Core losses of a nanocrystalline motor under inverter and sinusoidal excitations

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In this paper, we focus on an evaluation of core losses in permanent magnet synchronous motors (PMSMs) made of nanocrystalline magnetic materials under inverter and sinusoidal excitations. To discuss the core loss properties of a nanocrystalline motor, comparison with PMSMs made of amorphous magnetic materials and non-oriented (NO) silicon steel sheets is also performed. Under sinusoidal excitation, the core losses of the nanocrystalline motor were about 0.7 and 0.5 times smaller than those of the amorphous and NO motors, respectively. In particular, we found that the nanocrystalline motor reduced the core loss on the basis of time harmonic components in comparison with not only the NO motor but also the amorphous motor. On the basis of our results, the nanocrystalline motor is expected to be suitable for use in high-speed and high-frequency regions.

Key words: core loss, iron loss, nanocrystalline magnetic materials, PMSM, non-oriented steel sheets, amorphous magnetic materials

1 Introduction

The losses in the driving electric motors mainly consist of mechanical, copper, and core losses (iron losses). Recently, in order to reduce core losses of the motors, the motors based on core with amorphous magnetic materials (AMM)1–12) and nanocrystalline magnetic materials (NMM)13–15) have been developed and examined. NMM and AMM exhibit lower iron loss16) than non-oriented (NO) silicon steel sheets. In particular, NMM offers potential reduction of core loss, compared to AMM. In our study, we examine core loss properties of the motor with NMM under inverter and sinusoidal excitations.

In order to control the rotational torque and speed of the motor, pulse width modulation (PWM) inverters are usually used. In the recent times, several researchers have shown that the iron losses of the magnetic core under PWM inverter excitation increase due to time harmonic components17–29). Therefore, it is necessary to estimate the influence of time harmonic components in the motor with NMM to develop the low loss motor systems.

Previous studies have addressed that the motor with NMM core exhibits low core losses “under PWM inverter excitation”13,15). Thus, the next phase is to correctly understand the core loss properties of the motor with NMM core “under sinusoidal excitation”. Since the motor core loss under sinusoidal excitation does not have time harmonic components, the evaluation of the sinusoidal-excited motor can obtain the smallest core losses of the motor core at the same experimental conditions (the same speed, torque, and vector control method)12).

In addition, by comparing losses under inverter and sinusoidal excitations, we can experimentally estimate the core losses caused by time harmonic components12). Because of a deterioration of the iron losses caused by the manufacture process and so on15), it is difficult to accurately obtain the core loss of the NMM motor based on iron losses of the materials by numerical simulations. Therefore, based on the experimental results, it is important to estimate the core losses caused by time harmonic components of the motor with NMM.

This study focuses on the experimental evaluation of core losses of permanent magnet synchronous motor (PMSM) with NMM cores excited by inverter and sinusoidal inputs. In order to discuss the core loss properties of the PMSM with NMM, we compare the PMSMs with NO and with AMM under PWM inverter and sinusoidal excitations. By comparing core losses under inverter and sinusoidal excitations, we experimentally estimate core losses caused by higher harmonic components (in particular, time harmonic components) of the PMSM with NMM.

2 Experimental method

In our study, we use three kinds of motor cores. Figure 1 shows stator and rotor cores made of NMM (FT-3M), NO electrical steel sheets (35H300), and AMM (SA-1) that consist of Fe-Si-B-Cu-Nb, Fe-Si, and Fe-Si-B, respectively. Table 1 shows the specifications of three different materials used for those cores. From here on, the PMSMs with the stator and rotor cores made of NMM, NO sheets, and AMM is called NMM-PMSM, NO-PMSM, and AMM-PMSM, respectively. Here, these three PMSMs made of different materials are the same design. In these PMSMs, the Sm-Fe-B bonded magnets (SSP-12ME, Aichi Steel Corporation) are used. The stacking factors of NMM-, NO-, and AMM-cores are about 80 %, 100 %, and 90 %, respectively. Table 2 shows the characteristics of the motor (stator and rotor) cores. Figure 2 shows the schematic of cross-sectional view of motor cores. See Refs.2,12,14,15) for the details of design and fabrication process of rotor and stator cores.

