



IEEE Guide for the Application of Rogowski Coils used for Protective Relaying Purposes

IEEE Power and Energy Society

Developed by the
Power System Relaying and Control Committee

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STANDARDS

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Power System Relaying and Control Committee
of the
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Approved 9 November 2021

IEEE SA Standards Board

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Abstract: Guidance for the use and application of Rogowski coils (RCs) (air-core current sensors) for protective relaying in electric power systems is described and provided in this guide. The selection and application of RCs for the more common protection schemes are also addressed.

Keywords: air-core current transformer, IEEE C37-235™, low-power instrument transformer, Rogowski coil

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Introduction

This introduction is not part of IEEE Std C37.235–2021, IEEE Guide for the Application of Rogowski Coils used for Protective Relaying Purposes.

Conventional iron-core current transformers (CTs) have traditionally been used for protection and measurement applications in part because of their ability to produce the high-power output required by electromechanical equipment. Microprocessor-based devices consume less power than traditional electromechanical equipment, thereby making high-power current sensors unnecessary. When conventional CTs are used with new microprocessor-based relays, commonly recognized CT problems such as saturation and remanence can affect the relay performance in a similar way as with traditional schemes. Manufacturers use different algorithms to achieve proper performance of relays during CT saturation.

Rogowski coil current sensors have high measurement accuracy and are linear (do not saturate), providing a wide operating current range. Rogowski coils make protection schemes possible that were not achievable with conventional CTs because of saturation, size, and/or weight. Unlike CTs that produce secondary current proportional to the primary current, Rogowski coils produce output voltage that is a scaled time derivative of the primary current. Signal processing is required to extract the power frequency signal for phasor-based protective relays and microprocessor-based equipment designed to accept these type signals.

This guide is the first one on Rogowski coil usage for protective relaying. It is intended to present the principle of operation of Rogowski coils and to compare performance characteristics with other current sensing devices. This document includes guidelines for Rogowski coil installation, interface to relays, testing, and applications for different relay protection schemes. The guide was revised to update Rogowski coil requirements and to harmonize with IEC 61869.

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IEEE Guide for the Application of Rogowski Coils used for Protective Relaying Purposes

1. Overview

1.1 Scope

This guide establishes criteria and requirements for application of Rogowski coils (~~RCs~~) (air-core current sensors) used for protective relaying in electric power systems. The selection and application of [Rogowski coils](#) ~~RCs~~ for the more common protection schemes are addressed.

1.2 Purpose

This document provides a guide for application of Rogowski coils used for protective relaying in electric power systems. It is intended to assist the relay application engineer in the correct selection and application of [Rogowski coils](#) ~~RCs~~ for protective relaying purposes. It provides [guidelines](#) ~~requirements~~ relevant to the performance, operation, testing, and maintenance of Rogowski coil-based current sensors. This guide applies to all types of Rogowski coils used for protective relaying purposes.

1.3 [Word usage](#)

[The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted \(*shall equals is required to*\).^{6,7}](#)

[The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required \(*should equals is recommended that*\).](#)

[⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.](#)

[⁷The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.](#)

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may equals is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can equals is able to*).

1.3 Protective relaying principles using Rogowski coils

Part a) of Figure 1 shows protective relaying principles using a Rogowski coil directly interfaced to an intelligent electronic device (IED), and part b) of Figure 1 shows solutions described in IEC 60044-81 for electronic current transformers (ECTs). Figure 1 is explained in 5.7.

