Enhancing Fault Detection in Steelmaking Power Systems With Rogowski Coil Technology

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ABSTRACT

This paper presents the implementation of Rogowski coil-based differential protection across the electric arc furnace (EAF) transformer in a steelmaking facility. The scope centers on enhancing fault detection and localization in environments where conventional current transformers (CTs) are ineffective due to extremely high secondary currents. Rogowski coils offer precise, real-time current measurement without saturation, enabling reliable differential protection across critical transformer zones. Integrated with multifunction relays and validated through operational testing and waveform analysis, the system demonstrates improved fault response speed, selectivity, and reduced downtime. This architecture provides a scalable and resilient protection solution for modern EAF operations.

Keywords: Electric Arc Furnace, Reliability, Transformer Protection, Rogowski Coils, Protective Relaying

INTRODUCTION

EAF (electric arc furnace) transformers pose unique challenges for electrical safety and protection beyond even traditional utility transformers of similar size and capacity. Primarily this manifests in the exceptionally high secondary current, which can at times have a sustained throughput of more than eighty thousand amperes. This, in turn, means all the secondary connections—from delta closures to shunt cables and mast arms—must be of exceptional size with supplemental cooling.

Secondary current transformers (CTs) are typically internal to these transformers and, at most, monitor a single bus bar of a single phase, which is sufficient for power calculations but insufficient for protection, as it leaves major gaps in coverage. They also require considerable installation work, as secondary bus work can have upwards of one hundred fittings and several thousand pounds of copper bus, cooling, and structural components, typically in rather confined and restricted spaces. Based on consultation with some industry veterans, we learned of only one comprehensive secondary CT system for an EAF, and it was approximately the size of a small economy automobile.

Beyond the challenges related to size and scale, the physics of CTs pose limitations to dynamic current sensitivity and current saturation inherent in their design. While there are often manufacturing and design considerations that can be implemented to improve susceptibility to saturation, it will always affect the ability to read into the highest range of short circuit currents—which can at times exceed three hundred thousand amperes sustained in some failure modes.

Rogowski coil current sensors, prevalent in Europe but seeing limited use in the United States, have provided a solution to these challenges for decades—but have only seen limited and crude roles in the field of protection. They offer easy installation due to their flexible nature and quick disconnect/wrap-around design, as well as increased survivability and economic advantages over conventional CTs.

This paper demonstrates the results of an active trial at Nucor Steel Crawfordsville (the steel mill) regarding the combination of Rogowski coil secondary measurement and differential protection relay hardware. The steel mill has made use of Rogowski coils for decades to regulate power delivery into their furnace and has a furnace transformer that is on the higher end of power capacity, providing a representative test environment for almost any other EAF.

This work extends the comprehensive protection architecture previously implemented at the steel mill [1], which introduced line differential protection, arc-flash detection, breaker failure logic, and advanced monitoring to safeguard the EAF power supply. While those measures significantly improved reliability, the EAF transformer remained protected primarily by overcurrent elements due to the impracticality of CT-based differential protection at extremely high secondary currents. The addition of Rogowski coil-based differential protection completes the envisioned protection suite, providing high-speed, sensitive, and secure coverage for the most critical component in the steelmaking process.

DISCUSSION

1. Operating Principle of Rogowski Coil

A Rogowski coil consists of a uniformly distributed winding placed around a current carrying conductor (Figure 1). Unlike conventional current transformers, the coil does not have a ferromagnetic core. When the current flows through the primary conductor, a magnetic field is established around it. Any variation in this magnetic field induces a voltage in the Rogowski coil proportional to the rate of change of current. The output voltage is proportional to the derivative of the primary current as per Faraday's law of induction (1).

$$V \propto M \bullet dI/dt \tag{1}$$

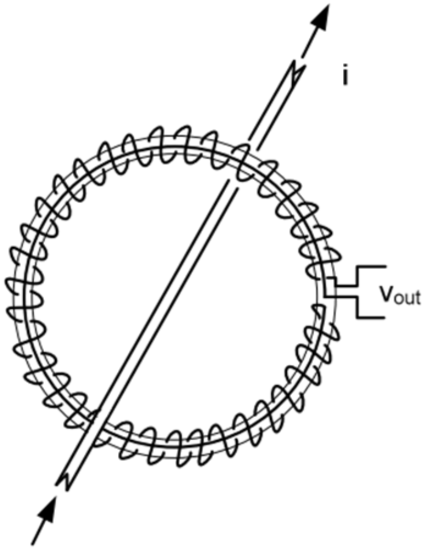

Figure 1. Operating principle of Rogowski coil [2].

