Vector Magnetic Technology for Development of High Efficiency Machines in Oita National Project

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In this paper we will discuss about the development of IE4 level motor proposed by IEC, which is new target for international efficiencies. Efficiency classes IE1-IE4 are defined in international standard IEC 60034-30. The draft version of IEC 60034-31 defines the new class IE4. The IE-codes replaces the former voluntary Eff classification of electric motors as shown in Table 1. The Eff classes are based on a voluntary agreement between the EU and the CEMEP in 1998.r.

<table>
<thead>
<tr>
<th>IEC 60034-30</th>
<th>Eff classes</th>
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<tbody>
<tr>
<td>IE1 (Standard Efficiency)</td>
<td>Comparable to Eff2</td>
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<tr>
<td>IE2 (High Efficiency)</td>
<td>Comparable to Eff1</td>
</tr>
<tr>
<td>IE3 (Premium Efficiency)</td>
<td>Approximately 15-20% better than IE2</td>
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<tr>
<td>IE4 (Super Premium Efficiency)</td>
<td>-</td>
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</table>

Table 1 Minimum energy performance standards for electric motors.

**Keywords**: vector magnetic property, high efficiency motor, iron loss, high density, stress effect.

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1. Introduction

As an effective alternative which prevents Global Warming, the energy saving of electrical machinery and apparatus is a problem of the important universal. As a standard of the efficiency upgrading of the motor, the IEC announced especially IE4 efficiency improvement level from IE1 as shown in Fig. 1. Though it is realizable to the IE2 level by the improvement on the conventional technology. Fig. 2 has summarized the technology until now. From the approach of which the loss is a function of the magnetic flux density, we will be able to decrease the loss of motor only on lowering the magnetic flux density level. But we must approach it on keeping the level. In order to aim at the efficiency upgrading to the IE4 level motor, the control method of the vector magnetic characteristic instead of the conventional method will be useful.

Fig. 3 shows the core loss increase factor of real motor. It is necessary to improve these factors for making into low loss. In addition, there is a limit on conventional electromagnetic field analysis method which solves only magnetic flux density distribution as a tool of making into low loss of machines.

![Fig. 1. High efficiency standard by IEC.](image)

![Fig. 2. Outline of design for development of high efficiency motor.](image)

![Fig. 3. Core loss increase factor of real machines.](image)

![Fig. 4. Vector relation between H and B.](image)
2. Vector Magnetic Characteristics

Vector magnetic property means the relationship between the vector $\mathbf{B}$ and the vector $\mathbf{H}$ as shown in Fig. 4. Therefore the conventional magnetic property is positioned with the scalar magnetic property. In general the vector $\mathbf{B}$ is not always parallel to the vector $\mathbf{H}$ [1][2].

1) Vector behavior in motor core

Fig. shows the distribution of the vector $\mathbf{B}$ and the vector $\mathbf{H}$, and its locus respectively measured by the special V-H (vector hysteresis) probe [3]. As shown in this figure, the rotational flux and field generate in back yoke division and the behavior of the vector $\mathbf{B}$ is different from the vector $\mathbf{H}$. Furthermore Fig. 6 shows the distribution the maximum magnetic flux density $|\mathbf{B}|_{\text{max}}$ and the maximum field strength $|\mathbf{H}|_{\text{max}}$. From these measurement results, it is greatly different in the distribution, and the distribution of the magnetic field strength due to exciting current is important for decreasing the magnetic power loss.

2) Vector magnetic property of electrical steel sheet.

Fig. 7 shows the vector magnetic characteristic of the non-oriented and the grain oriented electrical steel sheet measured by two-dimensional measurement system (V-H analyzer, vector hysteresis analyzer). These results show the vector relation between the vector $\mathbf{B}$ and the $\mathbf{H}$ in arbitrary direction under alternating flux condition. Until 1.2 T level the rolling anisotropic phenomena or orientation are seen and over 1.3 T level the crystal anisotropic phenomena are appeared, respectively. Fig. 8 shows the magnetic power loss under vector magnetic property. In this figure $\theta_0$ means the inclination angle from the rolling direction of the non-oriented electrical steel sheet for the motor core and $\alpha$ is axis ratio of rotational flux. It is found that the loss change in the induced direction [4][5].

