Iron loss and hysteresis properties of nanocrystalline magnetic materials under high frequency inverter excitation

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Recently, wide-bandgap (WBG) power semiconductors made of silicon carbide (SiC) and gallium nitride (GaN) have been widely developed as high-speed switching devices. Many researchers have studied novel magnetic materials, such as nanocrystalline magnetic materials (NMMs), for low-loss electric motors and transformers. This study experimentally examines the hysteresis ($B$–$H$) curve and iron loss properties of the NMM core excited using a pulse width modulation (PWM) inverter at high carrier frequencies on the order of MHz with and without the dead time. For comparison, the magnetic properties of amorphous magnetic materials (AMMs) core are also evaluated. Particularly at high carrier frequencies (approximately 1 MHz), the iron loss of NMM and AMM cores significantly depends on the dead time. Compared with the case of the AMM core, the NMM core suppresses the increasing rate of iron losses caused by the dead time because the area of minor loops in NMM becomes small, particularly in high-frequency regions.

**Key words:** Nanocrystalline magnetic materials, iron loss, $B$–$H$ curve, inverter, high frequency, wide-bandgap semiconductor

1 Introduction

Transformer and motor systems often comprise inverters and cores composed of soft magnetic materials. In motor systems, pulse width modulation (PWM) inverters are commonly used to perform speed and torque control. Thus, magnetic material cores are excited using a PWM inverter. The waveform generated using the PWM inverter exhibits high-order harmonic components and induces complex hysteresis ($B$–$H$) curves in soft magnetic material (motor) cores.\(^1\)\(^-\)\(^17\). Owing to these complex hysteresis ($B$–$H$) curves of the cores, the iron loss under PWM inverter excitation increases by approximately 10%–50% compared with that under sinusoidal excitation.\(^2\) The objective of this study is to clarify the complex hysteresis ($B$–$H$) curve and iron loss properties of nanocrystalline magnetic materials (NMMs)\(^18\),\(^19\) core fed using the PWM inverter at the MHz high carrier frequency.

Recently, several researchers have focused on motor cores composed of NMM and amorphous magnetic materials (AMMs) to perform iron loss reduction\(^6\),\(^12\),\(^20\),\(^21\). NMM and AMM have lower iron loss density than conventional nonoriented (NO) silicon steel\(^11\),\(^12\),\(^21\). Moreover, a previous study has shown that the iron loss of the NMM motor is smaller than that of the AMM motor, and the NMM motor core is expected to be suitable for use in high-speed and high-frequency regions.\(^21\) The iron loss characterization of NMM cores under high carrier frequency excitation using the inverter is useful for core design in high-speed and high-frequency regions. Therefore, examining the fundamental magnetic properties in the NMM core under high carrier frequency inverter excitation is necessary.

Wide-bandgap (WBG) power semiconductors made of silicon carbide (SiC) and gallium nitride (GaN) have been widely studied and developed as high-voltage, low loss, and particularly high speed switching devices.\(^4\),\(^10\),\(^11\) Recently, using these WBG devices, magnetic properties of conventional NO silicon steel cores have been shown under PWM inverter excitation at high carrier frequencies on the order of MHz and without the dead time.\(^17\) To use inverters that employ WBG devices, the next step is to understand the hysteresis ($B$–$H$) curve and iron loss properties of the NMM core under MHz high carrier frequency inverter excitation with and without the dead time. In the PWM inverter, the dead time is necessary for practical use to prevent a short circuit between the upper and lower arms.

This study experimentally examines the hysteresis ($B$–$H$) curve and iron loss properties of the NMM core excited using a GaN inverter at the MHz high carrier frequency. For comparison, the magnetic properties of the AMM core are also evaluated. Moreover, the impact of dead time on the magnetic properties of NMM and AMM cores excited using the high carrier frequency inverter with and without the dead time is discussed. When the ratio of the iron loss caused by the dead time to the total iron loss becomes small, the magnetic material is suitable for high-speed and high-frequency applications.

