

# Magnetic characteristic analysis by dynamic vector magneto-hysteretic E&S model

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This paper presents the dynamic modeling of the vector magnetic hysteretic property, which is called “Dynamic E&S Model”. This paper deals with the dynamic vector magnetic hysteretic engineering model, “Dynamic E&S Model”, which can analyze the effect of eddy current under vector magnetic behavior. It is well known that the vector of magnetic field strength  $\mathbf{H}$  is not always parallel to the magnetic flux density  $\mathbf{B}$  in the core. Furthermore when the wave of magnetic flux distort, the eddy current occurs. We will report the dynamic magnetic characteristic analysis taken care of eddy current.

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## 1. Introduction

Recently, there are many hopes that high-efficiency and low loss electric devices will allow us to reduce energy consumption and environmental problems. The rapid development of the computer leads the new design tool of electrical machinery and apparatus. The utilization of the magnetic characteristic will develop from the material evaluation guideline to the material recipe. The data volume of vector magnetic characteristic drastically exceeds the conventional magnetic characteristic quantity. It is required that we construct the method for utilizing the vector magnetic property. We newly deduced the magnetic characteristic analysis instead of the magnetic field analysis using vector magnetic hysteretic E&S model. Until now, though many researchers have devised various hysteresis models, the practical result has not been obtained. The reason is not based on a grasp of the vector magnetic property presented by the relationship between the vector  $\mathbf{H}$  and the vector  $\mathbf{B}$ . Furthermore on conventional models, the vector relation between the vector  $\mathbf{H}$  and the vector  $\mathbf{B}$  is not considered in the hysteresis. The most difficult phenomenon is to reverse the phase  $\theta_{BH}$  relation between  $\mathbf{H}$  and  $\mathbf{B}$  by the angle in order to make modeling. Then, we should handle engineering modeling from the mathematical modeling for such vector magneto-hysteretic representation. Furthermore, when the magnetic flux waveform distorts, the effect of eddy current increases by the harmonic flux components.

In this paper, as the magnetic field analysis, we will show the dynamic model of the vector magnetic property and clarify the effect of the eddy current.

## 2. Dynamic E & S model

In the same way of the ring-core measurements, the measurement of the average magnetic flux density in stator cores is comparatively easy by using search coils wound over the cores.

$$H_x = v_{xr}B_x + v_{xi} \int B_x d\tau + \frac{\pi(f - f_0)\sigma d^2}{6} \frac{\partial}{\partial \tau} B_{1x}(\tau + \gamma_x) + \frac{\pi f \sigma d^2}{6} \frac{\partial}{\partial \tau} \sum_{n=2}^N B_{nx} \left( \tau + \frac{\gamma_x}{n} \right) \quad (1)$$

$$H_y = v_{yr}B_y + v_{yi} \int B_y d\tau + \frac{\pi(f - f_0)\sigma d^2}{6} \frac{\partial}{\partial \tau} B_{1y}(\tau + \gamma_y) + \frac{\pi f \sigma d^2}{6} \frac{\partial}{\partial \tau} \sum_{n=2}^N B_{ny} \left( \tau + \frac{\gamma_y}{n} \right)$$

Where,  $v_{xr}$  and  $v_{yr}$  are magnetic reluctivity coefficient,  $v_{xi}$  and  $v_{yi}$  are magnetic hysteresis coefficient,  $\sigma$  conductivity,  $d$  the thickness of sheet,  $f_0$  the measurement frequency,  $f$  frequency,  $\gamma$  phase angle. The  $n$  is the order of harmonic component.

$$v_{xr}(B_{m,ham}, \theta_B, \alpha, \tau + \beta_x, f_0) = - \frac{\sum_{n=1}^m (I_{(2n-1)H_x} \sin\{(2n-1)(\tau + \varphi_x + \beta_x)\})}{B_{mx} \sin(\tau + \varphi_x + \beta_x)}, \quad (2)$$

$$v_{xi}(B_{m,ham}, \theta_B, \alpha, \tau + \beta_x, f_0) = - \frac{\sum_{n=1}^m (R_{(2n-1)H_x} \cos\{(2n-1)(\tau + \varphi_x + \beta_x)\})}{B_{mx} \cos(\tau + \varphi_x + \beta_x)},$$

where  $\beta$  is the phase correction. Y-component is also same.

