Design and Characteristics of Two Rogowski Coils Based on Printed Circuit Board

Chen Qing, Li Hong-bin, Zhang Ming-ming, and Liu Yan-bin

Abstract—**Rogowski coils are special types of mutual inductors often used to measure large alternating and transient currents. Traditional handmade Rogowski coils lack accuracy and cannot be easily mass-produced. Two new structures of Rogowski coils based on printed circuit board are presented. Theoretical analyses on the mutual inductances of two designs are discussed. The measurements of basic characteristics, linearity tests, frequency-response tests, temperature performance tests, and related positional sensitivity tests for the two new coils and traditional coil are carried out. The two new Rogowski coils are proved to have excellent accuracy and temperature performance and can be easily applied in mass production.**

Index Terms—**Linearity, positional sensitivity, printed circuit board (PCB), Rogowski coil.**

I. Introduction

Rogowski coils were introduced in 1912 to measure magnetic fields. At that time, they could not be used for current measurements because the coil output power was not sufficient to drive measurement equipment. With today's microprocessor-based protection and measurement equipment, Rogowski coils become suitable for current measurements. Current transformers (CTs) have been traditionally used for protection and measurement applications, partly because of their ability to produce the high output power needed by electromechanical equipment. Microprocessor-based equipment does not require high output power from the measuring devices, and therefore, this makes many measurement techniques, such as Rogowski coils that are better than conventional CTs, become practical.

Rogowski coils are useful for the measurement of alternating or transient currents from tens to many thousands of amperes. Because Rogowski coils do not have ferromagnetic material in their cores, the coils will not be saturated [1], [2]. When a Rogowski coil is placed around a current-carrying conductor, the coil generates a voltage, which is proportional to the rate of change of current $di(t)/dt$ and the mutual inductance M. The output voltage is integrated to provide the flux linkage, which is proportional to the current.

To provide proper signals to both metering equipment and protection equipment, Rogowski coils must have excellent linearity, good frequency response, and low temperature coefficient and be insensitive to disturbances from other signal sources, such as the nearby current-carrying conductors, to some extent [3]. Traditional handmade Rogowski coils lack accuracy and are not easily applied in mass production; thus, new structures and materials are needed in designs of coils. Kojovic [1] and Karrer and Hofer-Noser [4] gave a new configuration of Rogowski coil based on printed circuit board (PCB), which was proved to be useful in transient current measurement.

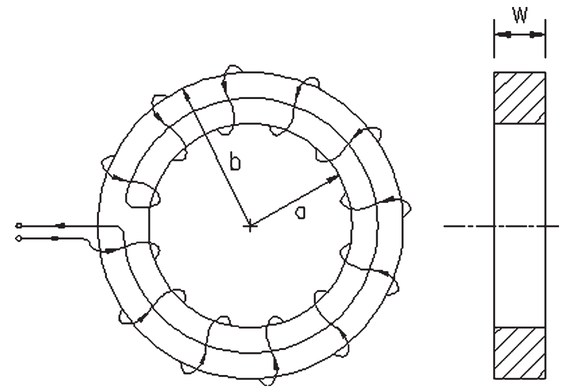

Fig. 1. Construction of TRC.

II. Rogowski Coil Designs

A. Traditional Rogowski Coils (TRCs)

TRCs are commonly wound on a rigid toroidal core form. For toroidal coils having a rectangular cross section such as that shown in Fig. 1, the mutual inductance is [3]

$$M = \frac{\mu_0 N w}{2\pi} \ln \frac{b}{a}$$

where M is the mutual inductance (in henry); μ_0 is the permeability of air, which equals $4\pi \times 10^{-7}$ H/m; N is the number of turns of coils; w is the width of the toroid in meters; a is the inside diameter in meters; and b is the outside diameter in meters.

Rogowski coils may be wound having a single- or multiple-layer windings. Multilayer coils will have higher values of mutual inductance, series self-inductance, series resistance, and distributed capacitance. A typical single-layer TRC is shown in Fig. 1. To prevent the influence of magnetic fields crossing the coils, a return loop is necessary. The existing conductor through the core center serves as the return (second) loop, just as shown in Fig. 1.

