Iron Loss and Hysteresis Properties under High-Temperature Inverter Excitation

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We experimentally and numerically examined the magnetic properties of magnetic materials under room- and high-temperature inverter excitations. We show that the iron loss and hysteresis properties of magnetic materials under pulse width modulation (PWM) inverter excitation depend strongly on the temperature dependence of semiconductor characteristics. The iron loss under PWM inverter excitation decreased as the temperatures of semiconductors (Si-insulated gate bipolar transistors and Si-diodes) increased. In addition, it was found that the rate of change of iron loss based on the temperature dependence of semiconductor characteristics at a high carrier frequency was larger than that at a low carrier frequency.

Key words: iron loss, hysteresis property, inverter, high-temperatures, play model

1 Introduction

High-temperature (HT) motor drive systems have been used in harsh environment conditions such as automotive, aerospace, and fire sites \(^{1-3}\). In the motor drive system, in order to control the rotational speed, pulse width modulation (PWM) inverters are normally utilized. Several researchers have recently shown that due to the higher harmonic components the iron losses in the magnetic core under PWM inverter excitation increase in comparison with sinusoidal case \(^{4-14}\). In the HT motor system, the inverter and magnetic material cores are exposed to HT. To realize HT and high efficiency motor drive system, it is to understand magnetic properties of magnetic materials fed by inverter in harsh temperature environments. To separate the effects of temperature properties of the semiconductors and the magnetic materials on the magnetic properties, it is necessary to consider the following two steps: (1) to evaluate magnetic properties of “magnetic materials at HT” under “room temperature (RT) inverter” excitation and (2) to investigate magnetic properties of “magnetic materials at RT” fed by “HT inverter”. In the recent times, we have examined magnetic properties in magnetic materials at HT under “RT inverter” excitation\(^{12,15}\). The next step is to understand magnetic properties of RT magnetic materials fed by “HT inverter”. This paper aims to estimate the iron loss and hysteretic properties of a non-oriented (NO) material, which is conventionally utilized as the motor core, under RT and “HT inverter” excitations.

We recently have shown that the power semiconductor properties affect iron loss and hysteresis properties of magnetic materials under PWM inverter excitation\(^{16,17}\). It is well known that the power semiconductor properties depend strongly on the temperature. Here, in order to estimate the relation between power semiconductor and iron losses properties under HT inverter excitation, it is necessary to correctly understand the influence of carrier frequency that relates to the number of switching times.

In this paper, we experimentally and numerically examine the iron losses and hysteretic properties of magnetic materials under RT and HT (300°C) inverter excitations. This paper addresses the experimental iron loss properties as a function of carrier frequency of a NO ring excited by HT inverter. Furthermore, by using the play model\(^{18-20}\) with the Cauer circuit\(^{15,21-25}\) which takes into account power semiconductor properties\(^{26}\), we numerically investigate the magnetic hysteretic properties under RT and HT inverter excitations.

2 Experimental and numerical methods

Figure 1 shows a schematic of the experimental setup used to measure the iron loss characteristics under RT and HT inverter excitations. The single phase PWM inverter consists of Si-insulated gate bipolar transistors (IGBT) and Si-diodes (GT200J341). We use a ring specimen made of laminations of standard NO electrical steel sheets (35H300) \(^{11}\). Here, the semiconductors (Si-IGBTs and Si-diodes) of the inverter are exposed to ambient temperature variations in a temperature-controlled oven (STH-120) to evaluate iron loss properties based on the temperature dependence of the semiconductor characteristics. Note here that the ring specimen (magnetic core) is set at RT. This ring specimen has two (primary and secondary) coils wound with round wires that are used as an exciting-coil and a B-coil. Tab. 1 shows the characteristics of the ring specimen and semiconductors.

In the experiments, by integrating \(H\) and \(B\), the iron losses \(W_{\text{iron}}\) of the ring specimen are given by\(^{15,17}\)

\[
W_{\text{iron}} = \frac{1}{TP} \int H dB, \quad (1)
\]

\[
H = \frac{N_1 I}{T}, \quad (2)
\]

\[
B = \frac{1}{N_2 S} \int V dt, \quad (3)
\]

where \(\rho\) (\(= 7650 \text{ kg/m}^3\)) denotes the density of the NO electrical steel sheet, \(T\) (\(= 0.02\) s) is the period, \(N_1\) (\(= 264\)) is the number of turns of the exciting coil, \(I\) (\(= 0.36\) m) is the magnetic path length, \(N_2\) (\(= 264\)) is the number of turns of B-coil, \(S\) (\(= 87.5 \text{ mm}^2\)) is the cross section area of the ring, \(I\) is the current flowing in the primary coil of the ring specimen, and \(V\) is the B-coil voltage.
The fundamental frequency \( f \) and the switching dead time are set to 0.5, 0.2 T, and 3500 ns, respectively. The iron loss and hysteresis loop is described by Eq. (5).