The Rogowski coil output is then passed through an integrator to obtain a signal proportional to the actual current waveform. Since the coil is air-cored, the resulting signal represents current over a wide range of magnitudes and frequencies. In microprocessor-based protection relays, the integrated Rogowski coil signal is digitized and processed using embedded signal processing algorithms to derive accurate measurements for protection and monitoring functions.

In steel plant applications, currents are often nonsinusoidal and contain significant harmonic and transient components. The lack of magnetic core in the Rogowski coil benefits applications like this to maintain linear behavior during extreme currents, fast transients, and short duration overloads. Since they are immune to saturation, it enables accurate monitoring of real operating conditions that are difficult or impossible to capture with conventional current transformers.

2. Advantages Over Conventional CTs

Rogowski coils can measure currents ranging from a few amperes to several hundred kiloamperes using the same sensor design, unlike conventional CTs that must be sized specifically for the expected current levels.

Rogowski coils are lightweight and flexible, even for extremely high current measurements, allowing easy installation around conductors without disconnecting the circuit. This is particularly advantageous in retrofit applications like the steel mill, where downtime is costly.

In steel plants, safety and reliability during maintenance are major concerns. Conventional CTs pose a risk of high secondary voltages in case of open circuits. [3] Rogowski coils eliminate these risks, as their output voltage remains low even under open-circuit conditions.

Rogowski coils ensure stable measurements irrespective of the prior operating history, whereas the conventional CTs may retain residual magnetism, or remnant flux, after exposure to high fault currents. This is especially valuable in steel plants where frequent load cycling and fault events are common.

3. EAF Transformer Specifications

The EAF transformers at the steel mill were all originally manufactured in 1988; over the years they have seen several rebuilds, most recently during 2021 when they underwent substantial upgrades that raised their maximum rated power from 120 MVA to 152 MVA. Their secondary voltage can range from 955 to 1255 but nominally hovers around 1058 volts phase-to-phase during most operating conditions. Their secondary bus is rated for a continuous current of 69,000 amperes (Figure 2). However, current spikes as high as 140,000 amperes are frequent during the earlier stages of the melting process, when shorts and circuit breaks are most common. EAF transformers differ from conventional utility transformers in that they are rated for far more abuse and often feature far heavier construction processes allowing them to handle large spikes as part of their expected use case. For electrical system control, a cutting-edge regulation platform is deployed to ensure consistent power delivery and to control set point changes throughout the heat.

