Technical Note

AC/DC Current Sensor CT6904/CT6904-60

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***Abstract*—The AC/DC Current Sensor CT6904/CT6904-60 is a high-precision current sensor that delivers a broad, 4 MHz (±3 dB) measurement frequency band with a current rating of 500 A/800 A. Thanks to newly developed coil and shield designs engineered to facilitate measurement of currents in environments with noise caused by increasingly high switching frequencies, the product delivers broadband performance and high noise resistance. This paper offers an overview of the products along with information about their features, architecture, and characteristics.**

I. Introduction

Manufacturers worldwide are working to develop smaller, more efficient components such as inverters and converters, which are key components of systems being used to electrify automobiles, trains, and aircraft.

These power supplies incorporate high-speed, low-loss power semiconductors fabricated from materials such as SiC and GaN, and their switching frequencies continue to rise. In recent years, power supplies that deliver even a large current in the order of 100 A are being driven at switching frequencies in excess of 100 kHz, pushing conversion efficiency beyond 90%. Since development of such power supplies demands efficiency improvements on the order of 0.1%, engineers must not only measure input and output power with a high degree of precision, but also assess loss from inductors and other system elements on a component-by-component basis. The ability to measure large currents across a broad frequency band at high precision is essential in such applications. However, as mentioned in [1] and [2], the measurement bands of previous high-precision current sensors were limited to several hundred kilohertz, resulting in large measurement errors for current and power with high-frequency components.

Hioki designed and developed the AC/DC Current Sensor CT6904/CT6904-60 to resolve this problem.

II. Overview

The CT6904 delivers basic measurement accuracy of ±0.027% and linearity of ±10 ppm with a 500 A rating. By using a newly developed opposed split coil, the product is able to minimize the effects of conductor position, nearby conductors, and magnetic fields while providing a broad measurement frequency band that extends to 4 MHz.

The sensor is used in environments that are characterized by high-frequency switching. Hioki has completely shielded the opposed split coil with a solid shield machined from aluminum to allow stable measurement that is unaffected by ambient noise, even in such environments. The result is exceptional, 120 dB (100 kHz) noise resistance.

Appearance of the CT6904.

When measuring large, high-frequency currents, conductor inductance and parasitic capacitance cause measurement error factors to increase in proportion to the length of the measured conductor. It is necessary to keep the measured conductor as short as possible in order to minimize these error factors. To make it possible to do so, Hioki has designed the CT6904's profile so that it can be installed in any orientation, allowing users to choose from a variety of installation methods. The company has also added the CT6904-60, which delivers a 4 MHz band with an 800 A rating, to the product line to facilitate measurement of even larger currents.

III. Features

A. High Precision

The CT6904 delivers basic measurement accuracy of ±0.027% and linearity of ±10 ppm with a rating of 500 A, yielding about twice the measurement performance of the previous model. Its specifications also define accuracy when used in combination with the Power Analyzer PW6001, including basic measurement accuracy of ±0.077% for power.

The CT6904-60 delivers basic measurement accuracy of ±0.034% and linearity of ±12.5 ppm with a rating of 800 A. Its specifications also define accuracy when used in combination with the PW6001, including basic measurement accuracy of ±0.082% for power. Ordinarily, calculated measurement accuracy deteriorates due to f.s. error when the input level is low compared to the current rating. Because their specifications define accuracy when used in combination with the PW6001, the CT6904 and CT6904-60 eliminate the need to take current sensor f.s.

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error into account, allowing both products to deliver high-accuracy measurement across a broad input range.

B. Broad Measurement Band

Thanks to a newly developed coil structure, the CT6904 and CT6904-60 achieve a measurement band of 4 MHz (±3 dB) at a 500 A or 800 A rating, respectively, 40 times greater than that of the previous model. This feature allows accurate current measurement of increasingly high-speed switching devices. The product's current characteristics are flat to about 1 MHz, with a small error component during high-frequency current measurement. Fig. 1 offers a comparison of amplitude characteristics.