B. Planar Rogowski Coils (PRCs) Based on PCB

PRCs based on PCB have similar constructions to TRC. The PCBs in a PRC exist in pairs, and a pair consists of

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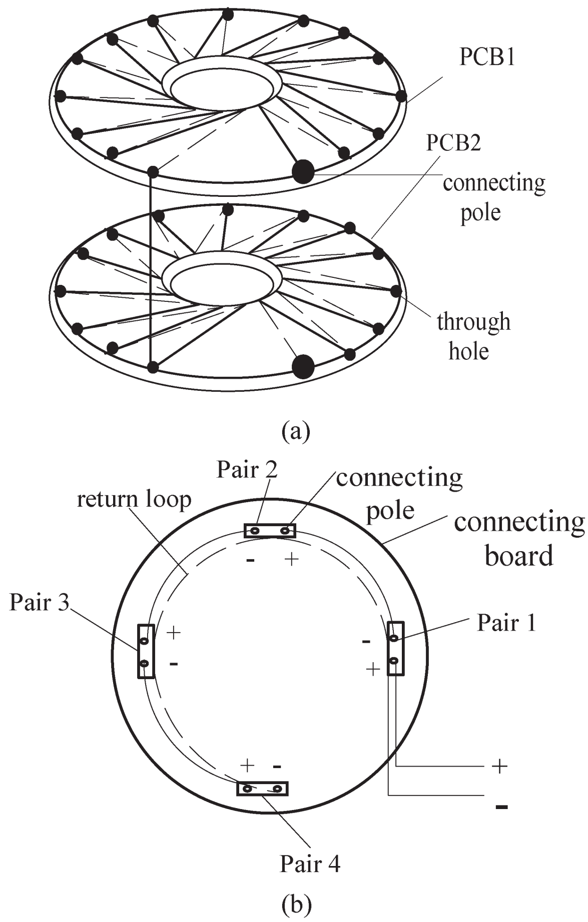

Fig. 2. (a) Construction of PRC. (b) Connecting board.

two coils located next to each other. Each PCB contains one imprinted coil wound in opposite directions [Fig. 2(a)]. The top and bottom sides of each PCB are imprinted to form a coil around the center of the board. The conductive imprints on the upper and lower sides of the PCB are interconnected by conductive-plated holes. The formula on how to deduce the mutual inductance of a pair of PCBs is similar to that of the TRC. The mutual inductance, self-inductance, and series resistance of a PRC are the sum of those of all PCBs.

The magnetic fields crossing through the PCBs vertically will induce no voltage because PCB1 and PCB2 are wound in opposite directions, and the turn (second) loop is not necessary. To eliminate the disturbance of nearby conductors carrying high currents, many pairs of PCBs, usually four pairs, make a PRC [Fig. 2(b)]. Four pairs of connecting poles are placed in four different directions, that is, up, right, down, and left. The connecting board provides a series circuit for four pairs of PCBs. A turn (second) loop is necessary to the connecting board.

For more information about the PRC, the work in [4] is very helpful.

C. Combined Rogowski Coil (CRC) Based on PCB

As shown in Fig. 3(a), a CRC consists of a main PCB and several assistant PCBs. The main board provides the series circuit for the assistant boards. The purpose of assistant boards is to produce the induced voltage. There are many loops on

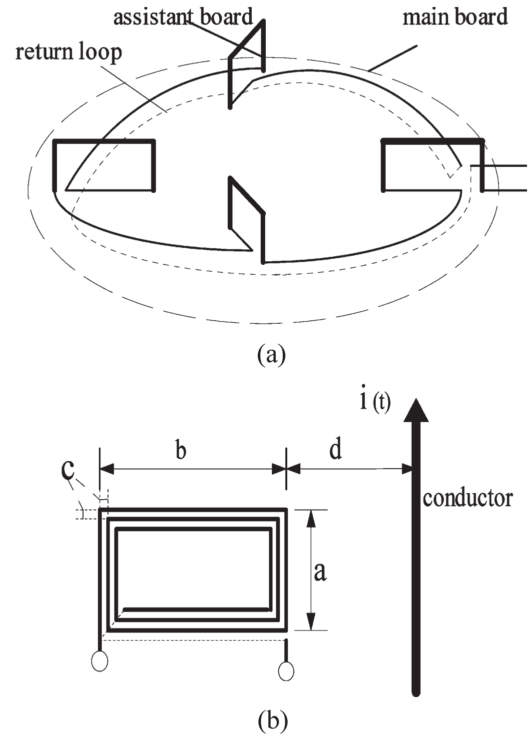

Fig. 3. (a) Construction of CRC. (b) Assistant board and conductor.

one assistant board, which will increase the mutual inductance greatly. Multilayer PCBs may be applied in assistant boards, if necessary, to obtain high enough output voltage. The output voltage of every assistant board is proportional to the mutual inductance of it and the time rate of the measured current change. The mutual inductance, self-inductance, and series resistance of a CRC are the sum of those of all assistant boards.

