Regular Paper

Magnetic Property Evaluation of the High-Speed Motor Stator Core Under Sinusoidal and Pulse Width Modulation Wave Excitation Using the Stator Winding Excitation Method

Mohachiro OKA *1 (Mem.), Masato ENOKIZONO *2 (Mem.)

Development of a small, high-speed and high-power motor is necessary to improve the performance of machines such as robots, and drones. The motor is excited by a high frequency voltage when the motor rotates high-speed. Moreover, the motor is driven by the pulse width modulation (PWM) inverter because efficiency and controllability is good. The driving voltage of the PWM inverter contains many higher harmonics waves. In such a motor, generation of heat due to the loss is a major problem. The loss of the motor includes an iron loss, a copper loss, and a machine loss; here we focus on the iron loss. Eddy-current loss increases especially under a condition of high frequency excitation. To suppress the eddy-current loss, we produced the stator core for a small, high-speed and high-power motor using a 0.08-mm-thick ultrathin electrical steel sheet. Additionally, to evaluate the magnetic properties of this new stator core with complex shape, we also developed a stator winding excitation method using a dummy rotor made of the 0.08-mm-thick ultrathin electrical steel sheet. In this paper, the effectiveness of a small, high-speed, and high-power motor stator core made of the 0.08mm-thick ultrathin electrical steel sheet is shown using the stator winding excitation method when it is excited by the PWM wave.

Keywords: high-speed motor, ultrathin electrical steel sheet, PWM, carrier frequency, modulation signal frequency.

(Received: 21 July 2018, Revised: 7 December 2018)

1. Introduction

Recently, the development of equipment such as robots and drones that uses small, high-speed and high-power motors is active. However, an eddy-current loss increases in the motor during high-speed rotating. In the high power motor, the copper loss also increases. Moreover, a heat radiation problem occurs if the size of the motor is reduced. Therefore, the development of such a motor is not easy. We focus on the iron loss to solve this problem. One of possible solution is reduction of an eddy-current loss in stator core. When the motor rotates at a high-speed, an effective method of decreasing eddy-current loss is to thin the thickness of the electrical steel sheet that composes the stator core of the motor. [1-3]. Eddy-current loss in the stator core also increases when the motors are driven by PWM inverters [4-6]. To decrease eddy-current loss in the stator cores of small, high-speed high-power motors, we developed a 0.08-mm-thick ultrathin electrical steel sheet.

Additionally, we developed the evaluation methods for the iron loss in the actual stator core for a small motor. They are an inside excitation method and an outside excitation method. We also developed the stator winding excitation method with a dummy rotor to form the magnetic circuit.

We prepared two stator cores that used a 0.08-mm-thick ultrathin electrical steel sheet and a 0.35-mm-thick conventional electrical steel sheet. Moreover, we compared iron loss ($W_{\text{sin}}$ [W/kg]) excited by sinusoidal waves with iron loss ($W_{\text{ipwm}}$ [W/kg]) excited by PWM waves using the stator winding excitation method. Results revealed that $W_{\text{ipwm}}$ was greater than $W_{\text{sin}}$ and that the increasing rate of $W_{\text{ipwm}}$ in the stator cores was especially low. We report measured iron losses excited by sinusoidal waves and PWM waves.

2. Iron loss and Specimens

2.1 Iron loss, hysteresis loss, and eddy-current loss

The iron loss ($W_s$ [W/kg]) of the specimen can be calculated using (1).

$$B_s \times H_s \times \rho \times T = W_s,$$

where $B_s$ and $H_s$ are the magnetic flux density and magnetic field strength of the stator core, respectively, $\rho$ [kg/m³] is the density of the core material, and $T$ [s] is the period of the excitation current ($I_{ex}$ [A]). Moreover, $H_{ex}$ and $B_{ex}$ can be evaluated using (2) and (3), respectively. In these equations, $I_{ex}$, $N_s$, $L_s$ [m], $N_v$, and $S$ [m²] represent the excitation current, the number of turns of the excitation coil, the effective magnetic path length, the number of turns of the search coil, and the sectional area of the search coil, respectively. $B_{ex}$ was obtained using $v_i$ [V], which is the induced voltage of the search coil, whereas $H_{ex}$ is obtained from $N_v$, $L_v$, and the measured $I_{ex}$ using $v_i$ [V]. The value of $B_{ex}$ is the induced voltage of the shunt resistor. The values of $K_v$ and $K_e$ in (4) were calculated by the dual frequency separation method. Hysteresis loss ($W_h$ [W/kg]) and eddy-current loss ($W_e$ [W/kg]) were obtained using (5). In this case, anomalous eddy-current loss was not considered.
2.2 Specimens