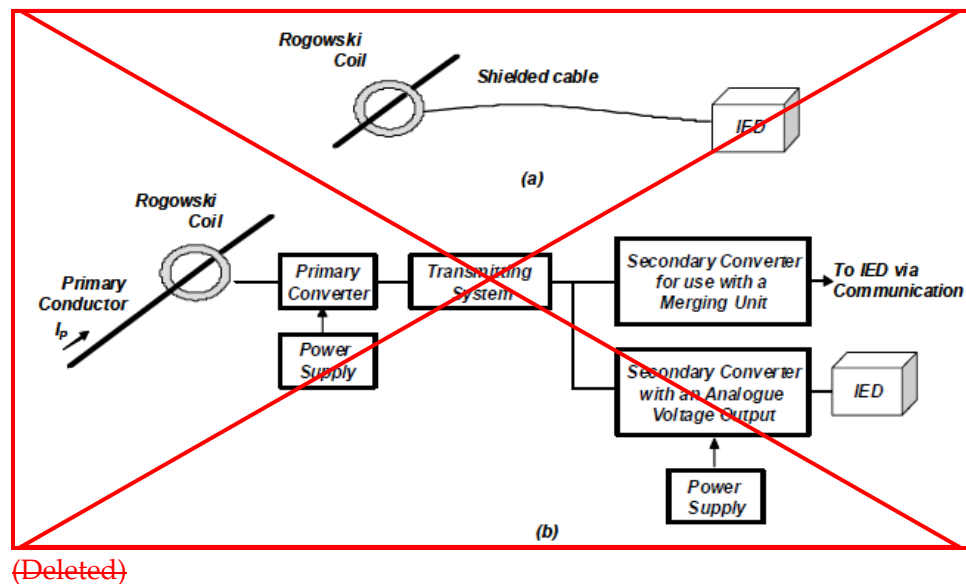


Figure 1 Application of Rogowski coils used for protective relaying purposes

1-Information on references can be found in Clause 2.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC [61869-1](#) ~~60044-8~~, Instrument transformers – Part [1](#) ~~8~~: [General requirements](#).⁸ ~~Electronic current transformer.~~²

[IEC 61869-2, Instrument transformers – Part 2: Additional requirements for current transformers.](#)

[IEC 61869-3, Instrument transformers – Part 3: Additional requirements for inductive voltage transformers.](#) [IEC 61869-4, Instrument transformers – Part 4: Additional requirements for combined transformers.](#)

[IEC 61869-5, Instrument transformers – Part 5: Additional requirements for capacitor voltage transformers.](#)

[IEC 61869-6, Instrument transformers – Part 6: Additional general requirements for low power instrument transformers.](#)

[IEC 61869-7, Instrument transformers –Part 7: Additional requirements for electronic voltage transformers.](#) [IEC 61869-8, Instrument transformers – Part 8: Additional requirements for electronic current transformers.](#) [IEC 61869-9, Instrument transformers – Part 9: Digital interface for instrument transformer.](#)

[IEC 61869-10, Instrument transformers – Part 10: Additional requirements for low power stand-alone current sensors.](#)

⁸ ²IEC publications are available [from the International Electrotechnical Commission \(https://www.iec.ch\)](https://www.iec.ch) and ~~in the United States from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA (http://global.ihs.com/).~~ Electronic copies are available ~~in the United States from~~ the American National Standards Institute, ~~25 West 43rd Street, 4th Floor, New York, NY 10036, USA~~ ([https](https://www.ansi.org/) ~~http://www.ansi.org/~~).

[IEC 61869-11, Instrument transformers –Part 11: Additional requirements for low-power passive current transformers.](#)

[IEC 61869-12, Instrument transformers – Part 12: Additional requirements for combined electronic instrument transformers or combined low-power passive instrument transformers.](#)

[IEC 61869-13, Instrument transformers – Part 13: Stand-alone metering units.](#)

[IEC 61869-14, Instrument transformers – Part 14: Additional requirements for current transformers for DC applications.](#)

[IEC 61869-15, Instrument transformers – Part 15: Additional requirements for voltage transformers for DC applications.](#)

IEEE Std C37.92™, IEEE Standard for Analog Inputs to Protective Relays from Electronic Voltage and Current Transducers.[9,10](#)

IEEE Std C57.13™, IEEE Standard Requirements for Instrument Transformers.

~~IEC 61850-9-1, Communication networks and systems in substations –Part 9-1: Specific communication system mapping (SCSM) –Sampled values over serial unidirectional multidrop point-to-point link.~~

~~IEC 61850-9-2, Communication networks and systems in substations –Part 9-2: Specific communication system mappings (SCSM) –Sampled values over ISO/IEC 8802-3.~~

~~IEEE Std C37.1™, IEEE Standard Definition, Specification, and Analysis of Systems Used for Supervisory Control, Data Acquisition, and Automatic Control.[3, 4](#)~~

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3. Definitions, acronyms, and abbreviations

3.1 Definitions

No terms and definitions are listed in this standard.

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~~For the purposes of this document, the following terms and definitions apply. The Authoritative Dictionary of IEEE Standards Terms [B43]⁵ should be referenced for terms not defined in this clause.~~

~~**3.1.1 accuracy:** The designation assigned to an electronic current transformer, the current error and phase displacement of which remain within specified limits under prescribed conditions of use.~~

~~**3.1.2 digital output:** An optical or an electrical output interface at the merging unit. It supplies measuring instruments, meters, and protective or control devices with digitally coded time coherent sets of current and/or voltage data.~~

~~**3.1.3 electronic current transformer:** Electronic instrument transformer in which the output of the secondary converter, in normal conditions of use, is substantially proportional to the primary current and differs in phase from it by a known angle for an appropriate polarity of the connections.~~

~~**3.1.4 electronic instrument transformer:** Arrangement of current or voltage sensor(s) connected to transmitting systems and secondary converters for the purpose of supplying a signal proportional to the sensed quantity to measuring instruments, meters, and protective or control devices. In the case of a digital interface, this is accomplished by using a merging unit for a set of electronic instrument transformers.~~

