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Influence of Inverter Excitation on Iron Loss of Non-Oriented Electrical Steel

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Abstract:

The influence of material thickness and ON voltage on iron loss of non-oriented electrical steels under PWM inverter excitation was investigated. The increase of iron loss with the increase in material thickness under inverter excitation was larger than that under sinusoidal excitation. This may be because the ratio of eddy current loss to iron loss under inverter excitation is larger than that under sinusoidal excitation. The iron loss under PWM inverter excitation increased with the increase in the ratio V_{ON}/V_{DC}*. This is thought to be due to an increase in hysteresis loss caused by the generation of minor loops formed by superposition of magnetic flux densities.*

1. Introduction

In response to calls for greater energy conservation, improvement of motor efficiency has become an important challenge. As one trend, motor drive by PWM control utilizing inverter excitation in order to reduce power consumption and improve controllability is continuing to become the main stream technology, particularly in brushless DC motors. On the other hand, the electrical steels used as the motor core materials are also expected to contribute to improved performance in inverter-fed motors.

In high-efficiency motors using inverters, it is known that the harmonics included in the voltage waveform increase iron loss[1)]. The effects of the sheet thickness, Si content, *etc*. on the magnetic properties of electrical steel are evaluated by the single sheet test (SST), Epstein test and ring test pieces [2,3)], and effective materials for improving motor efficiency are selected referring to the magnetic measurement values obtained by these tests. However, in the magnetic property evaluation methods which are normally used, magnetic properties are evaluated under sinusoidal excitation, which does not include harmonics, resulting in a discrepancy between the iron loss of motors driven by inverter excitation and that of electrical steel specimens evaluated under sinusoidal excitation[4)]. For this reason, it is important to consider the magnetic properties under the effect of the harmonics caused by inverter excitation in motor design. Based on this background, Fujisaki *et al.* investigated iron loss under inverter excitation using test pieces with the same iron loss under sinusoidal excitation and different sheet thicknesses, and reported that materials with thinner sheet thicknesses displayed lower iron loss under inverter excitation[4)], and Honda *et al.* investigated the relationship between the characteristics of induction motors under inverter feed and the Si content and sheet thickness of the core material, and reported that the motor efficiency improved as the sheet thickness decreased[5)].

However, in the reports to date, the relationship between the thickness of the core material and iron loss under inverter excitation has not been evaluated quantitatively, and there are almost no examples of research that offers a detailed explanation of the decrease in iron loss due to sheet thickness reduction which discuss the mechanism responsible for that behavior. Therefore, the authors reported the results of an evaluation of the material iron loss under excitation by the inverter control method when using magnetic measurement test pieces in which only the sheet thickness was changed[6)].

Sasayama *et al.* evaluated iron loss under inverter excitation using ring test pieces consisting of different numbers of laminated sheets, and reported that iron loss under inverter excitation is affected by the change in the area of the minor loop caused by the ON voltage when the cross-sectional area of the test piece is

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changed[7)]. Yun *et al.* excited test pieces with voltage waveforms simulating PWM inverter feed with different ON voltages using a function generator, and reported that iron loss was reduced by decreasing the inverter ON voltage[8)]. Based on these results, it can be said that a detailed understanding of the effects of the power source and the measurement specimens on iron loss will be necessary when evaluating iron loss under PWM inverter excitation conditions. Therefore, we will also report the results of measurements of iron loss under different test piece conditions and excitation waveform conditions with the aim of evaluating the effect of the inverter ON voltage on material iron loss under actual PWM inverter excitation[9)].

2. Effect of Thickness of Non-Oriented Electrical Steel Sheet on Iron Loss under Inverter Excitation

2.1 Experimental Procedure

This experiment was conducted by magnetic measurements in which the measurement test pieces were excited by PWM control using an inverter. **Figure 1** shows the measurement system. A single-phase Si-N channel IGBT inverter was used in the inverter part. The waveforms of the primary current I and the secondary voltage V were recorded with a digital oscilloscope using a current sensor. As the evaluation samples, cold-rolled steel sheets with the three thicknesses of 0.25 mm, 0.35 mm and 0.50 mm were prepared from a Si: 3 mass% ingot and subjected to final annealing. These three types of samples had the same Si contents, and the fact that the grain size was also on the same level was confirmed from the cross-sectional microstructure. Ring-shaped samples with an inner diameter of 60 mm and an outer diameter of 80 mm were processed from the final-annealed steel sheets by wire cutting, and were then introduced into a polyacetal ring case with a thickness of 1 mm, and a primary winding N_1 of 150 turns and secondary winding N_2 of 100 turns were applied. Since the cross section of the core affects iron loss under inverter excitation[7)], the lamination thickness of the sheets of each thickness was set to 7 mm, and the number of laminated sheets was adjusted so that the weight variation was within 2%. The strength of the magnetic field H and the magnetic flux density B were obtained from the primary current waveform and the secondary voltage waveform, respectively. The calculation formulas for H and B are as follows.

