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FROM CONVENTIONAL TO ELECTRONIC CURRENT TRANSFORMERS FOR PROTECTIVE RELAYING

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***Abstract**. This paper presents electronic current sensor technologies and compares their operating characteristics to conventional iron-core current transformers. An overview of IEEE and IEC standards and application considerations for relay protection are included.*

Two protection solutions that use Rogowski coils for differential protection of electric arc furnace transformers and mobile substation power transformers are presented.

***Key words**: Electronic Instrument Transformer, Current Sensor, Rogowski Coil, Optical Current Sensor, Faraday Effect, Hall Effect, Relay Protection*

I. INTRODUCTION

Current transformers (CTs) have been traditionally used for power system 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 CT output unnecessary and opens the door for low-energy measurement techniques using electronic current transformers (ECT). CT saturation has been a recognized problem confounding reliable relay protection operation. If the CT characteristics are not properly selected for fault conditions, saturation will occur, and relays can misoperate. Though some protection schemes have been designed to tolerate a certain amount of errors caused by CT saturation, the majority of applications need faithfully reproduced primary currents. Other CT disadvantages include their large size and weight.

ECT systems typically include multiple components such as sensing device, transmitting media, and signal processing/conditioning for interface with relays and other intelligent electronic devices (IEDs). The ECT technology can be based on optical arrangements equipped with electrical components, on air-core coils (with or without a built-in integrator), or on iron-core coils with a built-in shunt resistor used as a current-to-voltage converter. They can have an analog or a digital output. ECTs can have analog output signals with magnitudes substantially proportional to the primary current and phase angle that is in phase with the primary current or differs from it by a known angle. For ECTs with digital output, IEC Standards specify a point-to-point connection from ECTs to relays/IEDs to achieve compatibility with the overall system of communication in the substation allowing interoperability between various devices from different manufacturers.

ECTs make possible protection solutions that could not be realized by conventional iron-core CTs. They have already been applied around the world at all voltage levels (low, medium, and high voltage). This paper describes novel solutions using ECTs for advanced relay protection.

II. ELECTRONIC CURRENT TRANSFORMERS

Conventional iron-core current transformers are typically designed with secondary rated currents of 1A or 5A. Their primary rated current is adapted to the rated current of the switchgear. Accuracy class, performance and accuracy limit factors are determined by the protection and measuring requirements. Different load currents of the feeder, different transient requirements and applications may lead to a large variety of current transformers including separated cores for metering and protection. New generation ECTs have performance characteristic that are favorable compared to conventional CTs such as high measurement accuracy and wide operating range allowing the use of the same device for both metering and protection. However, ECTs are low power sensors and cannot be directly interconnected with the conventional equipment. They need new microprocessor-based equipment designed to accept signals from ECTs. This paper presents performance characteristics for the following ECT types:

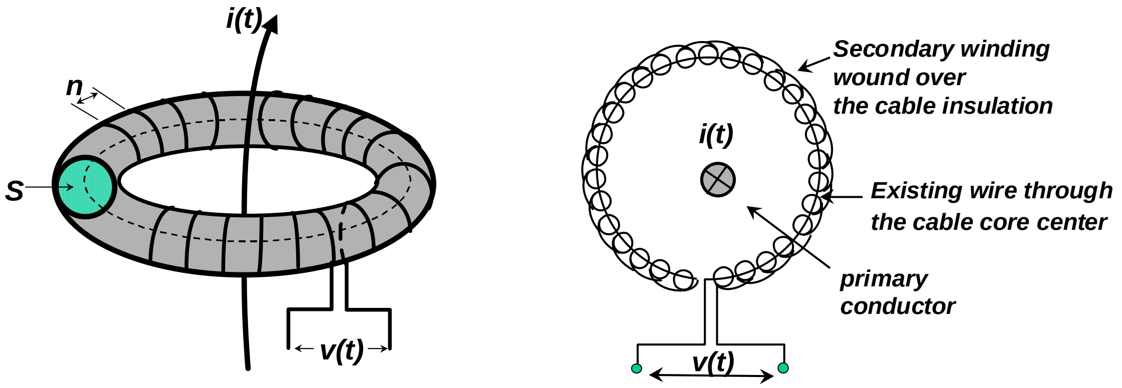
- *Rogowski coils,*
- *Low power iron-core current sensors,*
- *Optical current sensors, and*
- *Special-application current sensors.*

Common performance characteristics for ECTs include:

- *Metering class accuracy allowing usage the same ECT both for protection and metering*
- *High short-circuit current withstand ratings*
- *Galvanic isolation from the primary conductor*
- *No environmental problems (oil and SF6 free)*
- *Safe for personnel (no open secondary high voltage hazard, no violent failures such as with oil insulated CTs)*
- *Immune to EMI (shielded)*

A. Rogowski Coils

Rogowski coils consist of wire wound on a non-magnetic core (μ_r=1). The coil is placed around conductors whose currents are to be measured (Figures 1a, 1b). The voltage induced in the coil is defined by Equation 1.



(a)

(b)

Figure 1. Rogowski Coil Principle of Operation

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

where:
μ_0 – permeability of air
μ_r – relative permeability
n – winding density (turns per unit length)
S – core cross section
M – mutual coupling

For an ideal Rogowski coil, M is independent of the conductor location inside the coil loop. Rogowski coil output voltage is proportional to the rate of change of the measured current. To obtain signals proportional to the measured current, the output voltages must be integrated (Equation 2), which can be performed in the relay (by using analog circuitry or digital signal processing techniques) or immediately at the coil location.

$$v(t) = \frac{M}{R_i C_i} i(t) \tag{2}$$

R_i and C_i in Equation 2 represent the integrating resistor and capacitor.

If the measurement is restricted to a single frequency sinusoidal current (50 or 60 Hz), the coil output voltage will have the RMS value defined by Equation 3 and phase shift nearly 90° vs. the primary current.

$$V_{rms} = M\omega\sqrt{2}I_{rms} \tag{3}$$

To prevent the influence from nearby conductors carrying high currents, Rogowski coils must be designed with two wire loops connected in the electrically opposite direction (Figure 1b). This will cancel all electromagnetic fields coming from outside the coil loop. This other loop can be formed by returning the wire through the winding center or by adding an additional winding wound in the opposite direction. In the past, the predominant method of designing Rogowski coils was to use flexible cores such as coaxial cables or straight rods. Measurement accuracy using flexible cores is in the range 1% to 3%. Metering accuracy Rogowski coils can be designed using printed circuit boards (PCBs), containing two imprinted coils wound in opposite directions (clockwise and counter-clockwise). This can be achieved by imprinting two windings on one PCB or using two PCBs located next to each other, each containing one imprinted winding as shown in Figure 2. This design with two PCBs can be manufactured as multi-layered PCBs. High precision is obtained because the manufacturing process is computer controlled, providing accurate coil geometry.

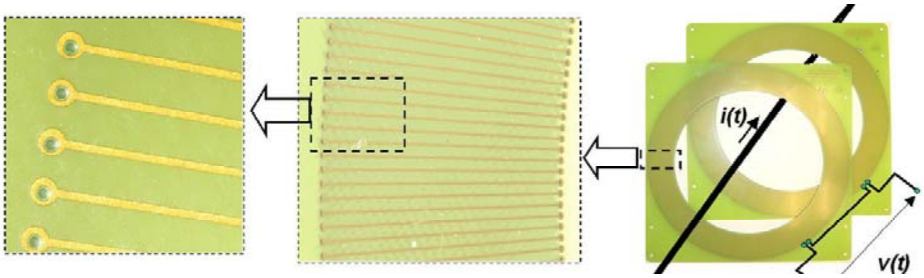


Figure 2. Principle of a PCB Rogowski Coil Design

To adjust for the application, Rogowski coils can be designed with circular, oval, and rectangular shapes. Rogowski coils designed in an oval or rectangular shape are suitable to embrace all three-phases of a conductor (for measurement of residual currents) or to embrace parallel conductors that carry heavy currents. Rogowski coils can also be designed in split-core style for installation without the need to disconnect a primary or secondary conductor (Figure 3). Connections to relays can be by wires or through fiber-optical cables.

