Operational Performance of Relay Protection Systems based on Low Power Current Sensors

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Abstract *This paper compares the operating characteristics of non-conventional current sensors, Rogowski Coils, and conventional iron-core current transformers for protective relaying applications.*

INTRODUCTION

Rogowski Coils (RCs) are transformers that operate on the same principles as conventional iron-core current transformers (CTs). The main difference between RCs and CTs is that RC windings are wound over an air core, instead of over an iron core. As a result, RCs are linear since the air core cannot saturate. However, the mutual coupling between the primary conductor and the secondary winding in RCs is much smaller than in CTs. Therefore, Rogowski Coil output power is small, so they cannot drive current through low-resistance burden like CTs are able to drive. Rogowski Coils can provide input signals for microprocessor-based devices that provide a high input resistance, and these devices therefore measure voltage across the RC 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. 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. Rogowski Coils can replace conventional CTs for protection, metering, and control. RCs 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 phasor-based protective relays and microprocessor-based equipment must be designed to accept these types of signals.

COMPARATIVE ANALYSIS

Principle of Operation

Conventional iron-core current transformers (CT) are typically designed with rated secondary currents of 1 Amp or 5 Amps, to drive low impedance burden of several ohms. 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 fault currents up to 20 times the CT rated current and up to the standard burden (maximum ohm value of burden that can be connected to the CT secondary). CTs are designed to meet this requirement. But, if a symmetric fault current exceeds 20 times the CT rated current or if the fault current is smaller 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 (RC) consist of a wire wound on a non-magnetic core (μ_r=1). The coil is then placed around conductors whose currents are to be measured. New designs may use printed circuit boards (PCB) with imprinted windings on the board (see Figure 1).

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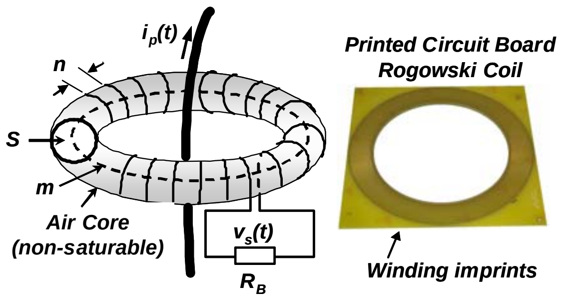


Figure 1. Rogowski Coil

Because RCs use a non-magnetic core to support the secondary windings, the mutual coupling between the primary and secondary windings is weak. Because of the weak coupling, to obtain quality current sensors, two main criteria must be met when designing Rogowski Coils:

1. The Rogowski Coil output signal should be independent of the primary conductor position inside the coil loop,
2. The impact of nearby conductors that carry high currents on the Rogowski 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 wound on a core that has a constant cross-section S and wound perpendicular on the middle line m (dashed line in Figure 1) with constant turn density n. Mutual inductance M is defined by the formula:

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

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 RC primary and secondary windings are weakly coupled, to prevent the unwanted influence from nearby conductors carrying high currents, RCs 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 or near this winding. If both loops are constructed as windings, then they must be wound in opposite directions. In this way, the RC output voltage induced by currents from the inside conductor(s) will be doubled.

Equivalent Circuits

Figure 2 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 DC 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.

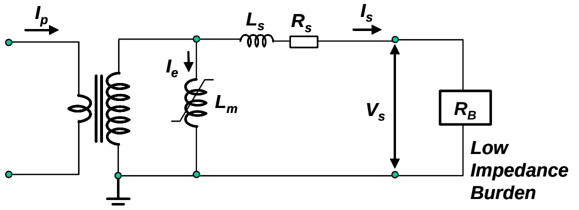


Figure 2. Current Transformer Equivalent Circuit

Figure 3 shows the equivalent circuit of a Rogowski coil. The phase angle between the RC primary current and the secondary voltage is nearly 90° (displaced from 90° by a small angle caused by the coil inductance Ls).

