

Differential Protection

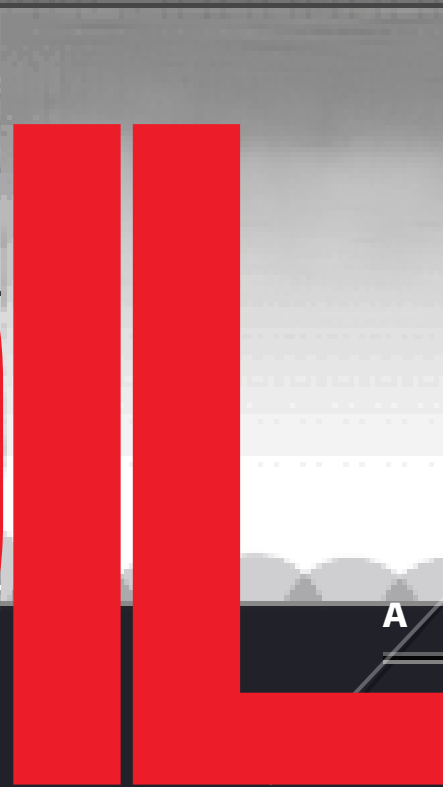
Rogowski

COIL

Designs

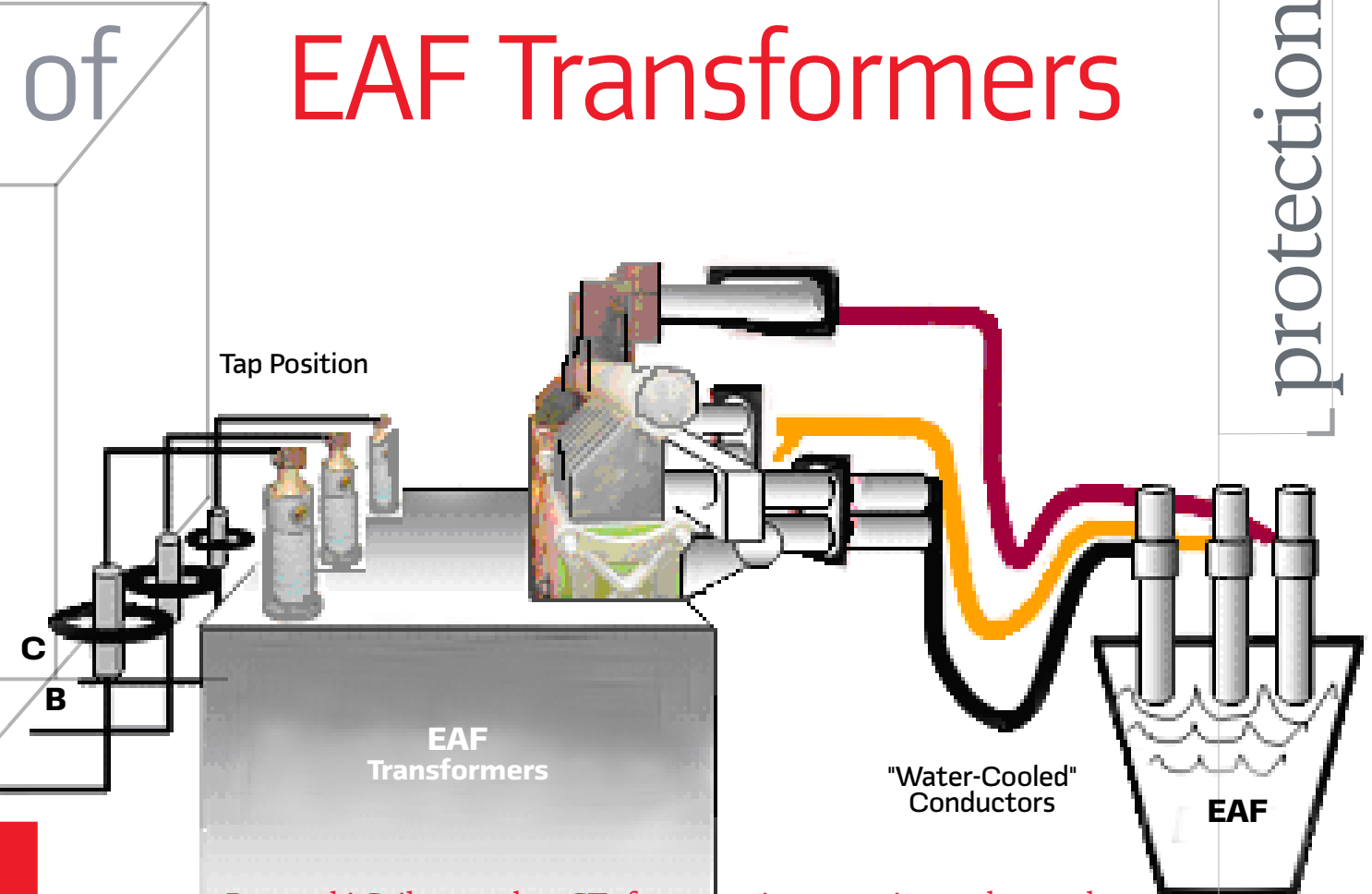


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EAF Transformers



protection

- Rogowski Coil can replace CTs for protection, metering, and control purposes.
- Rogowski Coils are accurate, small, light, and easy to install.
- They do not saturate.
- Rogowski Coils provide superior differential protection for power transformers, substation busbars, generators, and large motors.
- Rogowski Coils make it possible to set protection levels to lower fault current thresholds (increased sensitivity of the scheme) while preserving high stability of the scheme for Out-Of-Zone faults.

THIS ARTICLE PRESENTS ADVANCED RELAY PROTECTION SYSTEMS that incorporate Rogowski Coil current sensors and multifunction relays. Rogowski coils are accurate and do not saturate, making it possible to set protection levels to lower fault current thresholds (increased sensitivity of the scheme) while preserving high stability of the scheme for through faults. This reduces the stress on the protected equipment during faults. Even though Rogowski Coils are low power sensors, the protection system is immune to external electromagnetic fields. The schemes are simple, user friendly and require less wiring and space than conventional solutions.

The Rogowski coil (RC) current sensors presented here operate on the same principle as coils that were first introduced in 1912 for magnetic field measurements. At that time, the coils could not be used for relay protection because their output power was not sufficient to drive electro-



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mechanical relays. However, with today's microprocessor-based equipment, RC current sensors are suitable for such applications. Current transformers have traditionally been 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. This article presents novel solutions for differential protection of power transformers, busbars, generators, and large motors. The initial projects included differential protection of EAF transformers, which are the first such applications in the U.S. and most likely in the world.