$$H = \frac{N_1}{L} \times I \ \ [\mathrm{A/m}] \quad \cdots\cdots\cdots\cdots (1)$$

$$B = \frac{1}{N_2 S} \times \int V dt \ \ [\mathrm{T}] \quad \cdots\cdots\cdots\cdots (2)$$

Iron loss W was obtained from the inner area of the hysteresis loop, as shown by the following equation. Here, L is the magnetic path length of the ring sample, S is the cross section of the sample, f is the fundamental frequency and ρ is the density of the electrical steel.

$$W = \frac{f}{\rho} \times \int H dB \ \ [\mathrm{W/kg}] \quad \cdots\cdots\cdots\cdots (3)$$

The iron loss increase rate R_{inc} due to inverter excitation was defined as follows from the iron loss under inverter excitation W_{inv} and the iron loss under sinusoidal excitation $W_{\sin}$.

$$R_{\mathrm{inc}} = \frac{W_{\mathrm{inv}} - W_{\sin}}{W_{\sin}} \times 100 \ \ [\%] \quad \cdots\cdots\cdots\cdots (4)$$

The changes in the magnetic flux density and the strength of the minor loop in the vicinity of $B = 0$ in the hysteresis loop under inverter excitation were defined as ΔB and ΔH, respectively, as shown in **Fig. 2**.

The fundamental frequency was 50 Hz, and iron loss was measured by changing the maximum magnetic flux density B_{m} between 0.1 to 1.5 T, the carrier frequency f_{c} between 1 k to 20 kHz and the modulation index m between 0.1 to 3.0. In measurements of hysteresis loss, the excitation rate was adjusted so that 1 cycle was 120 s, and the measurements were carried out at maximum flux densities B_{m} between 0.1 to 1.5 T.

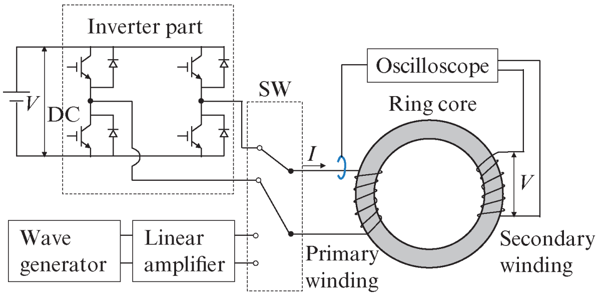

Fig. 1 Measurement system

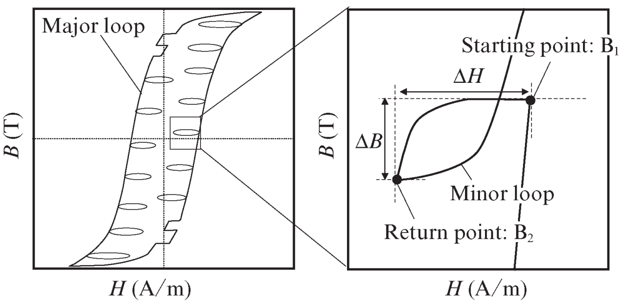

Fig. 2 BH curve and minor loops

2.2 Experimental Results and Discussion

Figure 3 shows the iron loss under sinusoidal excitation W_{sin} when the maximum magnetic flux density B_{m} is 1.5 T and the fundamental frequency f is 50 Hz, and the iron loss under inverter excitation W_{inv} when the magnetic maximum flux density B_{m} is 1.5 T, the fundamental frequency f is 50 Hz, the carrier frequency f_{c} is 1 kHz and the modulation index m is 0.4. It can be understood that iron loss decreases under both sinusoidal excitation and inverter excitation as the sheet thickness decreases, and the iron loss under inverter excitation is large compared with that under sinusoidal excitation. Furthermore, the amount of change in iron loss accompanying changes in sheet thickness is also larger under inverter excitation than under sinusoidal excitation.