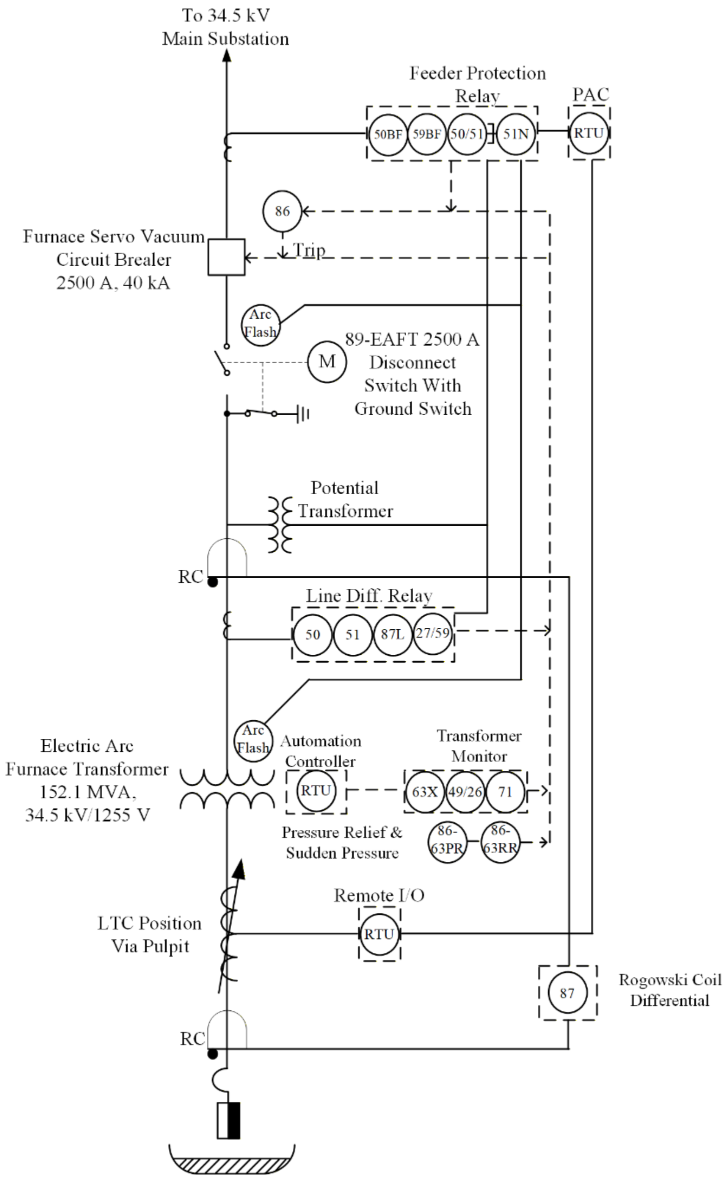

Figure 2. Furnace power system one-line diagram.

During the initial melting phase, the transformer can be subject to very high secondary currents nearing full short-circuit current until the furnace regulation system can respond. This operating cycle is effectively equivalent to repeated through-fault events over the transformer service life. As a result, the transformer must be mechanically robust, with adequate bracing to withstand the substantial electromechanical forces produced by these high-current conditions.

4. Installation Process and Relay Configuration

The steel mill had both pre-existing primary and secondary Rogowski coils that were used during the course of testing. The secondary Rogowski coils were, up until very recently, the primary means of measuring secondary current for the arc regulation control system. These have been in active service, with minimal maintenance, since around 2001. The primary Rogowski set made use of existing coils of a similar age, but they had not been in active service for some time, and therefore their specific origins were not known. Both sets of coils tested positively and showed comparable measurements of current compared to existing primary CTs, providing a good demonstration of how this monitoring technology can make use of existing and even obsolete measurement hardware.

Installation primarily consisted of wiring the pre-existing coils into the protection relay. All protection circuitry, as well as the coils, already existed in a single cabinet from an upgrade in 2022, [1] so minimal downtime was needed and there were few to no risks with doing the installation during regularly scheduled eight- to sixteen-hour shutdowns and only rudimentary safety and lockout practices needed to be put in place.

5. Compliance and Safety Considerations

EAF operations frequently demand changes to power delivery and control as means of continuous process improvement; as secondary systems, such as spray ring cooling, baghouse conductive gas removal, and slag generation through chemical processes, improve, the ceiling is raised for potential power delivery and, by extension, more profitable and efficient control practices. Thus, it is critical that the protection system not only be functional but cover as many areas of the system as accurately as possible—allowing for increasing power delivery without the fear of damaging equipment if new set points create unstable conditions with current spikes and mechanical conditions, which have an adverse effect on electrical performance.

The addition of differential protection to the transformer provides a method of ensuring continuous operation while simultaneously providing high-speed removal in the event of an internal fault in the transformer. This added protection minimizes the incident energy experienced during an arcing fault condition. In addition to minimizing incident energy for personnel safety, increased tripping speed of the system minimizes potential damage to the transformer.

TESTING

The transformer in this application is a delta-delta configuration, and the Rogowski coils have the ratings shown in Table I.

The Winding 1 primary nominal current (IPR1) and Winding 1 Rate Sensor voltage at nominal frequency (USR1) values were selected such that IPR1/USR1 value yielded the desired primary coil ratio of 22.

The Winding 2 primary nominal current (IPR2) and Winding 2 Rate Sensor voltage at nominal frequency (USR2) values were calibrated during testing, and an IPR2/USR2 ratio of 7.69 provided accurate measurements as compared to the secondary coil ratio of 16.5.

Table I. Rogowski Coil Ratings

Coil Matrix—NSI Phase	Primary Coil Ratio (kA/V)	Secondary Coil Ratio (kA/V)
A	22.0	16.5
B	21.3	16.5
C	21.9	16.5

1. Operational Testing Methodology

The testing campaign was structured to evaluate the full operating range and stability of the Rogowski coil-based differential protection system. Since EAF transformers operate across an unusually wide current spectrum, from low magnetizing and regulation currents to momentary surges exceeding 70 kA, it was essential to confirm that the Rogowski coils and protection logic maintained accuracy, stability, and selectivity under all operating conditions. Additionally, because the EAF transformer is frequently tap-changed during the melt cycle, potentially introducing small amounts of false differential, the slope settings were programmed with a 10 percent increase to accommodate this. The testing specifically verified that these transitions did not cause nuisance operations.