All the assistant boards are dispersed equitably at one side or both sides of the main board around the center. Just as the return loop is necessary in the TRC, some similar measures must be taken in the CRC to obtain high precision. The main board is not necessarily close.

The size and position of an assistant board are shown in Fig. 3(b). In the derivation of the mutual inductance of an assistant board, Ampere's law is used. Then, the mutual inductance of a CRC is given by

$$\begin{aligned} M &= NM' \\ M' &= \int_{d}^{d+b} \frac{\mu_0}{2\pi x} a dx + \int_{d+c}^{d+b-c} \frac{\mu_0}{2\pi x}(a-2c)dx + \cdots \\ &\quad + \int_{d+(k-1)c}^{d+b+(k-1)c} \frac{\mu_0}{2\pi x}\left[a-2(k-1)c\right] dx \end{aligned}$$

where M' is the mutual inductance of one assistant board, whereas M is that of the CRC (in henry); μ_0 is the permeability of air, which equals $4\pi \times 10^{-7}$ H/m; k is the number of turns of loops on one assistant board; a, b, c, and d are the position characteristics of one assistant board; and N is the number of assistant boards. The CRC is different from the TRC and PRC

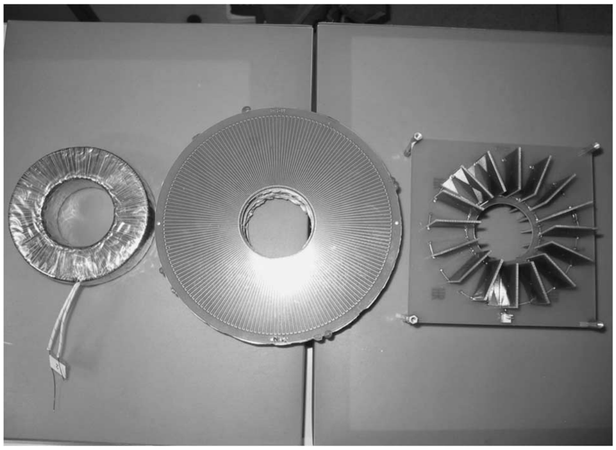

Fig. 4. Photo of three Rogowski coils.

because the loops of the TRC and PRC are completely symmetrical, whereas those of the CRCs are relatively symmetrical. To conform to the mathematical model used to calculate the mutual inductance, the assistant boards must be perpendicular to the plane of the main board. To keep the invariability of the mutual inductance, all the assistant boards must be connected with the main board with soldering tin.

III. Basic Characteristics of the Three Coils

Just as shown in Fig. 4, the three coils are, from left to right, the TRC, PRC based on PCB, and CRC based on PCB. The mutual inductance, self-inductance, and series resistance were measured. It is suggested in [5] that the distribution capacitance of the Rogowski coil is very important and cannot be neglected when the Rogowski coil is used in high-bandwidth current measurement (20 M, for example), but the distribution capacitances can be ignored when the Rogowski coil is used in rated frequency (50 or 60 Hz) current measurement. The distribution capacitances of the PRC and CRC are due to the number, width, and distribution of the lines of the PCB; thus, the deduction of the distribution capacitances is difficult, and it will be continued in the further research. The three coils were made in the laboratory, and the mass-production (100 coils, for example) prices resulted from relevant consultations.

The measured values of size, weight, prices of samples, and prices in mass production are given in Table I. The structure of PRC is more symmetrical than TRC and CRC, whereas CRC has higher mutual inductance, lower prices, and smaller size than TRC and PRC. The variation between measured value and designed value of mutual inductance is more than 2% in TRC, but below 0.5% in PRC and CRC. CRC and PRC have good repeatability. All of the CRCs (or PRCs) in the same group have the same mutual inductance, self-inductance, and resistance, whereas the mutual inductances of TRCs in the same group differ from each other.

IV. Linearity and Frequency-Response Tests

To get the voltage signal proportional to the measured current, the induced output voltage of the coils must be integrated and magnified. The linearity and stability of three integrators have been tested in the laboratory, and the errors caused by them are the same. Fig. 5 shows the linearity of three coils with integrators. The current through the conductor is measured by a traditional CT, which can meet the requirements of 0.001 class. The rated current passing through the coil is 300 A. The rated frequency is 50 Hz. The output of integrator is u, whereas that of traditional CT is u'. The error equals $(u - u')/u'$.

