NOVEL DIFFERENTIAL PROTECTION SYSTEMS FOR IMPROVED NETWORK OPERATION RELIABILITY

Ljubomir A. KOJOVIC

Cooper Power Systems - USA

lkojovic@cooperpower.com

ABSTRACT

This paper presents novel differential protection systems that incorporate Rogowski coil current sensors and multifunction relays. The protection systems are stable, reliable, and have fast response times to faults. Since Rogowski coils are very accurate and do not saturate, protection levels can be set to lower fault current thresholds increasing the sensitivity of the scheme sensing without affecting the reliability of operation. This reduces the stress on the protected equipment during faults. The whole system is immune to external magnetic fields. The schemes are simple, user friendly and require less wiring and space than conventional solutions.

INTRODUCTION

Short circuit currents at generators and substations may be very high causing extreme current transformer (CT) saturation, resulting in substantial CT secondary current distortion. Differential protection systems must be designed to reliably operate under these conditions since the impact on power system may be serious in both cases, if the differential protection operates due to CT saturation for a through fault (lack of security) or if it does not operate for a fault inside the zone (lack of dependability). Special algorithms and solutions must be applied on conventional schemes to satisfy these requirements.

This paper presents advanced differential protection schemes for power transformers, generators, and busbars using Rogowski coil current sensors and multifunction relays. Rogowski coils are linear (do not saturate) and can be applied at any fault current levels.

CURRENT TRANSFORMERS

The CT equivalent circuit and vector diagram for resistive load are shown in Figure 1. The CT iron-core is a non-linear element that saturates whenever flux inside the CT core exceeds the saturation level, resulting in distorted and reduced secondary current that may cause relay misoperation. Standards [1]-[3] specify CT performance. Guides [4] and [5] give instructions for the CT selection for protective relaying applications. However, CT cannot saturate immediately upon the fault inception. Time that takes to begin the CT saturation is called time-to-saturation. Manufactures use different algorithms to achieve proper relay performance during the CT saturation or design relays to operate prior to the CT saturation (time-to-saturation). Remanent flux in the CT core can also cause relay misoperation. To reduce remanent flux, gapped-core CT have been used [6].

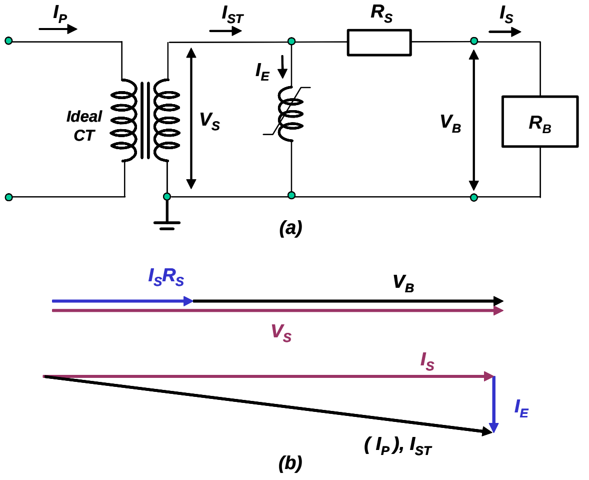

Figure 1 Current Transformer Equivalent Circuit and Vector Diagram

ROGOWSKI COILS

Rogowski coils consist of wire wound on a non-magnetic core. The coil is placed around the conductor whose current is measured as shown in Figure 2 [7]. If the core has a constant cross-section ***S*** and the wire is wound perpendicular on the middle line ***l*** with constant density ***n***, then the coil output voltage is defined by Equation 1.

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

For an ideal Rogowski coil, mutual coupling *M* is independent of the conductor location inside the coil loop.

The Rogowski coil equivalent circuit and vector diagram are shown in Figure 3 .