2. Low-Current Sensitivity Testing

Low-current testing was performed during furnace energization, the end-of-heat cycle, and the early regulation stages of a heat cycle, when actual load current remains minimal. These operating points typically range between 50 A on the primary and 20 kA on the secondary side, far below the normal EAF operating region but essential for validating:

- Linear response in the bottom of the Rogowski coil's measurement range (Figure 3).
- Absence of integration drift or zero-offset error.

  Ability of the differential element to maintain a near-zero operating current under typical load conditions (Figure 4).

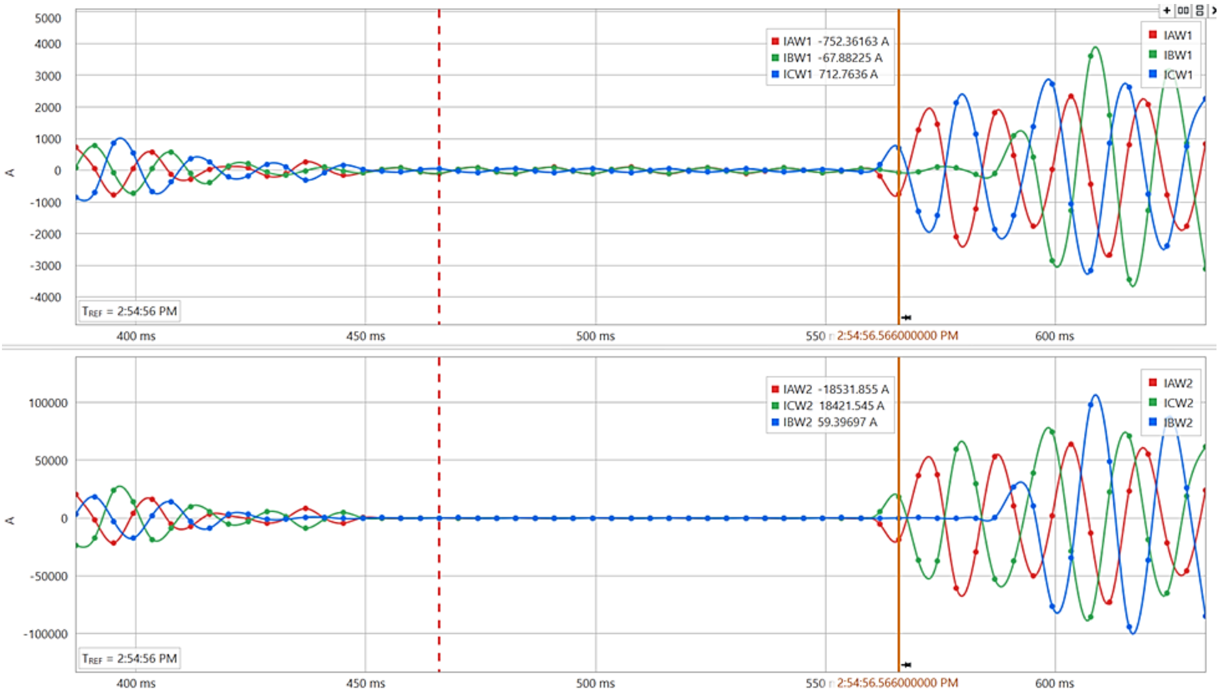

Figure 3. Linear response during low-current conditions.

