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RESEARCH ARTICLE

A Novel Approach for Power System Protection Simulation via the IEC 61850 Protocol

ABDULVEHHAB AĞIN, AYŞEN DEMİRÖREN, AND ÖMER USTA, (Senior Member, IEEE)
Department of Electrical Engineering, Istanbul Technical University, 34485 İstanbul, Türkiye

Corresponding author: Abdulvehhab Ağin (agin@itu.edu.tr)

ABSTRACT This research addresses a significant gap in power system protection methodologies by developing a dedicated simulation environment that supports the communication of protection relays via the IEC 61850 protocol. Current studies have focused on hardware-in-the-loop approaches, but there is a lack of research in the software-in-the-loop domain. This limitation means that manufacturer-independent simulations cannot be performed, restricting testing to the capabilities provided by the manufacturer. By introducing a relay capable of communicating within a Simulink-modeled power system through socket programming, this study harnesses the capabilities of the IEC 61850 GOOSE protocol and sampled values. This work aims to eliminate the manufacturer dependencies present in hardware-in-the-loop approaches, thereby enabling the independent development of new protection and control strategies in an academic context. Furthermore, by facilitating advanced communication strategies through a detailed simulation framework, this research contributes to the broader field of electrical engineering by offering a robust tool for developing, testing, and validating new relay communication techniques and protection schemes. This approach not only fills a critical gap in simulation capabilities but also paves the way for future advancements in power system protection and management regarding the IEC 61850 protocol.

INDEX TERMS Electrical power systems, GOOSE protocol, IEC 61850 standard, power system modeling, power system protection, power system simulation, relay communication, sampled values, Simulink, socket programming.

I. INTRODUCTION

A. BACKGROUND

The International Electrotechnical Commission (IEC) developed the IEC 61850 protocol to establish a universal standard for communication in electrical substations and power systems. It was initially launched in 2004 and has since undergone several revisions to enhance its functionality and adapt to modern power system requirements [1]. The protocol was developed to address the limitations of traditional communication protocols, such as Modbus, IEC60870, and DNP3, and to provide a standardized framework for interoperability and seamless integration of various intelligent devices and systems in the power industry [2]. It incorporates concepts from other relevant standards, such as TCP/IP and Ethernet, to enable efficient and reliable communication between power system components, including protection relays, RTUs, HMIs, and SCADA systems. The protocol supports both peer–to-peer and client–server communication models and offers various services, such as control, monitoring, logging, and data exchange, to facilitate the operation, maintenance, and optimization of power systems [3].

B. RELATED WORK

The IEC 61850 protocol plays a crucial role in protection control in power systems. Its standardized communication framework enables seamless integration and coordination among substation protection relays and other intelligent electronic devices (IEDs) [4]. This ensures efficient and reliable operation of a protection system, which is essential for safeguarding a power system against faults and abnormalities. The importance of the IEC 61850 protocol for protection control lies in its ability to enable high-speed data exchange, precise time synchronization, and advanced

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functions such as peer-to-peer communication, data, and information exchange. These features facilitate faster fault detection, accurate fault location, and rapid isolation of faulty zones, thus minimizing downtime and reducing the risk of cascading failures [4].

The evolution of power system simulation tools, especially those incorporating the IEC 61850 protocol for protection relay communication, has attracted considerable interest and development. However, a review of the research in this field reveals a distinct gap in the availability of simulation environments integrated for protection relays via this protocol within a power system analysis environment.

In 2017, Fuentes Suarez and Ragaini's study on the "IEC 61850-based Protection System for MV-LV Substations" marked a significant advancement in the integration of IEC 61850 into substation protection systems. Their focus on data standardization and real-time diagnostics illuminated the complexities and potential of applying IEC 61850 in practical settings [7]. Although instrumental, this work predominantly addressed implementation in physical systems rather than simulation environments.

In 2018, the "Integrated Simulation Model of Power System Protection Schemes and Process Bus Communication Networks" presented a comprehensive model for designing future substation automation systems. This model bridged theoretical research with practical applications but still left a gap in the specific simulation of protection relays communicating via the IEC 61850 protocol [8].

The 2020 work of Pazderin et al., titled "Platform for Testing IEC 61850 Control Systems Using Real-Time Simulator", provided an essential dynamic platform for testing IEC 61850 control systems [9]. Despite advancing the field of digital substation simulations, it did not directly address the development of a simulation environment for protection relays communicated via IEC 61850 [9].

In 2021, Delavari, Brunelle, and Mugombozi's "Real-Time Modeling and Testing of Distance Protection Relay Based on IEC 61850 Protocol" and Memon and Kauhaniemi's "Real-Time Hardware-in-the-Loop Testing of IEC 61850 GOOSE-Based Logically Selective Adaptive Protection of AC Microgrids" contributed significantly to understanding the IEC 61850 protocol's application in real-time simulations and HIL testing [10], [11]. However, these works focused primarily on hardware-specific protocol applications rather than on a comprehensive simulation environment for power system protection relays.

C. RESEARCH GAP

This research addresses a significant gap in power system protection methodologies by developing a dedicated simulation environment that supports the communication of protection relays via the IEC 61850 protocol. While current studies have focused on hardware-in-the-loop approaches, there is a lack of research in the software-in-the-loop domain. This limitation means that manufacturer-independent simulations cannot be performed, restricting testing to the capabilities provided by the manufacturer. This paper addresses this critical need by creating a simulation environment consisting of a protection relay communicating over IEC 61850 protocols and power systems. This environment, designed to be compatible with MATLAB/Simulink, focuses on simulating line differential protection, a key aspect in safeguarding three-phase ground faults. The contribution of this research lies in its potential to enhance the testing and validation processes of protection relays in real-world scenarios.

D. CONTRIBUTIONS

By introducing an intelligent electronic device capable of communicating within a Simulink-modeled power system through socket programming, this study harnesses the capabilities of the IEC 61850 GOOSE protocol and sampled values. This work aims to eliminate the manufacturer dependencies present in hardware-in-the-loop approaches, thereby enabling the independent development of new protection and control strategies in an academic context. Furthermore, by facilitating advanced communication strategies through a detailed simulation framework, this research contributes to the broader field of electrical engineering by offering a robust tool for developing, testing, and validating new relay communication techniques and protection schemes. This approach not only fills a critical gap in simulation capabilities but also paves the way for future advancements in power system protection and management regarding the IEC 61850 protocol.

II. IEC 61850 OVERVIEW

In recent years, significant advancements in electronic and communication technologies have directly influenced power systems. However, these developments have also introduced the challenge of interoperability among intelligent electronic devices (IEDs) from different manufacturers within a substation system. This issue primarily arises from each manufacturer implementing its own communication protocols. The IEC 61850 standard was developed to standardize communications in substations for this purpose [12].

IEC 61850-5 broadly defines logical nodes (LNs). LNs are subdivided elements of the functions of a substation automation system and are defined by abstract models. These models specify which information or data will be transferred and are configured according to the characteristics of the devices in the field [13].

The models defined by IEC 61850 determine the structures in the power system, object models related to these structures, and data structures. Additionally, IEC 61850 outlines the abstract communication service interface (ACSI), which expresses how data exchange is abstractly conducted to ensure that the correct information reaches the intended destination at the right time. The standardization of this information and the interface models facilitates communication between devices from different manufacturers [13].

LNs are defined independently of physical devices. Multiple LNs can exist in the same device, and the number of

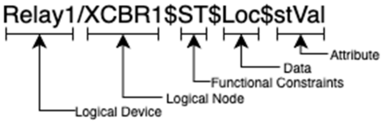

FIGURE 1. Logical node identification [13].

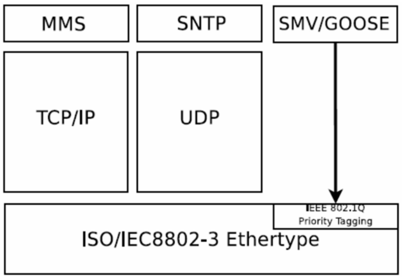

FIGURE 2. IEC 61850 protocol scheme [13].

data pieces contained within an LN is related to its functionality. All these nodes are used for object name identification, as shown in Figure 1. Each signal identification must be unique; thus, LN prefixes and instance numbers are used to distinguish data objects with the same LN functions [13].