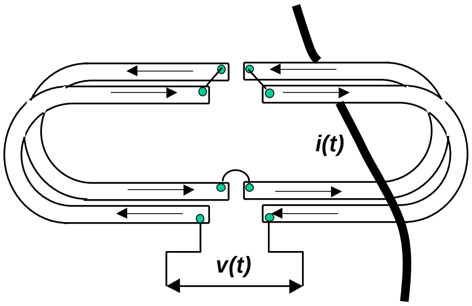
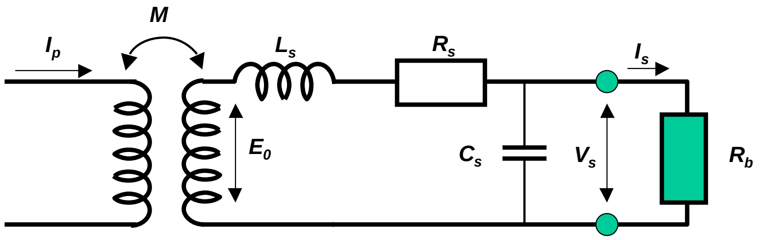


Figure 3. Split-Core Style PCB Rogowski Coil Design

The Rogowski coil equivalent circuit is shown in Figure 4 and the associated vector diagram in Figure 5. The coil output voltage V_s is shifted in phase nearly 90° relative to the measured current i_p since the output voltage is proportional to the rate of change of measured current (di/dt) enclosed by the coil. Therefore, the non-integrated signal can be significantly different from the waveform of the measured current since the fault current DC offset will be attenuated and higher frequency components amplified by the coil.



M	*Mutual coupling*
E_0	*RC induced voltage*
L_s	*Winding leakage inductance (can be neglected for power applications)*
R_s	*Secondary winding resistance*
C_s	*stray capacitance (can be neglected for relay protection analyses)*
R_b	*secondary burden resistance and wire connections*

Figure 4. Rogowski Coil Equivalent Circuit

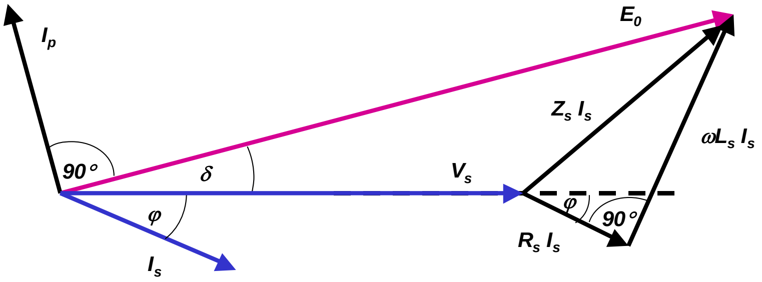
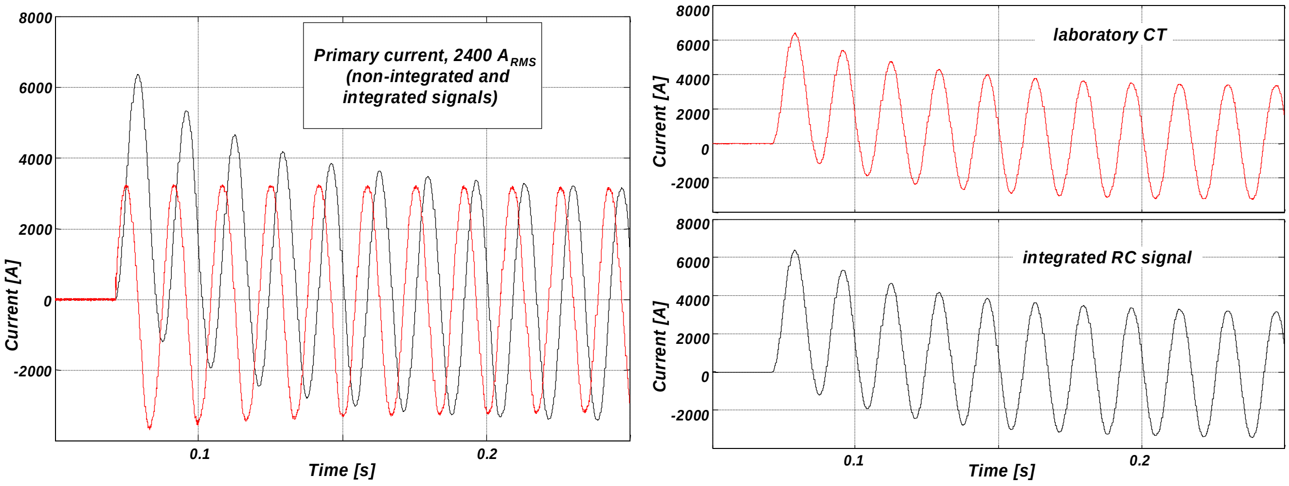


Figure 5. Rogowski Coil Vector Diagram

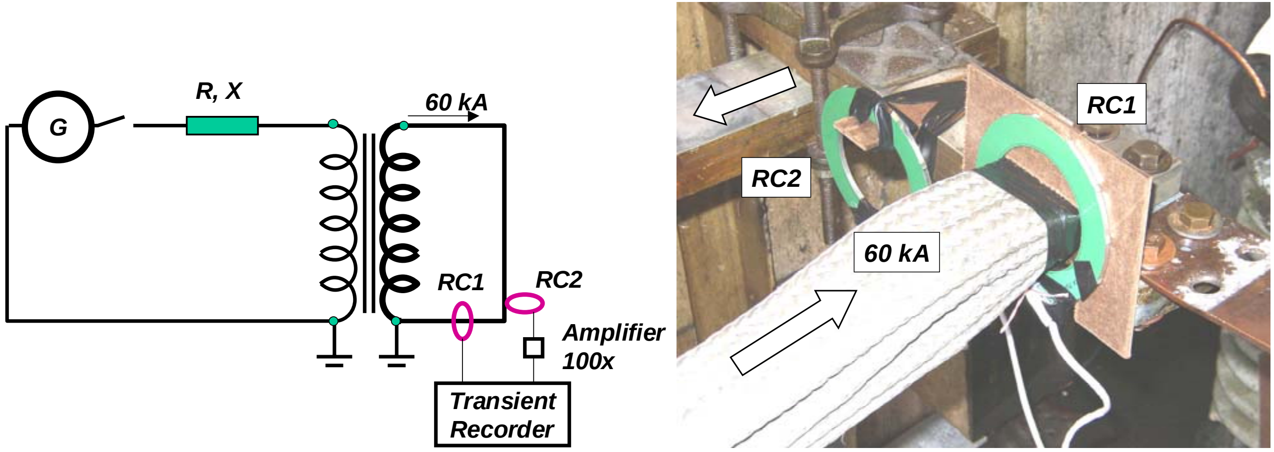
Figure 6a shows non-integrated and integrated Rogowski coil output signals, which are obviously different. However, the integrated signal accurately reproduces the waveform recorded by a laboratory current sensor (Figure 6b).



