An Accurate Iron Loss Analysis Method based on Finite Element Analysis considering Dynamic Anomalous Loss

Katsuyuki Narita
JMAG Buisiness Company
JSOL Corporation
Tokyo, Japan
narita.katuyuki@jsol.co.jp

Hiroyuki Sano
JMAG Buisiness Company
JSOL Corporation
Tokyo, Japan
sano.hiroyuki @jsol.co.jp

Takashi Yamada
JMAG Buisiness Company
JSOL Corporation
Tokyo, Japan
yamada.takashi@jsol.co.jp

Ryosuke Akaki
Electric Component Development Dept.
SUZUKI Motor Corporation
Shizuoka, Japan
ryosukeakaki@hhq.suzuki.co.jp

Masahiro Aoyama
Department of Electrical and Electronics Enginnering
Shizuoka Uvinversity
Shizuoka, Japan
aoyama.masahiro@shizuoka.ac.jp

***Abstract*— To estimate the iron loss with higher harmonics accurately, the method based on the finite element analysis is proposed. The accuracy of the conventional methods based on the empirical approach deteriorates at the high frequencies and in the case with the minor loops, because they rely on the material measurement that differs from the actual operating conditions. The proposed method can calculate the hysteresis losses with the minor loops accurately using the Play-Hysteron model. It can estimate the "classical" eddy current losses at higher frequencies using the 1D method. Regarding the "anomalous" eddy current loss, "dynamic" anomalous loss factor is introduced in this research.**

The iron losses due to the minor loops of the lamination steel sheets are measured and compared with the simulation result using the Play-Hysteron model and the 1D method. The iron losses are also measured under the conditions considering the effect of the slot harmonics and PWM carrier harmonics. The proposed method reproduces well the measurement.

Keywords—Hysteresis, Anomalous loss, finite element analysis (FEA)

I. Introduction

In recent years, as demands for the miniaturization and the high speed rotation have been increasing with automobile driving motors etc., the magnetic flux waveform inside a motor tends to be distorted. In addition, the optimization of overall efficiency of a motor drive system including an inverter is required. From such backgrounds, the accuracy of the iron loss calculation under the magnetic flux waveform in motors including the spatial harmonics and time harmonics is required.

It is well known that iron losses in a motor greatly increase when the spatial harmonics in magnetomotive force and the time harmonics caused by inverter carriers overlap with the fundamental magnetic flux wave. The loss evaluation methods based on the empirical approach proposed by Steinmetz [1] have been widely used for electrical machine analyses. It is pointed out that such conventional method underestimates iron losses of actual machines with the waveform including harmonics because it utilizes the iron loss properties under sinusoidal magnetic flux excitation condition. On the other hand, the Play-Hysteron model [2] and the 1D method [3][4] have been proposed to calculate iron losses by arbitrary magnetic flux waveforms. We applied the Play-Hysteron model and the 1D method to the iron loss analysis of the switched reluctance motor and showed that the iron loss calculation accuracy greatly improved [5]. However, in order to put the Play-Hysteron model and the 1D method into practical use, there remains big issue that an "anomalous eddy current loss" are not taken into consideration in the 1D method. The influence by anomalous eddy current losses are especially remarkable in motors for automobile driving because high grade steel sheets which have large anomalous eddy current losses are often used.

First, we state the definition of the anomalous eddy current losses in this research. We define the anomalous eddy current loss as the eddy current loss except "classical eddy current loss", a loss due to eddy currents generated in a uniform conductor. One of the cause of the anomalous eddy current loss is magnetic domain wall movement. A magnetic body such as an electromagnetic steel sheet has magnetic domains, and their magnetic domain walls move or "bow" due to an alternating magnetic field. The anomalous eddy current loss refers to the eddy current loss caused by the movement of the magnetic domain walls.

At present, it seems that the practical physical modeling has not been established for the anomalous eddy current loss calculation. The empirical approach have been studied to consider anomalous eddy current losses as the correction factor (anomalous loss factor : κ) to classical eddy current losses given by the 1D method. The conventional method to decide the anomalous loss factor κ is shown in Fig.1. In this method, the anomalous loss factor κ is often determined by the ratio of the eddy current loss including the anomalous eddy current loss separated from the measured iron loss by the two-frequency method and the classical eddy current loss W_e by the theoretical formula (1) that does not consider the skin effect [6].

$$W_e = \frac{\sigma \pi^2 h^2}{6} B_m^2 f^2 \tag{1}$$

σ:electric conductivity(1/(ohm m)), h:thickness(m)

B_m: magnetic flux density amplitude(T), f :frequency(Hz)

This separation method needs to be performed at the low frequencies at which the skin effect can be ignored. When the anomalous loss factor κ at the low frequencies is applied to the iron loss calculation at the high frequencies, the accuracy may be deteriorated.