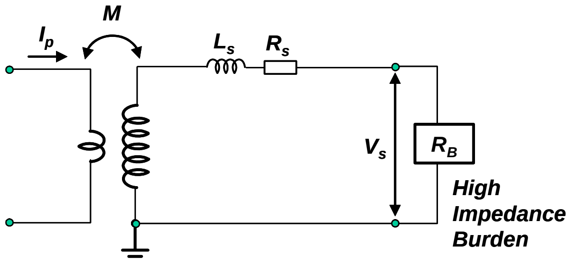


Figure 3. Rogowski Coil Equivalent Circuit

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.

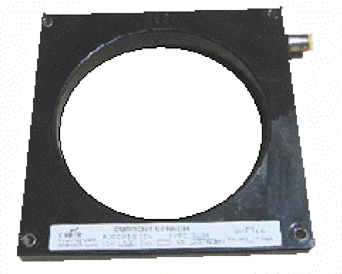
Integration of the signals can be performed in the relay (by analog circuitry or by digital signal processing techniques) or immediately at the coil. To use the Rogowski Coil non-integrated analog signal, it is necessary to perform the signal corrections for both the magnitudes and phase angles. For phasor-based protective relaying applications, the Rogowski Coil secondary signal must be scaled by magnitude and phase-shifted for each frequency.

Designs

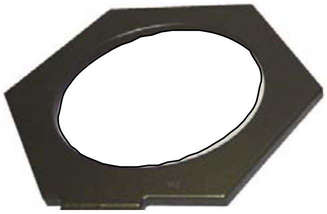
Rogowski Coils may be designed with different shapes such as round and oval. The coils may be made of rigid or flexible materials. Coils can be made as non-split style, or alternatively as split-core construction that can be opened to assemble around a conductor that cannot be opened. The cross-sectional shape upon which the coil is formed is generally either circular or rectangular.

Rigid RCs have higher accuracy than flexible RCs and may be designed using PCBs as window (non-split-core) type or split-core type. PCB Rogowski Coils can be designed using one or two printed circuit boards to imprint windings. Designs using one PCB have both windings imprinted on the same PCB. Designs using two PCBs have one coil imprinted on each PCB, wound in opposite directions.

Figure 4 shows two designs of window-type PCB Rogowski Coils for indoor and outdoor applications around primary conductors that can easily be opened to insert the Rogowski Coils, similar to conventional bushing-type current transformers. Figure 5 shows a split-core Rogowski Coil designed for installation around primary conductors without the requirement to open primary conductors. Figure 6(a) shows a split-core Rogowski Coil measuring current in multiple conductors. Figure 6(b) shows installation around one water-cooled conductor with a large cross section.



(a) Rogowski Coil for indoor applications



(b) Rogowski Coil for outdoor applications

Figure 4. Two Non-Split-Core PCB Rogowski Coil Designs

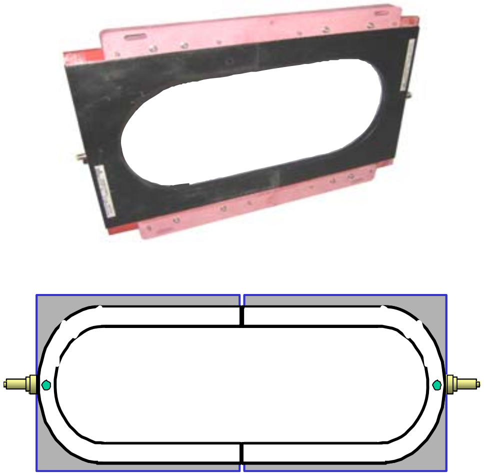
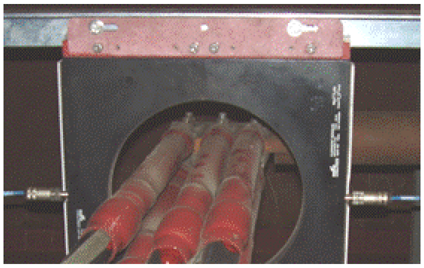
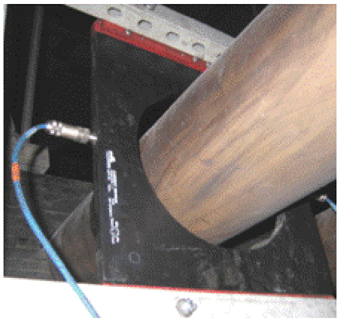


Figure 5. One Split-Core PCB Rogowski Coil Design



(a) Rogowski Coil monitors six conductors



(b) Rogowski Coil measures current in one water-cooled conductor

Figure 6. Split-Core Rogowski Coil Designs

Interface to relays

Current transformers require heavy gauge secondary wires for interconnection to relays and other metering and control equipment (Figure 7). 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. Other CT disadvantages include large size and weight. For example, Figure 7 shows a 2000/5 A, C800 class CT connected to a relay. This CT has the core and winding height of 10 cm and weighs 90 kg.

