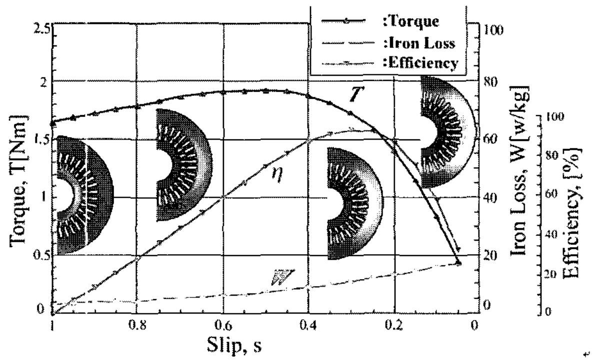



**Fig. 4** Load characteristic curve of three-phase induction motor obtained by the E&S$^2$ analysis.

Fig. 5 shows the analyzed three-phase induction motor model core and the arrangement of the stator windings. The number of stator and rotor core are equal to be 36 and 28, respectively.

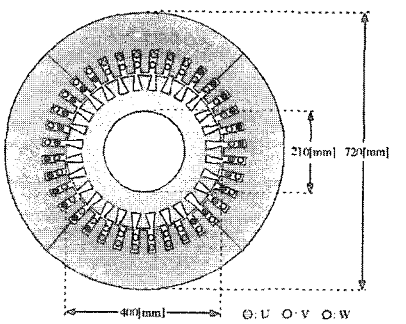



**Fig. 5** Induction motor model core.

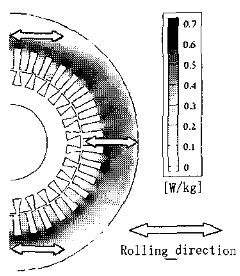



**Fig. 6** Distribution of iron loss (conventional model).

Fig. 6 shows the iron loss distributions when the slip equals 0.03 and exciting frequency is 50 Hz. The arrows show the rolling direction of the sheet materials. The conventional model core was made by one sheet material without assembling, and the easy axis was agreed with the rolling direction. The relative permeability in the rolling direction was about three-times larger than one in the perpendicular direction. In the conventional core, large iron loss was observed at the back part of tooth due to the rotational iron losses.

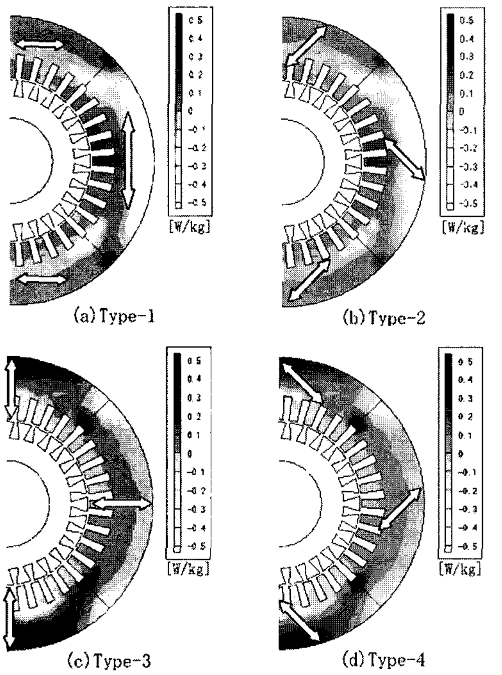



**Fig. 7** Difference of the iron loss from that of the conventional model

As shown in Figs. 7(a), (b), (c) and (d), four assembled models were tested to reduce the total iron loss through magnetic pass design. Also to make loss-changes clear, the difference of the iron loss from that of the conventional model was illustrated in Fig. 21. As we expected, Type-1 showed a good tendency and had the lowest loss in comparison with the other types. The loss distribution changes were very complicated and non-symmetry, because the shapes of rotating flux vector trajectories were depending on the flux rotating direction and the easy axis direction. We have obtained lower loss characteristics in the assembled core model (Type-1).

## 4 Conclusions

As a new evaluation method, the concept of two-dimensional vector magnetic property by the two-dimensional magnetic measurement was proposed. By using this method, the two-dimensional vector magnetic property was clarified. The engineering model ("E&S$^2$ model") was defined to express the two-dimensional vector magnetic property and can analyze the hysteretic magnetic behavior. The magnetic field analysis introduced by the E&S$^2$ model can clarify the magnetic power loss (iron loss) directly. Therefore this new method can solve the various kinds of magnetic characteristics of magnetic material core and is very useful for the development of high efficiency electrical machines.

The benefits of this method, which can be called the magnetic characteristic analysis, are as follows:

(1) It can obtain the behaviors both the vector **B** and the vector **H**.

(2) It can get the relationship between the vector **B** and the vector **H**.

