Interoperability Challenges in Multivendor IEC 61850 Devices for Parallel Power Transformer Differential Protection

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***Abstract*—Interoperability of GOOSE messages is essential for the proper operation of protection schemes such as the parallel power transformer (PTRF) differential protection scheme, especially when using multivendor IEC 61850 devices. GOOSE messages allow for fast and reliable communication between intelligent electronic devices (IEDs) and are based on Ethernet communication. To ensure the interoperability of GOOSE messages between multivendor devices, adherence to the IEC 61850 standard specifications is crucial. The standard defines the format and content of GOOSE messages, including the data object model, data types, and communication protocols. Third-party testing and certification programs can also ensure compliance with the standard and help guarantee interoperability between different vendors. Device conformance with these standards does not ensure interoperability when devices from various manufacturers are utilized. Interoperability is necessary between the relevant devices from various vendors to provide system power stability and protection. If multivendor device interoperability is achieved, power utilities will be able to utilize multivendor devices in substations. The study investigates and provides comprehensive methods for achieving IEC 61850 standard-based interoperability problems in parallel with PTRF's current differential protection schemes between IEDs (SEL-487E and MiCOM-P645) produced by different vendors under fault conditions. In a lab-scale environment with RTDS for real-time simulation in Hardware-in-the-Loop (HIL), the designed technique is simulated and tested.**

***Index Terms*—current differential protection, hardware-in-the-loop testing, IEC 61850 GOOSE message, IEDs, interoperability**

I. Introduction

Protection schemes are vital for the safe and reliable operation of power systems. The increasing demand for electric power systems and the growth of renewable energy sources have led to the integration of parallel power transformers in electrical networks. Parallel power transformers (PTRFs) are widely used in electrical networks to increase power capacity and improve the reliability of the system. The parallel PTRF differential protection scheme is a critical protection scheme that detects and clears faults in PTRF windings [1]. The scheme relies on the proper functioning of IEC 61850 GOOSE communication messages to detect these faults and quickly isolate them before they cause damage to the transformer [2]. In parallel operation, the HV and LV of two (or more) transformers are connected to the source and load busbars, respectively. The reliability of parallel operation is higher than that of a single larger unit [3, 4].

Current differential protection systems based on the IEC 61850 standard are commonly employed to protect these PTRFs [5]. The IEC 61850 standard provides a unified approach to the communication and interoperability of multivendor IEDs used for protection and control in electrical networks [6]. In IEC 61850 substations, several IEDs provide monitoring, control, and protection duties in the substation communication networks (SCN). The IEC 61850 standard defines logical nodes (LNs) and data items for these IEDs. LNs are the most critical component of IEC 61850 for implementing interoperability activities between IEDs [6, 7]. The IEC 61850 communication offers various opportunities for advancing protection relay speed, safety, reliability, and sensitivity [8]. The IEC 61850 standard defines the format and content of GOOSE messages, including data object models, data types, and communication protocols [9, 10]. For IEC 61850 GOOSE communication messages to be published via the Ethernet network, the Real-Time Digital Simulation (RTDS) uses the GTNET-GSE card, which enables transmitting and receiving signals from the IED relays [11]. However, due to differences in how different IEDs have implemented the standard, implementing the IEC 61850 standard presents significant interoperability issues.

The widespread adoption of IEDs in power systems has led to significant improvements in power systems of protection and control. The key aspect of modern power systems is interoperability, which ensures that various IEDs can operate seamlessly, regardless of their origin, and communicate with each other using GOOSE messages [7, 12, 13]. The interoperability of GOOSE messages is essential for the proper operation of protection schemes, especially for multivendor IEC 61850 devices used in PTRF differential protection. However,

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the lack of interoperability among IEDs relay from different vendors has led to several issues, including delays in commissioning, increased costs, and reduced system efficiency. These significant challenges of interoperability are due to the differences in the implementation of the standard by multi vendors [14, 15]. This is particularly relevant for PTRF differential protection schemes, which require the cooperation of multiple devices from different vendors to provide system power stability and protection [16, 17].

Contribution: The paper aims to investigate and resolve interoperability challenges in using multivendor IEC 61850 devices for the parallel PTRF differential protection scheme. It emphasizes the importance of GOOSE message interoperability for proper parallel PTRF operation and fault detection, unlike other similar works that only focus on a non-parallel PTRF. The study proposes methods to achieve interoperability for SEL-487E and MiCOM-P645 IEDs, conducting fault condition tests in a lab-scale environment. By achieving interoperability, the study aims to ensure operational efficiency, system stability, and reliable protection for the parallel PTRF, following IEC 61850 standard specifications. The proposed method offers a superior solution to overcoming interoperability challenges in this specific application.