(a) *(b)*

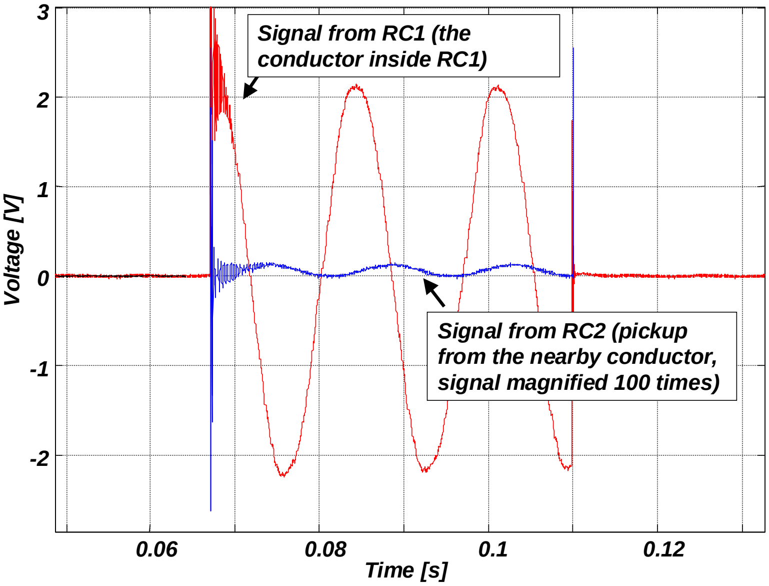
Figure 6. PCB Rogowski Coil Non-Integrated and Integrated Signals (a), Test Current recorded by a Precision Laboratory Current Sensor and by PCB Rogowski Coil with Integrated Signal (b)

The impact from nearby conductors (cross talk) is one of the most important performance characteristics that classify the Rogowski coil accuracy. Figures 7a and 7b show a test setup to determine the impact from nearby conductors carrying a current of 60 kA$_{RMS}$. Two Rogowski coils were tested. RC1 was installed to measure the test current, and RC2 was located next to the primary conductor to determine the impact from the primary conductor. Since the induced signal in RC2 was very small, a 100x amplifier was used to increase the signal to the level acceptable by the transient recorder. The results are shown in Figure 8. The impact from the nearby primary conductor was bellow 0.01%, verifying very good coil immunity to the external electromagnetic fields. In most applications, Rogowski coils are installed at a distance from nearby conductors, which further minimizes their impact.



(a) *(b)*

Figure 7. High Power Test Setup for Testing the Impact of Nearby Conductors



Signal from RC1 (the conductor inside RC1)

Signal from RC2 (pickup from the nearby conductor, signal magnified 100 times)

Figure 8. Influence from the Primary Conductor

Rogowski coils are linear and do not saturate. They have wide operating range, and the same coil can be used to measure currents from several amps to hundreds of kilo amps. Frequency range typically is from 0.1 Hz to over 1 MHz (depending on the coil design). Rogowski coils are lightweight and compact, therefore, switchgear size and weight can be reduced significantly compared to designs using conventional CTs. In addition, Rogowski coil installation is simple since they can be mounted around circuit breaker and transformer bushings.

Figures 9a and 9b compare the transient performance of Rogowski coils with conventional CTs. Figure 9a shows that when measuring fault current having DC offset the Rogowski coil secondary signal (integrated) is NOT distorted and accurately reproduces the original waveform. For the same case, the CT secondary current *is distorted due to saturation (secondary signals referred to the primary). Figure 9b shows calculated RMS values of the primary current from Figure 9a. Trace (a) is the original primary current with DC offset. Traces (b) and (c) are the RMS values derived by the relay for same primary current when DC offset is filtered by the relay. Trace (b) is the RMS value using Rogowski coils, and Trace (c) is the RMS value using current transformers when saturate. The shaded area is the reduced RMS value of the primary current that the relay cannot sense due to current transformer saturation.*

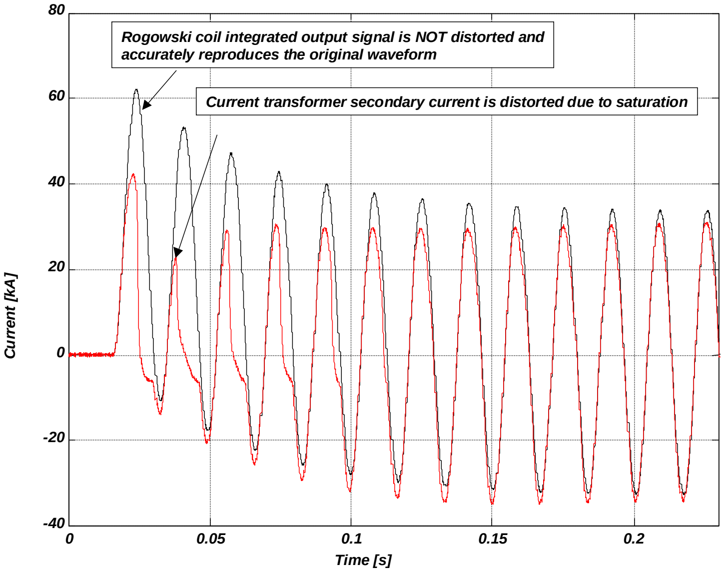


Figure 9a. Rogowski coil secondary signal (integrated) is NOT distorted and accurately reproduces original waveform, while the current transformer secondary current is distorted due to saturation (secondary signals referred to the primary)

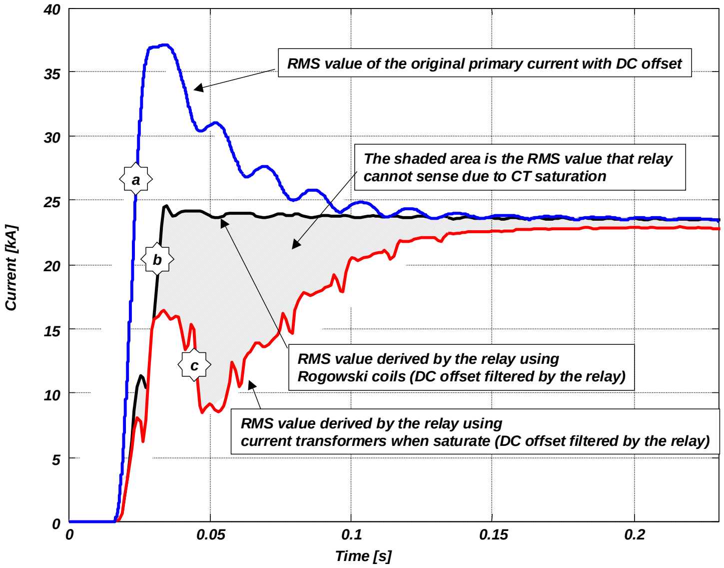
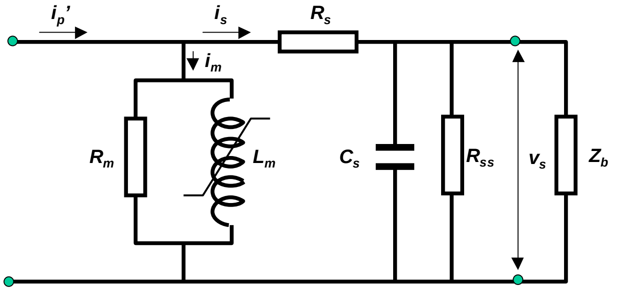


Figure 9b. Comparison of the RMS values: Trace (a) is the original primary current from Figure 9a with DC offset, Trace (b) is the RMS value derived by the relay using Rogowski coils for the same primary current when DC offset is filtered by the relay, Trace (c) is the RMS value derived by the relay using saturated current transformers

B. Low Power Iron-Core Current Sensors

Low power iron-core current sensors have similar designs to conventional CTs but employ a minimized iron core, resulting in a reduced size and weight. The equivalent circuit is shown in Figure 10. Reduction of the core size is possible since new protective relays are designed to accept low power signals (milli-volt range). A resistor R_{ss} (1Ω - 2Ω) is internally connected across the output terminals, producing the output voltage directly proportional to the current. The burden Z_b is typically higher than 10 kΩ to minimize the impact on the sensor accuracy. Because of the iron core, they can saturate similar to conventional CTs, which must be considered when selecting these sensors.



i_p'	Primary current (referred to the secondary)	R_m	Iron core loss resistor
i_s	Secondary current	L_m	Magnetizing inductance
i_m	Magnetizing current	R_s	Secondary winding resistance
v_s	Secondary voltage	C_s	Capacitance of the secondary
R_{ss}	Internal shunt resistor	Z_b	Burden

Figure 10. Equivalent Circuit of the Low-Power Iron-Core Current Sensor

The output voltage v_s as a function of primary current i_p is given in Equation 4.

$$v_s = R_{ss} \cdot i_s = R_{ss} \frac{N_p}{N_s} i_p \tag{4}$$

N_p, N_s: Number of primary and secondary winding turns

C. Optical Current Sensors

Optical current sensors have been in use in high voltage systems since the late 1980’s, first for metering and then for both metering and relaying using the same device. They operate on the principle of the Faraday rotation effect using a monochromatic (single frequency) light source. Current flowing in a conductor creates a magnetic field, which rotates the plane of polarization of the light traveling in optical crystals or fibers encircling the conductor proportionally to the current flowing in the enclosed conductor. The Faraday effect has been explored with both optical crystals and fibers.

