Innovative Differential Protection of EAF Electrical Systems Using Low Power Current Sensors

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Abstract. This companion paper to the paper [1] **presented at the 2009 IEEE IAS Annual Meeting describes new differential protection solutions for electric arc furnace (EAF) power systems that use Rogowski Coils as current sensors. These novel solutions provide multiple protection zones, covering the entire EAF electric supply system. The protection philosophy includes multiple differential zones of protection such as cables serving the EAF vault, series reactors, EAF transformers (including all power apparatus in the protection zones), and busbars.**

Key words***: Rogowski Coil; Relay Protection; Electric Arc Furnace Transformer Protection; Transformer differential relay protection***

I. Introduction

Typically, electric arc furnace (EAF) circuits consist of a circuit breaker (CB) located in a local substation, a power cable (or multiple parallel 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. Some designs apply an additional set of these devices local to the EAF vault. 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. In the past, EAF transformers were not protected individually by differential protection since current transformers (CTs) were not available for such application due to the high currents and large physical size required.

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

This paper presents a novel solution for the protection of power cables based on differential protection principles with currents measured by Rogowski Coil current sensors. This solution has been designed for general power line applications that may be two-source or single-source lines. This paper reviews protection system application on seven parallel connected in-service power cables that interface a 34.5 kV substation bus with a 90 MVA electric furnace transformer. The protection scheme has been subjected to extensive testing in a high-power laboratory and in an operating EAF circuit application that represents extreme power system operating conditions. All tests have verified the high dependability and security of the solution.

The first Rogowski Coil-based protection systems implemented were differential protection of EAF transformers. As an expansion, a cable differential scheme was applied on one set of parallel cables supplying electric power for one EAF. Two additional relays were required for the cable differential protection system, one relay on each end of the cables, interconnected with a fiber-optic communication link. Also two sets of current sensors are required for the cable differential protection system, one current sensor per phase on each end of the cable. 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 sensor for both the cable and EAF vault differential protection systems.

The line differential protection application establishes a new zone between the substation and the EAF vault that provides protection for all equipment between sensors in the substation and sensors in the EAF vault. In this solution, the series reactor and the bypass switch are also inside the zone of protection (as illustrated in Figure 1). In this plant, the power supply from the substation to the EAF vault includes seven cables per-phase (in order to carry large load currents). The multiple cables per-phase require many cable terminations, and a failure in one termination may result in damage to multiple terminations if the fault is detected and cleared by time-delayed overcurrent relays. The shorter fault clearing times associated with differential systems results in less damage at the fault point.

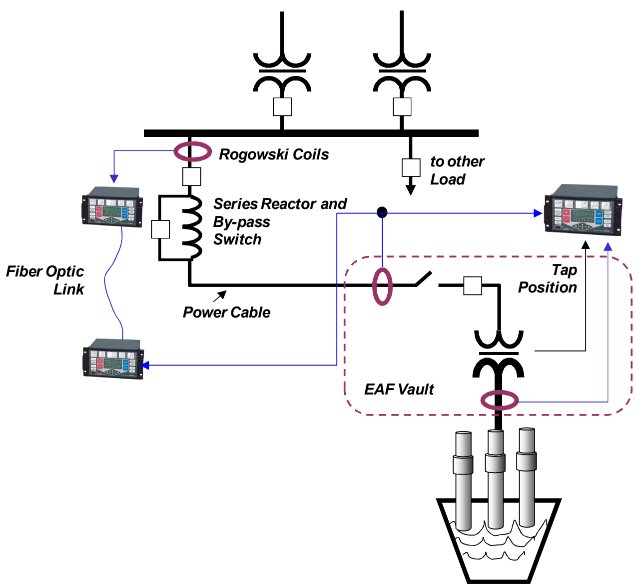

Figure 1 Furnace Supply Circuit with EAF Vault and Line Differential Protection System

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.

II. 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 iron-core current transformers.

Rogowski Coils are low-power current sensors since their secondary signal is different than the typical CT secondary signal. IEC Standard (that is under development) includes Rogowski Coils in the group of Smart instrument transformers. 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. IEEE Std C37.235™-2007 provides guidelines for the application of Rogowski Coils used for protective relaying purposes [2]-[5].

