# Real Operating Loss Measurement of Low-Loss Inductors Using High-Precision Wideband Power Analyzer and Current Sensor

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## 1. Introduction

Electric vehicles (EVs) and hybrid electric vehicles (HEVs) use inductors (reactors) in a variety of locations. Examples include step-up DC/DC converters between the battery and inverter, and AC/DC converters in battery charging circuitry. To boost overall system efficiency, it is necessary to improve the efficiency of each of the system's constituent circuits. Inductors account for a significant portion of loss in such circuits [1]. Consequently, in order to boost overall system efficiency, it is necessary to accurately measure inductor loss. Generally speaking, these inductors are often switched at high frequencies during use. Since the voltages and currents applied to inductors have distorted waveforms, for example rectangular waves and triangular waves, instruments used for this purpose must be capable of accurate measurement across a broad frequency range. Additionally, the phase difference between the voltage and current applied to inductors approaches 90°, with the result that the measuring instrument's phase error has a significant effect on error in loss measurement [2]. For these reasons, direct measurement of inductor loss has been considered a difficult task [3]. This paper describes the results of measuring loss in operating inductors using a measurement system consisting of a Power Analyzer PW8001 and AC/DC Current Sensor CT6904 [4][5], a combination that offers low phase error even at high frequencies. It also introduces the results of comparing measurement results from the Power Analyzer with measured values from a measurement system developed by the Shimizu Lab at Tokyo Metropolitan University and values calculated using extended Steinmetz equations in order to determine the suitability of the Power Analyzer for use in inductor loss measurement applications.

## 2. Experimental Method

### Measurement Target

Figure 1 provides a schematic diagram for the excitation device that was measured. This setup measured the loss in a type of inductor used in a high-efficiency 100 kW-class dual-active-bridge converter incorporating low-loss SiC-MOSFETs [6]. Figure 2 illustrates the measurement setup. Table 1 lists the specifications of the inductor, while Figure 3 illustrates the inductor's excitation waveforms. The excitation current was varied from 80 Apk to 160 Apk by changing the voltage pulse's duty ratio. The switching frequency was 20 kHz.

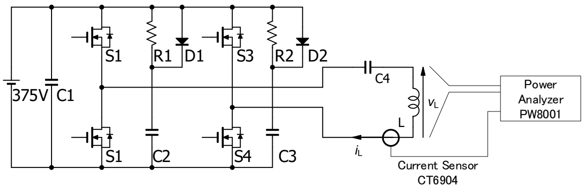

**Figure 1. A circuit to measure loss in the inductor**

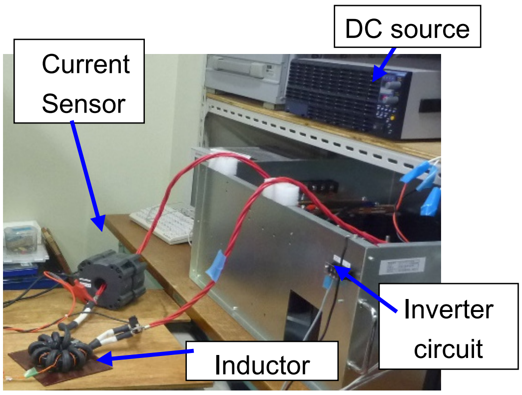

**Figure 2. A photo of the measurement.**

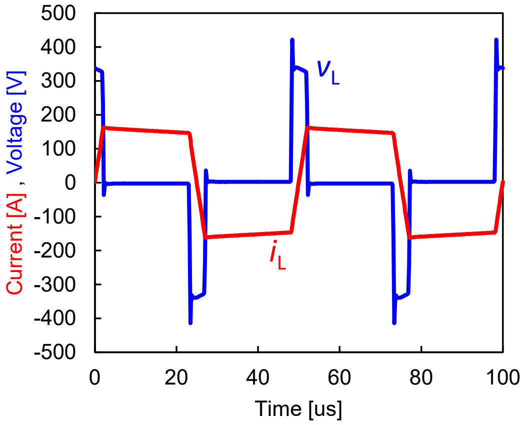

**Figure 3. Excitation waveforms of the inductor.**

**Table 1 Parameters of the inductor.**

| | |
|---|---|
| Core material | Sendust |
| Core shape | Toroidal |
| Wire | Litz wire |
| Inductance, *L* | 4.5 uH |