Figure 1 illustrates a component of the IEC 61850 standard's data model, delineating the hierarchical relationship between a logical device (LD), a logical node (LN), and a data object, along with an associated functional constraint and attribute. The notation "Relay1/XCBR1STLoc$stVal" is indicative of the following hierarchy:

Relay1 denotes the LD, which abstractly represents either a physical device or a collection of functionalities within a virtual device context in the substation automation system.

XCBR1 signifies the LN within the LD, encapsulating the functionality pertinent to a specific piece of equipment, such as a circuit breaker (XCBR), within the automation hierarchy.

ST corresponds to the functional constraint 'status' (ST), categorizing the data in terms of its operational context, such as status information.

Loc likely abbreviates the 'local operation' data object within the circuit breaker's location information, encapsulating the device control's local/remote status.

stVal is the attribute of the "Loc" data object, representing the actual value of the status (e.g., whether the circuit breaker is opened or closed).

This structured approach is emblematic of the IEC 61850 standard, facilitating interoperable and flexible communications between IEDs in electrical substation automation systems.

In Figure 2, the manufacturing message specification (MMS), simple network time protocol (SNTP), sampled values (SVs), and generic object-oriented substation events (GOOSEs) are shown as different types of communication services. These services operate on top of various network protocols [13].

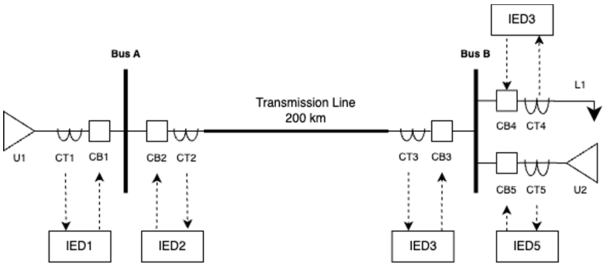

FIGURE 3. Single-line diagram of the power system.

The MMS operates on the transmission control protocol/internet protocol (TCP/IP) stack, a standard communication protocol for exchanging data over the internet or intranet. It is typically used for client–server communications within substations across wide area networks (WANs) and local area networks (LANs) [13].

The SNTP, a simplified version of the network time protocol (NTP), is used for time synchronization across network devices and operates over the user datagram protocol (UDP) [13].

SMV/GOOSE messages are used for real-time control and monitoring within substations and are designed to work efficiently with low latency and high reliability. They operate directly on top of the Ethernet layer, bypassing some higher-level protocols to minimize delay [13].

The bottom layer, the ISO/IEC 8802-3 ether type, is the IEEE standard defining Ethernet, a network protocol that controls how data are transmitted over a local area network (LAN). The IEEE 802.1Q tag in the diagram refers to a standard for implementing virtual LANs (VLANs) and priority tagging, which helps manage traffic by segregating it into different categories on the basis of priority levels [13].

III. DESIGNING THE NOVEL FRAMEWORK FOR SIMULATING PROTECTION IN POWER SYSTEMS

A. DESIGN OF THE POWER SYSTEM ARCHITECTURE AND MODEL

Figure 3 illustrates the 735 kV power system designed for efficient long-distance transmission.

Circuit Breaker 1 (CB1) is situated to connect Utility 1 (U1) from Bus A. CB1's operation is critical for system protection; it disconnects U1 during maintenance or if a fault is detected within U1, preventing the fault from affecting the remaining system.

Circuit Breaker 2 (CB2) provides a connection to the transmission line and Bus A. If a fault occurs on the line or when maintenance is needed, CB2 can be actuated to isolate the line, thereby safeguarding the bus and connected components.

For Bus B, Circuit Breaker 3 (CB3) controls the connection between the bus and the transmission line. CB3 can disconnect Bus B from the transmission line to contain faults to the line or for system maintenance, ensuring that the fault does not propagate to Bus B or its connected loads.

TABLE 1. **Utility 1 parameters.**

Properties	Values [a]
Rated Power	1500 MVA
Short Circuit Capacity	5400 MVA
Rated Voltage	735 kV
X/R Ratio	12
Frequency	60 Hz

TABLE 2. **Utility 2 parameters.**

Properties	Values [a]
Rated Power	7500 MVA
Short Circuit Capacity	30000 MVA
Rated Voltage	735 kV
X/R Ratio	14
Frequency	60 Hz

Circuit Breaker 4 (CB4) is required to connect Load 1 (L1) to Bus B. This also allows for the maintenance or fault protection of L1 without disrupting service to other loads supplied by Bus B. Circuit Breaker 5 (CB5) is placed to connect Utility 2 (U2) to Bus B. Similar to CB1, CB5's operation is critical when a fault occurs within U2 or during its maintenance, ensuring that the utility can be safely disconnected without impacting the grid.

Merging units (MUs) play a crucial role in digital protection schemes. They publish these digitized current values with all subscribed IEDs, ensuring that each IED has access to accurate real-time data for monitoring and protection. This data sharing is critical for coordinated protection actions across IEDs, which are tasked with processing digital signals to execute protection algorithms. Upon detecting a fault, the IEDs quickly command the relevant CBs over the circuit broker control unit to isolate the faulted section, which is crucial for maintaining system reliability and stability. The IEC 61850 standard facilitates the necessary communication and interoperability among these devices, allowing sophisticated and real-time control within the substation environment.

Table 1 lists the parameters for Utility 1, including its power handling capacity, fault tolerance, operating voltage, impedance characteristics, and system frequency. These parameters are critical for the design and protection of the utility's electrical infrastructure.

Table 2 outlines the parameters for Utility 2, indicating a higher capacity and different impedance characteristics than those of Utility 1 while operating at the same voltage and frequency. These details are essential for modeling utility performance and coordinating protection systems.

TABLE 3. **Line parameters.**

Properties	Values [a]
Positive sequence resistance (r_1)	0.01273 Ohms/km
Negative sequence resistance (r_2)	0.01273 Ohms/km
Zero sequence resistance (r_0))	0.3864 Ohms/km
Positive sequence inductance (l_1)	0.9337e-3 H/km
Negative sequence inductance (l_2)	0.9337e-3 H/km
Zero sequence inductance (l_0)	4.1264e-3 H/km
Positive sequence capacitance (c_1)	12.74e-9 F/km
Negative sequence capacitance (c_2)	12.74e-9 F/km
Zero sequence capacitance (c_0)	7.751e-9 F/km
Line length	200 km
Rated voltage	735 kV
Frequency	60 Hz

TABLE 4. **Load 1 parameters.**

Properties	Values [a]
Rated power	5000 MVA
Power factor (lagging)	0.8
Rated voltage	735 kV
Frequency	60 Hz

TABLE 5. **Current transformer (CT1–CT5) parameters.**

Properties	Values [a]
Primary current	78.5 A
Secondary current	3.92 A
Ratio	100/5
Frequency	60 Hz

Table 3 presents the electrical parameters of a transmission line, including the sequence resistances, inductances, and capacitances, as well as the line length, operational voltage, and frequency. These parameters are critical for understanding the behavior of a line under normal and fault conditions and are crucial for system protection and stability. Importantly, the positive, negative, and zero-sequence parameters are identical in the three-phase line, indicating that r_2, l_2, and c_2 mirror r_1, l_1, and c_1, respectively. These are required to analyze the power system under balanced and unbalanced operation conditions.

Table 4 presents the parameters for a load, specifying its rated power, power factor, and operating voltage and frequency. These define the load's electrical demand and efficiency, which is fundamental for power system analysis, load flow studies, and the assessment of system performance under various operating scenarios and fault conditions.