Figure 1 shows stator core specimens with excitation coils. The cores were made of two kinds of electrical steel sheets including a 0.08-mm-thick ultrathin electrical steel sheet and a 0.35-mm-thick electrical steel sheet. Hereafter, the two stator cores were called the 0.08mm_Core and the 0.35mm_Core. The outer diameter, inner diameter, and thickness of the two cores were 28.4 mm, 12.6 mm, and 12.5 mm, respectively. The 0.35mm_Core had conventional specifications for comparison with the 0.08mm_Core. Only one piece was prepared for each of the cores. Figure 2(a) shows a dummy rotor made of the 0.08-mm-thick ultrathin electrical steel sheet used in this experiment. The outer diameter, inner diameter, and thickness of the dummy rotor were 12.4 mm, 3.2 mm, and 12.5 mm, respectively. Two cores and the dummy rotor were cut out using the wire electrical discharge machining method. The electrical steel sheets for the core and the dummy rotor were each laminated by a bonding agent.

In the case of the 0.08mm_Core, the diameter of excitation coils was 0.25 mm. Moreover, the diameter of excitation coils was 0.22 mm in the 0.35mm_Core. The number of turns of each excitation coil was 40 in both cores. The search coil for the magnetic flux density measurement was wound on the tooth of each stator core. The number of turns of the search coil was one in both cores. The diameter of the search coil was 0.2 mm. In the case of the 0.08mm_Core, the 7th and 8th excitation coils were used in this experiment, and connected with the series. In the case of the 0.35mm_Core, exciting coils were wound on two teeth as shown in Fig. 1(b). In this case, two excitation coils were connected with the series.

2.3 The stator winding excitation method

Figure 2(b) shows the arrangement of a stator core, the dummy rotor, the excitation coil, and the search coil for the stator winding excitation method. Figure 2(b) also shows the magnetic path of this method. Two excitation coils were connected so that the magnetic flux passed the magnetic path shown in Figure 2(b). In this experiment, the magnetic properties of the stator core were measured using this method.

2.4 Finite element method analysis of the stator winding excitation method

We analyzed the magnetic flux distribution and the magnetic flux line of the stator winding excitation method using the 2 dimensional Finite element method (FEM). In this FEM analysis, we considers magnetic saturation, the eddy-current of the stator core. The material of the stator core used in this analysis was 50A1000, and the excitation frequency was 50 Hz. Fig. 3(a) and Fig. 3(b) show the magnetic flux density distribution and the magnetic flux line distribution in the stator core. From these two figures, it is understood that the magnetic flux passes two teeth and a back yoke and the dummy rotor.

3. Measurement system and conditions

3.1 Measurement system

The block diagram of the system used to evaluate the magnetic properties of the small, high-speed and high-power motor stator core is shown in Fig. 4. The excitation voltage outputted from the D/A converter, amplified with the power amplifier, was applied to two excitation coils. Values of $v_s$ and $v_r$ were inputted to a computer using the A/D convertor. The excitation current was measured using the voltage generated in the shunt resistor (0.1 Ω).
3.2 Measurement method

When the iron loss ($W_{is}$) was measured under the sinusoidal wave excitation, the waveform of the excitation voltage was controlled by feedback so that the excitation magnetic flux density ($B_{ex}$) of the stator core became a sinusoidal wave. In this case, the iron loss ($W_{is}$) was measured specifying the maximum excitation magnetic flux density ($B_{exmax}$). When the iron loss ($W_{ipwm}$) was measured under the PWM wave excitation, the excitation magnetic flux density controlled the maximum value of the fundamental wave of the measured magnetic flux density in the stator core. In this case, the fundamental wave was extracted using the Fast Fourier Transform method (FFT) from the measured $B_{ex}$.