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 presented in this paper are designed using two PCBs sandwiched together as a multi-layer PCB design. Each PCB has an imprinted coil. These 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 [6]. Note the compact size in Figure 2. Rogowski Coils also weigh many times less than conventional CTs. The coils as shown in Figure 2 weigh approximately 12 pounds.

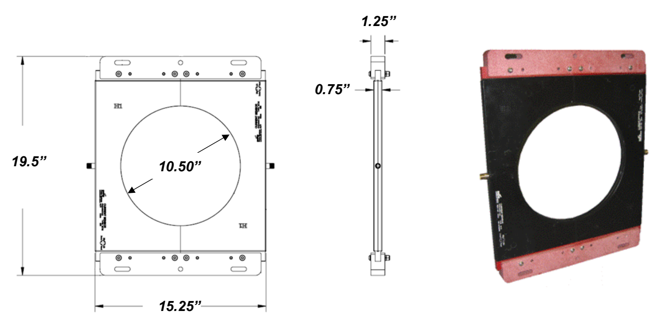

Figure 2 Split-Core Style Rogowski Coils

III. Traditional Relay Protection of Electric Arc Furnace Transformers

A. System Layout

A traditional EAF supply system is shown in Figure 3. In this application there is a substation bus supplied by one or more step-down transformers and a number of circuit breakers supplying the EAF and other plant loads. In larger plants there may be one bus dedicated to serving EAF load and a second bus for roll mill and other plant loads. The EAF supply bus might have filter banks and in many cases a static var compensation system (SVC) for power factor improvement, minimizing voltage flicker and suppression of harmonic current flow to the power system.

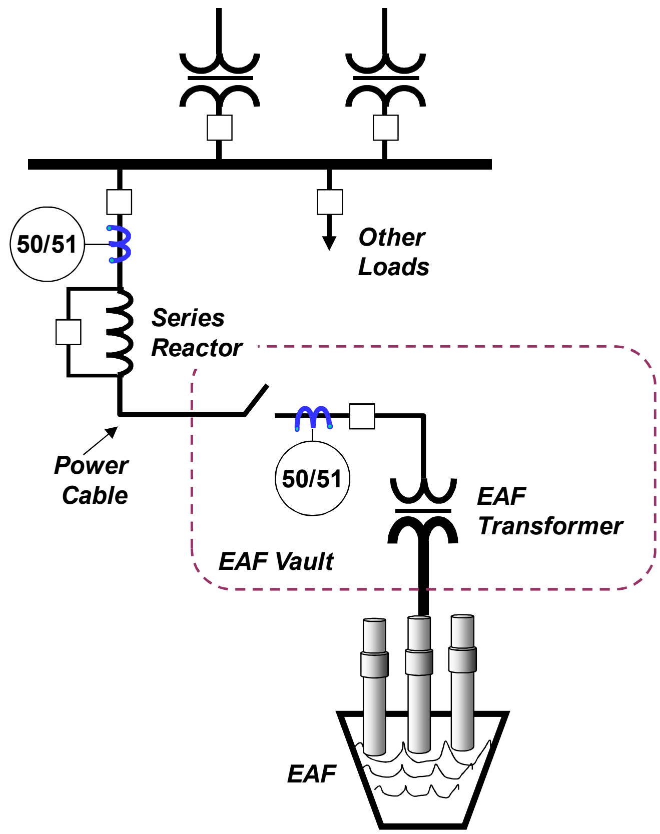

Figure 3 Arc Furnace Supply Circuits Protected by Overcurrent Protection

A series reactor may be added to the primary circuit serving the EAF transformer. The series reactor is added to provide arc stability with longer arc operation and the overall design goal is to provide higher power to the furnace at lower electrode current magnitudes. In some applications the reactor is located in the vault near the furnace transformer and in others it is located in the substation. The series reactor may also be installed with a bypass switch, so it can be bypassed according to the power scheduled for the heat cycle.

Typical EAF electric supply systems have been protected from short circuits by overcurrent relays connected to substation CTs. The overcurrent relays include instantaneous (50-device) and time-delay (51-device) elements and, in most cases, there are phase and ground fault elements. A second layer of overcurrent protection may be added at the EAF transformer vault.