Figure 3 shows the schematic of the PMSM and its control system under no-load condition. Here, we can perform good accuracy of core loss measurement in no-load condition in comparison with the case in load condition19). By using this experimental system, we perform two excitation method tests. The first
depth is given as about 1.5 mm at 2 kHz. Thus, it is thought that the copper wire resistivity, $\rho$, is the frequency, and $\mu$ (\( \approx 1.26 \times 10^{-6}\) H/m) is the permeability. Here, the skin depth of the copper wire is obtained as about 1.5 mm at 2 kHz. Thus, it is thought that the copper wire is almost unaffected by the skin effect. In this study, by using a rotor without magnetization, the mechanical loss $P_m$ is measured. In our study, the mechanical losses are estimated as about 0.34, 0.88, and 1.4 W at 750, 1500, and 2250 rpm, respectively (see Ref. 1) for the details of the mechanical loss measurement method.

It is well known that the core loss under inverter excitation depends on fundamental, space harmonic, and time harmonic components. On the other hand, the core loss under sinusoidal excitation relates to only fundamental and space harmonic components. Thus, the core losses caused by time harmonic components $W_{thc}$ can be obtained by (4)

$$W_{thc} = W_{inv} - W_{sin}. \quad (4)$$

where $W_{inv}$ denotes the core loss under PWM inverter excitation and $W_{sin}$ is that under sinusoidal excitation.

Under PWM inverter excitation, the carrier frequency $f_c$, the switching dead-time, and the DC bus voltage $V_{dc}$ are set to 1 kHz, 3500 ns, and 250 V, respectively. In our study, three rotational speeds (750, 1500, and 2250 rpm) are evaluated. The rotational speeds of 750, 1500, and 2250 rpm correspond to electrical frequencies of 50, 100, and 150 Hz, respectively. The PMSM under sinusoidal and inverter excitations shown in Fig. 3 is operated by zero d-axis current control. Note that the core losses caused by time harmonic components (space harmonic components) depend mainly on losses at about 2 kHz (at three times electrical frequency).

### 3 Results and discussion

Figure 4 shows the core loss characteristics of three PMSMs with respect to the rotational speed under sinusoidal excitation. Here, the rms current values of the NMM- and AMM-PMSMs (NO-PMSM) are about 0.14, 0.16, and 0.18 A (0.13, 0.14, and 0.16 A) at 750, 1500, and 2250 rpm, respectively. Then the core losses are caused by fundamental and space harmonic compo-

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**Table 1** Specifications of different materials used for cores.

| Characteristic            | Symbol | Value |
|---------------------------|--------|-------|
| Reference                 | FT-3M  | 35H300| SA-1 |
| Density $\phi$ [kg/m$^3$] |        |       |      |
| 7300                      |        | 7650  | 7180 |
| Composition               |        |       |      |
| Fe-Si-B-Cu-Nb             |        | Fe-Si | Fe-Si-B |
| Thickness [\( \mu \text{m} \)] |        | 18    | 350  | 25  |
| Relative permeability     |        | 70,000| 1,400| 5,000|
| Saturation magnetic flux density [T] |    | 1.23  | 2.0  | 1.56 |

**Table 2** Motor specifications.

| Characteristic          | Symbol | Value |
|-------------------------|--------|-------|
| Poles / Slot number     |        | 8 / 12|
| Radius of stator core   | $R_s$  | 64 mm |
| Radius of rotor core    | $R_r$  | 37 mm |
| Air gap                 | $G$    | 1.25 mm |
| Yoke width              | $W_y$  | 9.2 mm |
| Tooth width             | $W_t$  | 10 mm |
| Axial core length       | $L_{pm}$ | 47 mm |
| Permanent magnet length | $L_{pm}$ | 20 mm |
| Permanent magnet width  | $W_{pm}$ | 2 mm |
| Winding method          |        | Concentrated |

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Fig. 1 Photographs of motor cores assembled with nanocrystalline magnetic materials (left, FT-3M), non-oriented (NO) silicon steel sheets (center, 35H300), and amorphous magnetic materials (right, SA-1). (a) stator and (b) rotor cores.
In our study, we use two excitation methods. One method is sinusoidal excitation by using three linear amplifiers and other method is inverter excitation by using three phase PWM inverter.