¹¹IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

⁵~~The numbers in brackets correspond to those in the bibliography in Annex B.~~

~~**3.1.5 excitation characteristic:** A graphical or tabular presentation of the relationship between the root-mean-square (RMS) value of the exciting current and a sinusoidal RMS voltage applied to the secondary terminals of a current transformer, the primary and other windings being open-circuited, over a range of values~~

~~**3.1.6 merging unit:** Physical unit used to do the time-coherent combination of the current and/or voltage data coming from the secondary converters. The merging unit can be part of one of the transformers in the field or may be a separate unit, for example, in the control room.~~

~~**3.1.7 power supply:** Power source to the primary and/or secondary converter and/or primary current sensor.~~

~~**3.1.8 primary converter:** Arrangement that converts the signal coming from one or more primary current sensors into a signal suitable for the transmitting system.~~

~~**3.1.9 primary current sensor:** Electric, electrical, optical, or other device intended to transmit a signal corresponding to the current flowing through the primary terminals to the secondary converter, either directly or by means of a primary converter.~~

~~**3.1.10 rated burden:** The value of the burden on which the accuracy requirements are based.~~

~~**3.1.11 rated insulation level:** The combination of voltage values that characterizes the insulation of a transformer with regard to its capability to withstand dielectric stresses.~~

~~**3.1.12 rated secondary output:** For analog output, it is the root-mean-square (RMS) value of the secondary voltage output at the fundamental frequency on which the performance of the electronic current transformer is based. Rated secondary output for digital output is the hexadecimal number representing the rated primary current on the digital side.~~

~~**3.1.13 Rogowski coil:** Specially designed air-core mutual inductor whose output voltage is proportional to the time rate of change of current of the input (primary) current.~~

~~3.1.14 secondary converter:~~ Arrangement that converts the signal transmitted through the transmitting system into a quantity proportional to the primary current being measured by the sensor to supply measuring instruments, meters, and protective or control devices. For electronic current transformers with analog output, the secondary converter directly supplies measuring instruments, meters, and protective or control devices. For electronic instrument transformers with digital output, the secondary converter is generally connected to a merging unit before supplying the secondary equipment.

3.2 Acronyms and abbreviations

CT current transformer

~~CTI coordinating time interval~~

ECT electronic current transformer

EMC electromagnetic compatibility

~~EVT electronic voltage transformer~~

GIS gas insulated switchgear

IED intelligent electronic device

LPCT low-power passive current transformer

PCB printed circuit board

rms root mean square

~~RC Rogowski coil~~

~~RIV radio interference voltage~~

~~SCSM specific communication service mapping~~

4. Review of conventional current sensor technologies

4.1 Iron-core current transformers

This [subclause guide](#) compares Rogowski coil characteristics with conventional bushing-type iron-core current transformers (CTs). The CT [circuit diagram is illustrated in Figure 1](#), the CT [connections and equivalent circuits is are](#) shown in Figure 2, [and in an equivalent circuit with the CT parameters scaled to the secondary is presented in](#) an ideal CT [operates will operate](#) with an ampere-turn balance [Equation (1)]:

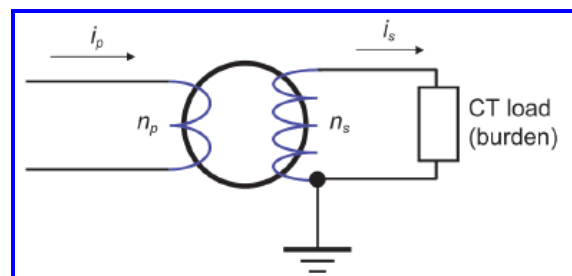
$$i_p \times n_p = i_s \times n_s \quad (1)$$

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$$i_p \cdot n_p = i_s \cdot n_s \quad (1)$$

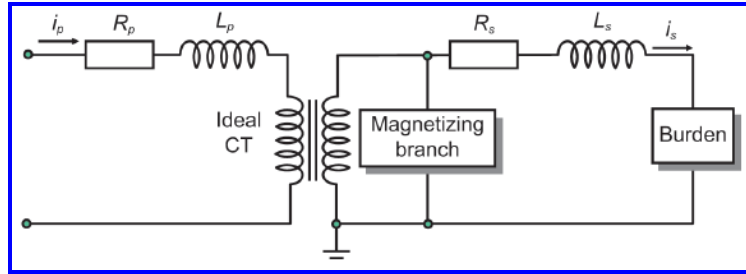
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An actual CT does not behave as an ideal transformer. The CT secondary voltage is generated by the rate of flux change in the core. To produce flux in the CT core, magnetizing (exciting) current is [required needed](#). This magnetizing current introduces ratio and phase errors. [The equation of an actual CT can be written as Equation \(2\):](#)



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Figure 1—CT circuit diagram



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Figure 2 – CT equivalent circuit