2 Experimental Method

Figure 1 illustrates a schematic of the ring core, single-phase GaN inverter, and measurement system to obtain the hysteresis ($B$–$H$) curve and iron loss properties. The ring core with a thickness of 7 mm, inner diameter of 102 mm, and outer diameter of 127 mm is composed of NMM (FT-3M) laminations.\(^13\) For comparison, the ring core with identical geometries of AMM (SA-1) laminations is also used. Both ring laminations (NMM and AMM) are impregnated with acrylic resin and cut using the same wire-cutting technique. The stacking factor $S_F$ of NMM and AMM ring cores is 0.873 and 0.935, respectively. These two ring cores have two (primary and secondary) coils that are wound using a wire. Here, the primary (secondary) coil is used as the exciting coil ($B$-coil to measure the magnetic flux density $B$). See Refs.\(^10\),\(^11\),\(^15\),\(^16\) for further explanation of the ring cores.
The single-phase inverter with GaN field-effect transistors (GaN-FET) \cite{10,17} is used to measure the hysteresis \((B-H)\) curve and iron loss properties of two (NMM and AMM) ring cores. The frequency \(f_0\) of the fundamental sinusoidal waveform is set to 50 Hz. The carrier frequency \(f_c\) of the triangular carrier waveform is varied from 400 kHz to 1 MHz in 200-kHz steps. The modulation index is defined as the ratio of the fundamental waveform \(I_w\) to the carrier frequency waveform amplitude and is set at 0.7. The maximum magnetic flux density \(B_{\text{max}}\) of two ring cores is set at 0.5 T. The dead time \(D\) is set at 0, 10, and 20 ns.

To estimate the magnetic field intensity \(H = N I/l\) and the magnetic flux density \(B = \int V dt/(N S_c S_I)\) in ring cores, the primary current \(I\) flowing through the primary winding and the \(B\)-coil voltage \(V\) induced in the secondary winding are measured. Here, \(N_1 = 10\) denotes the number of turns in the primary coil, \(I = 0.36\) m is the magnetic path length of the ring cores, \(N_2 = 10\) is the number of turns in the secondary coil, and \(S_c = 87.5\) mm\(^2\) is the cross-sectional area of the cores. To measure \(I\) and \(V\), a current probe (HIOKI E.E. Corp., CT6711), a voltage probe (Iwatsu Electric Co., Ltd., SS-320), and a high-performance A/D converter (NI Corp., PXIe-5163, 14 bit, 1 GS/s) are used. Using \(H\) and \(B\), the iron loss \(W\) of the ring cores can be calculated by

\[
W = \frac{f_0}{\rho} \int HdB, \quad (1)
\]

where \(\rho\) denotes the density of the cores. Here, \(\rho\) of NMM and AMM is 7300 and 7180 kg/m\(^3\), respectively.

To clarify the impact of the increasing rate of iron loss caused by the dead time, the ratio \(\eta_0\) of the loss without the dead time to that with the dead time is discussed. Here, \(\eta_0\) is defined by the following equation:

\[
\eta_0 = \frac{W_0}{W_n}, \quad (2)
\]

where \(W_0\) denotes the iron loss without the dead time and \(W_n\) is that with the dead time. In this study, \(n (W_n)\) can be set to either 10 or 20 ns (\(W_{10}\) or \(W_{20}\)).

3 Results and Discussion

Figures 2 and 3 show the hysteresis \((B-H)\) curves at \(f_c = 400\) kHz and 1.0 MHz when the NMM and AMM ring cores are excited using the GaN inverter at \(D = 0, 10,\) and 20 ns. Owing to the high-harmonic components, the PWM carrier waveform is responsible for many minor loops in the hysteresis \((B-H)\) curves (See Refs. \cite{10,11} for the further explanation of the minor loops). In Ref. \cite{17}, the hysteresis \((B-H)\) curve and its minor loop of the conventional NO silicon steel core fed using an inverter under carrier frequencies on the order of MHz without the dead time were observed. For the first time, this study shows that the NMM and AMM cores also have minor loops under inverter excitation at a relatively high carrier frequency of 1 MHz. As shown in Figs. 2 and 3, the width and area of the minor loops in both NMM and AMM cores increase with an increase in the dead time. It is assumed that owing to the dead time, the return current becomes large; then, the change in the minor loop becomes large (See Refs. \cite{4,14} for further explanation of the relationship between the dead time and the minor loop). Under inverter excitation, the width and area of the minor loops of NMM become small compared with those of AMM. There are two possible reasons for these phenomena. First, \(H\) of the minor loop in the NMM core is smaller than that in the AMM core; then, the variation in \(H\) of the minor loop of NMM condenses. Second, because the thickness of the NMM sheet (approximately 18 \(\mu\)m) is thinner than that of the AMM sheet (approximately 25 \(\mu\)m), the eddy current loss of NMM becomes small compared with that of AMM; then, the area of the minor loops of NMM becomes small.