This article is formatted as follows: Following the introduction, Section II discusses a brief literature review of the related research that has been covered. The proposed methodology of interoperability multi-vendor evaluation is described in Section III. The design and implementation of a LAB scale in HIL are described in Section IV. Development of the GOOSE communication IEC 61850 based on interoperability is discussed in Section V. The results are discussed in Section VI. Section VII elaborated on the topic under discussion. Sections VIII provide the conclusion of the paper.

II. Literature Review

The literature indicates that several studies have been conducted to address the interoperability challenges in multivendor IEC 61850 devices for protection schemes.

The author in [16] explained how the worldwide standard IEC 61850 delivers high-speed peer-to-peer communications for power system protection and automation applications, providing interoperability among multifunctional protection IEDs from multiple vendors. The standard's major influence on the interoperability and dependability of protection methods is also covered in the study. The author in [18] proposed a framework that includes a set of requirements and guidelines to ensure interoperability and interchangeability between different Microgrid protection systems. In [19], the authors indicated that the interoperability of the IEC 61850 process bus is affected by various factors, including network configuration, message configuration, and hardware configuration.

Authors in [20] provided a clear picture of the importance of interoperability testing for merging units based on the IEC 61850-9-2 standard. In [21], the authors presented the common functional testing of IEDs, the authors also emphasized the significance of IEC 61850-based SAS integrated system testing. In [22] the authors investigated the compatibility of the IEC61850 protocol in a HIL Microgrid testbed using an emulated IED and identified issues related to GOOSE message configuration and data types. The study identified issues related to GOOSE message configuration, such as the inconsistent use of data types and the incorrect mapping of signals. Authors in [23] investigated the interoperability of three different vendor devices using real-time simulation and emphasizes the importance of proper configuration of GOOSE messages. The study found that the proper configuration of GOOSE messages is critical to ensuring the reliable transfer of protection signals between devices.

Authors in [24] highlighted the difficulties in implementing substation automation systems based on IEC 61850. They identified issues related to the complexity of the standard and the lack of interoperability testing tools. Reference [25] presented the design and testing of a digital substation test platform that includes equipment from multiple vendors. This platform will help substation engineers choose multivendor installations by providing answers to difficulties related to a multivendor system. Authors in [26] evaluated and identify the engineering issues for the various vendor digital substation, researchers provide a System for testing virtual digital substations with interoperability tools (VDSTS). Three parts make up VDSTS:

- A VDSTS modeling for creating scenarios for real-time digital substations.
- A communication network modelling for simulating the communication network.
- An interoperability analysis tool for assessing the interoperability of the digital substation.

Reference [27] discussed how, since 2013, KEPCO, a public utility in Korea, has built roughly 100 IEC 61850-based digital substations that will be utilizing a various vendor approach, with 4-6 manufacturing devices selected from 30 KEPCO-registered manufacturers. The work by TNB to test and confirm interoperability between various vendors' digital substation devices utilizing the open communication standard IEC 61850 is also highlighted in the study. The author in [28] explained how some unclear sections that are not protected within the IEC 61850 standard are the cause of interoperability failures that lead to communication failures. This issue arises from the fact that IEC 61850's implementation of information exchange between facilities uses different methods for processing and interpreting communication signals. The testing automation system is a device that can detect compatibility issues in the field and carry out the testing procedure automatically.

Previous studies have explored various techniques for achieving interoperability of IEC 61850 devices for protection schemes. Some studies have focused on the conformance testing of IEC 61850 devices, while others have focused on interoperability testing. However, achieving interoperability between devices from different vendors remains a significant challenge, particularly for protection schemes such as PTRF differential protection schemes that require the cooperation of multiple devices.

III. Proposed Interoperability Multi-Vendor Evaluation Methodology

This paper presents a proposed interoperability multi-vendor evaluation methodology for evaluating IEC 61850 devices for parallel power transformer differential protection. The proposed methodology includes the design and implementation of lab-scale HIL testing and real-time simulation techniques for parallel PTRF current protection. Additionally, the development of a GOOSE communication system based on IEC 61850 for interoperability is presented. The system also utilizes real-time simulation to emulate real-world conditions, allowing for accurate testing of interoperability among devices from different vendors. The proposed methodology shown in Fig. 1 includes the following steps [7, 26]:

1) Planning: Define the scope of the evaluation and identify the devices to be tested.
2) Test Setup Environment: Prepare a controlled testing environment with compatible hardware and software components, ensuring proper physical connectivity, power supply, and configuring communication interfaces (e.g., Ethernet, serial) for device linkage.
3) Functional Compatibility Testing: Conduct functional tests to evaluate the compatibility and interoperability of the devices, validating their interpretation and response to commands. Verify standard operational requirements and test data exchange capabilities by sending/receiving commands, signals, and data points between MiCOM-P645 and SEL487E devices.
4) Protocol Conformance Testing: Assess the devices' compliance with communication protocols like IEC 61850, ensuring proper handling of protocol-specific procedures, error handling, and data synchronization. Verify adherence to standards by evaluating message formats, communication modes, data models, and procedures.
5) Configuration: Configure the device's hardware and software settings and communication according to the IEC 61850 standard and ensure that they are properly interconnected using suitable interfaces.
6) Define Interoperability Requirements: Determine the interoperability requirements for both IED devices, including protocols, data formats, communication interfaces, and any necessary additional functionalities to be supported.
7) Interoperability Testing: The IEDs are tested for interoperability with each other, by conducting functional tests to assess communication between IEDs evaluating data exchange and message comprehension.
8) HIL Testing: The IEDs are tested in a HIL simulation environment to evaluate their interoperability under realistic operating conditions. Execute the test by sending GOOSE messages between the devices and verifying that the messages are received and processed correctly.
   a. Performance Testing: Measure response times, throughput, and latency in data exchange between the devices, evaluating their performance under high data loads and stress conditions. Analyze latency to identify potential bottlenecks that could impact interoperability.
   b. Fault Tolerance Testing: Evaluate the devices' fault detection, isolation, and recovery capabilities by simulating various fault scenarios. Assess how both IEDs respond and recover from errors, testing fault detection mechanisms and the accuracy of failure isolation and reporting
9) Analyze Test Results: Analyze test results to identify interoperability issues or discrepancies, assessing if the devices meet defined interoperability requirements. Document observed problems such as error messages, failed communication attempts, or incorrect data exchanges.

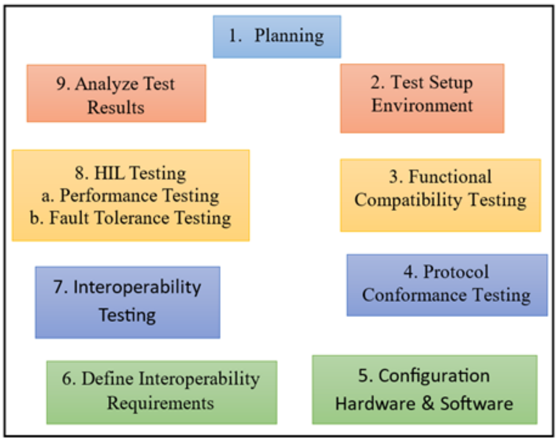

Fig. 1. A method for assessing interoperability that has been proposed.

The evaluation of interoperability between multi-vendor IEC 61850 devices requires a comprehensive methodology that includes testing and verification procedures. To ensure that IEDs are thoroughly vetted, GOOSE message interoperability must be evaluated methodically. The vetting or evaluation of GOOSE message interoperability adheres to test methodologies developed over time for IEC 61850, compliant devices. The interoperability between devices, irrespective of the vendor, is one of the most advancing features of the IEC 61850 specification assessed with the test facility. This is an opportunity to share messages and use knowledge through multi-vendor IEDs [29, 30].

IEDs from different manufacturers can operate on a network or path to communications, sharing data and commands on the LAN substation as specified in IEC 61850 Interoperability. The test facility proved that this standard could deliver vital information between two different families of IEDs. Building upon the established groundwork, the following subsections provide an in-depth of crucial testing and verification aspects for the interoperability of IEC 61850 devices. These aspects include SCL, Vendor Selection, Interoperability Issues and Testing Tools, test setup configuration, and system configuration. Table I: summarizes the main differences between two types of testing: system specification and testing purpose [31, 32].

TABLE I: TYPES OF TESTING DEVICES IN SUBSTATION PROTECTION BASED ON IEC 61850

Testing	Descriptions
Product testing	This includes all tests related to the devices, including Factory Acceptance Testing, Integration Testing, Device Interoperability Testing, and Device Acceptance Testing based on their technical requirements.
Systems testing	This includes all features and performance tests relevant to and compliant with the optimized IEC61850 substation system, such as Site Acceptance Testing, Conformance Testing, Commission Testing, and Maintenance Testing.

A. Substation Configuration Language (SCL)

SCL files are XML-based files used in the context of the IEC 61850 standard to describe the configuration of substation automation systems. These files contain essential information about the devices, communication settings, and data models within a substation, facilitating interoperability between different systems. IEC 61850-6 defines six types of SCL configuration files namely as follows [5, 7, 24, 33].