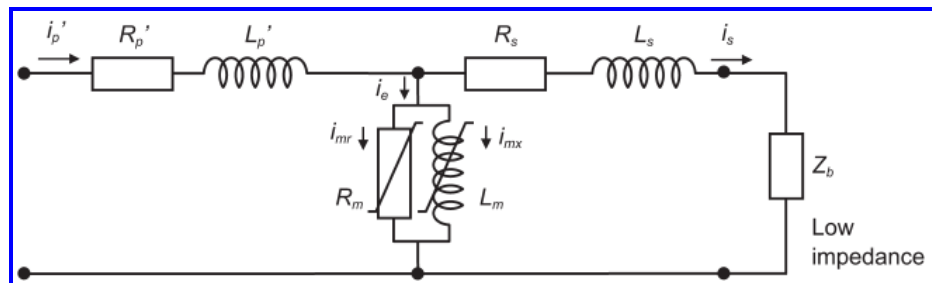
The equation of an actual CT can be written as Equation (2):

$$\vec{I}_p = \vec{I}_s + \vec{I}_e \quad (2)$$

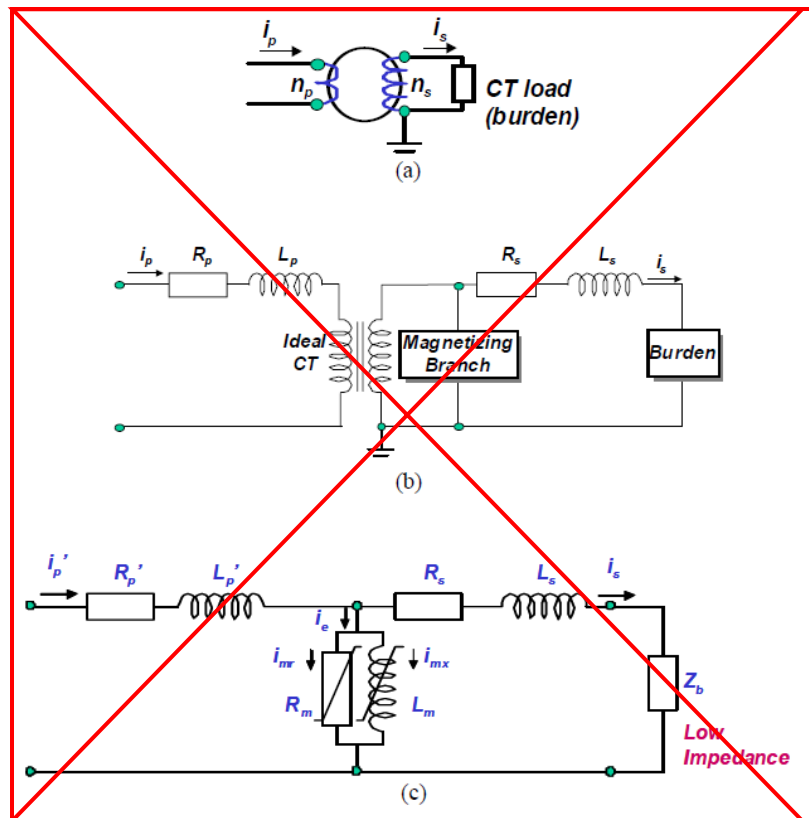
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~~$$\vec{I}_p' = \vec{I}_s + \vec{I}_e \quad (2)$$~~

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i_p, i_s is the primary and secondary currents, [respectively](#)

n_p, n_s is the number of primary and secondary turns, [respectively](#)

R_p, L_p is the primary winding resistance and leakage inductance, [respectively](#)

R_s, L_s is the secondary winding resistance and leakage inductance, [respectively](#)

i_p' is the primary current referred to the secondary

R_p', L_p' is the primary winding resistance and leakage inductance referred to the secondary, [respectively](#)

i_e is the exciting current

L_m is the magnetizing inductance

i_{mx} is the magnetizing current, reactive component

i_{mr} is the magnetizing current, active component

R_m is the iron loss resistance

Z_b is the CT load (burden), including lead resistance

Figure 3—CT Current transformer principle of operation: (a) connections, (b) equivalent circuit, and (c) equivalent circuit, parameters scaled to the secondary

In most cases, for relay applications, satisfactory CT transient analysis can be performed by simplifying the CT equivalent circuit of ~~part c) of~~ Figure 3 to an equivalent circuit 2-as shown in Figure 4 3. The CT parameters R_p , L_p , and R_m can be neglected. Leakage inductance L_p can be neglected for CTs that have fully distributed secondary winding. Inter-winding capacitance can also be neglected at the frequencies of interest to protection studies. Generally, CT parameters that are ~~should be~~ represented include magnetizing branch L_m (a non-linear element) and the CT burden. Typically, microprocessor-based relays are low burden devices having a low resistance as seen by the CT and can be neglected. Therefore, the CT burden R_b may be represented only by the CT wire resistance and lead resistance.