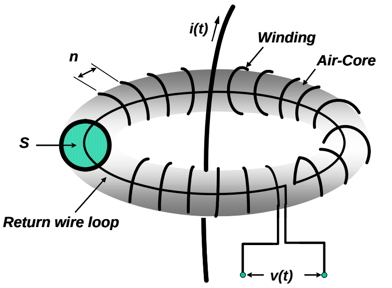

Figure 2 Principle of the Rogowski Coil Design

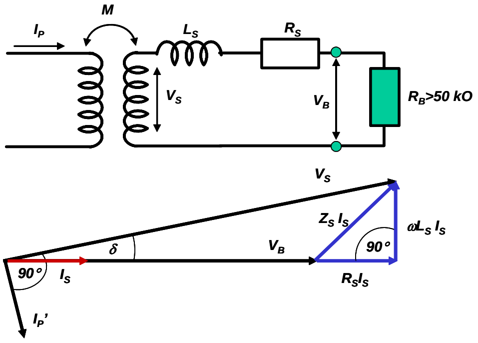

Figure 3 Rogowski Coil Equivalent Circuit and Vector Diagram

A Rogowski coil signal is a scaled time derivative *di/dt* of the primary current. To use such signals with phasor-based protective relays, signal processing is required to extract the power frequency signal. This may be achieved using one of the following methods: (a)-integrating the Rogowski coil output signal, or (b)-using non-integrated signal and perform signal processing to adjust magnitudes and phase shift signals 90°.

To prevent the influence of nearby conductors carrying high currents, Rogowski coils are designed with two wire loops connected in the electrically opposite direction. This cancels electromagnetic fields coming from outside the coil loop. This other loop can be formed by returning the wire through the winding or near the winding. Another solution is adding an additional winding wound in the opposite direction over the existing one or placing the second winding near the first winding. High precision Rogowski coils may be designed using printed circuit boards (PCB), which contain imprinted windings. Rogowski coils can be designed with different shapes to accommodate the application; for example, circular, oval or rectangular [8] and [9]. Rogowski coils can also be designed in a split-core style for installation without the need to disconnect a primary or secondary conductor. Example of a non split-core style PCB RC design is shown in Figure 4 and a split-core style in Figure 5. Connections to relays can be by wires or through fiber-optic cables.

The PCB Rogowski coil has the following characteristics: metering accuracy achievable; measurement range from 1 A to over 100 kA; frequency response linear up to 1 MHz; unlimited short-circuit withstand; galvanically isolated from the primary conductors; can be installed around bushings or cables, avoiding the need for high insulation. Rogowski coils can be connected in series to increase the output signal.

Figure 4 Printed Circuit Board Rogowski Coil (non split-core style)

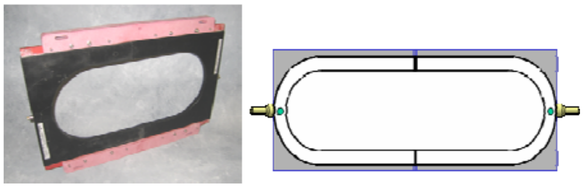

Figure 5 Printed Circuit Board Rogowski Coil (split-core style)

Due to low output signal levels (in the order of 150 mV at nominal currents), Rogowski coils should be shielded to prevent capacitive coupling to the high voltage primary conductors, and minimize influence of high frequency electromagnetic fields.

PERFORMANCE CHARACTERISTICS

Figure 6 compares V-I characteristics for non-gapped CT, gapped CT, and Rogowski coils. Introduction of an air gap in the CT core reduces the CT V-I characteristic slope. This results in the reduced remanent flux, but increases the phase error. Rogowski coils have linear V-I characteristics. However, they need appropriately designed relays that accept these types of signals.

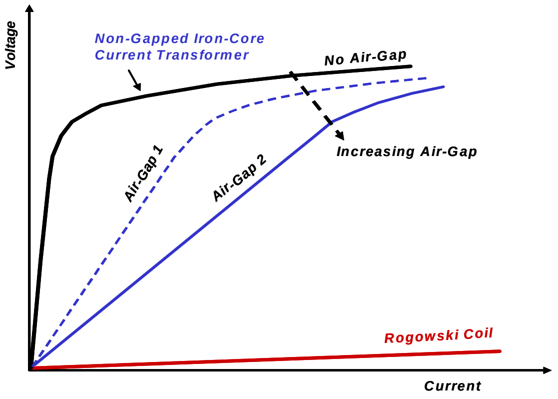

Figure 6 V-I Characteristics of Current Transformers and Rogowski Coils

ROGOWSKI COIL APPLICATIONS

Rogowski coils can replace conventional current transformers in all metering and protection applications. Standards [10]-[12] specify performance characteristics for electronic current transformers. The following examples illustrate some of applications.

