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Special Report

Practical Aspects of Rogowski Coil Applications to Relaying

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Practical Aspects of Rogowski Coil Applications to Relaying

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1 Introduction

1.1 Assignment

Produce a special report describing applications of Rogowski Coils used for protective relaying in electric power systems.

1.2 Summary

Rogowski Coils operate on the same principles as conventional iron-core current transformers (CTs). The main difference between Rogowski Coils and CTs is that Rogowski Coil windings are wound over an (non-magnetic) air core, instead of over an iron core. As a result, Rogowski Coils are linear since the air core cannot saturate. However, the mutual coupling between the primary conductor and the secondary winding in Rogowski Coils is much smaller than in CTs. Therefore, Rogowski Coil output power is small, so it cannot drive current through low-resistance burden like CTs are able to drive. Rogowski Coils can provide input signals for microprocessor-based devices that have a high input resistance; therefore, these devices measure voltage across the Rogowski Coil 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. This can result in reduced inventory costs since fewer sensors are needed for all applications. Less variation in inventory requirements should also improve installation time when replacements are needed, reducing equipment downtime; thereby, lowering overall sensor costs to the utility or industrial company. This is achieved through higher unification and standardization of products, which benefits manufacturers and users.

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.

An additional advantage of Rogowski Coil current sensors is significantly lower power consumption during operation. Rogowski Coils are connected to devices that have high input resistance, resulting in negligible current flowing through the secondary circuit. Conventional CTs contain a ferromagnetic core that also consumes energy/power due to hysteresis losses. Rogowski Coils have no core losses. In fact, an operating Rogowski Coil has much smaller power loss than conventional CTs – which leads to significant savings of energy and ultimately reduced lifecycle costs.

Rogowski Coils can replace conventional CTs for protection, metering, and control. Rogowski Coils 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 di(t)/dt of the primary current. Signal processing is required to extract the power frequency signal for applications in phasor-based protective relays and microprocessor-based equipment must be designed to accept these types of signals.

1.3 Abbreviations and Acronyms

A/D	-	Analog to Digital
AIS	-	Air Insulated Switchgear
CT	-	Iron-Core Current Transformer
CB	-	Circuit Breaker
DC	-	Direct Current
EAF	-	Electric Arc Furnace
ECT	-	Electronic Current Transformer
EVT	-	Electronic Voltage Transformer
EIT	-	Electronic Instrument Transformer
GIS	-	Gas Insulated Switchgear
HV	-	High Voltage
IED	-	Intelligent Electronic Device
IT	-	Instrument Transformer
LAN	-	Local Area Network
LPCS	-	Low Power Stand Alone Current Sensors
LTC	-	Load Tap Changer
MU	-	Merging Unit
OPDL	-	Optically Powered Data Link
PCB	-	Printed Circuit Board
RMS	-	Root Mean Square
SU	-	Sensing Unit
TW	-	Traveling Wave
TWC	-	Traveling Wave Current
TWV	-	Traveling Wave Voltage
VT	-	Voltage Transformer

2 Rogowski Coils

2.1 Theory of Operation

Conventional iron-core current transformers (CTs) are typically designed with rated secondary currents of 1 Amp or 5 Amps, to drive low impedance burden of several ohms. Figure 2-1 shows the principle of a CT connection. ANSI/IEEE Standard C57.13™-2008 [1] 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 a fault current 20 times the CT rated current and up to the standard burden. CTs are designed to meet this requirement. But, if the standard burden is connected to the CT secondary and the RMS value of a symmetric fault current exceeds 20 times the CT rated current or if the RMS value of a fault current is smaller than 20 times the CT rated current 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 consist of a wire wound on a non-magnetic core (relative permeability μ_r=1). The coil is then placed around conductors whose currents are to be measured (Figure 2-2).

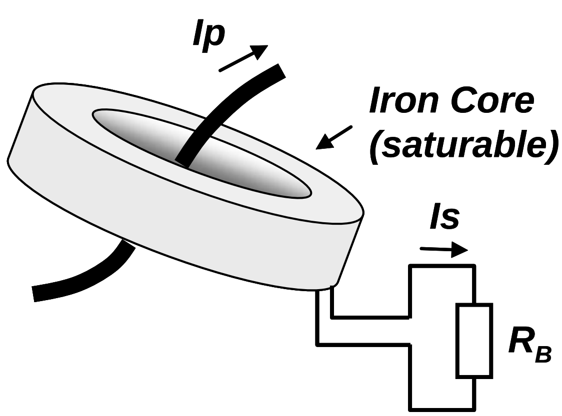


Figure 2-1. Current Transformer

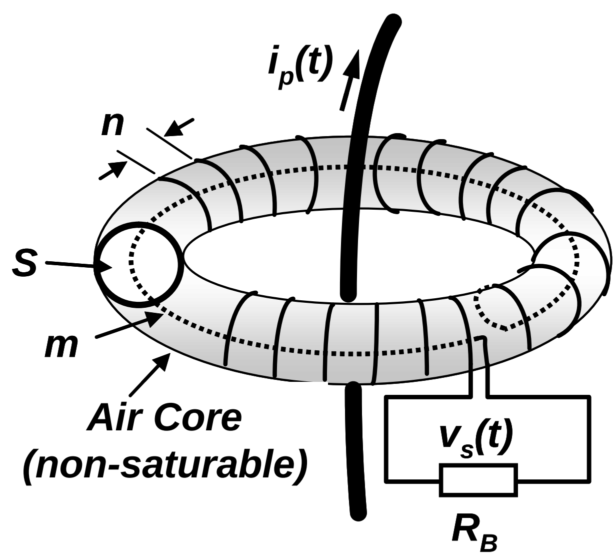


Figure 2-2. Rogowski Coil

As Rogowski Coils use a non-magnetic core to support the secondary windings, mutual coupling between the primary and secondary windings is weak. Because of weak coupling, to obtain quality current sensors, Rogowski Coils should be designed to meet two main criteria:

- the relative position of the primary conductor inside the coil loop should not affect the coil output signal, and
- the impact of nearby conductors that carry high currents on the coil output signal should be minimal.

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:

1) on a core that has a constant cross-section S,

2) perpendicular to the middle line m (dashed line in Figure 2-2 that also represents return wire through the winding), and

3) built with constant turn density n.

Mutual inductance M is defined by the formula:

$$M = \mu_0 \cdot n \cdot S$$

Where μ_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 the Rogowski Coil primary and secondary windings are weakly coupled (to prevent the unwanted influence from nearby conductors carrying high currents) Rogowski Coils 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 (Figure 2-3) or near this winding (single-layer coils). If both loops are constructed as windings, then they must be wound in opposite directions (multi-layer coils). In this way, the Rogowski Coil output voltage induced by currents from the inside conductor(s) will be doubled if windings are identical.

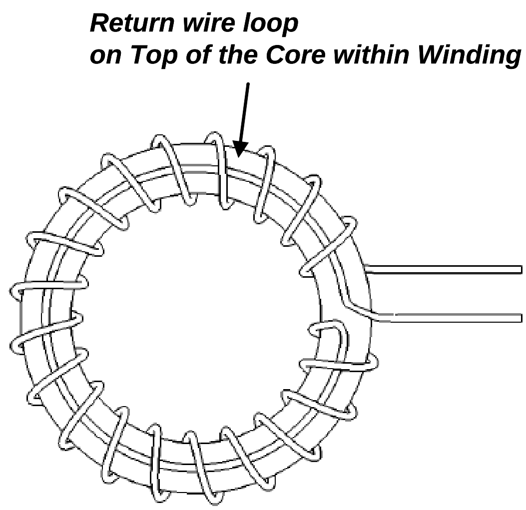


Figure 2-3. Rogowski Coil with the Return Wire Loop through the Winding

Figure 2-4 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, or when a DC component is present in the primary current. When the CT saturates, the magnetizing current increases and the secondary current produced decreases (ie. CT ratio error increases). This may negatively impact relay performance, resulting in delayed operation, non-operation, or unwanted operation in the case of differential protection schemes.

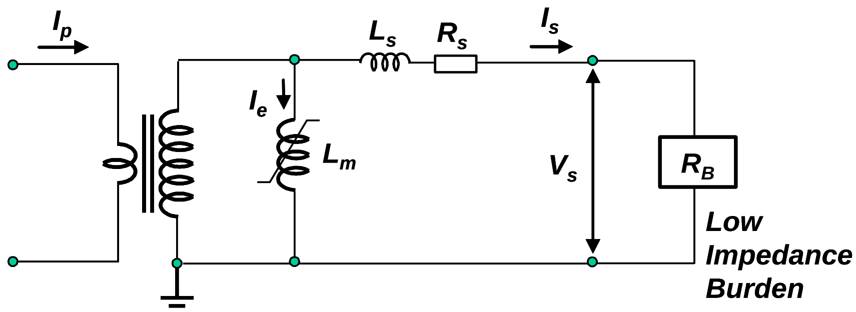


Figure 2-4. Current Transformer Equivalent Circuit

Figure 2-5 shows the equivalent circuit of a Rogowski Coil. The phase angle between the Rogowski Coil primary current and the secondary voltage is nearly 90° (displaced from 90° by a small angle α caused by the coil inductance Ls). Figure 2-6 shows the Rogowski Coil vector diagram.

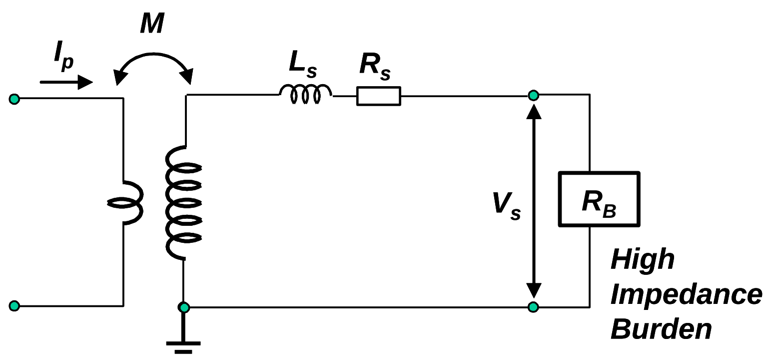


Figure 2-5. Rogowski Coil Equivalent Circuit

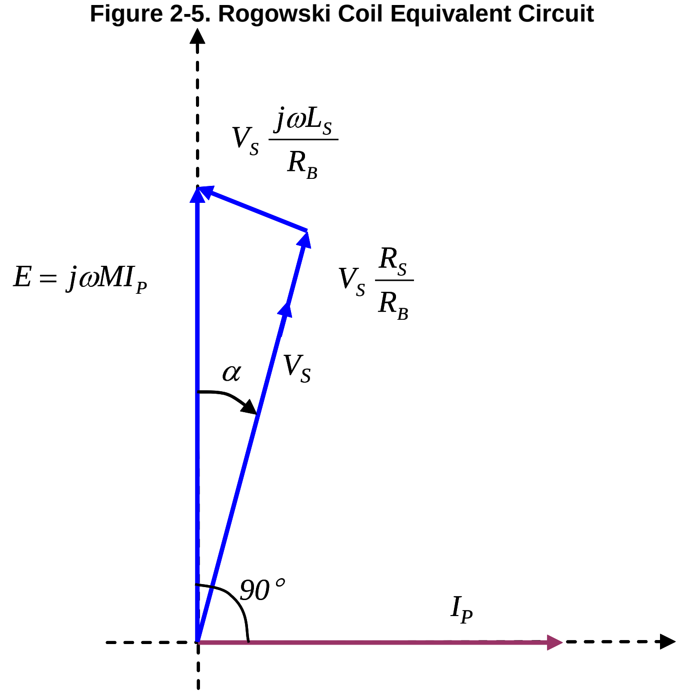
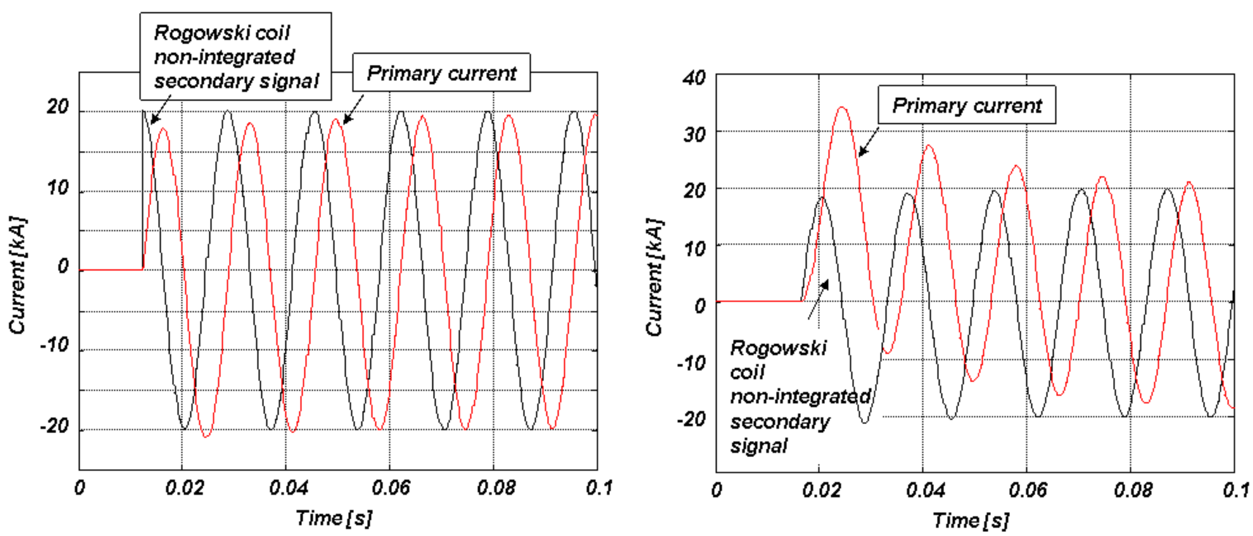


Figure 2-6. Rogowski Coil Vector Diagram

As the Rogowski Coil signal 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. This may be achieved by integrating the Rogowski Coil output signals, or using non-integrated Rogowski Coil output signals in other signal processing techniques.

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 phasor-based protective relaying applications, the Rogowski Coil secondary signal must be scaled by magnitude and phase-shifted for each frequency.

Because the Rogowski Coil output voltage is proportional to the rate of change of measured current (*di/dt*) enclosed by the coil, the waveform of the Rogowski Coil output signal is different from the waveform of the measured current. For symmetric primary current faults, the Rogowski Coil secondary voltage signal is shifted in phase by 90° versus the primary current as shown in Figure 2-7a. For an asymmetric primary current fault, the DC offset will be attenuated by the Rogowski Coil and phase shifted as shown in Figure 2-7b. However, the integrated signal accurately reproduces the primary current waveform.



(a) Symmetric Primary Currents (b) Asymmetric Primary Currents

Figure 2-7. Rogowski Coil Non-Integrated Output Signals

To achieve high accuracy, Rogowski Coils should be connected to devices that have high input impedance. Figure 2-8 shows the impact of the device input resistance on the secondary output voltage for an example of Rogowski Coil that produces 150 mV at rated current. In reality, different Rogowski Coils may have different requirements on the input resistance of connected devices. In addition, capacitances of the burden and/or connected cable may affect the phase error; nevertheless the effect of such capacitances is relatively small.

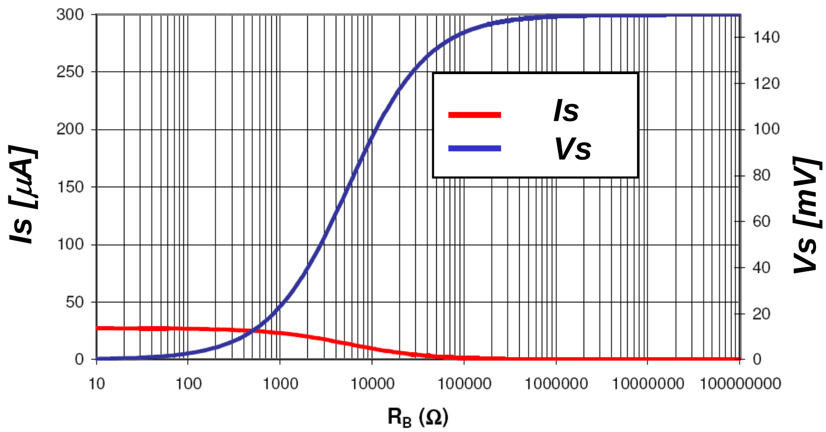


Figure 2-8. The Impact of Burden on the Rogowski Coil Output Voltage

Figure 2-9 illustrates characteristics of Rogowski Coils that can improve actual metering and protection system designs. When compared to conventional CTs, Rogowski Coils are linear and have a wide current range of application so one device can replace multiple conventional CTs and can be used as a multi-purpose sensor for both metering and protection.

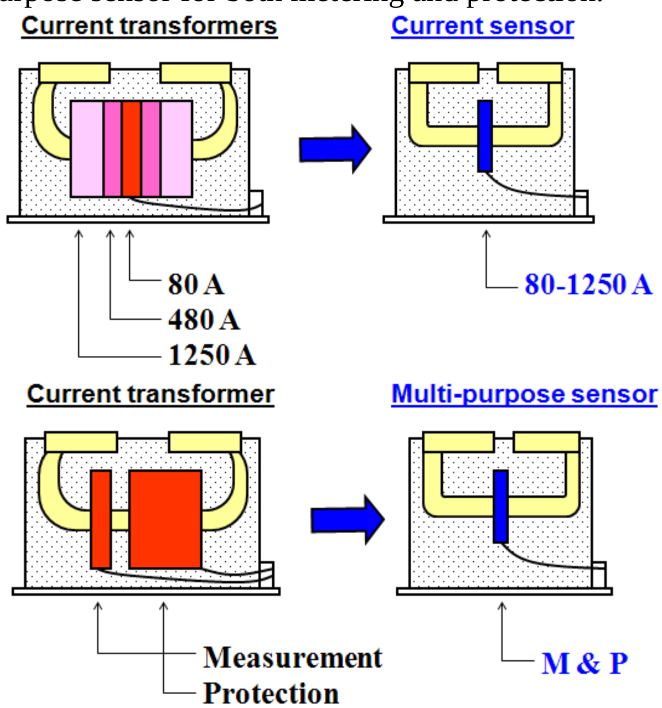


Figure 2-9. One Rogowski Coil can replace Multiple Current Transformers

2.2 Gapped-Core Current Transformers

Some iron-core current transformers are designed with an 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 70-80% 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 de-magnetized. An air-gap in the core reduces remanent flux. Typically, air gaps of 0.0001 – 0.0003 per unit of mean length of the magnetic path reduce remanent flux to an acceptable level. The main advantages of gapped core CTs are smaller CT size, since the air gap reduces the large core size needed to avoid saturation. Disadvantages are increased CT phase error, and the need for more time to allow stored energy to dissipate.

2.3 Linear Couplers

Traditionally, the problem of CT saturation was eliminated using linear couplers. A linear coupler is an air core mutual inductor that produces an output voltage proportional to the derivative of the primary current (Figure 2-10). Because there is no ferromagnetic material, 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 volts 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 busbars, 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 near zero. In actual operation, a small voltage exists due to effects such as different coil sensitivities resulting from manufacturing tolerances and external electromagnetic fields. Linear couplers will not be damaged and do not create a high voltage hazard for personnel when the secondary is open-circuited.

A linear coupler is constructed as a single coil and in some designs a return path is included. In the case of a Rogowski Coil, the return path geometry is critical to reduce the influence of external magnetic fields. Linear coupler designs generally result in the ratio being dependent on the conductor position in the window and is susceptible to external electromagnetic fields. Linear couplers are scaled with a fixed primary conductor location in the window.

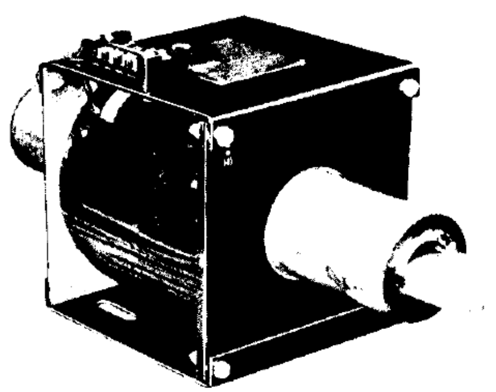


Figure 2-10. Linear Coupler

2.4 Comparison of V-I Characteristics

A comparison of V-I characteristics for non-gapped iron-core CTs, gapped iron-core CTs, linear couplers, and Rogowski Coils is shown in Figure 2-11. Non-gapped iron-core CTs are saturable and may retain remanent flux in the core up to 80% of the saturation flux. Gapped iron-core CTs are also saturable, but remanent flux is significantly reduced by the air gap. However, magnetizing current increases in a gapped iron-core CT, resulting in increased phase error. Linear couplers are air-core inductors and do not saturate, but are susceptible to external magnetic fields and do not have high accuracy. Rogowski Coils are linear and may be used for metering applications. Phase displacement is nearly 90°.

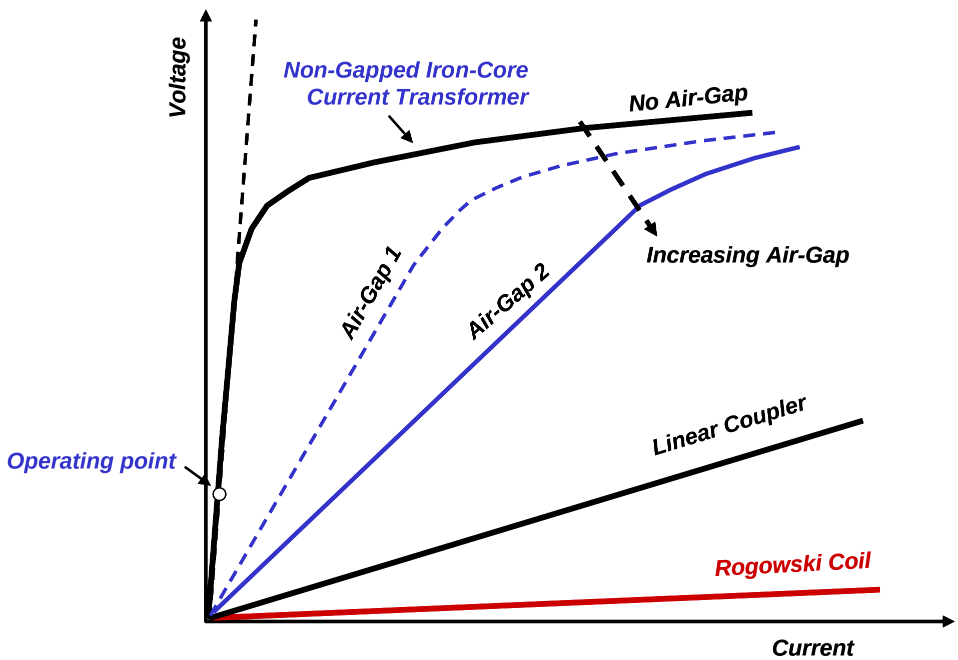


Figure 2-11. Comparative V-I Characteristics for Iron-Core CTs, Linear Couplers, and Rogowski Coils

2.5 Rogowski Coil Designs

There are different Rogowski coil designs such as single- or multi-layer, and rigid or flexible. Rigid Rogowski Coils are wound over a non-magnetic core usually having toroidal shape. This core may be made of plastic, epoxy, or other insulating material. The main advantage of using non-ferromagnetic material is obtaining the coil linearity since non-ferromagnetic material cannot saturate at high currents.