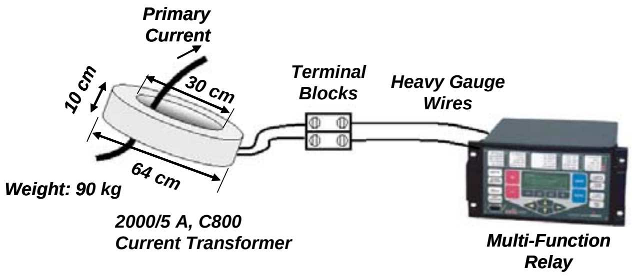


Figure 7. Current Transformer Connections to Relays

Rogowski Coils may be connected to relays via twisted pair shielded cables with connectors (Figure 8). 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 8 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 7, but can be applied to a significantly larger current range than the CT.

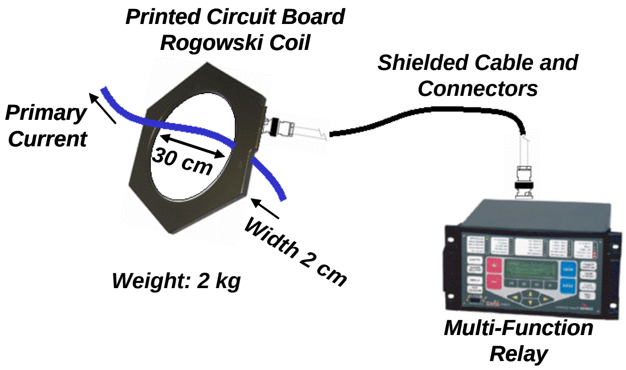


Figure 8. Rogowski Coil Connections to Relays

APPLICATIONS FOR RELAY PROTECTION

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.

Differential Protection

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 9 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. Transformer inrush currents are 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.

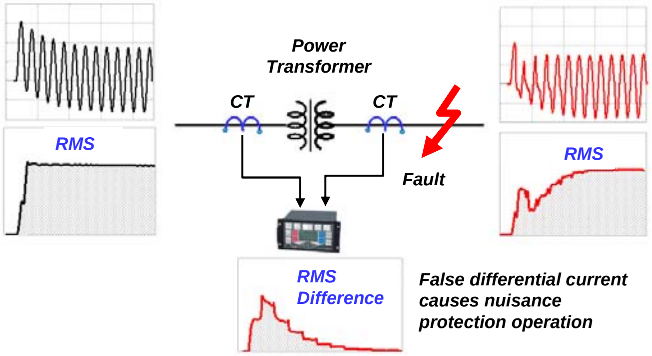


Figure 9. Current Transformer-based Power Transformer Differential Protection

The introduction of Rogowski Coil-based sensors for metering and protection is a paradigm shift in technology. Protection engineers had legitimate concern that new sensors may have 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 Rogowski Coil protection system was implemented for the first time on two 90 MVA, 34.5/1 kV EAF transformers equipped with an LTC. Primary RCs 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 RCs were designed in split-core styles (Figure 10).