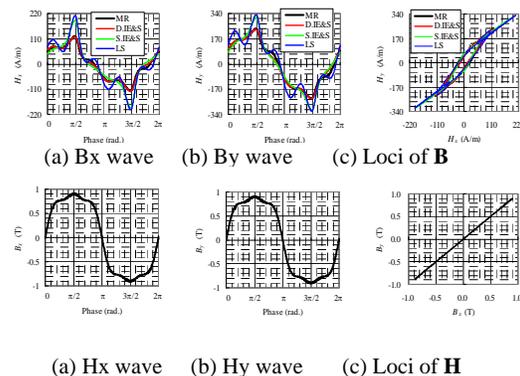


Fig.1 Comparison of dynamic E&S and Static E&S model.

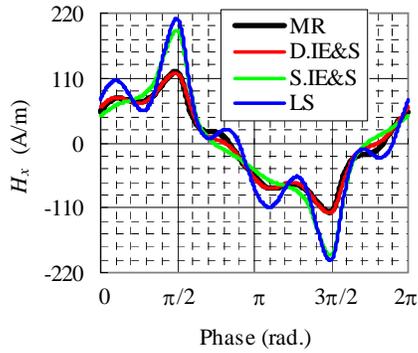


Fig. 2. Enlarged view of waveform of  $H$ .

Fig. 1 shows the comparison of the results by the dynamic E&S model and the static E&S model (conventional model), the linear scaling model as reference. The dynamic E&S model gets the good agreement with the measurement results. From this result we can evaluate the effect of eddy current about model. The amplitude of the waveform of  $H$  is compressed by eddy current. Figure 2 shows it in detail by using the enlarged view.

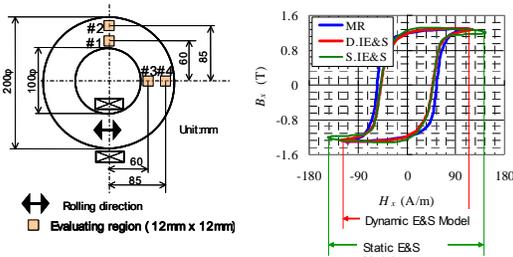


Fig. 3 Comparison between measurement result and models.

Fig. 3 shows the comparison between the measurement result and the analyzed results by dynamic E&S model and static E&S model, respectively. From this result, the analyzed result by the dynamic E&S model has gotten the good agreement than the static E&S model. Furthermore, it was clarified that Magnetic field is suppressed by the effect of the eddy current. The static analysis excessively analyzes magnetic flux density and magnetic field.

### 3. Magnetic characteristic analysis of three-phase transformer

In the same way of the ring-core measurements, the measurement of the average magnetic flux density in stator cores is comparatively easy by using search coils wound over the cores.

$$H_x = v_{yr} B_x + v_{yi} \int B_y d\tau + \frac{\pi(f - f_0)\sigma d^2}{6} \frac{\partial}{\partial \tau} B_{ix}(\tau + \gamma_x) + \frac{\pi f \sigma d^2}{6} \frac{\partial}{\partial \tau} \sum_{n=2}^N B_{nx} \left( \tau + \frac{\gamma_x}{n} \right)$$

$$H_y = v_{yr} B_x + v_{yi} \int B_y d\tau + \frac{\pi(f - f_0)\sigma d^2}{6} \frac{\partial}{\partial \tau} B_{iy}(\tau + \gamma_y) + \frac{\pi f \sigma d^2}{6} \frac{\partial}{\partial \tau} \sum_{n=2}^N B_{ny} \left( \tau + \frac{\gamma_y}{n} \right)$$

Where,  $v_{xr}$  and  $v_{yr}$  are magnetic reluctivity coefficient,  $v_{xi}$  and  $v_{yi}$  are magnetic hysteresis coefficient,  $\sigma$  conductivity,  $d$  the thickness of sheet,  $f_0$  the measurement frequency,  $f$  frequency,  $\gamma$  phase angle. The  $n$  is the order of harmonic component. Equation (4) shows the fundamental equation for magnetic characteristic analysis. The coefficient parameter,  $a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4$  mean the expression due to the coordinate transformation.

Fig. 4 shows the analysis model of three-phase 5-legs constructure transformer. The used material is the grain-oriented electrical steel sheet. Figure 5 shows the distribution of magnetic flux density. Furthermore, the inclination angle  $\theta_B$  from rolling direction of the vector  $B$  is shown in Fig. 6 in order to evaluate the structure of the three-phase 5 legs typed transformer.

