INTEGRATION OF RELAY PROTECTION FUNCTIONS

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ABSTRACT

This paper presents a novel solution that integrates protection of power transformers and power cables based on differential protection principles. Primary currents are measured by Rogowski Coil current sensors. In this solution, one Rogowski Coil set shares signals for two protection functions, simplifying the protection installation and reducing the project cost. This solution has been designed for all power transformer and cable/line installations.

INTRODUCTION

This paper presents an integrated protection system for an electric arc furnace (EAF) transformer and seven parallel connected power cables that interface a substation bus with the EAF transformer. These are the first protection solutions based on Rogowski Coil current sensors in the world. In the past, EAF transformers were not protected by differential protection because current transformers (CTs) were not available for such application (due to the high currents and installation difficulties).

The first Rogowski Coil-based differential protection system for an EAF transformer was implemented in 2004. As an expansion, a cable differential scheme was applied in 2009. Traditionally, two additional sets of current sensors would be required for the cable differential protection. Since there was already a Rogowski Coil-based EAF transformer differential system implemented, the primary-side sensors in the EAF vault were used as the current sensors for both the cable and EAF vault differential protection systems (see Figure 1).

The line differential protection system establishes a new zone between the substation and the EAF vault providing protection for all equipment between sensors in the substation and sensors in the EAF vault.

The differential protection system presented here is based on peer-to-peer communication over Ethernet using the GOOSE messaging system. The communication system uses single-mode fiber-optic cable interconnected through an Ethernet switch located in the substation. The switch manages communications between the relays as well as the Ethernet traffic between the substation and the LAN inside the facility. This enables remote PCs to access various relay event records and to download relay settings.

Typically, EAF circuits consist of a circuit breaker (CB) located in a local substation, power cables between the CB and a transformer switching device located at the other end of the cable, an EAF transformer, and water-cooled conductors that power EAF electrodes. Traditionally, protection of EAF circuits included only overcurrent protection with phase and ground elements connected to the substation CB. Setting and coordination of overcurrent protection is difficult due to the balance required between fault sensitivity, speed, and avoiding nuisance-trip operations on normal overcurrent events.

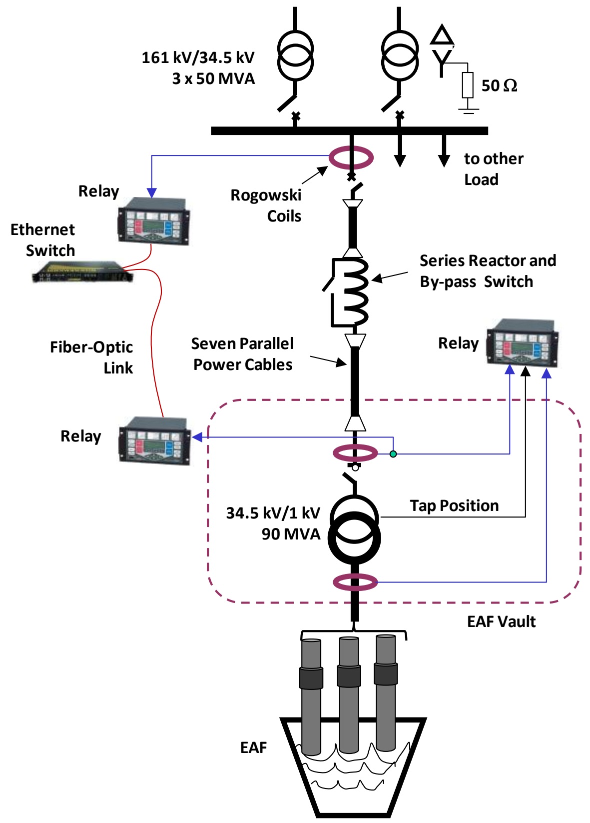

Figure 1 Furnace Supply Circuit with EAF Vault and Line Differential Protection Systems

The Rogowski Coil-based differential systems are fault-sensitive (can detect low-fault currents without jeopardizing the scheme security) and operate fast (no intentional time delays). The protection schemes are immune to the high-current load swings common to EAF circuits. The differential systems presented here allow the conventional overcurrent devices to be set as a true backup protection. The improvement in fault detection and security against mis-operations has been demonstrated in actual practice on operating systems.

ROGOWSKI COIL CURRENT SENSORS

Rogowski Coil current sensors operate on the same principles as conventional iron-core CTs. However, Rogowski Coils are wound over a non-magnetic core instead of over an iron core. As a result, Rogowski Coils are linear since the non-magnetic core cannot saturate. Rogowski Coil applications for protective relaying purposes follow the same rules as conventional CTs.