The curves show that the three coils have excellent linearity and when the current is low, the TRC has larger errors than the other two coils because the induced voltage from the TRC has a lower signal-to-noise ratio. The PRC and CRC can meet the requirements of the 0.2S class described in the IEC Standard 60044-8, and the exact experimental results can be found in [6]. In [6], one Rogowski coil based on the PCB was used for both metering and protection, which is almost impossible for the TRC. However, the induced voltages of the three coils get smaller with the increase of current. A logical explanation for this phenomenon is given in [7]. The core material is assumed to have a uniform and constant relative magnetic permeability of free space, $\mu_0 = 4\pi \times 10^{-7}$ H/m. Even very small amounts of impurities that contain ferromagnetic material can alter the permeability and, hence, create nonlinearities in the coil response. To improve the range of good linearity, augmenting the size of the coil, the goal of which is to reduce the magnetic field in the core of the coil, is a convenient and effective way.

Kojovic [1], Ward *et al.* [2], and Karrer and Hofer-Noser [4] give particular expressions for Rogowski coils used in protection and transient current measurement. The bandwidth of Rogowski coils is more than 10^4 Hz, which is affected by the self-inductance, the distribution capacitance, and the characteristics of the integrator. Ramboz [3] and Oates *et al.* [5] presented some methods to reduce the self-inductance and distribution capacitance, which can improve the frequency response of the coil up to 1 MHz, even 20 MHz. The improved construction of Rogowski coils is similar to the PRC to some extent, the kernel of which is to reduce the self-inductance. The PRC shown in Table I is supposed to have the best frequency-response property if each of the three coils is connected with the same integrator.

V. Temperature Tests

In the IEC Standard 60044-8, the electronic CT must keep good accuracy when the temperature changes in a certain range. The three coils presented above are tested. A conductor carrying 300-A current is passed through the coil window. First, the temperature is kept at common conditions, 20 °C, for 1 h. Then, the temperature is increased until 90 °C and held at 90 °C for 2 h. Then, the temperature is decreased until −30 °C and held at −30 °C for 2 h. The induced voltage is integrated and measured, and the measured voltage E equals KMI where K is the coefficient of the integrator, M is the mutual inductance, and I is the current passing through the window of the coil. The integrators have been tested and proved to have the same linearity and stability; thus, the errors caused by integrators are equivalent. Before temperature tests, the initial mutual inductance M^* can be calculated through the equation $E^* = KM^*I$. A standard CT is used to provide the voltage signal proportional

TABLE I
BASIC PARAMETERS OF THREE COILS

	Size (mm)			weight	Sample price	Mass price	Mutual inductance	Self-inductance	Resistance
Type	Inside D	Outside D	Width	(g)	(USD)	(USD)	(μH)	(mH)	(Ω)
TRC	45	95	32	350	20	10	1.1	1	20
PRC	48	162	33	1000	45	10	0.5	0.2	230
CRC	40	127	59	130	20	5	1.9	2	110

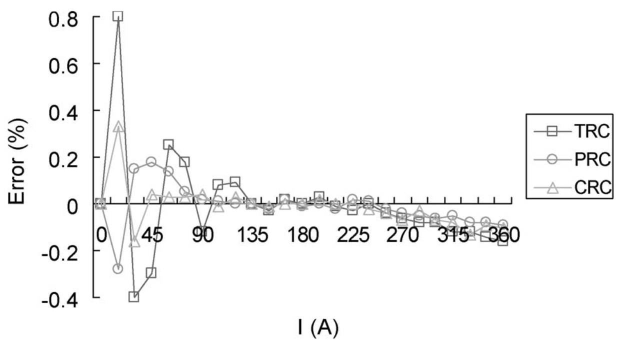

Fig. 5. Linearity tests of the three coils: Rated current at 300 A.

TABLE II
CHARACTERISTICS OF TEMPERATURE PROPERTY

Type	20°C error	90°C error	-30°C error
TRC	0.02	2.10%	-0.30%
PRC	0.03	0.20%	-0.15%
CRC	-0.01	0.20%	-0.16%

to the measured current I. A data acquisition system based on NI PCI-4474 and LabVIEW collects the signal E from the integrator and signal I from the standard CT, calculates the mutual inductance M at any moment during temperature tests, and compares it to M^*. The errors, which equal $(M - M^*)/M^*$, are given in Table II.

The two coils based on the PCB are proved to have better temperature properties. The TRC seems to be very sensitive to high temperature. Copper expands more rapidly than the core when the temperature increases; thus, the wound loops of the TRC can expand freely to some extent. The core contracts less rapidly than the loops when the temperature decreases; thus, the loops of the TRC cannot contract freely. The copper circuits on the PRC and CRC are all restrained by the PCBs and cannot expand or contract freely, and the boards have excellent temperature properties. Thus, the mutual inductances at high and low temperatures are very close to the initial one.