Differential Protection of Power transformers

In steel facilities that use electric arc furnaces (EAF) to manufacture steel from scrap, the EAF transformer is one of the most critical pieces of electric power equipment in the plant. Failures in the EAF transformer or its buswork interrupt production and require costly and time-consuming repairs. Traditional overcurrent protection is often applied at the circuit breaker that supplies the cable serving the furnace transformer. This protection is normally set to reach into the furnace transformer primary winding for faults in the winding, but may not have sufficient sensitivity to reach through the transformer into the secondary winding or into the secondary leads. Faults that occur in the secondary buswork, water cooled leads, or in the conducting arms above the furnace are not detected by the upstream overcurrent protection and are normally interrupted only after personnel manually open the circuit breaker. The damage due to the extended fault duration can result in long or costly outages. Differential protection schemes are not typically applied on EAF transformers due to the difficulty in providing conventional CT of sufficient rating for the secondary leads carrying load currents of 60 kA or more. Some modern EAF transformers are rated to deliver a steady state secondary current of 80 kA. In some cases, a CT is built into the transformer that monitors the current in only one secondary winding (there are typically multiple secondary windings per phase group). This current signal has been used for metering or regulator control purposes, and the magnitude is calculated externally with a scale factor assuming the current in each winding is the same. The accuracy of this technique is not sufficient for a reliable differential protection system.

The differential protection of EAF transformers uses similar principle to conventional solutions where the differential protection zone is defined by the location of the Rogowski coils. Rogowski coils installed on the primary side may be designed as non-split-core style since primary conductors can easily be opened.

The EAF transformer secondary side may include large conductors consisting of water-cooled bus tubes. In a project, split-core style RC sensors have been applied for two per phase 9-inch bus tubes on 10-inch, 12-inch, and 26-inch center-to-center spacing. All have worked successfully with sufficient ease of installation [13]. Figure 7 compares RC secondary signals of a EAF transformer primary and secondary currents during an EAF operation. Waveforms are nearly identical even though currents are heavily distorted and magnitudes exceed 100 kA. Several EAF transformer differential protection projects have been implemented. They have reliably operated since their installation (now over two years).

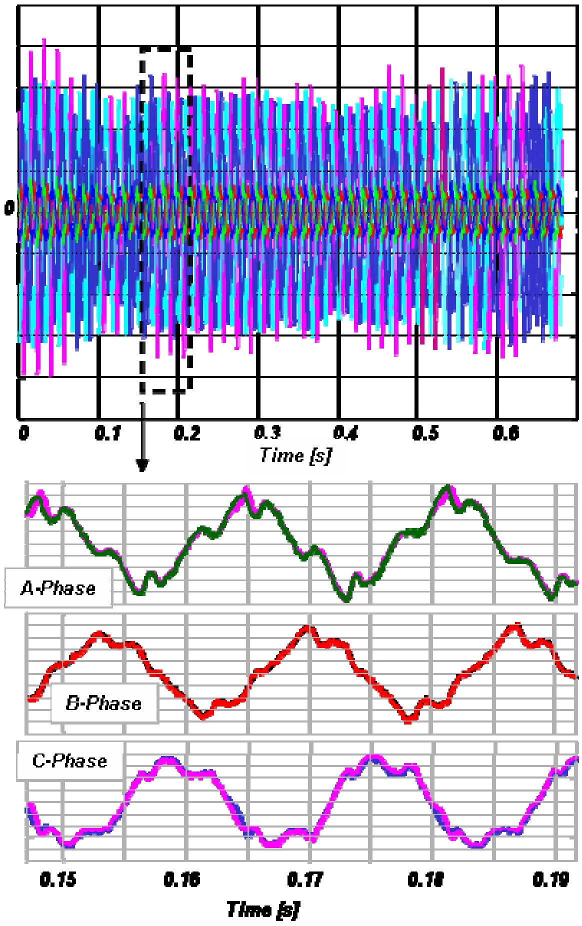

Figure 7 Rogowski Coil Secondary Signals of an EAF Transformer Primary and Secondary Currents

Differential Protection of Power Transformers

The same principle applied for EAF transformer differential protection may be used to protect all power transformers. The initial projects included differential protection of mobile substation power transformers, which require that the equipment tolerate the motion and vibration associated with movement over the road on a trailer. The Rogowski coil approach offered much less weight and size in the sensor when compared to conventional CT along with improved protection system performance.

Differential Protection of Generators and Motors

The primary system time constant near generators are large. Unless physically impractical CT designs are applied, CT saturation for close-up through fault conditions and some other external disturbances cannot be avoided. Even where CT are of similar design and the leads between each set of CT and the differential relay are balanced, the CT will not saturate to the same degree at the same time because of remanent flux. Traditional differential protection schemes require stabilization for external faults/disturbances that cause CT saturation since it is not feasible to avoid CT saturation under all circumstances.

