Protection Up the Arc – Protecting Electric Arc Furnace Transformers and Open-Air Bus

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ABSTRACT

Protecting the power system for electric arc furnace (EAF) steel production presents unique challenges. Dynamic secondary load currents, ultrafine dust, intermittent loading, and frequent breaker operations contribute to higher failure risks. Overcurrent-based protection alone is insufficient to address these issues. A modern, multilayer protection scheme was developed using ruggedized arc-flash sensors, communications-based differential protection, and voltage-based breaker failure protection. This approach effectively overcomes these challenges to significantly improve safety and reliability while protecting the most critical asset in the steelmaking operation.

Keywords: Arc-flash protection, breaker failure, transformer monitoring, electric arc furnace, reliability, transformer protection

INTRODUCTION

Electric arc furnaces (EAFs) play a critical role in modern steel production by enabling efficient recycling of scrap metal and precise control over the melting process. Unlike traditional blast furnaces, EAFs utilize high-current electric arcs to generate the extreme temperatures required for melting steel, often exceeding 3,000°F (1,650°C). While efficient, this process introduces significant electrical and environmental challenges that complicate power system protection.

Protecting the power infrastructure of an EAF-based steel production facility requires addressing unique stress factors that conventional protection schemes struggle to mitigate. Dynamic secondary load currents frequently exceed the capabilities of standard transformer differential protection. The steelmaking process also generates ultrafine dust, which accumulates on electrical components despite rigorous containment efforts. This conductive dust can lead to high-impedance faults and flashovers if left unchecked. Maintenance procedures such as routine compressed air cleaning introduce further risks by subjecting sensitive components—especially fiber-optic sensors—to abrasive conditions akin to sandblasting.

Breaker failure detection presents another major challenge. EAF power systems rely on specialized breakers designed for high-frequency operation, often featuring independent pole mechanisms instead of traditional, mechanically interlinked designs. This increases the likelihood of pole disagreements. Furthermore, the load characteristics of these circuits—typically oscillating between full load and near zero—make traditional breaker failure protection methods unreliable. If undetected, a failed breaker can lead to improper operation of motor-operated knife switches and grounding switches, introducing additional failure risks.

To address these challenges, a multilayered protection scheme was implemented at Nucor Steel Indiana – Crawfordsville. The system safeguards a 34.5 kV servomotor-style breaker, motor-operated switches, air-insulated bus sections, instrument transformers, and an EAF transformer housed in two indoor vaults. The facility previously relied on overcurrent protection but now utilizes ruggedized arc-flash sensors, communications-based differential protection, and voltage-based breaker failure detection. This modernization enhances safety, reliability, and asset protection in the demanding EAF steelmaking industry.

DISCUSSION

Main Substation

A simplified single-line diagram of the main power distribution system at Nucor Steel Indiana is shown in Figure 1. The facility receives power from a 345 kV switching station adjacent to the main substation. The utility switching station supplies two independent 345 kV feeds to the main substation; each feed is dedicated to a separate bus. Six transformers are responsible for stepping down the 345 kV service to 34.5 kV, which is then distributed to various processes throughout the plant.

The 345 kV Bus 2 and its corresponding 34.5 kV Bus 2 (EAF bus) are exclusively dedicated to EAF and ladle metallurgical furnace (LMF) loads. The 345 kV Bus 1 and 34.5 kV Bus 1 serve all other facility loads. Transformer 3 is configured to be switchable between Bus 1 and Bus 2, allowing the ability to either supply EAF loads or other plant loads as required.

The EAF bus serves two EAFs and three LMFs, comprising the system of five arc furnaces. It is equipped with a static VAR compensation (SVC) system. This system serves to minimize voltage distortion and flicker, improve power quality, and reduce harmonic current produced by operation of the arc furnace loads.[1]