Figure 4 shows the change in iron loss W_{inv} under inverter excitation when the maximum flux density B_{m}, fundamental frequency f and modulation index m are fixed at 1.5 T, 50 Hz and 0.4, respectively, and the carrier frequency f_{c} is changed. Iron loss decreased as the carrier frequency increased. **Figure 5** shows the relationship between the iron loss increase rate R_{inc} and the carrier frequency f_{c}. The iron loss increase rate became larger as the sheet thickness increased but decreased as the carrier frequency increased. Moreover, the changes in both iron loss and the iron loss increase rate became larger at carrier frequencies below 5 kHz. **Figure 6** shows the change in iron loss W_{inv} under inverter excitation when the maximum flux density B_{m}, fundamental frequency f and carrier frequency f_{c} are fixed at 1.5 T, 50 Hz and 1 kHz, respectively, and the modulation index m is changed. Iron loss decreased as the modulation index increased. **Figure 7** shows the relationship between the modulation index m and the iron lose increase rate R_{inc}. The iron loss increase rate decreased as the modulation index increased, but became constant at modulation indexes 1.6 or larger regardless of the sheet thickness.

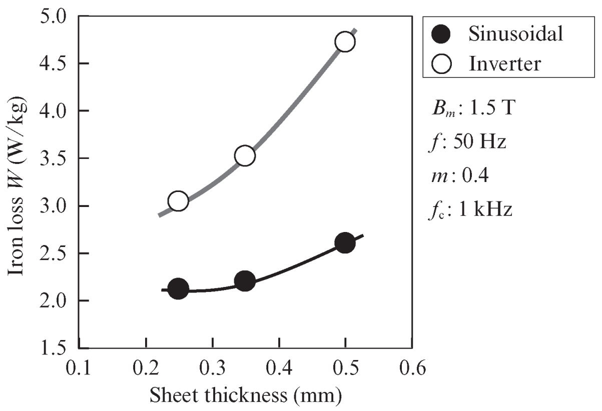

Fig. 3 Iron losses under sinusoidal wave and inverter excitation

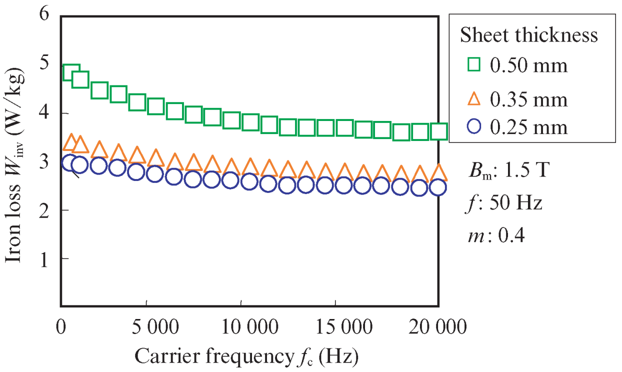

Fig. 4 Influence of carrier frequency on W_{inv}

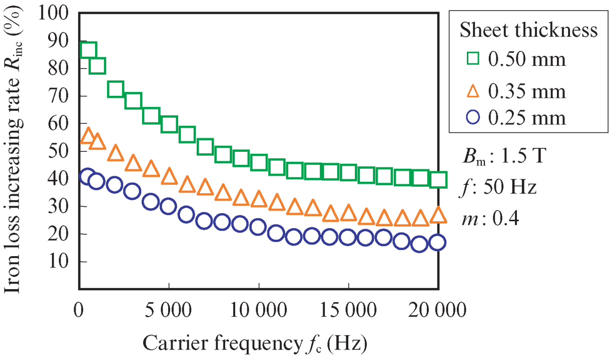

Fig. 5 Influence of carrier frequency on R_{inc}

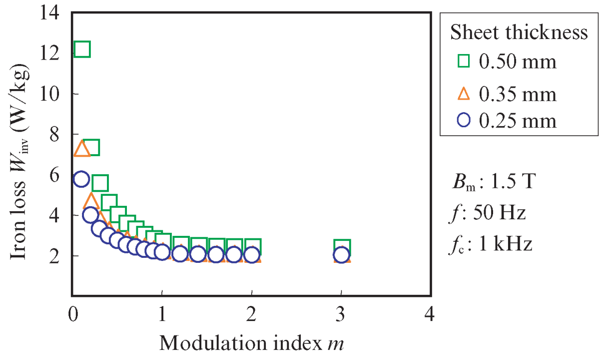

Fig. 6 Influence of modulation index on W_{inv}

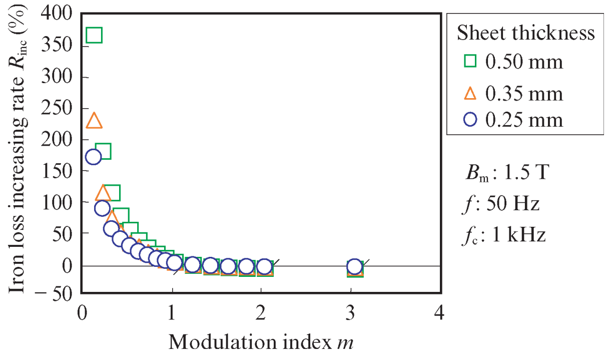

Fig. 7 Influence of modulation index on R_{inc}

Figure 8 shows the change in the strength of the magnetic field ΔH of the minor loop around 0 T and the change of the magnetic flux density ΔB for various inverter excitation conditions and sheet thicknesses. As the carrier frequency and the modulation index decrease, the amount of change in the magnetic flux density ΔB and the strength of the magnetic field ΔH became larger. However, when the sheet thickness was reduced, almost no change was observed in the amount of change in the magnetic flux density ΔB, but the change in the strength of the magnetic field ΔH decreased. Because this tendency could be confirmed in all the minor loops, it is thought that the large decrease in iron loss under inverter excitation when thinner sheets were used occurred because the change in the strength of the magnetic field ΔH of the minor loop decreased due to the reduction of sheet thickness, and iron loss decreased by an amount corresponding to the decrease in ΔH.