(3) From the relationship between the vector **B** and the vector **H** various kinds of magnetic characteristics such as the hysteresis loop, coercive force, permeability and so on.

(4) It can analyze the magnetic power loss directly.

(5) The evaluation of building factor for electrical machines and apparatus can be discussed from the results of total magnetic power loss.

(6) It can analyze the load characteristic of rotating machines such as torque characteristic, efficiency, magnetic power loss, and power factor.

(7) Furthermore it is easily propose the new evaluation method for electrical machines and apparatus.

The most beneficial advantage is to be able to estimate the characteristic of the machines and apparatus by the various kinds of magnetic material.

## References

[1] W.Brix, K.H.Hempel, F.J.Schulte,"Improved Method for the Investigation of the Rotational Magnetization Process in Electrical Steel Sheets", *IEEE Transactions on Magnetics*, Vol. MAG-20, No.5, pp.1708~1710, 1984

[2] J.Sievert, "One-and Two-dimensional Magnetic Phenomena in Electrical Steel and their Measurement", Advanced Computational and Design Techniques in Applied Electromagnetic Systems(ed. S.-y.Hahn, Elsevier Science B.V., pp.639~645, 1995

[3] M. Enokizono, "Two-Dimensional Magnetic Properties", Journal of IEE of Japan, Vol. A-115, No.1, pp.1~8, 1995

[4] M. Enokizono, T. Todaka, K. Yuki,"Constitutive Equation of Magnetic Materials and Magnetic Field Analysis", *IEEE Transactions on Magnetics*, Vol. MAG-29, No.2, pp.1538~1541, 1993. 4

[5] M. Enokizono, K. Yuki, S. Kawano,"An Improved Magnetic Field Analysis in Oriented Steel Sheet by

Finite Element Method considering Tensor Reluctivity", *IEEE Transactions on Magnetics*, Vol. MAG-31, No.3, pp.1797 ~1800, 1995. 5

[6] M. Enokizono, N. Soda," Magnetic Field Analysis by Finite Element Method using Effective Anisotropic Field", *IEEE Transactions on Magnetics*, Vol. MAG-31, No.3, pp.1793 ~1796, 1995. 5

[7] M. Enokizono, S. Mori, O. Benda,"A Treatment of the Magnetic Reluctivity Tensor for Rotating Magnetic Field", *IEEE Transactions on Magnetics*, Vol. MAG-33, No. 2, pp. 1608~1611, 1997

[8] M. Enokizono, N. Soda," Direct Magnetic Loss Analysis by FEM considering Vector Magnetic Properties", *IEEE Transactions on Magnetics*, Vol. MAG-34, No.5, pp.3008~3011, 1998.9

[9] N. Soda, M. Enokizono,"Improvement of T-Joint Part Constructions in Three-Phase Transformer Cores by Using Direct Loss Analysis with E&S Model", *IEEE Transactions on Magnetics*, Vol. MAG-36, No.4, pp.1285~1288, 2000.7

[10] M. Enokizono, N. Soda," Iron Loss Analysis of Transformer Core Model by FEM Considering Vector Magnetic Properties", *IEEE Transactions on Magnetics*, Vol. MAG-35, No.5, pp.3008~3011, 1999.9

[11] M. Enokizono, T. Miyazaki,"Study on Torque Improvement of Single-Phase Induction Motor by using FEM", *IEEE Transactions on Magnetics*, Vol. MAG-35, No.5, pp. 3703~3706, 1999.9

[12] M. Enokizono. M. Morikawa, K. Kawamura, J. Sirvert, "Distribution of Two-Dimensional Magnetic Properties in Three-Phase Induction Motor Model Core", IEEE Transaction on Magnetics, Vol. MAG-32, No.5, pp.4989~4991, 1996

[13] M. Enokizono, H. Amano,"Examination of the High Accuracy of E&S Modeling", *Journal of The Magnetics Society of Japan*, Vol. 25, No. 4-2, pp. 1110, 2001.4

**Masato Enokizono**

He is at present an associate professor at the Department of Electric and Electronic Engineering, Faculty of Engineering, Oita university, Oita, Japan, and has been engaged in improving computational electromagnetic engineering, and two-dimensional magnetic measuring methods, and research work on the electrical machine. He is member of the IEEE Magnetics Society.

He received the B.E. degree in electrical engineering from Kyushu Institute of Technology, Fukuoka, Japan in 1973, and the M.S. degree in electrical engineering and Dr.E. degree form Kyushu University, Fukuoka, Japan, in 1975 and 1979, respectively,

He is a member of the Institute of Electrical Engineering of Japan, the Magnetic Society of Japan, the Japan Society of Applied Electromagnetics, the Japan Society of Simulation Technology and the IEEE Magnetic Society.

Tel: 81-97-554-7821, Fax: 81-97-554-7822