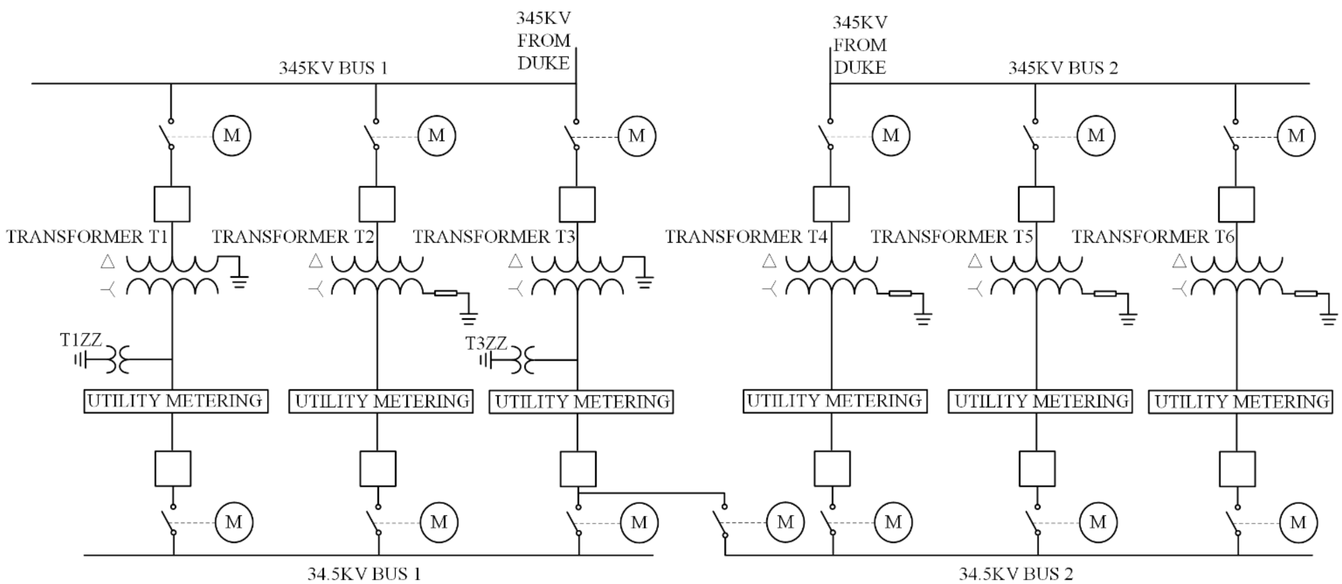


Figure 1. Single-line main substation

Each arc furnace feed has a dedicated feeder from the EAF bus. An example of an EAF feed is illustrated in Figure 2. Each EAF feed includes a gas-insulated circuit breaker, motor-operated disconnect, and series reactor. The gas-insulated circuit breaker isolates faults on the primary equipment between the breaker and the EAF vault breaker and acts as a backup breaker in the case of a failed breaker in the EAF vault. The disconnect switch provides visual system isolation for maintenance in the breaker vault. The series reactor in the circuit provides reduced electrode consumption, a decrease in heat times, and ultimately an increase in the average power delivered to the furnace because of the increased arc stability.[2] The series reactor is equipped with a vacuum-style load tap changer to dynamically control the reactive power from 0 kVAR to 24,420 kVAR depending on arcing conditions at the EAF.

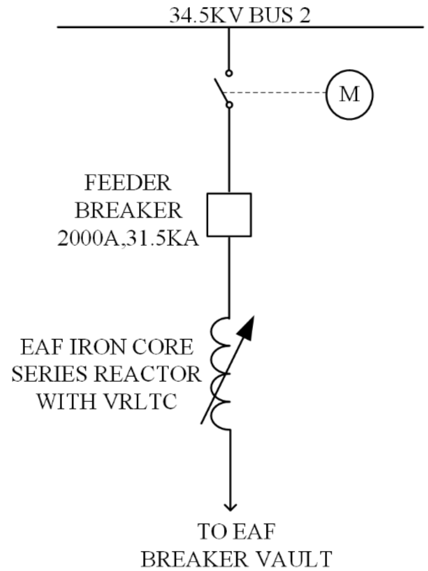


Figure 2. Example EAF feed

EAF Breaker/Transformer Vault

From the main substation, four parallel sets of 1,000 kCMIL copper conductors travel to the EAF breaker vault. The EAF breaker vault serves as the primary switching and protection interface for the furnace power supply. Figure 3 illustrates an example of a typical EAF breaker vault. The breaker vault includes a manually operated ground switch on the line side of the circuit breaker, a motor-operated disconnect/ground switch on the load side of the breaker, instrument transformers for monitoring and protection, and a 34.5 kV servomotor-controlled vacuum circuit breaker.

The line-side ground switch ensures safety during maintenance in the breaker vault. A transfer key system is in place to prevent access and operation of the ground switch until the circuit is isolated through the disconnect switch in the main substation. The motor-operated ground/disconnect switch on the load side of the breaker provides visual and system isolation during maintenance in the transformer vault and is interlocked with the circuit breaker to prevent opening while the circuit breaker is closed.