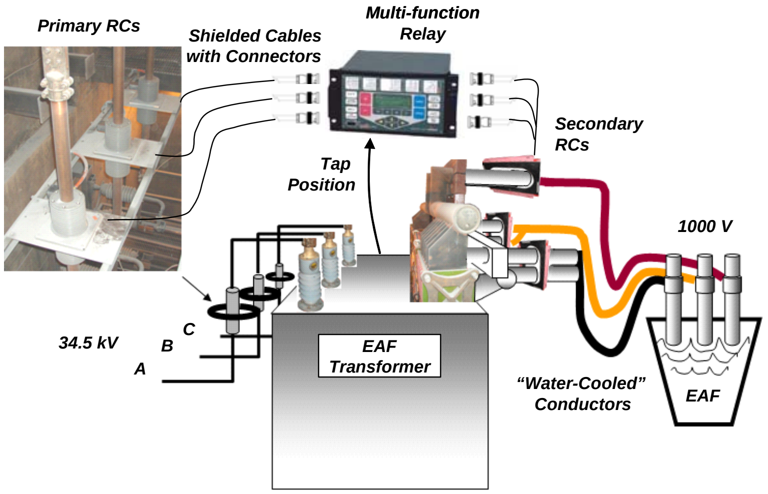


Figure 10. Rogowski Coil-based EAF Transformer Differential Protection

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 for 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 11. The current in RMS ampere values are shown in Figure 12. The RMS values are averaged per one second of recording.

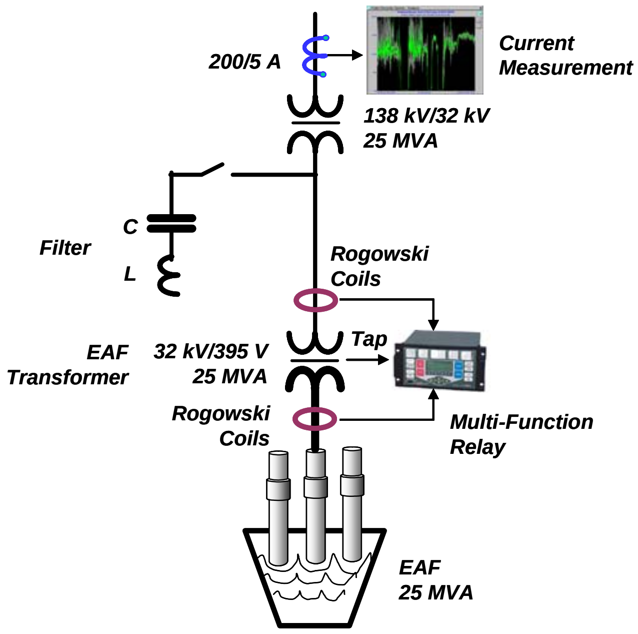


Figure 11. EAF Operation

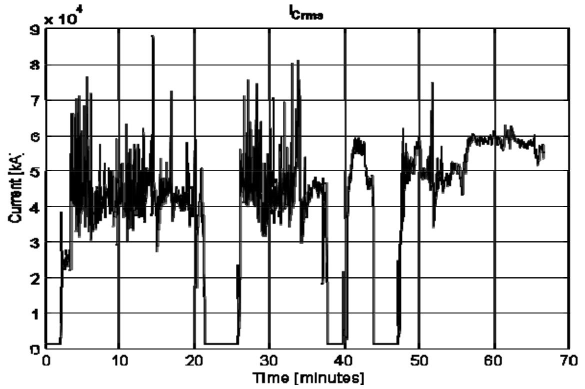


Figure 12. RMS Values of EAF Currents during one Heat Cycle (averaged during one second)

In the routine operation of the furnace a heat cycle starts with charging the furnace with cold scrap. The heat cycle starts when the electrodes are lowered into the scrap ("bore in" phase) starting the arc. This causes a short circuit that momentarily develops 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 transformer may experience. The next stage of the cycle is referred to as the early melt period. 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 13 shows RMS values of EAF currents during one heat cycle that includes three heating periods for the steel recharging or tapping the furnace. Three periods of current interruptions are intentional and are required for the steel recharging. Figure 13 shows minimum and maximum current values to better depict chaotic current changes. Currents rapidly change from low values to over 90 kA — back and forth.