In the proposed method, the anomalous loss factors κ for arbitrary magnetic flux density amplitudes B_m and frequencies f are determined by separating the anomalous eddy current loss at each conditions. We report that the accuracy of the iron loss calculation caused by harmonics is greatly improved by using those $\kappa(B_m,f)$.

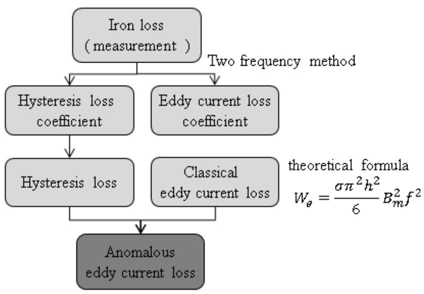


Fig. 1. Conventional anomalous loss separation method

II. Proposed Method

A. Separate anomalous loss from iron loss

To separate anomalous eddy current losses for arbitrary magnetic flux density amplitudes and frequencies, it is necessary to calculate accurately hysteresis losses and classical eddy current losses in consideration of the skin effect due to nonlinear permeability.

For that purpose, we first calculated the classical eddy current loss by the 1D method with the initial magnetizing curve as the nonlinear permeability. However, that method often gave $\kappa(B_m,f)$ less than 1.0, in other words, the anomalous eddy current loss is negative. For example, Fig. 2 shows $\kappa(B_m,f)$ of 50A470 by the initial magnetizing curve. We think that phenomenon is caused by incorrect permeability of the initial magnetizing curve. Because the permeability of the initial magnetizing curve is usually smaller than the permeability of DC hysteresis curve, the skin effect becomes weak and the classical eddy current loss by the 1D method is overestimated.

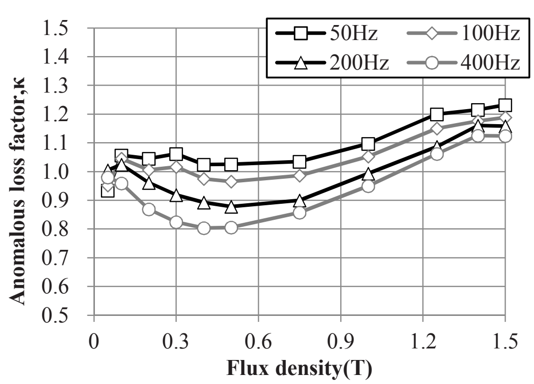


Fig. 2. Anomalous factor of 50A470 given by initial magnetizing curve

To improve above issue, the anomalous eddy current losses are separated by the method shown in Fig. 3, and the anomalous loss factors $\kappa(B_m,f)$ are obtained.

- Measure the iron losses for the sinusoidal magnetic flux with each amplitudes B_m and frequencies f.
- Utilize the 1D method. In the 1D method calculation, the non-linear permeability is given by the Play-Hysteron model.
- Calculate the hysteresis loss and the classical eddy current loss from the result of the 1D method.
- Calculate the anomalous eddy current loss by subtracting the hysteresis loss and the classical eddy current loss from the measured iron loss.
- Decide $\kappa(B_m,f)$ as $\kappa(B_m,f)$=*(classical eddy current loss + anomalous eddy current loss) / classical eddy current loss.*

Fig. 4 shows the results of the calculated $\kappa(B_m, f)$ by applying above method to the electromagnetic steel sheet 35A360. It tends to decrease as the frequency increases.

