Vector Magnetic Hysteresis Characteristics of Electrical Steel Sheet and its Application

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Vector magnetic characteristics have been proposed as magnetic characteristics required to effectively utilize magnetic materials for the purpose of reducing the loss and increasing the efficiency of electric machines.¹⁾

Conventional magnetic characteristics represent the relationship between magnetic flux density and magnetic field strength in one direction, particularly rolling direction. However, conventional magnetic characteristics are extremely unsatisfactory for design and development to realize low loss and high efficiency of power electrical machines such as motors and transformers. At this time, the magnetic flux density vector **B** and the magnetic field strength vector **H** are not aligned with each other and have a spatial phase difference angle θ_{BH} . In other words, since the magnetic characteristics represent the vector relation between the **B** vector and the **H** vector, they can be generally said to be vector magnetic characteristics.

This can be seen in the dualities established between the electrical characteristics (voltage, current, power factor) and magnetic properties (**B**, **H**, θ_{BH}) of the electrical machines as shown in Fig. 1. ²⁾ Since it is not possible to satisfy this duality relation from the conventional scalar magnetic characteristics, expressing only the size of **B** and **H**, it is impossible to introduce to the magnetic characteristic analysis and design of electrical machines.



1g.1 Duality between motor electric characteristics and magnetic material magnetic characteristics.

Fig. 2 Definitions of vector characteristic.

In addition, handling of electrical machine is carried out under voltage drive, resulting in the problem of obtaining current and power factor. When voltage is applied, the reactance is larger than the circuit resistance, so the magnetic flux density level is automatically determined. Similarly, in the magnetic characteristic analysis, it is a problem to calculate the **B** vector and **H** vector and the spatial phase difference angle θ_{BH} . These constitute an inverse problem analysis of solving I, cos θ , **H**, θ_{BH} by applying a voltage. In other words, it indicates that the hysteresis loop of magnetic properties is not given but solved. In order to clarify the relationship between **B**, **H** and θ_{BH} constituting the vector magnetic characteristics, we indicate this as shown in Fig. 2.

In the case of the electrical steel sheet, taking the rolling direction as a reference, the inclination angle θ_B of the **B** vector from the rolling direction is defined and represents the vector magnetic characteristic in an arbitrary direction. The spatial phase difference angle θ_{BH} between vectors is expressed as the difference between the inclination angle θ_H of the **H** vector and the inclination angle θ_B of the **B** vector. The following equation (1) is a magnetic power loss (core loss) calculation formula.

$$W = \frac{1}{\rho T} \int \left(\mathbf{H} \cdot \frac{\partial \mathbf{B}}{\partial t} \right) dt = \frac{1}{\rho T} \int \left(H_x \frac{\partial B_x}{\partial t} + H_y \frac{\partial B_y}{\partial t} \right) dt = \frac{1}{\rho T} \int \left\{ \left| \mathbf{H} \right| \left| \frac{\partial \mathbf{B}}{\partial t} \right| \cos\left(\frac{\pi}{2} - \theta_{BH}\right) \right\} dt \tag{1}$$

The above expression shows the relationship by introducing θ_{BH} . The ρ is mass density. Figure 3 shows the **B-H** characteristic in an arbitrary direction under the alternating magnetic flux condition as the characteristic including

 $\theta_{\rm BH}$. Comparing the features of the non-oriented electrical steel sheet and the grain-oriented electrical steel sheet shown in this figure, it is possible to clarify the characteristic difference with respect to the conventional characteristic expression. Instead of the conventional core loss characteristic expression, Fig. 4 newly shows the core loss characteristics in an arbitrary direction.



Although basic vector magnetic characteristics can be seen from Fig. 5 and Fig. 6, we show the characteristics $\theta_{BH} - \theta_B - |\mathbf{B}|$ of Fig. 5 and the characteristics $|\mathbf{H}| - \theta_B - |\mathbf{B}|$ of Fig. 6 in order to extract the features due to the dif-

ference between the magnetic characteristics and the magnetization process.

From the viewpoint of vector magnetic characteristics, the behavior of θ_{BH} and **H** vectors is also a very important characteristic because it gives the necessary knowledge to the design of electrical equipment. In the magnetic characteristics of the electrical machine core, examining the material characteristics of the **H** vector and θ_{BH} leading to the current and the power factor as described above will lead to the establishment of an effective utilization technique for the electric machine core, providing knowledge necessary for the development and design for loss reduction and high efficiency.



The motor and the three-phase transformer generate rotational magnetic flux in the iron core, and the rotational core loss caused by the rotating magnetic flux is larger than the alternating iron loss. In the magnetic characteristics under the rotational magnetic flux conditions, the involvement of θ_{BH} appears more prominently.

By virtue of hysteresis loop expression of vector magnetic characteristics, it can be sufficiently predicted that θ_{BH} and change of **H** vector affect each other, so we can capture those behaviors as a whole. In addition, it is possible to analyze the influence of various factors governing the core loss increase, and to indicate the utilization technique for development and improvement of materials based on physical phenomena. Vector magnetic characteristics are taken as a waveform of one period about $\pm |\mathbf{B}|, \pm |\mathbf{H}|$ and θ_{BH} when the waveform obtained from Fig. 3 is displayed as $\pm |\mathbf{B}| - \pm |\mathbf{H}|$ and $\theta_{BH} - \pm |\mathbf{H}|$ characteristics, it is drawn as shown in Fig. 7. This vector magnetic hysteresis characteristic clarifies the hysteresis modeling of characteristics and the effect of stress.²⁾

Reference

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