3) Effect of stress on vector magnetic property.

As shown in Fig. 3, the effect of the residual stress is very sensitive on magnetic property, and the building factor of the motor increases. However, the residual stress distribution in the iron core of the motor has not been clarified until now. Fig. 9 shows the distribution of residual stress measured by x-ray diffraction technology [6]. As shown in this figure, the residual stress is shown by circumferential $\sigma_0$ and axial component $\sigma_r$, and shearing force $\tau_{0r}$. Fig. 10 shows the distribution of the stress vector. It was clarified that in the part of the tooth, the tension circumferentially worked, and the compressive force axially works in actual motor core. Furthermore, in the part of back yoke, the shearing force $\tau_{0r}$ worked. Since the compressive force works in the direction of the vector $\mathbf{B}$, and since the tension works in the right-angled direction, this worry about degradation of the magnetic characteristic. In the back yoke region the shearing force $\tau_{0r}$ works, and the rotational magnetic flux is generated. As the rotational power loss is larger than the alternating loss under an alternating magnetic flux, the research on the effect of the shearing force is important for the evaluation of core loss of motor for development of high efficiency machines.
Fig. 9. Distribution of residual stress in motor core.

Fig. 10. Distribution of residual stress vector.

Fig. 11 Effect of residual stress on magnetic property in stator core.

Fig. 12. Effect of residual stress on magnetic property in teeth core.

Fig. 13. 2D magnetostriction of arbitral direction.

4) Two Dimensional Magnetostriction

This degradation originates from the amplitude of the magnetostriction of the material. However, the characteristic of magnetostriction measured by conventional evaluation method does not become a reference. Then we proposed and reported the two-dimensional magnetostriction by the tensor method using three-axial strain gauge [7]. Fig. 13 shows the magnetostriction of non-oriented and grain oriented electrical steel sheet in arbitrary direction under alternating flux condition $B = 1.0$ T, respectively. The magnetostriction increases with increasing the inclination angle $\theta_B$. The value obtained from the two-dimensional magnetostriction is larger than conventional value. Furthermore the magnetostriction of grain oriented sheet is also large which is four times over.

5) Loss Visualization

Furthermore we succeeded in the visualization of the magnetic power loss in motor core by using the thermography system. The principle of this measurement is based on the gradient of the temperature rise by loss generation being proportional to the magnetic power loss [8]. Fig. 14 shows the magnetic power loss distribution in the case of punching process and wire cutting, respectively. The former strongly receives the effect of the stress by the processing, but the latter does not receive the effect. It is possible to know the effect of processing stress on the loss distribution from the both comparison. Fig. 15 shows the loss distribution by the increase in rotational frequency ($400$ rpm~$800$ rpm) of the motor. The visualization of such magnetic power loss gives the important knowledge which is useful for the improvement in the efficiency of the motor.
3. Vector magnetic Characteristic Analysis

The magnetic characteristic analysis for this project is mentioned as one of the generic technologies, which can treat the vector magnetic property. Fig. 16 shows the problem of conventional magnetic field analysis method. There is no large difference on the magnetic flux density distribution between present analysis method and our method. However, the distribution of the magnetic loss is completely different. It is possible to know the reason of the difference from Figs. 17 (a) and (b). There is large difference for the analysis of the magnetic field distribution. The conventional analysis method cannot analyze the magnetic field strength. Since magnetic power loss cannot be directly analyzed by using conventional method using scalar magnetic property, the relational expression with magnetic loss shown in following equation is required.

\[ P = f \left( |B| \right), \quad \text{[w/kg]} \]  