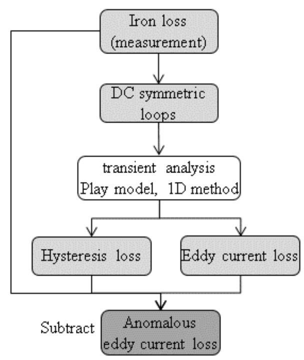


Fig. 3. Proposed anomalous loss separation method

B. Decide dynamic anomalous loss factor

In order to apply the anomalous loss factor to arbitrary waveforms by the transient response magnetic field analysis, $\kappa(B_m, f)$ need to be converted to the dependency on the equivalent magnetic flux density variation dB/dt. In the case of the sinusoidal magnetic flux which has the amplitude B_m and the frequency f, the effective value of dB/dt is given by (2).

$$\frac{dB}{dt} = \frac{2\pi B_m f}{\sqrt{2}} \tag{2}$$

Those $\kappa(dB/dt)$ after conversion are called as "dynamic" anomalous loss factor[7]. Fig.5 shows $\kappa(dB/dt)$ of 35A360 converted from $\kappa(B_m, f)$ shown in Fig.4. Fig.5 shows $\kappa(dB/dt)$ tend to decrease as dB/dt increases, and it can be fitted approximately by the logarithmic function of dB/dt as shown by (3) (solid line in Fig. 5). When referring to the frequency and the magnetic flux density outside the measurement range, $\kappa'(dB/dt)$ is decided by extrapolating by the function. We attempted the same method for several other grades of steel sheet and those $\kappa(dB/dt)$ were possible to fit in the same way.

$$\kappa'\left(\frac{dB}{dt}\right)=\alpha-\beta ln\left(\frac{dB}{dt}\right) \quad (3)$$

C. Apply anomalous factor to arbitrary magnetic flux waveform

For arbitrary magnetic flux waveforms including harmonics, the anomalous loss factors $\kappa'(dB/dt)$ are determined by (3) from dB/dt between the time steps of the FEA, and the anomalous eddy current loss is calculated by multiplying the classical eddy current loss by the average value of $\kappa'(dB/dt)$ for one electric cycle.

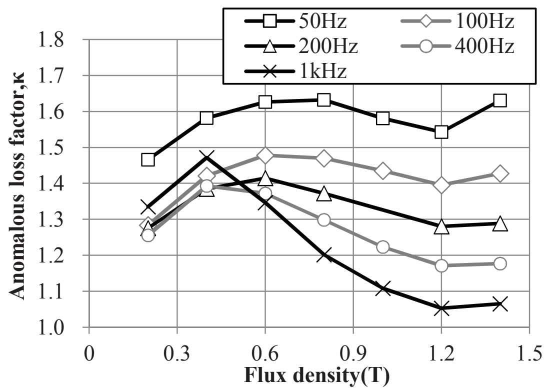


Fig. 4. Anomalous loss factor(35A360)

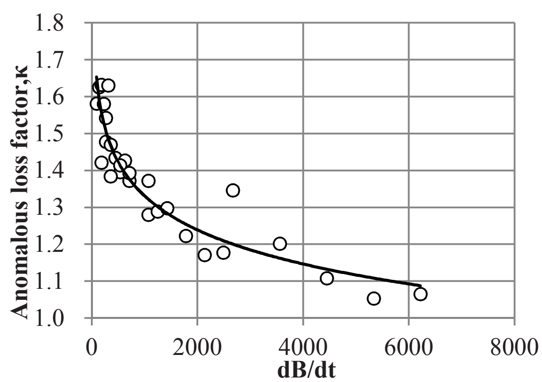


Fig. 5. Dynamic anomalous loss factor(35A360)

III. VALIDATION OF PLAY-HYSTERON MODEL FOR ESTIMATING MINOR LOOP LOSS

The iron losses by harmonics consist of the hysteresis losses, the classical eddy current losses, and the anomalous eddy current losses. Among those components, the classical eddy current losses are calculated by inputting the magnetization characteristics and the electric conductivity to the 1D method, so it is considered that the error factors are relatively small. On the other hand, since the shape functions used in the Play-Hysteron model are identified from the set of measured major loops (symmetric loops), the Play-Hysteron model can not necessarily reproduce the minor loop losses. Regarding the anomalous eddy current loss, it is separated from the iron loss as described above, because no practical physical model has been established yet. Therefore, there are two error components, which makes the error evaluation difficult. Prior to the verification of the iron losses by harmonics, the calculation accuracy of minor loop losses by the Play-Hysteron model was confirmed by comparing with the measurement.

A. Measurement and analysis condition

The minor loop losses were measured by the DC B-H analyzer to remove the effect by the eddy currents. The ring shape test piece which has 127mm outer diameter and 102mm inner diameter was made from 35A360. The amplitude of minor loops B_m were 0.05, 0.1, 0.4 T and the maximum magnetic flux density of the minor loops B_{max} were 0.2 – 1.8 T (see Fig.6).