The nominal current for a component, such as a power line in a three-phase system, is derived from its rated power and rated voltage via (1).

$$I_{nominal} = \frac{S_{rated}}{\sqrt{3} \times V_{rated}} \tag{1}$$

Here, $I_{nominal}$ represents the nominal current, S_{rated} is the rated power, and V_{rated} is the rated phase-to-phase voltage. The next critical step is selecting suitable CT ratios after the nominal current [14] is determined. The ideal CT ratio is

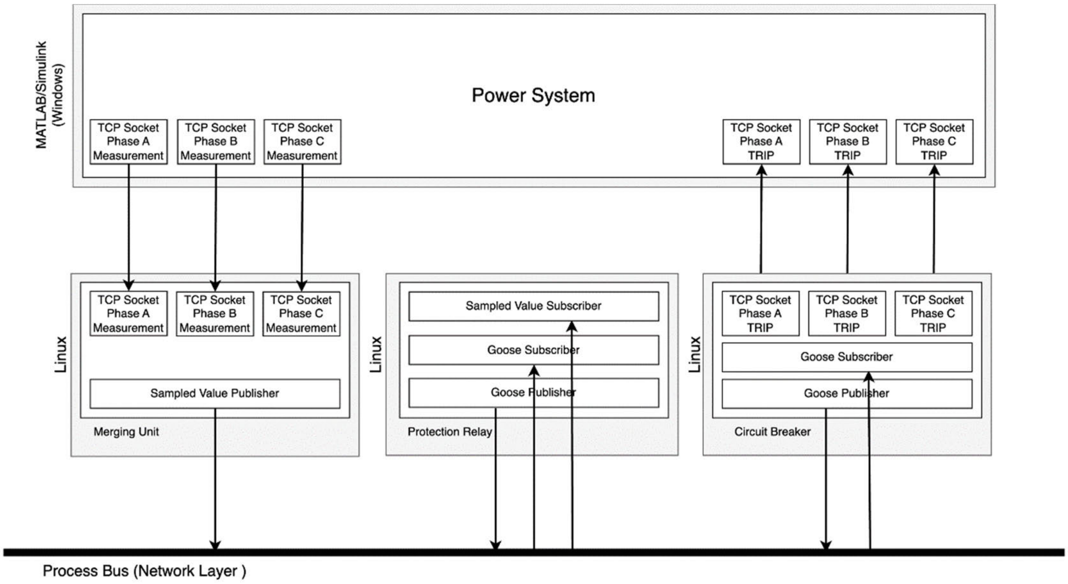

FIGURE 4. Power system design and IED communication.

computed as (2):

$$CT\ Ratio = \frac{I_{primary}}{I_{seconday}} \tag{2}$$

The chosen CT ratio should ensure that the secondary current lies within the standard range under normal operation while accommodating the full spectrum of operational currents, including potential overloads and fault conditions, without causing CT saturation [14].

Table 5 lists the parameters of a current transformer (CT), detailing its rated primary and secondary currents, transformation ratio, and operating frequency. These specifications ensure accurate current measurements and protection relay operations within power systems.

Differential protection functionalities are crucial for detecting various types of faults, with breaker failure protection included in enhancing system reliability by identifying and isolating circuit breaker malfunctions. These protection mechanisms are implemented through IEDs, which communicate via the IEC 61850 protocol. This allows for advanced features such as real-time monitoring and control, interoperability among different vendors' equipment, and seamless integration into smart grid power systems [15].

The system is designed for integration with a simulation environment capable of IEC 61850 protocol communications. This provides a valuable approach for testing and validating protection schemes under various fault conditions and operational scenarios.

B. INTEGRATED DESIGN BETWEEN POWER SYSTEMS AND INTELLIGENT ELECTRONIC DEVICES

Figure 4 illustrates the complex interplay between power systems and intelligent electronic devices (IEDs), depicting a layered network architecture that is pivotal to the simulation environment for assessing protection schemes under various operational conditions. The hybrid setup shown here runs the power system model on MATLAB/Simulink within a Windows platform, while the merging units, protection relays, and circuit breaker logics operate in Linux environments. The foundation of this research is the integration of a power system and IEDs via real-time TCP socket connections, a method proposed to bridge the gap identified in the current literature. This approach enables a level of synchronization and data exchange between the systems that are critical for monitoring, protecting and controlling power systems, thus filling the existing void with a solution that enhances both integration and system reliability.

Central to this network, TCP socket communication channels transmit phase-specific measurements (Phases A, B, and C) and merge these inputs between Simulink and the IEDs. Power system measurements are routed to merging units, and digitalized values are processed through distinct TCP sockets. Owing to the concurrent transmission of values from each phase to designated ports, the merging units are crafted with multiple-threading capabilities to independently capture and process the values from each phase.

Merging units link to the sampled value publisher, ensuring synchronized release and real-time data sharing for system observation and coordinated protective responses.

Protection relays are connected to the sampled value subscriber, and the data are analyzed for differential protection. If a fault is identified, the system communicates this through a GOOSE publisher. The GOOSE subscriber plays a role in overseeing the operational health of circuit breakers.

Circuit breakers are equipped with a GOOSE subscriber that remains vigilant for any trip commands from the protection relays. Upon receiving a trip signal, the circuit breaker node (the CB control unit) transmits this signal to the power

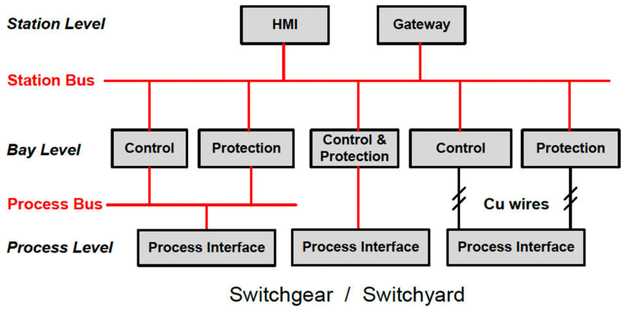

FIGURE 5. The architecture of a substation automation system [17].

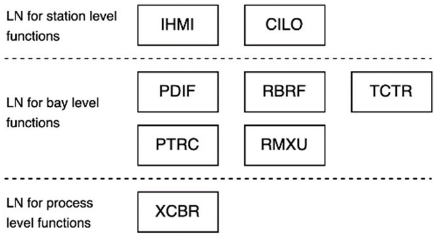

FIGURE 6. Hierarchy of logical nodes (LNs) in an IEC 61850-based substation automation system.

system via a TCP socket, thereby enabling the system to clear the fault effectively. Additionally, a GOOSE publisher is designed to broadcast the circuit breaker's health condition.

The lib61850 library represents a foundational element of this communication framework and is utilized specifically for coding IEDs. This comprehensive library supports a vast array of IEC 61850 services, which are crucial for the communication and management of devices within a power system network [16]. The reliance on a networked process bus is highlighted, guaranteeing a continuous flow of data, which is vital for real-time system monitoring and control.

The strategic layout of the design, with distinct pathways for data and clearly defined roles for each device, underscores the necessity of sophisticated communication protocols and dependable equipment for effective fault isolation and system resilience. This configuration not only serves as a blueprint of the current simulation framework but also directly addresses a significant gap in the literature, offering a progressive solution for power system protection. The diagram thus provides valuable guidance for future enhancements, proposing a robust model for bridging the existing gap and advancing the reliability of power systems globally.

C. DESIGN OF INTELLIGENT ELECTRONIC DEVICE LOGICAL NODES

Figure 5 shows the substation automation system architecture; hierarchical levels are demarcated as station, bay, and process levels, each incorporating intelligent electronic devices (IEDs) for specific functional operations. Communication across these levels is categorized into 'station bus' and 'process bus', terms denoting the physical layout of the communication systems rather than their functionalities. The station bus orchestrates connectivity between station-level entities (such as computers and gateways) and bay-level IEDs (including protection and control devices), whereas the process bus links bay-level IEDs to power process-level interfaces for key switchyard components [17].