Rogowski Coils are low-power current sensors since their secondary signal is different than the typical CT secondary signal. Standard IEC 61869-10 (under development) defines requirements for Rogowski Coil applications for metering and protection. Unlike CTs that produce secondary current proportional to the primary current, Rogowski Coils produce an output voltage that is a scaled time derivative di(t)/dt of the primary current and require microprocessor-based equipment designed to accept these types of signals. Standards IEEE C37.92™-2005, IEC 60044-8, and IEC 61850 define the interface between low-power sensors and protective relays or other substation intelligent electronic devices [1]-[3]. IEEE Std C37.235™-2007 provides guidelines for the application of Rogowski Coils used for protective relaying purposes [4].

Rogowski Coils may be designed using printed circuit boards (PCB) with imprinted windings on the boards. Properly designed Rogowski Coils meet these two main criteria:

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

High-precision Rogowski Coils used in this project are designed using two PCBs sandwiched together as a multi-layer PCB design. Each PCB has an imprinted coil and are wound in opposite directions. Rogowski Coils have been designed in a split-core style for installation around primary conductors without the requirement to open primary conductors [5]. Figure 2 and Figure 3 show two different designs of split-core style coils. A non-split-core style coil is shown in Figure 4. Rogowski Coils have compact size and weigh many times less than conventional CTs. The coil shown in Figure 2 weighs approximately 5 kg.

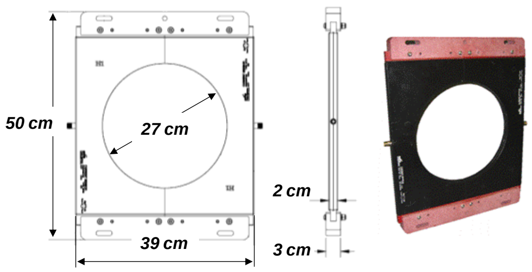

Figure 2 Split-Core Style Rogowski Coils Installed around the Circuit Breaker Bushings

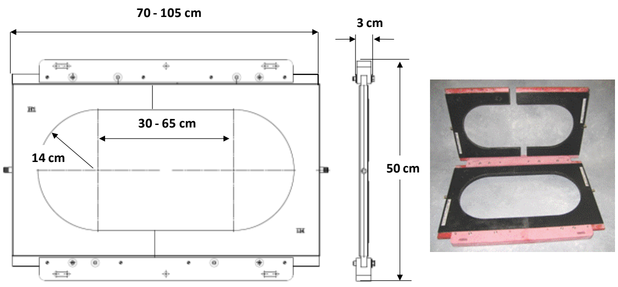

Figure 3 Split-Core Style Rogowski Coils Installed at the EAF Transformer Secondary Side around two parallel water-cooled Conductors

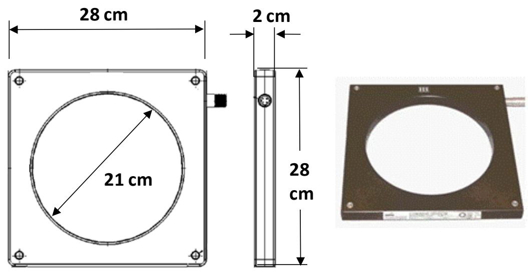

Figure 4 Non-Split-Core Style Rogowski Coils Installed at the End of Power cables near the EAF Transformer

MULTIPLE PROTECTION ZONES

Multiple protection zones provide significant improvement in the fault-detection and protection systems for EAF supply circuits and equipment. This may include EAF transformers, lines/cables, busbars, and all other devices inside the protection zones.

<u>Line/Cable Differential Protection</u>

Figure 1 shows a power system layout upgraded with the line differential protection zone. Line differential systems can be applied by adding a set of sensors to the substation in the vicinity of the circuit breakers. Typically, they can be applied on the circuit breaker, mounted in similar fashion to conventional CTs. In systems that already have a Rogowski Coil-based EAF vault differential system, the primary-side sensors can be used for both the line/cable and EAF vault differential protection systems. In both cases, one relay must be added on both ends of the line differential protection zones and interconnected with a fiber-optic communication link.

The line differential protection system settings are similar to most differential types of systems. The protection engineer will select a minimum trip level in differential amperes and also a percentage differential slope characteristic. With the Rogowski Coil current sensor, a lower slope is normally selected (as compared to CT-based systems). The protection scheme has logic that can be enabled to compensate for the charging current of the cable or line (when charging currents are high they would be seen as In-Zone faults by the protection system). This feature can be disabled if charging currents are small.