Next, in order to evaluate the sheet thickness dependence of eddy current loss and hysteresis loss under inverter excitation, the hysteresis loss when the *B-H* loop includes minor loops was measured by the following method.

When a minor loop is formed, is it known that hysteresis loss is affected by the origin B_1 of the minor loop and the magnitude of ΔB [10,11]. Therefore, the origins B_1 and the reversal points B_2 of all the minor loops formed by inverter excitation are read, the voltage is controlled so that the magnetic flux density waveform of the hysteresis loss measurement is inverted at the same magnetic flux density as the magnetic flux density waveform in inverter excitation, and hysteresis loss was measured at the excitation rate where 1 cycle becomes 120 s. **Figure 9** shows an example of a *B-H* loop in a hysteresis loss measurement. The major loop followed the same track regardless of whether a minor loop existed or not. The hysteresis loss of each minor loop was calculated from the obtained areas of the minor loops, and the sum of the hysteresis losses of the major loop and all the minor loops was taken as the hysteresis loss under inverter excitation. The eddy current loss under inverter excitation was then determined by subtracting the hysteresis loss calculated by the method described above from the iron loss under inverter excitation.

Figure 10 shows the hysteresis loss W_h, eddy current loss W_e and iron loss under sinusoidal excitation W_{sin} and under inverter excitation W_{inv}. Although there is no significant change in hysteresis loss with the different sheet thicknesses between under inverter excitation and under sinusoidal excitation, the change in eddy

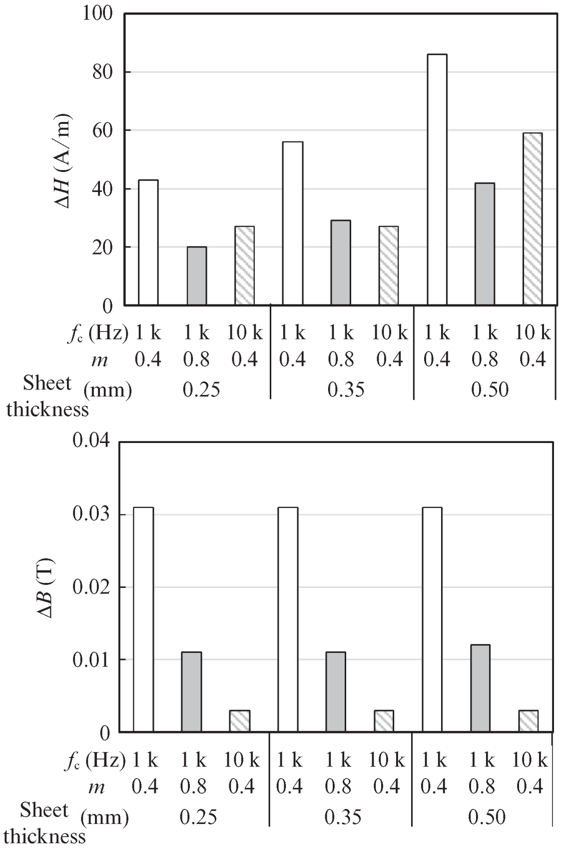

Fig. 8 ΔH and ΔB in various inverter excitation conditions and sheet thicknesses

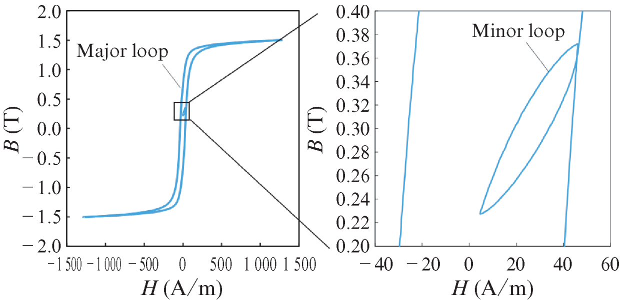

Fig. 9 Hysteresis losses under sinusoidal wave and inverter excitation predicted by empirical composition