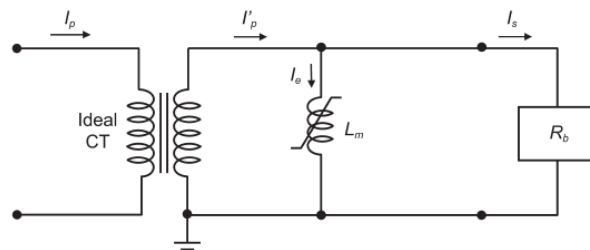


Figure 4 3—Simplified CT representation for transient analysis

IEEE Std C57.13 specifies CT behavior only under steady-state and symmetrical fault conditions. The CT ratio error is specified to be $\pm 10\%$ or less for fault currents up to 20 times the CT rated current and up to the standard burden. CTs are designed to meet this requirement. But if a symmetric fault current ~~exceeds 20~~ times the ~~CT-rated current~~ burden exceeds the standard or if the fault current is smaller but contains dc offset (asymmetric current), the CT ~~may will~~ saturate. The secondary current ~~distorts~~ will be distorted and the current rms value ~~reduces~~ will be reduced. Figure ~~5~~ 4 demonstrates levels of a 600/5 A, C100 CT saturation for symmetric fault currents. The CT loading consists of the CT wire resistance of $0.5\ \Omega$ and standard burden of $1\ \Omega$. The CT ratio errors calculated based on the value of rms current at different saturation levels are correlated to CT operating points on the V-I curve shown in the insert of Figure ~~5~~ 4. This CT meets the accuracy class specified by IEEE Std C57.13 since at 20 times the CT rated current, the CT error is 7%, which is less than specified 10%. However, at higher fault currents, this error rapidly increases as shown in Figure ~~5~~ 4. Rogowski coils do not have this limitation.

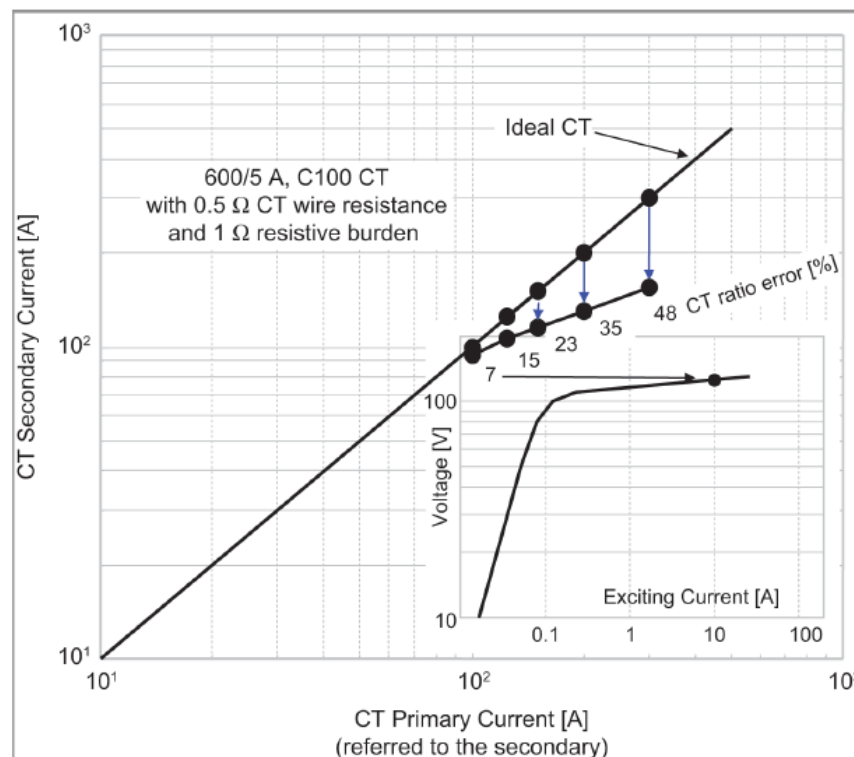


Figure ~~5~~ 4—Example of a 600/5 A, C100 CT saturation characteristic

~~current transformer characteristics~~

4.2 Gapped-core current transformers

Iron-core current transformers can be designed without or with air gap in the core. In non-gapped-core CTs, a remanent flux may remain in the core after a fault current interruption. In grain-oriented iron-core CTs, when saturated, a remanent flux of 70% to 80% of saturation flux may remain in the core. Very little of the remanent flux can dissipate during normal CT operation, and it ~~remains will remain~~ in the core until the CT is demagnetized. An air gap in the core reduces remanent flux. Typically, air gaps of 0.0001 through 0.0003 per unit of mean length of the magnetic path reduce remanent flux to the acceptable level. Main advantages of gapped-core CTs are smaller CT size and smaller core over sizing requirements to avoid saturation. Disadvantages are increased CT phase error and the need for more time to allow stored energy to dissipate.

