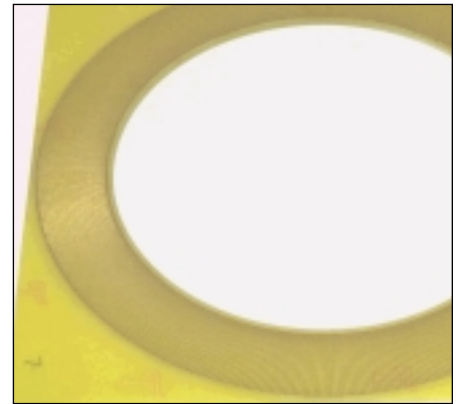


# High-Precision Rogowski Coils for Improved Relay Protection, Control and Measurements

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## Introduction

Rogowski coils were first introduced to measure magnetic fields. They could not be used for current measurements because coil output voltage and power were not sufficient to drive measuring equipment. However, with today's microprocessor-based equipment, Rogowski coils are more suitable for such applications. Current transformers (CTs) have been traditionally used for protection and measurement applications in part because of their ability to produce the high power output needed by electromechanical equipment. Microprocessor-based equipment makes high-power output unnecessary and opens the door for other measurement techniques such as Rogowski coils, which have many advantages over conventional CTs. This article presents an innovative design for which a U.S. patent has been granted.

## Principle of Operation

Traditional Rogowski coils consist of wire wound on a non-magnetic core. The coil is then placed around conductors whose currents are to be measured. The output voltage is proportional to the rate of change of measured current. To obtain measured current, coil output voltages must be integrated. For an ideal Rogowski coil, measurement accuracy is independent of conductor location inside the coil loop.

To prevent influence of nearby conductors carrying high currents, Rogowski coils must be designed with two-wire loops connected in electrical opposite directions. This cancels all electrical fields coming from outside the coil loop. One or both loops can consist of wound wire. If only one loop is made of wire wound on a non-

magnetic core, then the other can be formed by returning the wire through the center of the winding. If both loops have wound wire, then the second winding must be wound in the opposite direction. In this way, induced voltages in the Rogowski coil from the inside conductor will be doubled. The traditional method of designing Rogowski coils was to use flexible cores such as coaxial cables. The cable shield was removed and the wire wound over the plastic cable core. The existing conductor through the cable core center served as the return (second) loop. To design high-performance coils, straight rods have been used. The cross-sectional area can be manufactured more uniformly with rods than

coils located next to each other. To obtain high precision, the design was implemented on printed circuit boards. The principle is shown in Figure 1. Each printed circuit board contains one imprinted coil. Coils are wound in opposite directions (right-handed and left-handed). The principle is shown in Figure 2a. The right-handed coil is shown in Figure 2b. The top and bottom sides of the circuit board are imprinted to form a coil having a right-handed nature and progressing in a clockwise direction around the center of the board. The conductive imprints on the upper and lower sides of the printed circuit board are interconnected by conductive-plated holes. The left-handed coil is designed in a

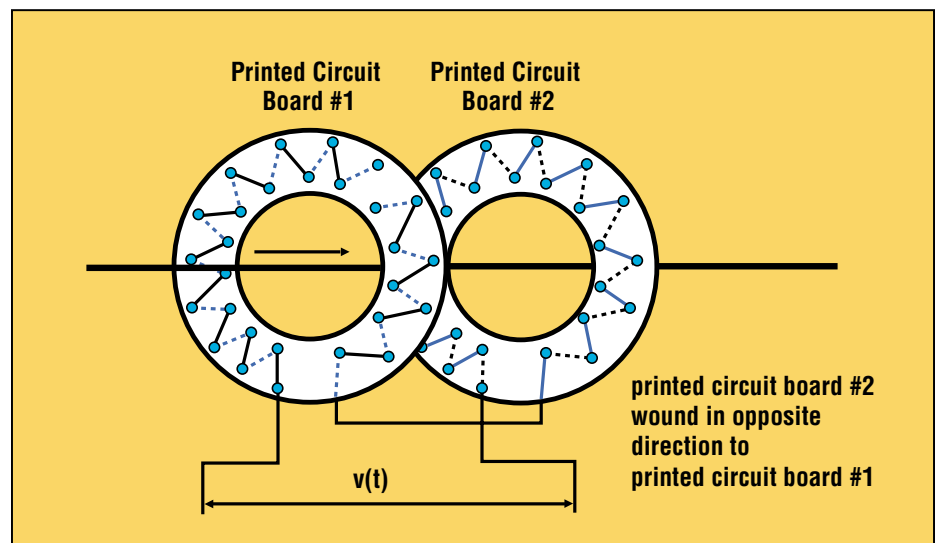


Figure 1 Principle of the new Rogowski coil design using printed circuit boards

with flexible cores. It is also easier to control the winding process using rods. This design requires shielding all ends where rods have to be interconnected.

## Printed Circuit Board Rogowski Coils

The newly patented design is a Rogowski coil consisting of two wound

similar manner except that it has to be wound in the opposite direction. Printed circuit board Rogowski coils can be connected in series to increase output signal.