Single-layer coils have lower values of mutual inductance, series self-inductance, series resistance, and distributed capacitance than multi-layer coils that consist of two windings wound over each other. These parameters should be taken into consideration when performing measurements when high-frequency and low phase-displacement is required. The winding capacitance of the multi-layer coil increases approximately linearly with the number of turns. The series self-inductance of the coil increases with the square of the number of turns. These parameters influence the coil's frequency response.

Flexible Rogowski Coils may be wound over a silicone rubber core. In most cases, the winding is a single-layer style. The wire from the end of the coil winding ‘returns’ along the length of the coil through a conductor along the axis of the core as illustrated in Figure 2-3. This arrangement reduces magnetic pick-up and ensures that the coil terminals are at the same end of the coil. Flexible Rogowski Coils are convenient for measuring electric current in large or “awkwardly shaped” conductors, where space around the conductor is restricted or where only a lightweight transducer can be suspended on the conductor. Misalignment of the joining faces of a split Rogowski Coil has only a small effect on the amplitude and no effect on the phase. (Split iron-cored devices such as current transformers are subject to appreciable amplitude and phase errors if the halves are misaligned by even a small amount.) Flexible Rogowski Coils are usually delivered together with a device that integrates the coil output signal (Figure 2-12). Flexible Rogowski Coils are split-core style and can be installed without any need for electrical or mechanical interruption of the current-carrying conductor, while also ensuring galvanic insulation. This makes them easy to use. Accuracy of flexible coils is not as high (can be improved by proper positioning of the primary conductor).

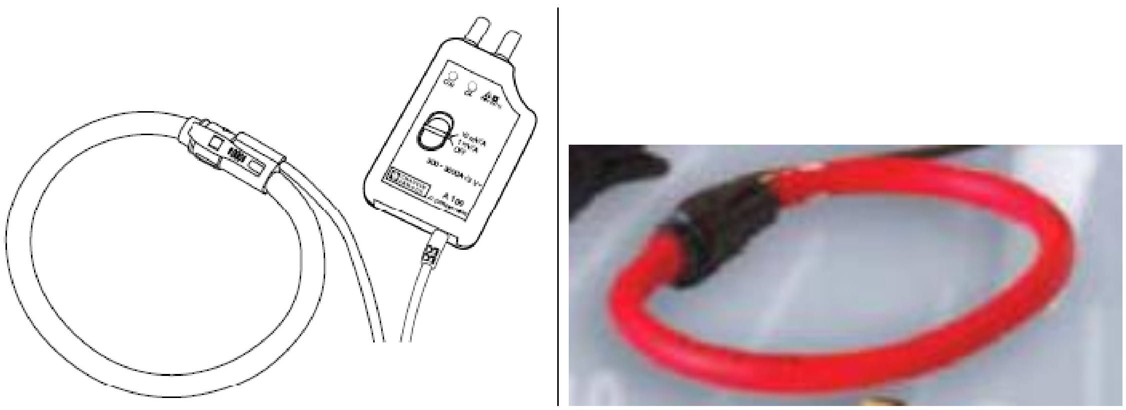


Figure 2-12. Flexible Rogowski Coil with Integrator

Paper [7] published in 1994 describes a combined current and voltage sensor for metering and protection in high voltage power systems. The sensor consists of an electric E-field voltage sensor and a magnetic H-field current sensor suitable for applications in 10 kV, 200 A. The H-field sensor shown in Figure 2-13 is in the form of a toroid having 1000 turns wound on an insulating former with an average diameter of 10.75 cm. It has an axial length of 10 cm, and radial thickness of 0.5 cm. The output voltage at 60 Hz and 200 A is 140.38 mV. The coil is compensated against any stray axial magnetic fields by using a compensating turn and a potentiometer.

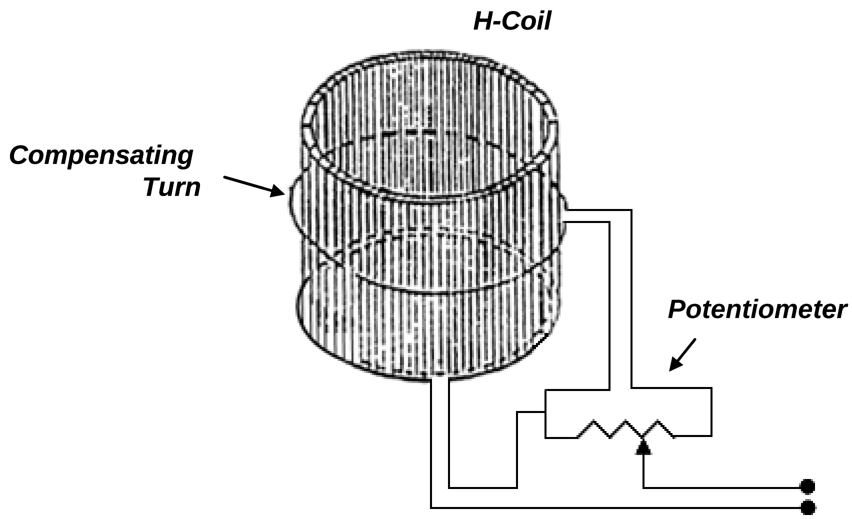


Figure 2-13. H-Coil with Compensating Turn and Potentiometer

Figure 2-14 shows a Rogowski Coil design that uses piecewise straight (discrete) coils connected in series to create a chain. Each coil may have several layers in order to provide sufficient output voltage. This chain may form a circle as a toroidal Rogowski Coil. In comparison to classical Rogowski Coils, this discrete coil solution is smaller and is thus suitable for applications with small space available. Due to the fact that the coils are straight, their production is easier than in the case of a continuously wound toroidal core. However, in this design the number of turns per unit length is no longer constant over the whole length of the winding of the measuring device. A structural discontinuity exists due to the fact that the last turn of one coil is joined with the first turn of the next coil through a wire. The mutual induction coefficient between the device and an external circuit is not zero. As a result, the impact from the external electromagnetic field is larger than in designs with a continuous winding. This impact can be reduced by implementing a larger number of discrete coils.

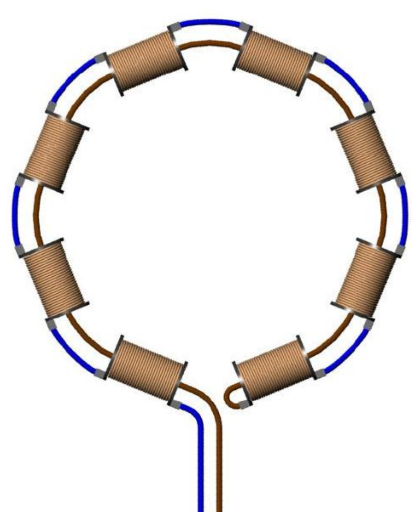


Figure 2-14. Rogowski Coil consisting of piecewise straight coils

Figure 2-15 shows a design that uses piecewise straight (discrete) coils implemented on PCBs. Several coils are connected in series forming a circular shape. The use of more PCB coils results in higher accuracy, lower sensitivity to positioning the conductor, and better external field rejection performance. Another advantage of this solution is lower production costs.

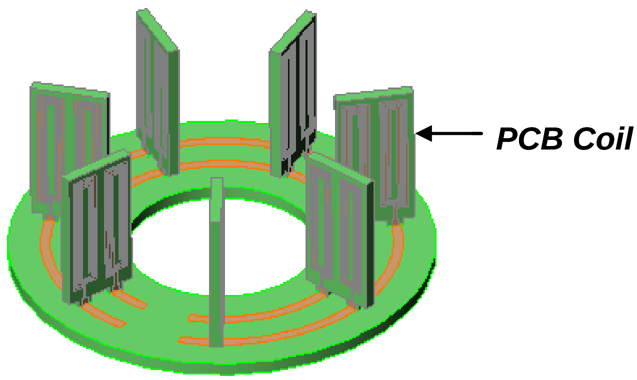


Figure 2-15. Rogowski Coil designed with Discrete Coils made on Printed Circuit Boards

Figure 2-16 shows a design where two windings are implemented on one single PCB. Two windings are wound in opposite directions to reduce magnetic pick-up from nearby conductors. Figure 2-17 shows a design using two PCBs sandwiched together as a multilayer PCB design. Each PCB has an imprinted coil. To reduce magnetic pick-up from nearby conductors, coils are wound in electrically opposite directions. The output voltage of PCB Rogowski Coils is smaller than the output voltage of Rogowski Coils designed with conventional wire wound over an "air-core" since the core cross-section area is smaller. However, this design allows precise coil manufacturing, resulting in high accuracy and higher immunity to external fields. Rogowski Coils have also been designed using the PCB design technique in a split-core style for installation around primary conductors without the requirement to open the primary conductors.

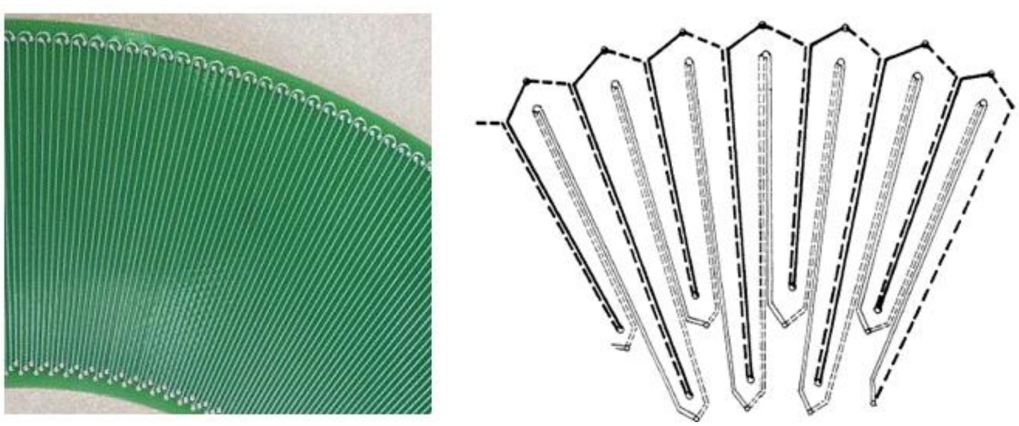


Figure 2-16. Rogowski Coil Designed on One Single Printed Circuit Board

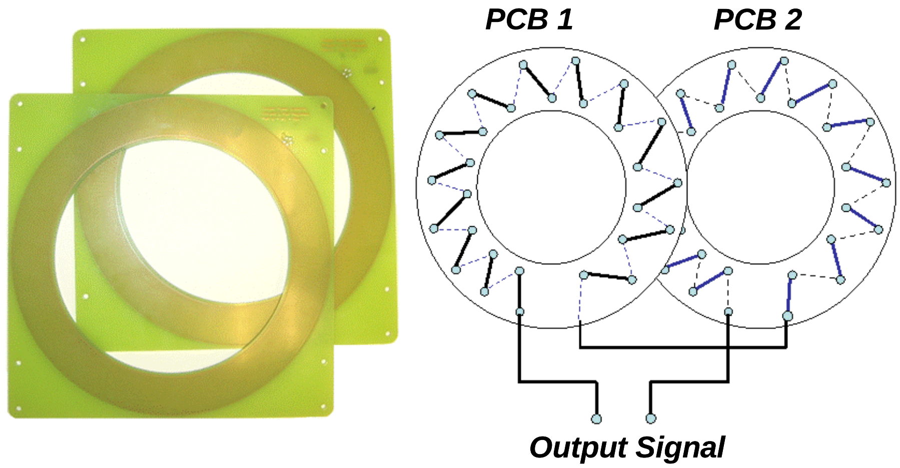


Figure 2-17. Rogowski Coil Designed on Two Printed Circuit Boards

The accuracy of flexible split-core Rogowski Coils is about 1%-3% and the position accuracy is about 2%. Figure 2-18 shows designs of non split-core Rogowski Coils from three different manufacturers. The accuracy of each coil depends on the coil design and operating conditions. Generally, the accuracy class is 0.5%, but coils can be designed for 0.1% accuracy class, making them suitable for metering and protection applications.

Non split-core style printed circuit board Rogowski Coil designs from three different manufacturers are shown in Figure 2-19. The accuracy of PCB coils depends on the coil design. Generally, the accuracy class is 0.2%-0.5%, but coils can be designed for 0.1% accuracy class, making them suitable for metering and protection applications. For installation of non split-core style coils, primary conductors must be opened. Figure 2-20 illustrates a split-core Rogowski Coil design for installation around primary conductors that cannot be opened. Figure 2-20 also shows a split-core Rogowski Coil used to measure current in multiple conductors and one application measuring current in a water-cooled conductor with a large cross-section. PCB coil designs have usually lower output voltages compared to rigid Rogowski coils due to small turn area, therefore special care must be taken to protect low-output signal from external disturbances.

Some companies have manufactured combined voltage and current sensors as one device. As Rogowski Coils can be made much smaller than conventional CTs and there exist technologies that could replace conventional VTs as well, there is a great benefit to combining these separate devices into one unit. A combined classical inductive transformer is a bulky device, having big size and weight. The combination of Rogowski Coil and some Low-power voltage sensor can fit basically into the same body as a classical block-type CT with a lot of margin or can be made much smaller. Some companies are using these advantages and they have manufactured combined voltage and current sensors as one device. Figure 2-21 shows designs from two different manufacturers.

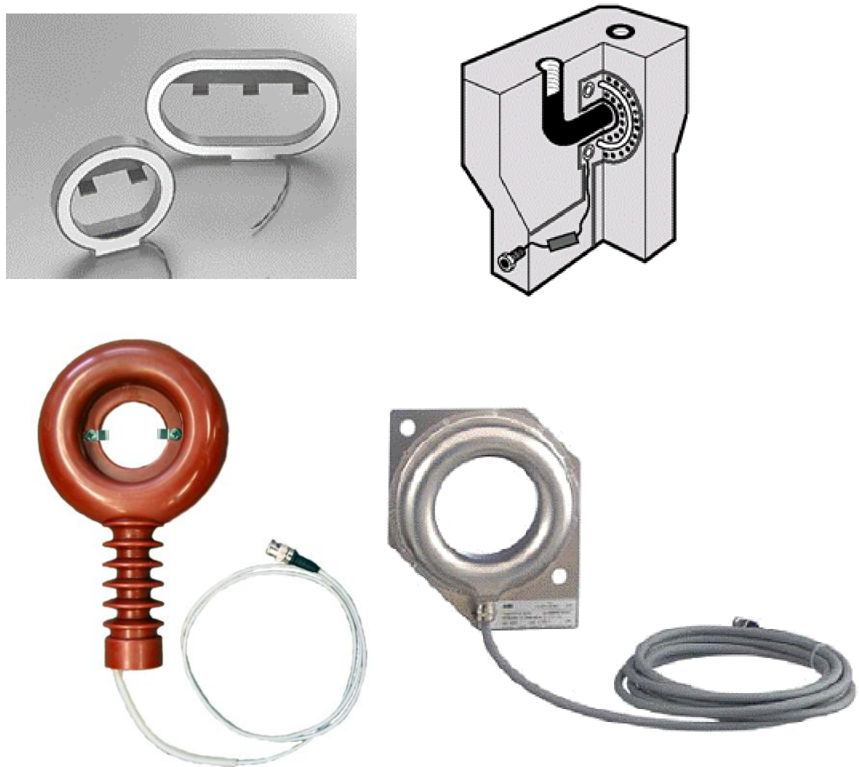


Figure 2-18. Rigid Non-Split-Wound-Core Rogowski Coil Designs

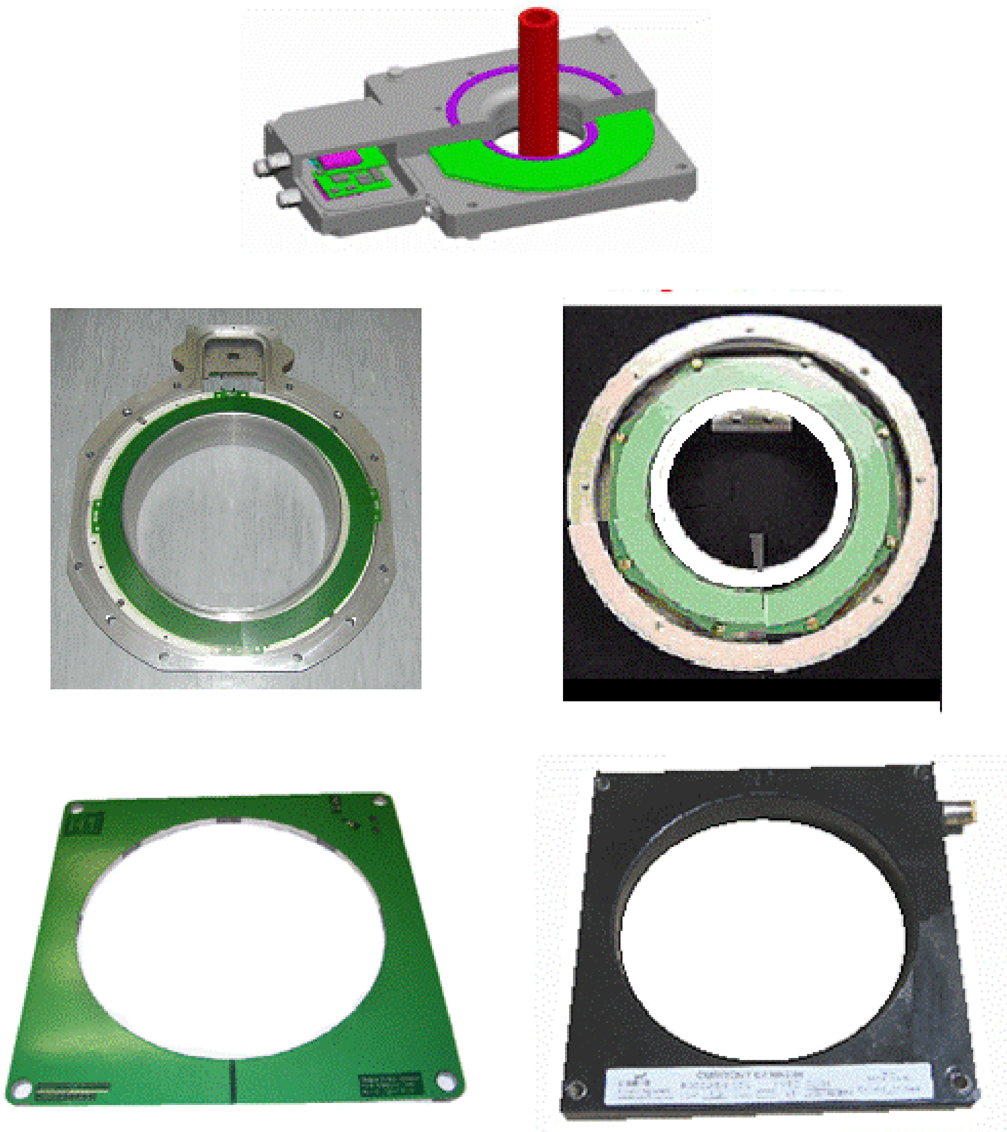
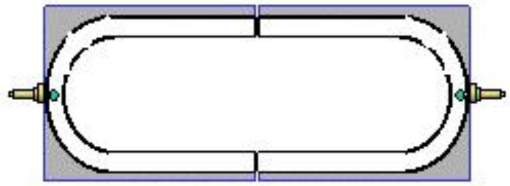


Figure 2-19. Printed Circuit Non-Split Core Board Rogowski Coils



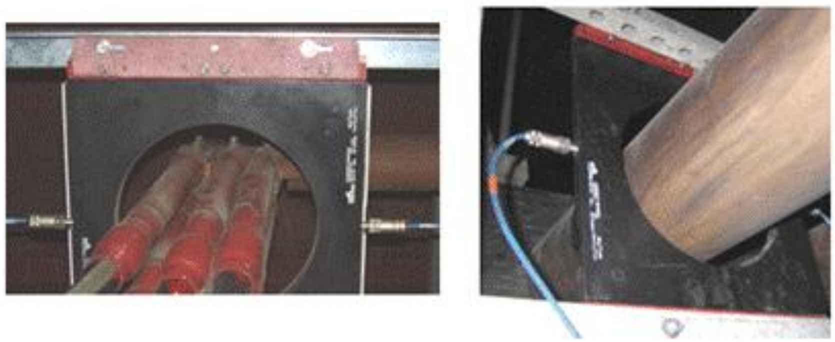


Figure 2-20. Split-Core PCB Rogowski Coil Design (design illustration, coil measuring current in six conductors, and coil measuring current in one water-cooled conductor)

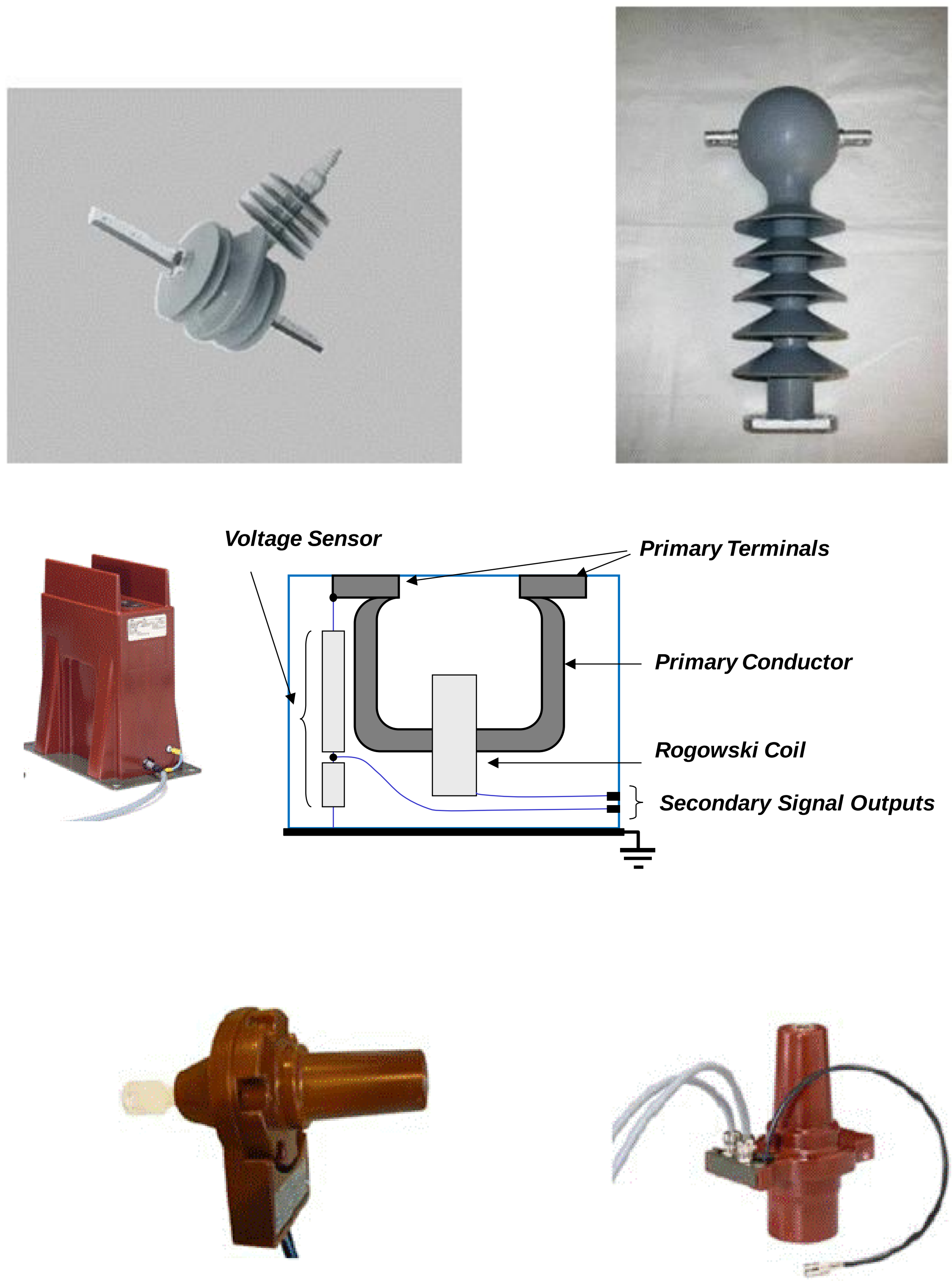


Figure 2-21. Combination Voltage and Current Sensors

2.6 Linearity

Rogowski Coils are wound over a non-magnetic (air core) material, instead of over an iron core like a conventional CT. As a result, Rogowski Coils are linear since the air core cannot saturate. Figure 2-22 shows the Rogowski Coil linearity in the current range of 1 A to 100 kA.