The PWM excitation wave form that was the excitation voltage wave form shown in Fig. 5(b) was made with software using a sinusoidal modulation signal and a triangular carrier signal shown in Fig. 5(a). This PWM excitation wave was amplified with a linear power amplifier, and supplied to the excitation coil. In both cases, the magnetic properties were measured three times and then averaged.

3.3 Measurement condition under the sinusoidal wave excitation

The value of $B_{exmax}$ was applied from 0.4 T to 1.2 T in 0.1 T steps. The excitation frequencies ($f_{ex}$ [Hz]) were 50 Hz, 100 Hz, 200 Hz, 500 Hz, 1 kHz, and 2 kHz.

3.4 Measurement condition under the PWM wave excitation

In this case, $B_{exmax}$ was applied from 0.4 T to 1.2 T in 0.1 T steps. The modulation signal frequency ($f_{m}$ [Hz]) was 50 Hz. Carrier frequencies ($f_{c}$ [Hz]) were 1 kHz and 2 kHz. The iron loss was measured three times and then averaged. Moreover, when the peak to peak value of the carrier signal and the maximum value of the modulation signal were defined as $E_{c}$ [V] and $E_{m}$ [V], modulation index ($m$) could be written as (6).

$$m = \frac{E_{m}}{E_{c}} \quad (6)$$

4. Experimental results and discussions

4.1 $H_{c}$ and $B_{r}$ of the 0.08mm_Core and 0.35mm_Core under the sinusoidal wave excitation

Figure 6 shows the frequency characteristics of coercive force ($H_{c}$) and residual magnetic flux density ($B_{r}$) of the 0.08mm_Core and the 0.35mm_Core when $B_{exmax}$ was 1.0 T. From these figures, $H_{c}$ and $B_{r}$ were greatly changed in the 0.35mm_Core according to an increase in the excitation frequency. Moreover, they were slightly changed in the 0.08mm_Core according to an increase in the excitation frequency. This shows that the eddy current of the 0.08mm_Core is smaller than that of the 0.35mm_Core.

4.2 $B$-H curves of the 0.08mm_Core under the PWM wave excitation

Figure 7 shows $B$-H curves of the 0.08mm_Core when $f_{ex}$, $f_{c}$, $B_{exmax}$, and $m$ were 50 Hz, 1 kHz, 1.2 T, and 0.8, respectively. From this figure, the $B$-$H$ curve is long and slender shape because there is a gap of 0.1 mm between the stator core and the dummy rotor. Moreover, the minor loop by the influence of PWM excitation is observed.

4.3 $W_{is}$, $W_{ih}$, and $W_{e}$ under the sinusoidal wave excitation

Figure 8 shows the relationship between $W_{i}$ and excitation frequencies of two cores such as the 0.08mm_Core and the 0.35mm_Core. In this case, $B_{exmax}$ was 1.0 T. Values of $W_{i}$ of two stator cores
increased according to the increase in excitation frequencies. When $f_{ex}$ was 2 kHz, $W_i$ of the 0.08mm_Core was about 42% of $W_i$ of the 0.35mm_Core. It is understood that $W_i$ of the stator core made of the 0.08-mm-thick ultrathin electrical steel sheet was very small for a high excitation frequency of 2 kHz.

Figure 9 shows the relationship between $W_h$ and $W_e$ of two cores and excitation frequencies. There was no big difference into $W_h$ of both cores even if the excitation frequency changed. However, there was big difference into $W_e$ of both cores due to the excitation frequency. This phenomenon happened because of the difference of the thickness of both electrical steel sheet.

Figure 10 shows the relationship between $W_i$ and $B_{exmax}$ of two cores. When $B_{exmax}$ was 1.2 T, $W_i$ of the
0.08mm_Core was about 52% of $W_i$ of the 0.35mm_Core. Figure 11 shows the relationship between $W_h$ and $W_e$ of two cores and $B_{\text{exmax}}$ as same as Fig. 10. There was no big difference into $W_h$ of both cores even if $B_{\text{exmax}}$ changed. However, there was big difference into $W_e$ of both cores due to $B_{\text{exmax}}$.