4.3 Linear couplers

Traditionally, the problem of CT saturation was eliminated using linear couplers. A linear coupler (air-core mutual inductor) produces output voltage proportional to the derivative of the primary current. Because no ferromagnetic material exists, linear couplers do not saturate. The number of secondary turns is much greater than in a conventional CT. The linear coupler V-I characteristic is a straight line having a slope of about 5 V per 1000 ~~A ampere~~-turns at the rated frequency. By agreement between manufacturer and customer, the linear coupler V-I characteristic can have any slope.

For differential protection of bus bars, linear couplers are typically connected in a voltage-differential circuit. For normal load or external-fault conditions, the sum of the voltages induced in the secondary is zero, except for the very small effects caused by different coil sensitivities resulting from manufacturing tolerances.

~~Linear couplers will not be damaged and do not create a high voltage hazard for personnel when the secondary is open-circuited.~~

5. Rogowski coil ~~coils~~

5.1 Theory of operation

Rogowski coils were introduced in 1912 to measure magnetic fields. At that time, they could not be used for current measurements, since the coil output voltage and the deliverable output power were not sufficient to drive electro-mechanical measuring and protection equipment (relays). ~~With today's low-burden~~ Microprocessor-based devices consume less power than traditional electro-mechanical protection and measurement equipment, making high-power current sensors unnecessary and Rogowski coils became suitable for metering and relaying ~~such~~ applications.

In a simple instance, a Rogowski coil consists of wire wound on a non-magnetic core ($\mu_r = 1$). The coil is placed around the conductors whose currents are to be measured as shown in Figure 6 5. ~~Design criteria for~~ Rogowski coil design requires ~~coils include~~ that the core has a constant cross-section S and ~~that~~ the wire is wound perpendicular on the middle line l (dashed line in Figure 6 5) with constant turn density n . For this design example, formulas to calculate performance characteristics are presented next.

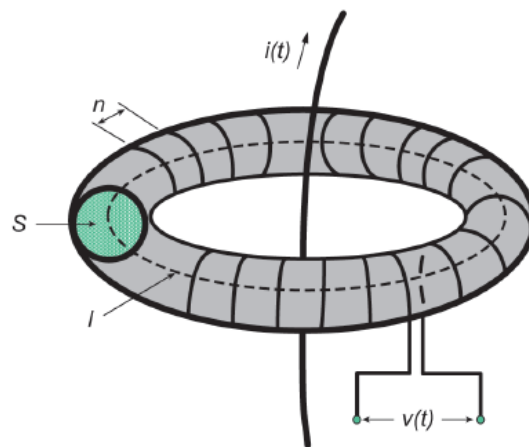


Figure 6 5—Principle of Rogowski coil design

The voltage induced in the coil is defined by Equation (3).

$$v(t) = -\frac{d\psi}{dt} \quad (3)$$

Where [the](#) ψ is total flux in the coil. The total flux ψ when applying Rogowski coil design criteria is defined by Equation (4).

$$\psi = \mu_0 \mu_r n \oint_l dl \oint_s \vec{H} \cdot d\vec{S} \quad (4)$$

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$$\Psi = \mu_0 \mu_r n \oint_l dl \int_s \vec{H} d\vec{S} \quad (4)$$

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where

l is the [mean](#) core length

n is the winding density (windings per unit length)

S is the core cross-section area

H is the magnetic field intensity

μ_0 is the permeability of air

μ_r is the relative permeability of the core material

[Further](#), ~~Furthermore~~ Equation (5) applies.

$$d\vec{S}dl = dSd\vec{l} \quad (5)$$

Now, Equation (4) can be rewritten as Equation (6):

$$\psi = \mu_0 \mu_r n \int_s dS \oint_l \vec{H} \cdot d\vec{l} = \mu_0 \mu_r n \int_s i(t) dS = \mu_0 \mu_r n Si(t) \quad (6)$$

[\(New\)](#)

$$\Psi = \mu_0 \mu_r n \oint dl \int \vec{H} d\vec{S} \quad (6)$$

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The coil output voltage (the unloaded, open-circuited) is then:

$$v(t) = -\mu_0 \mu_r n S \frac{di(t)}{dt} = -M \frac{di(t)}{dt} \quad (7)$$

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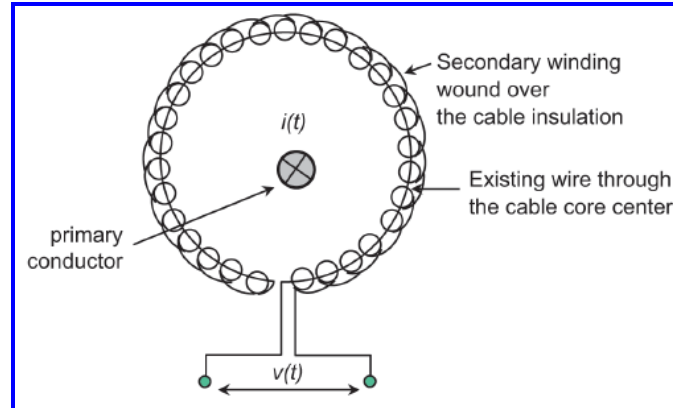
$$v(t) = -\mu_0 \mu_r n S \frac{di(t)}{dt} = -M \frac{di(t)}{dt} \quad (7)$$