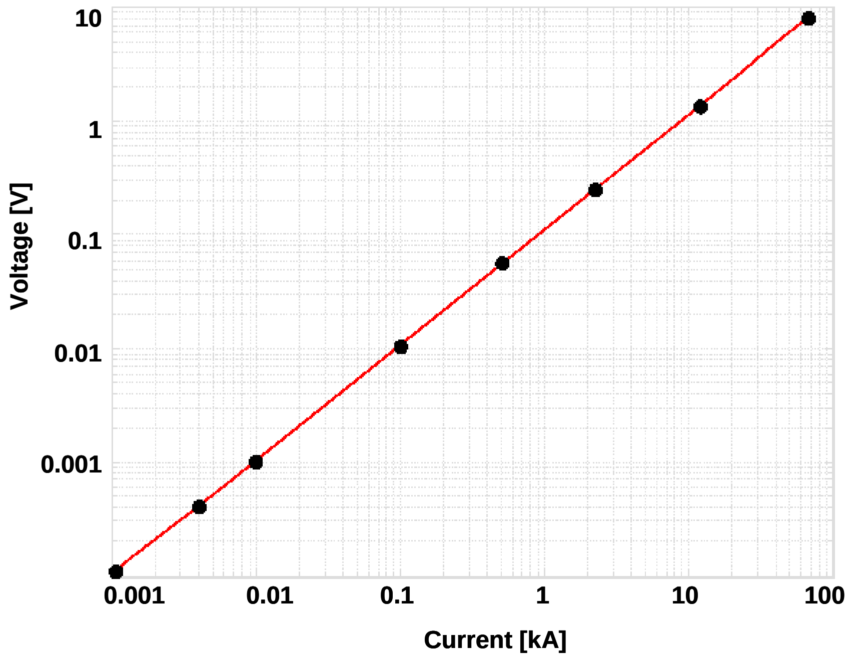


Figure 2-22. Rogowski Coil Linearity

2.7 Transient Response

Figure 2-23 shows a comparison in transient response between conventional CTs and Rogowski Coils. When the iron-core current transformer saturates, its secondary current waveforms are distorted. The Rogowski Coil output signals cannot be distorted. The integrated signal accurately reproduces the original waveform. In Figure 2-23, the Rogowski Coil output signal overlays the primary current waveform. To visually depict the difference in transient response between CTs and Rogowski Coils, Figure 2-24 shows the calculated RMS values of the primary current from Figure 2-23. Trace (a) is the original primary current with DC offset. Traces (b) and (c) are the RMS values derived by the relay for the same primary current when the 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 saturated. The shaded area is the reduced RMS value of the primary current that the relay cannot sense due to CT saturation.

Figure 2-25 shows non-integrated and integrated Rogowski Coil signals for high power tests at 68 kA fault currents. The Rogowski Coil preserves linearity at high fault currents. The non-integrated Rogowski Coil signal attenuates the primary circuit DC component. However, the integrated Rogowski Coil signal accurately reproduces the primary currents.

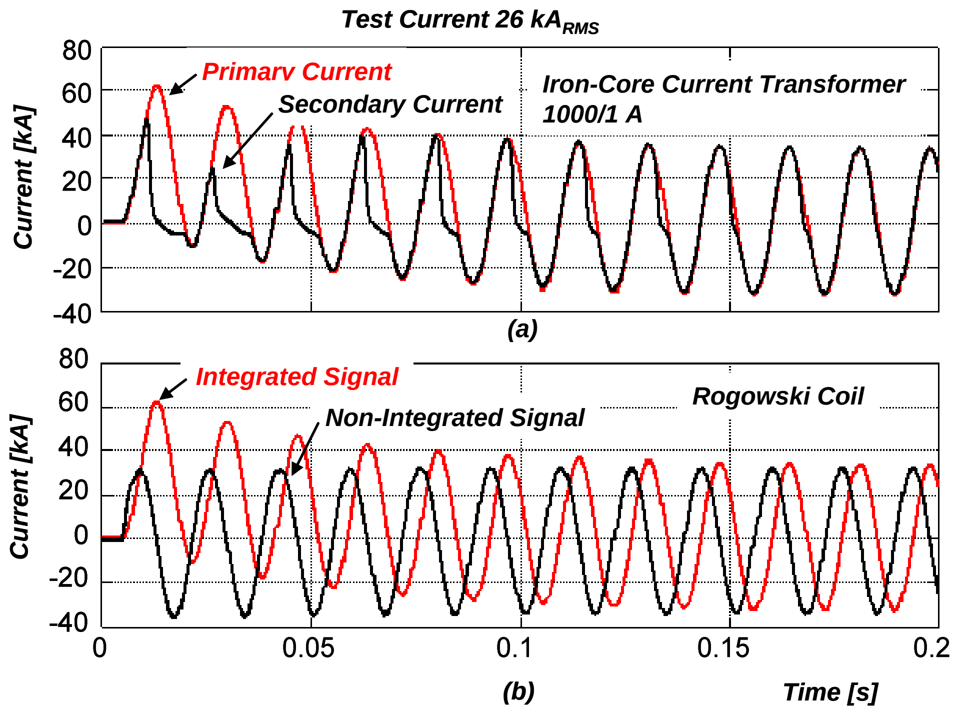


Figure 2-23. Comparison of Current Transformer and Rogowski Coil Transient Response

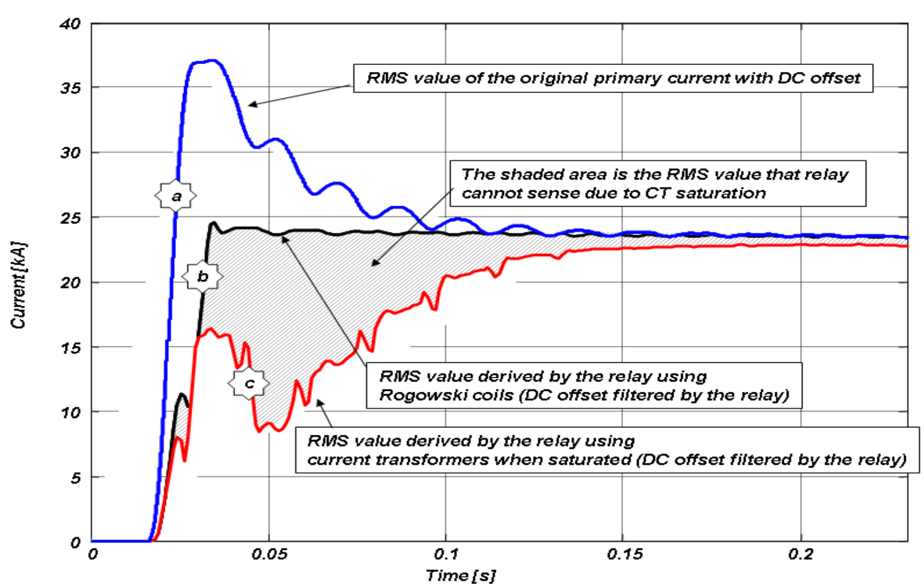


Figure 2-24. Comparison of the Rogowski Coil Integrated Secondary RMS Signal and the Saturated Current Transformer Secondary RMS Current for an Asymmetrical Fault Current

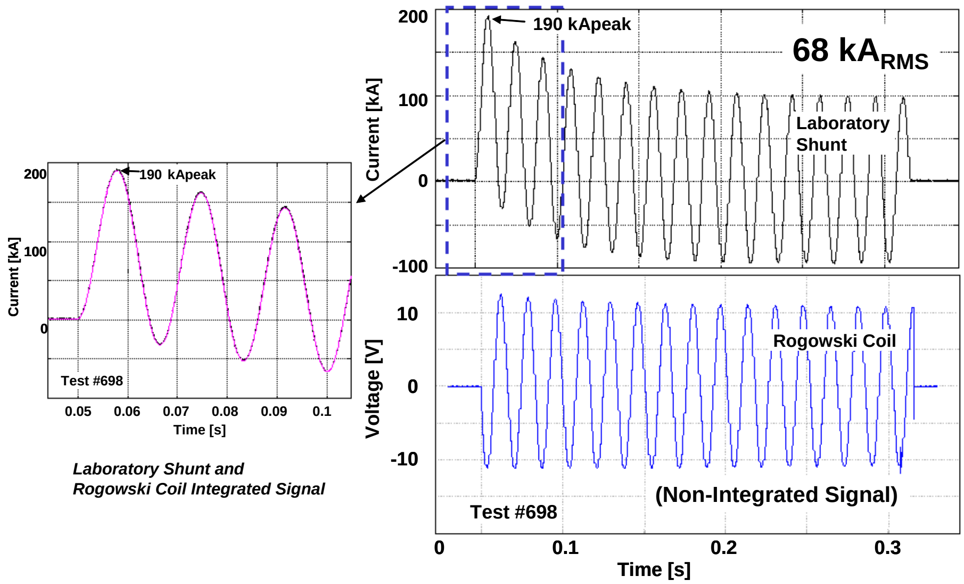


Figure 2-25. Laboratory Test Results of a Rogowski Coil Transient Response

2.8 Frequency Response

Rogowski Coil designs generally have high frequency response relative to conventional CTs. Depending on the design, the Rogowski Coil frequency response can be significantly higher than 1 MHz which makes them suitable for traveling wave-based protection applications. Rogowski Coils are frequency-dependent devices. However, the Rogowski Coil output signals are linearly proportional to the frequency. Integrated signals are frequency-independent (see Figure 2-26) over typical operating ranges of frequency until the self resonance point of the sensor is reached.

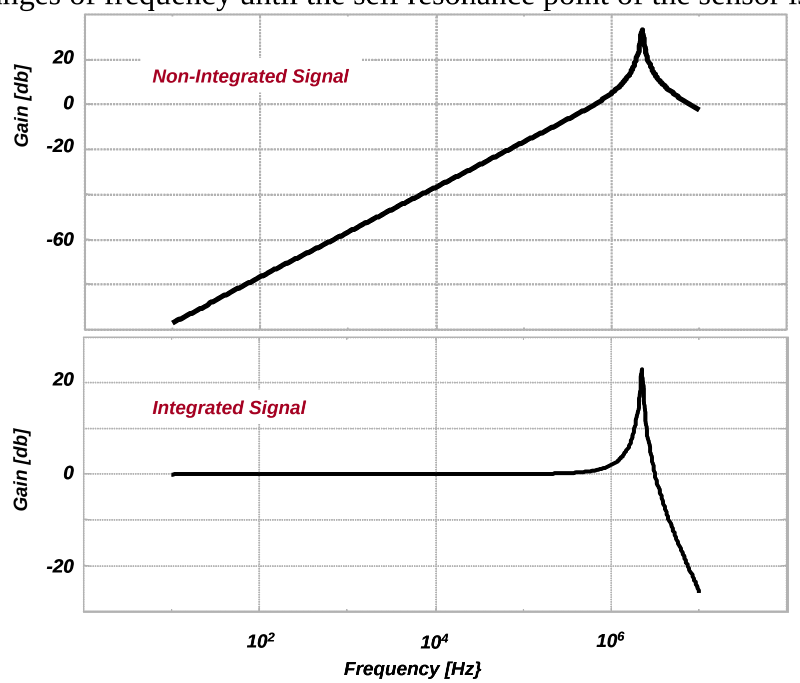


Figure 2-26. Rogowski Coil Frequency Response

2.9 Rejection of External Electromagnetic Fields

Influence from nearby conductors is one of the most important tests to determine the Rogowski Coil current sensor accuracy. The effectiveness of Rogowski Coils in rejecting an external electromagnetic field depends on the coil design. The main factors are consistency in the coil core cross section, winding implementation, and counter loop designs. The effectiveness in rejecting an external electromagnetic field for printed circuit board Rogowski Coils designed by imprinting windings on two separate boards sandwiched together is shown in Figure 2-28. Tests were performed in a high power laboratory at test current magnitudes of 60 kA_{RMS}. The test setup is shown in Figure 2-27. For comparison, two Rogowski Coils were tested. RC1 was installed to measure the test current and RC2 was located 2 inches 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 by the recorder. The results are shown in Figure 2-28. The influence from the primary conductor was below 0.01%, verifying very good coil immunity to the external magnetic fields. In most applications, Rogowski Coil current sensors will be installed at a distance from nearby conductors. Since the magnetic field from a current carrying conductor declines proportional to the distance squared, the influence will be near zero.

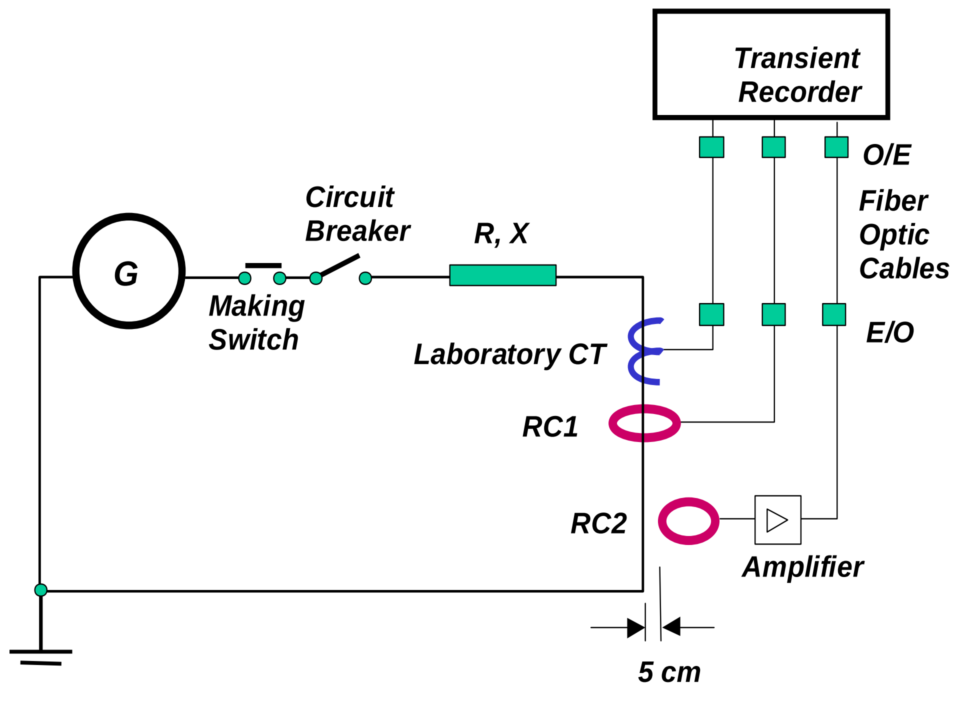


Figure 2-27. High Power Test Setup for Testing the Impact of External Electromagnetic Fields

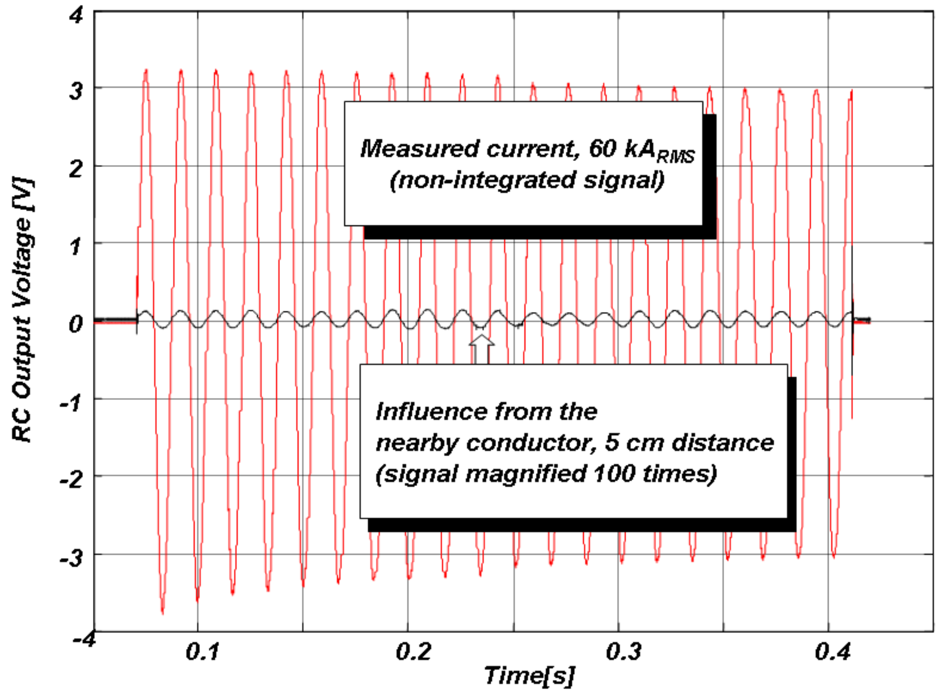


Figure 2-28. Influence from the Nearby Conductor

2.10 Review of Rogowski Coil Characteristics

2.10.1 Accuracy

Rogowski Coils can be used for metering, protection, and control. Traditionally, separate secondary windings for measurement and protection have been used. The wide range linearity of sensors makes it possible to combine sensors for measurement and protection in one single device, resulting in smaller sensor dimensions, simpler low-voltage circuit cabling, and more uniform cubicle design.

2.10.2 Linearity (No Saturation)

Rogowski Coils are linear over a wide range of currents. No order-specific calculation for various primary currents is necessary. There is no need for calculation of accuracy limit factors.

2.10.3 No Accuracy versus Burden Calculation

Rogowski Coils are used with micro-processor IEDs that have high input impedance. Therefore, no calculation for accuracy versus burden is required.

2.10.4 Size

Rogowski Coils are small and compact. They can easily be combined with voltage sensors in one device: a combi-sensor. They can be integrated into other equipment like switches, reclosers, circuit breakers, and power transformers. They can be installed around bushings or post insulators, resulting in more compact equipment and switchgear.

2.10.5 Weight

Rogowski Coils are lightweight, especially compared to conventional current transformers with heavy cores. An even bigger weight/size benefit results from the use of combined units, comprising both current and voltage sensors.

2.10.6 Safety

Low Secondary (Transmitted) Voltage. Figure 2-29 shows hazardous voltages that may exist when a conventional CT secondary opens. The Rogowski Coil output signal is low enough to be harmless to secondary equipment and people, even when the highest currents and voltages occur on the primary side. A broken circuit or short-circuit in the signal cable will cause no hazards or damage. Even under fault conditions such as a primary short-circuit, the transmitted signal is approximately 10 V (depending on scale factor in specific application) or less. In addition, Rogowski Coils have a small mutual inductance so they cannot produce significant current, even if the terminals are shorted. These voltage levels are generally below the values where operating personnel need to apply specific safety precautions and cannot cause hazards to secondary insulation and instruments. Therefore, there is no need to calculate an instrument security factor.

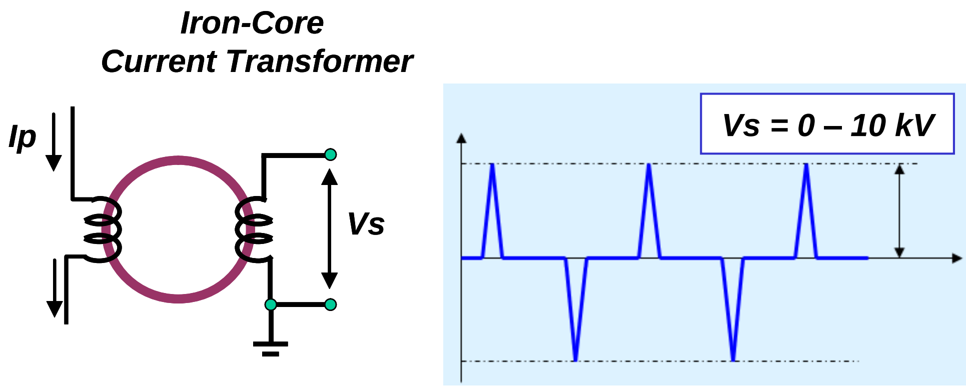


Figure 2-29. Hazardous Voltages for an Open CT Secondary

Terminal Blocks Not Required. Rogowski Coils are interconnected to relays by shielded cables and connectors (Figure 2-30). Terminal blocks are not used since Rogowski Coils can be open-circuited without any risk of developing voltages dangerous for personnel. In addition, a cable is a part of the Rogowski Coil and the whole setup is accuracy tested. Therefore, there is no need for additional cabling and calculation of burden impedance/influence and providing fast installation on-site without any tools.