Figure 4 shows the core loss properties of three PMSMs fed by inverter input as a function of the rotational speed. Here, the NO-PMSM (AMM-PMSM) exhibits the rms current of about 0.27, 0.51, and 0.80 A (0.31, 0.59, and 0.92 A) at 750, 1500, and 2250 rpm, respectively. The rms current values of the NMM-PMSM at 750, 1500, and 2250 rpm are about 0.33, 0.63, and 0.99 A, respectively. For sinusoidal and inverter excitations, the current caused by fundamental wave is almost the same value. See Appendix for the details of waveforms, magnetic flux density, and the related values. Under inverter excitation, the core losses are caused by fundamental, time harmonic and space harmonic components. In the experiments, the tested NMM-PMSM presents small core loss in comparison with that of the AMM- and NO-PMSMs. The core losses of the NMM-PMSM are 0.78 W at 750 rpm, 1.7 W at 1500 rpm, and 2.5 W at 2250 rpm, respectively. The core losses of the NMM-PMSM is about 0.6 and 0.4 times of those of the AMM- and NO-PMSMs, respectively. Here, the magnet losses of the PMSMs accounts for less than 1 % of the total core losses because the Sm-Fe-B bonded magnets have extremely low loss.

We now discuss the core losses caused by time harmonic components of three PMSMs obtained with Eq. (4). Figure 6 shows the obtained $W_{thc}$ results at each measurement point. The core losses caused by time harmonic components of the NMM-PMSM are drastically smaller than those of the AMM- and NO-PMSMs. The average core loss reduction caused by time harmonic components of the NMM- and AMM-PMSMs under PWM inverter excitation is about 70% and 45% as compared to the core loss of the NO-PMSM, respectively. In average, the $W_{thc}$ of the NMM-, AMM-, and NO-PMSMs accounts for 40 %, 48 %, and 53 % of the core losses, respectively. Thus, we found that the NMM-PMSM can achieve core loss reduction caused by time harmonic components, which correspond to losses in the high-frequency region, in comparison with not only the NO-PMSM but also the...
AMM-PMSM. Therefore, the NMM-PMSM is expected to be suitable for use in high-speed and high-frequency regions.

4 Conclusion

We have for the first time examined the fabricated nanocrystalline motor under both sinusoidal and inverter excitations. In addition, the NO and amorphous motors were compared to discuss the core loss properties of the nanocrystalline motor. Under sinusoidal excitation, the core loss of the NMM-PMSM was about 0.7 and 0.5 times smaller than that of the AMM- and NO-PMSMs, respectively. In particular, we found that the NMM-PMSM can realize core loss reduction caused by time harmonic components, which correspond to high-frequency region, in comparison with not only the NO-PMSM but also the AMM-PMSM. These results open the way to further research for ultimate low loss motor system based on the nanocrystalline motor, especially in the high-speed motor. In our future works, we will perform the examination of building factor to understand the core losses of the PMSM caused by factors such as the manufacturing process based on both experiments and numerical simulations. In near future, we will examine the core loss, the rated power, the rated torque, the torque capacity, and the efficiency properties under load condition. The more precise measurement of mechanical loss and the loss and current for each frequency will be investigated.

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Appendix: Waveforms and magnetic flux density

Appendix Figs. 1 (a) and (b) show voltage and current waveforms at 750 rpm of three PMSMs under PWM inverter excitation. Here, the maximum magnetic flux densities in the teeth parts of the NMM-, NO-, and AMM-PMSMs (under both excitations) are about 0.6, 0.4, and 0.5 T, respectively. The average difference between magnetic flux densities under sinusoidal and inverter excitations is about 3 % or less.