The vacuum circuit breaker serves as both the primary fault isolation device and the main switching mechanism for energizing the EAF electrodes. As the primary means of isolation to the arc furnace electrodes, the vacuum circuit breaker endures a heavy-duty cycle with a high number of no-load interruptions. The vacuum circuit breaker employed in this system utilizes independent servomotor actuation for each pole. An electronic control unit on the breaker allows for full control of contact movements in addition to phase synchronization. This actuation method helps mitigate current and voltage transients during operation.[3]

After the disconnect switch, cables ascend to the EAF transformer vault, which houses critical equipment including a resistor-capacitor (RC) network, surge arrestors, an EAF transformer with a vacuum load tap changer for dynamic voltage control, instrument transformers, and a water-cooled delta on the secondary side.

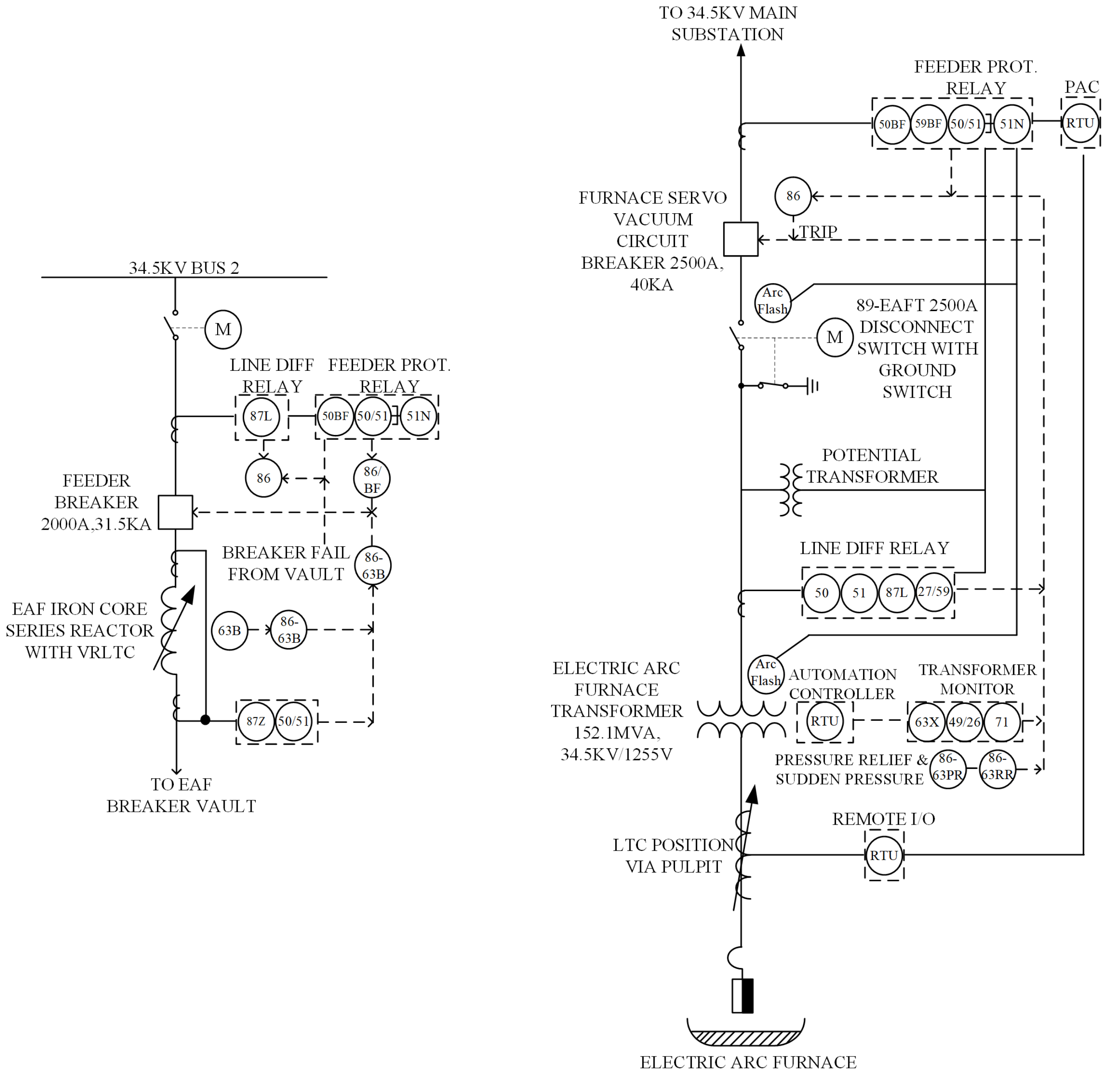
The EAF transformer in this system has a delta-to-open-delta configuration and is rated 152.1 MVA with a secondary voltage of 1255 V at the nominal tap position. The transformer is cooled using forced oil through an oil-to-water heat exchanger. The transformer utilizes a vacuum load tap changer to dynamically change output voltage to the furnace as needed. By dynamically controlling the reactance of the circuit through the use of the series reactor and the voltage through the use of the transformer tap changer, consistent power transfer can be achieved to the arc furnace.[2]