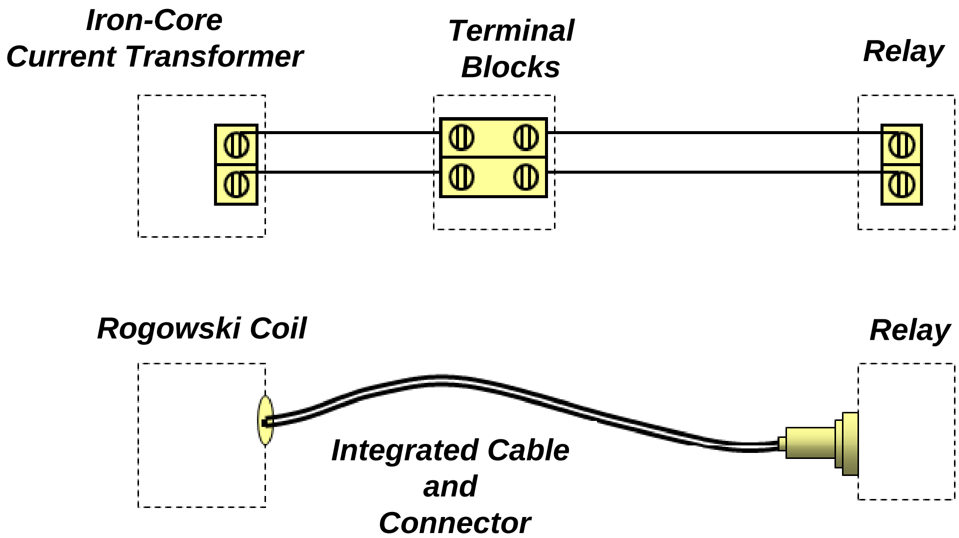


Figure 2-30. Interface to Relays for CTs and Rogowski Coils

2.10.7 Simplified Ordering

Since one Rogowski Coil basic design can cover a wide range of applications, the amount of product versions is considerably small. Order-specific actions are minimal and the logistic process short. As a result, the delivery time for standard sensors may be shorter than for traditional instrument transformers.

2.10.8 Improved Switchgear Design and Performance

Rogowski Coils enable improving switchgear design by reducing switchgear dimensions and improving metering, control, and protection performance. This is possible because Rogowski Coils accurately reproduce primary currents under normal and fault conditions, including harmonics and high-frequency disturbances.

Switchgear features enhanced by modern relays and sensors:

- Better selectivity
- Improved fault location
- Better disturbance analysis
- Power quality measurements
- Remote monitoring and control
- Easy maintenance
- Optimized maintenance program
- Simplified IED testing
- Faster installation within switchgear
- Optimized wiring

- Lower weight
- Small Rogowski coil size contributes to improved air-flow (cooling) inside switchgear
- Lower total costs of ownership

2.10.9 Environmental Aspects

Less use of raw materials. Sensors with small dimensions enable design of compact and uncomplicated cubicles.

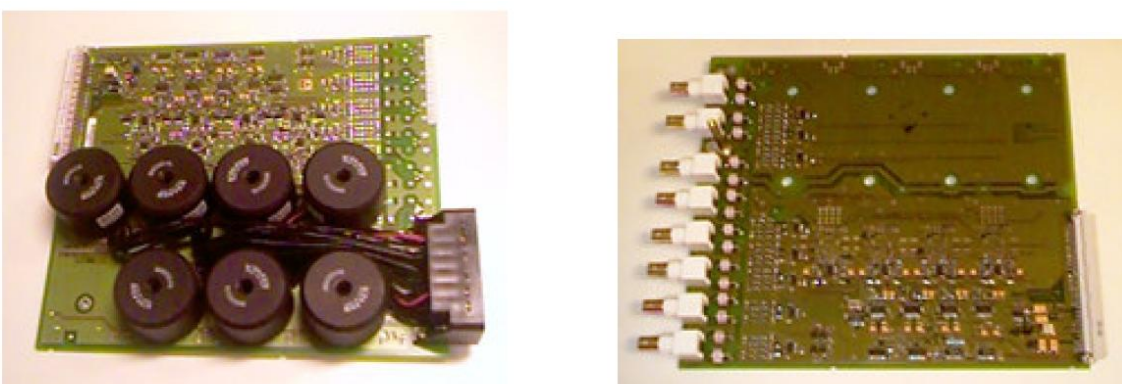
Less copper inside cast resin. The amount of copper in a single Rogowski Coil current sensor is only a fraction of that used in a corresponding multi-core current transformer. The absence of iron cores makes the recycling of the primary winding possible.

Small Power Consumption. The efficiency of a sensor is high when compared with instrument transformers. In addition, there are no losses in the secondary cabling.

2.10.10 Relay Design Simplification

Current transformers 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 equipment does not require high power sensor output and allows the use of novel high performance sensors, such as Rogowski Coils for current measurements.

Figure 2-31b shows simplification in the relay input board design when using Rogowski Coils compared to a conventional CT based input board shown in Figure 2-31a. In addition, this design requires less space inside the relay, and the weight and cost of the relay can be reduced. However, the relay may be designed to have input boards that accommodate both technologies.



a) Input Board for Conventional CTs

b) Input Board for Rogowski Coils

Figure 2-31. Relay Input Board for Conventional CTs and Rogowski Coils

3 Standard Requirements for Protective Relaying and Metering

Standards IEEE C37.92™-2005, IEC 60044-8, IEC 61850-9-1, and IEC 61850-9-2 define the interface between low-power sensors and protective relays or other substation intelligent electronic devices. IEEE Std C37.235™-2007 provides guidelines for the application of Rogowski Coils used for protective relaying purposes. Existing Standard IEC 60044-7 and 60044-8 will migrate into the new structure of IEC 61869.

International Standard IEC 61869 is a family of standards that specify requirements for conventional and non-conventional instrument transformers. Standard IEC 61869-10 specifies requirements for Low Power Stand Alone Current Sensors (LPCS). This Standard is based on the IEC 61869-1 and IEC 61869-9-1 and shall be read in conjunction with the IEC 61869-1 and the IEC 61869-9-1. This section includes selected paragraphs from Standard IEC 61869-10.

3.1 Scale Factor

Factor by which the value of the secondary voltage is to be multiplied to obtain the value of the primary current.

$$k_{sf} = \frac{I_{pr}}{U_{sr}}$$

Where

k_{sf} is the scale factor;

I_{pr} is the r.m.s. value of the rated primary current;

U_{sr} is the r.m.s. value of secondary voltage at rated primary current.

Note: This definition is only related to rated burden and rated frequency. It does not take into account direct signal components ($U_{sdc} = 0$) as well as harmonic and sub-harmonic components ($i_{p\ res}(t) = 0$, $u_{p\ res}(t) = 0$).

Note: Scale factor is determined for each individual sensor.

Rogowski coils can be used under different system frequencies without any change in design and without loss of accuracy. However, when the system frequency is different from the rated frequency, the rated scale factor must be calculated by using the following equation

$$k_{sf} = \frac{I_{pr}}{U_{sr}\dfrac{f}{f_r}}$$

Where

f_r is the rated frequency;

f is the system frequency.

3.2 Standard Accuracy Classes

3.2.1 Metering LPCS

The standard accuracy classes for measuring LPCS are:

0.1 – 0.2 – 0.5 – 1 – 3

Limits of current error and phase displacement for LPCS. For classes 0.1 – 0.2 – 0.5 and 1, the current and phase errors at rated frequency and at rated burden shall not exceed the values given in Table 3-1.

Note 1: In general, the prescribed limits of current and phase errors are valid for any given position of an external conductor spaced at a distance in air not less than that required for insulation in air at the highest voltage for equipment.

Note 2: Proper positioning of primary conductor should be defined by manufacturer in the installation instructions

Table 3-1 Limits of current and phase errors for measuring LPCS (classes from 0.1 to 3)

Accuracy class	± percentage current (ratio, scale factor) error at primary current shown below				± phase error at primary current shown below							
					Minutes				Centiradians			
	$0.05I_{pr}$	$0.2I_{pr}$	I_{pr}	$K_{pcr}\ I_{pr}$	$0.05I_{pr}$	$0.2I_{pr}$	I_{pr}	$K_{pcr}\ I_{pr}$	$0.05I_{pr}$	$0.2I_{pr}$	I_{pr}	$K_{pcr}\ I_{pr}$
0.1	0.4	0.2	0.1	0.1	15	8	5	5	0.45	0.24	0.15	0.15
0.2	0.75	0.35	0.2	0.2	30	15	10	10	0.9	0.45	0.3	0.3
0.5	1.5	0.75	0.5	0.5	90	45	30	30	2.7	1.35	0.9	0.9
1.0	3.0	1.5	1.0	1.0	180	90	60	60	5.4	2.7	1.8	1.8
3.0	-	4.5	3	3	-	-	-	-	-	-	-	-

For classes 0.2 S and 0.5 S, the current error and phase error of current transformers for special applications at rated frequency shall not exceed the values given in Table 3-2.

Table 3-2 Limits of current and phase errors for measuring LPCT for special applications

Accuracy class	± percentage current (ratio, scale factor) error at primary current shown below					± phase error at primary current shown below									
						Minutes					Centiradians				
	$0.01\ I_{pr}$	$0.05\ I_{pr}$	$0.2\ I_{pr}$	I_{pr}	$K_{pcr}\ I_{pr}$	$0.01\ I_{pr}$	$0.05\ I_{pr}$	$0.2\ I_{pr}$	I_{pr}	$K_{pcr}\ I_{pr}$	$0.01\ I_{pr}$	$0.05\ I_{pr}$	$0.2\ I_{pr}$	I_{pr}	$K_{pcr}\ I_{pr}$
0.2 S	0.75	0.35	0.2	0.2	0.2	30	15	10	10	10	0.9	0.45	0.3	0.3	0.3
0.5 S	1.5	0.75	0.5	0.5	0.5	90	45	30	30	30	2.7	1.35	0.9	0.9	0.9

3.2.2 Protective low-power stand-alone current sensors

Rated accuracy limit primary current. The standard accuracy limit currents are:

5000 – 7500 – 12500 – 25000 – 31500 – 40000 – 50000 – 63000 A

NOTE: Depending on the application, other values can be used.

Accuracy class designation. For protective electronic current transformers, the accuracy class is designed by the highest permissible percentage composite error at the rated accuracy limit primary current prescribed for the accuracy class concerned, followed by the letter “P” (meaning protection) or by the letters “TPE” (meaning transient protection electronic classes).

Standard accuracy classes. The standard accuracy classes for protective LPCS are:

5 P, 10 P, and 5TPE.

Limits of error. At rated frequency and at rated burden, the current (ratio or scale factor) error, phase error and composite or composite scale factor error and, during application of specified duty cycle if transient performance is specified, the maximum peak instantaneous error shall not exceed the values given in Table 3-3. The phase error indicated in the tables of limits of errors are the values remaining after the compensation of the rated delay time.

Table 3-3 Limits of error

Accuracy class	Current (ratio, scale factor) error at rated primary current %	Phase error at rated primary current		Composite (composite scale factor) error at rated accuracy limit Primary current %	At accuracy limit condition Maximum peak instantaneous error %
		Minutes	Centiradians		
5TPE	± 1	± 60	± 1,8	5	10
5 P	± 1	± 60	± 1,8	5	-
10 P	± 3	-	-	10	-
NOTE 1 Information on transient conditions related to class TPE and classes (PR and PX) defined in IEC 60044-1 and other classes (TPS, TPX, TPY, TPZ) defined in IEC 60044-6 are given in annex A.					

3.3 Multipurpose ECT

Multipurpose electronic current transformers (ECT) are designed for both measurement and protection. Multipurpose ECT should comply with all the clauses of Standard IEC 61869.

3.4 Standard values for rated primary current

The standard values of rated primary currents are:

25 – 50 – 100 A

and their decimal multiples or fractions..

NOTE: The same LPCS could be used in a wide range of primary current values. Selection of proper primary and secondary rated values should be done in line with input limits of the measuring equipment.

3.5 Standard values for rated extended primary current factor

The standard values for rated extended primary current factor are:

5 – 10 – 20 – 50 – 100

and their decimal multiples or fractions.

NOTE: The same LPCS could be used in a wide range of primary current values. Selection of proper primary and secondary rated values should be done in line with input limits of the measuring equipment.

3.6 Rated continuous thermal current

The rated continuous thermal current shall not be lower than the rated primary current or the rated extended primary current if specified.

3.7 Standard values of rated secondary voltage

The standard r.m.s. values of rated secondary voltage at rated primary current are:

22.5 mV and 200 mV

NOTE: Typical electronic relays and meters can easily accommodate a small variation in the rated value of the standard rated secondary voltage. For example, an electronic relay expecting a secondary voltage of 200 mV can easily accommodate secondary voltage of 150 mV and 225 mV.

For existing designs, the following r.m.s. values of rated secondary voltage at rated primary current are also allowed

225 mV for LPCT delivering an output voltage proportional to the current

150 mV for Rogowski coil delivering an output voltage proportional to the derivative of the current.

NOTE: The same LPCS could be used in different applications requiring different rated secondary voltage values. Selection of proper primary and secondary rated values should be done in line with input limits of the measuring equipment.

3.8 Rogowski Coil Burden

The standard values of rated burden in ohms are:

2 kΩ – 20 kΩ – 100 kΩ – 1 MΩ – 4 MΩ

The burden connected to LPCS has to be equal to, or higher than, the rated burden.

NOTE: Attention should be paid to the parallel capacitance of electrical measuring instruments or electrical protective devices.

3.9 Range of Operation

Figure 3-1 shows the accuracy limits of a multipurpose ECT (i.e. an ECT which obeys measuring and protective requirements), which is also specified for transient response.

The marks show at which primary current the accuracy is actually tested during type tests. The lines show in which primary current range the accuracy is supposed to be maintained.

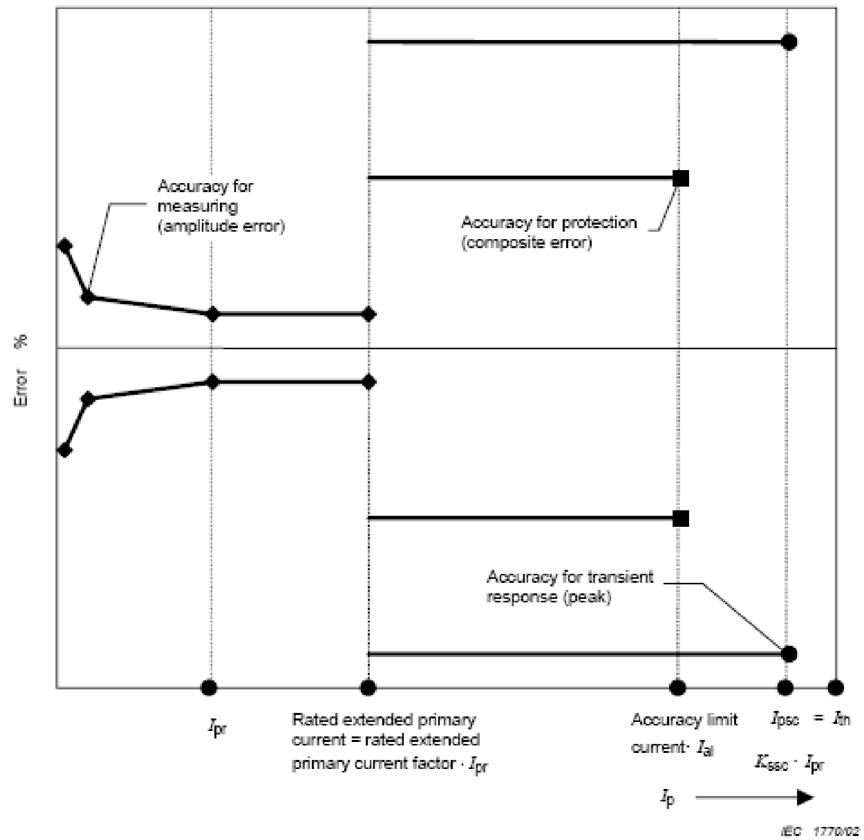


Figure 3-1. Accuracy Limits of a Multi-Purpose ECT

If an application requires a small deviation between the phase and/or amplitude error between the ECTs on different phases, the user shall select a set of electronic current transformers with similar calibration data, as is also done with conventional transformers. The calibration data is available from routine testing. A special test is not required.

4 Rogowski Coil Application Designs

Rogowski Coils have been designed and applied at all voltage levels (low, medium, and high voltage). They have been designed for indoor and outdoor installations and applied for metering, protection, and control. This section reviews different designs and applications.

4.1 Low Voltage Application Designs

Figure 4-1 shows low-voltage switchgear that uses Rogowski Coils for metering and protection. Circuit breakers are equipped with self-powered, microprocessor-based trip-devices to sense overload and short circuit conditions. Rogowski Coil accuracy is better than 1%.

Figure 4-1. Rogowski Coil Applications in Low Voltage Switchgear

4.2 Energy monitoring

Figure 4-2 shows flexible Rogowski Coils for energy measurements in applications such as industrial production machines, supermarkets, data centers, schools, and TV studios.

Figure 4-2. Rogowski Coil Application for Energy Measurements

4.3 Medium Voltage Application Designs

Figure 4-3 and Figure 4-4 show applications of Rogowski Coils combined with voltage sensors.

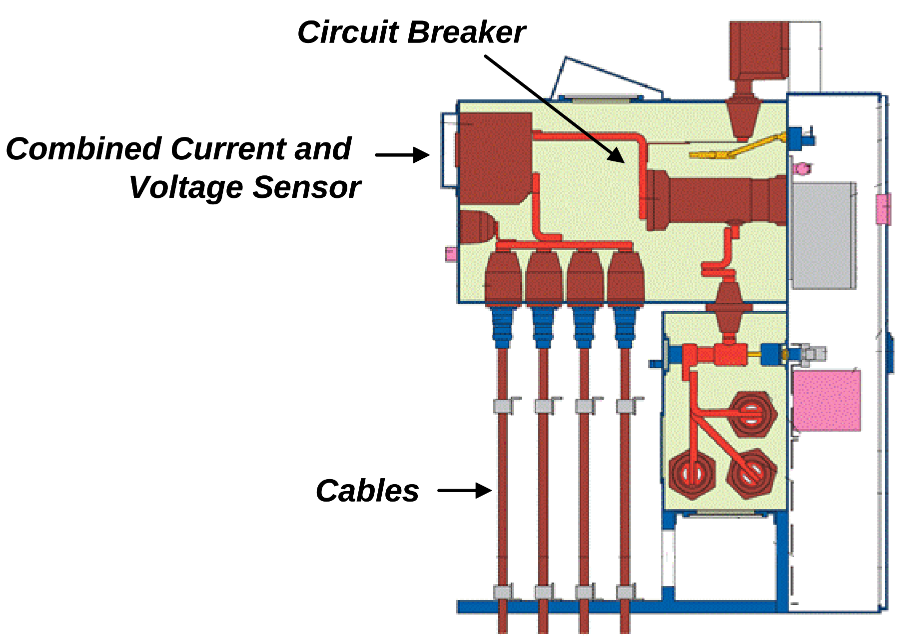


Figure 4-3. Rogowski Coil Applications in Medium Voltage Switchgear (combined current and voltage sensor)

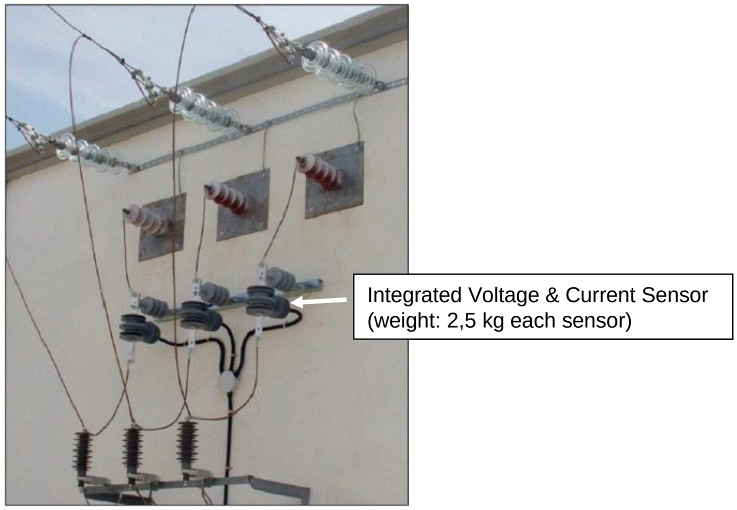


Figure 4-4. Outdoor Application of Rogowski Coils Combined with Voltage sensors

Figure 4-5. Rogowski Coil Integration with Medium Voltage Circuit Breakers

Figure 4-6. Rogowski Coil Applications in Medium Voltage Switchgear (Rogowski coil integrated into bushings)

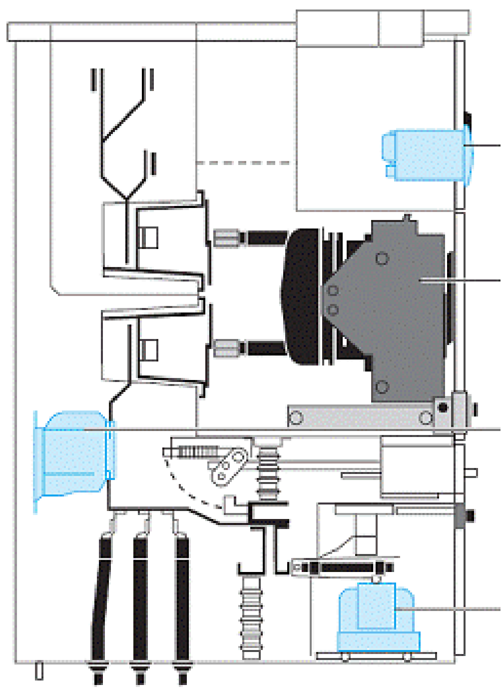


Figure 4-7. Rogowski Coil Applications in Medium Voltage Switchgear

Applications in Reclosers. Figure 4-8 to Figure 4-11 show Rogowski Coil applications integrated with reclosers. Figure 4-10 is an application of voltage and current measurement on all six bushings of the recloser using capacitively coupled voltage sensors and Rogowski Coil current sensors.