### Measurement Method

The inductor's excitation voltage waveform $v_L$ and excitation current waveform $i_L$ were measured, and the inductor's total loss $P$ was calculated using equation (1). Two measurement systems were used to measure the same inductor's loss, and the results were compared.

$$P = \frac{1}{T}\int_0^T v_L \, i_L \, dt \qquad \cdots \ (1)$$

### Measurement system consisting of the Power Analyzer PW8001 and AC/DC Current Sensor CT6904

Inductor loss was measured using the Power Analyzer PW8001 and 15 MS/s Input Unit U7005 (5 MHz band). An AC/DC Current Sensor CT6904 (500 A rating, 4 MHz band) was used as the current sensor. The PW8001's current sensor phase error correction function [7] was used to correct the current sensor's phase error. Figure 4 and Figure 5 depict the PW8001 and CT6904.

**Figure 4. Power analyzer PW8001**

**Figure 5. AC/DC current sensor CT6904**

### Measurement system developed by the Shimizu Lab at Tokyo Metropolitan University

Voltage measurement was accomplished using a differential probe, while current measurement used the AC/DC Current Sensor CT6904. Output from the differential probe and the current sensor was captured by an oscilloscope. Generally speaking, the difference between the differential probe's delay time and the delay time between oscilloscope channels is not constant relative to the frequency. Consequently, it's not possible to cancel phase error across a broad frequency band, even if the oscilloscope's deskew function is used to correct for the delay time between the voltage and current signals. The phase error-frequency characteristics of the oscilloscope, differential probe, and current sensor in this measurement system were acquired in advance, and the phase correction method [2] was used to minimize phase error across a broad frequency band.

**Calculation methods**

Iron loss $P_i$ was calculated using extended Steinmetz equations (2) and (3) [8]. The Steinmetz coefficients were calculated based on core material data as follows: $k = 3.524$, $\alpha = 1.459$, $\beta = 2.048$.

$$P_i = \frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} \Delta B^{\beta-\alpha}\, dt \quad \cdots \ (2)$$

$$k_i = \frac{k}{(2\pi)^{\alpha-1}\int_0^{2\pi}|\cos\theta|^{\alpha} 2^{\beta-\alpha} d\theta} \quad \cdots \ (3)$$

Copper loss $P_c$ was calculated using equation (4) based on the winding wire's DC resistance value $R_{DC}$ and the RMS value $I_{rms}$ of the excitation current.

$$P_c = R_{DC} \cdot I_{rms}^2 \quad \cdots \ (4)$$

The total loss $P$ was calculated using equation (5) based on the iron loss $P_i$ and copper loss $P_c$.

$$P = P_i + P_c \quad \cdots \ (5)$$

## 3. Results

Figure 6 illustrates the inductor loss measurement results when the inductor's peak current was varied from 80 Apk to 160 Apk. The results from the Power Analyzer-based measurement system, the measurement system developed by the Shimizu Lab, and the values calculated using extended Steinmetz equations agree within a range of approximately ±5%.