$$\frac{\partial}{\partial x} \left( a_4 \frac{\partial}{\partial x} A_x(\tau) - a_3 \frac{\partial}{\partial y} A_x(\tau) \right) + \frac{\partial}{\partial y} \left( a_1 \frac{\partial}{\partial x} A_x(\tau) - a_2 \frac{\partial}{\partial x} A_x(\tau) \right) + \frac{\partial}{\partial x} \left( b_3 \int \frac{\partial}{\partial x} A_x(\tau) d\tau - b_3 \int \frac{\partial}{\partial y} A_x(\tau) d\tau \right) + \frac{\partial}{\partial y} \left( b_1 \int \frac{\partial}{\partial y} A_x(\tau) d\tau - b_2 \int \frac{\partial}{\partial x} A_x(\tau) d\tau \right) + \frac{\pi(f - f_0)\sigma d^2}{6} \left\{ \frac{\partial}{\partial \tau} \left( \frac{\partial}{\partial y} \frac{\partial}{\partial y} A_x(\tau + \gamma_x) + \frac{\partial}{\partial x} \frac{\partial}{\partial x} A_x(\tau + \gamma_y) \right) \right\} + \frac{\pi f \sigma d^2}{6} \sum_{n=2}^N \left\{ \frac{\partial}{\partial \tau} \left( \frac{\partial}{\partial y} \frac{\partial}{\partial y} A_{xn} \left( \tau + \frac{\gamma_x}{n} \right) + \frac{\partial}{\partial x} \frac{\partial}{\partial x} A_{yn} \left( \tau + \frac{\gamma_y}{n} \right) \right) \right\} = -J_z$$

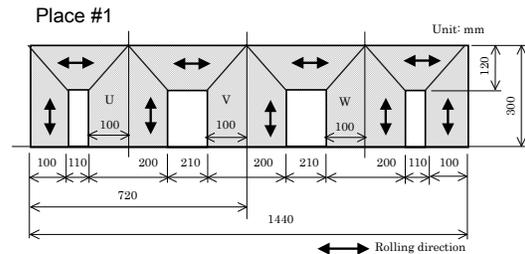


Fig. 4. Analysis model of transformer.

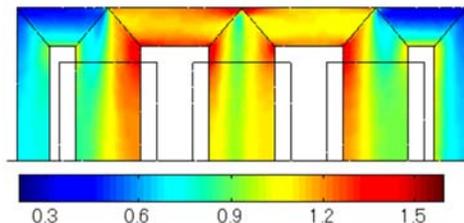


Fig. 5. Distribution of magnetic flux density.

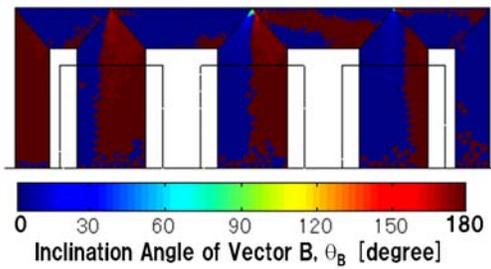


Fig. 6. Distribution of inclination angle of vector  $B$  from rolling direction.

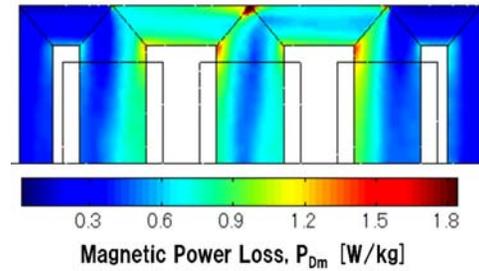


Fig. 9. Distribution of magnetic power loss.

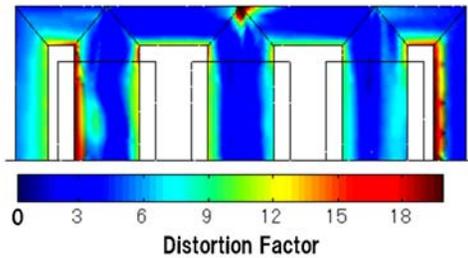


Fig. 7. Distribution of distortion factor of flux waveform.

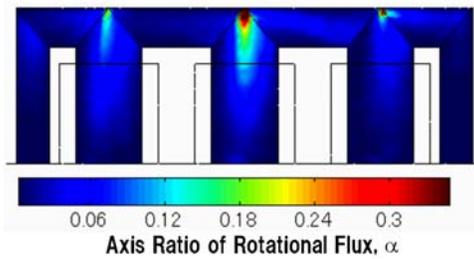


Fig. 8. Distribution of axis ratio of rotational flux.

Fig. 7 shows the distribution of distortion factor of magnetic flux waveform. The eddy current generates by distorting the magnetic flux waveform. The evaluation of waveform distortion gives large effect for the dynamic analysis. Furthermore, the magnetic power loss under the rotational flux is larger than under alternating flux. Figure 8 shows the distribution of axis ratio (long length/short length) of rotational flux. The rotational magnetic flux is shown near the joint part. Fig. 9 shows the distribution of magnetic power loss by the dynamic E&S model.

## References

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