Optical crystals. One or more crystals can be used, located around the conductor in which the current to be measured flows.

Optical fibers. The sensing element is an optical fiber wound several times around the primary conductor, providing increased sensitivity. Optical fiber sensors are not sensitive to external currents (return conductor, other phases, other circuits), whereas optical crystal sensors are, depending on their design. However, optical characteristics of both sensing elements (crystal or fiber) are affected by variations in temperature and mechanical stresses. These influences have been minimized by new designs.

The principle of the Faraday rotation effect is shown in Figure 11. The polarization rotation angle (α) is proportional to the circulation of the magnetic field (H) along the optical path (l).

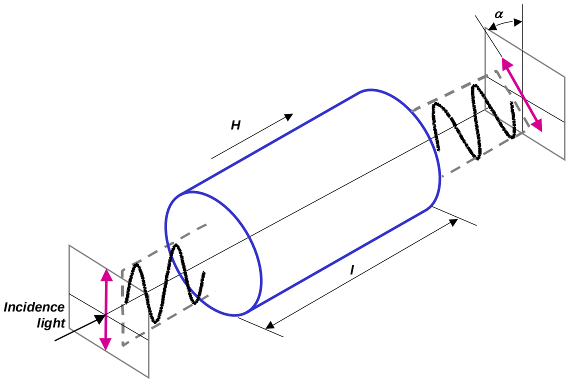


Figure 11. Principle of the Faraday Rotation Effect

$$\alpha = V \int \vec{H} d\vec{l} \tag{5}$$

In Equation 5, V is the Verdet constant that indicates the rotation angle of the polarization per unit magnetic field per unit propagation length. If the optical path has N number of turns then the angle α is proportional to the primary current defined by Equation 6.

$$\alpha = V \cdot N \cdot I_p \tag{6}$$

There are different designs that use Faraday rotation effect to measure current from the angle α. In one design, linearly polarized light waves are input to the optical fiber of which then two circular polarized (right-hand and left-hand) light waves have been created. The magnetic field around a current carrying conductor induces a circular birefringence inside the optical fiber coil. When light passes through the fiber coil, a relative phase difference between two circular polarization components is generated, resulting in the rotation of the linear polarization angle in proportion to the enclosed current and the number of fiber turns.

A typical optical current sensor system consists of an optical sensor, installed at the high voltage level, embracing the primary conductor. The interface between the sensor and the electronic module in the control house is over optical fibers that in addition provide isolation from the high voltage and prevents induced voltages in the secondary system. The electronic module converts the optical signal to a low-energy electrical signal for use with low power equipment or amplified for use with conventional equipment.

D. Special-Application Current Sensors

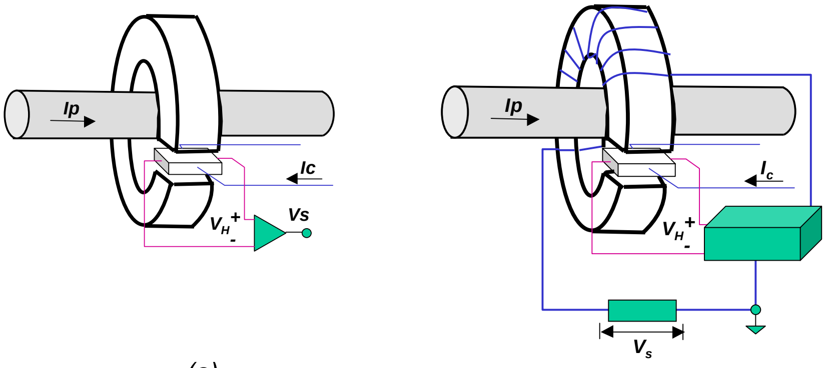
Special-application current sensors are available such as Hall effect and zero-flux sensors. There are two main types of Hall effect sensors, open-loop and closed-loop (zero-flux sensors). They can measure both DC and AC currents. The closed-loop sensors offer better accuracy and wider dynamic ranges but are more expensive than open-loop sensors. The Hall effect sensors have high frequency response and are capable of measuring very high magnitude currents. However, the drawbacks include the output having a large temperature drift and the requirement for external driving circuitry resulting in higher cost than conventional current transformers.

Open-loop current sensors use a Hall element that has four terminals (Figure 12a). Control current I_c flows between two terminals, and the Hall voltage V_H is measured across the remaining two terminals. To increase sensitivity, the Hall element is placed in the air gap of a magnetic core to be subjected to high flux density B caused by the primary current. When control current I_c flows through the Hall element, primary current causing flux density B develops a potential difference V_H defined by Equation 7:

$$V_H = K \cdot I_c \cdot B \tag{7}$$

where K is the sensor's coefficient of sensitivity.

Zero-flux current transformers consist of an iron-core current transformer in which the flux created by the primary current is cancelled by the secondary current that is adjusted automatically by an electronic power *amplifier. Controlled voltage for the amplifier can be obtained from an auxiliary winding, wound on the same iron core or by using a Hall element inserted in the core gap (Figure 12b). Zero-flux current transformers can have high frequency bandwidth (DC to 100 kHz and more), however they are mainly used to measure DC currents such as in HVDC systems.*



I_p – Primary current
I_c – Control current
V_H – Hall voltage
V_s – Secondary voltage

(a) *(b)*

Figure 12. Open-Loop (a) and Closed-Loop (b) Hall Effect Current Sensor

III. STANDARDS FOR ELECTRONIC CURRENT TRANSFORMERS

A. Standard IEEE PC37.92

Standard IEEE PC37.92-2005 defines the interface between ECTs and electronic voltage transformers (EVTs), and protective relays or other substation measuring equipment. The specified ECT output voltage at nominal (rated) current I_n is 200 mV_{RMS} and dynamic range 0.05xI_n to 40xI_n. The acceptable magnitude and phase errors are given in Table 1.

Table 1. Magnitude and Phase Errors

Current Range (multiple of I_n)	Magnitude Error [%]	Phase Error [degree]
0.05 to 0.1	1	1
0.1 to 1.0	0.6	0.5
1.0 to 5.0	1	1
5.0 to 40	10	10

If the accuracy from Table 1 is acceptable, the nominal output voltage for informational metering can be 2 V_{RMS}, with a maximum output of 4 p.u. For revenue metering, the ECT manufacturer shall separately state compliance with relevant accuracy standards.

To clarify its domain of application, this standard uses an optical voltage or current sensing system as an example of an ECT or EVT with an optical-to-electronic interface (secondary converter). Figure 13 shows a typical configuration of such a system in a high voltage substation. The optical signal is transmitted through fiber-optic cables to the ground level before being converted to electrical signals, scaled and formatted for use by protective relays and other IEDs.

The interface between the current sensing element and the secondary converter is a proprietary design and is not subject to standardization. The output of the secondary converter and the input of relays and other IEDs is standardized to assure interoperability.

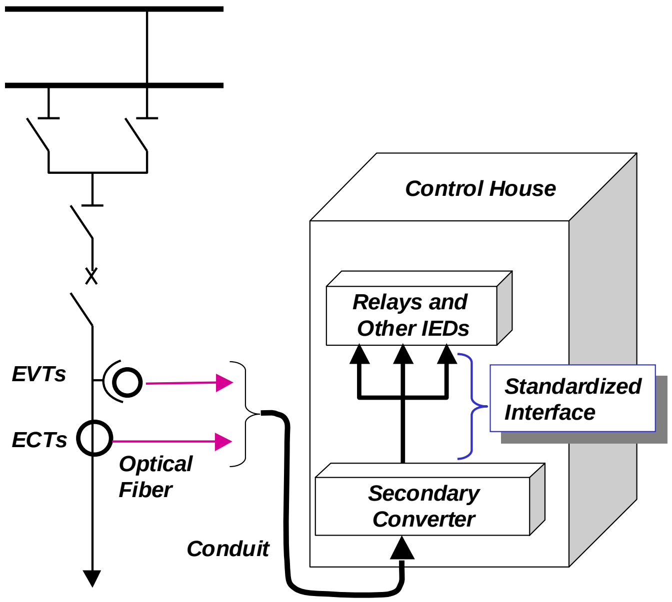


Figure 13. Typical ECT and EVT Interface to Relays and IEDs

B. Standard IEC 60044-8

IEC 60044-8 standard defines requirements for ECTs having an analog voltage output or a digital output for protection and measurement functions. For example, this standard defines rated secondary voltages that correspond to primary rated currents. Since ECTs can provide wide current range, the rated extended primary current factor was introduced, describing a rated current range. For example, in the case of a primary rated current of 50A and a rated extended primary current factor of 10, the rated current range is from 50A to 500A.