Rogowski Coils provide superior differential protection of large motors and generators since they are linear (do not saturate), reject external electromagnetic fields, and are accurate, providing simpler and more reliable protection. Rogowski Coil physical dimensions and weight are much smaller than of conventional current transformers.

Differential Protection of Busbars

Short circuit currents at substations may be high to cause severe CT saturation, resulting in substantial CT secondary current distortion. Busbar protection (BBP) systems must be designed to operate reliably under these conditions. It is common that CT in a substation may have different ratings and V-I characteristics. Feeders with low nominal currents may have CT with a low ratio. In such applications, if the fault occurs adjacent to the CT on its load side, it can cause severe CT saturation even with symmetrical fault currents. Internal faults at the bus determine the busbar protection dependability. External faults determine the busbar protection security and should be considered for each different CT type. Figure 8 shows BBP performance for a fault In-Zone and Out-of-Zone. For faults In-Zone BBP operated in less than one cycle. For Out-of-Zone fault BBP was stable (did not operate) until breaker backup protection issued trip command as designed.

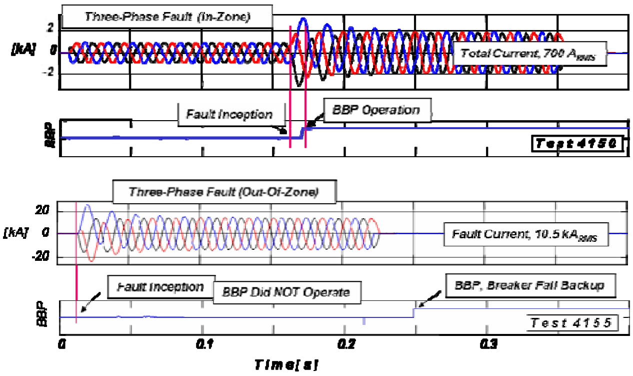

Figure 8 BBP Performance for In-Zone and Out-of-Zone Faults

Applications in High Voltage Systems

Rogowski coils designed for low voltage insulation level may be used in gas insulated substations (GIS) and air-insulated switchgear. For applications in GIS, RC are implemented in the switchgear enclosure. For applications in open-air substations, RC 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 conventional CT located at the high voltage level near RC or from the ground level by light emitted diodes transmitting light power through the fiber optic cables. The advantages of optically interfaced RC with relays compared to the conventional designs (high voltage, free standing iron-core CT) are: no oil or SF6 gas (environmentally friendly), lightweight, and no seismic or explosion concerns. In some designs, voltage and current sensors may be combined allowing measuring current and voltage with one device.

References

[1] IEEE Standard C57.13,“Requirements For Instrument Transformers”.

[2] IEC Standard 60044-1, Instrument transformers – Part 1: Current transformers

[3] IEC Standard 60044-6, Instrument transformers – Part 6: Requirements for protective current transformers for transient performance

[4] IEEE Standard C37.110,“IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes”.

[5] CIGRE Report, “Coordination of Relays and Conventional Current Transformers”, CIGRE_B5.02 Draft 8a, August 2004.

[6] IEEE PSRC Report, ”Gapped Core Current Transformer Characteristics and Performance”, IEEE Transactions on Power delivery, Vol. 5, No. 4, November 1990.

[7] Lj. A. Kojovic, ”Rogowski Coils Suit Relay Protection and Measurement”, Computer Application in Power, IEEE Magazine, July 1997.

[8] Lj. A. Kojovic, V. Skendzic, S. E. Williams, “High Precision Rogowski Coil”, Patent Number: 6,313,623; Date of Patent: November 6, 2001.

[9] Lj. A. Kojovic, “Measuring Current Through An Electrical Conductor”, Patent Number: 6,680,608 B2; Date of Patent: January 20, 2004.

[10] IEC Standard 60044-8,“Instrument transformers – Part 8: Electronic current transformers”.

[11] IEC Standard 61850-9-1, “Communication networks and systems in substations – Part 9-1: Specific communication system mappings (SCSM) – Serial unidirectional multidrop point-to-point link”.

[12] IEC Standard 61850-9-2, “Communication networks and systems in substations – Part 9-2: Specific communication system mappings (SCSM) – Sampled analog values over ISO 8802-3”.

[13] Lj. A. Kojovic, M. T. Bishop, S. E. Williams, D. Sharma, “Applications of Low-Energy Sensors for Differential Protection of Large Power Transformers and Generators”, the North American T&D Conference and Expo, Toronto, Canada, May 11-19, 2005.