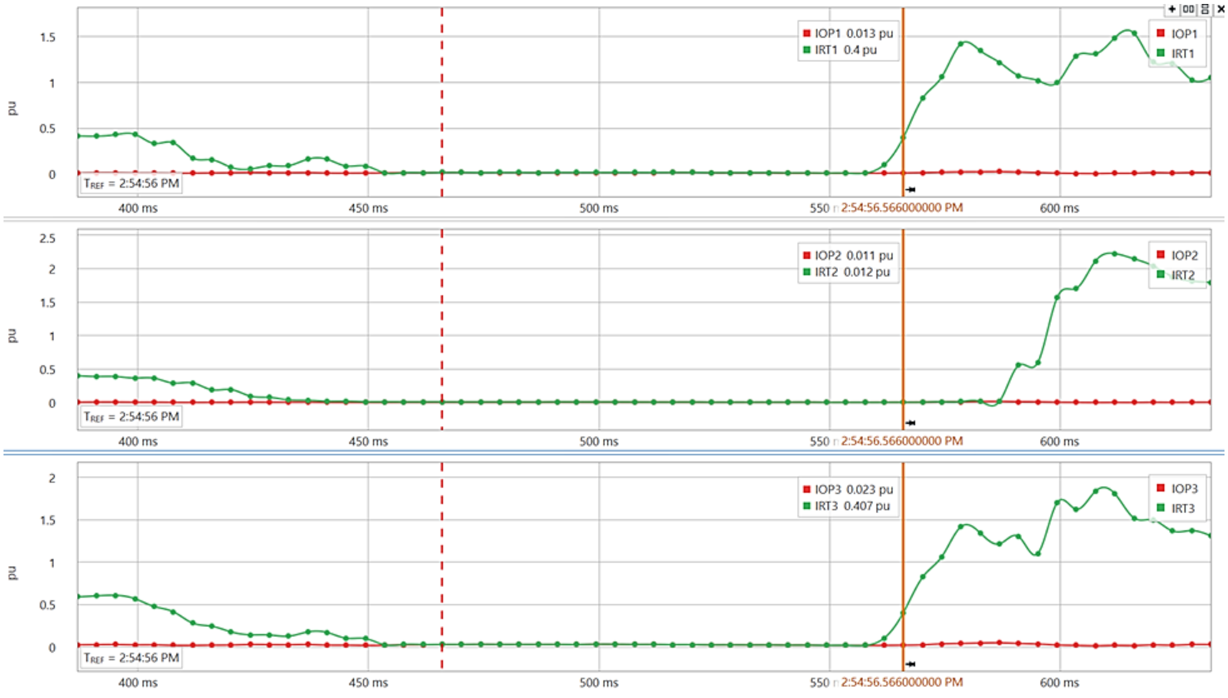

Figure 4. Operating current under low current conditions.

Recorded waveforms during low-load periods show that the coils accurately tracked subtle current changes, with the differential current remaining within 1 percent of expected baseline. The results confirmed that signal conditioning is sufficiently precise to support protection of operation even at very low currents.

3. High-Current Dynamic Testing

High-current performance was validated during full production heats, where secondary currents regularly reach 60–100 kA, and transient spikes can exceed 100 kA during scrap cave-ins or electrode shorts. Under these conditions, Rogowski coils demonstrated:

- No saturation during steep current rise events (Figure 5).
- Undistorted sinusoid across all phases.
- Accurate tracking compared with reference CTs on the primary side and near-zero operating current under high load conditions (Figure 6).

The protection relay maintained stable differential current calculations, even during extreme waveform distortion associated with arc instability. These tests verified that Rogowski coils maintain a fully linear output across the entire dynamic range of the furnace cycle.