Phase Current: Range 0 - 630A, Accuracy ± 1% or ± 4A

Residual Current: Range 0 - 400A, Accuracy ± 5% or 0.5A

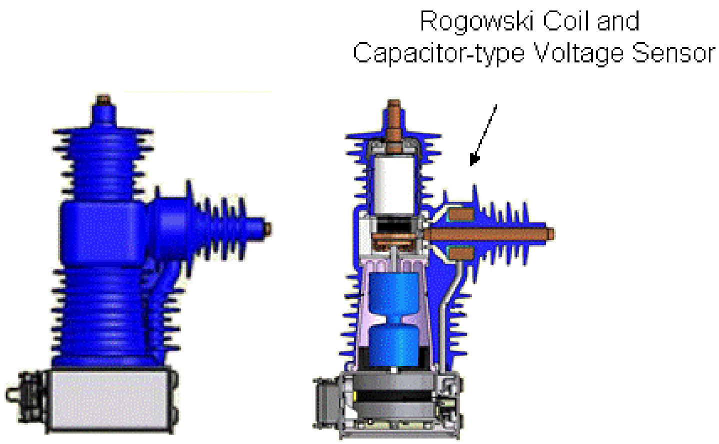


Figure 4-8. Rogowski Coils Integrated in Recloser (example 1)

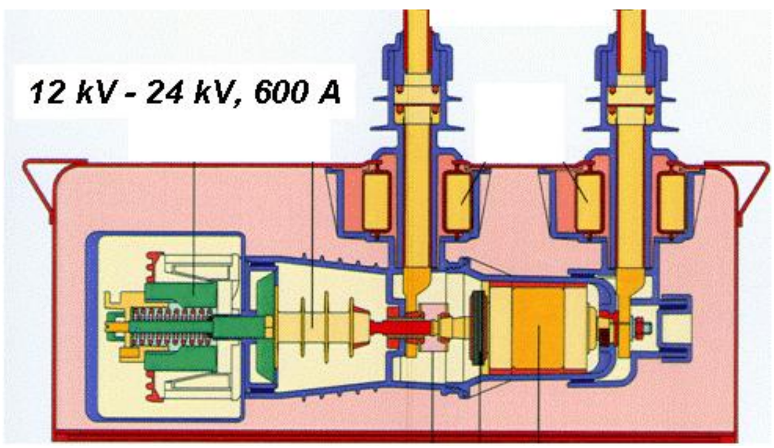


Figure 4-9. Rogowski Coils Integrated in Recloser (example 2)

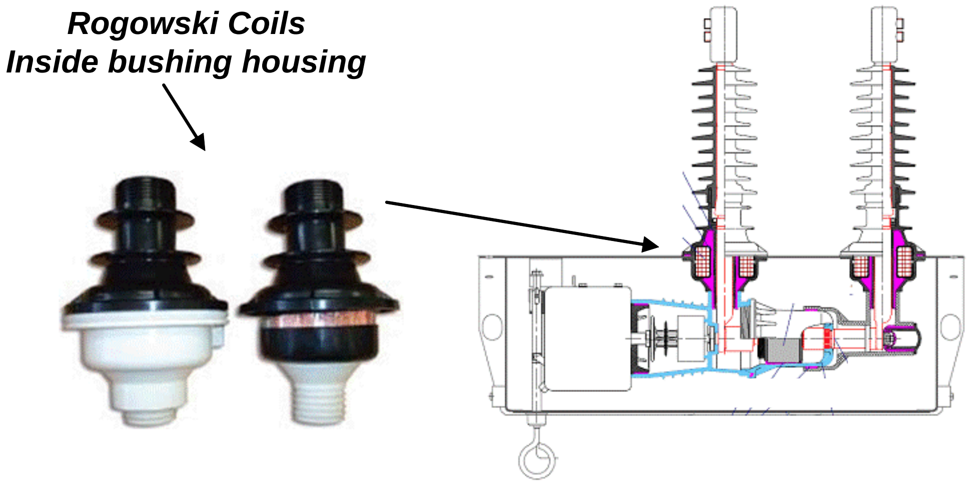


Figure 4-10. Rogowski Coils Integrated in Recloser (example 3)

Figure 4-11. Rogowski Coil Integrated into Bushings

Applications in Industrial Complexes. Figure 4-12 shows two different designs of Rogowski Coils applied in steel companies for protection of electric arc furnace transformers. Coils in Figure 4-12 are non-split core style installed on the primary side of transformers. Split-core style coils are installed on the secondary side of transformers because secondary conductors cannot be opened for the coil installation.

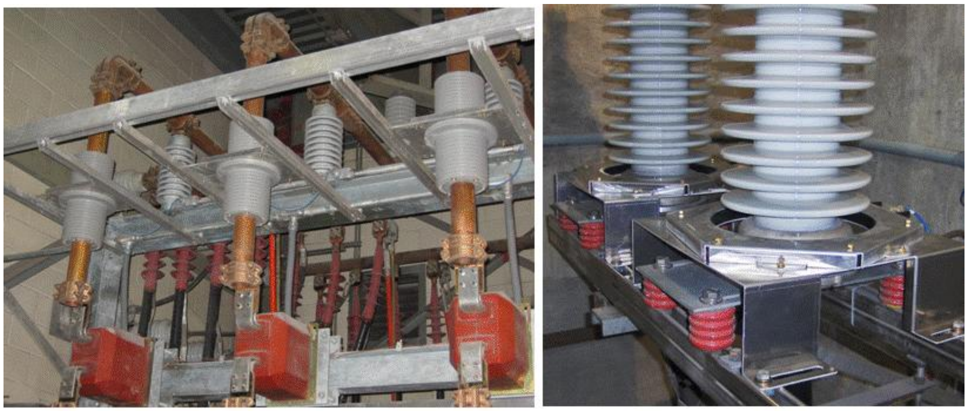


Figure 4-12. Rogowski Coil Applications fir Electric Arc furnace Transformer Protection

Motor Protection. Rogowski Coil technology provides a lighter and more compact solution compared to overload protection based on conventional CTs, and improves fault diagnosis, motor protection, and reductions in inventory. In addition, the units are considerably easier to install. Electronic integrators accurately reproduce primary current waveforms. Figure 4-13 shows a motor protection solution based on Rogowski Coils.

Figure 4-13. Application of Rogowski Coils for Motor Protection

The motor-protective system applies for motor currents from 1A to 820A. Relays provide the standard functions of protection in the event of phase failure, overload, or current imbalance.

Other advantages include:

- Small control panel design with a volume reduction of 58:1 compared to conventional transformers
- Small light-weight sensors with wide current ranges
- A small number of devices, resulting in reduced storage costs
- Simple installation. Fixing bands enable Rogowski Coil sensors to be easily mounted.

4.4 High Voltage Application Designs

Figure 4-14 shows a stand-alone Rogowski Coil design. Performance characteristics include:

- Continuous Current: 600 A, 1200 A, 2000 A
- Voltage: 7.5 kV - 500 kV (line-to-line)
- BIL Rating: 95 kV - 1470 kV
- Accuracy: +/- 0.15%

Figure 4-14. Stand-Alone Rogowski Coil for Current Measurements at 69 kV, 1200 A (44 lb)

Figure 4-15 illustrates a stand-alone Rogowski Coil design using the Optically Powered Data Link (OPDL) technology. OPDL transmit data from the Rogowski Coil and remote unit that are located at high-voltage potential to ground potential using fiber-optic cables and laser technology. Recent applications include current measurement for protection and metering with metering accuracy. Rogowski Coils are installed at high-voltage levels, suspended from the primary conductor or a busbar. This eliminates the need for a supporting insulator. The advantages of these methods as compared to the conventional solutions that use free-standing iron core CTs are: no oil or SF_6 gas, light weight, no seismic or explosion concerns, and use of low-voltage insulation class RCs.

In this solution, the Rogowski Coil output signal is fed into the remote unit of the OPDL. The remote unit is interfaced to the ground unit over two fiber-optic cables. One cable provides power for the remote unit and the second cable transmits data from the Rogowski Coil. The remote unit is shielded against EMI or RFI noise and converts the coil voltage into digital signals. The electrical power to operate this unit is provided by the photovoltaic power converter that is connected to the laser over one of the fiber optic links. The fiber-optic cables are incorporated into a composite insulator, a lightweight structure similar to suspension insulators made of composite, silicone material. The OPDL ground unit includes the laser with its associated laser driver and the data processing circuit. A self-check function supervises all vital functions of the system.

Figure 4-16 shows a solution to create a compact high-voltage switchyard bay by integrating circuit breaker, isolator, and grounding switch as well as current and voltage sensors in one gas-insulated compartment. Figure 4-17 shows the combined voltage and current sensor for measuring current and voltage with one device. The sensor consists of a Rogowski Coil for the current measurement and a capacitive voltage sensor for the voltage measurement. It provides a sufficient accuracy for revenue metering purposes. The current metering system is linear over a range from 400 A up to 63 kA and therefore is applicable for all protection purposes. The sensor is equipped with an interface to the process bus as well as a point-to-point link, so that the data are distributed over digital communication paths to IEDs (protection relays, control units, energy meters) without loss of quality. If redundancy is required, the sensor can be equipped with two Rogowski Coils and two metering systems. The Rogowski Coil measures the 1st derivative of the primary current, while the voltage sensor measures the 1st derivative of the voltage. The voltage/current metering system handles the analogue digital conversion of the measured values as well as the filtering, integration, and calculation of RMS values, frequency, active, and reactive power. The handling of communication mechanisms is also accomplished in the voltage/current metering system. In addition, an SF_6 gas density sensor is integrated in the combi sensor. The primary apparatus monitoring such as contact wear and advanced functions like point-on-wave switching are also integrated in the same metering system.

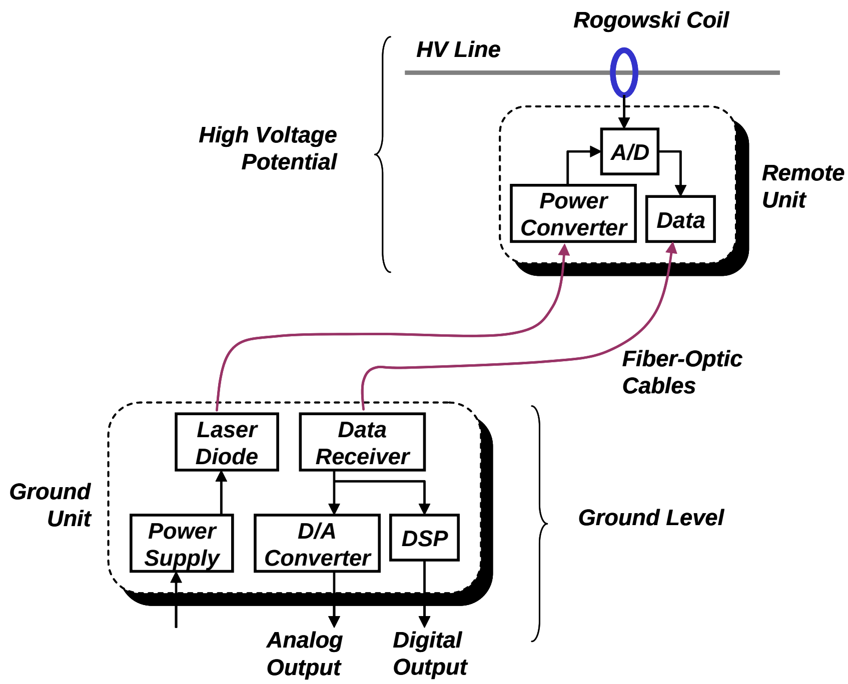


Figure 4-15. Stand-Alone Rogowski Coil with Fiber-Optic Interface

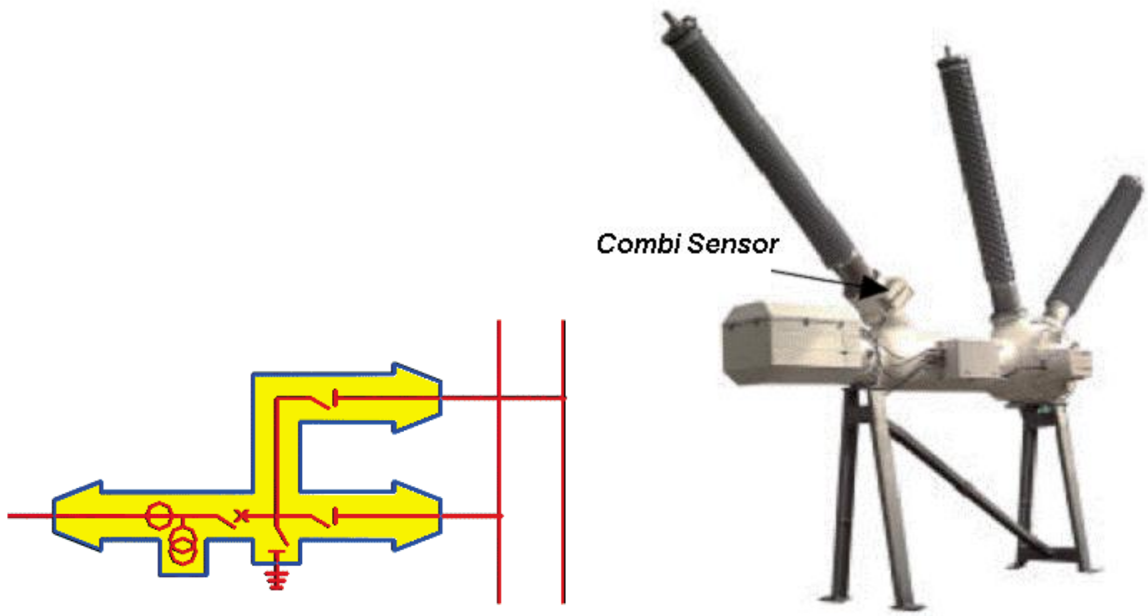


Figure 4-16. Rogowski Coil Integration with High Voltage Circuit Breakers (example 1)

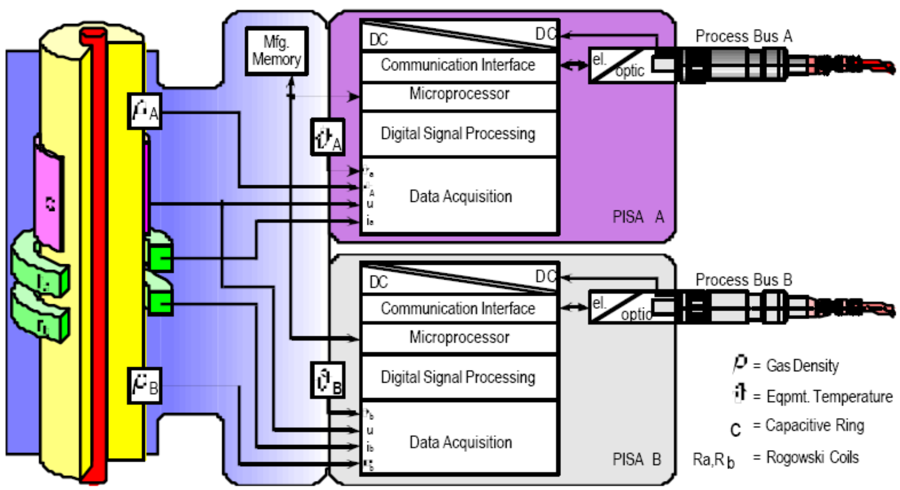


Figure 4-17. Combo Voltage/Current Sensor Interface to Relays

Figure 4-18 shows a solution to create a compact high-voltage switchyard that consists of one disconnecting circuit breaker, one or two isolators, one grounding switch, and a local control panel. The disconnecting circuit breaker functions as both a circuit breaker and an isolator.

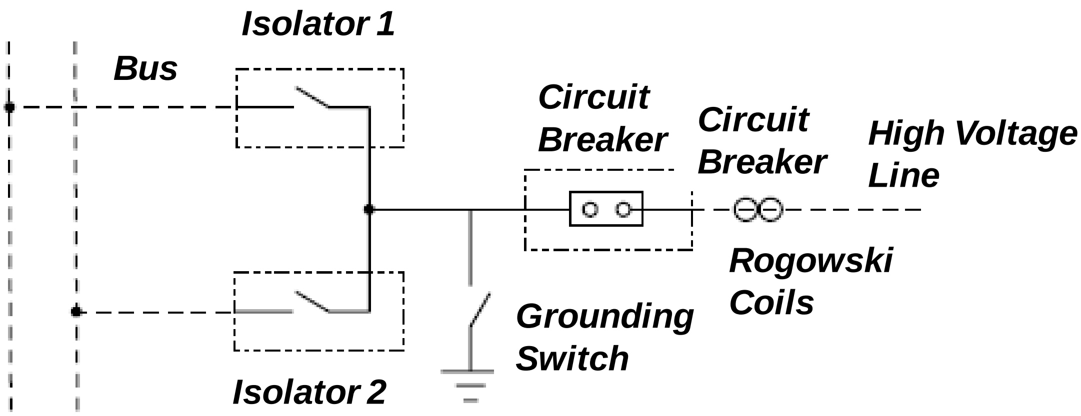


Figure 4-18. Compact High-Voltage Switchyard

Figure 4-19 shows the system configuration of a 245 kV I-AIS with ECT. The Rogowski coil and sensing unit are mounted at top of the circuit breaker. Power to supply the sensing unit at the high-voltage potential is provided by a Laser Diode Unit (LDU) at ground potential. The sensing unit at the high-voltage potential and the merging unit at ground potential are interfaced by a fiber-optic link within an insulator. The analog signal from the Rogowski coil is converted into 16-bit digital signal by the sensing unit, and is transmitted to merging unit through the fiber-optic cable. The specification of ECT for 245 kV I-AIS is given in Table 4-1.

Table 4-1 Specification of Electronic CT for 245kV I-AIS.

Item	Specification
Rated Primary Current	3150 A
Rated Transient Current	50 kA
Rated Frequency	50 Hz / 60 Hz
Rated Secondary Output (16bit Digital Output)	For measuring : 2D41 H (Decimal : 11585) For Protection : 01CF H (Decimal : 463)
Sampling Rate	2.4 kHz for 50Hz 2.88 kHz for 60Hz
Accuracy Class	For measuring : IEC Class 0.5 For Protection : IEC Class 5P
Standard	IEC 60044 – 8 IEC 61850 – 9

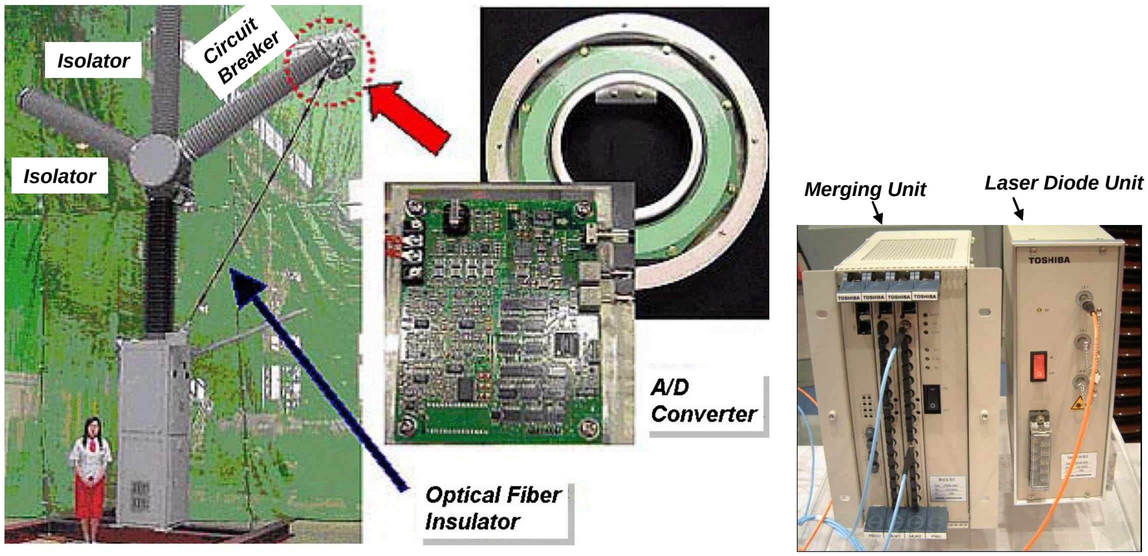


Figure 4-19. Rogowski Coil Integration with High Voltage Circuit Breakers (example 2)

Mobile substations require that the equipment tolerate the motion and vibration associated with movement over the road on a trailer. The Rogowski Coil approach offers much less weight and size in the sensor when compared to conventional CTs — along with improved protection system performance. Figure 4-20 shows a 20 MVA, 161/13.8 kV, delta/grounded-wye power transformer with Rogowski Coil based differential protection. The 161 kV side Rogowski Coils are mounted at the base of the primary bushings on the transformer. The 13.8 kV side Rogowski Coils are mounted on the front of the trailer in the existing support structure. An additional Rogowski Coil is mounted around the neutral bushing on the secondary side of the transformer for monitoring neutral current and for restricted earth fault protection.

Figure 4-20. Rogowski Coil Installation around Bushings in a Mobile Substation

4.5 GIS Application Designs

The combined electronic voltage and current transducer (EVT/ECT) shown in Figure 4-21 is designed according to IEC 60044-7 and IEC 60044-8. It consists of two fully independent measurement systems, each with protection and metering data.

- Current: 100 – 4000 A, 0.2S / 5P TPE
- Voltage: 330 – 550 kV/√3, 0.2 / 3P

A single-phase primary converter contains two independent sets of voltage sensors and Rogowski Coils. Two redundant secondary converters are mounted directly on the primary converter, containing signal acquisition, signal processing, and digital transmission circuits. Merging units provide interfaces to IEDs over Ethernet link according to IEC 61850-9-1 / 9-2. Separate devices are used for metering and control, and protection applications.

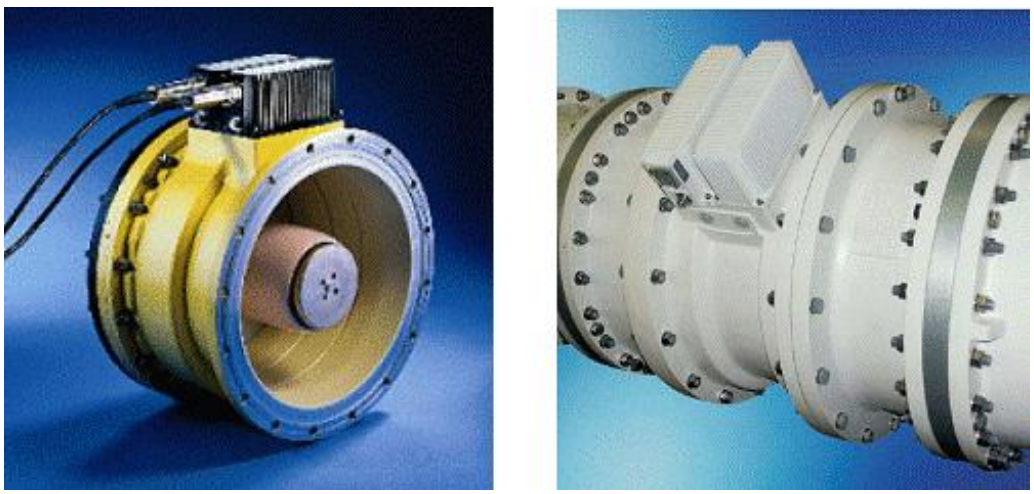


Figure 4-21. Rogowski Coil designs for GIS Applications (example 1)

Figure 4-22 shows the system configuration of electronic CTs and VTs for the 500 kV H-GIS. The 500kV H-GIS is designed based on both gas-insulated switchgear concepts and conventional air-insulated switchgear concepts and classified in terms of application of Air/ SF_6 gas insulation and live/ dead tank switchgear. Figure 4-23 shows an example of the 500 kV H-GIS with the ECTs/ EVTs. The ECT sensor is based on the principle of a Rogowski coil by taking into account saturation-free characteristics and economical efficiency. As for the voltage detection sensor of the EVT, a capacitive voltage divider of high reliability and simple insulated construction was applied. A/D converters are arranged near the Rogowski coil and the capacitive voltage divider, and to the MUs. Each A/D converter is connected to the MU by optical fiber, and the MU is connected to digital protection relays or control units by optical fiber. The ECTs and EVTs are designed based on IEC 60044-8 and -7, respectively. The output analog signals from the Rogowski coil and the voltage divider are converted into digital signals at each A/D converter, synchronized by a time synchronization signal from the MUs, and transmitted to the MUs. The MUs add the time stamps to the sampled digital signals from each A/D converter, and merges them into combined serial current and voltage data, and transmits this data to a protection relay unit or control unit through optical communication network design based on IEC61850-9.