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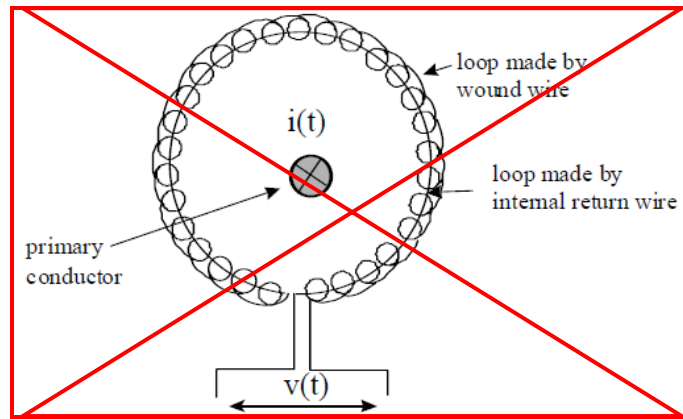
then

$$M = \mu_0 \mu_r n S \quad (8)$$

For an ideal Rogowski coil, the mutual inductance M is independent of the conductor location inside the coil loop. The Rogowski coil output voltage is proportional to the rate of change of the measured current and its frequency. To reduce ~~minimize~~ the influence of nearby conductors carrying high currents, Rogowski coils may be ~~are~~ designed with two wire loops connected in the electrically opposite direction. Ideally, this design cancels ~~will-cancel~~ the induced voltages due to external magnetic fields. In practice, complete cancellation is difficult to achieve when the external fields contain severe gradients and curvature. Two loops can be formed by making one winding and returning the wire through the center of the winding as shown in Figure 7 ~~6~~. The second method is to make the second winding on top of the first winding wound in the opposite direction. The third method is to make two separate windings of identical design and having identical number of turns wound in the opposite direction and located next to each other as illustrated in Figure 8 ~~7~~.



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Figure 7 6—Rogowski coil with the return wire through the winding center

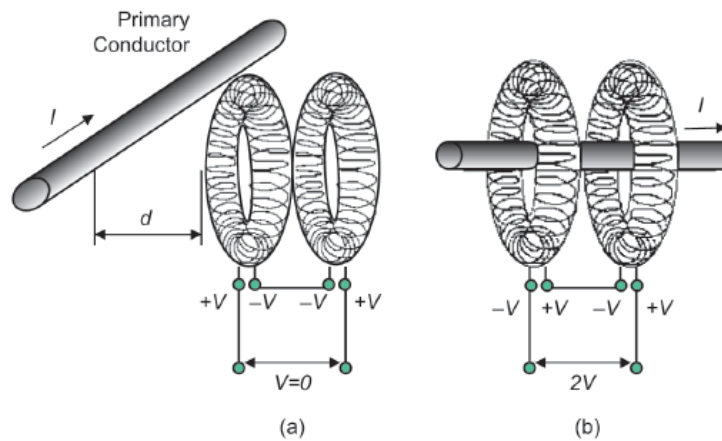
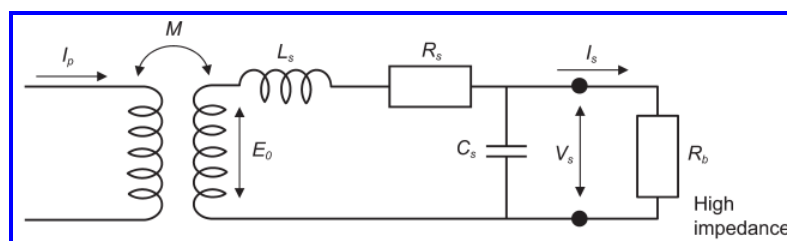
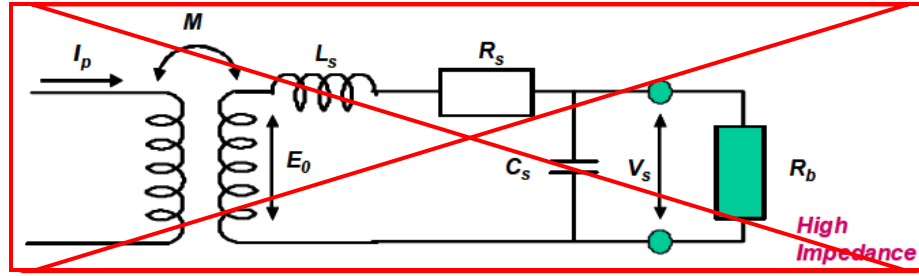


