



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

IEEE Power Engineering Society

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Power System Relaying Committee

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Abstract: 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 RCs for the more common protection schemes are addressed.

Keywords: current sensor, current transformer, relay protection, Rogowski coil

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Introduction

This introduction is not part of IEEE Std C37.235-2007, 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 by conventional CTs because of saturation, size, and weight. However, unlike CTs that produce secondary current proportional to the primary current, Rogowski coils produce output voltage that is a scaled time derivative $di(t)/dt$ 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 this topic. 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.

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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 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 RCs for protective relaying purposes. It provides 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 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.

¹ Information on references can be found in Clause 2.

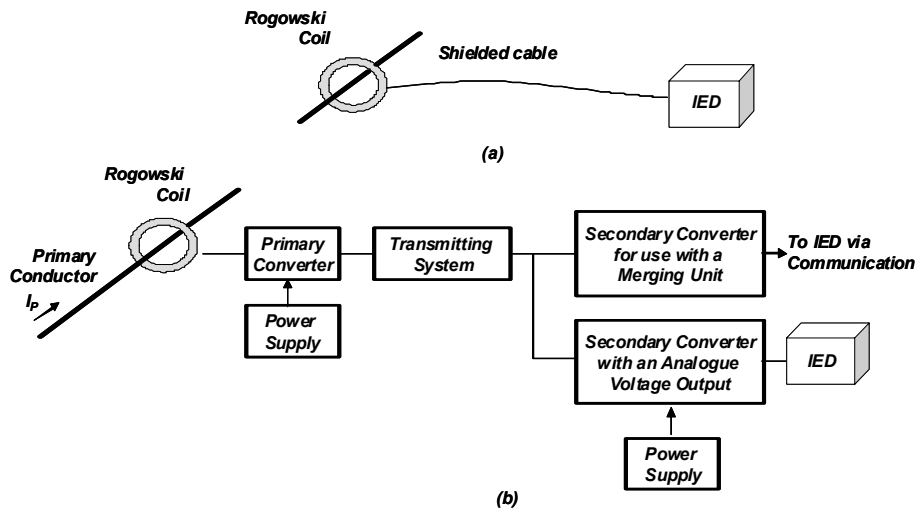


Figure 1—Application of Rogowski coils used for protective relaying purposes

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 60044-8, Instrument transformers—Part 8: Electronic current transformer.²

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}

IEEE Std C37.92™, IEEE Standard for Analog Inputs to Protective Relays from Electronic Voltage and Current Transducers.

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

² IEC publications are available 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 (<http://www.ansi.org/>).

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3. Definitions, acronyms, and abbreviations

3.1 Definitions

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.

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

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

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
PCB	printed circuit board
RC	Rogowski coil
RMS	root mean square
RIV	radio interference voltage
SCSM	specific communication service mapping

4. Review of conventional current sensor technologies

4.1 Iron-core current transformers

This guide compares Rogowski coil characteristics with conventional bushing-type iron-core current transformers (CTs). The CT connections and equivalent circuits are shown in Figure 2.

An ideal CT will operate with an ampere-turn balance [Equation (1)]:

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

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 needed. This magnetizing current introduces ratio and phase errors. The equation of an actual CT can be written as Equation (2):