The transformer has a continuous current rating of 70,000 A at the secondary. For this reason, a water-cooled delta is installed to close the secondary of the transformer, and from there water-cooled shunt cables connect the delta to the graphite electrodes of the furnace.

Protection Architecture

Reliable power and maximizing power system uptime are essential for steel manufacturing with EAFs and LMFs. Failures in the EAF power supply can occur at the transformer vault, breaker vault, or main substation. Long spans of rigid and flexible bus sections, open-air conductors, and environmental dust can lead to high-impedance faults. A momentary short circuit occurs at the start of a heat cycle. During this cycle, the series reactor adjustments that modify the available short-circuit current occur. Technological limits have historically prevented these critical power systems from having much more than coordinated overcurrent protection. Those schemes were usually effective at tripping faults but lacked selectivity, sensitivity, and situational awareness after the fault. The protection applications applied at this location aimed to improve these elements of the system and overall safety of operation, and backup protection for the equipment.[3]

Conventional multi-element protection philosophy was applied upstream from the EAF breaker. The roughly 1,000 feet of cable between the main substation breaker and the vault breaker was protected with an overall differential zone leveraging C37.94 fiber-optic communication between two line-current differential relays. Within this zone of protection resides an oil-immersed, iron-core reactor. A dedicated high-impedance differential protection relay was applied to the reactor itself for selectivity and tighter protection. Typical overcurrent-based backup and breaker failure protection was provided in a separate multifunction relay protecting the feeder from the main substation to the EAF breaker vault. The application of these three protection schemes provided an N-1 redundancy for the line itself and N-2 redundancy protection for the reactor and its pressure and temperature monitoring and tripping instruments (see Figure 3).



(a) **(b)**

Figure 3. Single-line EAF breaker vault

Slip-on doughnut current transformers (CTs) were applied to the high side of the transformer within the EAF breaker to extend the differential zone to the transformer so the EAF breaker, knife switch, bus potential transformers, and EAF transformer bushings were within a high-speed differential zone of protection. Traditional overcurrent protection was applied to the transformer leveraging CTs located at the EAF vault breaker. This multifunction relay was also tasked with performing voltage-based breaker failure and knife switch protection, as well as breaker failure initiation to the backup overcurrent and breaker failure relay in the main substation. Leveraging a technology typically used in metal-clad switchgear, an optically sensitive arc-flash scheme was applied to the entire EAF breaker and transformer vault.

The two greatest challenges in applying arc-flash protection to the air-insulated bus of the EAF vault are the size of the area to be covered and how inhospitable the environment is to the sensors. The arc-flash sensors of the relay come in two forms: loop and point. With continuous fiber as long as 70 meters in total, loop sensors would typically be regarded as ideal for covering potential visible arcs over a large area such as the vault. The environment for these sensors is subject to significant amounts of dust. Though the vaults are conditioned with positive pressure to abate the collection of this dust, the vaults undergo regular dusting via pressurized air to manually clean the primary equipment. With significant area of exposed unjacketed fiber-optic cable susceptible to dust collection, abrasion, and contact with sharp edges and/or support lashing, loop sensors were deemed inappropriate for a long-term reliable application in the vaults. The second type of sensor available is a point sensor. Point sensors accommodate a lead of as long as 35 meters. This length accommodates all reaches desired in the vault. Point sensors have a small collector lens intended to capture light in a specific area. The multifunction relay was equipped with eight (8) point sensors targeted at selected areas of the vault. Though slightly more robust than loop sensors, the point sensors would also be susceptible to the environment of the vault. Installation technicians were instructed to install the jacketed sensors through a non-metallic conduit to protect them; the technicians provided a purpose-designed assembly for mounting the point lens to endure the vault environment for the duration of installation (see Figure 4).

Figure 4. Jacketed point sensor

Arc-flash sensors are used in conjunction with the current observed on the CT above the vault breaker (see Figure 5). The objective is to place the arc-flash sensors in a position to observe a fault on any portion of the bus work/apparatus downstream from the CTs mounted above the breaker. Optimal sensor locations balance proximity to the bus with line-of-site to the flash source.