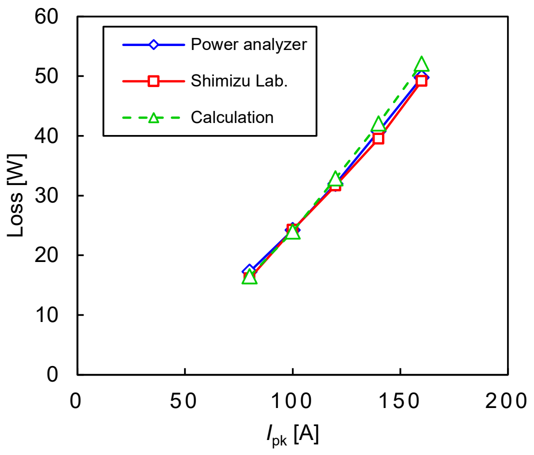

**Figure 6. Measured loss and calculated loss in the inductor.**

## 4. Observations

The inductor's power phase angle φ at an excitation current of 160 Apk was 89.82°. The power phase angle φ was calculated using equation (6) based on the loss $P$, voltage RMS value $U_{rms}$, and current RMS value $I_{rms}$ as measured by the power analyzer.

$$\phi = \cos^{-1}\frac{P}{U_{rms} \cdot I_{rms}} \quad \cdots \ (6)$$

When the phase angle of measurement target is $\phi$, the loss measurement error $k$ resulting from the measurement system's phase error $\Delta\phi$ can be estimated using equation (7) [2].

$$k = \frac{\cos(\phi+\Delta\phi)-\cos\phi}{\cos\phi} \times 100\ [\%] \quad \cdots \ (7)$$

Based on equation (7), when the measurement target's phase angle is 89.82°, a measurement system phase error of ±0.01° will result in a loss measurement error of ±5.56%.

Figure 6 indicates that the measurement results obtained from the two different measurement systems and the calculation results obtained from the extended Steinmetz equations agree with precision of ±5%. Consequently, it can be inferred that the Power Analyzer-based measurement system and the measurement system developed by the Shimizu Lab have realized a phase precision of approximately ±0.01°.

Figure 7 illustrates the phase-frequency characteristics for the combination of the PW8001 and CT6904 used in this test.

Phase error was ±0.01° or less at 100 kHz. These characteristics indicate that the setup is capable of accurate measuring loss for a switching frequency of 20 kHz and associated harmonic components. This capability, in turn, suggests that the combination can accurately measure loss in extremely low-loss inductors with a phase angle of 89.82°.

When the PW8001 is used with the CT6904, users can choose a maximum range of 1500 V/500 A. This setting can be used to measure loss in high-power inductors in an operational state. Additionally, the CT6904 current sensor implements zero-flux operation. As a result, the device does not exhibit magnetic saturation or changes in characteristics since the magnetic field applied to its magnetic core remains constant, even if a DC current is superposed on the measurement current. Consequently, the CT6904 can accurately measure inductor loss even under operating conditions in which a DC current is superposed on the inductor, as is typical with DC/DC converters.

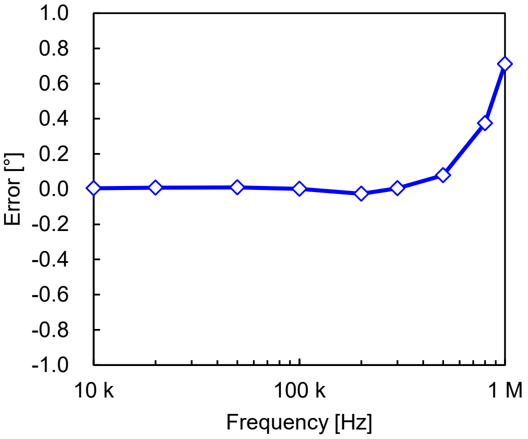

**Figure 7. Phase characteristics of combination of PW8001 and CT6904.**

## 5. Summary

A Power Analyzer PW8001 and AC/DC Current Sensor CT6904 were used to measure inductor loss.
The results were compared to measured values obtained from a measurement system developed by the Shimizu Lab at Tokyo Metropolitan University and to values calculated using extended Steinmetz equations.
The results indicate that the Power Analyzer PW8001 and AC/DC Current Sensor CT6904, which exhibit low phase error, can measure loss in operating inductors easily and at a high level of precision.
A measurement system consisting of the Power Analyzer PW8001 and AC/DC Current Sensor CT6904 can be used to easily measure loss in power conversion devices and to accurately ascertain the factors that account for device loss.

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