ECTs are defined by:
- *rated primary current*
- *rated extended primary current*
- *rated accuracy-limit primary current*

The standard RMS values of the rated secondary voltage at rated primary current are 22.5 mV, 150 mV, 200 mV, 225 mV, and 4 V.

For application without secondary converters (transmitting system directly connected to the low voltage equipment) generally used at medium-voltage level, the standard rated values are:

- *22.5 mV and 225 mV for ECTs delivering an output voltage proportional to the current (e.g. transformer with iron core and integrated burden)*
- *150 mV for ECTs delivering an output voltage proportional to the derivative of the current (e.g. air core coils)*
- *The rated secondary voltages 40 mV, 100 mV and 1 V may be used for existing design*

For applications using electronic secondary converter, the standard rated value for protection is 200 mV and 4 V for measurement.

The standard values of rated burden are 2 kΩ, 20 kΩ, and 2 MΩ.

Example for ECT specifications as per IEC 60044-8 (Figure 14):

Metering

- Rated primary current I_{pn}
- Rated extended primary current Ipe = $10I_{pn}$
- Class 0.5
- accuracy 0.5% from I_{pn} to $10I_{pn}$
- accuracy 0.75% at $0.2I_{pn}$
- accuracy 1.5% at $0.05I_{pn}$

Protection

- Primary current I_{pn}
- Class 5P from $10I_{pn}$ to $40I_{pn}$

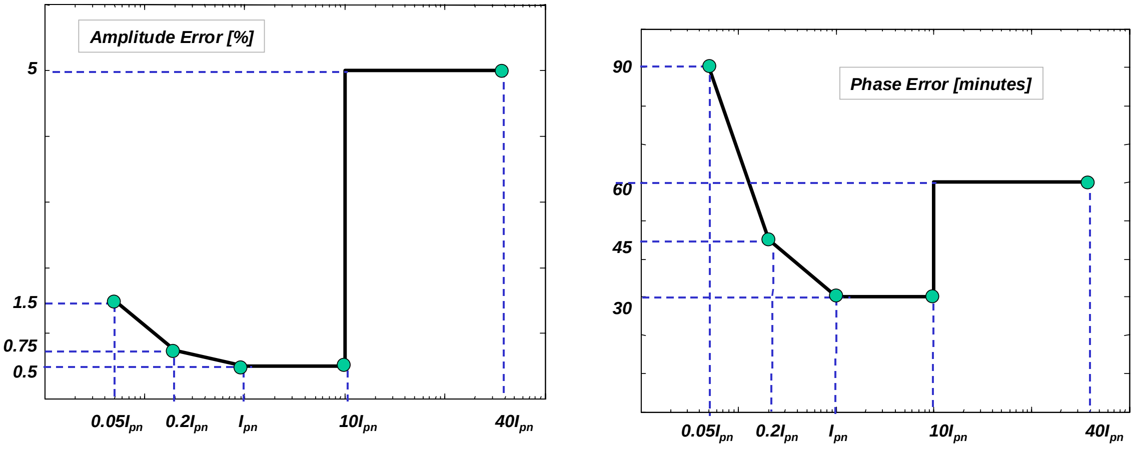


Figure 14. ECT Amplitude and Phase Errors as per IEC 60044-8

C. Standard IEC 61850

Standard IEC 61850 addresses substation networks and systems, consisting of a set of documents divided into ten major parts. It defines communication between IEDs of different manufacturers networked together to perform protection, monitoring, automation, metering, and control. The objective is the interoperability between IEDs, enabling the unrestricted exchange and usage of data to perform their individual dedicated functionality. Two documents, IEC 61850-9-1 and IEC 61850-9-2, specifically relate to ECTs and EVTs.

Standard IEC 61850-9-1 defines a unidirectional serial communication interface connecting ECTs and EVTs with digital output to protection devices and other IEDs in accordance with IEC 60044-8. Specifically, it relates to a serial communication interface between the Merging Unit and equipment using the digital output of the Merging Unit such as protection and metering equipment. Merging Unit is a physical unit used to do the time-coherent combination of the current and/or voltage data coming from the secondary converters. For the specification of that serial interface, a subset of the abstract communication services defined in IEC 61850-7-2 is mapped on an ISO/IEC 8802-3 based communication link, usually referred to as Ethernet.

This allows the exchange of synchronized phasor measurements using Global Positioning System signals for synchronization. Another real-time requirement is met by the Generic Object Oriented System Event – GOOSE that defines the transmission of high priority information such as trip commands or interlocking information. Additional applications that are necessary for a complete system may include: metering, protection and control, remote monitoring and fault diagnosis, automated dispatch and control, data retrieval, site optimization of electrical/thermal outputs, asset management, as well as condition monitoring and diagnosis.

Standard IEC 61850-9-2 defines the specific communication service mapping (SCSM) for the transmission of sampled values according to IEC 61850-7-2 and includes an extended mapping specification of IEC 61850-9-1.

IV. INTERFACE WITH RELAYS

A. ECT Insulation Level

For gas insulated switchgear applications, some ECT types can be implemented in the switchgear enclosure requiring only low voltage insulated sensors. For applications in open-air substations, ECTs can be combined with fiber optical technology, which also permits applications of low voltage insulated ECTs, since the secondary signals can be transmitted from high voltage level to ground potential using fiber optical cables. Power required for the electronics located at the high voltage level can be achieved by using conventional CTs installed at the high voltage level or powered from the ground through the fiber optical cables using power LEDs.

B. Shielding

When wires are used to interface ECTs with metering and protection equipment, shielding should be applied to prevent electromagnetic influence on the ECT secondary signals. Typically, single or double shielded twisted pair conductors can be used. Only one shield termination, at the relay or receiving end of the connection, is directly grounded. Ceramic disc capacitors (10 nF) may be connected from shield to ground at each ungrounded shield termination point to provide improved high frequency electromagnetic shielding. For connections involving switchyard-mounted equipment, some applications may require more elaborate shielding [3].

C. Secondary Wiring

ECT secondary wiring is simplified compared to the solutions using conventional current transformers. Shielded cables with integrated connectors can be used which simplifies installation and requires less wiring.

D. Interface Methods

A generic block diagram in Figure 15 represents an ECT system. Primary current sensors provide information to the primary converter, which performs signal processing. The Primary Converter module may be placed near the ECT to amplify, convert or encode low level signals prior to transmission. It can be interfaced with relays using optical fibers or wires. The link between the primary and secondary converters can be proprietary and is not covered by standards.

