COMPARATIVE PERFORMANCE CHARACTERISTICS OF CURRENT TRANSFORMERS AND NON-CONVENTIONAL CURRENT SENSORS

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ABSTRACT
This paper compares operating characteristics of non-conventional current sensors, Rogowski Coils, and conventional iron-core current transformers for protective relaying applications.

INTRODUCTION
Rogowski Coils (RCs) are transformers that operate on the same principles as conventional iron-core current transformers (CTs). The main difference between RCs and CTs is that RC windings are wound over an air core, instead of over an iron core. As a result, RCs are linear since the air core cannot saturate. However, the mutual coupling between the primary conductor and the secondary winding in RCs is much smaller than in CTs. Therefore, Rogowski Coil output power is small, so they cannot drive currents through the low-resistance burden like CTs are able to drive. Rogowski Coils can provide input signals for microprocessor-based devices that provide a high input resistance and they practically measure voltage across the RC secondary output terminals.

In general, Rogowski Coil current sensors have performance characteristics that are favorable when compared to conventional CTs. These characteristics include high measurement accuracy and a wide operating current range allowing the use of the same device for both metering and protection. In addition, Rogowski Coils make protection schemes possible that were not achievable by conventional CTs because of saturation, size, weight, and/or difficulty encountered when attempting to install current transformers around conductors that cannot be opened.

Rogowski Coils can replace conventional CTs for protection, metering, and control. RCs have been applied at all voltage levels (low, medium, and high voltage). However, unlike CTs that produce secondary current proportional to the primary current, Rogowski coils produce output voltage that is a scaled time derivative \(\text{d}i(t)/\text{d}t\) of the primary current. Signal processing is required to extract the power frequency signal for phasor-based protective relays and microprocessor-based equipment must be designed to accept these types of signals.

COMPARATIVE ANALYSIS

Principle of Operation
Conventional iron-core current transformers (CT) are typically designed with rated secondary currents of 1 A or 5 A and low impedance burden of several ohms. ANSI/IEEE Standard C57.13™-2008 specifies CT accuracy class for steady state and symmetrical fault conditions. Accuracy class of the CT ratio error is specified to be ±10% or better for fault currents up to 20 times the CT rated current and up to the standard burden (maximum ohm value of burden that can be connected to the CT secondary). 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 reduced.

Traditional Rogowski Coils (RC) consist of a wire wound on a non-magnetic core \((\mu_r=1)\). The coil is then placed around conductors whose currents are to be measured. New designs may use printed circuit boards (PCB) with imprinted windings on the board (see Figure 1).

Because RCs use air core to wind the secondary windings, mutual coupling between the primary and secondary windings is weak. Because of weak coupling, to obtain quality current sensors, two main criteria must be met when designing Rogowski Coils:

1. The Rogowski Coil output signal should be independent of the primary conductor position inside the coil loop,
2. The impact of nearby conductors that carry high currents on the Rogowski Coil output signal should be minimal.

Figure 1 Rogowski Coil
To satisfy the first criteria, mutual inductance \( M \) must have a constant value for any position of the primary conductor inside the coil loop. This can be achieved if the windings are wound on a core that has a constant cross-section \( S \) and wound perpendicular on the middle line \( l \) (dashed line in Figure 1) with constant turn density \( n \). Mutual inductance \( M \) is defined by the formula:

\[
M = \mu_0 \cdot n \cdot S
\]

\( \mu_0 \) is permeability of air.

The output voltage is proportional to the rate of change of measured current as given by the formula:

\[
V_s(t) = -M \frac{di_p(t)}{dt}
\]

Because RC primary and secondary windings are weakly coupled, to prevent the unwanted influence from nearby conductors carrying high currents, RCs are designed with two wire loops connected in electrically opposite directions. This cancels electromagnetic fields coming from outside the coil loop. One or both loops can consist of wound wire. If only one loop is constructed as a winding, then the second wire loop can be constructed by returning the wire through or near this winding. If both loops are constructed as windings, then they must be wound in opposite directions. In this way, the RC output voltage induced by currents from the inside conductor(s) will be doubled.

**Equivalent Circuits**

Figure 2 shows the equivalent circuit of an iron-core current transformer. Magnetizing current \( I_e \) introduces amplitude error and phase error. Since the CT iron-core has a non-linear characteristic (it saturates at high currents), when it saturates, the magnetizing current increases and the secondary current seen by the relay decreases. This may negatively impact relay performance, resulting in delayed operation, non-operation, or unwanted operation.

**Designs**

Rogowski Coils may be designed with different shapes such as round and oval. The coils may be made of rigid or flexible materials. Coils can be made as non-split style, or alternatively as split-core construction that can be opened to assemble around a conductor that cannot be opened. The cross-sectional shape upon which the coil is formed is generally either circular or rectangular.