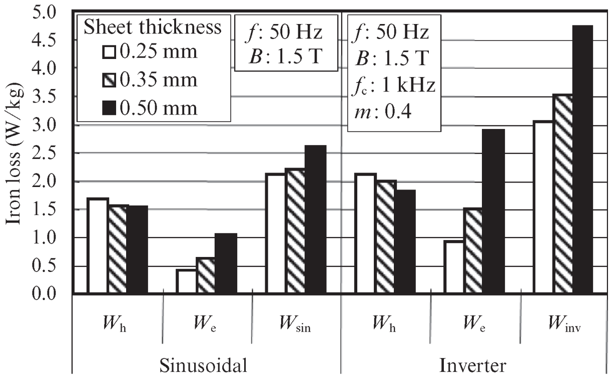

Fig. 10 Hysteresis loss W_h, eddy current loss W_e, and iron loss under sinusoidal wave W_{sin} and inverter excitation W_{inv}

current loss accompanying changes in the sheet thickness is larger in the case of inverter excitation, and is strongly affected by the sheet thickness. This is considered to reflect the increase in the ratio of eddy current loss to iron loss because the inverter excitation waveform includes harmonics.

Next, a spectrum analysis of the magnetic flux density waveform under inverter excitation was conducted by FFT. **Figures 11** to **13** show the FFT analysis results when the carrier frequency or the modulation index was changed for a sheet with a thickness of 0.25 mm. Frequency components which are multiples of the fundamental frequency of 50 Hz and the carrier frequency were detected in the spectra. The relationship between the spectrum intensity and the modulation index and carrier frequency are shown in **Fig. 14** for the fundamental frequency and in **Fig. 15** for the 2nd harmonic. Accompanying increases in the modulation index or carrier frequency, the intensity of the fundamental frequency increased, while the intensity of the harmonic component (2nd harmonic) of the carrier frequency decreased.

Subsequently, iron loss was calculated based on the spectrum components of the magnetic flux density waveform. Since no significant differences in the spectral distribution depending on the sheet thickness were recognized, the spectrum components and spectrum intensity of the sheet with a thickness of 0.25 mm were analyzed.

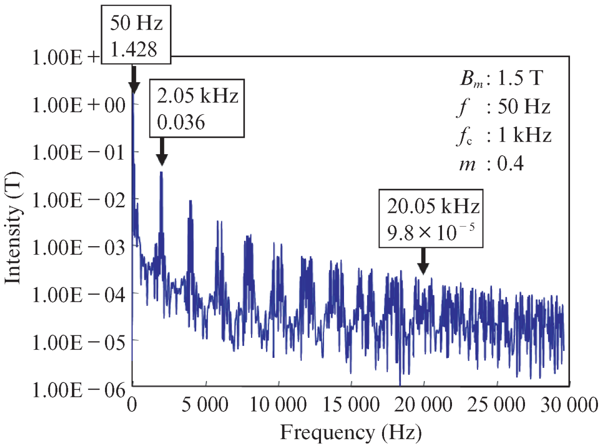

Fig. 11 Frequency spectrum of flux density

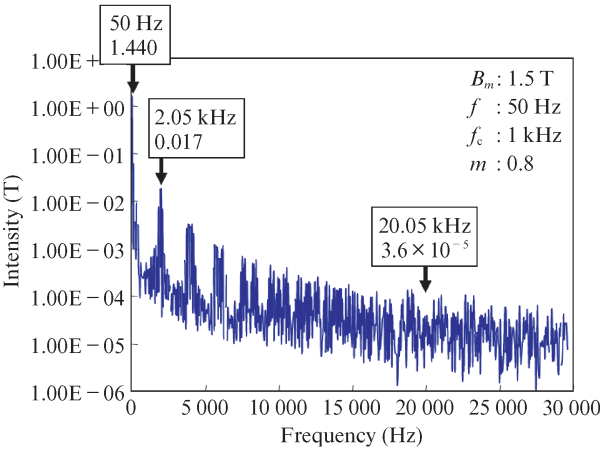

Fig. 12 Frequency spectrum of flux density

First, iron loss was measured under sinusoidal excitation conditions, assuming that the intensities of the spectra obtained from the FFT analysis represent the