To illustrate the simulation environment, a high-level IED design is shown in Fig. 6. This schematic representation aligns with the IEC 61850 standard, which prescribes a structured framework for substation automation protocols via the definition of logical nodes (LNs). These nodes encapsulate distinct functionalities of system protection, control, and monitoring elements, organized hierarchically across station, bay, and process levels.

At the station level, as shown in Fig. 6, the LNs comprise the following:

IHMI (human–machine interface): This node affords an interactive interface for system monitoring and control, which is critical for user–system communication.

CILO (control interlocking): CILO ensures operational safety through station-level interlocking that precludes the execution of conflicting or unsafe commands.

Figure 6 shows the LNs that cater to the autonomous control and protection of individual bays at the bay level.

PDIF (differential protection): This LN provides differential protection, which is crucial for isolating faults within line sections.

RBRF (breaker failure protection): The RBRF activates backup protection mechanisms upon detecting circuit breaker anomalies.

PTRC (trip conditioning): This LN orchestrates the coordination of protection functions, amalgamating starts and operations into a singular trip command while offering configurable indications for enhanced system responsiveness.

RMXU (measurement): Tasked with the acquisition of electrical measurements, the RMXU is a cornerstone for operational analytics.

TCTR (current transformer): This LN underpins the functionality of current transformers within the bay for protection and metering.

At the process level, as indicated in Figure 6, the LNs engage directly with the field apparatus:

XCBR (circuit breaker): The XCBR governs the functionality of process-level circuit breakers, encompassing status and control aspects.

The delineation of LNs into distinct operational levels, as portrayed in Figure 6, underpins a modular design philosophy. This enables scalability and flexibility in substation design, ensuring interoperability and systematic management of the automation system.

D. DESIGN OF INTELLIGENT ELECTRONIC DEVICE COMMUNICATIONS

Figure 7 presents a schematic of a protection relay system per the IEC 61850 standard, facilitating communication within

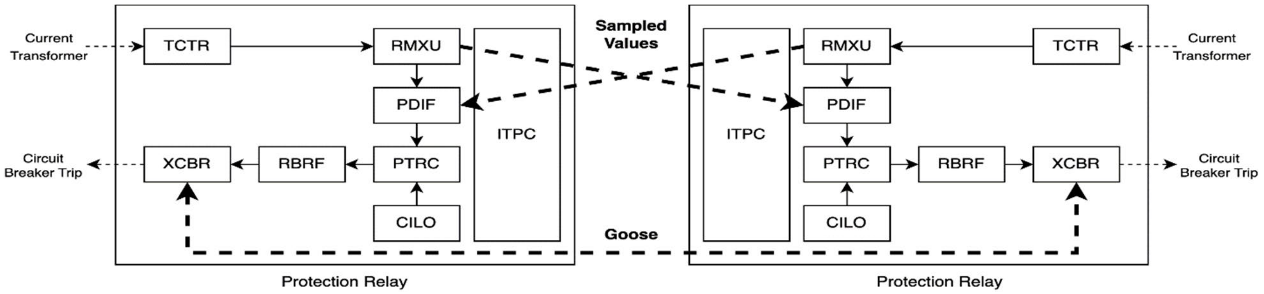

FIGURE 7. Schematic of line differential protection via IEC 61850 communication services.

substation automation. This finding illustrates two protective relay arrangements with associated LNs that perform various functions. The schematic is symmetrical, showing two relays, each with a similar configuration of LNs and functionalities. Two communication links interconnect the relays: one for sampled values (SV) and the other for GOOSE messages.

Figure 7 depicts the exchange of sampled values and GOOSE messaging between two protection relays. The schematic depicts the interaction between LNs within the IED, demonstrating a critical sequence for fault management and breaker status communication per IEC 61850 standard protocols. The RBRF and CILO LNs are integral to the assessment of the circuit breaker's operational state, which is an important component of the XCBR LN functionality.

In the system design, the PTRC LN is responsible for input synthesis from the PDIF and CILO LNs. This node executes the critical function of circuit breaker tripping, utilizing the collective intelligence of these inputs to determine the necessity of opening the breaker, thus enabling fault clearance.

In the outlined configuration, the RMXU LN receives current measurements from the TCTR LN, which is essential for real-time operational analysis. The PDIF logical node relies on these data to identify faults by comparing current inputs from both local and remote RMXU logical nodes. The transfer of real-time current data from remote IEDs is facilitated by the SV protocol, which is integral to the PDIF LN's ability to perform its differential protection role within the protection zone.

The RBRF LN monitors the performance of the circuit breaker, specifically detecting malfunctions during operation. If the circuit breaker is deemed inoperable and a fault is coincidentally detected within the system, the RBRF LN responds by initiating a sequence of actions to mitigate the situation. Concurrently, the CILO LN maintains a supervisory role, ensuring that the interlocking commands are adhered to and preventing any conflicting operations that could exacerbate the system condition.

If a fault persists, necessitating the clearance of the fault zone, the GOOSE communication protocol is employed. This protocol is designed for the rapid propagation of messages, ensuring swift and reliable delivery of critical control commands. In this scenario, the GOOSE protocol facilitates the dissemination of signals to adjacent IEDs, specifically targeting their XCBR LNs. This prompts these devices to activate their respective circuit breakers to isolate and clear faults, thereby mitigating the risk of system-wide disturbances.

This orchestrated process underscores the synergy between the protection LNs and the communication mechanisms within the IED, emphasizing the importance of real-time data exchange and interoperability among substation automation devices.

The protocol's design ensures that even at a single point of failure—such as an inoperable circuit breaker—system resilience is upheld, and the integrity of the power system is maintained through coordinated, decentralized actions. This level of automation and communication is paramount in contemporary power systems, which demand high reliability and swift fault resolution to ensure uninterrupted service and system stability.

The ITPC is an interface within the IEC 61850 standard framework, and it is instrumental in orchestrating communication flows for protection and control. It is not classified as a logical node; instead, it functions as a conduit through which GOOSE messages and sampled values are transmitted [17]. This ensures the seamless integration of protection commands and control actions across the system, which is necessary for maintaining the operational integrity of the automated substation environment.

E. DESIGN OF A DIFFERENTIAL PROTECTION RELAY

Differential protection is a foundational aspect of power system security, serving as a reliable method for detecting faults within electrical components. As articulated by Redfern et al., this form of protection is predicated on the current differential relaying principle, where an imbalance in currents at the line terminals exceeding a set threshold prompts the tripping mechanism [18]. The basic formula (3) that underpins differential protection is as follows:

$$I_d = |I_{in} - I_{out}| \tag{3}$$

Under normal operating conditions, I_{in} is equal to I_{out}, rendering I_d negligible. However, in the event of a fault within the protected zone, this balance is disturbed, yielding a nonzero I_d, which triggers the protection relay to actuate the circuit breaker and isolate the fault.

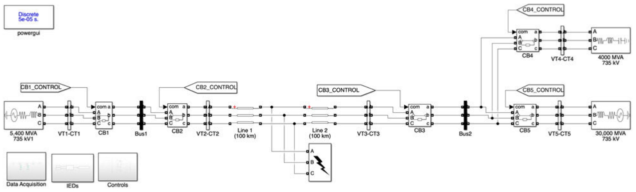

FIGURE 8. Implementation of a power system model in Simulink.

The following relationship typically defines the relay operation (4):

Operate if

$$|I_{in} - I_{out}| \geq k\,(I_{in} + I_{out}) \tag{4}$$

The IEC 61850 standard enhances differential protection by allowing for precise communication of the required measurements and statuses necessary for this calculation. This approach supports the use of an SV to transmit digitized analog values, such as currents and voltages, from various points of the system to the protection relay in real time. This capability is critical for the relay to calculate I_{in} and I_{out} and determine the presence of a fault. By incorporating the IEC 61850 standard, differential protection schemes have significantly enhanced interoperability and real-time communication capabilities. For example, the standard has been instrumental in providing a structured approach for seamless integration and coordination among protection relays and other IEDs, which is crucial for the efficient and reliable operation of protection systems [19].

