Technologies of Magnetic Power Loss Analysis for Rotating Machines

Authors: *Haruyuki Kometani** and *Yoshihiro Tani**

In this report, methods for estimating magnetic power loss due to harmonic flux, and increased magnetic power loss resulting from deterioration of magnetic core material, are formulated for application to magnetic power loss analysis for inverter-driven motors, and are proved effective from the results of analysis.

The technologies discussed in this report are actually being applied to enhance the efficiency of permanent magnet motors for air-conditioner compressors, drives in factory automation systems, automobiles, railway system motors, and turbine generators.

1. Introduction

“High-efficiency motor” is one of the most important factors influencing product competitiveness in today’s markets. With permanent magnet motors equipped with inverter drive systems, copper loss has successfully been reduced to the extreme by employing state-of-the-art technologies that include concentrated winding and interior permanent magnet structure. For further improved motor efficiency, reduction of magnetic power loss is indispensable. It is necessary to investigate the employment of high-efficiency materials for magnetic cores and the optimization of motor shapes and inverter specifications, aimed at reducing magnetic power loss, without the need for experimental manufacturing.

In this report, we discuss the new modeling methods we have developed, taking as an example their application to electromagnetic numerical analysis of magnetic power loss resulting from harmonics during inverter drive operation[1, 2].

2. Calculation Method for Magnetic Power Loss by High-frequency Flux[2]

For calculating the magnetic power loss of rotating machines, hysteresis loss, W_h, and eddy current loss, W_e, are calculated by conducting frequency analysis of the hysteresis of flux density, B, of each element obtained by electromagnetic numerical analysis and applying the result to the magnetic power loss curve after fitting[1].

$$W_h = \alpha B^{\gamma} f \tag{1}$$

$$W_e = \beta B^2 f^2 \tag{2}$$

where f is the frequency and α, β and γ are the constants obtained from the fitting curve.

When the frequency exceeds several kHz, becoming high frequency, flux and eddy current concentrate on the surface of the magnet core due to skin effect, which results in an increase in hysteresis loss and a decrease in eddy current loss. With the skin depth and average flux density in the magnet core sheet of defined as δ and B_0, respectively, the hysteresis loss is given by the equation below:

$$W_h = \frac{2}{t}\int_0^{t/2}\left(\alpha B^{\gamma} f\right)dx = \frac{2\alpha\delta f}{t\gamma}\left[\frac{B_0 t}{2\delta\left\{1-\exp\left(-\frac{t}{2\delta}\right)\right\}}\right]^{\gamma}\left\{1-\exp\left(-\frac{\gamma t}{2\delta}\right)\right\} \tag{3}$$

where t is the sheet thickness of the magnet core.

For an eddy current loss reduction coefficient κ, the eddy current loss is expressed as the following equation:

$$W_e = \beta B^2 f^2 \kappa \tag{4}$$

$$\kappa = \frac{6\left\{\left(\frac{3}{2}\delta + \frac{t}{2}\right)\exp\left(-\frac{t}{\delta}\right) + \frac{\delta}{2} - 2\delta\exp\left(-\frac{t}{2\delta}\right)\right\}}{\left\{1-\exp\left(-\frac{t}{2\delta}\right)\right\}^2 t} \tag{5}$$

where the skin depth, δ, is defined by the following equation using the average flux density in the skin depth, B_{av}, and average magnetic field strength, H_{av}.

$$\delta = \sqrt{\frac{\rho H_{av}}{\pi f B_{av}}} \tag{6}$$

where ρ is the resistivity of the magnetic core. Then, B_{av} is given by the following equation:

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$$B_{av} = \frac{B_0 t}{2\delta\left(1 - e^{-\frac{t}{2\delta}}\right)}\left(1 - \frac{1}{e}\right) \cdots\cdots \delta \le \frac{t}{2}$$
$$B_{av} = B_0 \cdots\cdots\cdots\cdots\cdots\cdots \delta > \frac{t}{2} \quad (7)$$

Figure 1 shows a comparison between the magnetic power loss values obtained by the equations above and the measured values. The figure clearly indicates that the values of high-frequency magnetic power loss agree well with the measurements and suggests that the calculation method employed is valid and effective.