Regarding the set of symmetric loops used for the Play-Hysteron model, the amplitude of the symmetric loops were from 0.1 to 1.8 T and number of loops was 18(the increments of amplitude is 0.1 T).

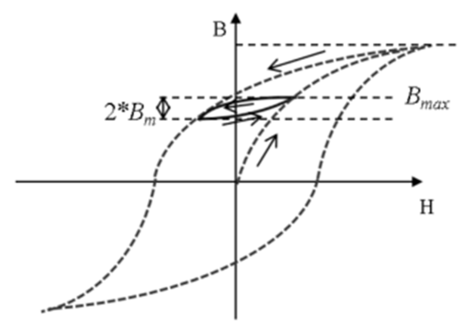


Fig. 6. Measurement of minor loop

B. Comparison between measurement and analysis

Fig.7 shows the result of the minor loop losses with B_m=0.1 T. There are two lines given by the Play-Hysteron model. One is the result by using the measured symmetric loop set as it is and the other is the result by interpolating the measured symmetric loop set into 0.05 T increments by using the appropriate interpolation technique [8]. From the comparison with the measurement, there is the deviation from the measurement when using the symmetric loop set with 0.1 T increments. In the principle of the Play-Hysteron model, the symmetric loop set with 0.1 T increments can certainly calculate minor loops with 0.1 T amplitude. However, in this case, the minor loops with 0.1 T amplitude are reproduced with only four polygonal lines, and the error occurs because resolution is insufficient to sufficiently reproduce the actually measured minor loop shape. On the other hand, the symmetric loop set with 0.05 T increments created by the interpolation technique can reproduce the measured minor loops. As a result, it was confirmed that by using the symmetric loop set that sufficiently reproduces the amplitude of the minor loops to be calculated, the Play-Hysteron model can calculate minor loop losses at least for this type of steel sheet and excitation conditions.

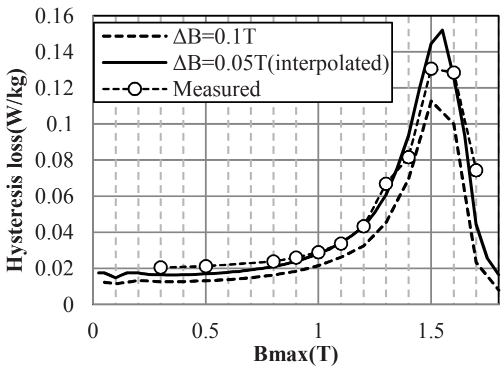


Fig. 7. Hysteresis loss of minor loop(B_m:0.1T)

IV. VALIDATION OF ANOMALOUS LOSS CALCULATION

A. Measurement and analysis condition

The measurement and analysis were done for same test piece of 35A360 for minor loop measurement. Fig. 8 shows the measurement system used to measure the iron losses for the anomalous eddy current loss separation and the iron losses due to harmonics. The magnetic flux is measured from the induced voltage of the secondary coil(120 turn). The magnetic field strength decided from the current of the primary coil(1017 turn). The feedback control is performed so that the magnetic flux waveform matches the command waveform. The iron losses are calculated from the area of B-H loops. The iron losses due to the harmonics were measured under the following two conditions.

- Assuming the spatial harmonics

  Fundamental waveforms + 20%, 7th order harmonics

- Assuming the time harmonics due to a PWM invertor

  Fundamental waveforms + 5%, 6 kHz harmonics

Fig.9 shows the example of the measured waveforms.

In the magnetic field analysis, 2D FEA model for the part of the ring was used for the loss calculation. The 2D FEA model is shown in Fig.10. The magnetic flux density waveforms obtained by the measurement were input as the vector potential boundary. The iron losses were calculated by the Play-Hysteron model and the 1D method, and the anomalous eddy current losses were calculated with the dynamic anomalous loss factor $\kappa(dB/dt)$ in Fig. 5. In the 1D method, although the influence to the eddy current by the edge of the steel sheet is ignored, we confirmed that the influence is small since the width of the ring is enough. Regarding the set of symmetric loops used for the Play-Hysteron model, the amplitude of the symmetric loops were from 0.05 to 1.8 T and number of loops was 36(the increments of amplitude is 0.05 T) and the increments were increased to 0.025 T by above interpolation technique.