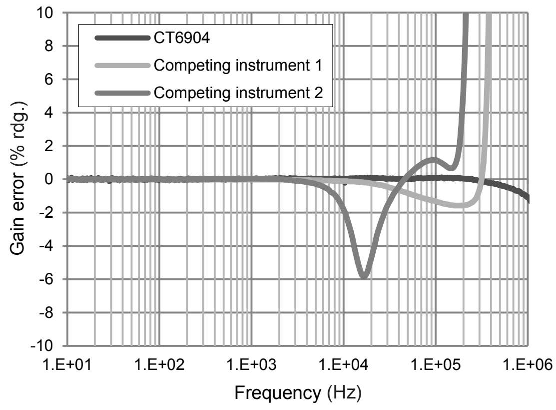

Fig. 1. Comparison of amplitude characteristics.

C. High Noise Resistance

A newly developed shield allows the product to deliver a common-mode rejection ratio (CMRR) of at least 120 dB at 100 kHz (1/1 000 000). The result is CMRR characteristics that are at least about 40 dB (1/100) better than the previous model, allowing highly reproducible measurement in which the effects of surrounding electric fields are minimized.

Fig. 2 illustrates the results of measuring a waveform in a noisy environment. Although common-mode voltage noise caused by voltage fluctuations is superposed on the current waveform obtained by the previous model and a competing instrument, the CT6904 exhibits excellent CMRR performance without any common-mode voltage noise.

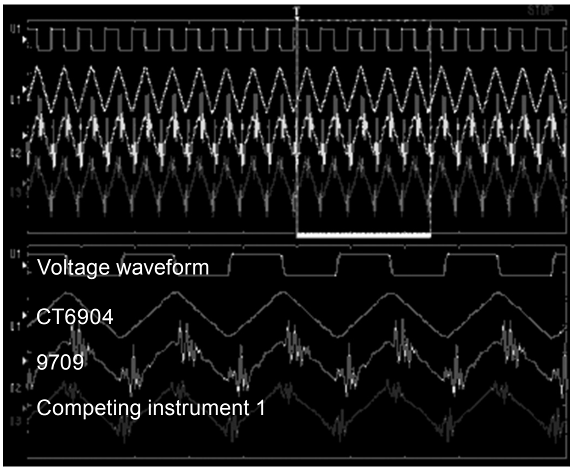

Fig. 2. Results of waveform measurement in a noisy environment.

IV. Architecture

A. *Measurement Principles and Circuit Architecture* (See [3] and [4])

Fig. 3 illustrates the AC/DC current sensor's circuit architecture. Like the previous model, the AC/DC Current Sensor 9709, the CT6904 and CT6904-60 use the flux gate method. This method for detecting magnetic fields, which takes advantage of the non-linearity of the B-H characteristics of a magnetic material, is typically used in applications such as detecting direction via terrestrial magnetism because it offers high sensitivity and an extremely high level of temperature stability. An excitation current in the form of a triangular wave (f = 10.4 kHz) is passed through the coil's magnetic material so that it reaches a state of saturation. While the current being measured flows under these conditions, the sensor performs differential detection of variations in the voltage waveform generated in the coil due to magnetic flux. By synchronizing the resulting detection signal with a 2f signal that is synchronized with the excitation current, it is possible to obtain an output signal that is roughly proportional to the current being measured. However, since the flux gate method does not yield sufficient sensitivity with a strong magnetic field in which the magnetic material is saturated, the sensor adds a negative feedback circuit in a design known as the zero-flux method to allow measurement of large currents up to its rating of 500 A or 800 A.

To deliver basic measurement accuracy of ±0.027%, which significantly exceeds that of the previous model, Hioki reduced the amount of output noise by means of a series of noise improvements achieved by optimizing the design of the flux-gate excitation circuit's filter. Additionally, the effects of electric and magnetic fields from the conductor under measurement on the detection circuit has been reduced by locating the feedback coil output detection circuit in a relay box in line with the output wiring and by separating the hardware into core and coil components.