The routine operation of the furnace creates a challenging electrical environment for any protection system. The heat cycle begins with the "bore in" phase when the electrodes are lowered into the cold scrap 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. During this phase current magnitudes change rapidly and chaotically 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 the 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. 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 mis-operations would cause unnecessary and costly downtime.

Field Implementation

In 2009, the line differential protection system was installed in an industrial power system that serves a steel production plant. The protection system was applied on a feeder that provides electric power to a 90 MVA EAF transformer. This is a trial protection system intended to prove its effectiveness in providing reliable differential protection for seven parallel-connected power cables. This was the first Rogowski Coil-based line differential protection system implemented in the USA. Two sets of Rogowski Coils are usually required for the line differential system. However, this system is unique since it uses only one set of Rogowski Coils to provide protection for two independent differential protection systems. One (new) set of Rogowski Coils was installed in the substation on the circuit breaker bushings in an empty source-side CT pocket as shown in Figure 5. In this application split-core style Rogowski Coils were installed at the circuit breaker location (see Figure 2).

At the other end of the cables, near the EAF transformer at the transition to bus tubes, non-split-core style sensors (see Figure 4 and Figure 6) were already in place for the vault differential system that has been operational for more than five years. This set of sensors was used as the second set of coils to simultaneously provide current signals for two separate differential protection systems (power cables and EAF transformer). This is a cost-effective solution that is easy to install and maintain, while providing reliable protection.

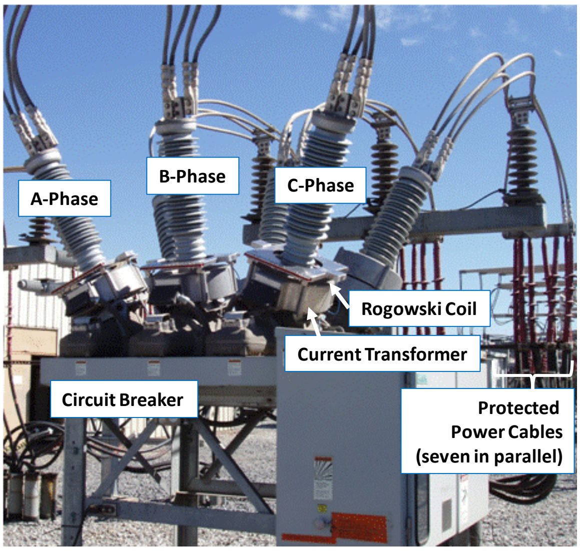

Figure 5 Rogowski Coils Installed around the Circuit Breaker Bushings

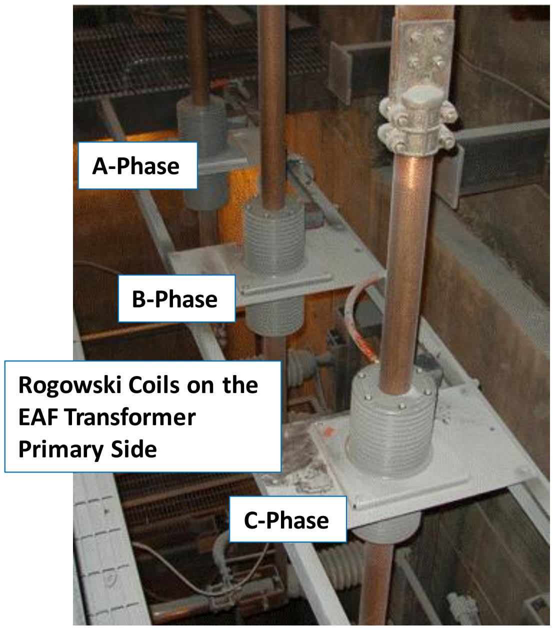

Figure 6 Rogowski Coils Installed at the Power Cable Ends near EAF Transformer

The third set of Rogowski Coils are split-core style coils (see Figure 3) that are already in place at the EAF transformer secondary side, providing input signals for transformer differential protection (see Figure 7).

One relay and the Ethernet switch were installed in the substation control room. The second relay was located in the EAF 2 differential relay panel in the EAF control room. Tee-style connectors were used to interconnect the twin-ax cable from the same set of Rogowski Coils into both the EAF 2 differential relay and the cable differential relay. Communication between two line/cable differential relays was provided through an existing fiber-optic cable.