This estimated method is generally used at present by almost commercial package software program. Therefore the result of magnetic power loss distribution obtained by conventional method is similar to the magnetic flux density distribution. The fundamental problem is raised. In order to decrease the magnetic power loss of machines, it must lower the magnetic flux density level. In this method, it is impossible to get high efficient and high density machine. The magnetic power loss is decided by phase angle between vector \( H \) and vector \( B \) and each amplitude. Therefore, the magnetic power loss is obtained as following equation,

\[ P = \frac{1}{\rho T} \int \left( H \cdot \frac{dB}{dt} \right) dt = \frac{1}{\rho T} \int \left( H_r \cdot \frac{\partial B_r}{\partial t} + H_i \cdot \frac{\partial B_i}{\partial t} \right) dt, \quad \text{[w/kg]} \]  

where \( \rho \) is density and \( T \) is period. Therefore it is possible to obtain the magnetic power loss directly, if the behavior of magnetic field strength vector can be analyzed. This fact gives the important knowledge for the optimum design to make into low-loss in the high magnetic flux density region. It is necessary to optimize amplitude of vector \( H \) and phase angle between vector \( H \) and vector \( B \) for making into low-loss.

![Fig. 14. Effect of production procedure.](image)

![Fig. 15. Visualized results of loss distribution in motor.](image)

![Fig. 16. Problem of conventional method](image)

![Fig. 17 Comparison between conventional method and our method.](image)

![Fig. 18. Analytical model.](image)
Fig. 19. Distribution of vector $\mathbf{B}$ and vector $\mathbf{H}$.

Fig. 20. Distribution of $|\mathbf{B}|$ and $|\mathbf{H}|$.

Fig. 21. Distribution of locus of vector $\mathbf{B}$ and vector $\mathbf{H}$, and procedure of loss calculation.

Fig. 22. Distribution of magnetic power loss obtained by magnetic characteristic analysis.

Fig. 23. Distribution of magnetic power loss of higher harmonic components.

4. Vector magnetic Characteristic Technology

Fig. 24 shows the outline of technology based on vector magnetic property. The development of the motor of the IE4 level will be difficult by the conventional technology based on the scalar magnetic characteristic. We should call the new technology based on the vector magnetic characteristic the vector magnetism engineering. This is composed of column of vector magnetic characteristic measurement, vector magnetic characteristic analysis and applied vector magnetic property. There are many technological problems to be solved in each column. The vector magnetic engineering
is based on vector magnetic characteristic measurement, vector magnetic characteristic analysis and applied vector magnetic property. The vector magnetic characteristic measurement is composed of vector magnetic property, 2D&3D magnetostriction, DC biased vector magnetic property, frequency dependence, vector magnetic magnetizing process. The vector magnetic characteristic analysis is composed of vector magnetic characteristic modeling, dynamic modeling, VMSW method for permanent magnet. The design of magnetizer is a key on the activation method. In order to design it we developed the long pulse measurement system in 40T and the soft program which is VMSW method [14]. The applied vector magnetic property is important and is composed of stress vector magnetic property which is a means for controlling the vector magnetic characteristic. Laser, plasma jet is considered as the means. Furthermore the low frequency induction heating technology gives some possibility for the controlling. The detailed relation is shown in Fig. 22.

5. Conclusion

"To measure is to know.", "To measure accurately is to understand." are quoted as "Measurement is Campus for Research and Development." In the improvement of the motor, there was no evaluation measurement and analysis apparatus for the efficiency upgrading until now. The conventional evaluation method is dependent only on the power wattmeter. In this paper we introduced the various measurement system for the utilization technique. I have also positioned analysis technology with the soft measurement.

The control of vector magnetic property by the stress effect is important for development of IE4 class motor. Furthermore in the analysis and simulation technology, the analysis of the component of magnetic field strength is also important. Because the control of magnetic field vector depends on exciting current. Therefore the magnetic characteristic analysis becomes useful technology. In order to use the modeling of behavior of vector magnetic property is demanded, we proposed "E&S model" as one of them.

![Fig. 24. Outline of vector magnetic engineering.](image)

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**Reference**