B. Construction

Fig. 4 provides an overview of the construction of the sensor. The newly developed opposed split coil (a design in which split coils are arranged opposite one another outside a magnetic core) limits unnecessary parasitic capacitive coupling between the coils by splitting the detection coil into two coils to yield a significantly broader measurement band. Furthermore, the symmetric arrangement of the split coils around a toroidal core improves the balance with which magnetism is detected, reducing the effects of conductor

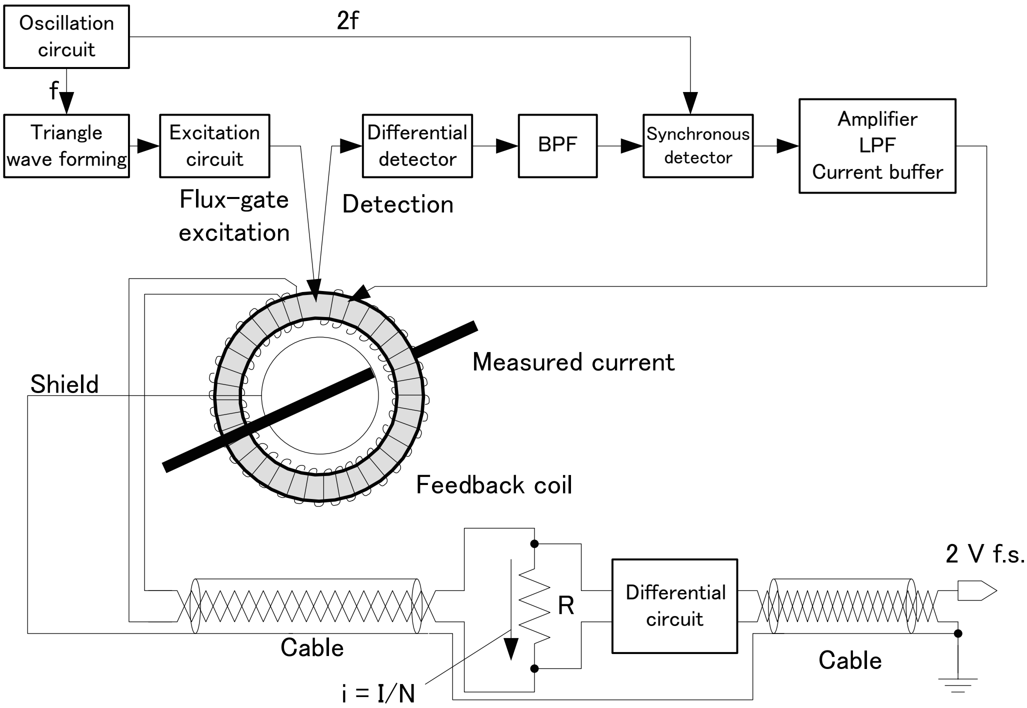

Fig. 3. Circuit architecture.

position. By placing the new coils in a solid shield machined from aluminum into a proprietary shape, Hioki has achieved an ideal shield structure without any unnecessary gaps. This design yields noise resistance that is superior to that of the previous model. Additionally, the CT6904 embodies a revamping of the previous design in order to offer users the ability to choose the optimal installation orientation, as shown in Fig. 5. When measuring large, high-frequency currents, measurement error caused by conductor inductance and parasitic capacitance increases with the length of the conductor under measurement. By adopting a unique shape for the CT6904 so that it can be installed in a variety of orientations, Hioki has created a design that allows the length of the conductor under measurement to be minimized, thereby reducing measurement error.

V. Characteristics Data

Figs. 6 through 17 illustrate various sensor characteristics. The CT6904 and CT6904-60 offer extremely good characteristics compared to the previous model, for example in terms of linearity, temperature stability, frequency characteristics (level and phase), and CMRR. These characteristics facilitate significant improvements in measurement accuracy and reproducibility when measuring the efficiency of inverter and power conditioner input and output, an application that requires measuring currents ranging from DC to high frequencies. This characteristics data, which was obtained by making measurements with the CT6904, is provided for references purposes only and does not constitute a guarantee of product characteristics.