- SSD (System Specification Description) File: It provides a standardized terminology for Logical Devices (LDs) and Logical Nodes' (LNs) prefixes and suffixes, promoting consistency and facilitating interpretation across different device configurations.
- SCD (Substation Configuration Description) File: It describes the overall configuration of the substation, including information about LDs, communication details, and mappings between LNs and communication links.
- ICD (IED Capability Description) File: It defines the capabilities and data models of an IED, enabling other devices to understand and interact with it. The ICD file provides essential information about the supported services, communication protocols, and data attributes of an IED.
- CID (Configured IED Description) File: Contains specific configuration data for an IED within the substation. This file includes details such as the IED's LNs, data attributes, communication settings, and associated functionality.
- IID (IED Information Description) File: Provides information about an IED's capabilities, data models, and support services.
- SED (Substation Engineering Data) File: It contains engineering data for the substation, including settings, control logic, protection configurations, and other relevant information for the engineering and operation of the substation.

The last two types of files were introduced with the second edition of IEC 61850. These standard SCL file types play a crucial role in the configuration, integration, enabling seamless communication, and interoperability among devices and systems compliant with the IEC 61850 standard.

B. Vendor Selection

Any class of logical architecture can have multiple device selection options. Real systems usually fall into one of three groups in terms of the use of devices from several vendors, with the integration of multivendor. The following are some criteria when choosing a Substation Network Equipment vendor, Compatibility and Interoperability, Experience in the Industry, Reputation, and reliability, customized solutions, Security, Scalability and Flexibility, Future-proofing, and Innovation [34]:

- A vendor with extensive expertise in protecting industrial substations and Protocols can have the highest payback on security technology investments.

In this study, IED vendors SEL-487E and MiCOM-P645 are considered for the evaluation purpose of PTRF protection schemes. The focus is on the differential transformer Protection functions provided by these vendors. However, it is important to note that a universal approach to interoperability in GOOSE messages for parallel PTRF, should not be dependent on specific vendors. As long as the IEDs comply with the standard and are designed for power transformer protection, their suitability should be sufficient.

C. Interoperability Issues and Testing Tools

There are still significant issues that power utilities are facing in terms of IED configuration for testing reasons since there aren't any easy-to-use IED configuration tools. Vendors configure IEDs with their proprietary tools, and they construct or modify CID and SCL files with their configuration tools [35].

The IEC 61850 standard provides a common framework for communication, but different versions or editions may introduce changes or updates that can impact interoperability between devices. When dealing with different vendors in the context of GOOSE-based communication, the following interoperability issues may arise [5]:

- Protocol and Standard Compliance: Vendors may implement the standard with variations or interpretations that are not fully compliant. Leading to compatibility issues and hinder the interoperability of devices from different vendors.
- Data Model Interpretation: Vendors may interpret and implement the data models differently, resulting in inconsistencies and difficulties in understanding and exchanging GOOSE messages.
- Configuration and Parameter Differences: Inconsistent settings across vendors hinder seamless interoperability between devices. Incompatible configurations may affect the proper transmission and interpretation of GOOSE messages.
- Vendor-Specific Extensions: Vendors may introduce proprietary extensions to enhance their devices' capabilities. While these extensions can offer benefits, they can also introduce interoperability issues when communicating with devices from other vendors that do not support or recognize those extensions.
- Interoperability Testing: Vendors may conduct interoperability testing primarily within their ecosystem or with a limited number of partner vendors, leading to potential interoperability challenges when integrating devices from different vendors that have not been adequately tested together.
- Communication Protocol Variations: While the IEC 61850 standard defines the communication protocols,

vendors may use different underlying technologies or variations in the implementation, leading to incompatibilities and difficulties in exchanging GOOSE messages between devices from different vendors.

- Firmware and Software Versions: Inconsistent behavior in different versions affects GOOSE message exchange. For example, SEL employs the quickest AcSELerator for IED configuration, whereas MiCOM must be configured using their proprietary tools called MICOM S1 Agile. This causes issues when an IED needs to be put up for testing in an active substation. Technicians or Engineers must be well-knowledgeable in all configurator tools.

To mitigate these interoperability issues, it is crucial to engage in thorough testing, collaboration, and communication with vendors. It is also advisable to ensure clear communication of requirements, adherence to standard specifications, and comprehensive validation of interoperability during the system design and integration phases.

D. The Test Setup's Configuration

The basic framework of the laboratory test setup, as shown in Fig. 2, incorporates the device hardware installed at the test facility. Additionally, it provides a concise overview of the vital components comprising the laboratory test setup.

- RTDS: The simulator's analogue outputs (GTAO) feed simulated voltage and current signals of the power system to protective relays.
- IEDs (MiCOM-P645 and SEL487E): Two safety relays from different vendors are employed to protect the PTRF. Each relay collects RTDS current signals through analogue outputs and uses GOOSE messages to send trip signals to the RTDS and retrieve circuit breaker status information via LAN.
- Industrial Ethernet switches: Ethernet is used for the IEC 61850 station bus to transmit GOOSE messages. Both relays and the RTDS are connected to a Ruggedcom Ethernet switch using 100 Mbps communication links.
- AC or DC Power Supply: All equipment is powered by different voltages. The auxiliary supply is used to supply auxiliary voltage to energize the IEDs. This power supply has a 220 VAC input and a 110 VDC output switching circuit.
- Omicron CMS356 and CMS156: These state-of-the-art hardware devices serve as voltage and current amplifiers for analogue low-level signals, enabling the testing of different protection devices.
- Personal Computer (PC) with software: The PC is equipped with the necessary software to support the setup of operations and other LAN-related applications.
- Ethernet Cabling: Standard Ethernet cables are used to connect the PC, RTDS, and IEDs through the industrial Ethernet switch. And it is also used to transport the GOOSE signals.