\[
H_{dc}(B) = H_{dc}(B) + \frac{7(B^2 - B_0^2)}{7R_0 \Delta t + 2L} + \frac{2L k_2^2}{35R_0 \Delta t}.
\]

where \( H_{dc}(B) \) denotes the static (DC) hysteretic property represented by the play model, \( L \) is the inductance that correspond to the magnetic permeability in the model, \( \Delta t \) is the time division, \( L' \) is the equivalent inductance to express the magnetic flux caused by eddy currents, \( k \) is the step number, and \( R_E \) is the resistance to represent eddy currents. Here \( d (=0.35 \text{ mm}) \) is the thickness of NO sheet, \( \sigma (=1.923 \times 10^9 \text{ S/m}) \) is the electrical conductivity at RT of NO sheet, and \( \alpha (=2.14) \) is the anomaly factor at RT to express anomaly eddy currents \cite{15}. Here, the parameters and DC hysteresis loops of magnetic material cores at RT are applied to the numerical simulations. In our paper, \( L' \) at \( f = 1, 4, 12, \) and 20 kHz is set to 3.53, 1.44, 0.558, and 0.348 mH, respectively. Here, we apply \( I - V \) characteristics of the semiconductors to the current calculated from \( H \) using Eq. (2) and then can obtain numerical hysteresis curves including the power semiconductor properties. See ref. \cite{15} for details of numerical and parameter estimation methods.

**3 Results and discussion**

Figures 2(a) and 2(b) show the \( I - V \) characteristics at RT and 300°C of the Si-IGBT and Si-diode measured using SMU. The \( I - V \) characteristics of Si-IGBT and Si-diode were measured using SMU. The collector current \( I_c \) is measured by sweeping the collector-emitter voltage \( V_{ce} \) at \( V_{ge} \) (gate-emitter voltage) = 8 V. For the \( I - V \) characteristics of Si-diode, the current is measured by sweeping the voltage at \( V_{ge} = 0 \) V. The current of the Si-IGBT and Si-diode at HT is larger than that at RT under the same voltage condition. It is assumed this is due to the fact that many carriers can overcome the barrier at HT.

Figure 3 shows the \( B \)-coil voltage \( V \) waveform of the ring specimen (shown in Fig. 1) at \( f = 20 \text{ kHz} \) under RT and HT inverter excitations by numerical simulations, we use the dynamic hysteresis model which combines the play model with the Cauer circuit \cite{24,25} which takes into account power semiconductor properties.

**Table 1 Specifications of ring specimen and semiconductors.**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td></td>
<td>35H300</td>
</tr>
<tr>
<td>Density</td>
<td>( \rho )</td>
<td>7650 kg/m³</td>
</tr>
<tr>
<td>Cross section area</td>
<td>( S )</td>
<td>87.5 mm²</td>
</tr>
<tr>
<td>Height</td>
<td>( d )</td>
<td>7 mm</td>
</tr>
<tr>
<td>Average magnetic path length</td>
<td>( l )</td>
<td>0.36 m</td>
</tr>
<tr>
<td>Primary coil winding</td>
<td>( N_1 )</td>
<td>264 turns</td>
</tr>
<tr>
<td>Secondary coil winding</td>
<td>( N_2 )</td>
<td>264 turns</td>
</tr>
<tr>
<td>Semiconductors</td>
<td></td>
<td>GT20J341</td>
</tr>
</tbody>
</table>

By using Eq. (1), we can calculate the iron loss caused by both fundamental and higher harmonic components. In the following experiments and numerical simulations of ring tests, the modulation index, the maximum magnetic flux density of the ring, and the switching dead time are set to 0.5, 0.2 T, and 3500 μs, respectively. The fundamental frequency \( f_0 \) is set to 50 Hz. The ring tests are carried out at carrier frequencies \( f_c \) of 1, 4, 12, and 20 kHz. See refs. \cite{15,17} for the details of the iron loss measurements.

In our paper, the rate of change of iron loss \( \eta \) based on semiconductor temperature is defined by

\[
\eta = \frac{W_{RT} - W_{300}}{W_{RT}}.
\]

where \( W_{RT} \) and \( W_{300} \) are the iron losses at RT and 300°C, respectively.
excitations. As shown in the magnified figure in Fig. 3, the on-voltage (almost 0 V) at 300°C is smaller than that (about 1 V) at RT because the voltage at 300°C becomes low compared to that at RT under the same current condition, as shown in Fig. 2 (See ref. 17 for details of on-voltages).