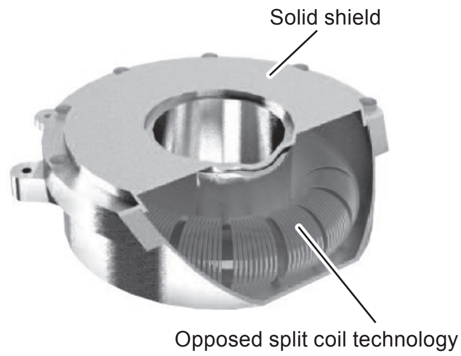

Fig. 4. Overview of sensor construction.

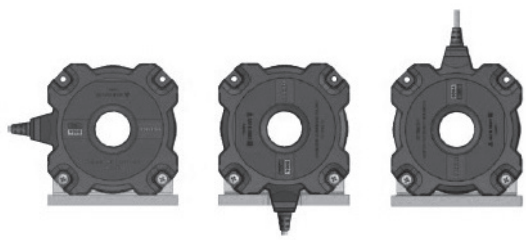

Fig. 5. Installation orientations.

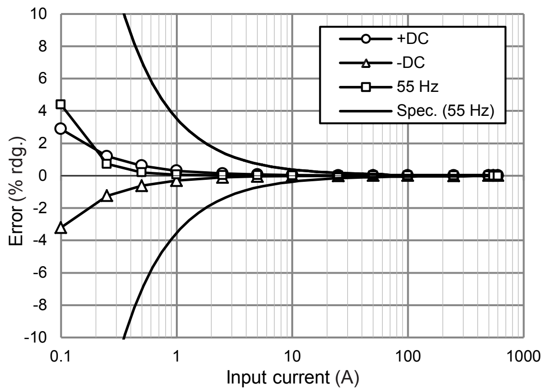

Fig. 6. Linearity (500 A).

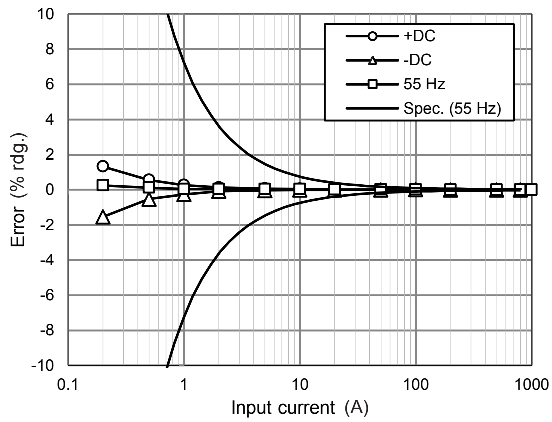

Fig. 7. Linearity (800 A).

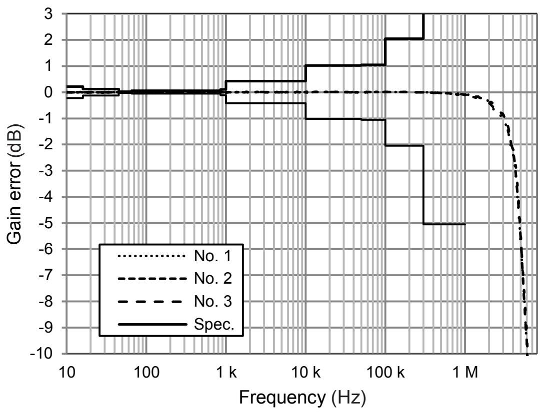

Fig. 8. Amplitude-frequency characteristics (500 A).

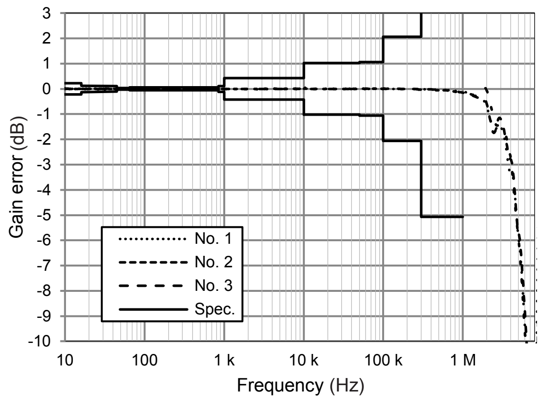

Fig. 9. Amplitude-frequency characteristics (800 A).