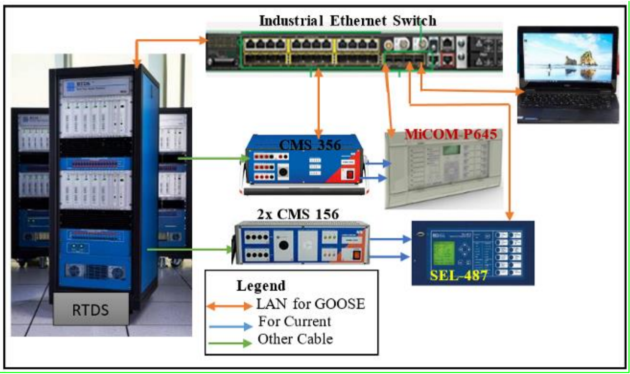

Fig. 2. The laboratory test setup of HIL employs a fundamental framework.

Fig. 3 depicts a detailed flowchart of the steps and processes involved in simulating and analyzing the proposed system. This visual depiction provides a clear overview of the simulation workflow, assisting in understanding the overall structure and operation of the system. The flowchart is a useful tool for visualizing the interconnection of various stages of the simulation process, helping researchers to grasp the systematic flow of operations and obtain insights into the complexities of the investigated system.

Fig. 4 illustrates the flowchart specifically focused on the communication of GOOSE messages in Area A is the flowchart of SEL-487E and Area B is the flowchart of MiCOM-P645. It highlights stages and interactions involved in transmitting and receiving GOOSE messages, providing insights into the system's communication dynamics. The logic control for GOOSE is specifically developed and explained in subsection D.

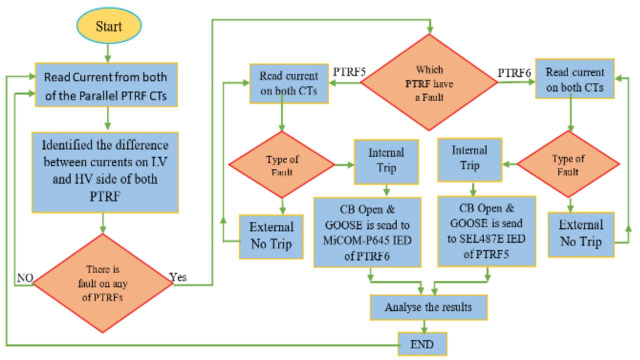

Fig. 3. Simulation process flowchart of the proposed system.

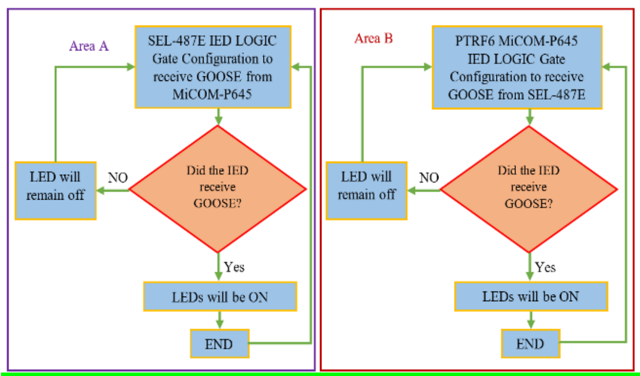

Fig. 4. Flowchart of GOOSE message communication.

E. System Configuration

The first step in setting up communication is to allocate IP addresses to all the devices such as IEDs, Ethernet switches, RTDS, and Computers. Configuring communication settings for the terminal unit and applying default protection settings to the relays is the next step in the process. The network mask address is 255.255.255.0.

IV. Design and Implementation of a Lab Scale in HIL Parallel Transformer Current Protection for Interoperability

A lab-scale HIL simulation environment is designed and implemented to evaluate the interoperability of the IEDs used for parallel power transformer differential protection. The IEDs are connected through an Ethernet switch using the IEC 61850 standard. The HIL simulation environment is used to evaluate the interoperability of the IEDs under different operating conditions such as fault conditions, transformer inrush current, and communication failures.