Figure 8-7—The impact of primary conductor location on Rogowski coil output voltage: (a) induced voltages from an external conductor are canceled at and (b) the coil output, (b) included conductor passing through the coil bushing induces voltages from the conductor embraced by the coil are summed at the coil output in both windings

Rogowski coil equivalent circuit for resistive load R_b is shown in Figure 9-8. The capacitance C_s is composed principally of the coil shielding capacitance, the output cable capacitance, and some stray capacitance. The distributed turn-to-turn capacitance of the coil is not shown and can be neglected. Both distributed turn-to-turn capacitance and C_s capacitance are small at the frequencies of concern for relaying applications application and can be neglected. A Rogowski coil vector diagram is depicted shown in Figure 10-9.



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Figure 9 8—Rogowski coil equivalent circuit

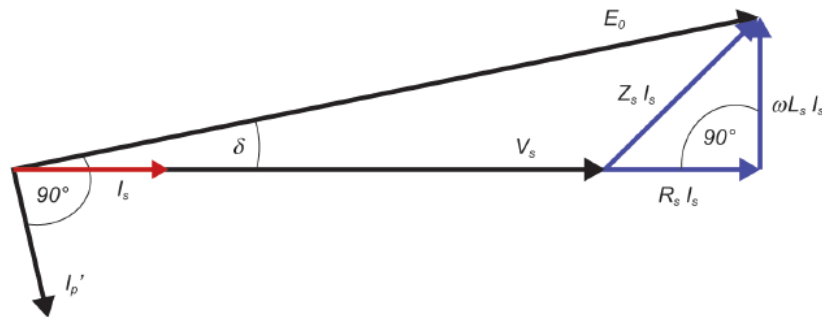


Figure 10 9—Rogowski coil vector diagram (for resistive load)

Rogowski coil parameters R_s and L_s cause a difference in the output voltage magnitude and phase angle between unloaded Rogowski coil (open circuited) and Rogowski coil loaded by burden R_b , which can be calculated as [Equation \(9\) and Equation \(10\)](#). follows:

$$\vec{V}_s = \vec{E}_0 - (R_s + j\omega L_s) \vec{I}_s \quad (9)$$

$$I_s = \frac{V_s}{R_b} \quad (10)$$

Magnitude difference ε is defined [in](#) ~~by~~ Equation (11):

$$\varepsilon = \frac{E_0 - V_s}{E_0} \quad (11)$$

Since $\omega L_s \ll R_b + R_s$ and $R_s \ll R_b$, magnitude difference ε can be approximately determined by Equation (12).

$$\varepsilon = 1 - \frac{R_b}{\sqrt{(R_b + R_s)^2 + (\omega L_s)^2}} \approx 1 - \frac{R_b}{R_b + R_s} \approx \frac{R_s}{R_b} \quad (12)$$

(New)

~~$$\varepsilon = 1 - \frac{R_b}{\sqrt{(R_b + R_s)^2 + (\omega L_s)^2}} \approx 1 - \frac{R_b}{R_b + R_s} \approx \frac{R_s}{R_b} \quad (12)$$~~

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Phase difference, in radians, δ is defined by Equation (13).

$$\begin{aligned} \tan \delta &= \frac{\omega L_s}{R_b + R_s} \\ \delta &= \arctan \left(\frac{\omega L_s}{R_b + R_s} \right) \end{aligned} \quad (13)$$

(New)

~~$$\begin{aligned} \tan \delta &= \frac{\omega L_s}{R_b + R_s} \\ \delta &= \arctan \left(\frac{\omega L_s}{R_b + R_s} \right) \end{aligned} \quad (13)$$~~

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Note, the above accuracy approximation is for the Rogowski coil only. It does not take into account manufacturing variations of the coils, temperature effects on the coils, or the accuracy of the digital signal processing electronics to which the coils are connected.

5.2 Rogowski coil designs

Rogowski coils may have various ~~be designed and made having~~ shapes including ~~that include~~ round, oval, rectangular, ~~tear-drop~~, and an open-ended fork. Generally, for applications of protection relaying, the common shapes used are round and oval. The coils may be made of rigid materials, or of flexible materials resembling coaxial cable or belt-like in nature. Coils can be made as non-split core, cores ~~or,~~ alternatively, ~~as openable split-core construction. The cross-sectional shape upon~~ ~~on~~ which the coil is formed is generally either circular or rectangular. Other cross-sectional shapes are possible ~~although generally less practical.~~