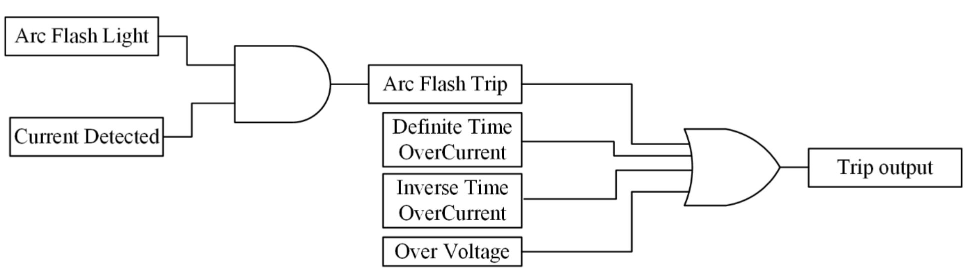


Figure 5. Trip logic

Eight (8) total sensors were connected to the arc-flash-capable multifunction relay (see Table 1).

Table 1: Arc-flash sensor locations

AF1	Breaker Vault/Knife Switch Arc Flash
AF2	Vertical Bus/Potential Transformers (PTs) Arc Flash
AF3	Transformer Vault Vertical Bus/PTs Arc Flash
AF4	Transformer Secondary Arc Flash
AF5	Transformer Primary Bus North Arc Flash
AF6	Transformer Primary Bus South Arc Flash
AF7	Transformer Primary Bus East Arc Flash
AF8	Transformer Primary Bus West Arc Flash

Each sensor was provided with approximately 35 meters (115 feet) in length. The sensor terminations click together and were able to be removed for routing through conduit (see Figure 6).

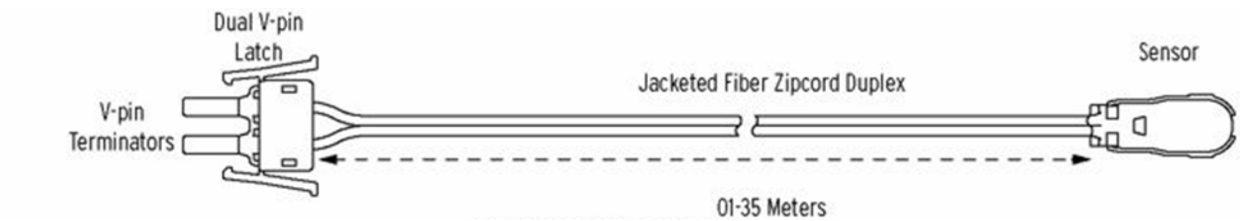


Figure 6. Point sensor termination

Voltage-based breaker failure protection was implemented in addition to current-based breaker failure protection due to the nature of the application load characteristics (see Figure 7). In the event of the electrodes being raised from the furnace, only magnetizing current would be carried by the bus. The light loading of this magnetizing current is below minimum pickups for current sensing by most multifunction relays. At the end of a heat cycle, the standard operating procedure is to open the vault breaker and open a downstream motor-operated knife switch disconnect with mechanical grounding mechanism to ensure full discharge of the transformer magnetizing current and any remaining charge on the electrodes and bus. This knife switch is not rated to break any degree of load. In the event of a breaker failure, operation of the knife switch would result in possible catastrophic destruction of the knife switch. The multifunction relay leveraged bus PTs downstream from the knife switch to confirm loss of voltage on the bus upon breaker operation (see Figure 8). The relay supervised knife and breaker operation based on the status of each and voltage on the bus.

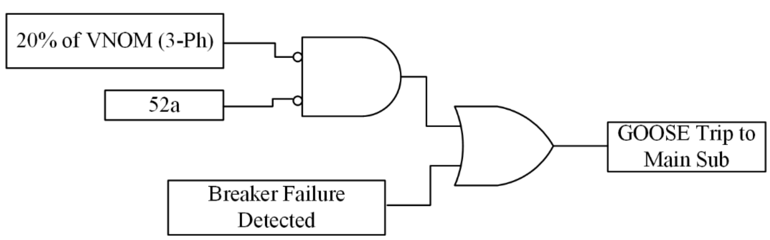


Figure 7. Breaker failure logic

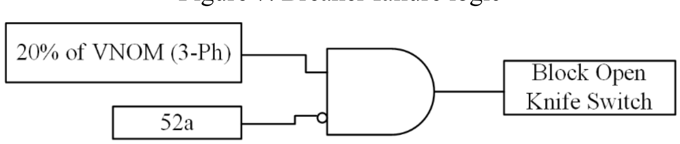


Figure 8. Knife switch block logic

All relays in the application were equipped with IEC 61850 GOOSE messaging and dual Ethernet connections to redundant dedicated Rapid Spanning Tree Protocol (RSTP) equipped power system subnetworks. This network allowed a high-speed direct transfer trip and an initiation of breaker failure protection from the vault multifunction relays to the main substation feeder multifunction relay.