4.4 $W_{\text{ipwm}}$ vs. $m$ under the PWM wave excitation

When $W_{\text{ipwm}}$ of the stator core under the PWM wave excitation was evaluated, modulation index ($m$) was an important parameter. We examined the relationship between $W_{\text{ipwm}}$ and $B_{\text{exmax}}$ of both cores as shown in Fig. 12(a) and Fig. 12(b) when $f_c$ was 1 kHz. The value of $m$ was changed to 0.4, 0.6, and 0.8. When $m$ was 0.4, $W_{\text{ipwm}}$ grew in both cores because the PWM excitation wave contained many higher harmonic waves. From Fig. 12(b), the tendency was especially clear in the 0.35mm_Core.

4.5 $W_{\text{isin}}$ and $W_{\text{ipwm}}$ under the sinusoidal wave excitation and the PWM wave excitation

Figure 13 shows the comparison between $W_{\text{isin}}$ and $W_{\text{ipwm}}$ of both cores when $f_{\text{ex}}$ was 1 kHz and 2 kHz. In the case of Fig. 13, $f_m$ was 50 Hz and $m$ was 0.4. The ratio of $W_{\text{isin}}$ to $W_{\text{ipwm}}$ ($W_{\text{ipwm}}/W_{\text{isin}}$) was 2.8 for the 0.08mm_Core and 6.7 for the 0.35mm_Core when $B_{\text{exmax}}$ was 1.2 T and $f_c$ was 1 kHz. When $B_{\text{exmax}}$ was 1.2T and $f_c$ was 2 kHz, they were 2.2 and 5.2. An increase in the iron loss by PWM wave excitation of the 0.35mm_Core is obviously larger than that of the 0.08mm_Core. This phenomenon attributed to the higher harmonic waves of the excitation voltage increasing when $f_c$ became high.
4.6 $W_{ipwm}$ vs. $f_c$ under the PWM wave excitation and the sinusoidal wave excitation

Figure 14 shows the comparison between $W_{isin}$ and $W_{ipwm}$ of both cores when $m$ was 0.8. In both case, $f_c$ was 1 kHz and 2 kHz, and $f_m$ was 50 Hz. $W_{ipwm}$ when $f_c$ was 2 kHz became smaller than it at 1 kHz. Reactance of the excitation coil increases when $f_c$ increases. Therefore, the higher harmonics waves of the excitation current decreases when $f_c$ increases, and $W_{ipwm}$ decreases.

5. Conclusion

To demonstrate the effectiveness of a stator core made of the 0.08-mm-thick ultrathin electrical steel sheet for a small, high-speed and high-power motor, we measured magnetic properties under the sinusoidal wave excitation and the PWM wave excitation using the stator winding excitation method. The magnetic properties in two cores such as the 0.08mm_Core and the 0.35mm_Core were compared. Consequently, we reached the following results.

(1) The stator winding excitation method using the dummy rotor that was developed by us clearly detected the magnetic properties of the actual stator core.

(2) The gap between the dummy rotor and teeth greatly influenced the $B$-$H$ curve of the 0.08mm_Core under the PWM wave excitation. Moreover, many minor loops were observed in the $B$-$H$ curve.

(3) The frequency dependency of magnetic properties ($H_{max}, B_{max}, W_{isin}, W_{ipwm}$) of the 0.08mm_Core was smaller than that of the 0.35mm_Core. This shows that the eddy current of the 0.08mm_Core is smaller than the eddy current of the 0.35mm_Core.

The stator core made of the 0.08-mm-thick ultrathin electrical steel sheet appears to be effective for decreasing the iron loss of a small, high-speed, high-power motor excited by the PWM wave. It is necessary to evaluate the iron loss of the stator core made of the ultrathin electrical steel sheet by using an actual inverter excitation system in the future.

Acknowledgment

We are indebted to Mr. Yuji Mori (Yoshikawa Kogyo CO., LTD.) and Mr. Kazumasa Yamazaki (Nippon Kinzoku CO., LTD.) for preparation of the sample used in this paper. We would like to thank the Tsugawa Foundation, and the Japan Society for the Promotion of Science (grant no.17K06480) for partly funding our study.

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