B. Comparison between measurement and analysis

Fig. 11 and Fig.12 shows the measured and analyzed iron losses. "Conv." in Fig.11, Fig.12 show the results by the conventional iron loss calculation method using the iron loss values under the sinusoidal magnetic flux excitation. The eddy current losses of "Conv." include the anomalous eddy current

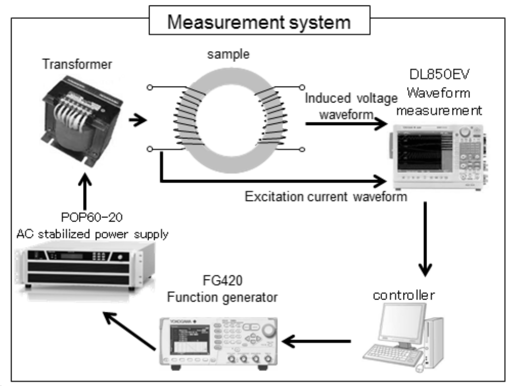
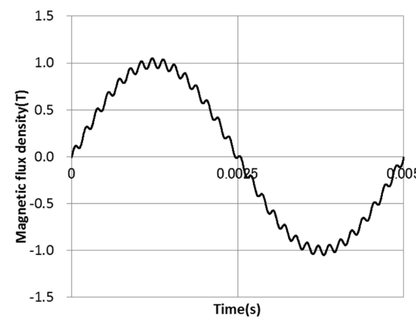
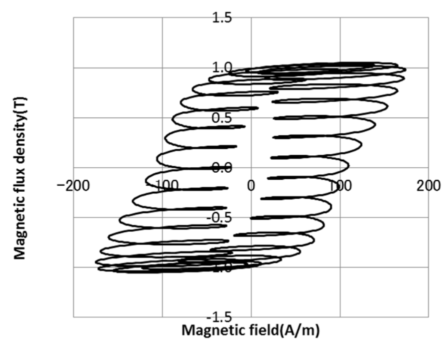


Fig. 8. Measurement system



(a)Magnetic flux density waveform



(b)B-H loops

Fig. 9. Example of measured waveform(1.0T,200Hz+6kHz harmonics)

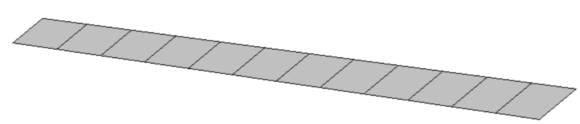


Fig. 10. 2D FEA model (2.5deg of the ring)

losses. "Prop." shows the results by the proposed method. From the results, when superimposing the 7th harmonics on the 1T fundamental wave, the errors from the measurement are less than 10% even in the conventional method, but the errors increase in the case of 1.4T fundamental wave. As can be seen from Fig. 7, the minor loop losses increase when the fundamental wave amplitude becomes high and the minor loops occurs at the high position in the major loop, but that phenomenon can't be taken into account in the conventional method. The errors in the proposed method are less than several percent regardless of the fundamental wave amplitudes and frequencies. Looking at the breakdown of the iron losses, the contribution of the Play-Hysteron model is large at the low frequencies because the ratio of the hysteresis losses is high, and the contribution of 1D method is large at the high frequencies. "Prop. (Const)" shows the results where the anomalous loss factor κ is fixed at the value at1T/50Hz (κ=1.58) by the conventional separation method in Fig.1. It is greatly overestimated at the high frequencies, resulting in deterioration in the accuracy over the conventional iron loss calculation method.

Finally, the influence of the extrapolation by the logarithmic function shown in (3) was investigated. Fig.13 shows the errors to the measurement iron losses(fundamental + 7th harmonics) when narrowing the range of measurement data used for deciding the anomalous loss factors from 50-1kHz to 50-400Hz and 50-100 Hz. Fig.13 shows only low frequencies data such as 50 and 100 Hz for deciding the anomalous loss factor is not enough for calculating the iron loss at 1kHz fundamental wave. It causes almost 10% error. If the data up to 400 Hz exist, the iron losses at the 1kHz fundamental wave can be reproduced by the extrapolation by the logarithmic function (3).

V. CONCLUSIONS AND FUTURE WORK

By applying the dynamic anomalous loss factors identified from arbitrary magnetic flux density amplitude and frequency conditions by the Play-Hysteron model and the 1D method. The obtained dynamic anomalous loss factors were applied to the calculation of the iron losses due to harmonics. The results match well to the measured losses.