Installation

After finalizing material specifications, design, and programming, the team developed an execution plan for installation and testing. Two key constraints were involved in the process:

1. Due to the significant strain they endure, arc furnace transformers are replaced more regularly than standard power transformers.The transformer vault has a removable ceiling allowing the old transformer to be lifted out and a new one installed quickly. With these changes, the protection scheme needs to remain in place for any arc furnace transformer. To address this, primary protection relays were installed in the breaker vault control cabinet and arc-flash sensors were mounted on walls and fixed structures. Only the monitoring equipment was placed in the transformer control cabinet.

The outage window only allowed seven (7) days to complete the installation and testing. To meet the deadline, the relaying was pre-mounted and pre-wired on a door. This door was poised with as many wires connected as safely possible while the mill was still operational before the outage began. An installation guide detailing sensor placement and wiring routes was developed. Using this guide, electricians streamlined the final installation by pre-installing piping and arc-flash sensors during scheduled downtime (see Figure 9).

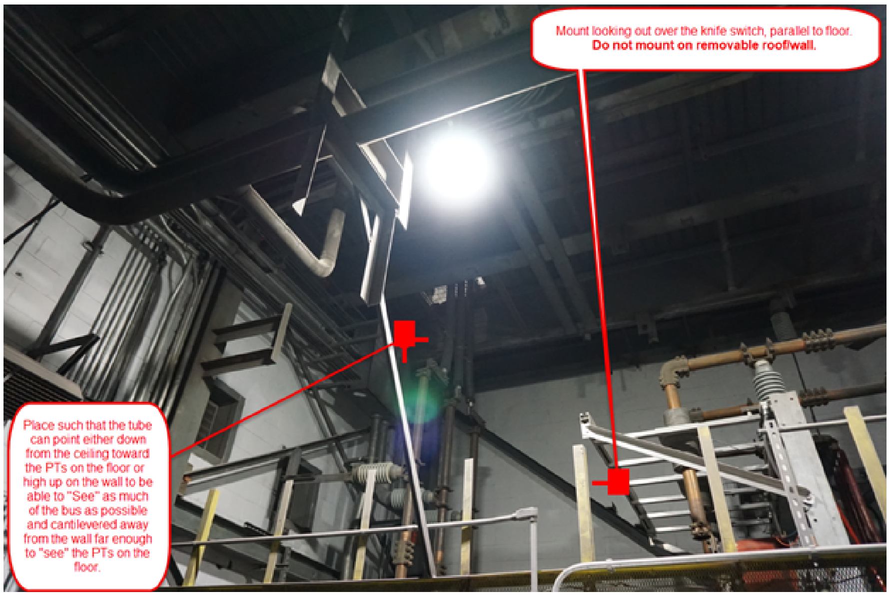


Figure 9. Example fiber mounting instructions

Testing of overcurrent, line differential, and arc-flash protection was conducted using a test set connected to the protective relays. Based on prior project experience, differential protection was disabled before initial energization to verify cable phasing from the main substation to the vault.

Monitoring and Control

The monitoring and control system for the EAF transformer was designed using a distributed automation architecture that seamlessly integrated data acquisition, real-time control, and secure communications.

A modular automation platform capable of handling a high volume of binary and analog inputs serves as a local data concentrator for peripheral devices. It collects transformer alarms, statuses, and analog measurements while utilizing the IEC 61850 communications protocol to transmit critical alarms to protection relays.

A programmable automation controller (PAC) resides on the plant operations network and acts as the primary interface (pulpit) for remote operators to monitor equipment status and issue control commands. Critical control functions from the pulpit are distributed between the transformer control cabinet and the breaker vault cabinet. To optimize connectivity and reduce reliance on copper wiring, a remote I/O module is installed in the breaker vault and connected serially to the PAC. This module facilitates pulpit operations, including breaker and knife switch open/close commands, breaker and switch status monitoring, protective trip indications, and relay failure alarms.