B. Typical Setting Decisions

Relay settings are formulated by the protection engineer — balancing security and dependability. Security is avoiding operation (nuisance tripping) of the relay during normal conditions. Dependability is the desire that relay protection reliably operate when there is a real fault on the system. Settings that tend to improve dependability (lower trip settings and shorter times) will tend to aggravate security (more nuisance trips) and managing an electric arc furnace is a particularly challenging task for the protection engineer. Some of the issues impacting setting decisions include the following:

Frequent Transformer Switching. The EAF transformer may be switched as many as 100 times per day — generating inrush currents through the supply circuit every time that the transformer is energized. Overcurrent device settings must be high enough to avoid operation on inrush currents. Power transformer inrush current magnitudes depend on the power system strength, transformer size, and voltage closing angle. For an EAF transformer, inrush currents magnitudes are up to 8 times the load currents and may last 10s of seconds. Series reactors in the circuit may reduce inrush current magnitudes to 2 times full load current or less as observed in one application, but decay times remain long.

High Currents during Bore-in and Cave-in Events. At the start of the heat cycle the electrodes touch the scrap steel, which results in a phase-to-phase high current short circuit. This high current pulse may be short in duration as the steel will move due to high electromagnetic forces initiating arcing. In some cases, currents can be interrupted for a short time until the scrap steel touches electrodes again. Early parts of the heat cycle can also have scrap cave-ins that trap the electrodes, resulting in longer periods of high currents until the regulator responds and pulls them out of the cave-in. The substation overcurrent relays must be set to at least detect system faults at the primary terminals of the EAF transformer. Setting overcurrent relays to reach through the furnace transformer to detect faults in the secondary is difficult to achieve without causing nuisance operations. At best, faults in the secondary that are detected by the remote overcurrent relays will result in long trip times.

Series Reactor Switching. Bypassing the series reactor also creates challenges for the protection engineer. The relay settings must be high enough to operate the circuit with the series reactor bypassed (higher inrush currents and bore-in currents) and at the same time have enough sensitivity to operate when the series reactor is in service. Fault current magnitude at the furnace transformer primary terminals might be half or less than half of the magnitude when the series reactor is in the circuit. Ideally, adaptive relays that can change settings with circuit topology or two relays with different settings selected by the programmable logic controller (PLC) would be required to follow the conditions with the reactor in and out of service.

Operational Experience with CT-based Overcurrent Relays. Most facilities operating electric arc furnaces using CT-based 50/51 devices for fault protection periodically experience nuisance operations. If a lockout relay is implemented, manual resetting of the lockout relay is required after the circuit breaker operates before the circuit breaker can be closed again. This causes production delay since the circuit breakers are located in substations that can be far from the control room.

Nuisance operations of ground overcurrent relays during energization of the EAF transformers have been reported in many plants. This was usually caused by CT saturation, resulting in false secondary zero sequence current components that actually do not exist in the primary currents during normal conditions.

Long trip times for fault events in the transformer vaults can result in extensive damage to buswork and other vault equipment. Faults at the EAF transformer secondary terminals external to the transformer may not be sensed for many seconds, causing extensive damage to the delta closure. An undetected fault then spreads to the transformer primary-side terminals causing a primary side short circuit, which initiates the overcurrent relay operation and the circuit breaker then clears the fault. In many of these events the result is severe damage to the EAF transformer primary bushings that requires the EAF transformer replacement with a spare unit. The damaged EAF transformer must be sent out for major repairs. Additional cost is loss of production during the repair/replacement time.

IV. Rogowski Coil-based Differential Protection Systems with Multiple protection Zones

Rogowski Coil-based multiple protection zones provide significant improvement to the fault detection system for EAF supply circuits. This includes protection of EAF transformers, lines/cables, and busbars.

A. Line/Cable Differential Protection

Figure 1 shows a system layout with the added 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 current transformers. 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 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 a line/cable charging current compensation 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.

To demonstrate the difficult requirements for differential protection of EAF cables, here is a brief description of EAF operation: In the routine operation of the furnace, a heat cycle starts by 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. (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. 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.

Field Implementation. The line differential protection system was installed in an industrial power system that serves a steel production plant during the autumn shutdown in October 2009 (Figure 4). 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-style Rogowski Coils were used at the circuit breaker location. Figure 5 shows a close-up view of the conventional CT and Rogowski Coil, which demonstrates that Rogowski Coils are much more compact than CTs.