The IEC 61850 framework has revolutionized differential protection by facilitating high-speed data exchange and precise time synchronization. These advancements contribute to faster fault detection and isolation, which is imperative for minimizing service interruptions and the risk of cascading failures within a power system [20].

F. IMPLEMENTATION OF THE POWER SYSTEM MODEL IN SIMULINK

Figure 8 shows that the Simulink schematic provides an abstract representation of a power grid, incorporating elements such as data interfaces, power transmission components, consumption nodes, and protective mechanisms. This model facilitates the examination of a grid's dynamic responses and the efficacy of its protective schemes, all framed within the context of the IEC 61850 communication standard.

The stream input and stream output components are in the Simulink desktop real-time module for transferring data from the simulation environment to the IEDs. IEDs accept data transfers via a data acquisition board. A board was identified for each phase stream, and the float data type was selected to transfer the relevant data. This means that a separate listing port is specified for each phase, and the current information on the intelligent electronic device is constantly updated from this data communication.

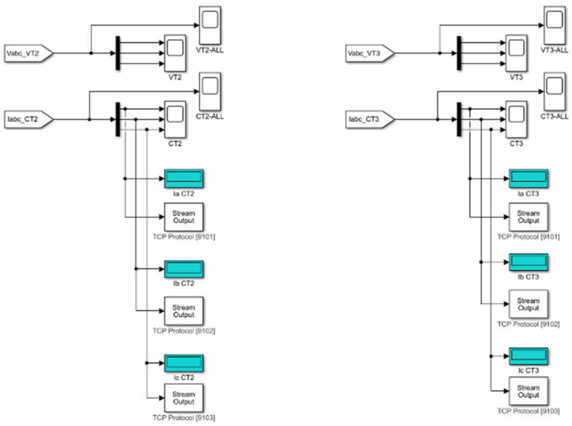

FIGURE 9. Simulink model for current transformer (CT) data streaming.

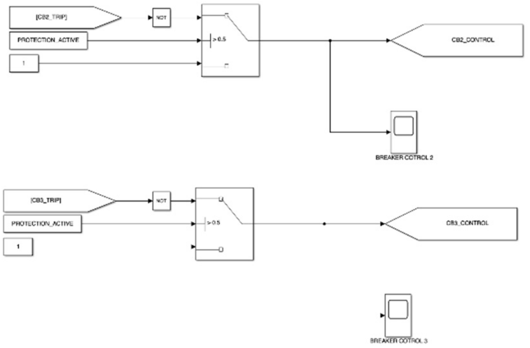

FIGURE 10. Logic diagram for circuit breaker status monitoring in a Simulink environment.

Figure 9 shows each stream output component designed in Simulink. This design enables consistent data transmission from the Simulink environment to IEDs implemented in Linux. The diagram illustrates the data flow from multiple CTs through individual processing blocks to the stream output blocks, indicating the setup for real-time data acquisition and processing in the IEDs.

Figure 10 shows the design of the IEDs communicating with Simulink. The TCP server is configured to transmit data via port 36880 to the circuit breaker as a trip signal so that IEDs can send the trip signals to MATLAB/Simulink.

IV. POWER SYSTEM PROTECTION SIMULATION: BRIDGING REAL-TIME IED COMMUNICATIONS WITH IEC 61850 STANDARDS

This section delineates the comprehensive simulation environment developed for evaluating transmission line differential protection schemes under the IEC 61850 standard. The simulation framework integrates MATLAB/Simulink for dynamic system modeling alongside network communication protocols, which are explained in Section IV-B. This architecture allows realistic emulation of power system operations under various fault conditions.

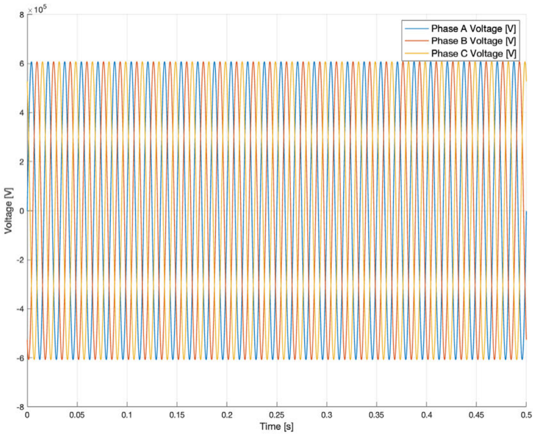

FIGURE 11. **Three-phase instantaneous voltage measurements on Bus B under normal operating conditions.**

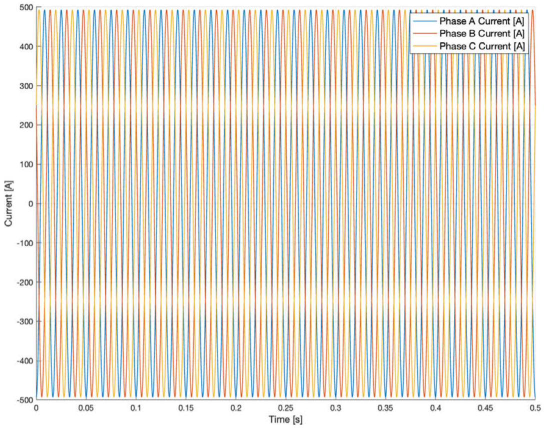

FIGURE 12. **Three-phase instantaneous current measurements at CT3 under normal operating conditions.**

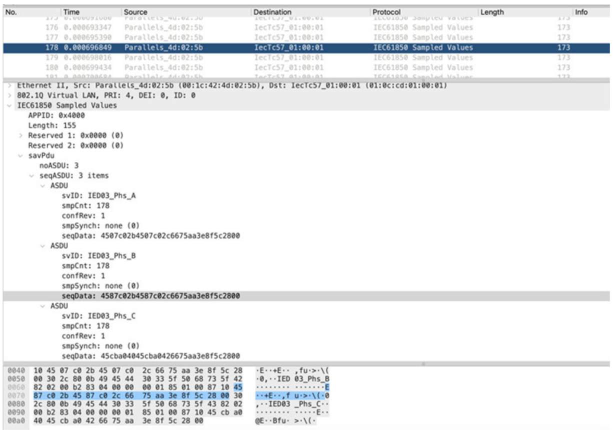
```
No.   Time         Source                Destination          Protocol                   Length  Info
  176 0.000693347  Parallels_4d:02:5b    IecTc57_01:00:01     IEC61850 Sampled Values       173
  177 0.000695390  Parallels_4d:02:5b    IecTc57_01:00:01     IEC61850 Sampled Values       173
  178 0.000696849  Parallels_4d:02:5b    IecTc57_01:00:01     IEC61850 Sampled Values       173
  179 0.000698016  Parallels_4d:02:5b    IecTc57_01:00:01     IEC61850 Sampled Values       173
  180 0.000699434  Parallels_4d:02:5b    IecTc57_01:00:01     IEC61850 Sampled Values       173
> Ethernet II, Src: Parallels_4d:02:5b (00:1c:42:4d:02:5b), Dst: IecTc57_01:00:01 (01:0c:cd:01:00:01)
> 802.1Q Virtual LAN, PRI: 4, DEI: 0, ID: 0
v IEC61850 Sampled Values
    APPID: 0x4000
    Length: 155
  > Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  v savPdu
      noASDU: 3
    v seqASDU: 3 items
      v ASDU
          svID: IED03_Phs_A
          smpCnt: 178
          confRev: 1
          smpSynch: none (0)
          seqData: 4507c02b4507c02c6675aa3e8f5c2800
      v ASDU
          svID: IED03_Phs_B
          smpCnt: 178
          confRev: 1
          smpSynch: none (0)
          seqData: 4587c02b4587c02c6675aa3e8f5c2800
      v ASDU
          svID: IED03_Phs_C
          smpCnt: 178
          confRev: 1
          smpSynch: none (0)
          seqData: 45cba04045cba0426675aa3e8f5c2800
0040  10 45 07 c0 2b 45 07 c0  2c 66 75 aa 3e 8f 5c 28   ·E··+E·· ,fu·>·\(
0050  00 30 2c 80 0b 49 45 44  30 33 5f 50 68 73 5f 42   ·0,··IED 03_Phs_B
0060  82 02 00 b2 83 04 00 00  00 01 85 01 00 87 10 45   ········ ·······E
0070  87 c0 2b 45 87 c0 2c 66  75 aa 3e 8f 5c 28 00 30   ··+E··,f u·>·\(·0
0080  2c 80 0b 49 45 44 30 33  5f 50 68 73 5f 43 82 02   ,··IED03 _Phs_C··
0090  00 b2 83 04 00 00 00 01  85 01 00 87 10 45 cb a0   ········ ·····E··
00a0  40 45 cb a0 42 66 75 aa  3e 8f 5c 28 00            @E··Bfu· >·\(·
```