Rogowski Coil Principle of Operation

For comparative analysis of Rogowski coils and iron-core current transformers (CTs), equivalent circuits and vector diagrams for resistive load are shown in Figure 1. The CT is a non-linear element that saturates whenever flux inside the CT core exceeds the saturation level, resulting in distorted and reduced secondary current that may cause relay misoperation. However, CTs cannot saturate immediately upon the fault inception. The time that it takes to begin the CT saturation is called time-to-saturation. Manufacturers use different algorithms to achieve proper relay performance during the CT saturation or design relays to operate prior to the CT saturation. Remanent flux in the CT core can also cause relay misoperation. To reduce remanent flux, gapped-core CTs have been used.

Traditional RCs consist of a 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 (Equation 1) where μ_0 is the magnetic permeability of air, n is the winding density (turns per unit length), S is the core cross-section, and M is the mutual coupling.

A Rogowski Coil signal is a scaled time derivative, $di(t)/dt$ of the primary current instantaneous signal. To

use such signals with phasor-based protective relays, signal processing is required to extract the power frequency signal.

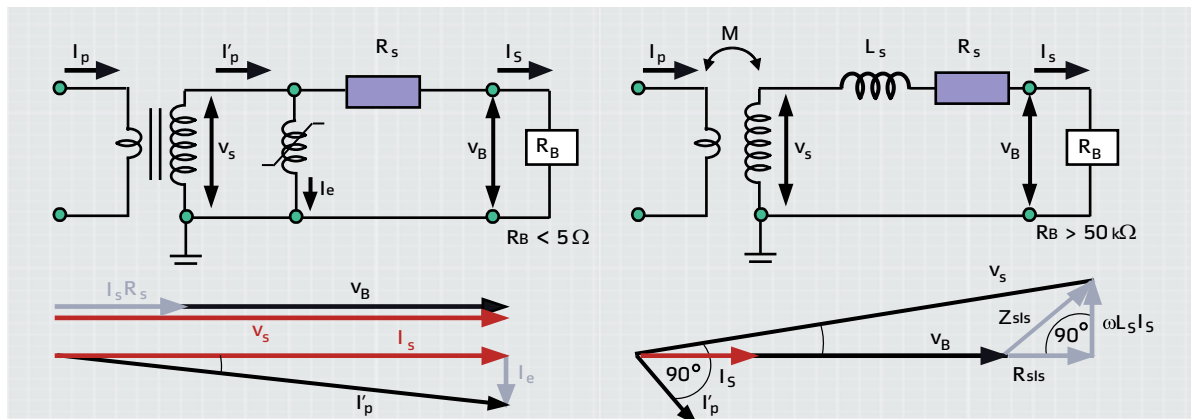
$$v(t) = -\mu_0 n S \frac{di(t)}{dt} = -M \frac{di(t)}{dt} \quad (1)$$

This may be achieved using one of the following methods: (a)-integrating the Rogowski Coil output signal, or (b)-using a non-integrated signal and perform signal processing to adjust magnitudes and phase shift signals 90°. For an ideal RC, measurement accuracy is independent of conductor location inside the coil loop. See Figure 2.