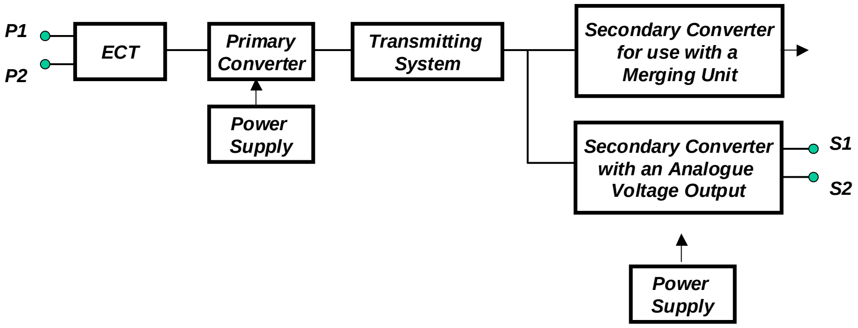


Figure 15. Block diagram of a single-phase ECT (IEC 60044-8)

Analog Interface*. The Primary Converter from Figure 15 is not needed if the insulation requirements are satisfied and distances between ECTs and relays/IEDs are not excessive. In this case, interconnection can be implemented using shielded/twisted pair cables/wires. The secondary converter block can be part of a protective relay/IED or Merging Unit input circuitry. The Secondary Converter provides necessary galvanic isolation and signal processing. Signals from the Secondary Converter can be forwarded (in analog or digital form) to relays/IEDs, through point-to-point links (IEC 6044-8, 61850-9-1), or Local Area Networks (IEC 61850-9-2).*

***Digital Interface**. IEC 60044-8 (and IEC 61850-9-1) also defines a digital interface to the secondary equipment. ECTs are not connected each separately to the secondary device but grouped by Merging Units (Figure 16). Multiple electronic instrument transformers can be connected to the Merging Unit such as seven ECTs (three for metering and four for protection) and five EVTs (four for protection/metering and one for bus voltage). The Merging Unit then supplies the secondary equipment via a multi-drop point-to-point link with a time coherent set of current and voltage data. The link between ECTs and the Merging Unit can be proprietary. The accuracy requirements are defined at the output of the Merging Unit. IEC 60044-8 defines a special interface to allow the use of interpolation schemes for the sampled data, while IEC 61850-9-2 specifies the additional process bus services.*

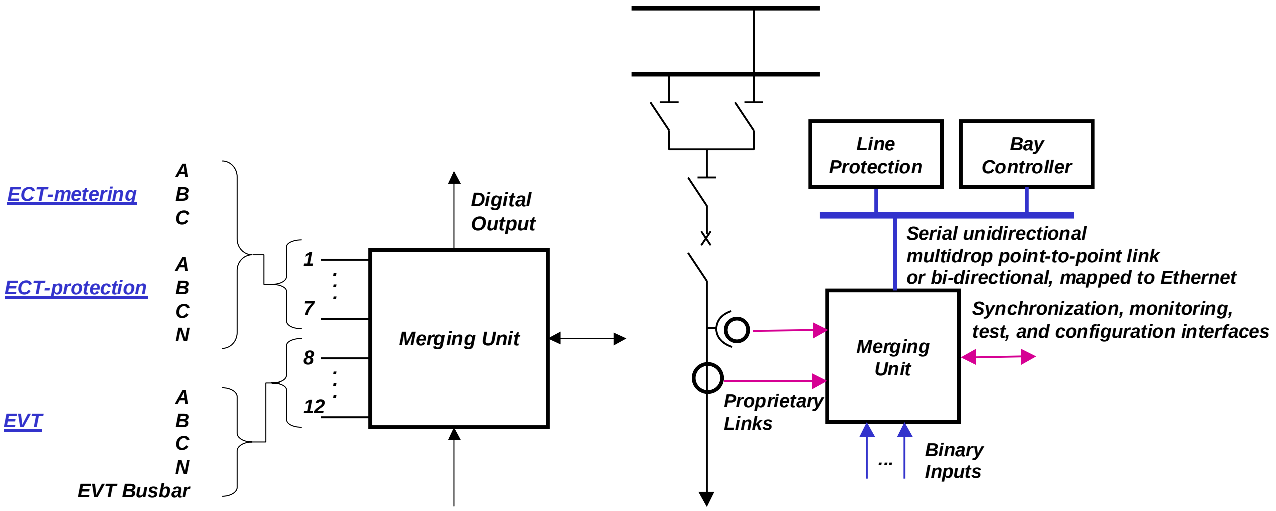


Figure 16. Digital Interface Block Diagram with Merging Unit

V. PROTECTION SOLUTIONS USING ROGOWSKI COILS

The projects that use Rogowski Coil current sensors for relay protection presented in this paper include differential protection of electric arc furnace (EAF) transformers and differential protection of power transformers in mobile substations. Additional possible applications include differential protection of generators and large motors.

A. Differential Protection of EAF Transformers

In steel facilities that use EAFs (Figure 17) to manufacture steel from scrap, the EAF transformer is one of the most critical pieces of electric power equipment in the plant. Failures in the EAF transformer or its buswork interrupt production and require costly and time-consuming repairs. Traditional overcurrent protection is often applied at the circuit breaker that supplies the cable serving the furnace transformer. This protection is normally set to reach into the furnace transformer primary winding for faults in the winding but may not have sufficient sensitivity to reach through the transformer into the secondary winding or into the secondary leads. Faults that occur in the secondary buswork, water cooled leads, or in the conducting arms above the furnace are not detected by the upstream overcurrent protection and are normally interrupted only after personnel manually open the circuit breaker. The damage due to the extended fault duration can result in long or costly outages.

Differential protection schemes are not typically applied on EAF transformers due to the difficulty in providing conventional CTs of sufficient rating for the secondary leads carrying load currents of 60 kA or more. Some modern EAF transformers are rated to deliver a steady state secondary current of 80 kA. In some cases, a CT is built into the transformer that monitors the current in only one secondary winding (there are typically multiple secondary windings per phase group). This current signal might be used for metering or regulator control purposes, and the magnitude is calculated externally with a scale factor assuming the current in each winding is the same. The accuracy of this technique is not sufficient for a reliable differential protection system.

The differential protection system presented in this paper uses Rogowski coils and multifunction relays (Figures 18 and 19). Two identical systems have been implemented for two 90 MVA, 34.5/1 kV EAF transformers equipped with 33-tap load tap changer (LTC). Similar to conventional solutions, the differential protection zone is defined by the location of the Rogowski coils. Both the primary and secondary Rogowski coils were located in the EAF vault. The secondary system voltage can have different magnitudes depending on the furnace regulator program with a maximum magnitude of approximately 1 kV line-to-line and secondary currents of approximately 60 kA$_{RMS}$.