In the future, we will apply this method to the iron loss calculation of motors and verify the accuracy. Future tasks include studying the physical background of fitting the dynamic anomalous loss factors with the logarithmic function and improvement of the fact that the factor κ becomes below 1.0 at the high frequencies. In addition, it is necessary to evaluate the errors by applying the anomalous loss factors κ identified by the sinusoidal magnetic flux excitation conditions to the minor loops.

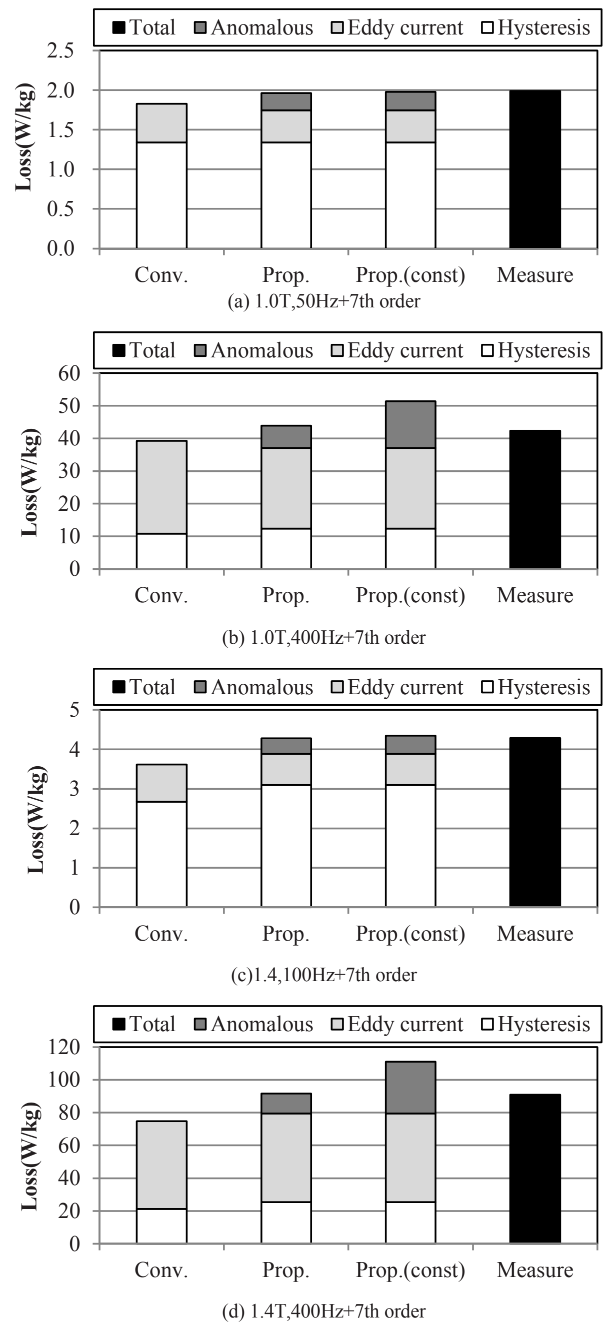
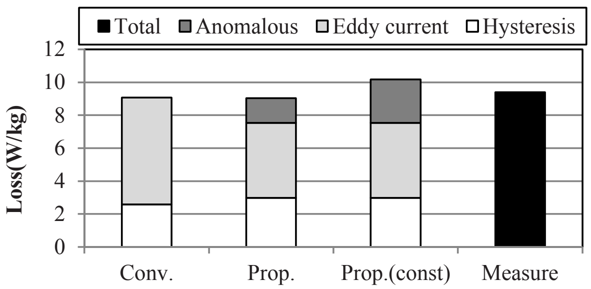
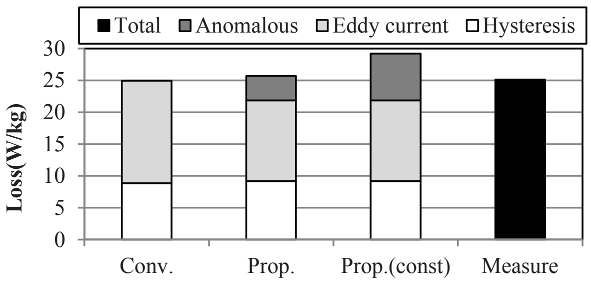