The second set of Rogowski Coils required at the other end of the cables, near the EAF transformer at the transition to bus tubes, were solid core-style sensors that were already in place for the vault differential system that has been operational for more than five years. This set of sensors will simultaneously provide current signals for two separate differential protection systems. This is a cost-effective solution that is easy to install and maintain, while providing reliable protection operation.

The Rogowski Coil secondary circuit consists of twisted-pair shielded cables that were pulled in conduit to the substation control building. One relay and the Ethernet switch were installed in the substation control room as shown in Figure 6 and Figure 7. The second relay was located in the EAF 2 differential relay panel in the EAF control room (Figure 8). 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. There was a spare fiber-optic cable between the substation control room and the pulpit that was available for the protection system.

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

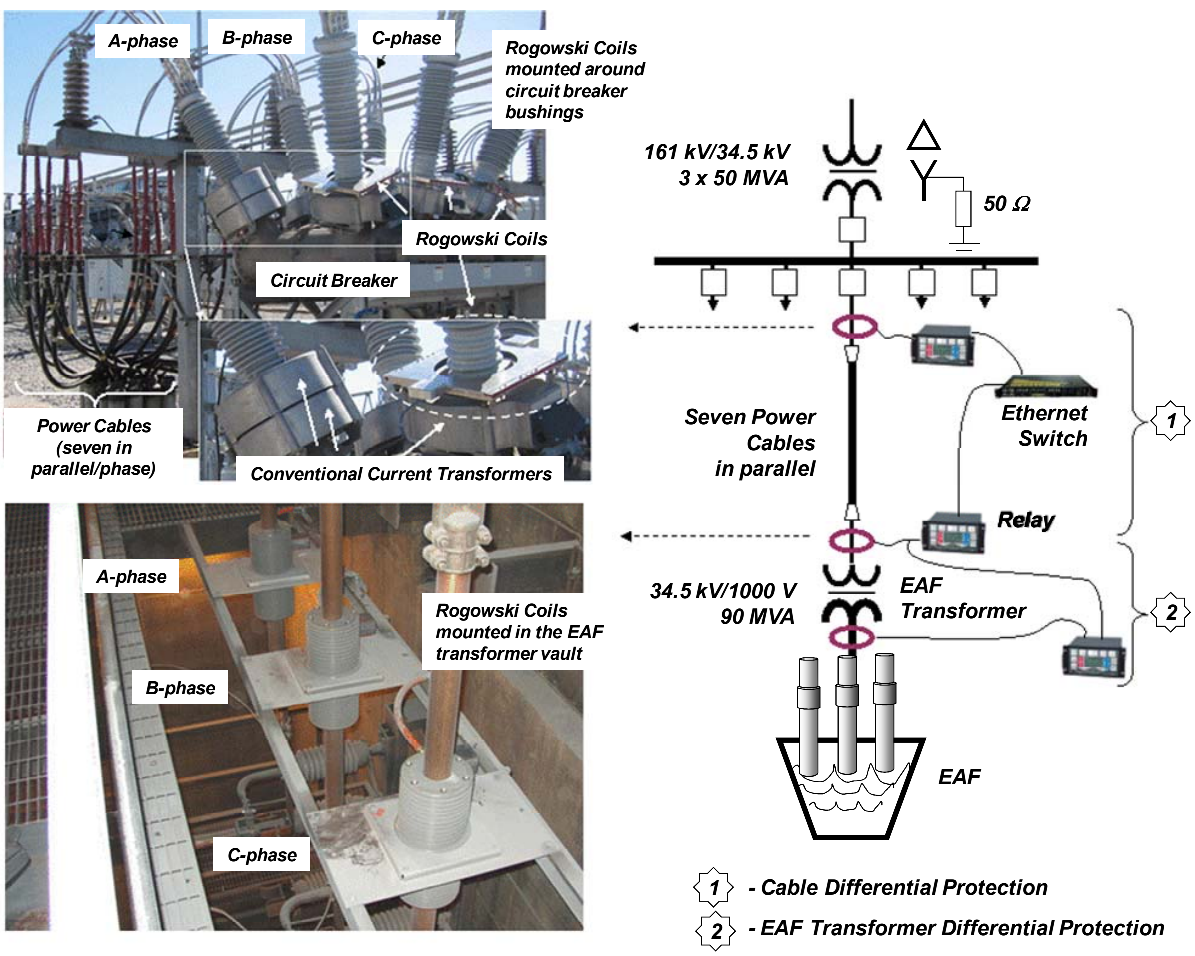

Figure 4 EAF Electric Power System

furnace regulator determines that sufficient arc stability is achieved).