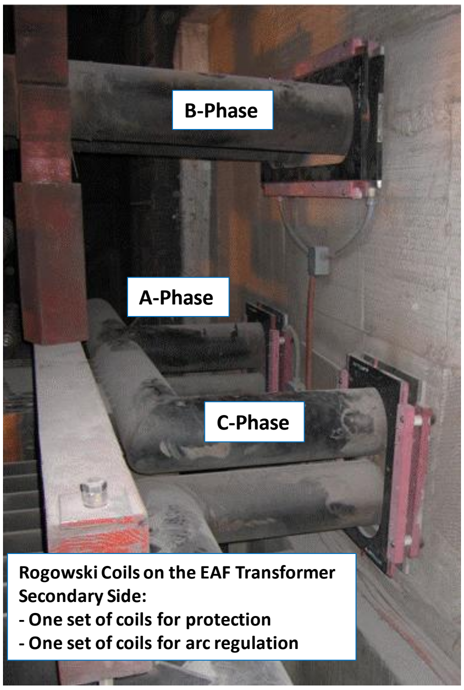

Figure 7 Rogowski Coils Installed at the EAF Transformer Secondary Side

A typical EAF has extreme operating conditions such as frequent EAF transformer energizing, fast and chaotic current magnitude changes, high EAF currents (can be over 100 kA), significant current distortion and unbalance, and frequent operation of the vacuum circuit breaker bypass for the series reactor. These extreme operating conditions make it difficult to design a protection system to provide both high dependability and high security. In this application, the EAF is energized at least 70 times per day and each energization also involves the operation of a vacuum circuit breaker bypass for the series reactor. Operation of the bypass breaker occurs in the middle of the heat cycle (when the reactors are shorted after the furnace regulator determines that sufficient arc stability is achieved).

The newly implemented Rogowski Coil-based protection system has already experienced tens of thousands of energization inrush events since installation and has performed with high security. Figure 8 shows a manually triggered oscillographic record during normal operation of the EAF at about 2300 A primary current (78 kA secondary current). The differential signals are typically on a few percent of the total restraint current.

The intention of the differential protection philosophy for the entire EAF electric circuit (from the substation to the secondary bus of the EAF transformer in two separate zones) is fast fault detection and fault clearing. Differential protection is also desirable because it provides high sensitivity, can detect low-fault currents, and is immune to large load current excursions through the protection zones. This level of protection cannot be achieved with conventional overcurrent protection since time delayed and instantaneous overcurrent devices must be set in such a way that minimizes nuisance operations for normal load current extremes. The downside of these high-current settings is that fault detection sensitivity is reduced and tripping times for actual fault events is increased. For example, in circuits that use series reactors with a bypass switch, fault currents may drop to less than half the magnitude of the fault current without the series reactor in the circuit. If a fault occurs when the series reactor is in-service overcurrent protection trip times may be on the order of several seconds. The new differential system responds to faults within two cycles, providing both high dependability and security.

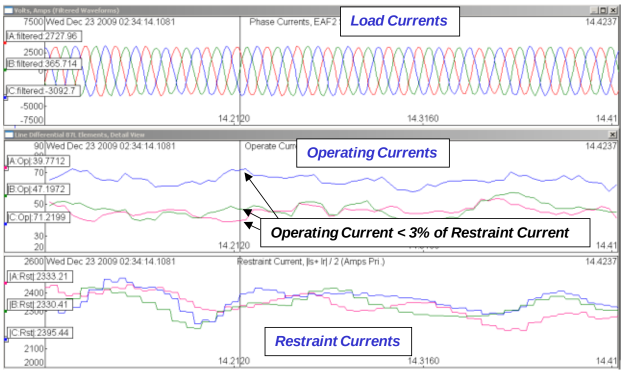

Figure 8 Manually Triggered Oscillograph Record during Normal Operation

An additional application of Rogowski Coils where their superior performance compared to conventional CTs has been demonstrated is the EAF electric arc regulation. Figure 7 shows two sets of Rogowski Coils, one set for protection and the second set for arc regulation. Rogowski Coils installed on the EAF transformer secondary side accurately measure currents through the water-cooled conductors under all operating conditions.

REFERENCES

[1] IEEE Standard C37.92™, Analog Inputs to Protective Relays from Electronic Voltage and Current Transducers.

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

[3] IEC Standard 61850, Communication networks and systems in substations.

[4] IEEE Document C37.235™, Guide for the Application of Rogowski Coils used for Protective Relaying Purposes.

[5] Lj. A. Kojovic, 2004, "Measuring Current Through An Electrical Conductor", U.S. Patent: 6,680,608 B2; Date of Patent: January 20.

[6] Lj. A. Kojovic, M. Bishop, "Electrical Arc Furnace Protection System", U.S. Patent: 6,810,069 B2; Date of Patent: October 26, 2004.