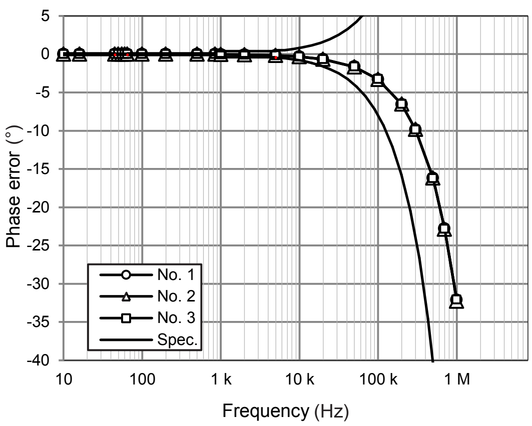

Fig. 10. Phase-frequency characteristics (500 A).

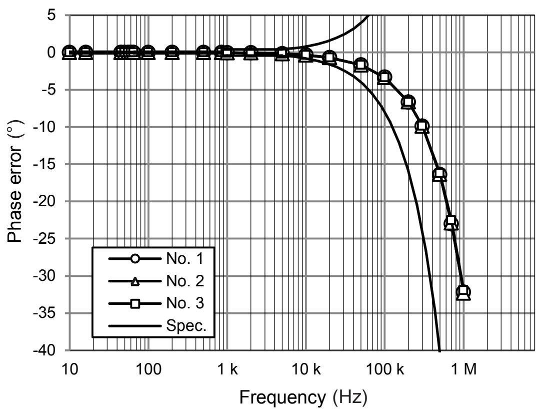

Fig. 11. Phase-frequency characteristics (800 A).

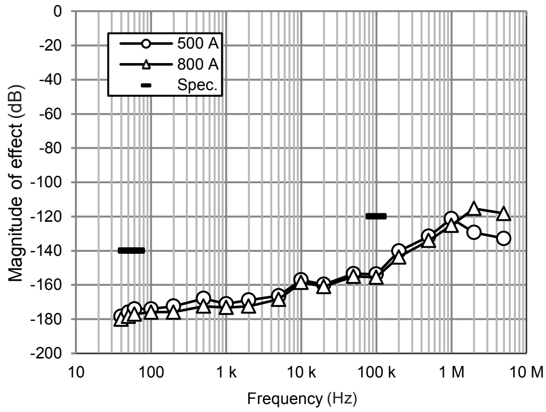

Fig. 12. Effects of common-mode voltage.

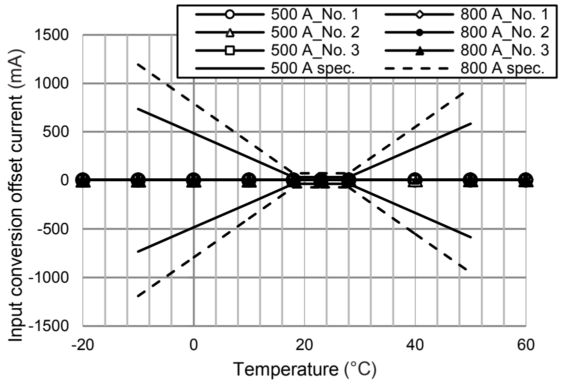

Fig. 13. Temperature-offset characteristics.

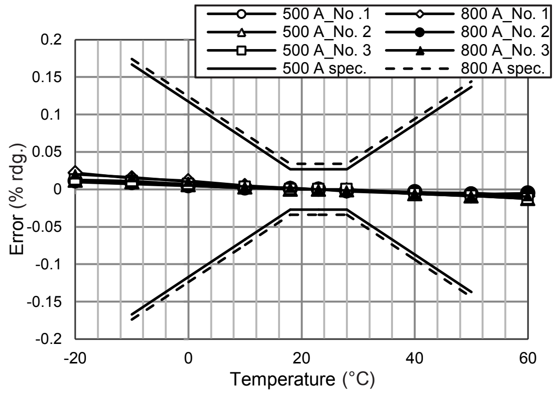

Fig. 14. Temperature-amplitude characteristics.