Figure 4(a) shows the experimental hysteresis curves obtained by the ring test system shown in Fig. 1. The blue and red lines correspond to curves at \( f_c = 20 \text{ kHz} \) under RT and HT (300°C) inverter excitations, respectively. In the experiments, ringing noises and the slight unbalance of the semiconductor characteristics occur. The corresponding numerical hysteresis curves results are shown in Fig. 4(b). Here, by using the \( I-V \) characteristics shown in Fig. 2, power semiconductor properties are taken into account in our numerical simulations. The calculated hysteresis curves are consistent with the experimental results. Here, we realize the experimental and numerical representation of the hysteretic phenomena of soft magnetic materials excited by inverter at RT and HT. The ring specimen excited by the inverter at RT and 300°C exhibits iron losses of about 81.1 and 71.6 mW/kg at \( f_c = 20 \text{ kHz} \), respectively. The trace of \( \alpha \rightarrow \beta \) in the minor loop shown in Fig. 4(a) corresponds to that in voltage waveform in Fig. 3. Here, the trace of \( \alpha \rightarrow \beta \) is operated in off-mode of inverter. When the inverter switches operate in off-mode, the area of the minor loops decreases with the increase of semiconductor temperature because the on-voltage at 300°C is smaller than that at RT (See refs. 15, 17 for details of the minor loop in off-mode.). The iron loss under PWM inverter excitation decreases with increase of temperature of the semiconductors because the area of the minor loop under HT inverter excitation becomes small in comparison with that at RT (See ref. 15 for details of the relation between area of loop and iron loss.). Based on both experiments and numerical simulations, we for the first time found that the iron loss and hysteresis properties of magnetic materials under PWM inverter excitation depended strongly on the temperature dependence of semiconductor characteristics in not only on-mode but also off-mode.

Figure 5 shows the iron losses of the ring specimen with respect to carrier frequency under RT and HT inverter excitations. The blue and red points correspond to the iron losses of NO ring fed by inverter at RT and 300°C, respectively. The carrier frequency property of the iron loss relates to semiconductor temperature. We quantitatively evaluated the iron losses of RT magnetic materials under RT and HT (300°C) inverter excitations.

Figure 6 shows the rate of change of the iron loss \( \eta \) calculated from Eq. (4). Note that \( \eta \) at a high carrier frequency is larger than that at a low carrier frequency. \( \eta \) increases with increasing carrier frequency. It is considered that the number of switching times increases with the increase of carrier frequency and then the influence of the temperature dependence of the semiconductor characteristics at the high carrier frequency becomes large. Based on our coupled studies of magnetic and semiconductor properties, it is thought that the core losses of the HT motor system under this experimental condition can be reduced at the high carrier frequency.

Consequently, this work shows for the first time that the iron loss and hysteresis properties of magnetic materials under PWM inverter excitation depend strongly on the semiconductor temperature. These results open the way to further research in HT and high efficiency motor system based on coupled studies of magnetic and semiconductor properties. It is expected that by using our numerical simulations we can calculate the magnetic hysteretic and iron loss properties fed by HT inverters based on other new materials such as silicon carbide (SiC) and gallium nitride (GaN). In addition, since we can achieve to represent the numerical magnetic hysteretic properties under RT and HT inverter excitations, it will be possible to estimate the loss repartition (e.g., between the hysteretic and eddy current losses) 15, 26.
of magnetic materials excited by inverter at RT and HT by using our numerical simulations. Also, for electrical power conversion system such as DC-DC converter (especially in high frequency applications), the semiconductor devices are used in HT environments\(^2\). Therefore, it is expected that our coupled studies of magnetic and semiconductor properties may be useful to reduce iron losses not only in HT motor but also in electrical power conversion system.

### 4 Conclusion

We experimentally and numerically examined magnetic properties of magnetic materials under RT and HT inverter excitations. We for the first time found that the iron loss and hysteresis properties of magnetic materials under PWM inverter excitation depended strongly on the temperature dependence of semiconductor characteristics. In addition, we showed that the rate of change of iron loss based on the temperature dependence of semiconductor characteristics at the high carrier frequency was larger than that at the low carrier frequency. These results open the way to further research for loss reduction of not only HT motor but also electrical power conversion system based on coupled studies of magnetic and semiconductor properties. In our future works, we will evaluate the impact of power semiconductor characteristics on iron loss properties in the driven motor and in other parameter settings. In addition, further experimental and numerical investigations are necessary under a wider range of temperatures. In future research, the iron loss and hysteresis properties of HT magnetic materials under HT inverter excitation will be addressed.

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**References**


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