The newly implemented Rogowski Coil-based protection system has already experienced several thousand energization inrush events since installation and has performed with high security. Figure 9 shows a manually triggered oscillographic record during normal operation of the EAF at about 2300 primary amps. The differential signals have been on the order of several percent of the total restraint current.

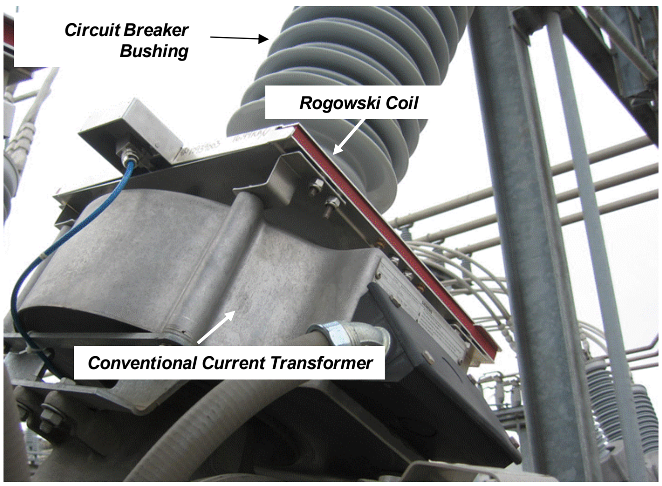

Figure 5 Comparison of Current Transformer and Rogowski Coil Sizes

Figure 6 Relay Installed in the Substation Control Room

Figure 7 Ethernet Switch Installed in the Substation Control Room

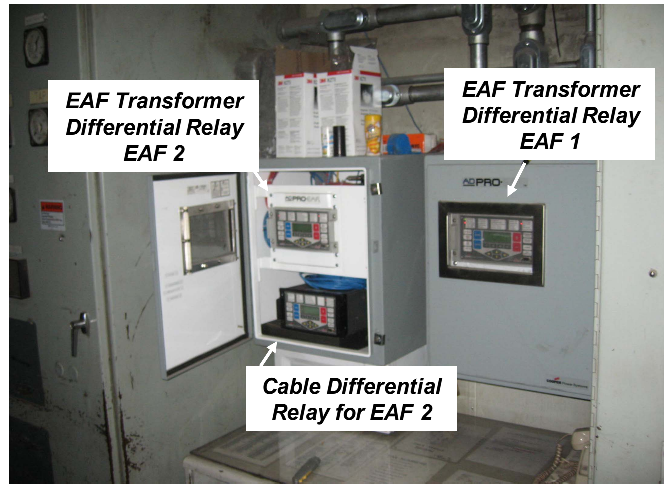

Figure 8 Cable Differential Relay Mounted in EAF 2 Differential Relay Panel

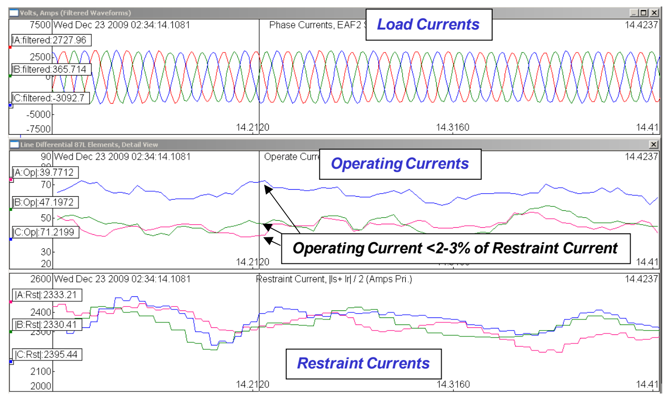

Figure 9 Manually Triggered Oscillograph Record during Normal Operation

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 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 zone. These characteristics make differential protection desirable for EAF circuits. 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 nuisance operations for normal load current extremes is low. 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 10 and Figure 11 show comparative performance of conventional 2000/5 A current transformers and Rogowski Coils during EAF transformer energizing. The current transformers saturated, while the Rogowski Coils accurately reproduced the primary currents. Figure 11 shows the waveform before the current transformer saturated with an integrated Rogowski Coil secondary signal superimposed. The two waveforms are almost identical.