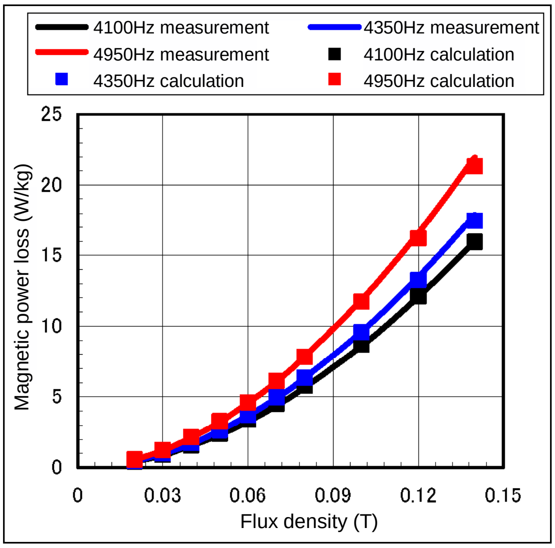

Fig. 1 Comparison between calculated values and measured values of magnetic power loss in single frequency mode

3. Calculation Method for Magnetic Power Loss by Fundamental Wave with Superimposed Harmonics[2]

The magnetic core of an actual motor has a flux waveform consisting of a fundamental wave and magnetic field with superimposed harmonics. For the purpose of this study, the magnetic power loss generated in actual motors is classified into five types as listed below:

(1) Fundamental wave hysteresis loss
(2) Fundamental wave eddy current loss
(3) Increment in fundamental wave hysteresis loss by harmonics
(4) Harmonic eddy current loss
(5) Minor loop hysteresis loss

The minor loop hysteresis loss[3] listed above is calculated from the flux density at a point where the minor loop is generated and the amplitude of the minor loop, as described in the references (3).

Figure 2 shows a comparison between the measured values and calculated values of magnetic power loss by fundamental wave with superimposed harmonics. It should be noted that the fundamental wave has a frequency of 100 Hz and the harmonics have a frequency of 2.5 and 5% of the fundamental. The figure clearly indicates sufficient accuracy of the calculation.

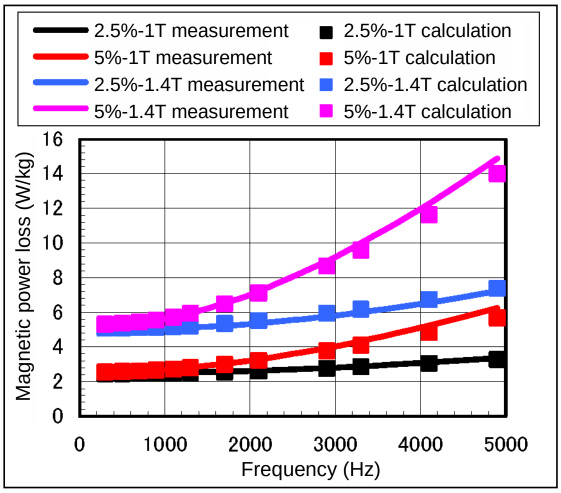

Fig. 2 Modeling of magnet power loss by fundamental wave with superimposed harmonics

4. Calculation of Deterioration in Magnetic Core

The magnetic properties and magnetic power loss characteristics of magnetic cores of rotating machines deteriorate through machining processes[4]. In this study, P-type deterioration (using coefficient p) and Q-type deterioration (using coefficient q) are considered in terms of deterioration of magnetic properties.

The flux density, $B_p(H)$, resulting from P-type deterioration is given by the following equation, with the original BH curve defined as $B(H)$:

$$B_p(H) = \mu_0(1-p)H + pB(H) \quad (8)$$

where μ_0 is the magnetic permeability of a vacuum. The equation is based on the assumption that the magnetic core has non-elastic damage near the cut surface due to strain by core punching.

The magnetic flux, $H_q(B)$, resulting from Q-type deterioration, with the original BH curve defined as $H(B)$, is given below:

$$H_q(B) = \frac{(1-q)B}{\mu_0} + qH(B) \quad (9)$$

This equation is based on the assumption that the deterioration is caused by residual stress in the compressive direction resulting from shrink fitting or the like.

Figure 3 shows a comparison between the measured values obtained when compressive stress (about 100 MPa) was applied and the calculated values of magnetic property considering magnetic core deterioration from the formulation above. The figure clearly indicates sufficient accuracy of the modeling.

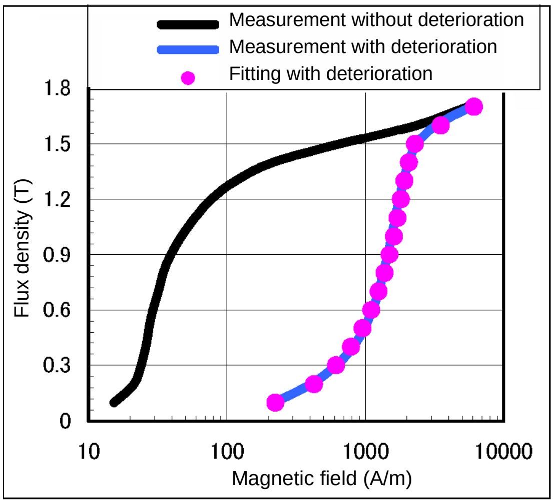

Fig. 3 Modeling of magnetic property considering magnetic core deterioration

For deterioration of magnetic power loss characteristics, coefficient u is calculated likewise. The hysteresis loss, W_h, after deterioration is given by the following equation:

$$W_h = \alpha B_u^{\gamma} fu \tag{10}$$

B_u is expressed by the following equation, using the magnetic property after deterioration, $H_r(B)$:

$$B_u = \frac{B-(1-u)\mu_0 H_r(B)}{u} \tag{11}$$

Figure 4 shows a comparison between the measured values obtained when compressive stress (100 MPa) was applied and the calculated values of magnetic power loss. The figure clearly indicates sufficient accuracy of the modeling.

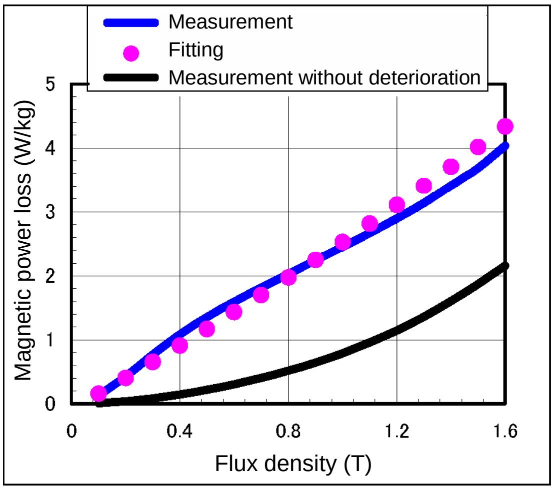

Fig. 4 Modeling of magnetic power Loss considering magnetic core deterioration

5. Analysis of Loss in Rotating Machines

The measured values of magnetic power loss represent losses other than copper loss under load, including the total mechanical loss and stray load loss in addition to loss occurring in the magnetic core. Stray load loss includes eddy current loss in rare earth magnets, at magnetic core edges, or frames, and additional copper loss due to the skin effect of coil winding subjected to high-frequency current.

Figure 5 shows a comparison between the measured values and calculated values of magnetic power loss analysis on the permanent magnet motor with the total losses mentioned above. The figure clearly indicates sufficient accuracy of the calculation.

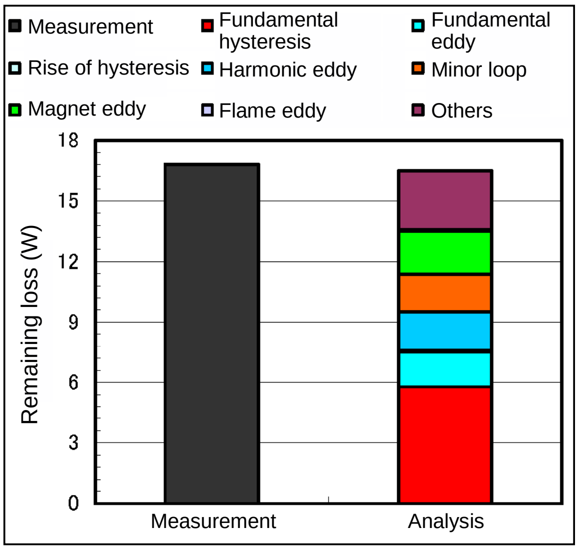

Fig. 5 Example of magnetic power loss analysis of permanent magnet motor

References

(1) IEEJ Technical Report No.1044: "Highly Accurate Modeling Technologies on Electromagnetic Analysis for Rotating Machines", (2006)

(2) H. Kometani and Y. Tani: "Analysis of Magnetic Power Loss Generated by the Flux Superimposed with the Harmonics", The papers of Joint Technical Meeting on Static Apparatus and Rotating Machinery, IEE Japan, RM-05-27, SA-05-27 (2005)

(3) Y. Tani and H. Kometani: "Influence on Core Loss Estimation in Distortion Wave by Approximation Method of Minor Hysteresis Loss (Continued Report II)", The papers of Technical Meeting on Magnetics, IEE Japan, MAG-05-44, pp.31 (2005)

(4) M. Nakano, A. Daikoku, S. Yamaguchi, Y. Tani, H. Arita, Y. Toide, T. Yoshioka and C. Fujino: "Cogging Torque Calculation Considering Distribution of Principal Stress of Stator Core in Permanent Magnet Motors", The papers of Joint Technical Meeting on Static Apparatus and Rotating Machinery, IEE Japan, RM-04-16, SA-04-16 (2004)