The automation platform housed in the transformer cabinet shares real-time data with the central automation controller at the main substation. This controller securely transmits information to the plant operations network via an Ethernet security gateway using an Ethernet/IP protocol. A dedicated human-machine interface (HMI) at the main substation provides operators with a visual overview of equipment status, alarms, and operating conditions while enabling remote control of transformer primary equipment.

The architecture provides redundancy and resilience to the operation system by using the PAC and a remote I/O module solely for operation use, keeping it directly on the plant operations network for providing operation-required statuses and control while keeping the modular automation platform on the power system network. Losing power system network connections under any circumstances results only in loss of non-critical alarms and monitoring data while keeping the system fully operational (see Figure 10).

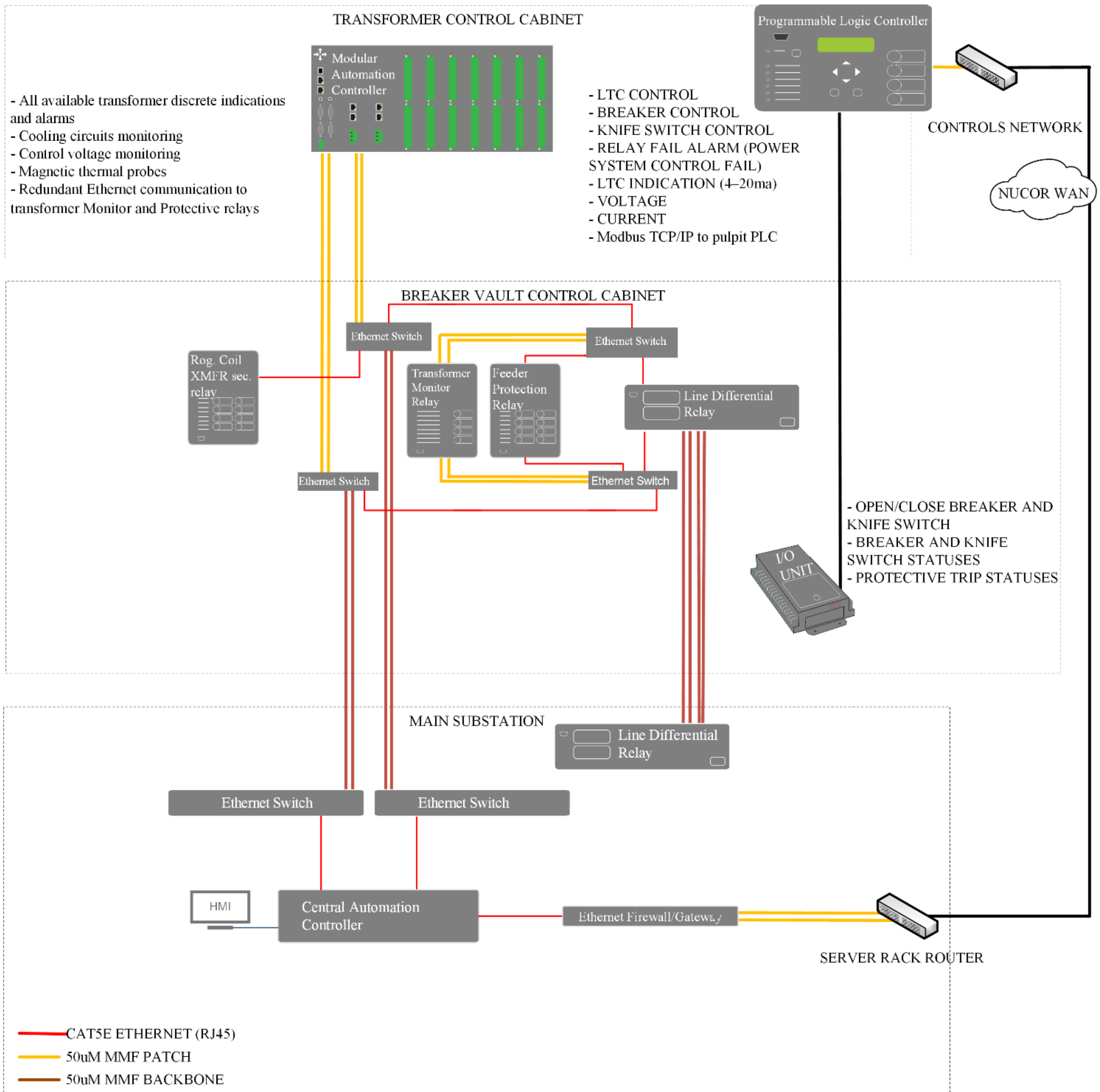


Figure 10. Network architecture

A combination of a transformer monitor relay and a modular automation platform provides comprehensive protection functionality for the EAF transformer. The modular automation controller located in the transformer cabinet gathers all statuses and alarms available via the onboard sensors. In addition, this device provides discreet and analog data over GOOSE (IEC 61850) protocol to the transformer monitor relay situated in the breaker vault, communicates data to the central automation controller in the main substation for HMI and operations network use, and provides all data over Ethernet/IP to the pulpit programmable logic controller. This device provides transformer protection through breaker operation for pressure and temperature events.