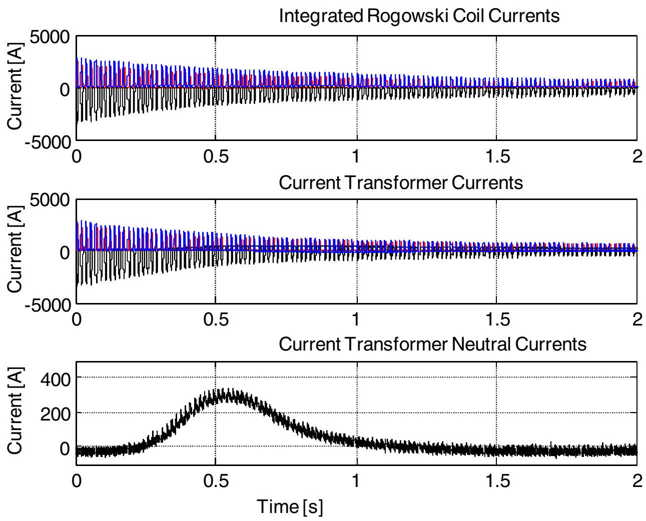

Figure 10 EAF Transformer Inrush Currents recorded by 2000/5 A Current Transformers and Rogowski Coils

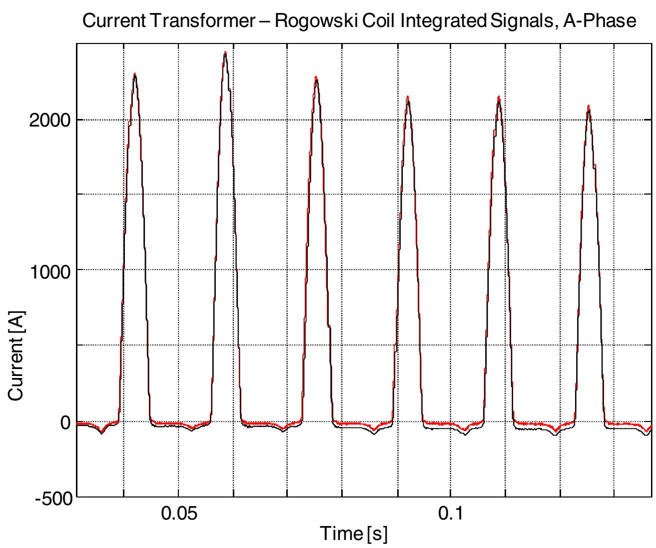

Figure 11 EAF Transformer Inrush Currents recorded by 2000/5 A Current Transformers and Rogowski Coils

B. Busbar Protection.

Short circuit currents at substations may be very high, causing extreme CT saturation and substantial CT secondary current distortion. It is common that CTs in a substation can considerably differ from each other, such as having different ratings and V-I characteristics. Feeders with low nominal currents can have CTs with low ratios. In such applications, a fault occurring next to the CT on its load side can cause CT saturation, even at symmetrical fault currents.

For simple busbar arrangements, high-impedance protection is efficient. Complex busbar arrangements may require several protection zones to adjust for different busbar configurations. Modern relays use low-impedance busbar protection schemes and provide dynamic busbar replica in the relay software for each zone of differential protection (without switching CT secondary currents). Low-impedance busbar protection schemes do not require matched CTs and can tolerate substantial CT saturation, while providing high-speed operation. Some manufacturers use different algorithms to achieve relay stability during CT saturation. For internal faults, relays are designed to operate in the presence of distorted waveforms, or prior to the CT saturation (time-to-saturation). Although modern digital protection relays can tolerate substantial CT saturation during faults, it is necessary to determine the CT time-to-saturation to verify that the requirements for proper CT selections are met. In some cases, this may not be easy to accomplish. In-Zone and Out-of-Zone tests must verify that the busbar protection will reliably operate for a fault at the bus and the protection is stable (high security) for external faults. Out-of-Zone tests should be considered for each different CT type.