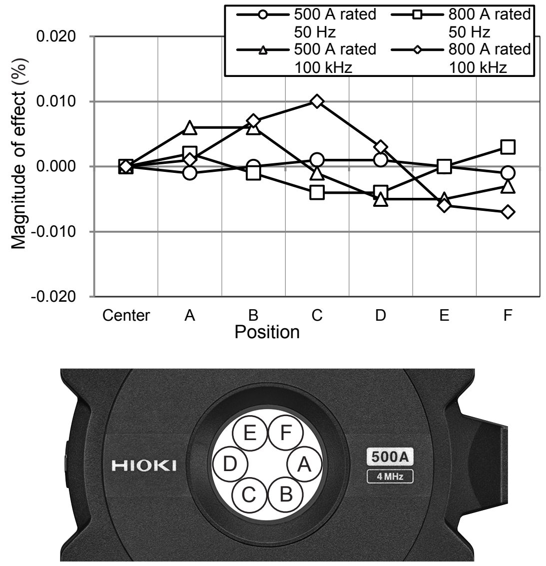

Fig. 15. Effects of conductor position in core (positions A through F).

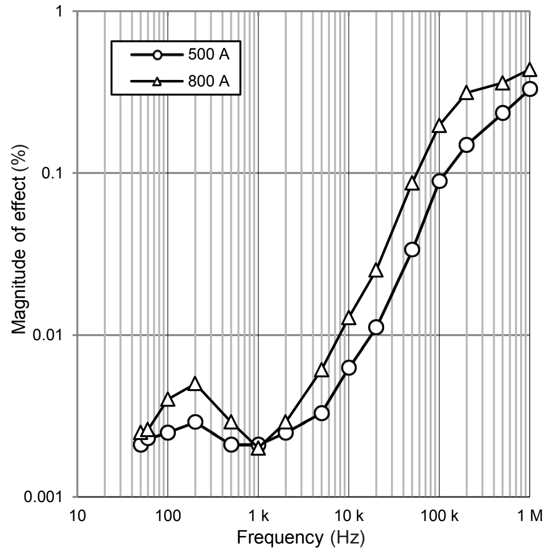

Fig. 16. Effects of nearby conductors.

VI. Conclusion

Measurement of component-level loss has become an area of growing need in recent years as manufacturers work to improve conversion efficiency of devices such as inverters and power conditioners that are switched at high frequencies. The CT6904 is an ideal product for customers that need to perform wideband, high-precision measurement in such applications. It is Hioki's hope that the sensor will contribute to improvements in power supply efficiency and energy efficiency worldwide, and by extension that it will help protect the global environment.

Ken-ichi Seki[1], Kazunobu Hayashi[1], Shuhei Yamada[1], Tetsuya Komiyama[1]

References

[1] K. Hayashi, "Measurement of Loss in High-Frequency Reactors," *Bodo's Power Systems*, February 2017, pp. 18-22. 2017.

[2] K. Hayashi, "High-Precision Power Measurement of SiC Inverters," *Bodo's Power Systems*, September 2016, pp. 42-47. 2016.

[3] K. Yamagishi, "AC/DC Current Sensor 9709," *Hioki Giho*, vol. 27, no. 1, pp. 33-40, 2006. (Japanese).

[4] K. Yamagishi, "AC/DC Current Sensor CT6862/CT6863," *Hioki Giho*, vol. 31, no. 1, pp. 25-34, 2010. (Japanese).

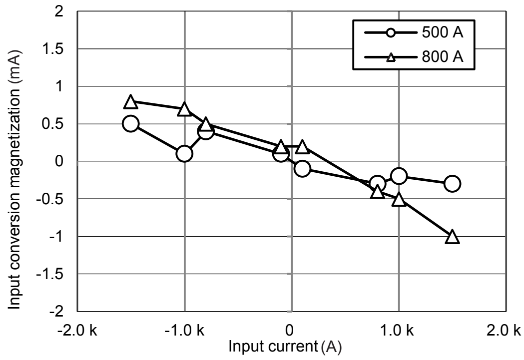

Fig. 17. Effects of magnetization.

[1.] AE Unit, Innovation Center