High-speed Core Loss Base Data Collection for Core Loss Calculation Under Power Electronics Converter Excitation

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The calculation of core loss of power electronics converters requires a large number of core loss data, including the excitation frequency, flux density ripple, and DC magnetic field bias characteristic under rectangular voltage excitation. However, in the case of the conventional method (that employs a B-H analyzer with a chopper circuit), a very long time is required to collect this core loss base data, because circuit parameter tuning is needed for each measurement point. Therefore, we propose a high-speed core loss base data collection method for core loss calculation under power electronics converter excitation. The core loss base data collection time was substantially reduced upon usage of a pulse width modulated (PWM) inverter and a neural network because various core loss characteristics were expressed upon excitation of the PWM inverter, and these core losses were learned by the neural network. The core loss base data, as measured via the proposed and conventional methods, were compared to validate the measurement accuracy of the proposed method, and the difference was found to be less than 12%. Thus, the proposed method achieves high-speed core loss base data collection.

Keywords: core loss calculation, core loss measurement, datasheet, inductor, transformer

1. Introduction

Advances in wide-bandgap power semiconductor devices, such as silicon carbide devices, have enabled the increase in the switching frequencies of these devices; they have also enabled maximization of the efficiency and minimization of the required inductance value and volume of these magnetic devices[15]. However, as shown by Refs. (2), (3), magnetic devices still occupy a large area, and the energy loss incurred by such devices is almost the same as or higher than that of power semiconductor devices. Therefore, the core loss of magnetic devices is important to consider in the context of enhancing the efficiency and minimizing the size of converters.

Conventionally, the core loss has been estimated using the datasheet provided by manufacturers of magnetic cores[16]. However, these estimated core losses differ significantly from the actual core losses sustained in power electronics converters because the excitation conditions of magnetic devices differ from those in the datasheet. In other words, the core loss datasheet expresses non-DC-bias sinusoidal-excited core loss data, although the excitation of power electronic converters requires rectangular voltage and DC-bias excitation[16].

Therefore, recent core loss calculation methods have considered core loss data under rectangular voltage and DC-bias excitation, and these methods enable calculation of the core loss in power electronics converters, such as AC filter inductors for pulse width modulated (PWM) inverters and DC inductors for buck and boost choppers[10]–[15]. However, core loss calculation of power electronics converters requires massive amounts of core loss data because the required excitation conditions correspond to not only DC-bias excitations but also rectangular voltage excitations, which are expressed by the amplitude, frequency, and duty ratio[16]. In Refs. (10)–(13), a B-H analyzer with a buck chopper circuit was used for core loss data measurement; however, collection of core loss base data using this system is time-intensive because the circuit parameters need to be changed manually for each measurement point. Therefore, a high-speed core loss base data collection method is required.

To reduce the core loss base data collection time, we used a PWM inverter and a neural network. Because various excitation conditions (i.e., various core losses) exist upon the excitation of the PWM inverter, the number of circuit parameter changes can be reduced. Subsequently, the core loss data are learned and sorted using a neural network. Ultimately, the core loss base data collection time observed as per our study was substantially lower than that of conventional methods.

To validate the proposed method, the core loss base data measured via both the proposed method and one of the conventional methods (that employs a B-H analyzer (SY-8232, Iwatsu Test. Instruments Co., Japan)) were compared. The difference between the measured values using these two methods was found to be less than 12%. It is thus clear that high-speed core loss base data collection can be achieved via our method.
2. Core Loss Calculation Method

Core loss data are required for core loss calculation because these calculation methods are primarily empirical.

A popular method used for core loss calculation involves the Steinmetz equation, which is given by (1); this equation is sometimes cited in the core datasheets of some manufacturers. The fitting parameters $\alpha$, $\beta$, and $k$ are extracted for obtaining frequency and flux density core loss characteristics under non-DC-bias sinusoidal voltage excitation.

$$P = k f^{\alpha} B^\beta$$  \hspace{1cm} (1)

where $P$ and $B$ represent core loss per volume and peak value of flux density, respectively.

The excitation of magnetic materials for power electronics converters is mainly achieved through rectangular voltage of flux density, respectively. However, there are times when the duty cycle $\alpha$ is zero) as $\sum_{n=1}^{\infty} P_n f_n$. The $P_n$ and $Q_n$ are calculated as $P_n = k f_n B^\beta (1 - e^{-\alpha t})$, $e^{-\alpha t}$, respectively.