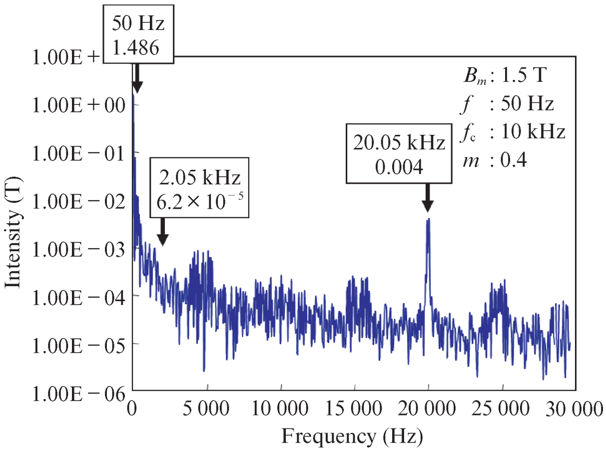

Fig. 13 Frequency spectrum of flux density

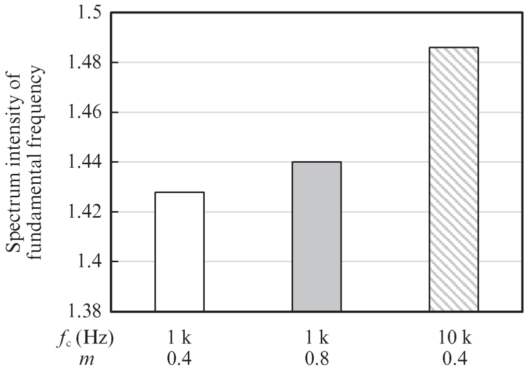

Fig. 14 Spectrum intensity of fundamental frequency at each carrier frequency and modulation rate

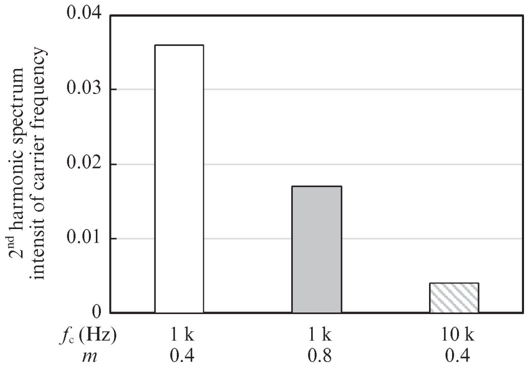

Fig. 15 2nd harmonic spectrum intensity of carrier frequency at each carrier frequency and modulation rate maximum magnetic flux density, and the estimated value of iron loss for inverter excitation was obtained by adding the results. The contributions of the fundamental frequency component and the harmonic components to iron loss under inverter excitation were estimated by adding the iron losses corresponding to the frequency components of each of the regions of 50 Hz, 0.1 k-1.9 kHz and 1.95 k-20.05 kHz.

Figure 16 shows the actual value of iron loss under inverter excitation and the estimated values of iron loss for each of the frequency regions. The estimated values of iron loss were small compared to the actual measured values. It is known that iron loss generally increases under direct current (DC) biased magnetization in comparison with unbiased magnetization [10,11]. Therefore, since a complete simulation of the iron loss of harmonic components superposed under various bias magnetisms is not possible, iron loss is considered to be underestimated by the technique used here. However, the tendency of the iron loss estimated from the spectral components of the magnetic flux density was in good agreement with the actual changes in iron loss associated with changes in the carrier frequency and modulation index, suggesting that the approach used here is useful for understanding the phenomenon of increased iron loss due to inverter excitation.

Focusing on the iron loss of harmonic components, the largest change in iron loss when the sheet thickness and excitation conditions were changed was observed in the 1.95 k-20.05 kHz frequency region, and the amount of that change showed comparatively good agreement with the amount of change in the measured iron loss under inverter excitation. The fact that the change in iron loss when the inverter excitation conditions are changed becomes larger as the sheet thickness increases is considered to be due to an increase in the ratio of iron loss occupied by eddy current loss, which is strongly affected by harmonic components, as the sheet thickness increases.

From Fig. 16, it can be understood that the increase in iron loss at larger sheet thicknesses becomes less significant under excitation conditions with higher modulation indexes. Moreover, as shown in Fig. 15, the intensity of harmonic components in the magnetic flux density waveform decreases when the modulation index is increased, suggesting that this behavior can also be attributed to a decrease in the ratio of eddy current loss to iron loss.