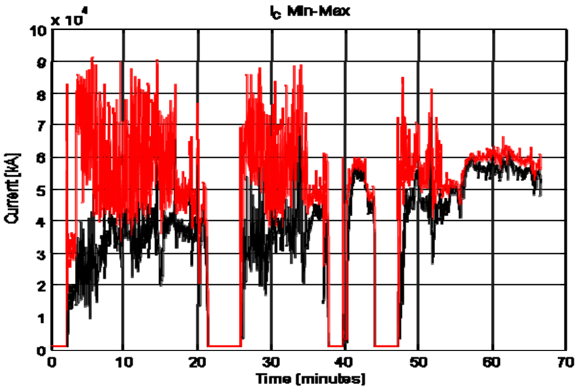


Figure 13. Max and Min Values of EAF Currents during one Heat Cycle (averaged during one second)

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

The first challenge is to provide high scheme security because EAF transformers are subject to frequent energizations, typically on the order of 70-100 energizations per day. Even a small percentage of failure to properly identify inrush conditions can result in many nuisance operations.

The second challenge is to maintain scheme sensitivity with 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 currents (In-Zone), 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. Despite all efforts to avoid dust penetration into the vault, dust cannot be completely prevented. Temperature in the vault can be low during winter time 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, EAF transformers and the whole building are exposed to high vibration from the operation of the EAF furnace.

Experience with RC-based Differential Protection

The Rogowski Coil sensor-based differential protection systems for EAF transformer protection have demonstrated superior performance since installation. 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 14.

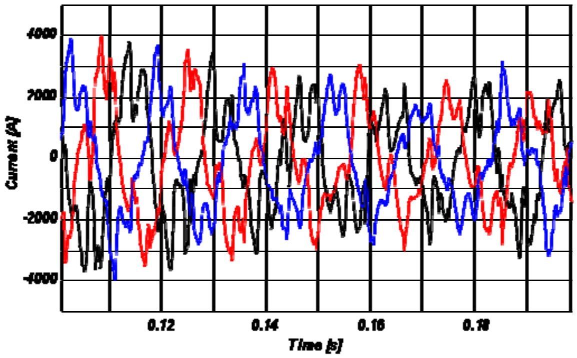


Figure 14. EAF Primary Currents (A, B, C phases) Recorded by a Transient Recorder

Another snapshot of EAF currents derived by the relay is shown in Figure 15. 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 16 demonstrates that the coil output signals of EAF primary and secondary currents recorded by a transient recorder match very well when adjusted for transformer tap position (turns ratio). Figure 17 demonstrates that the coil output signals of EAF primary and secondary currents derived by the relay also match very well to accurately derive differential currents.

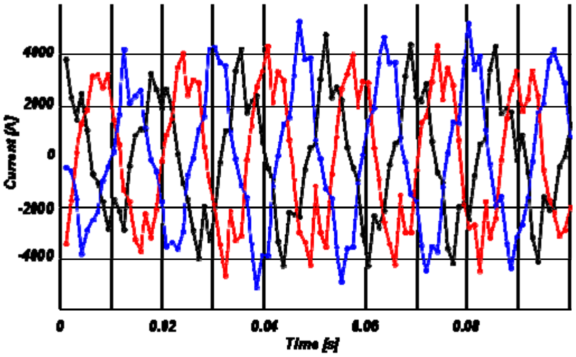


Figure 15. EAF Primary Currents (A, B, C phases) Derived by the Relay

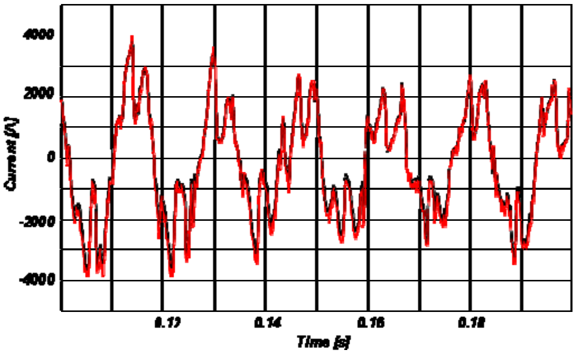


Figure 16. EAF Primary and Secondary Currents Recorded by a Transient Recorder (referred to the primary)

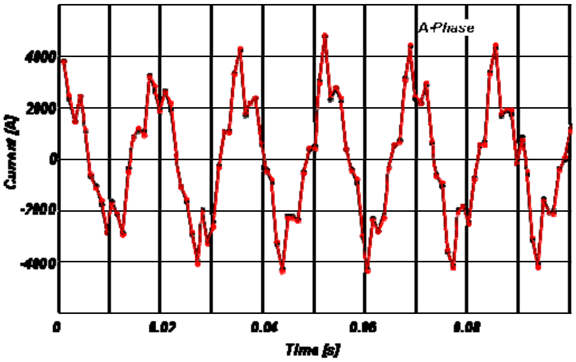


Figure 17. EAF Primary and Secondary Currents derived by the relay (referred to the primary)