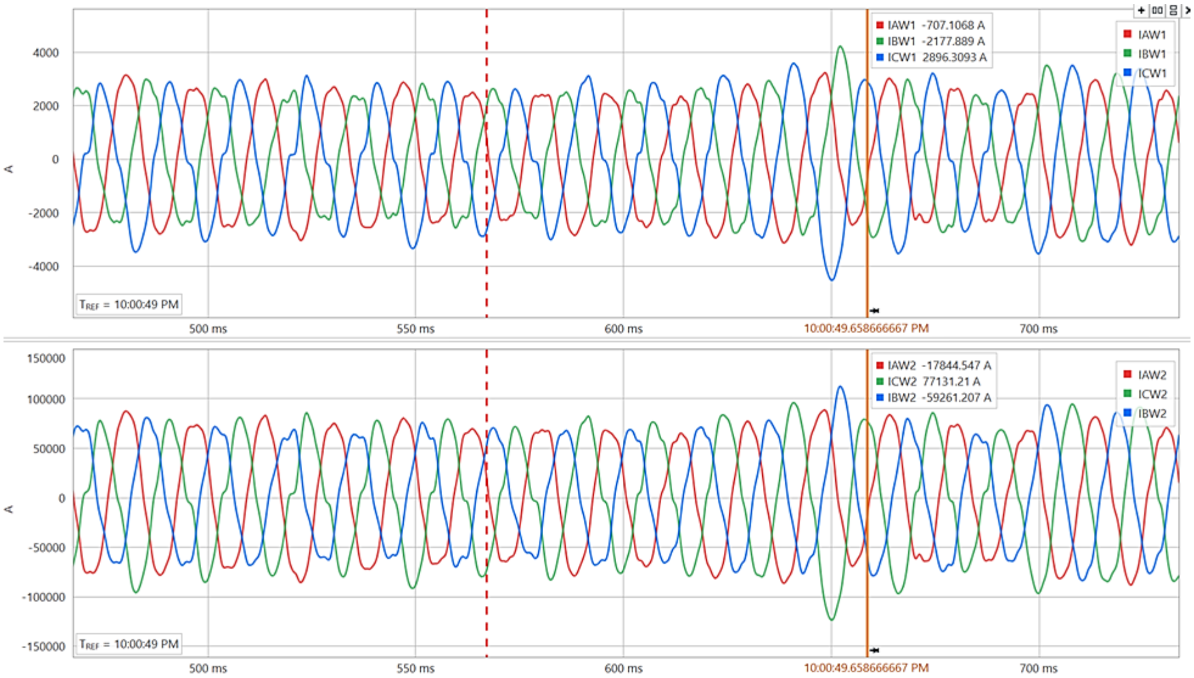

Figure 5. Rogowski coil performance at high-current conditions.

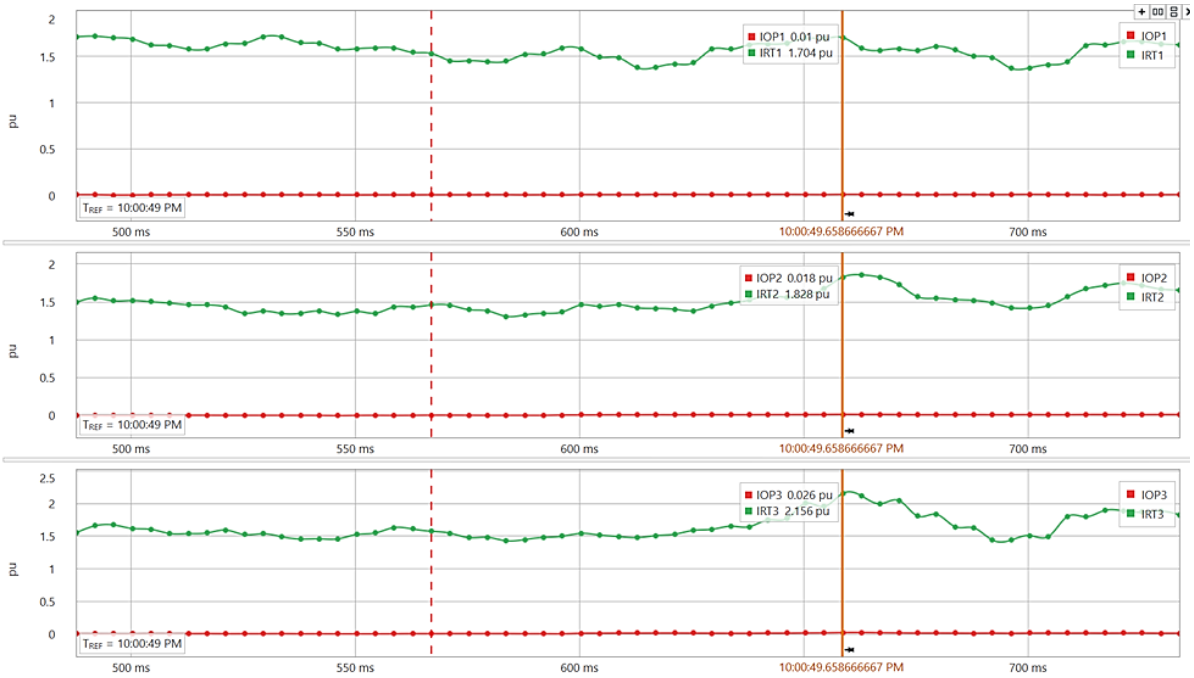

Figure 6. Operating and restraint currents at high-current conditions.

4. Tap-Change Stability Observations

A key objective of the testing program was to verify that the Rogowski coil-based differential protection remained stable during tap transitions on the EAF transformer. The furnace transformer, in consideration, is equipped with an on-load tap changer (OLTC) providing 33 coarse tap positions on the primary winding. These taps allow the secondary line-to-line voltage to vary from 939 V at Tap 1 to 1255 V at Tap 33 (see Appendix, Table II), representing a total regulation range of approximately 16.8 percent.

To confirm, the relay response events were triggered during each tap change observation.

The Rogowski coil measurements demonstrate stability through all observed tap transitions. Through multiple melt cycles and dozens of live tap changes, the differential element maintained a near-zero operating current, with no evidence of misoperation or abnormal restraint behavior. Figure 7 and Figure 8 show data with furnace operating at the maximum tap, Tap 33.