To demonstrate GOOSE message interoperability, a differential current protection application on the parallel PTRF is developed. A case study is created by combining a GOOSE message application and a differential current protection application. The transmission system of IEEE 9-Bus is selected as a case study. The IEEE 9 has been modified at bus 6 with sub-transmission and distribution. The modified part of sub-transmission and distribution consists of 10 buses (nodes), one load, two lines, and three transformers (2 in parallel) as shown in Fig. 5. The modified part of the network in Zone 1 of Fig. 5 consists of four CTs, 8 buses, two parallel transformers that have the same values as Voltage Ratio/Turns Ratio, Vector Group, etc. that will be the understudy.

The study utilized the parallel transformers that have a 110/22kV with a 56MVA protected by two IEDs (SEL-487E and ALSTOM MiCOM-P645 relays) transformer differential protection (87T), with a speed of fewer than 20 msec responding to the faults and has communication capabilities of the IEC 61850 standard [36]. The PTRF protection scheme is modeled using RTDS's RSCAD graphical user interface software, with CMS 156, CMS356 Omicron Amplifier for current injection, and the two IED relays as illustrated in Fig. 5. When one PTRF of the parallel receives an internal fault (PTRF5) it must trip using IEC 61850 GOOSE and also this GOOSE must send to another IED as a signal indicating that there is a fault on the other PTRF6 however this PTRF6 must not trip for this fault.

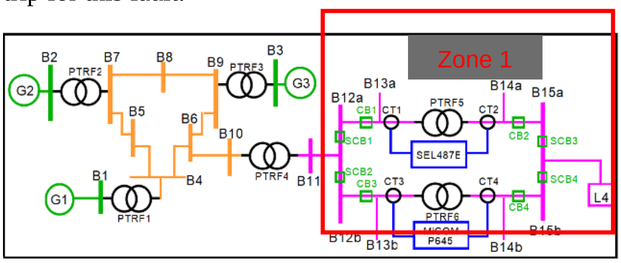

Fig. 5. RTDS model of the proposed network under study.

V. Development of the GOOSE Communication IEC 61850 Based on Interoperability

A GOOSE communication system based on the IEC 61850 standard is developed to improve the interoperability of the IEDs used for parallel power transformer differential protection. The GOOSE communication system is designed to provide a fast and reliable communication link between the IEDs. The GOOSE messages are tested in the HIL simulation environment to evaluate their performance under different operating conditions. The development of the GOOSE communication protocol based on interoperability involves the following steps:

- Identify the requirements and specifications of the communication system.
- Develop the communication architecture for the GOOSE protocol.
- Design the communication interfaces for the devices and systems that will be communicating using the GOOSE protocol.
- Test and validate: To guarantee that the GOOSE communication protocol satisfies the communication system's requirements and specifications.

The primary goal of the standard of IEC 61850 is to make substation IEDs two-way communications and to promote the interoperability of different vendors' IEDs. The ability of the IEDs from various vendors to communicate with one another is ensured through standard compliance. Special files in the IEC 61850 standard must be created to start GOOSE communication interoperability [17]. Interoperability is a key requirement for adequate integration and performance of multivendor systems and can be described in four different levels which are listed below [5, 18]:

- Interoperability of data communication: This level refers to the ability of different systems to exchange data with each other. It involves the use of common communication protocols and data formats.
- Functional interoperability: This is the ability of different systems to perform similar functions. It involves the use of common functional requirements and interfaces.
- Interchangeability: It is the ability to replace one device or system with another from a different vendor without disrupting the overall system functionality. It involves the use of common hardware and software components.
- Interoperability of engineering: This is the ability to seamlessly integrate devices or systems from different vendors into the overall engineering and configuration process. It involves the use of common engineering practices and standards.

The logical nodes (LNs) used in this, are to transmit data containing status events via Ethernet are used in place of those relay word bits. RTDS utilizes the GTnet cards for this application to transfer the status event messages for protection and control to RTDS from the physical device.

A. Configuration of the IEC 61850 Standard Communication

By configuring the IEDs devices, RTDS GTnet, to specify the signals that need to be broadcast, the communication between the GTNET cards in RTDS/RSCAD and IEDs is established. This part makes using the GTNET hardware for IEC 61850 standard communication possible. The configuration of the MiCOM-P645 and SEL-487E Differential Transformer Protection accomplishes the control device using the software MiCOM S1 Agile MCL and AcSELerator Architect, respectively. Both operational conditions of the resultant interconnected system are fulfilled after this scheme has been configured. For publishing status events across Ethernet, logical nodes (LNs) that correspond to the ANSI relay word bits must be used. Configurable IED description files, GOOSE messages, Datasets, MCL files, and SCL files can all be created and edited.

B. Configure GOOSE Subscribing/Receive

During the subscribing/receiving of the file from one vendor to another, we can see the interoperability between the two if possible. The file that has been configured is the IEC data models files shown in Table II.