Figure 17. Electric Arc Furnace Operation

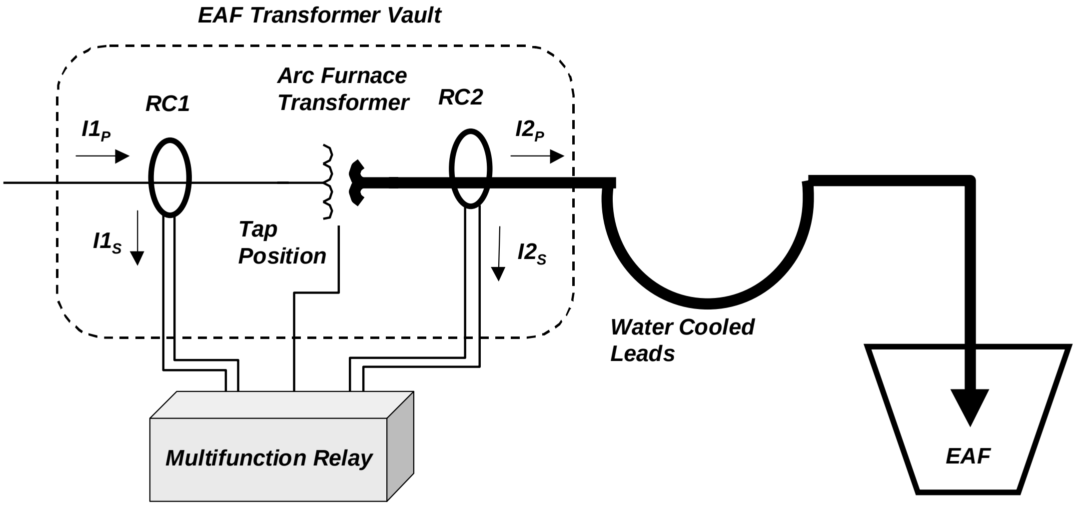


Figure 18. Principle of Arc Furnace Transformer Differential Protection

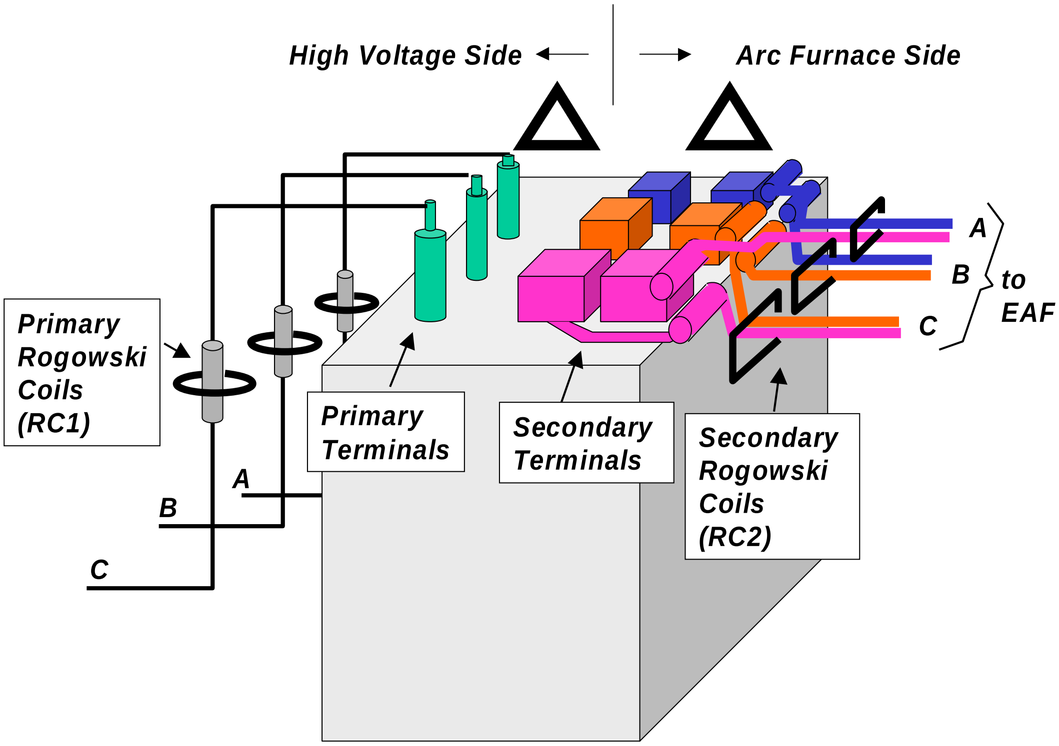


Figure 19. Installation of PCB Rogowski coils for Arc Furnace Transformer Differential Protection

Rogowski coils installed on the primary side were designed as non-split-core style. To provide the required dielectric strength and the BIL at 34.5 kV voltage level, the coils were mounted around air-air bushings. Figure 20 shows three primary Rogowski coils installed in one of the EAF vaults.

On the EAF transformer secondary side, the interconnection assembly at the top of the transformer collects the current from multiple secondary windings into 9-inch water-cooled bus tubes, two per 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 two outside phases is the same (10-inch spacing between tube centers), and the middle phase has two tubes that are on 26-inch spacing. The Rogowski coils were designed with two different sizes (instead of one, larger size), which optimizes the installation design. Since the secondary tubes cannot be opened, the Rogowski coils were designed in a split-core style. The secondary coils were mounted on the wall at the point where the secondary tubes leave the vault (Figure 21).

Before installation, this protection scheme was tested in the high power laboratory using the actual Rogowski coils and multifunction relays that were installed at the site. The tests verified both the protection scheme sensitivity and stability. The protection systems were commissioned one year after installation.

Figure 22 shows a relay's event record (manually triggered during commissioning) capturing user programmable data during operation of the EAF's mid period of a heating cycle. The waveforms in the top two panels are the primary and secondary EAF transformer currents. The next two panels are the operating and restraining currents in the transformer differential algorithm. The bottom panel in Figure 22 is the status of the trip signals. The scale on the secondary current panel is ±300 kA_{peak}. At the point of the cursor in Figure 22 the C-phase primary current peak value is 3900 A and the C-phase secondary current peak value is 132 kA. The relay operating signal at that point shows a mismatch between the primary and the secondary currents of less than 2% of transformer rated current.