To prevent the unwanted influence of 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 on a non-magnetic core, 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. Rogowski Coils can also be connected in series to increase the output signal.

Influence from nearby conductors is one of the most important tests to determine the RC current sensor accuracy. The test was performed in a high power laboratory at a test current magnitude of 60 kARMS (Figure 4). Two RC current sensors were tested, RC1 was installed to measure the test current and RC2 was located next to the primary conductor to test the influence from the primary conductor. Since the induced signal in RC2 was very small, a x100 amplifier was used to increase the signal to the level acceptable to the recorder. The influence from the primary conductor was below 0.01%, verifying very good coil immunity to the

1 Current Transformer and Rogowski Coil Circuits & Vector Diagrams





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external magnetic fields. In most applications, RC current sensors will be installed at a distance from nearby conductors and the influence will be nearly zero.

Performance characteristic comparison between conventional bushing type iron-core CTs and Rogowski Coils is shown in Table 1.

Designs

The high precision Rogowski Coil design presented here consists of two printed circuit boards (PCBs) located next to each other. Each PCB contains one imprinted coil wound in opposite directions (clockwise and counter-clockwise). 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. High precision is obtained because the manufacturing process is computer controlled, providing accurate geometry of the coils. New RC designs use multi-layer PCBs, which provides for higher accuracy and more efficient manufacturing.

PCB Rogowski Coils can be designed with different shapes to adjust for the application and in "split-core" styles for installation without the need to disconnect the primary conductors. Figure 3a shows an encapsulated circular shape RC current sensor implemented on multi-layer PCBs. Three PCB RCs designed for a three-phase application are shown in Figure 3b. An oval shape split-core style RC current sensor, designed to enclose all three-phase conductors (for measurement of residual currents) or to enclose parallel conductors that carry heavy currents is shown in Figure 3c

Application of Rogowski Coils for Protective Relaying Purposes

Rogowski Coil applications for protective relaying purposes use the same rules as conventional iron-core current transformers. Because Rogowski Coils are accurate and linear (do not saturate) simplifications in protection

schemes and settings are possible. The Rogowski Coil applications for relay protection presented here include differential protection of power transformers, busbars, generators, and large motors.

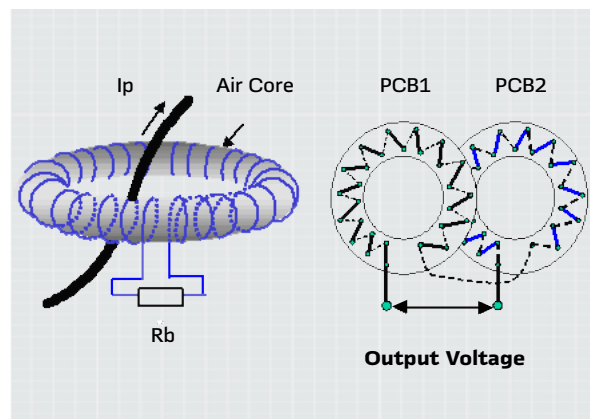
Differential Protection of Power Transformers

Figure 5 shows a traditional power transformer differential protection based on conventional CTs. The protection Zone is defined by the CT locations. A recognized problem of the CT-based protection schemes has been the CT saturation. For Out-Of-Zone faults, when the CTs saturate, false differential current is derived by the relay, which can cause unwanted relay operation (lack of stability). Manufacturers use different algorithms to achieve proper relay performance during the CT saturation or they may design relays to operate prior to the CT saturation. Remanent flux in the CT core can also cause relay misoperation. Rogowski Coils are linear and will not have remanence. This allows for improved relay performance or even protection scheme development that was not possible using CTs (such as differential protection of electric arc furnace transformers).