Rogowski Coils do not have constraints like CTs because they are accurate and linear. They can provide reliable protection for all types of bus bars and at any fault current level. Rogowski Coils can be connected in-series same as traditional schemes based on linear couplers. All Rogowski Coils must have equal ratio, and be connected to one channel/phase of a voltage relay. The coil uncertainties must meet criteria that during normal operation and for through faults, the secondary voltage remains small (well below the setting value). However, for a fault at the bus, the secondary voltage must exceed the setting value causing the relay operation. Other solutions may include a differential scheme that uses one relay and multiple channels. Each Rogowski Coil is connected to a separate input of the relay. In this scheme, the relay must have enough inputs to connect all Rogowski Coils or use more relays interfaced by communication. Other schemes may include Rogowski Coils connected to separate relays interfaced by communication. Dynamic isolator replica for more complex busbar systems are designed using the same criteria as for conventional current transformers.

V. CONCLUSIONS

When comparing Rogowski Coil-based differential protection schemes with current transformer-based schemes, the significant advantage of Rogowski Coil-based schemes is that Rogowski Coils are linear (do not saturate) and preserve scheme security (even at high fault currents such as 60 kA as presented in this paper). There is no big difference between the two technologies at load level and smaller fault currents; however, characteristics such as light weight and compact size may be a determining factor in selecting Rogowski Coil-based schemes. Increased personnel safety is also an important factor in selecting Rogowski Coil-based protection – since opening secondary wiring during operation does not result in hazardous voltages. Split-core style designs that provide easy installation without the need to open primary conductors are an additional advantage of Rogowski Coils.

The benefits of the Rogowski Coil-based differential protection systems with multiple zones can be summarized as follows:

- **Instantaneous tripping of the substation circuit breaker for faults occurring on any part of the system between the sensor locations.** This includes the power cables, cable terminations, any splices in the cables, the series reactor and associated bypass switching devices (if used), and all the cable interconnections and bus structures associated with the series reactor. These systems also protect cable terminations in EAF vaults, arresters and any other equipment bounded by the sensor location, such as the motor-operated disconnect.

  Because of the differential principle of operation, these protection systems are immune to the high load current surges that are common in an EAF operation during bore-in and cave-ins and are not dependent on the load current.
- **Instantaneous tripping for any fault downstream of the circuit breaker to the point where the water-cooled leads exit the vault.** High sensitivity and fast speed of the relay operation prevents major damage to the equipment in case of an In-Zone fault, which allows prompt service restoration and return to production.
- **The existing time overcurrent relays may stay in service, set to serve as backup protection to differential protection systems.**

Biographies

Ljubomir A. Kojovic is a Chief Power Systems Engineer for Cooper Power Systems at the Thomas A. Edison Technical Center. He has a Ph.D. in power systems with specialties that include protective relaying, distributed generation, testing, digital modeling, and systems analysis. Dr. Kojovic is an adjunct assistant professor at Michigan Technological University and is a registered professional engineer in Wisconsin. He is an IEEE Senior Member, member of the main committee, and member of several working groups of the IEEE Power System Relay Committee. He has been awarded twelve U.S. patents and authored more than 180 technical papers.

Timothy R. Day completed his undergraduate degree in electrical engineering at Georgia Tech and his master's degree in electrical power engineering at Washington State University. Timothy has been with Cooper Power Systems for sixteen years and is a Senior Relay Application Engineer in the Energy Automation Solutions business unit working at the Thomas A. Edison Technical Center in the Milwaukee, WI area. Timothy enjoys using his skills and passions in power system modeling and analysis, protection algorithm design, and customer support and training to develop and market both conventional relay systems and emerging protection systems employing Rogowski Coil technology. He is a registered Professional Engineer in the state of Washington.

Dharam Sharma is a Staff Engineer in the electrical maintenance department at Nucor-Yamato Steel in Blytheville, AR. Mr. Sharma's primary responsibility is the optimization of the electric arc furnace operation in the melt shop at Nucor-Yamato. As a part of that responsibility, he is involved in the oversight of the electric power supply to the melt shop, including relay and protection of the apparatus in the substation. Other substation equipment related to the furnace operation includes the series reactor, vacuum switch and circuit breaker selection and maintenance, protective relay applications and setting, capacitor filter and SVC operations, and transformer maintenance. Dharam is involved in the management of the AMI electric arc furnace regulator systems.

REFERENCES

[1] Lj. A. Kojovic, M. T. Bishop, D. Sharma, "Innovative Differential Protection of Power Transformers Using Low Energy Current Sensors", 2009 IEEE Industry Applications Annual Meeting Houston, TX, October 4-8, 2009.

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

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

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

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

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

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