Figure 4 shows the carrier frequency dependence of iron losses in the two ring cores under inverter excitation at \(D = 0, 10,\) and 20 ns. Each iron loss \(W\) is obtained from the average of five measurements. The error bars (standard deviation) of each measurement are shown. \(W\) at \(D = 0\) ns in these two cores decreases with respect to \(f_c\), up to approximately 800 kHz and then increases. \(W\) at \(D = 10\) and 20 ns in the NMM core monotonically increases with an increase in \(f_c\). \(W\) at \(D = 10\) and 20 ns in the AMM core almost reaches the minimum value when \(f_c = 600\) kHz. These results indicate that when the dead time increases, the carrier frequency at which the iron loss reaches the minimum value shifts to the low-frequency side. A previous study has shown that owing to the skin effect and the distortion of the input voltage, \(W\) decreases and increases with an increase in \(f_c\) on the order of MHz\cite{17}. This study shows that particularly at such high carrier frequencies (\(f_c = 1\) MHz), the iron loss of the NMM and AMM cores not only depends on the skin effect and the distortion of the input voltage but also significantly depends on the dead time.

Finally, the impact of increased iron loss owing to the dead time of the NMM and AMM cores excited using a PWM inverter under high carrier frequencies on the order of MHz is discussed. Figure 5 shows the ratio \(\eta_0\) with respect to \(f_c\) using Eq. (2). As shown in this figure, \(\eta_0\) monotonically increases with an increase in \(f_c\). In the high carrier frequency region, the impact of the dead time on one pulse becomes large; then, the minor loop in the case with the dead time increases compared with the case without the dead time, as shown in Figs. 2 and 3. Here, \(\eta_{10}\) and \(\eta_{20}\) of the...
NMM ring core are smaller than those of the AMM core. Thus, the increasing rate of loss owing to the dead time in the NMM ring core is smaller than that in the AMM core. It is assumed that this occurs because under inverter excitation, the area of the minor loops of NMM becomes small compared with that of AMM, as shown in Figs. 2 and 3. Therefore, for the first time, this study shows that the NMM core can have a low iron loss caused by the fundamental waveform and suppress the increasing rate of iron losses caused by the dead time compared with the case of the AMM core, particularly in the high carrier frequency region. The NMM core is expected to be suitable for use in motor and power converter systems using WBG devices, such as SiC and GaN, in high-speed and high-frequency regions, in which the influence of the dead time becomes large.

**Fig. 2** Hysteresis ($B$–$H$) curves of the NMM ring core fed using a PWM inverter. The left panels show the major loops, and right panels show the minor loops, which correspond to the enlarged view of the part of the left panels. (a) $f_c = 400$ kHz and $D = 0$ ns, (b) $f_c = 400$ kHz and $D = 10$ ns, (c) $f_c = 400$ kHz and $D = 20$ ns, (d) $f_c = 1$ MHz and $D = 0$ ns, (e) $f_c = 1$ MHz and $D = 10$ ns, and (f) $f_c = 1$ MHz and $D = 20$ ns

**Fig. 3** Hysteresis ($B$–$H$) curves of the AMM ring core fed using a PWM inverter. The left panels show the major loops, and right panels show the minor loops, which correspond to the enlarged view of the part of the left panels. (a) $f_c = 400$ kHz and $D = 0$ ns, (b) $f_c = 400$ kHz and $D = 10$ ns, (c) $f_c = 400$ kHz and $D = 20$ ns, (d) $f_c = 1$ MHz and $D = 0$ ns, (e) $f_c = 1$ MHz and $D = 10$ ns, and (f) $f_c = 1$ MHz and $D = 20$ ns
Fig. 4 Carrier frequency dependence of iron losses in the two ring cores under PWM inverter excitation at $D = 0$, 10, and 20 ns: (a) NMM and (b) AMM

Fig. 5 Ratio $\eta_n$ of loss without the dead time to that with the dead time as a function of $f_c$ using Eq. (2).

4 Conclusions

This study experimentally examined the hysteresis ($B$–$H$) curve and iron loss properties of the NMM core excited using a PWM inverter at high carrier frequencies on the order of MHz with and without the dead time. Here, the AMM core was compared with the NMM core to discuss the magnetic properties of the NMM core. For the first time, this study showed that the NMM core suppressed an increasing rate of iron losses caused by the dead time compared with the case of the AMM core because the area of the minor loops of NMM became small, particularly in the high-frequency region. Thus, it is considered important to make the main loop small and the thickness of magnetic materials thin while developing magnetic materials. These results provide a path for further research on the iron loss reduction of magnetic materials under PWM inverter excitation at high carrier frequencies in motor and power converter systems using WBG devices, such as SiC and GaN. In the future, the loss repartition at high carrier frequencies will be quantitatively evaluated by numerical simulations.

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