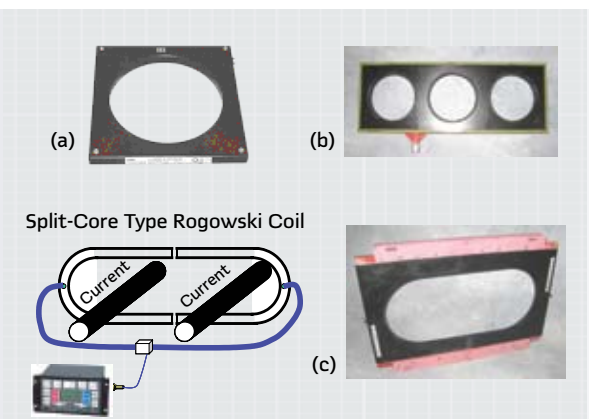
In steel facilities that use an electric arc furnace (EAF) to manufacture steel from scrap, the EAF transformer is one of the most critical pieces of electric power equipment in the plant. Differential protection schemes are not typically applied on EAF transformers due to the difficulty in providing current transformers (CTs) of sufficient rating for the secondary leads carrying currents of 60 kA or more.

The differential protection system presented here uses Rogowski Coil current sensors, and multifunction relays designed to accept the RC secondary signals. This novel protection system was implemented for the first time on two 90 MVA, 34.5/1 kV EAF transformers equipped with a 33-tap load tap changer (LTC). Both the primary and secondary RC sensors were located in the EAF vault. Primary RCs were designed as non split-core style. To

2 Principle of Rogowski Coil Design



3 PCB Rogowski Coil Design



PCB Rogowski Coils can be designed with different shapes to adjust for the application

Rogowski coils do not saturate making differential protection stable for through faults.

provide the required dielectric strength and the BIL at 34.5 kV voltage level, the RC current sensors were mounted around bushings. Because of high secondary currents exceeding 50 kA, the EAF transformer secondary has been designed with multiple parallel windings. To form a delta closure, two 9-inch water-cooled bus tubes have been used for each phase. The delta connection is closed external to the vault, so there are six of these bus tubes leaving the vault through an insulating wall assembly. The bus tube spacing for four outside tubes is the same (10-inch spacing between tube centers) and the middle two tubes are on 26-inch spacing. Because the RC can conveniently be designed for the application, the secondary RCs were designed with two different sizes (instead of one larger size), to optimize the installation design. Since the secondary tubes cannot be opened, the secondary RCs were designed in split-core.

Figure 6 shows the primary and secondary currents recorded during an EAF operation. Even though the currents are heavily distorted, the current waveforms are accurately reproduced. The relay's event recorder can be manually triggered to capture user-programmable data during operation of the EAF. Analysis of data records during a relatively flat bath point in the heating cycle have shown that the relay operating signal at that point results in a mismatch between the transformer primary and the secondary currents of less than 2% of rated current.

The first relay systems were put into service in late 2004. All these protection systems proved to offer a high level of dependability and stability. In the EAF applications, stability of the scheme is as important as dependability, since each EAF transformer experiences over 70 energizations a day. In

addition, at the beginning of the heating cycles, the currents are rapidly changing ON-OFF from zero to over 50 kA, are heavily unbalanced and distorted (harmonics), acting as Out-Of-Zone events that are much more severe than a typical utility substation transformer experiences with a downstream fault. The protection systems demonstrated exceptional stability that is literally tens of thousands of "Out-Of-Zone events" to a typical transformer. High dependability was proven by fast and successful clearing of several In-Zone faults that occurred on the transformer terminals. These resulted in minimal damage only requiring cleaning and allowed operations to resume in hours. Previously, without this system, when such faults occurred, EAF transformers and surrounding buswork had to be changed due to the extensive damage when using only time delayed overcurrent relays.