Detection of Inrush Currents. Traditionally, the second harmonic restraint method was used to avoid unwanted operations when energizing a power transformer. This method cannot reliably provide restraint signals for EAF transformers since there is the possibility of a low voltage arcing fault condition within the zone of protection that will result in current waveforms that are not that much different than the arcing in the furnace just outside of the zone of protection. The operation of an electric arc furnace results in harmonic currents due to the erratic nature of the arc. Applying a second harmonic restraint method could require setting a second harmonic inrush restraint element at a higher level to avoid blocking when a secondary arcing fault occurred in the zone. A higher setting makes the identification of inrush conditions less reliable. In addition, inrush currents can be combined with load currents that can reduce the amount of second harmonics derived by the relay. As a result, the relay will not be blocked and a nuisance operation of differential protection may result.

A novel transformer inrush current detector was developed to detect characteristic current waveforms during transformer energizing. This algorithm was implemented in all of the EAF applications.

Backup Ground Fault Element. Many EAF facilities apply ground overcurrent elements on conventional CT-based relays at the vault vacuum switch and/or at the substation circuit breaker. In one application, the plant was experiencing nuisance operations of the instantaneous ground element (50N) that was using three iron-core CTs in the three phases. The EAF transformer was connected in Delta on the primary side, so there should not be residual current flowing on the primary circuit from the transformer. The 50N device was set at 2000 A primary and there were a number of nuisance operations during transformer energizing, so the operator disabled this protection function. The cause of the relay nuisance operation was the CT saturation during transformer energization, producing false secondary residual currents.

The Rogowski Coil-based backup ground element can be set to operate at low fault currents, eliminating the nuisance operation. In the same application, the ground element was set to 500 A primary, which is 25% of the CT-based ground relay setting that caused nuisance operations. RC-based ground fault protection has not experienced any nuisance operation during transformer energizing or operation since the protection system installation. This protection function provides back-up for the differential (87-1) element in the event of a line-to-ground fault event during energization when an inrush detector might be blocking the 87-1 element.

OPERATING EXPERIENCE

Reliable performance of the power transformer protection must be preserved for both In-Zone faults (defined as the scheme dependability) and external Out-of-Zone faults (defined as the scheme security).

Dependability. For EAF transformers, faults at the transformer secondary have current magnitudes that are very much the same as the load currents. Therefore, only differential protection schemes can provide reliable fault identification and protection.

Security. For EAF transformers, load currents can exceed 100 kA_{RMS}, currents are very unbalanced and contain significant amount of harmonics. Therefore, for

EAF transformers, normal operation can be considered as permanent Out-of-Zone faults. In addition, inrush currents must be reliably detected to provide the scheme security.

Scheme Dependability

The first differential protection system was put in service in 2004. Since the relays were installed several fault events have been experienced and in all events protection operated properly. Three events are described in the following section.

Fault Event #1. On March 28, 2007, a fault occurred at the EAF transformer secondary terminals caused by water leaking from the roof in the EAF transformer vault. The water leak caused a phase-to-phase fault in the secondary bus, escalating quickly and eventually leading to a short circuit on the 34.5 kV side of the transformer. The transfer of the fault from secondary to primary was due to the proximity of the terminals and the plasma burst created by the secondary fault current, estimated to be approximately 250 kA. The fault was detected by the differential relay protection and the relay closed its output contact within one-half cycle, initiating circuit breaker operation. The circuit breaker operated in four cycles. Figure 18 shows the event record captured by the relay. Because of this fast relay operation, the EAF transformer was NOT damaged. After cleaning the affected area, the transformer was energized the same day (less than 6 hours after the fault) and the production of steel continued (see Figure 19).

