Cross terms of harmonics in iron loss induced by multi-frequency magnetic fields

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Various waveforms formed by multi-frequency currents are widely utilized in power electronics. Iron loss generated by multi-frequency magnetic fields has been simply expected by a linear combination of iron losses of each frequency component. In the present work, we studied the effects of harmonics on iron loss using sinc-pulse magnetic fields applied to a Sendust dust core. As a consequence, we found that the harmonics of hysteresis loop caused additional cross terms in iron loss, which reduced the frequency dependent iron loss of the Sendust toroidal core. We believe that our results indicate the potential use of the multi-frequency magnetic fields to reduce iron loss.

Keywords: Iron loss; multi-frequency excitation; power electronics

1. Introduction

In power electronic devices, various multi-frequency driving currents are applied to magnetic passive devices: *e.g.*, pulse trains for pulse width modulation, ripple current, and drift currents due to dead time. Since the frequency and magnetic flux dependence of iron loss is generally studied using sinusoidal waves, *i.e.* single frequency waves, iron loss is sometimes distorted in practical circumstances [1,2]. Therefore, we often utilize the linear combination of frequency-dependent iron loss in order to predict iron loss induced by the multi-frequency operation [3,4]. On the other hand, magnetic domain structures strongly depend on the applied oscillating magnetic field [5], implying that iron loss can be influenced by the cross terms between iron loss at different frequencies. In the present study, we applied the magnetic field with the waveform of sinc pulse to a Sendust toroidal core and investigated the harmonics of iron loss.

2. Results and discussion

Using inductive partial cancellation method [6], we measured iron losses of a Sendust toroidal dust core, which has an inner diameter of 8 mm, an outer diameter of 13 mm, and a thickness of 6 mm. To measure the iron losses, sinc function-based pulse currents $I(t)$ expressed by the following equations were applied to the primary coil wound on the Sendust core:

$$\begin{cases} I(t) = \dfrac{2I_0\left\{\sin\left(2\pi f_{\mathrm{BW}}^{\mathrm{up}} t\right) - \sin\left(2\pi f_{\mathrm{BW}}^{\mathrm{low}} t\right)\right\}}{t}, & t \neq 0 \\ I(t) = 4\pi I_0\left(f_{\mathrm{BW}}^{\mathrm{up}} - f_{\mathrm{BW}}^{\mathrm{low}}\right), & t = 0 \end{cases}.$$

Here, I_0 is the current amplitude at each frequency, t is the relative time of the measurements, and $f_{\mathrm{BW}}^{\mathrm{up}}$ and $f_{\mathrm{BW}}^{\mathrm{low}}$ are respectively the higher and lower frequencies. The "*arranged*" sinc wave is composed of multifrequency currents, and in the frequency domain, its amplitude stays at I_0 in the bandwidth between $f_{\mathrm{BW}}^{\mathrm{low}}$ and $f_{\mathrm{BW}}^{\mathrm{up}}$, and 0 for other frequencies.

We obtained the frequency dependence of iron loss P_{c} at two conditions: $\left(f_{\mathrm{BW}}^{\mathrm{up}}, f_{\mathrm{BW}}^{\mathrm{low}}\right) = (60\ \mathrm{kHz}, 0\ \mathrm{kHz})$ and $(60\ \mathrm{kHz}, 20\ \mathrm{kHz})$, shown in Figs.1 (a) and (b), respectively. By comparing the present results with the results obtained by sinusoidal waves, it is found that the multifrequency excitation produces the same results as single-frequency excitation when the bandwidth is limited to 20 kHz to 60 kHz. It indicates that the iron loss is reduced by the cross terms between the low frequency regime (< 20 kHz) and the bandwidth (from 20 kHz to 60 kHz).

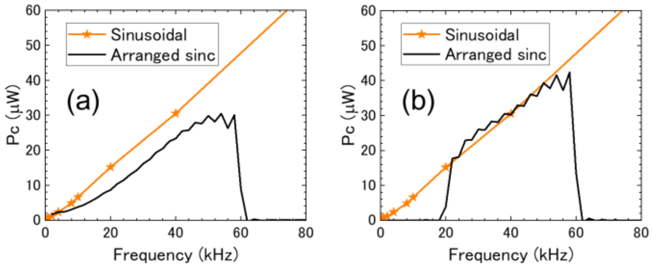

Figure 1: Iron loss as obtained by *arranged* sinc waves under the conditions of (a) $\left(f_{\mathrm{BW}}^{\mathrm{up}}, f_{\mathrm{BW}}^{\mathrm{low}}\right) = (60\ \mathrm{kHz}, 0\ \mathrm{kHz})$ and $\left(f_{\mathrm{BW}}^{\mathrm{up}}, f_{\mathrm{BW}}^{\mathrm{low}}\right) = (60\ \mathrm{kHz}, 20\ \mathrm{kHz})$. Black lines and orange markers are the results by *arranged* sinc waves and sinusoidal waves, respectively.

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