All the above configuration files can be exported as "CID" files and imported to different IEDs. However, on SEL-487E, you can export "CID, ICD, & IID" only, while on MiCOM-P645, you can export as "CID, IID, ICD, & XML."

C. RTDS GTNet GSE Card for GOOSE Configuration

The RTDS makes use of the GTNET-GSE card to publish GOOSE communication messages over the Ethernet network. To provide output data properties that match those specified during the IED's GOOSE configuration, this word input GOOSE is converted using a word-to-bit converter. The input logic that controls the virtual circuit breakers is then attached to the word-to-bit converter output. Smart circuit breakers typically operate in milliseconds. The interface for the GTnet-GSE to word-to-bit converter is shown in Fig. 6.

A GTNet's purpose is to subscribe to GSSE/GOOSE messages that are published by physical devices and use those signals to isolate faults by activating virtual system circuit breakers. On the GTNET-GSE (RTDS/RSCAD), you can import the following file IEC-61850 "SCD, icd, & .cid", and XMF files. And its SCL file is saved as ".scd".

TABLE II: IEC DATA MODEL FILES FOR IEDS RELAY

IEDs	IEC data models
SEL-487E	SEL_487_1_87T ST-PRO_D87RAPDIF1_OP.General
MiCOM-P645	MiCOM_P645_DIFF; System\LLNO-Protection/DIFPDIF1.ST.OP.General

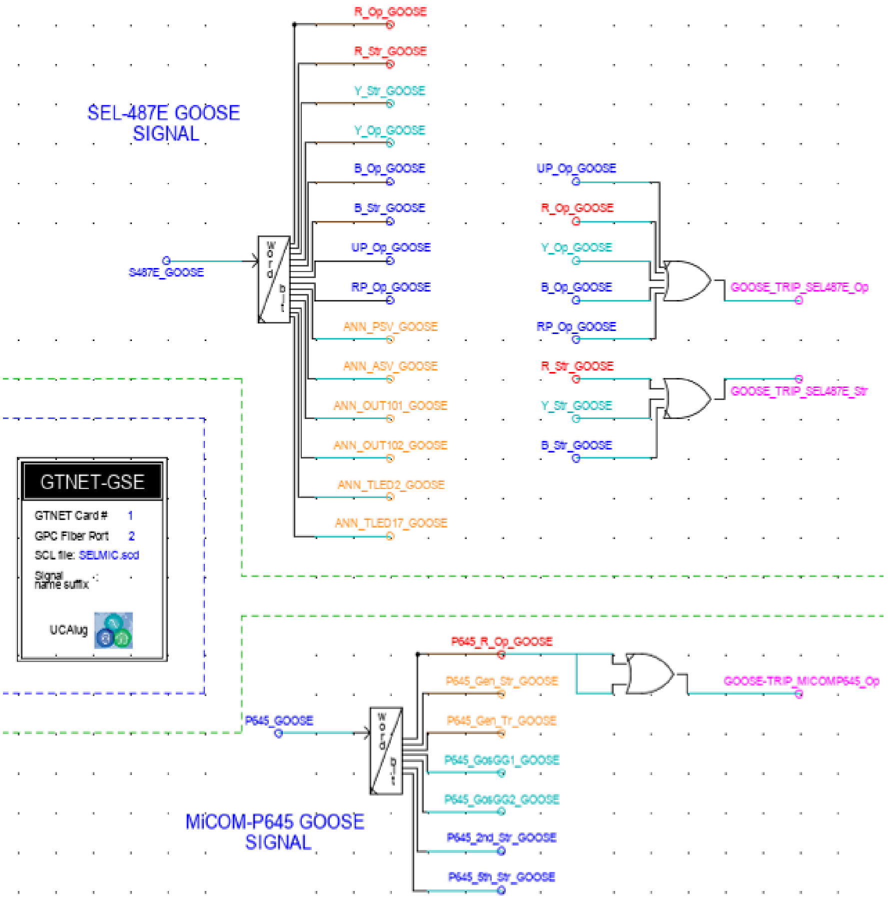

Fig. 6. Interface from GTnet to word-to-bit converter.

D. Configure Graphical GOOSE Logic for IEDs Interoperability

The next step is configuring the required logic control of the GOOSE for both IED devices to confirm the interoperability between various-vendor IEDs for PTRF differential current protection as per the case study shown in Table III. To ensure effective interoperability among IEDs, it is essential to make adjustments to logical device names and logical node nomenclature, including the date format. These adjustments play a critical role in facilitating the seamless exchange of information using the GOOSE messaging protocol. By harmonizing the logical device names and ensuring compatibility in the nomenclature, IEDs from different vendors can communicate seamlessly and work together cohesively, enhancing the overall interoperability of the substation system. These adjustments serve as a key foundation for promoting compatibility and smooth data exchange in modern substation environments. The case study in Table III summarises the graphical logic for GOOSE interoperability that has been developed in Fig. 7 and Fig. 8 for SEL-487E and MiCOM-P645, respectively.