Figure 20. EAF Transformer Primary Side Rogowski Coils

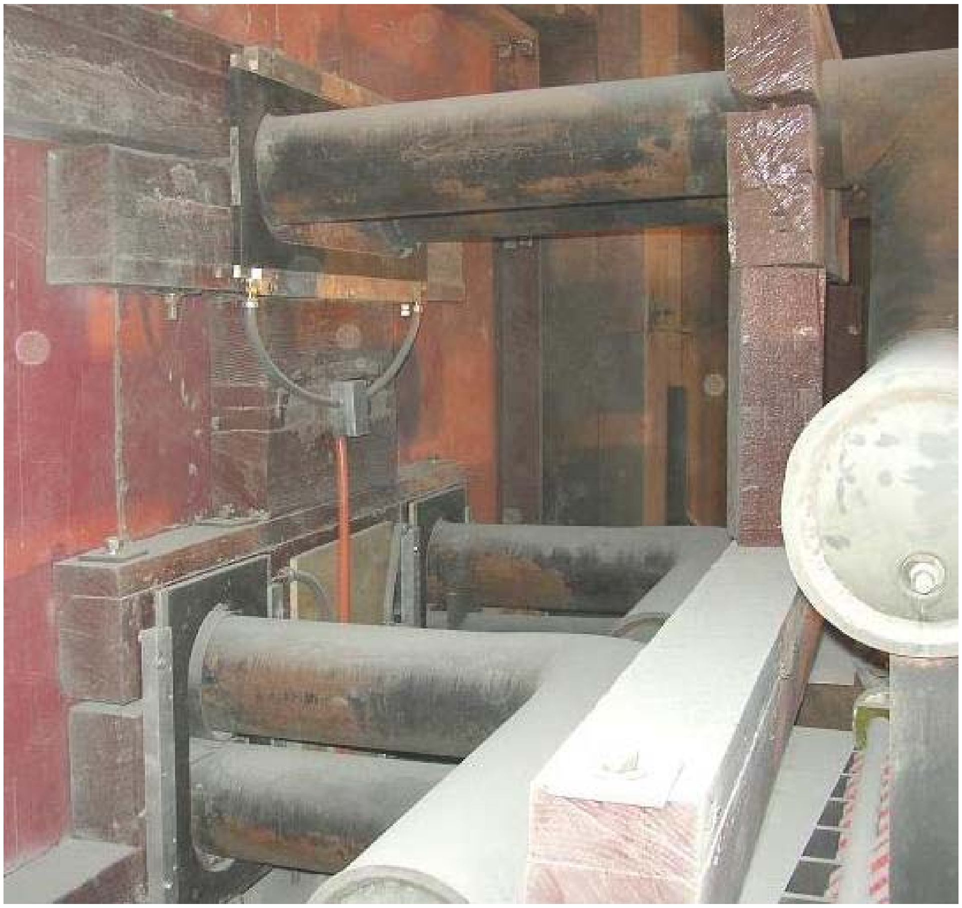


Figure 21. EAF Transformer Secondary Side Rogowski Coils

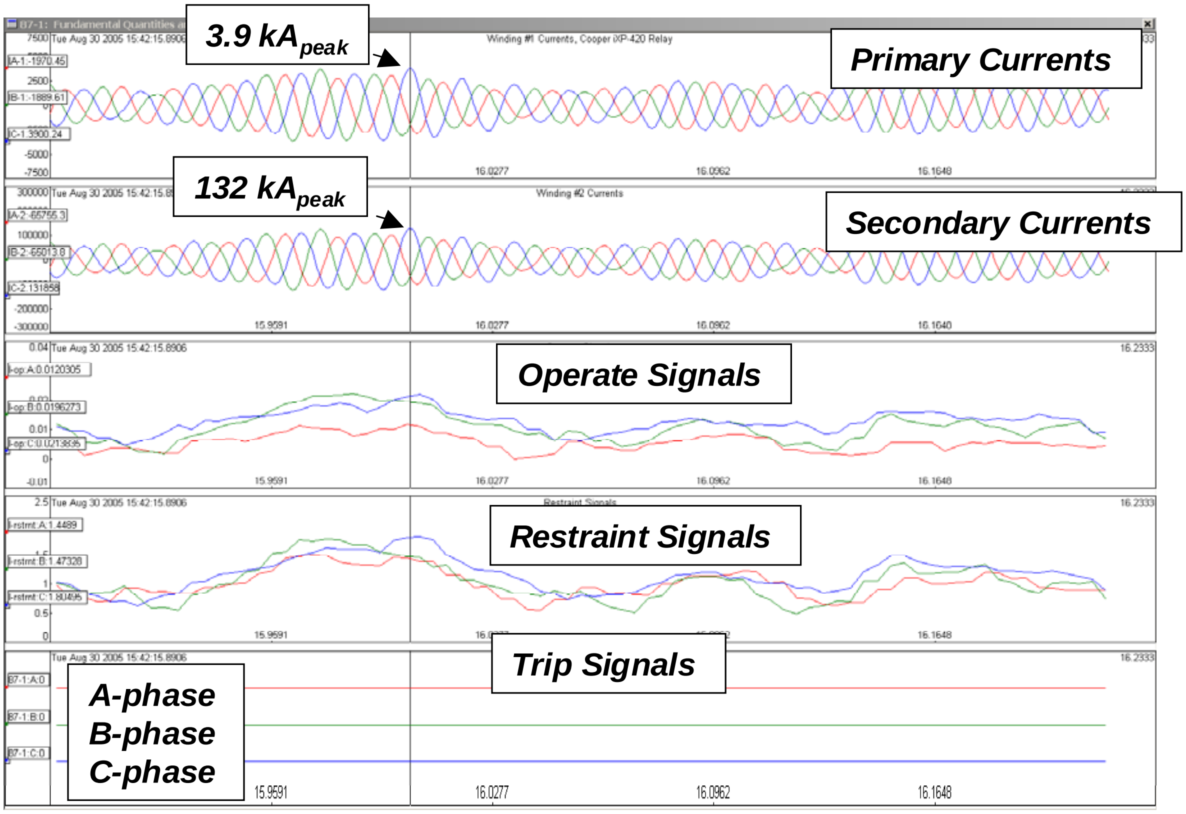


Figure 22. Manually Triggered Event Record

B. Differential Protection of Mobile Substation Power Transformers

In this project example the electric utility operates multiple mobile substations and wanted to offer improved protection and speed of installation by converting from fused high side protection to relayed protection with a switching device on the primary side. The mobile substation required that the equipment tolerate the motion and vibration associated with movement over the road on a trailer, which raised concern for using conventional CTs. The Rogowski coil approach offered much less weight and size in the sensor when compared to conventional CTs along with improved protection system performance.

The application included differential protection of a 20 MVA, 161/13.8 kV, delta/grounded-wye power transformer (Figures 23 and 24). The 161 kV side Rogowski coils were mounted at the base of the primary bushings on the transformer (Figure 23). The 13.8 kV side Rogowski coils were mounted on the front of the trailer in the existing support structure. They were of similar design as the primary Rogowski coils for the EAF transformer, mounted around air-air bushings. This provided an easier connection for the cables that normally travel with the trailer. An additional Rogowski coil was mounted around the neutral bushing on the secondary side of the transformer for monitoring neutral current and for restricted earth fault protection (Figure 24).

Figure 25 shows a manually triggered event record taken during normal operation of the mobile substation. At the time, the primary currents at the 161 kV level were approximately 18-20 amperes. Secondary currents were approximately 220, 179, and 249 amperes at the 13.8 kV level with about 56 amperes of zero sequence unbalance. As the figure shows, during normal operation the operating current, which is the difference between the primary and secondary current signals scaled to the same base value, is less than 1% of rated transformer current.

Figure 23. Primary Side Rogowski Coils

Figure 24. Secondary Side Rogowski Coils

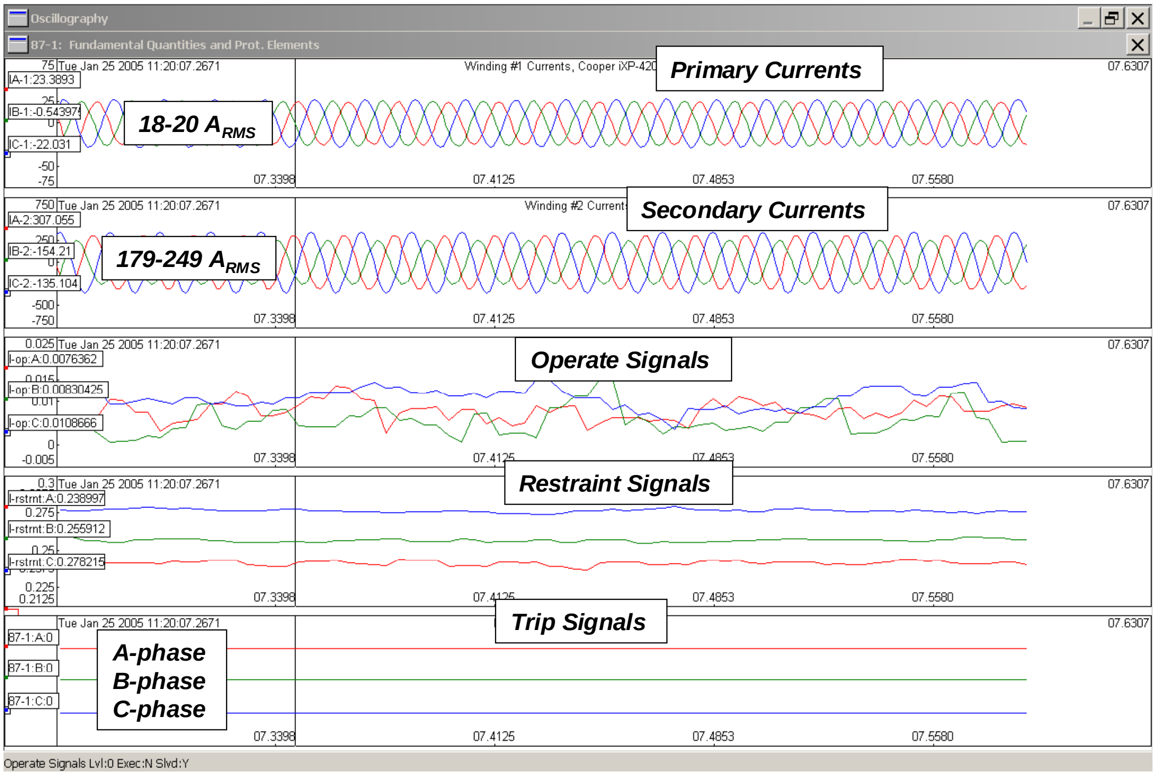


Figure 25. Manually Triggered Event Record during Light Load Operation

VI. CONCLUSIONS

This paper presents electronic current transformer (ECT) technologies and compares their operating characteristics to conventional current transformers. ECTs make possible protection solutions that could not be realized by conventional CTs. They are linear (do not saturate), reject external electromagnetic fields, and are accurate. The physical dimensions and weight are smaller than of conventional CTs and provide simpler and more reliable protection.

Example projects that use Rogowski coils for differential protection of electric arc furnace transformers and mobile substation power transformers are presented. The first two differential protection systems in the USA have been successfully designed, built, and installed for two 90 MVA, 34.5/1 kV electric arc furnace transformers. Reasons for choosing Rogowski coils instead of conventional CTs for differential protection for mobile substation transformers are better accuracy, smaller weight and size, and easier installation.

Biography

Ljubomir A. Kojovic *is a Chief Power Systems Engineer for Cooper Power Systems at the Thomas A. Edison Technical Center. He has a Ph.D. in power systems with specialties that include protective relaying, distributed generation, testing, digital modeling, and systems analysis. He is an adjunct assistant professor at Michigan Technological University. He is included on the roster of experts for the United Nations Development Organization (UNIDO) and is a registered professional engineer in Wisconsin. He is an IEEE Senior Member, member of the main committee, and member of several working groups of the IEEE Power System Relay Committee. He has earned seven U.S. patents and authored more than 120 technical papers.*

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