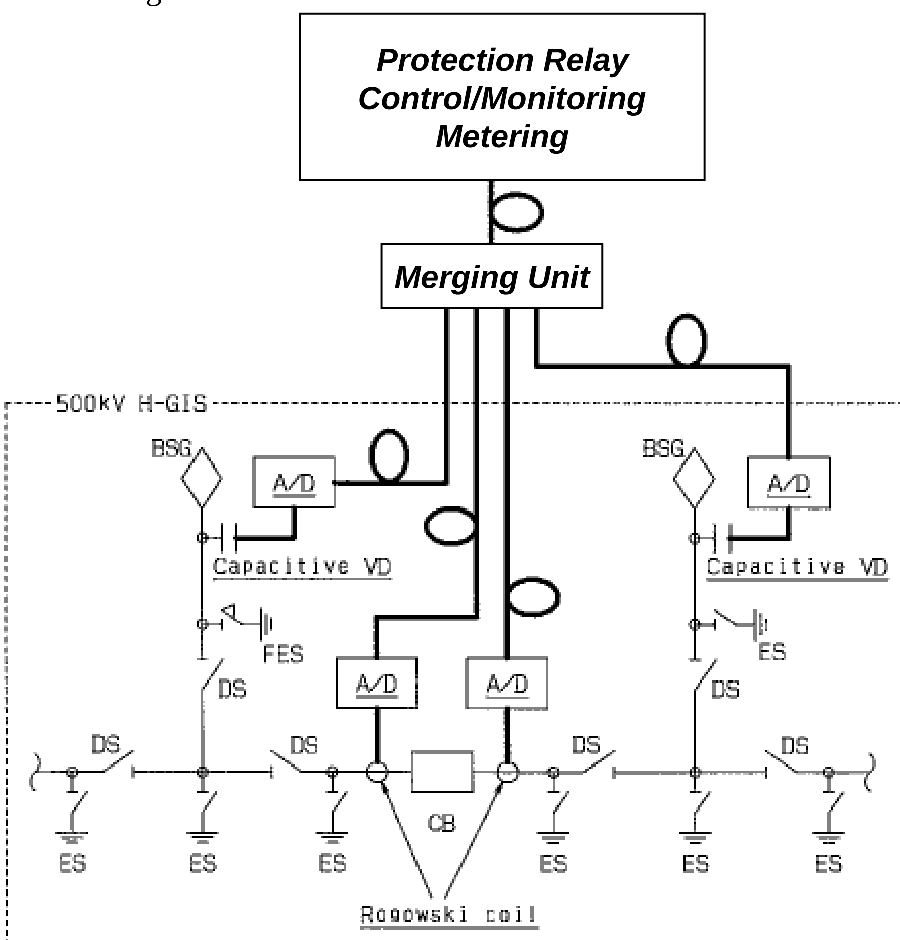


Figure 4-22. System configuration of Electronic CTs and VTs for 500kV H-GIS

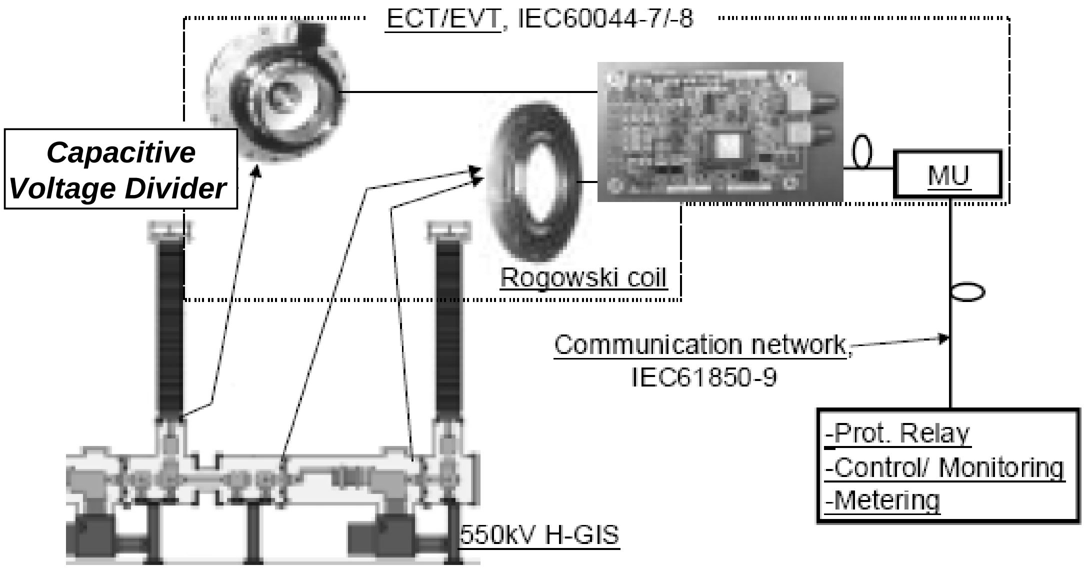


Figure 4-23. Example of 500kV H-GIS using ECTs/ EVTs

Table 4-2 Specification of Electronic CT for 500kV H-GIS.

	Metering	Protection
Rated Primary Current	4000A	4000A
Rated Transient Current	-	63kA
Rated Frequency	50 Hz	50 Hz
Rated Secondary Output (16bit Digital Output)	2D41 H (Decimal: 11585)	01CF H (Decimal: 463)
Sampling Rate	4800Hz	4800Hz
Accuracy Class	Class 0.2	Class 5P20/ TPY
Accordance Standard	IEC 60044-8	IEC 60044-8
Power on power supply for A/D converter	DC+110, 4W/ch	DC+110, 4W/ch

Figure 4-24 shows a GIS that uses Rogowski Coils for metering and protection. The coils have an accuracy class of 0.1 in a temperature range from –40 °C to +90°C.

Figure 4-24. Rogowski Coil implementations in GIS (example 3)

5 Interface to Relays

Figure 5-1a shows protective relaying principles using a Rogowski Coil directly interfaced to an Intelligent Electronic Device (IED), and Figure 5-1b shows solutions described in Standard IEC 60044-8 for Electronic Current Transformers (ECT).

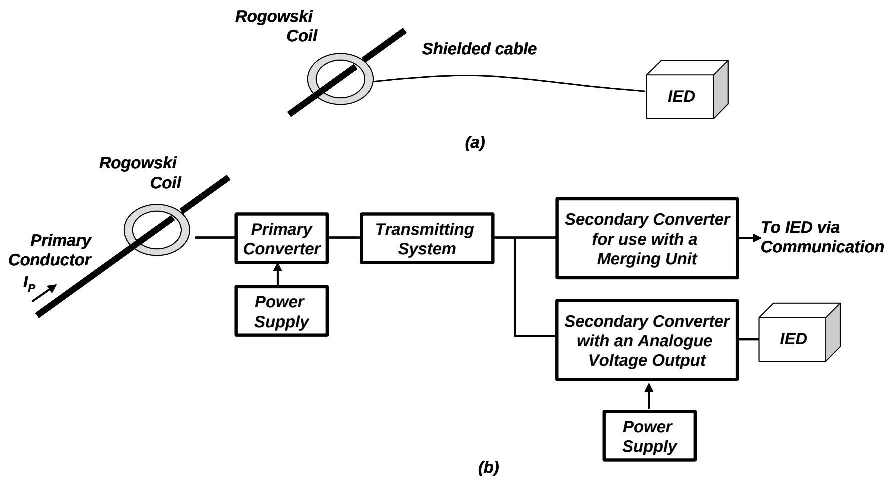


Figure 5-1. Application of Rogowski Coils used for Protective Relaying Purposes

The primary converter module represents signal processing circuitry which may be placed in the immediate vicinity of the Rogowski Coil, and used to amplify, convert, or encode low level signals prior to transmission. Depending on the design, the primary converter may be located at the high voltage (line) potential, and may use optical fibers for signal transmission and HV insulation. The primary Converter Power Supply from Figure 5-1 may need to be floated at the HV potential (along with the primary converter). The actual point-of-use of the Rogowski Coil signal may be at or after the secondary converter module. The link between the primary and the secondary converter may be proprietary.

Current transformers require heavy gauge secondary wires for interconnection to relays and other metering and control equipment (Figure 5-2). For example, Figure 5-2 shows a 2000/5 A, C800 class CT connected to a relay. The wire resistance adds to the CT burden and negatively impacts the CT transient response and may cause CT saturation at high 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. This CT has the core and winding height of 10 cm and weighs 90 kg.

Rogowski Coils may be connected to relays via twisted pair shielded cables with connectors (Figure 5-3). 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 5-3 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 5-2, but can be applied to a significantly larger current range than the CT.

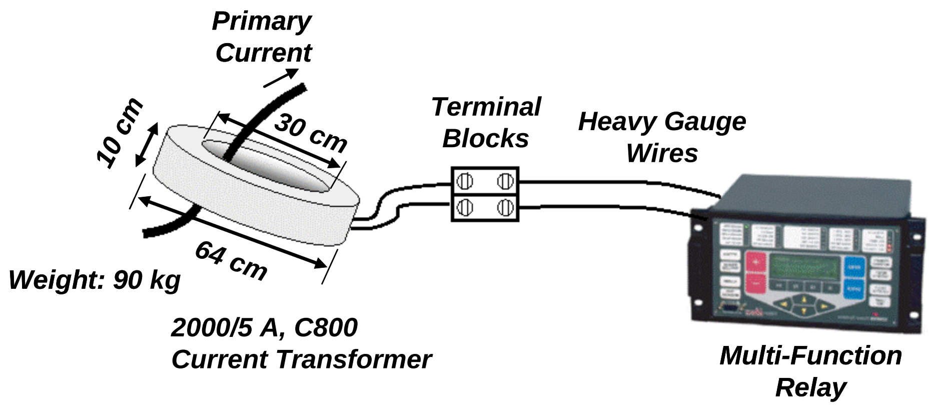


Figure 5-2. Current Transformer Connections to Relays

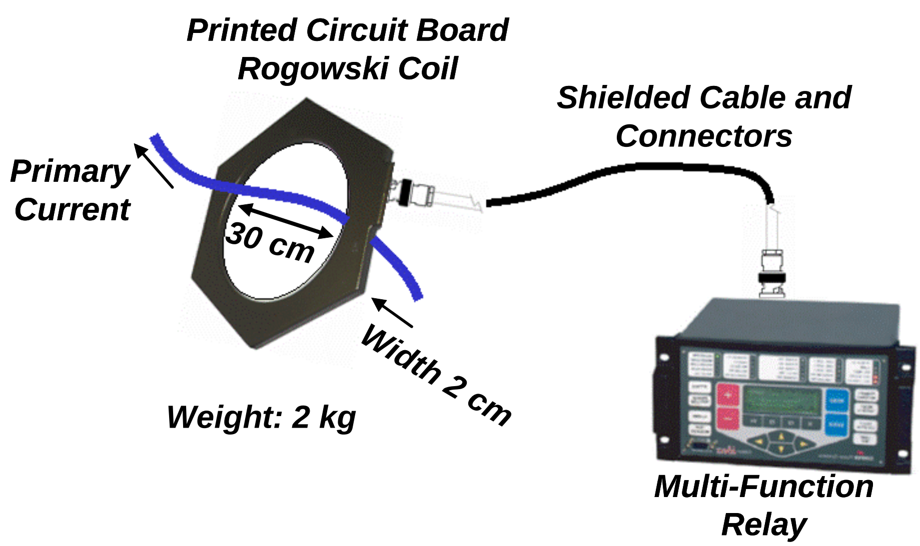


Figure 5-3. Rogowski Coil Connections to Relays

Cable Shielding. Rogowski coils and cabling should be shielded to prevent capacitive coupling to the high-voltage primary conductors and to minimize the influence of high-frequency electromagnetic fields (EMC environment). Cable shielding methods are provided in [2].

Length of secondary cables that can be used for interface of Rogowski Coils with relays depends on the measured signal levels, cable shielding, and environmental conditions. Reported distances used in actual projects are up to 300 meters to transport Rogowski Coil analog signals without amplification.

Voltages in secondary cables are small (even for fault conditions), so any number of cables can be installed in the same conduit without impact from each other.

Connectors. Standard IEC 61869-9-1 is under development. This standard recommends connector designs for the Rogowski Coil secondary signals given in Table 5-1.

Table 5-1 Connectors for Interface of Rogowski Coils and Relays

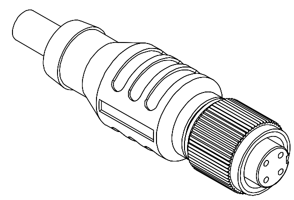
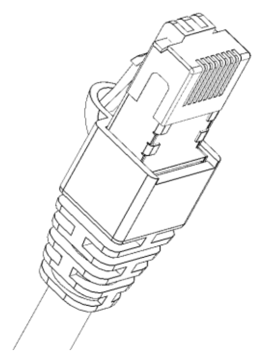
Twin-BNC Twin-BNC clamp-type plug for RG-108A	
M12 (generic version) Eurofast (Turck specific)	
ODU – MINI – SNAP	
RJ45 shielded	

Figure 5-4 shows an example of a system configuration using electronic instrument transformers (EITs). The electronic current transformers are based on the principle of a Rogowski Coil. The electronic voltage transformers are capacitive voltage dividers.

Sensing Units (SUs) are arranged near the Rogowski Coils and capacitive voltage dividers on each bay. One Merging Unit (MU) is provided. Each SU is connected to the MU by optical fiber. The merging unit is connected to the process bus by optical fiber. To ensure high reliability, the system included duplicated Rogowski Coils, SUs, MUs, and process bus. Only capacitive voltage dividers were not duplicated. The EITs were designed based on IEC 60044-7 and IEC 60044-8.

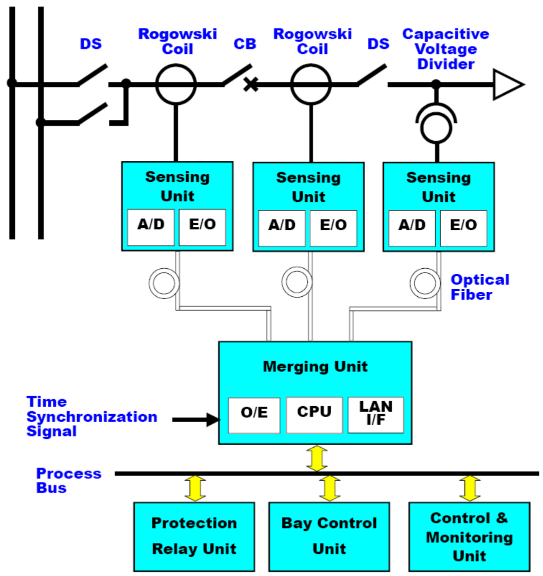


Figure 5-4. Volt/Current Sensor Interface to Relays

6 Redundancy and future replacement (maintenance)

Rogowski Coils can be designed to be used for metering and protection. If redundancy is required, a duplicate system can be applied.

7 Applications for Protective Relaying

Rogowski Coils may replace conventional current transformers for metering and protection. IEEE Std C37.235™-2007 [2] provides guidelines for the application of Rogowski Coils used for protective relaying purposes. Figure 7-1 shows feasible applications for Rogowski Coils in a power system.

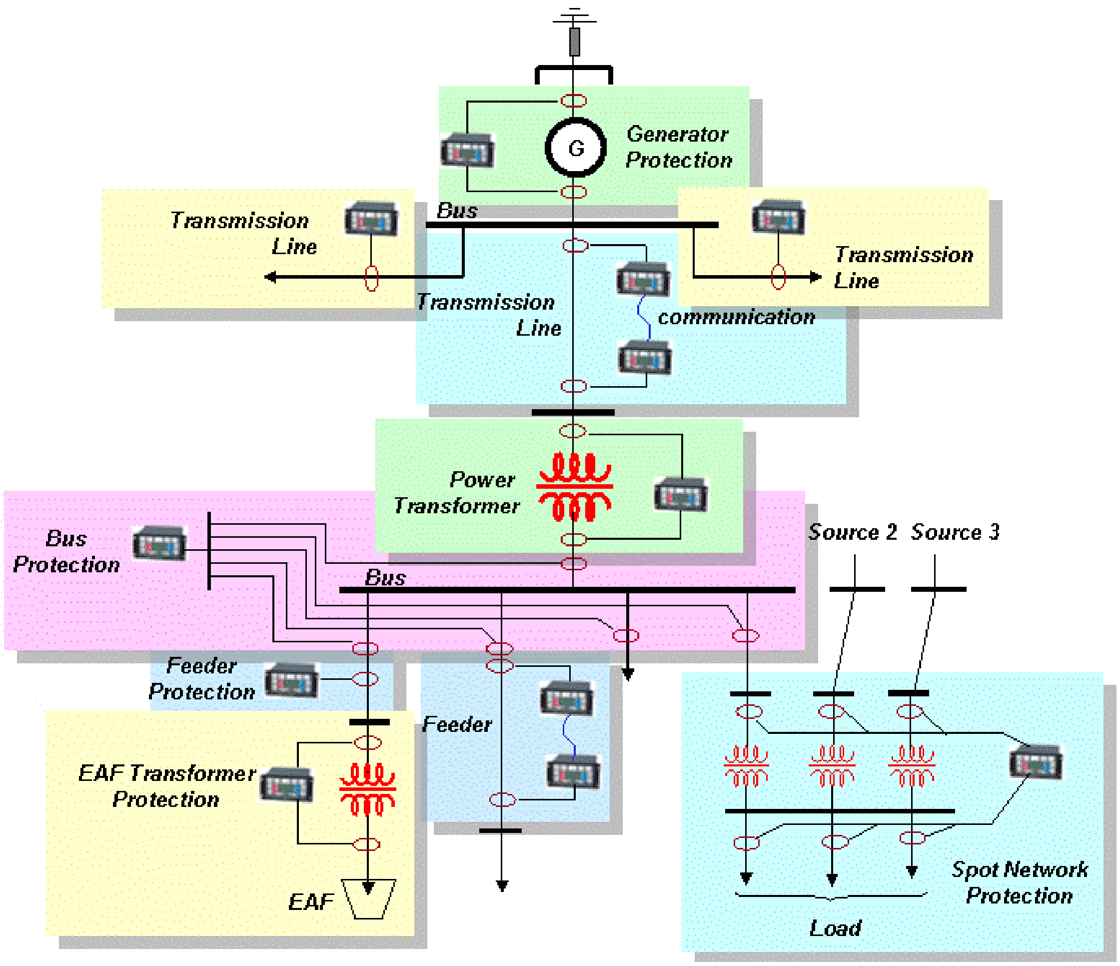


Figure 7-1. Feasible Applications of Rogowski Coil-based protection in Power Systems

7.1 Applications within Low-Voltage Systems

Spot networks are used to provide reliable electric power supply such as shown in Figure 7-2. However, these solutions have high available fault currents at the low-voltage side. Network protectors are connected between the secondary of the supply transformers and the secondary bus. Network protectors are not designed to interrupt the secondary fault currents. In most applications, current limiting fuses are used for fault current interruption. In case of a fault, arcing fault currents in the collector bus may be relatively low (as compared to maximum available fault currents for bolted faults) and not much higher than the load currents. Since these low currents may not be sufficient to operate the fuses, damage to network equipment can be extensive.

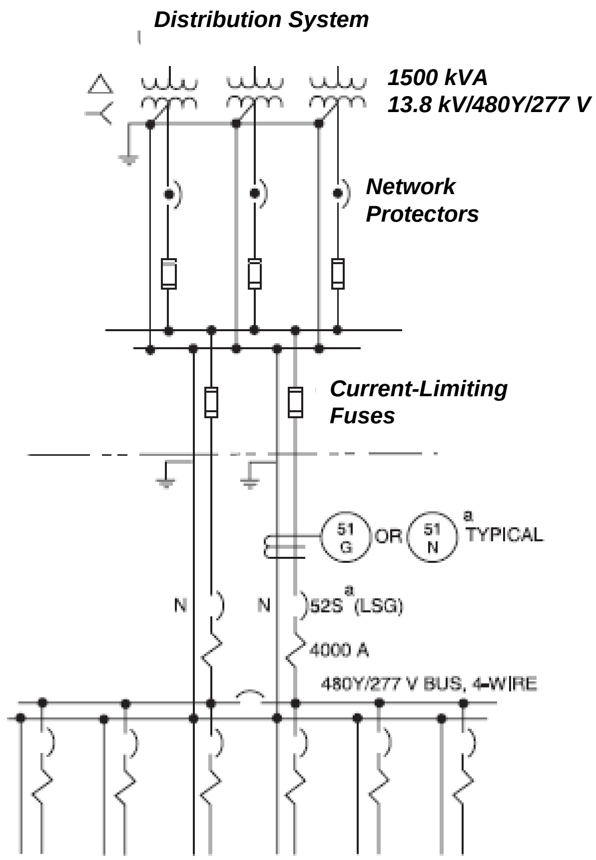


Figure 7-2. Low-voltage network supply (480Y/277 V or 208Y/120 V)

Differential protection of spot networks was not possible with conventional methods due to the risk of misoperation from CT-related errors. Rogowski Coil-based schemes provide reliable protection of spot networks. Figure 7-3 shows a protection scheme for differential protection of a spot network having three independent power sources SN1, SN2, and SN3.

Circuit breakers CB1, CB2, and CB3 are used for current interruption at the medium-voltage level. Network protectors NP1, NP2, and NP3 are used for current interruption at the low-voltage level. The network protector is a low-voltage air circuit breaker and is normally controlled by a network master reverse power relay (device 32), and may also be equipped with a phasing relay (device 78) to supervise closing of the network protector by comparing phase angles between the primary and secondary voltages. In order to maximize service reliability, network protectors generally do not have an overcurrent protection function and do not open for faults in the system downstream of the protector load side terminals, or for faults in other network protectors because arcing fault currents can be low and cannot reliably be differentiated from the load currents. Fuses F11, F21, and F31 may clear only sustained high-current faults in the low-voltage collector bus, in the customer switchgear, or the interconnection of the collector bus to the customer switchgear. The principle purpose of the fuse is to back up a network protector for an upstream primary cable fault.