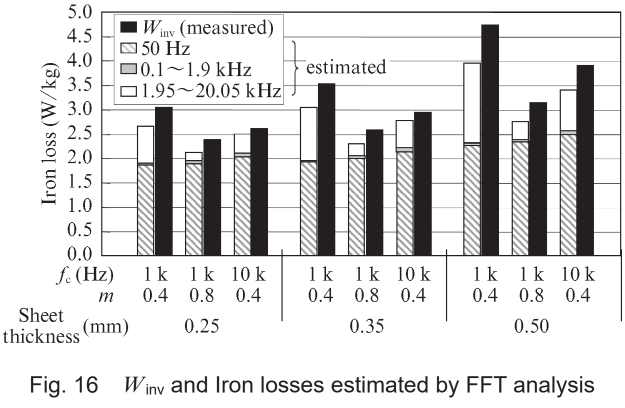

Fig. 16 W_{inv} and Iron losses estimated by FFT analysis

The change in iron loss when the sheet thickness was changed also became less pronounced under excitation conditions with a high carrier frequency. As in the case of the modulation index, the intensity of harmonic components also decreases under a high carrier frequency condition, indicating that this is due to a decrease in the ratio of eddy current loss to iron loss.

3. Effect of ON Voltage on Iron Loss under Inverter Excitation

3.1 Experimental Procedure

This experiment was carried out by magnetic measurement using a single-phase Si-N channel IGBT inverter circuit as the excitation source. **Figure 17** shows the measurement system. The average ON voltage V_{ON} read from the voltage waveform in the magnetic measurements was 1.2 V, and the target maximum magnetic flux density was obtained by adjusting the DC power source voltage V_{DC}. For comparison, measurements were performed with an excitation power source consisting of a function generator and a linear amplifier. Here, the ideal PWM voltage waveform of $V_{ON} = 0$ was used. In this magnetic measurement, the primary current waveform and secondary voltage waveform were recorded with a digital oscilloscope, and iron loss was determined from the temporal changes in the strength of the magnetic field H and the magnetic flux density B. As the PWM control conditions, the carrier frequency f_c and the modulation index m were fixed at $f_c = 1$ kHz and $m = 0.4$, and the maximum magnetic flux density $B_m = 1.0$ T and fundamental frequency f = 50 Hz were used. Inverter excitation and linear amplifier excitation were defined as W_{inv} and W_{amp}, respectively.

As samples for measurement, a non-oriented electri-

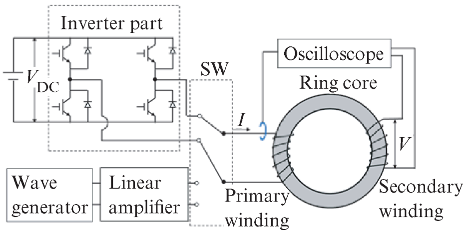

Fig. 17 Measurement system

cal steel sheet with a thickness of 0.35 mm with a ring shape with an inner diameter of 35 mm and an outer diameter of 55 mm was prepared by wire cutting, inserted into a polyacetal ring case with a thickness of 1 mm, and a primary winding of 100 turns and secondary winding of 100 turns were applied. In the measurements, the ratio of V_{ON} and V_{DC} was changed by changing the number of laminated sample sheets to the three levels of 13 sheets, 22 sheets and 55 sheets.

3.2 Experimental Results and Discussion

Figure 18 shows the relationship between the cross-sectional area S of the laminated specimens and iron loss. Although iron loss W_{inv} under PWM inverter excitation increased as the specimen area decreased, there was no significant change in iron loss W_{amp} under PWM linear amplifier excitation. Furthermore, when specimens with the same cross-sectional area were compared, iron loss W_{inv} was larger than W_{amp}. **Figure 19** shows the relationship between the ratio of V_{ON} to V_{DC} and iron loss. W_{inv} increased as V_{ON}/V_{DC} increased.

In order to clarify the effect of the excitation method on harmonic components, the amplitude of the harmonic components in the magnetic flux density waveform was obtained by a FFT analysis. With both excitation methods, components were detected for the fundamental frequency of 50 Hz and around 2 kHz, which is 2 times the carrier frequency. **Table 1** shows the results of the FFT analysis for PWM inverter excitation and PWM linear amplifier excitation. Under linear amplifier excitation, the spectrum intensity is constant independent of the cross-sectional area. However, under PWM inverter excitation, specimen cross-sectional area dependency can be observed in the spectrum intensity.