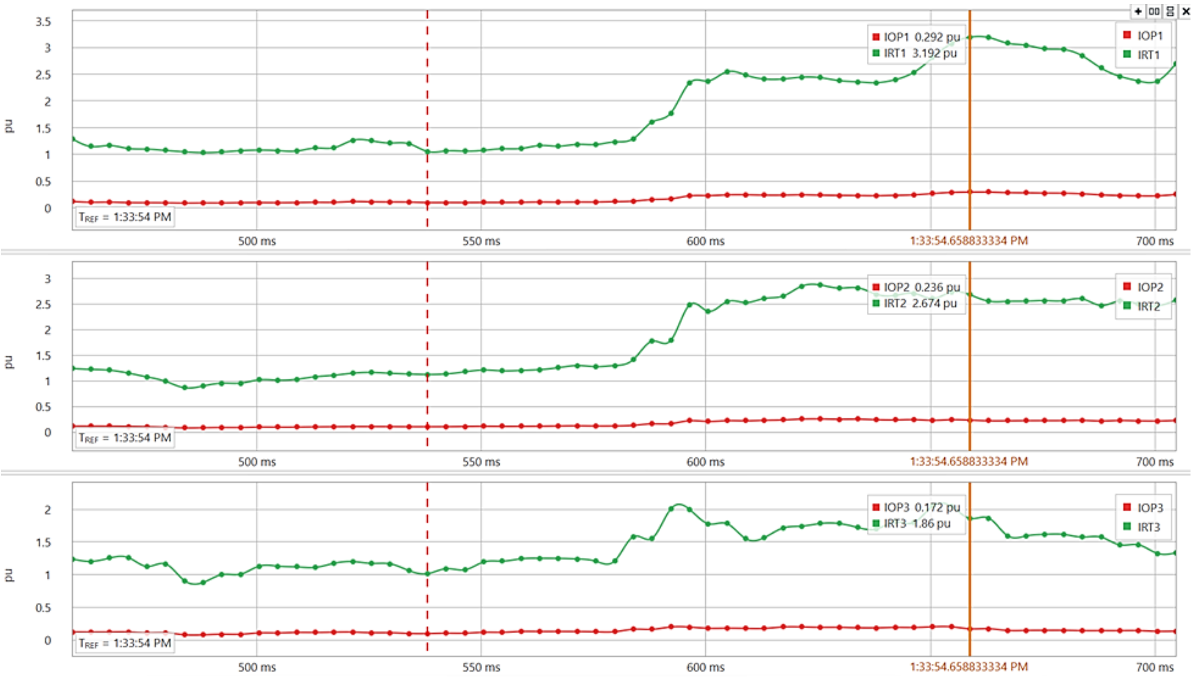

Figure 7. Operating and restraint currents at the maximum tap.