The effectiveness of EAF transformer differential protection based on Rogowski coil current sensors in preventing severe damage can be properly understood by comparing this fault event with a similar event that occurred in 2002 when EAF transformers were NOT equipped with differential protection. At that time, the instantaneous and time-delayed overcurrent relays in the substation were used to detect a fault condition in the EAF vault. The time-delayed relays resulted in longer fault events due to settings that minimized nuisance operations for inrush and bore-in current magnitudes. Because of longer exposure to the electric arc caused by the fault, the EAF transformer had to be replaced, resulting in several million dollars in damages and lost production cost.

Fault Event #2. On April 4, 2007, a second flashover was experienced in the secondary bus in the EAF vault. The 87-1 element detected the fault and closed the trip contacts in approximately 2 cycles. The fault occurred in the clamping assembly where the flexible bus sections are clamped to the water cooled bus tubes. The fast tripping resulted in minimal damage to the bus bars, but there was some resulting blackening of the insulating boards between the energized bus bars. At the discretion of the melt shop maintenance personnel, the clamping assembly was disassembled and new insulation boards were used in the assembly. The outage lasted about 12 hours — to do the required replacement work. The flashover was blamed on contamination from dust settling on the clamping assembly.

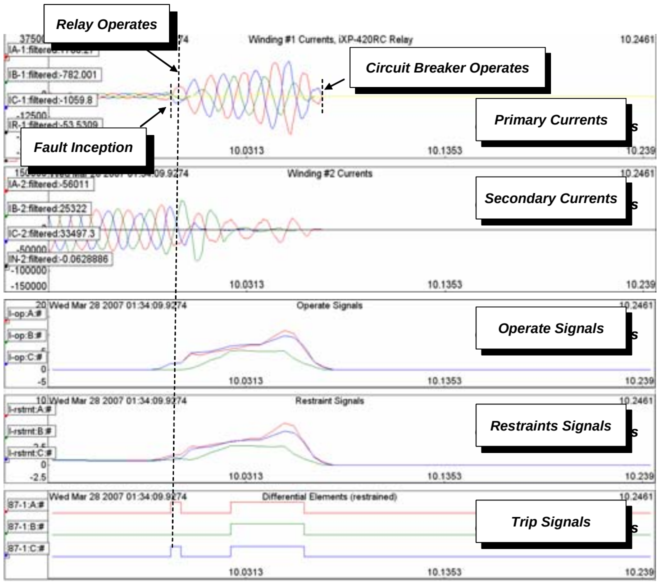


Figure 18. Idea Relay Event Recording of the Fault (Relay operated in one-half cycle, Circuit breaker operated in four cycles)

Figure 19. Photo of secondary flashover result with very fast tripping….minimal damage

Fault Event #3. On August 7, 2007, there was a failure in the diverter in the load tap changer tank on the EAF transformer. The overheating resulted in pressure in the load tap changer (LTC) part of the tank and ultimately a pressure relief device operated. The hot carbonized oil sprayed into the primary energized bus and resulted in a flashover on the primary 34.5 kV side of the transformer. The 87-1 element operated in less than 2 cycles. Prior to the fault event the secondary load currents were between 102-126 kA and the primary currents between 3200-4000 amperes per phase. Despite high currents, the differential elements were balanced in this period of operation, confirming high scheme security.

Scheme Security

The implementation of the Rogowski Coil-based transformer differential protection systems on a variety of transformers have operating history that preserves security without nuisance operations on energization or during extreme operating conditions. When called up to operate during in zone faults the systems have rapidly detected the fault conditions resulting in minimal equipment damage. At the time of this writing, there have been **over 500,000 energizations and heat cycles** on the multiple EAF systems in operation.

CONCLUSIONS

This paper presents novel relay protection systems that are the first differential protection systems applied to electric arc furnace (EAF) transformers in the USA and quite possibly in the world. The protection systems consist of novel Rogowski Coil (RC) current sensors and multifunction relays. Operating experience confirmed superior protection solution.

Scheme Dependability: In all fault events that occurred since the protection implementation faults were cleared fast, resulting in minimal damage to equipment despite high fault current magnitudes (250 kA). Production resumed within hours — saving substantial time and money.

Scheme Security has been preserved for an extraordinary number of EAF transformer energizing and heat cycle operations that is over 500,000 energizations over many different applications.

Biographies

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