The differential protection system shown in Figure 7-3 can effectively protect the spot network for

In-Zone faults and is stable for Out-of-Zone faults that are cleared by fuses F12, F22, and F32.

The protection scheme from Figure 7-3 has only one Protection Zone which means that for a fault anywhere inside the Zone all three transformers will be disconnected. By adding additional Rogowski Coils between fuses F11, F21, F31 and the bus the scheme becomes more flexible by having a Protection Zone for each transformer.

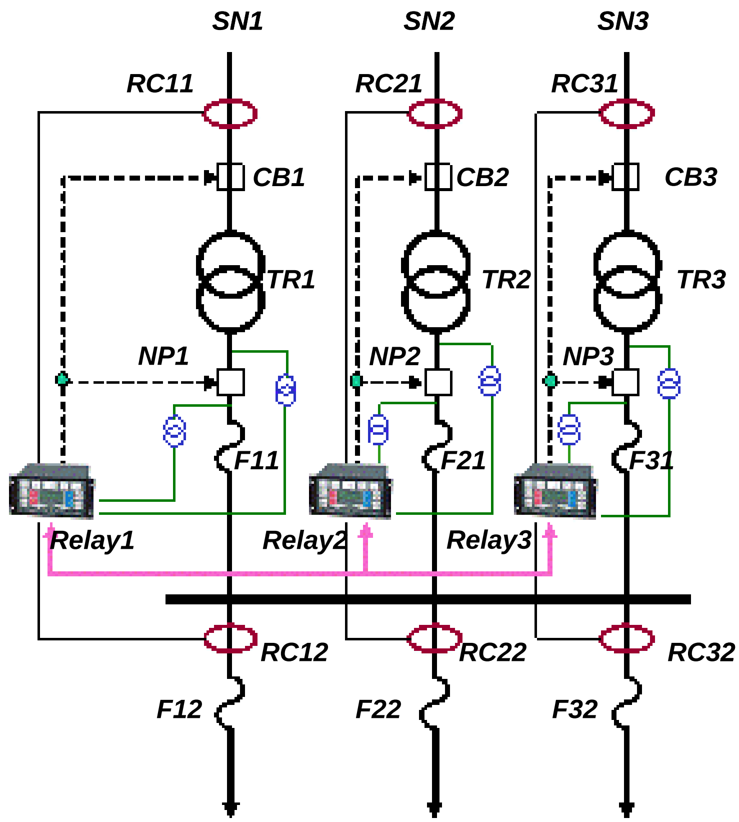


Figure 7-3. Protection of a Spot Network

7.2 Applications within Medium-Voltage Systems

The protection systems for medium-voltage applications (Figure 7-4) may include microprocessor-based multifunction relays, Ethernet switches, and Rogowski Coil current sensors to provide multiple Protection Zones for comprehensive protection in a substation. Ethernet switches manage communications between the relays as well as the Ethernet traffic between the substation and the LAN inside the facility. This also enables communication between office PCs and the relays for remote access to the relays to update the settings, view/download oscillographic event files and sequence of event records to review system events.

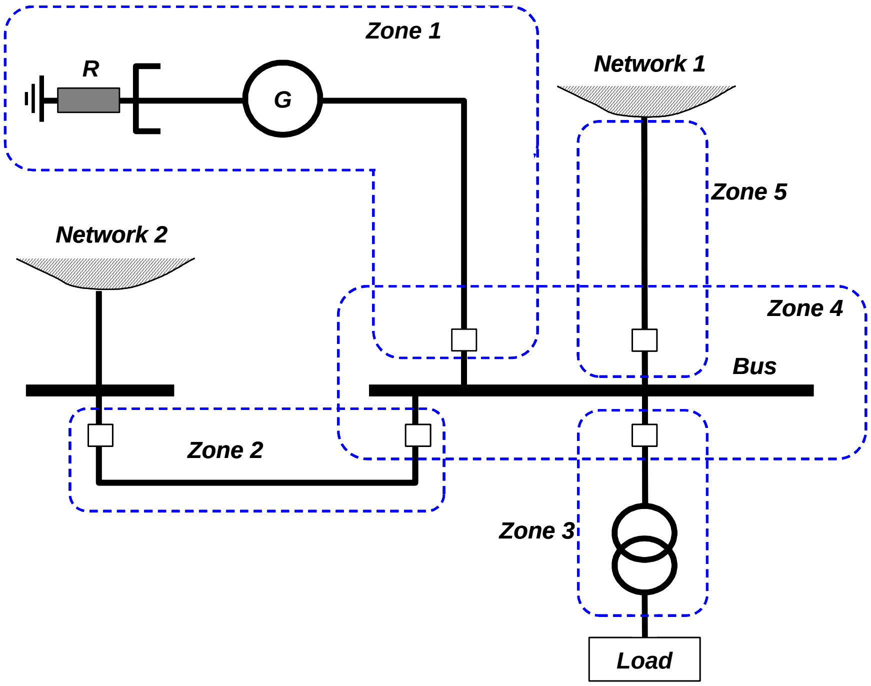


Figure 7-4. Medium-Voltage Power System

7.3 Applications within High-Voltage Systems

Rogowski Coils designed for low-voltage insulation levels may be used in gas-insulated substations (GIS) and air-insulated switchgear in high-voltage systems. For applications in GIS, Rogowski Coils are implemented in the switchgear enclosure. For applications in open-air substations, Rogowski Coils can be installed around the transformer and circuit breaker bushings. For current measurements on high-voltage potentials, Rogowski Coils can be suspended from the primary conductors and interfaced to relays using fiber-optic cables. Power required for the electronics located at the high-voltage level may be achieved using a conventional CT located at the high voltage level near the Rogowski Coil or from the ground level by light-emitted diodes transmitting light power through the fiber-optic cables. The advantages of optically interfaced Rogowski Coils with relays compared to the conventional designs (high-voltage, free-standing iron-core CT) are as follows: no oil or SF_6 gas (environmentally friendly), light weight, and no seismic or explosion concerns. In some designs, voltage and current sensors may be combined allowing current and voltage to be measured with one device.

7.4 Future Protection Application

7.4.1 Traveling Wave-based Protection

Faults in power systems cause traveling waves (TW) that propagate through the system near the speed of light away from the fault location and reflect at points where impedance changes. Traveling waves have a fast-rising front and a slower-decaying tail. Magnitudes of consecutively reflected waves decrease (attenuate). When TW are generated, both traveling wave voltages (TWV) and traveling wave currents (TWC) exist. Here, applications of traveling wave currents for protective relaying purposes and determining fault locations in power systems are considered. For relay protection applications, detection of the TWC polarity is more important than their magnitudes. The TWC magnitudes only determine thresholds to initiate protection algorithms. The TWC polarity determines the fault direction. If the polarity is positive, the fault is in the forward direction, and if the polarity is negative (180° opposite), the fault is in the reverse direction. By comparing input signals from all terminals of a Zone (two or more terminals), it is possible to determine if the fault is inside Zone or outside Zone. However, when a fault occurs near or at the voltage zero, TWC are not generated. In those events, TWC-based relays may not operate and protection should be provided by a backup protection method using different algorithms, such as phasor-based.

For phasor-based protective relays, signal processing is required to extract the power frequency signal. However, for TW-based protective relaying, all lower frequency components of the line current are not relevant. Rogowski Coils can be designed to have a 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 TWC reflections and refractions. Magnitudes of generated pulses can be different for different events and can also quickly attenuate. Therefore, TW-based protective relaying uses pulse magnitudes only for thresholds. The protection and fault location algorithms use the time difference between successive pulses and their polarity.

8 Field Experience with Rogowski Coil-based protection Systems

8.1 Differential Protection of Power Transformers

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 8-1 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 they have high dependability (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 (see Figure 8-2). Transformer inrush currents may reliably be determined using a current waveform recognition algorithm. Protection settings can be at a lower current threshold compared to conventional solutions based on CTs. The load tap changer position is also used by the relay to adaptively adjust the transformer ratio allowing the set threshold to be further reduced.

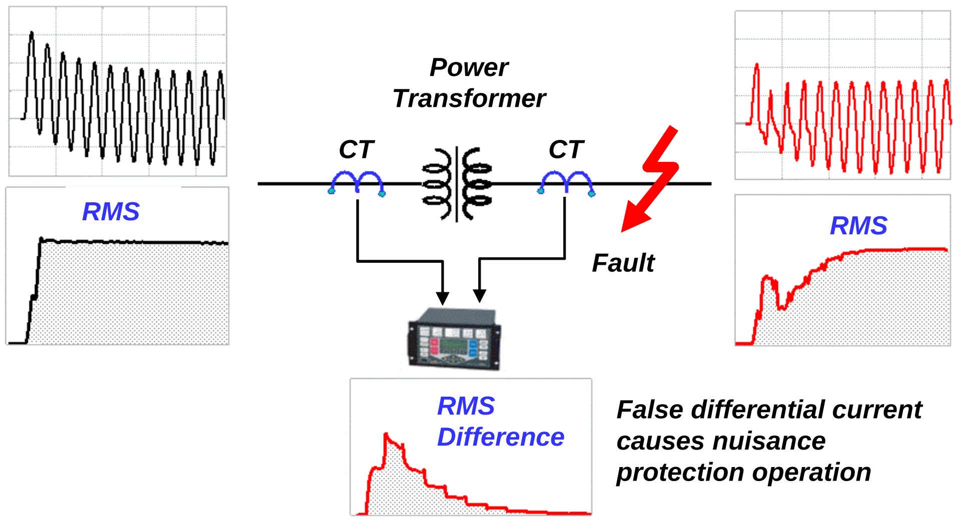


Figure 8-1. Differential current error caused by the CT saturation

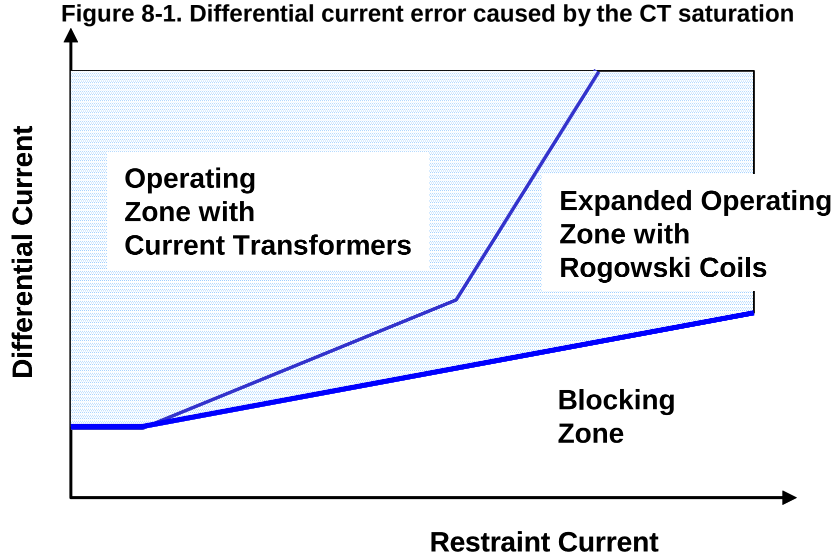


Figure 8-2. Operating Zones for CTs and Rogowski Coils

The introduction of Rogowski Coil-based sensors for metering and protection is a paradigm shift in technology. Protection engineers had a legitimate concern that new sensors may have a significant impact on existing metering and protection philosophy. To demonstrate that the change in paradigm is not a concern and that Rogowski Coil-based protection systems provide superior protection over conventional CT-based protection systems, the first Rogowski Coil-based systems were developed and applied for electric arc furnace (EAF) transformers. These critical units were not protected using differential protection in the past — due to the difficulty in designing conventional iron-core current transformers for load currents of 60 kA or more.

The operation of an EAF transformer is significantly different when compared to a utility power transformer of comparable size. These differences present many challenges to the protection system designer when developing a successful differential protection system. To explain why it is difficult (or impossible) to apply differential protection on EAF transformers using conventional iron-core CTs, a typical EAF operation powered by a 25 MVA transformer is presented next.

The electrical system single-line diagram is shown in Figure 8-3. The current in RMS ampere values are shown in Figure 8-4. The RMS values are averaged per one second of recording.

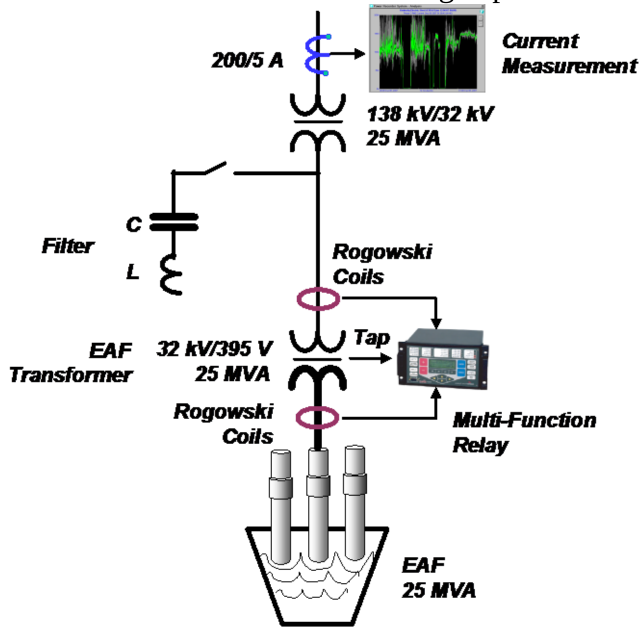


Figure 8-3. EAF Operation

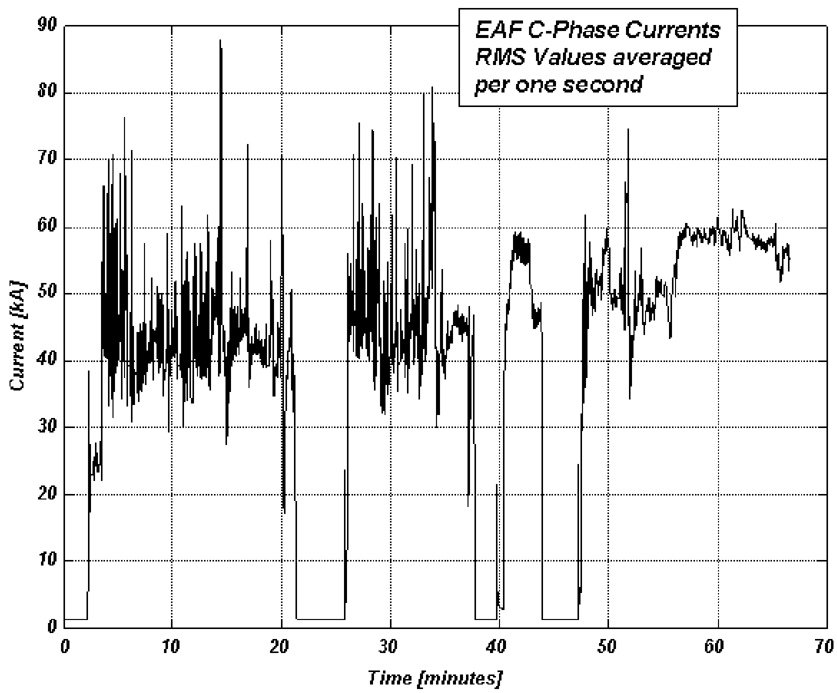


Figure 8-4. RMS Values of EAF Currents during one Heat Cycle (averaged during one second)

In the routine operation of the furnace a heat cycle starts with charging the furnace with cold scrap. To begin the heat cycle, the electrodes are lowered into the scrap ("bore in" phase) starting the electric arc. This causes momentary short circuits that develop very high currents resulting in excessive forces that blow the scrap away from the electrodes, sometimes interrupting the electric arc. Then the arc quickly re-ignites, and this process can last for several minutes. During this period, current magnitudes rapidly and chaotically change from low to high values. After 5 to 10 minutes, arc stability improves, but there is still a high degree of current variation as compared to current variation that a utility power cable may experience. To optimize the melting process, the EAF regulator may send a command to change the EAF transformer tap position. In a heat cycle, there is usually more than one scrap charge in order to fill the furnace. Figure 8-4 shows RMS values of EAF currents during one heat cycle that includes three heating periods for the scrap recharging or emptying the furnace. Three periods of current interruptions are intentional and are required for the recharging. EAF transformers typically undergo 70-100 energizations per day. For this type of operation high security of the protection system is essential since even a small number of misoperations would cause unnecessary and costly downtime.

In summary, the following challenges exist to design reliable differential protection for EAF transformers.

The first challenge is to provide high security of the scheme because EAF transformers are subject to permanent and frequent energizations. EAF transformer energizations cause severe inrush currents and during operation currents are high, so they look like through-fault conditions. Traditional schemes that use conventional CTs are susceptible to nuisance operations because of the CT saturation. Another aspect that can contribute to nuisance operations is the harmonic restraint method used in traditional schemes to block relay operation during energization. In applications where there is high presence of harmonics (such as EAF operation) this method may not be reliable. In the past, a small percent of nuisance operations was tolerated since traditional schemes could not provide better security. That level of scheme security could be tolerated since utility substation transformers are infrequently switched and high through-fault current events occasionally happen, which would cause a small number of nuisance operations per year. However, this same level of scheme security in the EAF applications would cause several nuisance operations per day, which would be absolutely unacceptable.

The second challenge is to maintain the scheme sensitivity to the frequent operation of on-load tap changers. EAF transformers might have 20 to 30 taps with a voltage variation of 800-1400 volts line-to-line on the secondary side. This may result in a mismatch of primary to secondary current of 30% for a relay set at a fixed ratio setting at the mid-point of the range. To provide a sensitive differential protection scheme that can detect low fault In-Zone currents, the relay must be able to adapt to changing taps during transformer operation.

The third challenge is to provide reliable operation of the scheme for distorted current waveforms during the arcing process in an EAF. The non-linear characteristic of the arc, plus the erratic nature of the continuity of the arc in the scrap, results in high percentages of lower order harmonics. A differential relay that uses harmonic content to determine an inrush condition may have a setting that will block the relay operation for a secondary arcing fault in the zone of protection.

The fourth challenge is to provide reliable relay protection system operation in severe environment conditions that include dust, vibration, and extremes of temperature and humidity. EAF dust has high iron content and is conductive in concentrated amounts. This dust is sometimes the cause of short circuits on the EAF transformer secondary terminals. To prevent dust penetration into EAF transformer vaults, air-handling systems keep positive pressure in the vault to minimize dust penetration. However, despite all efforts to avoid dust penetration into the vault, dust cannot be completely prevented. Temperature in the vault can be low during winter and high (over 100 degrees) in the summer, since the air for air-handling systems usually comes from outside the building (at prevailing relative humidity). In addition, the EAF transformers and the entire building are exposed to high vibration from the operation of the EAF furnace.

The Rogowski Coil protection system was implemented for the first time on two 90 MVA, 34.5/1 kV EAF transformers equipped with a load tap changer (LTC) (Figure 8-5). Primary Rogowski Coils 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 (23 cm diameter each). Since the secondary tubes cannot be opened, the Rogowski Coils were designed in split-core styles (Figure 8-6).

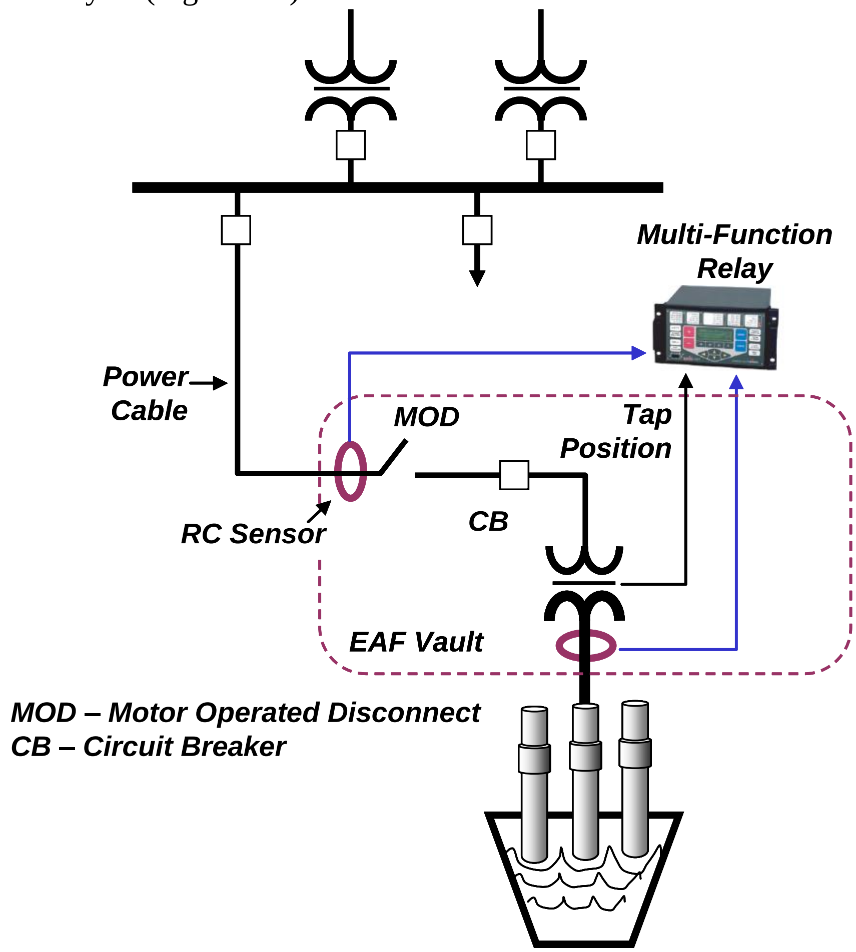


Figure 8-5. Single-Line Diagram of a EAF Power System

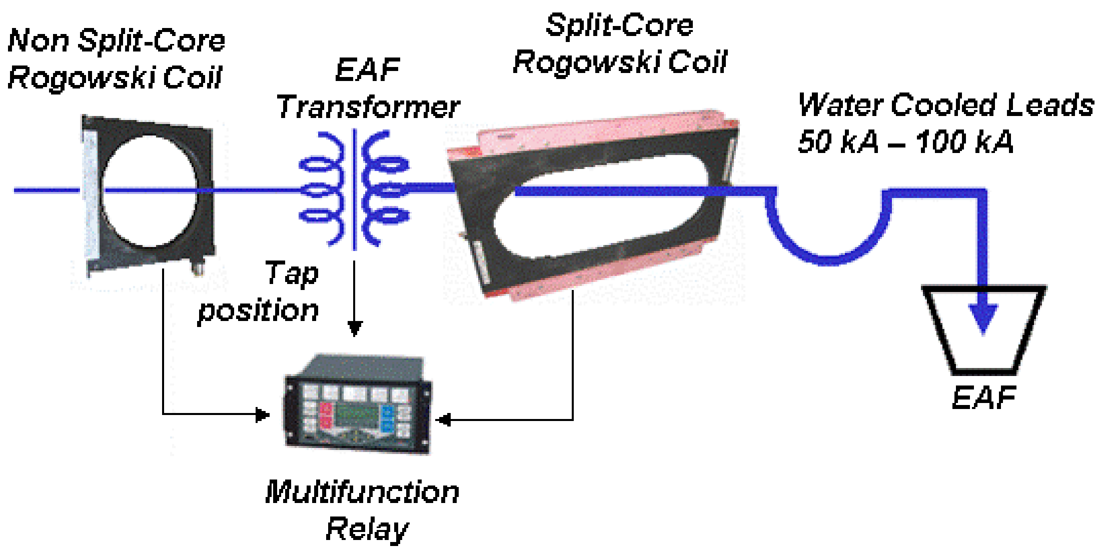


Figure 8-6. Rogowski Coil-based EAF Transformer Differential Protection

The Rogowski Coil sensor-based differential protection systems for EAF transformer protection have demonstrated superior performance since installation (6 years as of the writing of this report). Rogowski Coils are linear and accurately reproduce primary currents. The coil output signals of EAF currents recorded during a heat cycle by a transient recorder are shown in Figure 8-7. Another snapshot of EAF currents derived by the relay is shown in Figure 8-8. Even though the relay sampling rate is much smaller than the transient recorder, the current waveforms are detailed enough to properly represent waveform distortion and harmonic contents. Figure 8-9 shows that the coil output signals of EAF primary and secondary currents derived by the relay match very well and accurately derive differential currents.