Differential Protection of Busbars, Generators, and Motors

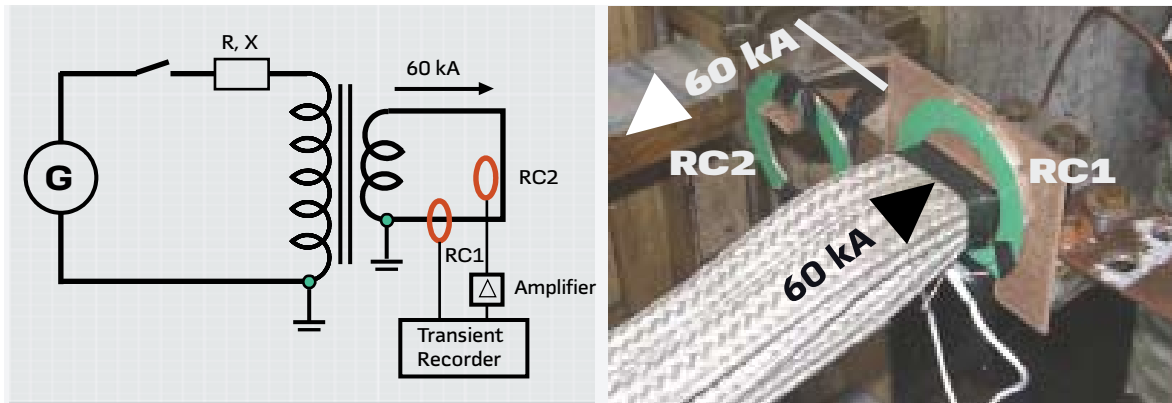
Short circuit currents at generators and substations may be very high causing extreme CT saturation, resulting in substantial CT secondary current distortion. Differential protection systems must be designed to reliably operate under these conditions since the impact on the power system may be serious in both cases. If the differential protection operates due to CT saturation for an Out-Of-Zone fault (lack of stability) or if it does not operate for an In-Zone fault (lack of dependability), the impact on the system or the equipment damage can be significant. Special algorithms and solutions must be applied on conventional schemes to satisfy these requirements. Rogowski Coils provide superior differential protection since they are linear (do not saturate), reject external electromagnetic fields, and are accurate, providing simpler and more reliable protection schemes. In addition, Rogowski Coil physical dimensions and weight are much smaller than conventional current transformers, allowing easier application on existing installations.

Table 1 Performance characteristics of bushing type CTs and Rogowski Coils

Characteristic	Bushing Type CTs	Rogowski Coils
Metering	Typically, two CTs are used, one for metering and one for protection	One metering class Rogowski Coil can be used for both metering and protection
Saturation	For symmetric currents, saturation starts near 20-times rated current and rated burden. For asymmetric currents, saturation can start at several times rated current depending on the primary system X/R value.	Does not saturate (linear).
High frequency range	Typically, up to 50 kHz	Up to 1 MHz or greater
Remanence	Remanence is possible	No remanence (No iron core)
Secondary wiring	Requires heavy gauge conductors with shorting type terminal blocks	Shielded twisted pair cable with connectors (no shorting blocks needed)
Size and Weight	Large and heavy	Small and light
Different protection schemes	Several CTs with different V-I characteristics may be required to cover multiple protection schemes.	One RC can be used for multiple protection schemes.
Personnel Safety	Open secondary can generate dangerous voltages.	Safe (open secondary voltages are small)
The impact on environment	Oil-insulated CT can leak oil and rupture. SF6-insulated CT can leak gas.	Environmentally friendly and safe (No oil or SF6)

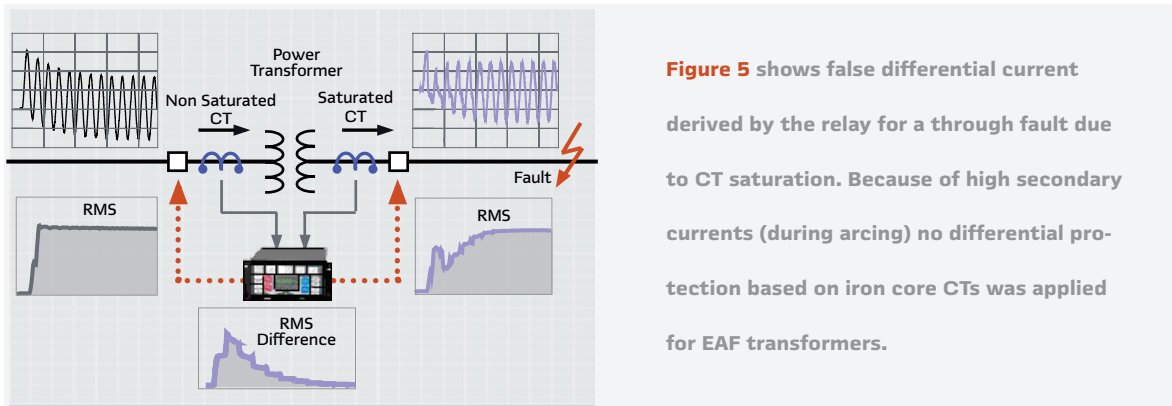
Rogowski coils can replace CTs for protection, metering, and control purposes.

4 High Power Tests (the impact of external electromagnetic fields)



Rogowski Coils do not create hazards for personnel with open secondary, as conventional current transformers.

5 Traditional CT Based Differential Protection of Power Transformers (through faults)



6 Rogowski Coil Signals of an EAF Transformer Primary & Secondary Currents