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

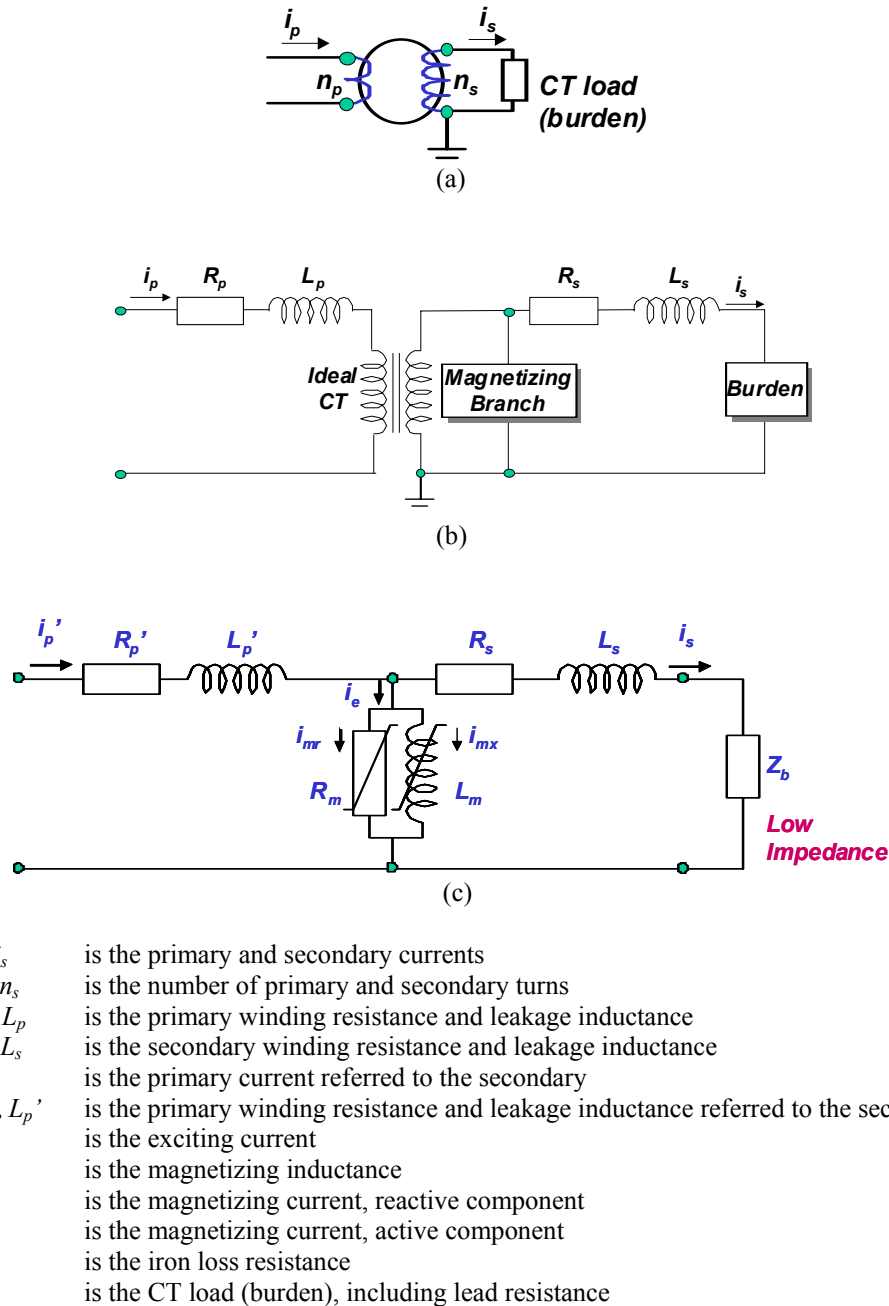


Figure 2—Current transformer principle of operation: (a) connections, (b) equivalent circuit, and (c) equivalent circuit, parameters scaled to the secondary

In most cases, for relay applications, satisfactory CT transient analysis can be performed by simplifying the CT equivalent circuit of part c) of Figure 2 as shown in Figure 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. Interwinding capacitance can also be neglected at the frequencies of interest to protection studies. Generally, CT parameters that should be represented include magnetizing branch L_m (a nonlinear 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.

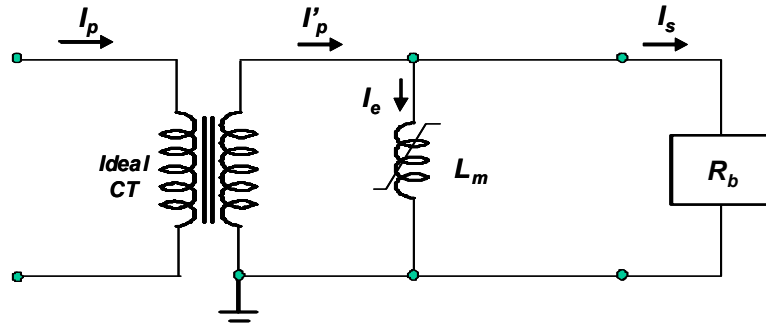


Figure 3—Simplified CT representation for transient analysis

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 or if the fault current is smaller but contains DC offset (asymmetric current), the CT will saturate. The secondary current will be distorted, and the current RMS value will be reduced. Figure 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 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 4. Rogowski coils do not have this limitation.

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 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.

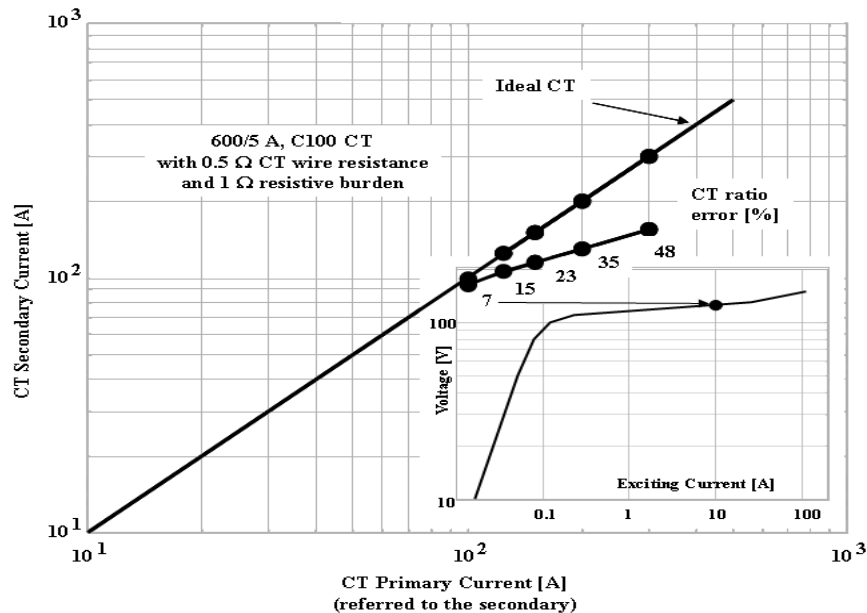


Figure 4—600/5 A, C100 current transformer characteristics

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 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 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 electromechanical measuring and protection equipment (relays). With today's low-burden microprocessor-based protection and measurement equipment, Rogowski coils became suitable for such applications.