FIGURE 13. **Network packet analysis of the sampled values.**

The key components of the simulation include modeling electrical power systems, implementing IEC 61850 communication protocols for data exchange, and simulating protective relays and their interactions with physical system dynamics. The simulation environment is designed to be flexible, supporting the modification and testing of different protection algorithms and communication strategies. In the simulation environment, the circuit breaker opening times that appear in real systems are considered. For this reason, the trip signal and the circuit breaker position status change simultaneously. In this research, differential protection for the transmission line between Bus A and Bus B was designed for the power system, for which the single-line diagram given in Figure 3 was investigated at a steady state and under various fault conditions.

A. NORMAL OPERATING CONDITIONS

This simulation environment models the power system's operational stability under normal operating conditions, as evidenced by the voltage and current measurements.

Figure 11 and Figure 12 illustrate these conditions, showing the steady state where the voltage and current values remain constant over time. This indicates the system's robustness in maintaining operational integrity without faults.

Figure 7 shows the architecture of data sharing between IEDs. In this study, current data were shared between IEDs for differential protection control via this implementation. Figure 13 shows the network packet detailed structure of the sampled value packet, including the Ethernet, application protocol data unit (APDU) information, and the sampled values, as part of a communication trace in a substation automation system. The network flow data for each phase are defined on an APDU, and 3 APDUs are transferred on a sampled value package.

Figure 14 illustrates the operational states of the circuit breakers in the simulated power system. It depicts circuit breakers maintaining a constant position, indicative of stable operational conditions without fault conditions. This visualization underscores the effectiveness of the protection scheme under normal operating conditions, highlighting the reliability of circuit breakers in maintaining system integrity and the readiness to respond to potential faults. This steady-state scenario serves as a baseline for comparing the system's behavior under fault conditions and assessing the operational efficacy of protection mechanisms.

The simulation confirms the robustness and operational integrity of the power system under steady-state conditions, demonstrating its ability to maintain constant voltage and current levels.

B. THREE-PHASE GROUND FAULTS WHEN THE PROTECTION SYSTEM IS DEACTIVATED

In this case, how the protection systems respond to a three-phase ground fault at the middle of the transmission line when the protection systems are deactivated is examined. Figure 15 displays the instantaneous current values measured by CT2 under three-phase fault conditions.

Figure 16 shows the RMS value of the instantaneous current measurement at CT2 under three-phase fault conditions. The RMS value of the current measured by CT2

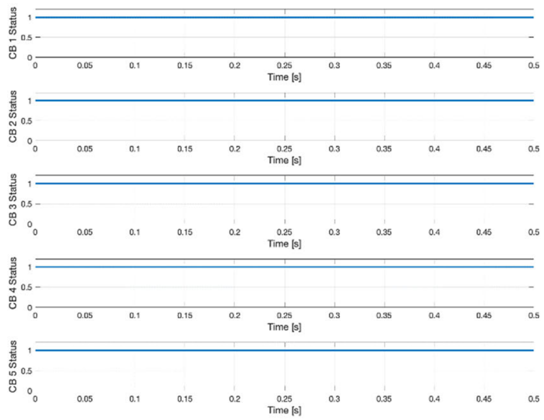

FIGURE 14. **Changes in the operational state of circuit breakers under normal operating conditions.**

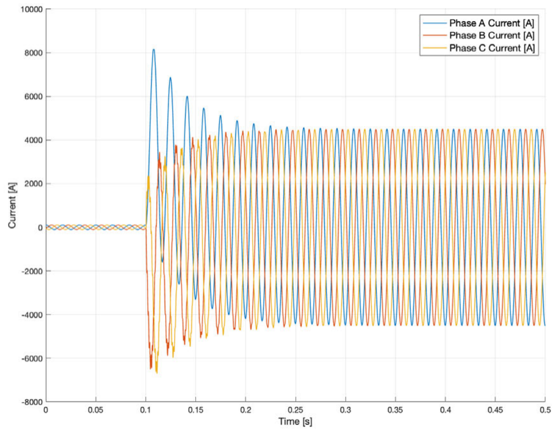

FIGURE 15. **Instantaneous current measurements at CT2 under three-phase fault conditions.**

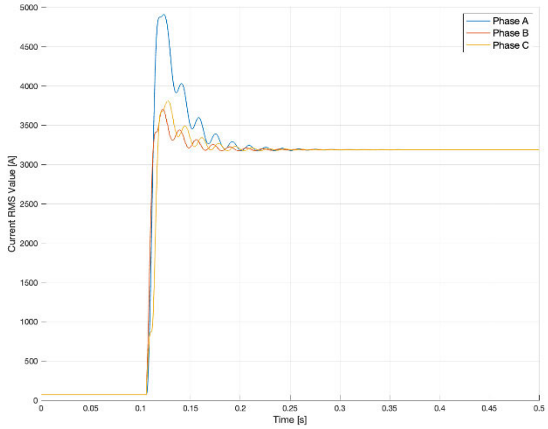

FIGURE 16. **RMS value of the instantaneous current measurement at CT2 under three-phase fault conditions.**

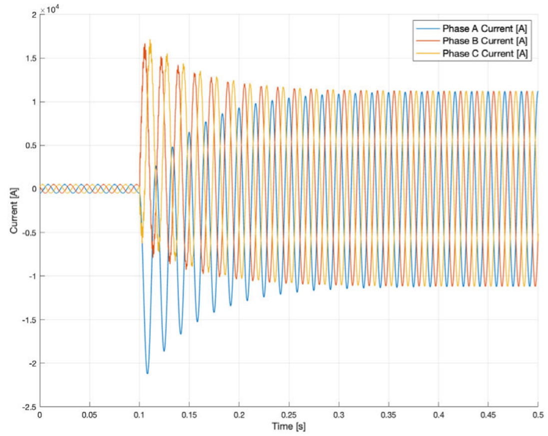

FIGURE 17. **Instantaneous current measurements at CT3 under three-phase fault conditions.**

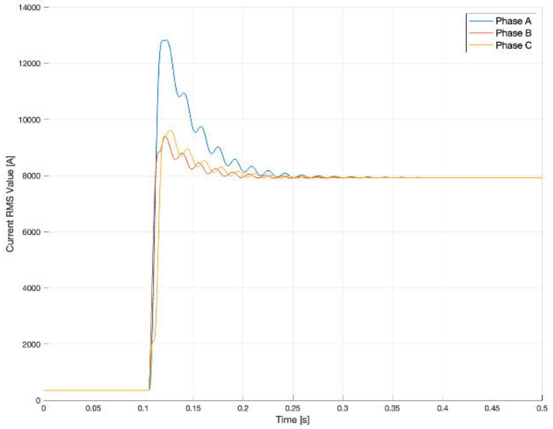

FIGURE 18. **RMS of the instantaneous current measurement at CT3 under three-phase fault conditions.**

during a fault condition provides a detailed analysis of the current's magnitude throughout the fault. This figure is essential for understanding the system's dynamic response under fault conditions and the role of RMS values in the operational efficiency of line differential protection schemes. This emphasizes the precision and reliability of the IEC 61850 protocol in monitoring and analyzing electrical parameters critical for fault detection and isolation.