The Steinmetz parameters $\beta$, $k_n$, and frequency, $f_n$, under rectangular voltage excitation. The consideration of the duty ratio characteristic for rectangular voltage excitation is not necessary when employing the piecewise linear method. However, the amount of required core loss data in this case is more than that required for the conventional sinusoidal excitation core loss calculation method.

Note: The magnetic relaxation loss occurs only when the dead time of inverter is higher than a time constant of the excitation condition is that of a dual active bridge (DAB) converter. Therefore, this paper does not focus on the magnetic relaxation loss.

3. Core Loss Measurement Method

Various methods have been proposed to measure the core loss of power electronics converters. In this section, the conventional core loss base data collection method and the core loss analysis method under PWM inverter excitation, which form the basis of the proposed system, are described.

3.1 Conventional Core Loss Base Data Collection Method

Core loss, which constitutes the base data required for parameter fitting in power electronics converter core loss models, is measured under excitation conditions in power electronics converters such as chopper circuits. In Refs. (10) and (13), the B-H analyzer (SY-8232, Iwatsu Test, Instruments Co., Japan) with a buck chopper was employed for core loss base data measurement (Fig. 1). As shown in Fig. 2, the excitation waveform can be changed on the basis of the input voltage, output resistance, and drive frequency to collect the different iron loss characteristics (i.e., the position of the B-H minor loop is changed, as shown in Fig. 3).

The core loss was determined via a dynamic minor loop of the required parameter fitting in power electronics converter core loss models, is measured under excitation conditions in power electronics converters such as chopper circuits. In Refs. (10) and (13), the B-H analyzer (SY-8232, Iwatsu Test, Instruments Co., Japan) with a buck chopper was employed for core loss base data measurement (Fig. 1). As shown in Fig. 2, the excitation waveform can be changed on the basis of the input voltage, output resistance, and drive frequency to collect the different iron loss characteristics (i.e., the position of the B-H minor loop is changed, as shown in Fig. 3).

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Some core loss measurement processes require at least a day or more, depending on the skill of the measurer.

In Ref. (15), the 180° switching single-phase full-bridge inverter was used; however, it must be replaced by the buck chopper circuit to measure the DC-biased core loss data. Therefore, the buck chopper circuit method is the most suitable for the conventional core loss base data measurement used to calculate the core loss of power electronics converters in the present system.

### 3.2 PWM Inverter-based Core Loss Analysis Method

In Ref. (10), the core loss analysis system under PWM inverter excitation, as shown in Fig. 4, was proposed. The magnetic materials of the device under test (DUT) were installed in the AC filter inductor. Under PWM inverter excitation, several dynamic minor loops in the B-H plane are generated (Fig. 5 and Fig. 6). Because the dynamic minor loops are related to core losses, the core loss calculation software detects each dynamic minor loop section and measures the corresponding core loss. Once the dynamic minor loop section, as shown in Fig. 7(a) and Fig. 7(b), is detected, the core loss for one dynamic minor loop is given by Eq. (4):

$$ P = \frac{1}{N_{\text{ratio}} T_{SW}} \int_{0}^{T_{SW}} v_{L2,\text{HF}}(t) i_{L,\text{HF}}(t) dt, \cdots, \cdots \quad (4) $$

where $v_{L2,\text{HF}}(t)$ and $i_{L,\text{HF}}(t)$ are high pass filtered voltage $v_{L2}(t)$ and current $i_{L}(t)$ signals, respectively, for removing low-frequency fundamental components.

Various core losses in different dynamic minor loop positions can be measured in one cycle of the fundamental output current. If these core losses can be used as core loss base data, the number of circuit parameters that must be tuned for core loss measurement and the measurement time can be reduced, compared to the buck chopper circuit. However, this system cannot be used as a core loss base data collection method under the current specifications because of two issues.