These coils can be designed with different shapes. An oval printed circuit

board Rogowski coil is shown in Figure 3, where high accuracy and reduced influence of external fields from nearby conductors is obtained by rounded angles. Each side is half of a circle.

To determine printed circuit board coil characteristics, tests were performed for linearity, frequency

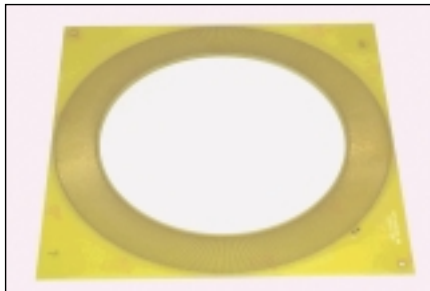


Figure 2a One printed circuit board with imprinted coil

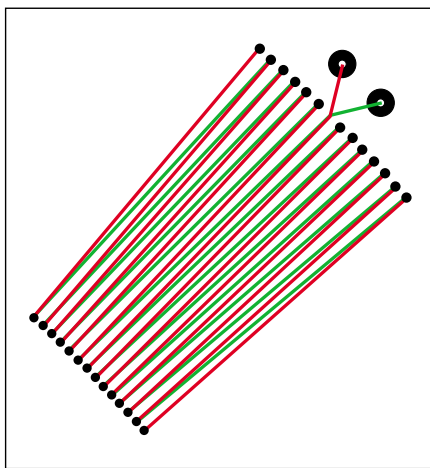


Figure 2b Detail of one printed circuit board imprinted coil

response, and real-life applications. Linearity was tested from 1ARMS to 190 kApeak, representing the extremes of coil applications. Results were encouraging in that the coil has linear characteristics over the whole current

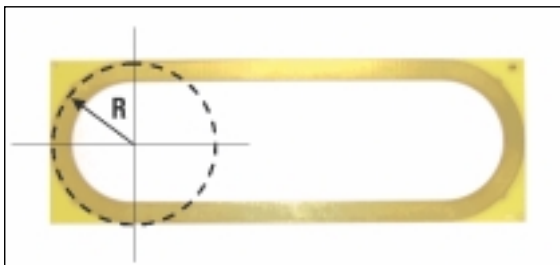


Figure 3 Oval design of Rogowski coils

range. Frequency response is also linear up to 700 kHz, which is significantly higher than any conventional CT.

Real-life application tests were conducted in Cooper Power Systems' high power laboratory at the Thomas A. Edison Technical Center. Two sets were performed: current measurements from the inside conductor (measurement accuracy), and current pickup from the nearby conductor carrying high current (measurement noise). Results were compared against laboratory CTs. Output signals were connected to a laboratory data acquisition system through fiber optic cables.

Figures 4a and 4b show results of current measurements during a test with 68 kApeak. Results demonstrate the applicability of Rogowski coils for measuring distorted current waveforms. Their high performance under severe operating conditions eliminates most of the accuracy problems with conventional CTs. The tested device failed after two cycles, causing arcing and current distortion. The printed circuit board coil output signal is given in Figure 4a. The coil signal is different than the signal recorded by the laboratory CT since it represents derivation of current per time, a unique feature of Rogowski coils. This is important since the speed of current change can be used for fast protection algorithms. To obtain coil output signal proportional to the measuring current, output signal was integrated using digital signal processing. A comparison of the primary current recorded by the laboratory CT and the integrated coil output signal is presented in Figure 4b. The coil waveform is essentially identical to the laboratory CT: Conventional 1000/1 A CT saturated during the first current loop.

Current pickup (measurement noise) by the Rogowski coil located four inches from the primary conductor was only 0.1 %, which verifies very good rejection of external fields.

## Conclusion

Rogowski coils enable the design of advanced protection, control, and metering systems with new multifunction relays and fiber optic communication, providing faster response times to faults and can easily adjust to load and/or power system configuration changes. Since the new Rogowski coils are very accurate, protection levels can be set to lower thresholds, reducing stress on the protected equipment. In addition, control and metering systems operate more accurately.

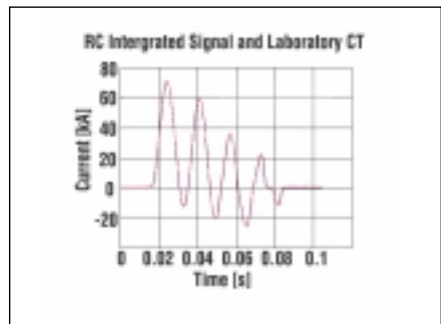
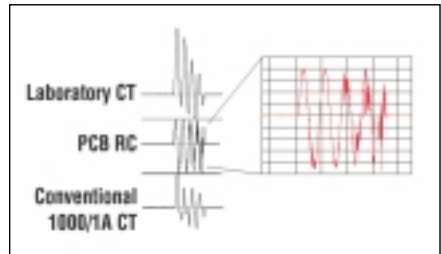


Figure 4a (top) Non- integrated and Figure 4b (bottom) integrated printed circuit board Rogowski coil output signals

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Visit Cooper in Booth 319 and see demonstrations of the Rogowski coils discussed in this article and the Peer-to-Peer network described on page 11 of this issue.

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