Rigid RCs have higher accuracy than flexible RCs and may be designed using PCBs as window (non-split-core) type or split-core type. PCB Rogowski Coils can be designed using one or two printed circuit boards to imprint windings. Designs using one PCB have both windings imprinted on each PCB, wound in opposite directions.

As the Rogowski Coil signal is a scaled time derivative, \( \frac{di(t)}{dt} \) of the primary current, signal processing is required to extract the power frequency signal for phasor-based protective relays. This may be achieved by integrating the Rogowski Coil output signals, using non-integrated Rogowski Coil output signals.

Integration of the signals can be performed in the relay (by analog circuitry or by digital signal processing techniques) or immediately at the coil. To use the Rogowski Coil non-integrated analog signal, it is necessary to perform the signal corrections for both the magnitudes and phase angles. For applications for phasor-based protective relaying purposes, the Rogowski Coil secondary signal must be scaled by magnitude and phase-shifted for each frequency.

Figure 3 shows the equivalent circuit of a Rogowski coil. The phase angle between the RC primary current and the secondary voltage is nearly 90° (displaced from 90° by a small angle caused by the coil inductance \( L_s \)).

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Interface to relays

Current transformers require heavy gauge secondary wires for interconnection to relays and other metering and control equipment (Figure 5). The wire resistance adds to the CT burden and negatively impacts the CT transient response and may cause the CT saturation at fault currents. In addition, terminal blocks are required so the CT secondary can be shorted. Hazardous voltages can be generated when the CT secondary circuit is opened while load current is flowing. Other CT disadvantages include large size and weight. For example, Figure 3 shows a 2000/5 A, C800 class CT connected to a relay. This CT has the height of the core when wound 10 cm and weighs 90 kg.

Rogowski Coils may be connected to relays via twisted pair shielded cables with connectors (Figure 6). Terminal blocks are not required since the coil output signal is a minimal voltage from the safety aspect, and this voltage does not increase when the secondary circuit is open. Figure 6 shows Rogowski Coil width and weight are much smaller than that of a CT. This coil has the same size window as the CT from Figure 5, but can be applied for significantly larger current range than the CT.

APPLICATIONS FOR RELAY PROTECTION

Rogowski coils may replace conventional current transformers for metering and protection. IEEE Std C37.235-2007 provides guidelines for the application of Rogowski Coils used for protective relaying purposes.

Differential Protection

Traditional differential protection schemes that use conventional CTs require stabilization for external faults or disturbances that cause CT saturation since it is not feasible to avoid CT saturation under all circumstances. Even where CTs are of similar design and the leads between each set of CTs and the differential relay are balanced, the CTs will not saturate to the same degree at the same time because of remanent flux. Figure 7 illustrates differential current error caused by the CT saturation.
To avoid misoperation for through-faults, the percentage restrained differential element is typically designed with two or more slope characteristics.

Protection solutions based on Rogowski Coils improve protection performance because these schemes sense and operate for low In-Zone fault currents and provide high security for Out-of-Zone faults (exceeding 60 kA). The protection algorithms are simple since Rogowski Coils do not saturate. In addition, multiple slopes are not required. Transformer inrush currents are determined using current waveform recognition algorithm. Protection setting can be set at lower current thresholds compared to conventional solutions based on CTs. The load tap changer position is also used by the relay to adaptively adjust transformer ratio allowing set threshold to be further reduced.

Rogowski coils made possible differential protection of electric arc furnace (EAF) transformers that were not applied in the past — due to the difficulty in designing current transformers for load currents of 60 kA or more. The Rogowski Coil protection system was implemented for the first time on two 90 MVA, 34.5/1 kV EAF transformers equipped with a LTC. Primary RCs were designed as non-split-core style. Because of high secondary currents exceeding 50 kA, the EAF transformer secondary has a delta closure consisting of two water-cooled tubes per phase each of 23 cm diameter. Since the secondary tubes cannot be opened, the RCs were designed in split-core styles (Figure 8).

Today there are a number of differential protection schemes developed and implemented for protection of power transformers, lines, cables, and busbars. Traveling Wave-based Protection

Rogowski coils also make possible protection solutions that are not feasible using conventional CTs such as traveling wave (TW) based protection. For TW-based protective relaying, all lower frequency components of the line current are not relevant. Rogowski Coils can be designed to have frequency response exceeding 100 MHz. Since they inherently amplify high frequency components, Rogowski Coils generate a pulse resulting from the step change in current magnitudes caused by TW current reflections and refractions. The protection and fault location algorithms use the time difference between successive pulses and their polarity.

REFERENCES