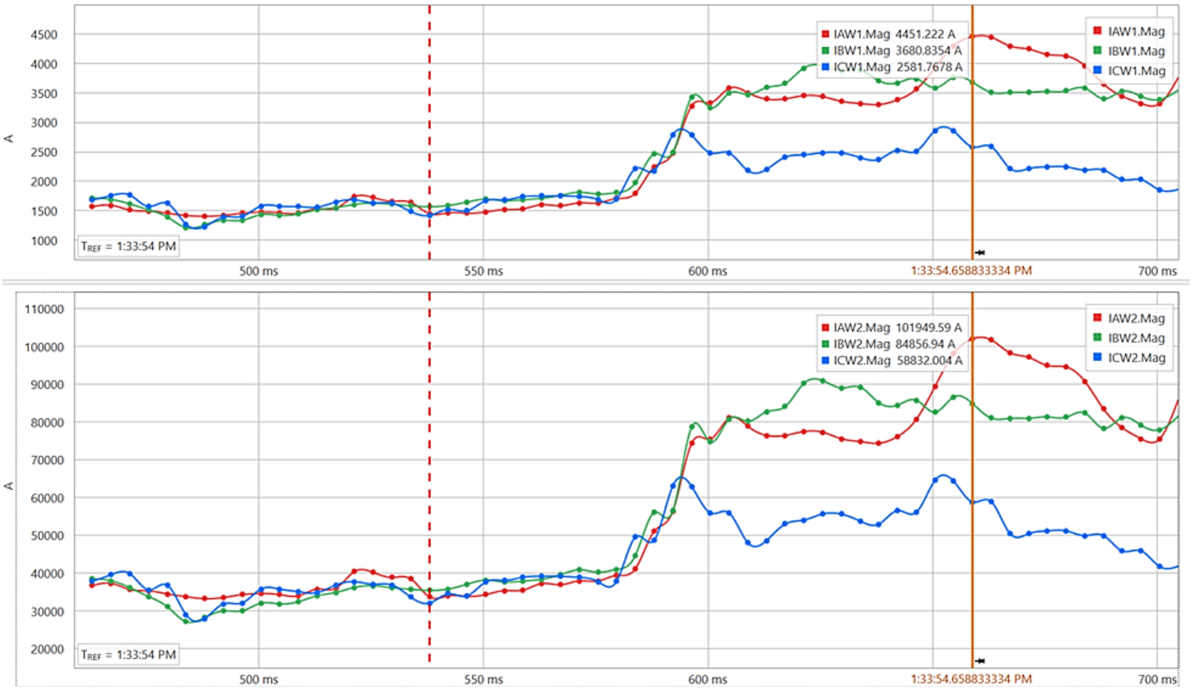

Figure 8. Winding current magnitudes at maximum tap.

5. Performance Metrics: Speed, Selectivity, and Reliability

Previous research on Rogowski coil-based differential protection for EAF transformers emphasizes the need for adaptive ratio compensation to maintain sensitivity during frequent tap-changer operations. [4] In those applications, tap changes introduced significant mismatch between primary and secondary currents, requiring dynamic ratio adjustment within the relay. In contrast, the system presented in this paper does not require adaptive ratio compensation. The EAF transformer under consideration operates within a ±15 percent tap range of its nominal voltage, resulting in a mismatch well within the restraint margin of the differential element. Consequently, a fixed ratio setting provides stable and secure operation across all tap positions without compromising sensitivity. This approach simplifies relay logic, eliminates dependency on external tap position signals, and enhances reliability.

Unlike prior implementations that relied on waveform recognition or traditional fixed harmonic blocking to avoid misoperation during transformer energization, this approach employs dynamic harmonic restraint logic as implemented in the protective relays. [5] Differential tripping through the harmonic restraint logic is slightly slower but provides a dependable tripping function when energizing a faulted transformer that might otherwise have the differential tripping element blocked by common harmonic blocking logic. This adaptive approach ensures security during inrush while maintaining sensitivity for internal faults, even under harmonic-rich conditions typical of EAF operations.

CONCLUSIONS

The EAF transformer remains the most critical component of the furnace power system, typically valued at USD 4–7 million. Achieving dependable differential protection for this equipment has long been a challenge. The implementation of Rogowski coil-based differential protection provides a practical and effective solution where conventional CTs are unsuitable due to extreme secondary currents and severe waveform distortion.

Testing performed over several months of real EAF operation validated the performance of this approach. The Rogowski coils demonstrated fully linear responses across the entire operating range, from low-current regulation periods to high energy arcs exceeding 100 kA, while maintaining accurate differential measurement with no evidence of saturation. Stability was also confirmed, as the differential element remained secure through all OLTC. No nuisance operations occurred.

With flexible installation options and robust real-life test data gathered over months of typical EAF operation, this is a proven, implementable addition. Coupled with robust protection, control, and monitoring of supporting power system apparatus as discussed in, [1] furnace operators can now enjoy improved up time, situational awareness, and peace of mind in operating their systems like never before.

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APPENDIX

Table II. OLTC Tap Changer

High-Voltage Amperes	Tap Position	Low-Voltage Line Volts	Low-Voltage Amperes
2545	33	1255	69972
2521	32	1243	69972
2499	31	1232	69972
2466	30	1216	69972
2444	29	1205	69972
2424	28	1195	69972
2403	27	1185	69972
371	26	1169	69972
2353	25	1160	69972
2322	24	1145	69972
2304	23	1136	69972
2206	22	1127	69972
2265	21	1117	69972
2239	20	1104	69972
2221	19	1095	69972
2194	18	1082	69972
2178	17	1074	69972
2154	16	1062	69972
2136	15	1053	69972

High-Voltage Amperes	Tap Position	Low-Voltage Line Volts	Low-Voltage Amperes
2119	14	1045	69972
2105	13	1038	69972
2081	12	1026	69972
2065	11	1018	69972
2050	10	1011	69972
2036	9	1004	69972
2014	8	993	69972
2000	7	986	69972
1977	6	975	69972
1963	5	968	69972
1951	4	962	69972
1937	3	955	69972
1917	2	945	69972
1904	1	939	69972

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