Figure 17 presents the current measurements at CT3. This figure illustrates the real-time current flow dynamics through CT3 under various fault conditions.

Figure 18 shows the RMS values of the current measured by CT3. This graphical representation is vital for understanding the magnitude of current flowing through a line over time, providing insights into the system's behavior under fault conditions.

Figure 19 focuses on the difference in RMS values between CT2 and CT3, an operation critical to the differential protection strategy within the power system. This subtraction process serves as a foundational method for identifying discrepancies in current measurements that indicate potential fault conditions. The visualization provides insight into the algorithmic approach used in differential protection, where subtracting RMS values helps in distinguishing between

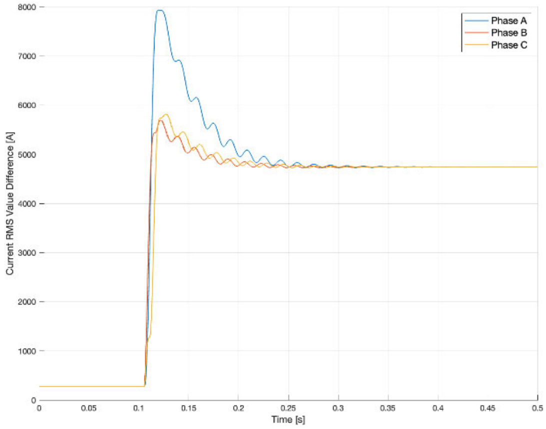

FIGURE 19. Differential current measurements during the three-phase fault condition.

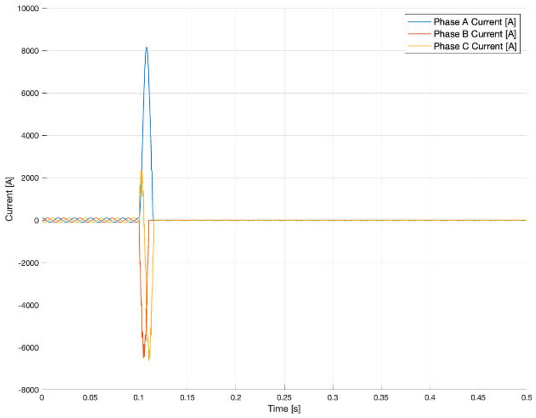

FIGURE 20. Instantaneous current measurements at CT2 under three-phase fault conditions.

normal operational variances and those indicative of faults. This figure illustrates the application's ability to process and analyze data in a manner that enhances the accuracy and reliability of fault detection mechanisms, thereby demonstrating the effectiveness of the simulation environment in replicating real-world protection system behaviors.

Without active protection systems, a three-phase ground fault significantly impacts system security and stability, illustrating the essential role of the protective relay. The observed voltage drop and current increase emphasize the need for efficient differential protection to mitigate disturbances and ensure system reliability.

C. THREE-PHASE GROUND FAULTS WHEN PROTECTION SYSTEMS ARE ACTIVE

Upon activation of the protection systems, the simulation demonstrates a marked improvement in the system's ability to handle a three-phase ground fault in the middle of the transmission line, as shown in Figures 20 to 23. The trip activation and dynamic response of circuit breakers are crucial for swiftly isolating faults, minimizing potential damage, and ensuring power system resilience.

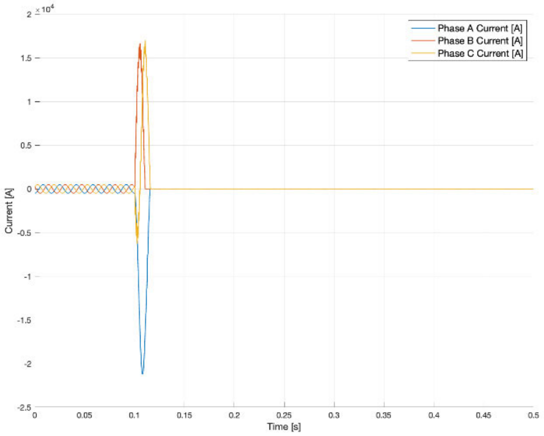

FIGURE 21. Instantaneous current measurements at CT3 under three-phase fault conditions.

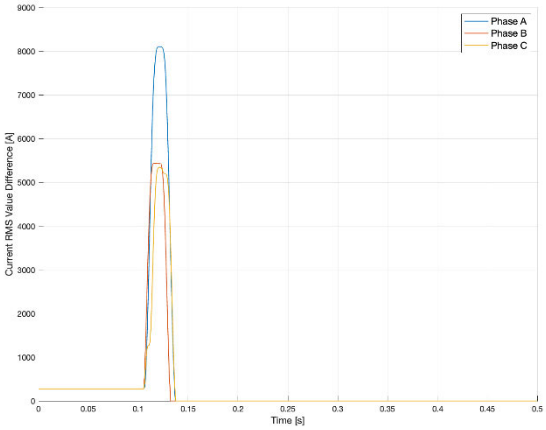

FIGURE 22. Differential current measurement during the three-phase fault condition.

Figure 20 presents the current values measured by CT2 during the fault. This figure provides insight into the dynamic current variations and the protection system's immediate response. This finding highlights the precision of current measurements and the critical role of IEC 61850-based communication in the accurate and timely activation of protection mechanisms.

Figure 21 presents the current measurements from CT3 under fault conditions. These data are essential for evaluating the system's response to faults and the effectiveness of the differential protection scheme. This highlights the precision of current sensing and the importance of real-time data for fault analysis.

Figure 22 illustrates the effectiveness of differential protection in an IEC 61850 communicative environment by presenting the absolute value of the subtracted RMS values of the instantaneous currents measured by CT2 and CT3 under fault conditions. This graphical representation highlights the precision and responsiveness of the differential protection relay, highlighting its critical role in fault detection and isolation. By analyzing the discrepancy between the RMS values

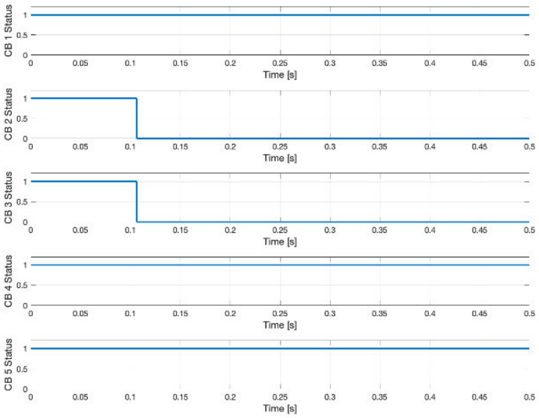

FIGURE 23. Circuit breaker operational state changes under three-phase fault conditions.

from CT2 and CT3, the figure demonstrates the system's ability to identify and mitigate faults accurately, thereby ensuring system reliability and stability within the context of an IEC 61850 standardized communication framework.

Figure 23 illustrates the operational states of circuit breakers in response to fault conditions, demonstrating their critical function in isolating faults and maintaining system stability. This figure highlights the importance of timely circuit breaker operation to prevent system-wide disturbances and ensure power system integrity.

The activation of protection systems significantly enhances the system's resilience against three-phase ground faults, as evidenced by the effective isolation of faults and maintenance of current stability. The fault was detected and cleared in nearly 0.025 seconds. The rapid detection and mitigation of faults underscore the critical role of the IEC 61850 protocol in supporting sophisticated protection schemes.

D. THREE-PHASE GROUND FAULT WHEN PROTECTION SYSTEMS ARE ACTIVE AND CIRCUIT BREAKER 3 IS FAILED TO CLEAR THE FAULT

This section delves into a nuanced scenario where despite activating protection systems, a malfunction in CB3's circuit breaker complicates the fault isolation process. Figures 24 to 27 detail the system's behavior under these compounded conditions. The integration of IEC 61850 GOOSE messages, as shown in Figure 24 and Figure 25, is crucial for enabling rapid communication and coordination among IEDs to address the fault effectively, underscoring the importance of reliable equipment and sophisticated communication protocols in maintaining system reliability.