VI. POSITIONAL TESTS

An important measure of performance for a Rogowski coil is its sensitivity to the position between the coil and the conductor. In the derivation of the mutual inductance, Ampere's law is used. The ideal position between coil and conductor is shown in Fig. 6(e). Practically, it is difficult to place them exactly. Moreover, outside magnetic sources such as that caused by

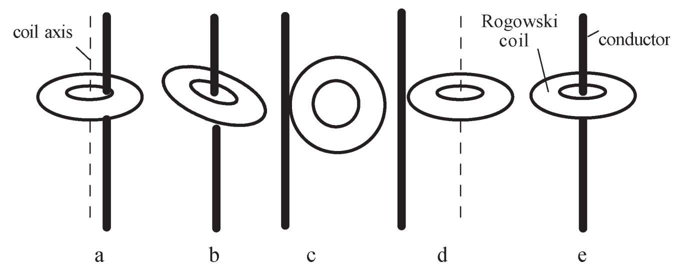

Fig. 6. Position between Rogowski coil and conductor.

nearby in-phase current will bring certain errors, which cannot be ignored in demanding situations where accuracy is paramount. As described above, a data acquisition system calculates the mutual inductance M at any moment, and the initial mutual inductance M^* is calculated and recorded when the position between conductor and coil is like Fig. 6(e).

A. Off-Center Test

The coil is placed on a conductor passing through the coil's window. The 18-mm diameter of the conductor is less than the inside diameter of the coil, so that the conductor can be placed far away from the center of the window. The conductor is close to the edge of the window, just as shown in Fig. 6(a). The axis of the conductor is parallel to the axis of the coil. The relevant errors, which equal $(M - M^*)/M^*$, are given in Table III.

B. Off-Center Rotational Test

The coil is placed on a conductor passing through the coil's window. The diameter of the conductor is less than the inside diameter of the coil, so that the coil can be positioned off-center. The coil is then rotated in eight 45° angular positions around the conductor, just as shown in Fig. 6(b). The relevant errors, which equal $(M - M^*)/M^*$, are given in Table III.

C. Edge-Transversal Test

The coil is placed with its outside edge against the conductor. The axis of the coil is perpendicular to the axis of the conductor, just as shown in Fig. 6(c). This configuration is good for testing the effectiveness of the compensation (turn, second) loop. When current is flowing, there should be no output from the coil because no current passes through the coil's window. However, no coils are ideal, and an induced voltage is obtained at the output of each coil. The relative mutual inductance can be calculated. The edge-transversal test errors, which equal M/M^*, are shown in Table III. There are four pairs of PCBs

TABLE III
RESULTS OF POSITION TESTS

Type	Off-center test	Off-center rotational test	Edge-Vertical test	Edge-Parallel test
	error	error	error	error
TRC	0.80%	1%	0.50%	0.80%
PRC	0.05%	0.08%	0.05%	0.1%
CRC	0.10%	0.10%	0.07%	0.11%

placed symmetrically, which can prevent the influence of currents from out of the coil's window; thus, the PRC has lower values of error than the TRC or CRC.

D. Edge-Parallel Test

The coil is placed with its outside edge against the conductor, but the conductor does not pass through the coil's window. In this configuration, the coil axis is parallel to the conductor axis, just as shown in Fig. 6(d). The edge-parallel test is good for testing the effectiveness of the nearby in-phase currents. When current is flowing, an induced voltage is obtained at the output of each coil. The relative mutual inductance can be calculated. The test errors, which equal M/M^*, are shown in Table III. Again, the PRC has the best performance, and the CRC takes the second place.

E. Correct Position

The conductor, which is cylindrical, is placed through the axis of the coil window. Then, the coil and the conductor have the same axis, which is vital in the ideal position between the coil and the conductor.

VII. CONCLUSION

The constructions of TRC, PRC based on PCB, and CRC based on PCB have been introduced. The formula on how to deduce the mutual inductance has been presented. Through some tests, the two coils based on PCB were proved to be more machinable, repeatable, and commercial. The PRC and CRC have better linearity than TRC even when the passing current is low, and the two coils based on PCB are less sensitive to the position change between coil and conductor. Hence, the PRC and CRC are preferred to TRC, and they can be used not only in transient current measuring but also in precise metering of sine-wave current. The PRC and CRC with their excellent performances can meet the requirements of mass production, whereas the handmade TRC cannot.

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