The first issue is that the core loss measured in one switching period is the loss of the open-form dynamic minor loop, as shown in Fig. 7(b), and not that of a closed loop, as shown in Fig. 3. In this case, the core loss of the open minor loop is measured as the core loss of a quasi-closed minor loop, as shown in Fig. 7(c). When the points $a$ and $c$, shown in Fig. 7(a), are close to each other, the core loss value of the quasi-closed minor loop is almost equal to that of the closed minor loop in the buck chopper circuit. However, the open points of minor loops generated during PWM excitation are not always close to each other. In such cases, the core losses of the minor loops are different from those of the buck chopper circuit\(^{(17)}\).

The second issue is that the measured core loss data are random characteristic data, such as $P(\Delta B_1, H_0(1), f_2)$, $P(\Delta B_1, H_0(3), f_3)$, and $P(\Delta B_2, H_0(8), f_6)$. These data should be used to sort the loss data map such as $P(\Delta B_1, H_0(1), f_1)$, $P(\Delta B_1, H_0(1), f_3)$, and $P(\Delta B_2, H_0(1), f_3)$. The actual core loss measurement data can also be seen in Fig. 12. Without the sorting and fitting functions, the PWM inverter-based measurement method is not suitable for the core loss base data collection system.
It is noteworthy that some studies have used linear amplifiers instead of PWM inverters. However, there are challenges associated with the bandwidth and limited output of linear amplifiers. In addition, in the process of generating a PWM signal (i.e., setting a function generator signal as the input of the linear amplifier), to apply an appropriate excitation voltage to the DUT, the impedance, including the internal impedance of the amplifier, and the load CR should be considered. This results in an increase in measurement time. If the DUT is steed under the L load of the PWM inverter, the function generator signal to the linear amplifier became a simple positive voltage plus in half cycle and negative voltage pulse. However, under the L load, the amplitude of each minor loop becomes very small and is not suitable for data collection.

4. Proposed Core Loss Base Data Collection Method

To address the two aforementioned issues in the PWM inverter-based core loss data collection system, we modified the core loss measuring software and used a neural network to reduce the data collection time. Figure 8 shows the system configuration of the PWM inverter-based core loss data collection method.

To address the first issue, when the piecewise linear method is used, the excitation waveform can be considered a symmetrical waveform to mimic the buck chopper excitation. The core loss value is regarded to be twice the value of the dB/dt segment. For instance, the core loss \( P(\Delta B_{ab}, H_{0(ab)}, f_{ab}) \) obtained as shown in section a-b (Fig. 9), is twice that obtained as shown in section a-b of the symmetric flux density waveform given by Eq. (5); thus, it is equivalent to the core loss obtained upon using the core loss data of buck chopper excitation \( P(\Delta B_{\text{chopper(ab)}}, H_{0(\text{chopper(ab))}}, f_{\text{chopper(ab)}}) \).

\[
P = \frac{2}{N_{\text{Ratio}} T_{ab}} \int_{0}^{T_{ab}} v_{L2,\text{HF}}(t) i_{L2,\text{HF}}(t) dt. \quad \cdots \cdots \cdots \quad (5)
\]

In the same manner, the core loss \( P(\Delta B_{bc}, H_{0(bc)}, f_{bc}) \) in the section extending from b to c was obtained.

If the circuit parameters of the PWM inverter are set as follows: fundamental frequency of 50Hz; modulation ratio of 0.5; and switching frequency of 20kHz, there exist 1593
The total measured time for one circuit parameter tuning of the PWM inverter is less than 300 ms, which includes the time taken for soft-starting of the PWM inverter, measuring the operating points, and soft-ending of the PWM inverter. A large amount of core loss data can be recorded without the DUT considerably rising in temperature. This indicates that this system demonstrates reproducibility and traceability.

It is noteworthy that the fundamental frequency should be set to a low-frequency value to facilitate constant magnetic field bias in one PWM switching.

To address the second issue, the calculated core losses were learned by a neural network. In this study, the neural network function of MATLAB (ver. R2019b) was used.

This neural network function comprised three inputs (flux density ripple, $\Delta B$; magnetic field bias, $H_0$; and frequency, $f$), one output (core loss $P$), and ten hidden layers (Fig. 10). The core loss base data was created following the completion of core loss learning.

When the core loss is learnt by the neural network, the data points should account for the characteristics of magnetic materials used by the end-user, such as the frequency, $f$; flux density ripple, $\Delta B$; and magnetic field bias, $H_0$.