Figure 24 presents the current measurements taken by CT2 under the three-phase ground fault. This figure illustrates the instantaneous current levels detected by CT2, providing crucial data for analyzing the system's response to the fault.

Figure 25 shows the current measurements obtained from CT3 under fault conditions. Similar to Figure 24, this figure provides insight into the current levels detected by another

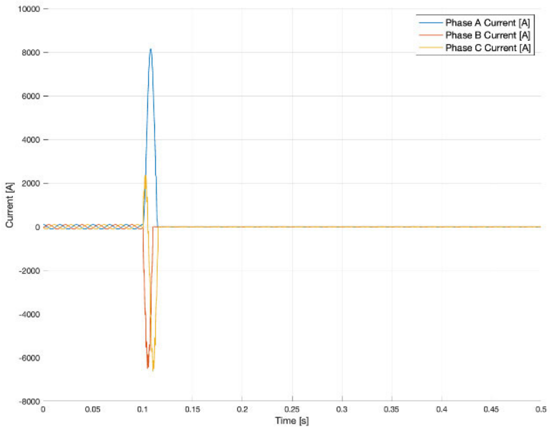

FIGURE 24. Instantaneous current measurements at CT2 under three-phase fault conditions.

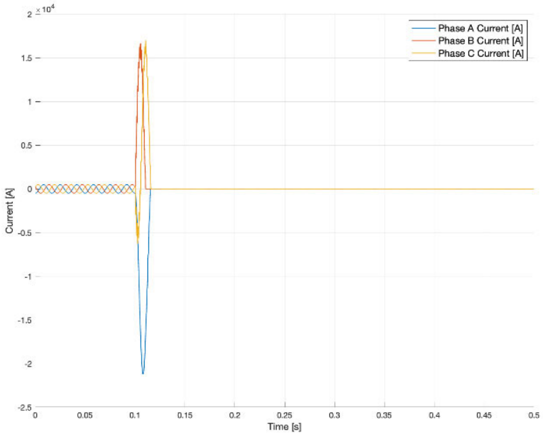

FIGURE 25. Instantaneous current measurements at CT3 under three-phase fault conditions.

transformer in the system, emphasizing the distributed nature of fault detection and the role of CT3 in the comprehensive monitoring strategy enabled by the IEC 61850 standards.

Figure 26 shows the absolute values of the subtracted RMS values of the instantaneous currents measured by CT2 and CT3 under fault conditions, which is a crucial parameter for differential protection schemes. This figure is instrumental for understanding how the differential protection system, supported by IEC 61850 protocol communication, detects and responds to fault conditions by analyzing current flow dynamics.

Figure 27 illustrates the states of circuit breakers controlled by GOOSE messaging during a fault, focusing on the breaker failure condition of CB3. This figure underscores the importance of sophisticated communication protocols and reliable equipment in ensuring effective fault isolation and system resilience.

This scenario underscores the system's ability to manage faults effectively even when facing CB3 equipment malfunctions. The fault was detected and cleared in nearly

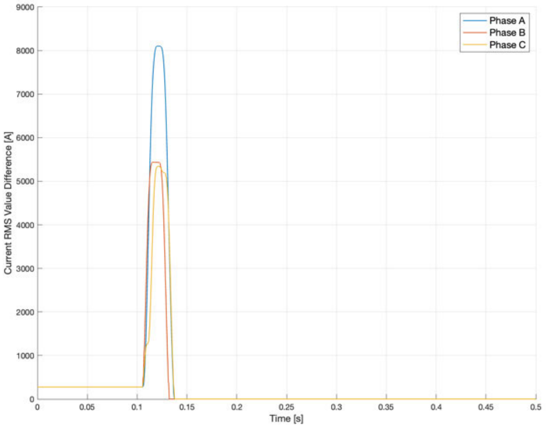

FIGURE 26. Differential current measurement during the three-phase ground fault condition.

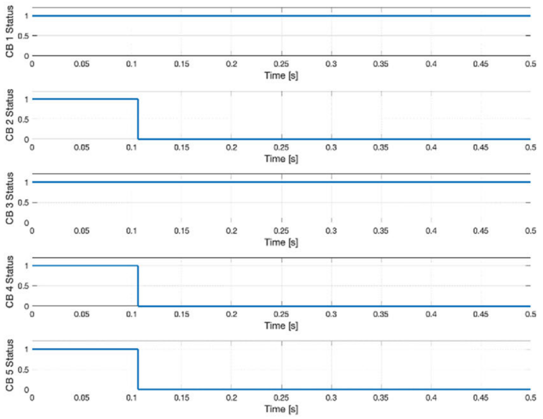

FIGURE 27. Circuit breaker operational state changes under three-phase fault conditions.

0.025 seconds by CB2 at one end of the line. Following the failure of CB3, the circuit breaker failure protection relay will trip CB4 and CB5. This can be seen in Figure 27. Integrating IEC 61850 GOOSE messaging is critical for enabling rapid communication and coordination among IEDs, highlighting the importance of reliable equipment and advanced communication.

V. CONCLUSION

This research addresses a significant gap in power system protection methodologies by developing a dedicated simulation environment that supports the communication of protection relays via the IEC 61850 protocol. By integrating MATLAB/Simulink with real-time TCP socket connections for IED communications, a novel approach that enables a more accurate and functional simulation of relay behavior across various protection methods was pioneered. This breakthrough not only enhances the reliability and efficiency of power systems but also provides a robust tool for developing, testing, and validating new relay communication techniques and protection schemes.

The simulation results from this framework are instrumental in demonstrating its effectiveness and utility. Through a series of detailed simulations, including normal operating conditions and various fault scenarios, the ability of the framework to accurately replicate real-world power system behaviors has been validated. These scenarios underline the crucial role of effective IED communication in rapid fault isolation and maintaining system stability. This highlights the framework's potential impact on the advancement of power system protection technologies.

Moving forward, the focus on advancing cybersecurity measures within the IEC 61850 framework and exploring further enhancements to the simulation environment promises to propel the capabilities for real-world application and reliability of power systems. The contributions of this research lay a solid foundation for future advancements in the protection, control, and optimization of power systems, making it a significant step toward ensuring the robustness and security of modern power networks in the era of smart grids.

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ABDULVEHHAB AĞIN was born in Bursa, Turkey. He received the master's degree from Istanbul Technical University, where he is currently pursuing the Ph.D. degree. He graduated second in his bachelor's degree program at Istanbul Technical University. Professionally, he works as a Senior Cybersecurity Architect. Leveraging his extensive knowledge and experience, he aims to enhance the security of power systems against cyberattacks.

AYŞEN DEMİRÖREN received the bachelor's and master's degrees in electrical engineering from Istanbul Technical University, Tükiye, in 1982 and 1985, respectively, and the Ph.D. degree from the Institute of Science and Technology, Istanbul Technical University, in 1993. Her Ph.D. thesis was related to the adaptive control of synchronous machines. She was an Assistant Professor, from 1993 to 1996, and an Associate Professor with the Department of Electrical Engineering, Faculty of Electrical and Electronics Engineering, Istanbul Technical University, from 1996 to 2003. She has been a Professor with the Department of Electrical Engineering, since 2003. She was the Head of the Electrical Engineering Department, from 2010 to 2013. Her research interests include power system control and modern control techniques, electrical energy generation, and renewable energy sources.

ÖMER USTA (Senior Member, IEEE) received the dual degree from Istanbul Technical University and the University of Bath. He is currently a Professor with ITU, specializing in power system protection automation. His career includes developing courses on smart grid technologies and leading research in smart grid applications, including metering, protection, and control. He has contributed significantly to the field with numerous publications and has held key academic and leadership roles at ITU, including as the Department Head and the Faculty Dean.

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