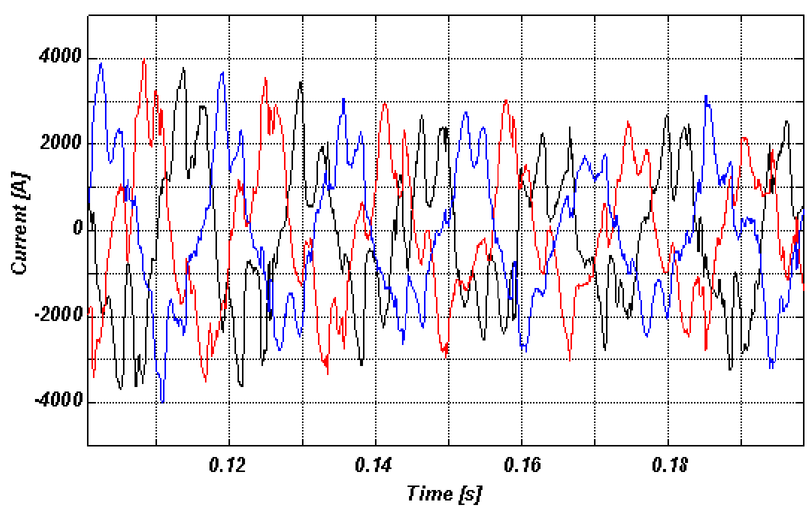


Figure 8-7. EAF Primary Currents (A, B, C phases) Recorded by a Transient Recorder

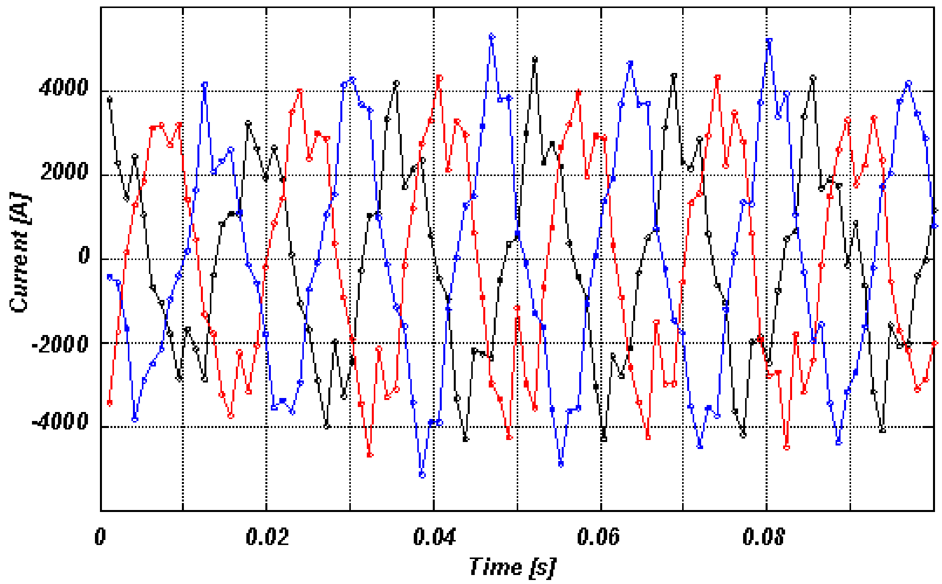


Figure 8-8. EAF Primary Currents (A, B, C phases) Derived by the Relay

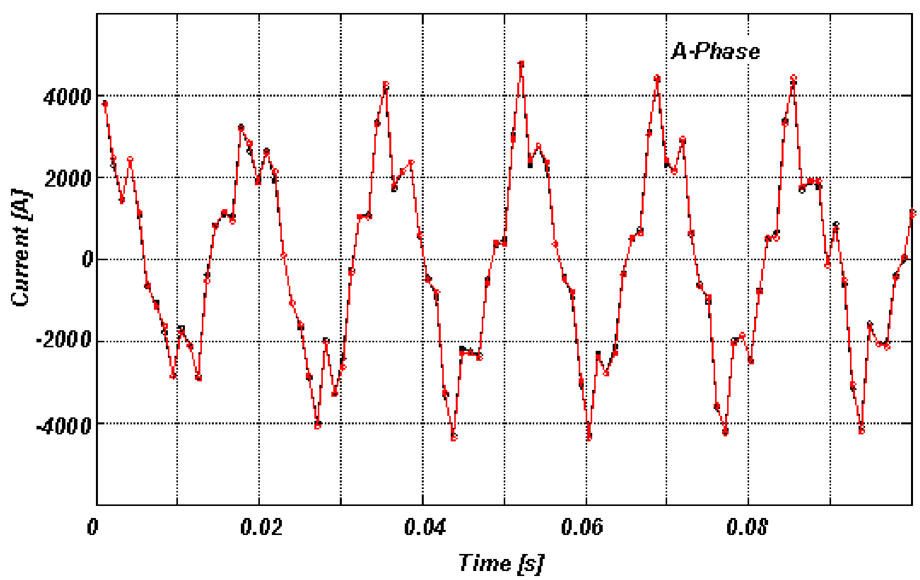


Figure 8-9. EAF Primary and Secondary Currents derived by the relay (referred to the primary)

8.2 Differential Protection of Power Line/Cables

Limited rights-of-way in populated areas may prevent delivery of electric power to substations via overhead transmission lines. This situation may force construction of a transition from overhead lines to power cables for power delivery to urban areas. Mixed overhead/cable topologies are becoming more common in both new and refurbished circuits and may require unique protection approaches.

To ensure reliable power supply, protection systems must differentiate between cable and overhead transmission line faults. For example, after operating for a line fault, the main protection system may initiate auto reclosing only after positive confirmation that there is no fault in the power cable. Therefore, cable differential protection provides reliable discrimination between faults in the cables or in the overhead line section. Because of limited space, traditional cable differential protection may not be feasible since the installation of conventional current transformers might be difficult in the cable/line transition stations.

Project Design and Implementation. Rogowski Coil-based cable differential protection has been designed for implementation on several in-service 220 kV power cables (each 2-km long) that interface gas-insulated switchgear (GIS) substation with overhead transmission lines. Previously, without cable differential protection, fault discrimination was based on the operation of distance protection. However, fault location was not precise enough to discriminate cable faults from faults in the overhead sections of the lines. As a consequence, and for security purposes, some faults in the overhead line sections were cleared without auto reclosing, reducing the reliability of the power supply in the region.

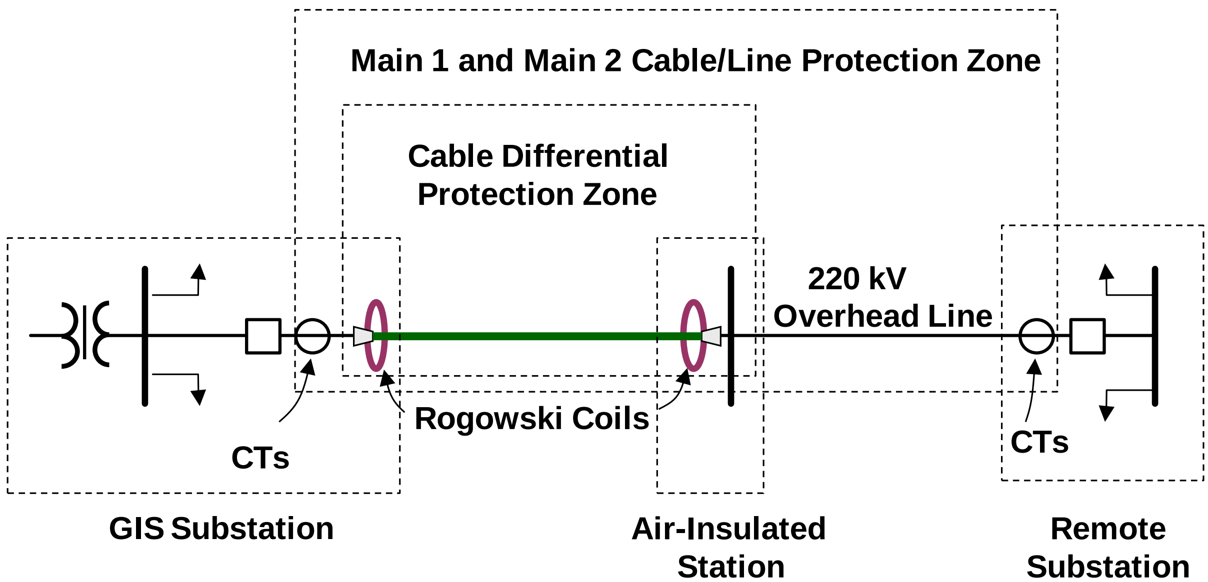


Figure 8-10. Relay Protection Zones

In the existing design, the overall mix of overhead/cable line is protected by a line differential protection as Main 1 and a distance protection as Main 2 with teleprotection systems. The new Rogowski Coil-based cable differential protection system creates an internal protection zone as illustrated in Figure 8-10. The adopted solution minimized changes in the high-voltage apparatus equipment.

The GIS substation includes three 170 MVA power transformers serving a 60 kV network and four feeder bays with cable interfaces to remote overhead lines. Split-core Rogowski Coils are installed around the GIS cable terminals as illustrated in Figure 8-11. The relays are installed in an existing equipment cabinet in the GIS substation.

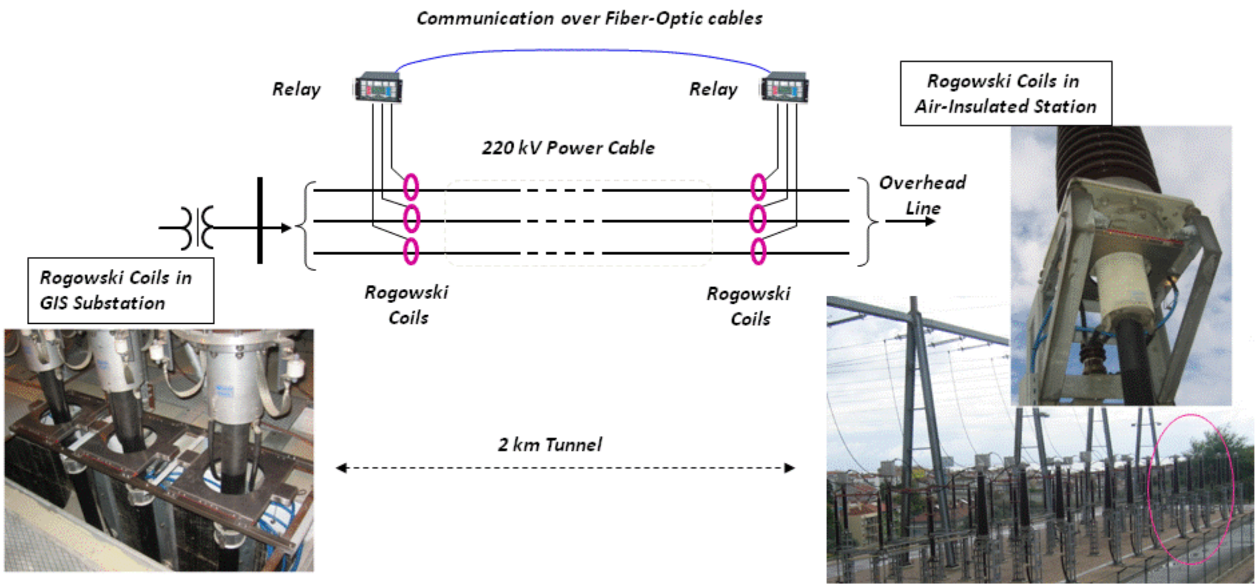


Figure 8-11. Project Installation

Power cables reside in a 2-km tunnel and are terminated with 220 kV bushings. The Rogowski Coils in the remote station are installed just below the bushing base as illustrated in Figure 8-11. A relay cabinet with the relays is installed in the power cable tunnel below the cable terminations. Fiber-optic cables are installed in the same tunnel near the power cables for communication between relays.

The differential protection system uses the GOOSE messaging system over Ethernet for peer-to-peer communication. For reliability, the communication system is dual-redundant; each relay has two independent, single-mode fiber-optic Ethernet ports (10/100 MBPS) interconnected via two Ethernet switches located in the GIS substation. The switches manage communications between the relays as well as the Ethernet traffic between the substation and the LAN inside the facility. This also enables remote PCs to access various relay event records and to download relay settings.

Rogowski Coil Current Sensors. High-precision Rogowski Coils applied in this project are designed using printed circuit boards (PCBs) in a split-core style for installation around primary conductors without the requirement to open primary conductors. Rogowski Coils are compact and weigh many times less than conventional CTs. The coils as shown in Figure 8-12 weigh approximately 10 pounds.

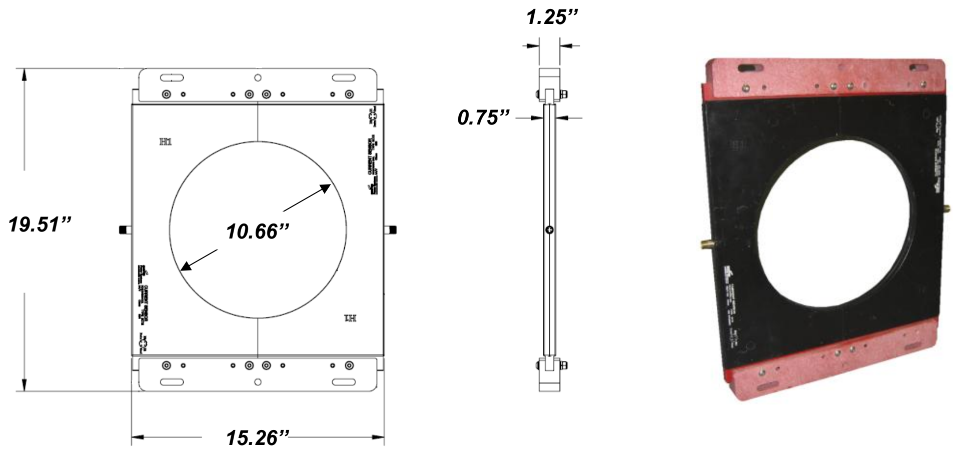


Figure 8-12. Split-Core Style Rogowski Coils

9 Testing, Commissioning, and Maintenance

9.1 Physical Maintenance

The physical construction of Rogowski Coils is similar to that of traditional CTs in that a coil is wound around a form, except, that in the case of the Rogowski Coil, the form is non-magnetic. The implication of this similarity is that there is no maintenance required on the actual coil itself. Iron core CTs are not routinely tested in most cases and are typically only examined in the event of some protection misoperation. If iron core CTs are examined at all, it is typically to determine if there is any remanent flux in the core which could, or has, caused the CT saturation, resulting in distortion and reduction of the RMS value of the CT output current. In the case of Rogowski Coils, no such condition can exist and the coil itself requires no maintenance except for the possibility of examination for physical damage to the coil itself or the cable/connector from the coil. Physical examination should only be necessary if the coil happens to be exposed to some harsh environment.

Since the output of the Rogowski Coil must be integrated in order to obtain the representative current, the integrator itself may be subject to drifting due to component aging and should be examined from time-to-time to verify its accuracy. Tests regarding the accuracy of the coil/integrator are given below.

Also, since the output of the Rogowski Coil is a low-level signal, grounding and shielding are important in the actual application of the coil. Inspection of the ground connection should be part of a routine inspection. A faulty ground could allow noise on the signal wires allowing it to be integrated with the actual current signal.

9.2 Maintenance

Rogowski Coil maintenance can borrow some of the procedures specified for calibration. IEEE C37.235™ provides specific calibration procedures for Rogowski Coils and refers to IEC 60044-8 for accuracy class type testing. IEC 60044-8 addresses various tests:

1. Short-time current tests

2. Temperature rise test
3. Lightening impulse test
4. Switching impulse test
5. Wet test
6. RIV test
7. Low voltage components voltage withstand test
8. EMC test: emission
9. EMC test: immunity
10. Accuracy tests
11. Additional accuracy test for protective electric current
12. Verification of the protection
13. Vibration test
14. Test for proper anti-aliasing
15. Test for accuracy vs. harmonics

These tests are not required for routine maintenance purposes and are typically only conducted once, aside from accuracy testing. The above list does not consider polarity checks, but this too is typically only conducted once, and that is during commissioning.

9.3 Accuracy tests

Rogowski Coils have a linear characteristic over their input range, and because of this, a simple injection of primary current above the minimum rating of the coil is adequate to perform accuracy testing. This injection test can be used to verify polarity (if necessary), as well as, phase and magnitude accuracy – all with respect to the manufacturer specifications.

If the Rogowski Coil output voltage is digitized it is important to examine the output. The following routine tests should be performed depending on whether the output is fiber-optic or copper.

For fiber-optic transmission, verify that the transmission (output) power is between the stated power levels of the manufacturer (typically between –15 dBm and –20 dBm). Verify that the receiving power is between stated power levels by the manufacturer (typically between –15 dBm and –30 dBm).

For copper-wire transmission, verify the line-driver characteristics by performing tests to verify the following with respect to manufacturer specification:

- Output impedance of the line-driver
- Signal amplitude
- Rise and fall time

And, also for copper-wire transmission, verify line-receiver characteristics by performing tests to confirm the following:

- Receiver input impedance
- Maximum positively detectable input signals
- Minimum positively detectable input signals

If the Rogowski Coil output is not digitized, but it is used as amplified analog signal, the following tests should be performed:

- Measure the secondary direct voltage offset and compare with specification

- If the electronics is powered by line current, measure the minimum primary current required to ensure nominal performance of the Rogowski Coil.

If the Rogowski Coil and its associated integrator has an alarm feature to indicate an open coil, then exercise this feature by temporarily removing the Rogowski Coil input to the integrator. This process should verify that an alarm will be asserted if the coil becomes open.

9.4 Other tests

Field testing of Rogowski Coil involves verifying the continuity of the coil and the connection to the integrator and the functionality of the integrator. Since the interface between the current sensor and the secondary converter is proprietary, injection of a voltage into the integrator that simulates the output of the coil cannot be standardized and is not recommended – unless specifically stated by the manufacturer.

To perform a field test, inject a known current into (through) the Rogowski Coil and verify the calibration of the integrator. Field tests may also include Rogowski Coil resistance measurement, visual inspection of the insulation, and a connector check for any inside contamination. Field tests are for the sake of testing performance, not accuracy.

10 Bibliography

[1] IEEE Standard C57.13™-2008, "Requirements for Instrument Transformers".

[2] IEEE Standard C37.235™-2007, "IEEE Guide for the Application of Rogowski Coils Used for Protective Relaying Purposes".

[3] IEC Standard 60044-8™, Instrument transformers – Part 8: Electronic current transformers.

[4] Future IEC 61869-10: Instrument transformers – Part 10: Specific requirements for low power stand alone current sensors.

[5] Published technical papers and product information from companies: ABB, Areva, Cooper Power Systems, Hitachi, Kelman, LEM, Mitsubishi, Moeller Electric, Noja Power, Schneider, SEECO, Siemens, Tavrida, Toshiba.

[6] Dupraz J. P., Fanget A., Grieshaber W., Montillet G. F., "Rogowski Coil: Exceptional Current Measurement Tool For Almost Any Application", IEEE General Meeting, Tampa, FL, June 24-28, 2007.

[7] Fam W. Z., "A Combined Current and Voltage Sensor for Metering and Protection in High Voltage Power Systems", Proceedings of CCECE/CCGEI 1994, IEEE Catalog Number: 94TH8023, ISBN: 0-7803-2416-1.

[8] Javora, R., Stefanka, M., Mahonen, P., Niemi, T., Rintamaki, "Protection in MV Networks using Electronic Instrument Transformers", CIRED 2009, 20th International Conference on Electricity Distribution, Prague, 8-11 June 2009.

[9] Kojovic Lj. A., Bishop M. T., Day T. R., "Operational Performance of Relay Protection Systems based on Low Power Current Sensors", Western Power relay Conference, Spokane, WA, October 20-22, 2009.

[10] Kojovic Lj. A., "Advanced Protective Relaying Based on Rogowski Coil Current Sensors", The 9th International Conference on Developments in Power System Protection, DPSP 2008, Glasgow, UK, March 17-20, 2008.

[11] Mähönen P., Virtanen V., Hakola T., "The Rogowski coil and the voltage divider in power system protection and monitoring", ABB, Vaasa, Finland.

[12] Ramboz, J. D., "Machinable Rogowski coil, design and calibration", IEEE Transactions, pp. 329-334, 1995.

[13] Reiter G., Looser T., Fischer D., Ilar M.,"Digital Protection and Control Systems in Substations using Sensor Technology", CEPSI 2000, Manila, Philippines, October 2000.

[14] Saitoh M., Kimura T., Minami Y., Yamanaka N., Maruyama S., Nakajima T., Kosakada M., "Electronic Instrument Transformers for Integrated Substation Systems",

[15] Saitoh M., Kishimoto K., Maeda Y., "Development of the Electronic Instrument Transformers for Intelligent Substation", TMT&D Review Vol.1,No.1,2003.

[16] Tian Ye Song, Zhang De Cai, Zhang Zhang Liang, Yasuhiro Meada, Minoru Saitoh, Kosuke Abe, Seiji Imafuku, "Verification Test of High Accuracy ECT/EVT Applied to 500kV Hybrid Switchgear", Document for ICEE, 2004.

[17] Ward, D., "Precision Rogowski coils, Rocoil", http://homepage.ntlworld.com/rocoil/flexible.htm, July 2006.