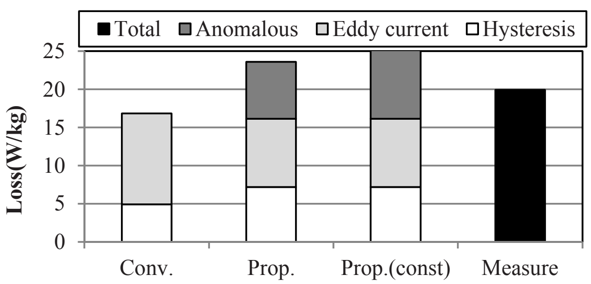
Fig. 11. Iron losses due to 7th orderharmonics



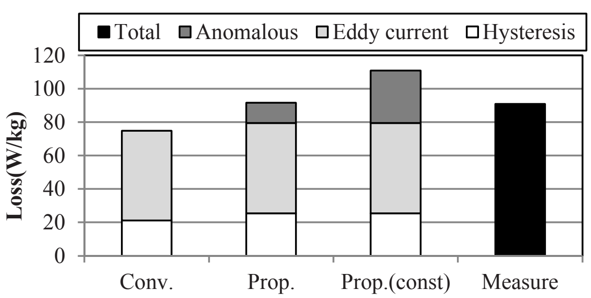
(a) 1.0T,100Hz+6kHz



(b) 1.0T,400Hz+6kHz

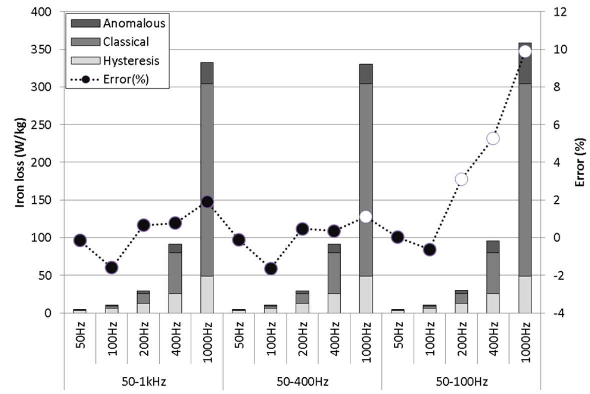


(c) 1.4T,100Hz+6kHz



(d) 1.4T,400Hz+6kHz

Fig. 12. Iron losses due to 6kHz harmonics



Solid circle : data exist, Hollow circle : data don't exist(extrapolated)

Fig. 13. Measurement data range to use identification and error

REFERENCES

[1] G. Bertotti, "General properties of power losses in soft ferromagnetic materials", *IEEE Transactions on Magnetics*, vol. 24, no. 1, pp.621-630, 1988

[2] T. Matsuo, D. Shimode, Y. Terada, M. Shimasaki, "Application of stop and play models to the representation of magnetic characteristics of silicon steel sheet", IEEE Transactions on Magnetics, vol.39, no.3, pp.1361-1364, 2003

[3] O. Bottauscio, "Advanced Model of Laminated Magnetic Cores for Two-Dimensional Field Analysis", *IEEE Transactions on Magnetics*, vol.36, no.3, pp561-573, 2000

[4] K. Yamazaki, N. Fukushima, "Experimental Validation of Iron Loss Model for Rotating Machines Based on Direct Eddy Current Analysis of Electrical Steel Sheets", International Electric Machines and Drives Conference (IEMDC), pp.851-857, 2009

[5] K. Narita, T. Asanuma, K. Semba, H. Sano, T. Yamada, K. Aiso, K. Akatsu, "An accurate iron loss evaluation method based on finite element analysis for switched reluctance motors", Energy Conversion Congress and Exposition (ECCE), 2015

[6] K. Yamazaki, N. Fukushima, "Iron-Loss Modeling for Rotating Machines: Comparison Between Bertotti's Three-Term Expression and 3-D Eddy-Current Analysis", *IEEE Transactions on Magnetics*, vol.46, no.8, pp. 3121- 3124, 2010

[7] R. Mitsuoka, T. Mifune, T. Matsuo, "Dynamic hysteresis modeling of silicon steel having nonuniform magnetic property", J. Appl. Phys. 111, 07D110 (2012)

[8] K. Narita, H. Sano, T. Yamada, "Study of processing and interpolation method of symmetric loops for play model", The Papers of Joint Technical Meeting on Static Apparatus and Rotating Machinery , IEE Japan, SA-17-58, RM-17-89 (2017) (in Japanese)