Next, assuming that the spectrum intensities of the respective specimens represent the maximum magnetic flux density, the estimated values of iron loss were found by measuring the iron loss under sinusoidal excitation at each frequency and adding the results (**Fig. 20**). The measured and estimated values of iron loss under PWM linear amplifier excitation showed good agreement. However, under PWM inverter excitation, the differences between the measured values and estimated values were large, and those difference increased as the specimen cross-sectional area became smaller. According to Lancarotte *et al.*, it has been reported that the minor loop area increases as minor loops are formed in the high magnetic flux density region, and as a result, hysteresis loss increases[10]. The estimated value of iron loss calculated from sinusoidal excitation centering on $B = 0$ is considered to be underestimated because it does not consider the increment of

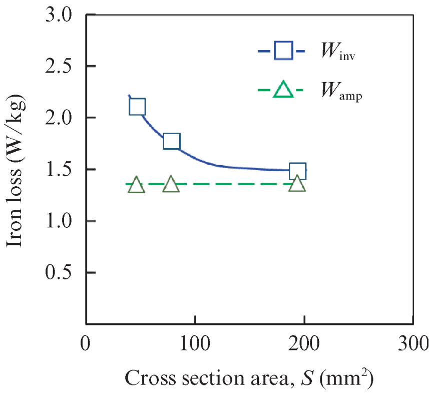

Fig. 18 Effect of cross section area of laminated specimen

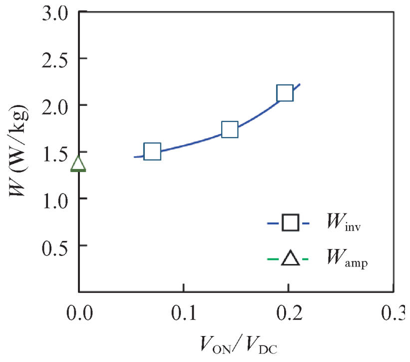

Fig. 19 Effect of ratio of ON voltage to secondary voltage on iron loss

Table 1 Spectrum intensity of flux density waveform

PWM operating condition		Intnsity of spectrum component (T)		
	S (m^2)	at 50 Hz	at 1.95 kHz	at 2.05 kHz
PWM-AMP	4.55	1.044	0.020	0.019
	7.70	1.047	0.020	0.020
	19.25	1.049	0.021	0.020
PWM-INV	4.55	0.853	0.036	0.033
	7.70	0.918	0.029	0.027
	19.25	0.985	0.029	0.022

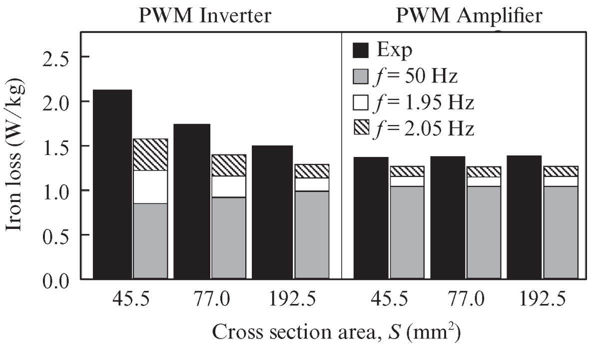

Fig. 20 Iron losses estimated by FFT analysis

hysteresis loss due to superposition of harmonic components on the magnetic flux density waveform. Moreover, it is also thought that error becomes larger as the specimen cross-sectional area becomes smaller because the area of the minor loop increases and the increment of hysteresis loss due to superposition of the harmonic components on the magnetic flux density waveform increases under this condition. Since minor loops are not formed under PWM linear amplifier excitation, it is considered possible to predict the measured iron loss with good accuracy from the iron loss of each spectrum obtained from the FFT analysis.

4. Conclusion

In motor design, it is important to consider magnetic measurements under the effect of the harmonics caused by inverter excitation. From this viewpoint, the following knowledge was obtained as a result of this study.

(1) It was shown quantitatively that the ratio of eddy current loss to iron loss due to the effect of harmonics is larger under inverter excitation than under sinusoidal excitation. Based on this finding, it is considered the eddy current reduction effect of using thinner core materials is more significant under inverter excitation than under sinusoidal excitation.

(2) The percentage of harmonic components included in the magnetic flux density waveform decreased as the carrier frequency and the modulation index increased. It is thought that the ratio of eddy current loss to iron loss decreased for this reason, and as a result, the sheet thickness dependence of iron loss became smaller.

(3) Iron loss increased as the ratio of the ON voltage to the DC voltage of the inverter increased.

(4) Iron loss under PWM excitation conditions without an ON voltage could be predicted with good accuracy from the frequency components of the magnetic flux density waveform. On the other hand, under inverter excitation conditions, divergence occurred between the measured values and predicted values of iron loss because the increase in hysteresis loss due to minor loop formation caused by the ON voltage was not taken into account in the predicted values obtained from the frequency components of the magnetic flux density waveform.

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