The stored core loss data are divided as follows: 70% of the total data is used for training the neural network, and 20% is used to assess the network generalization and halt training when the generalization stops improving. The last 10% of the data is used to provide an independent measure of network performance during and after training. The number of hidden layers was selected to reduce fitting error.

Although the piecewise linear interpolation method appears to be suitable as a fitting function, it is only appropriate for interpolation and cannot be used for extrapolation. Furthermore, we collect core loss data in various areas by changing the circuit parameters of the PWM inverter; however, it is impossible to cover all areas used by the end-user. Thus, we can consider extrapolation in data fitting, and the neural network is suitable.

It is noteworthy that a phase error between the voltage and current sensor affects the measurement accuracy. According to the proposed method, the phase error was measured using the B-H analyzer (SY-8219, Iwatsu Test. Instruments Co., Japan) and compensated for via the power spectrum method. When a current sensor (Hioki PW9100) and voltage probe (PMK BumbleBee) were used in the proposed system, the maximum phase error was less than 0.013° under the frequency band of 1 kHz–1 MHz. This indicates that the measurement error of the proposed system was less than 1.67% at an inductor phase angle of $-89.22^\circ$.

5. Proposed Core Loss Base Data Collection Method

To validate the measurement accuracy of the proposed method, the core loss base data measured via both the proposed method and the conventional method (that employs a B-H analyzer with a buck chopper circuit) were compared. In this study, an iron-powder material (SK-14M, Toho Zinc. co, Ltd.) was used for core loss measurement.

The input voltage and switching frequency were set to (60 V, 80 V, 100 V) and (5 kHz, 10 kHz, 20 kHz), respectively, for core loss measurement via the proposed method. Further, the output resistance and fundamental frequency of the output current were set to 25 Ω and 50 Hz, respectively. Under these conditions, 9,177 core loss data points were obtained for neural network learning. The data points have a typical value that results in coverage of the operating region of iron powered material by the proposed system.

Conversely, for the conventional method, the parameters of the buck chopper circuit were manually changed for each measurement point.

The core loss data obtained via both the proposed and conventional methods are shown in Fig. 11. The difference between the core losses measured via the two methods was lesser than 12%. In this case, the value measured by BH analyzer and that by the proposed method are 4.90 W and 4.29 W, respectively. The core loss base data collection time of the proposed method was also significantly reduced. The conventional method required at least a day (or more) for core loss measurements depending on the skill of the measurer, whereas the proposed method required only an hour.

Although the proposed system has sufficient core estimation accuracy as a core loss base data collection method, the reason for the loss differences at high dc-biased condition is considered for further improvement of measurement accuracy.

Figure 12 shows data points measured by the proposed method wherein measured data are classified according to frequency, DC magnetic field bias, and flux density ripple.
Fig. 12. Data points measured by proposed method

According to Fig. 12, there are sufficient learning data around maximum error points at $\Delta B = 200$ mT, $H_0 = 5000$ A/m, and $f = 20$ kHz. Therefore, the estimation error does not arise from a lack of learning points but the piecewise linear method.

Figure 13 shows BH minor loops under buck chopper excitation as shown in Fig. 1 and Fig. 2. As the magnetic field bias value increases, the minor loop shape of the BH curve becomes asymmetric. In the piecewise linear method, the minor loop shape should be symmetric to separate two same core loss elements. If the minor loop shape becomes asymmetric, the piecewise linear method estimation error arises. However, this error does not significantly affect practical inductor and transformer designs since an asymmetrical minor loop is observed in the saturation region of the magnetic device, and magnetic devices are designed in the linear region.

If more measurement accuracy is required for an asymmetrical minor loop, these core losses need to be measured under the buck chopper mode.

6. Conclusion

This paper presents a high-speed core loss base data collection method for core loss calculation under power electronics converter excitation. For reducing the core loss data collection required for core loss calculation, a PWM inverter and a neural network were used.

Because various core losses exist upon the excitation of the PWM inverter, the number of circuit parameter tunings required for core loss measurement could be reduced. Subsequently, these core loss data were learned and sorted using a neural network. Therefore, the core loss data collection time was significantly reduced compared to that of the conventional method. For validating the proposed method, the core loss data measured via the proposed and conventional methods were compared, and the difference was found to be lesser than 12%. It is clear that the proposed method has enabled successful achievement of high-speed core loss base data collection.

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