Beyond remote operation from the pulpit, both the PAC and transformer monitor relay offer local control and real-time status displays. Given the physical separation between the breaker vault and transformer vault, the transformer monitoring relay in the breaker vault also has the capability to issue open/close commands to the knife switch from the front pushbutton and has a small LCD display and target LEDs, along with a touchscreen HMI, on the feeder protection relay. Screens also include a display of the arc-flash location differentiating breaker and transformer vault (see Figure 11).

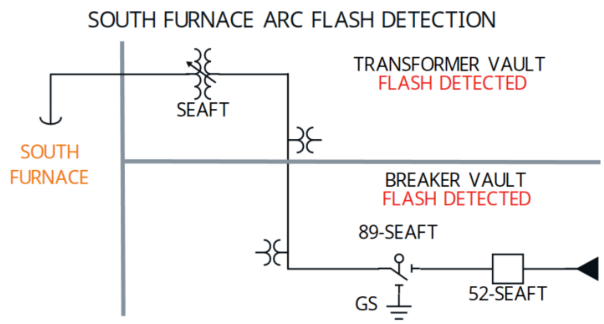


Figure 11. Arc flash display screen on MFR

HMI and Event Data Collection
The microprocessor-based relays incorporated in the system are capable of capturing event files that provide a detailed snapshot of power system conditions immediately before and after a trip. To further enhance operational visibility and event diagnostics, these event reports are automatically collected and stored in the central automation controller at the main substation, which serves as a centralized data concentrator for event analysis.

CONCLUSIONS

As of this writing, the protection system has been called upon merely one time for a power system fault within the zones of protection up the arc. It is believed that during the high-current event of a furnace cave-in, the insulation of one of the cable differential CTs failed, allowing it to short out. Rather than a complete catastrophic failure of the CT that would be expected during such an equipment failure, the line differential relaying cleared the system before it could evolve beyond the resin casing of the CT itself. Plant technicians and engineers were challenged to physically identify the failed equipment. Though this potentially resulted in additional troubleshooting time, a catastrophic failure of a bushing CT could have resulted in damage to the surrounding equipment and even irreparable damage to the transformer itself.

In addition to this event, the system has reliably operated with selectivity for downstream faults associated with furnace cave-ins time and time again. Compared to a normal burn-in or heat-run, furnace cave-ins often present themselves as phase-to-phase diminished impedance faults to the power system. As with any fault, decreasing the amount of time the power system is exposed to the stresses is preferred for equipment reliability and longevity. When furnace regulators are unable to clear these faults themselves, it is important for the power system protective equipment to respond in a controlled manner to allow system operators to quickly reset and continue the heat with as little down time as possible. Testament to the selectivity of the applied protection, these faults are regularly isolated at the closest means possible without over-tripping to the main substation breaker.

Along with system protection, the installed monitoring and control has provided operators with greater visibility and understanding of their power system apparatus. When comparing the two years prior to system installation to the two years after, the plant observed a 34% reduction in furnace downtime categorized as related to the high-voltage equipment. When alarms occur or power is interrupted, plant technicians and engineers can identify, troubleshoot, and restore the system to service with speed and confidence. With the improved situational awareness of the monitoring system, future problems can be anticipated, repairs can be planned for rather than occurring emergently, and data can be logged and relied upon for future analysis.

At the time of writing, the overvoltage breaker failure scheme has yet to be called upon. The authors are satisfied if it is never needed but enjoy the peace of mind provided by its availability.

The next step in the arc furnace protection will be to install a new Rogowski coil-based transformer differential relay to provide complete differential protection of the transformer. Presently, an overcurrent relay equipped with Rogowski coil current inputs is monitoring the secondary of the arc furnace transformer. Due to the extremely high currents and large physical size of the transformer, secondary traditional CTs are not an option; the size is prohibitively expensive and the CTs would regularly hit saturation. The addition of a full transformer differential will complete the suite of protection to keep the EAF functioning safely and effectively.

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