Fig. 7 shows the Configure Graphical GOOSE logic for SEL-487E in area A; there are two Incoming GOOSE "CCIN00x" that will accept GOOSE from MiCOM-P645, and the output is the LEDs, namely "T8_LED" and "T12_LED". While in Area B is to publish a GOOSE message to MiCOM-P645 during the SEL-487E internal trip fault; an output is required, "CCOUTx" and the two LEDs are set up to monitor the GOOSE message status.

TABLE III: CASE SUMMARY OF THE CONFIGURE GRAPHICAL LOGIC FOR GOOSE INTEROPERABILITY

Device's	Case study
SEL-487E	• SEL device subscribes to MiCOM device GOOSE message. • LEDs should illuminate on receiving the GOOSE message from the MiCOM device generated during the internal fault, and the SEL device should publish a GOOSE message.
MiCOM-P645	• MiCOM device subscribes to SEL device GOOSE message. • LEDs should illuminate on receiving the GOOSE message from the SEL device generated during the internal fault, and the MiCOM device should publish a GOOSE message.

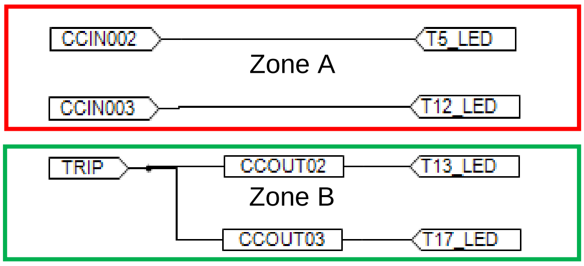

Fig. 7. Configure graphical GOOSE logic for SEL-487E.

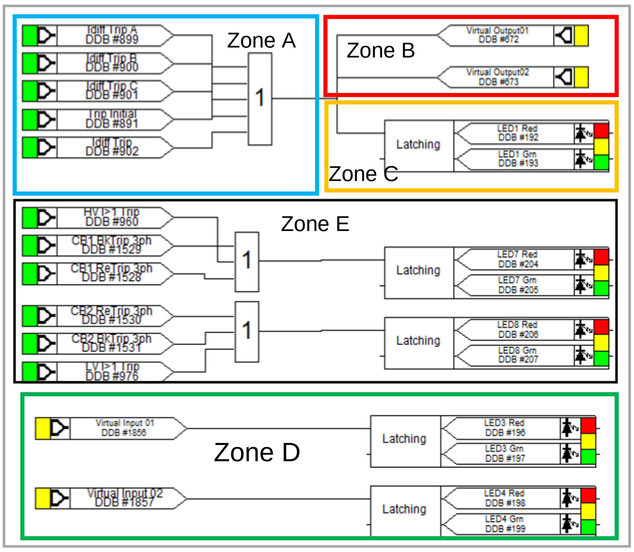

Fig. 8. Configure PSL graphical GOOSE logic for MiCOM-P645.

Fig. 8 shows the Configure Graphical GOOSE logic PSL for MiCOM-P645 with different areas, which function as follows. Area A shows the trip signal of the MiCOM-P645, area C is MiCOM LED that will indicate when there is a fault/trip simultaneously, area B is the outgoing GOOSE signal to publish a GOOSE message to the SEL-487E device during the MiCOM-P645 internal trip fault. Two Incoming GOOSE will accept GOOSE from SEL-487E, and the output is the LEDs, namely LED3 and LED4, as shown in area D it is configured to monitor the status of the GOOSE message.

VI. RESULTS

To discuss the results of a parallel transformer current protection system designed for interoperability, it is important to first understand the objectives and requirements of the system. A protection system designed for interoperability should be able to communicate with other devices and systems from different manufacturers and should be compatible with different communication protocols and interfaces. The GOOSE protocol, which is based on the IEC 61850 standard, is a widely used protocol for communication in substations and can enable interoperability between devices and systems.

The results of a parallel PTRF current protection system designed for interoperability can be evaluated based on its performance in detecting and responding to faults, its compatibility with other devices and systems, and its ability to communicate using the GOOSE protocol.

The design and implementation of a lab-scale HIL parallel PTRF current protection for interoperability will involve the identification of requirements and specifications, the selection of compatible hardware components, and the development of firmware and algorithms. The IEC 61850 and the RSCAD GTNET's IEC 61850 SCD files were configured and mapped to both IEDs and the GTNET card.

After mapping on both sides was completed, each CID/SCD file was compiled in preparation for publishing and subscribing to GOOSE messages for interoperability. The overall, methodology provides a structured approach for evaluating interoperability between multi-vendor IEC 61850 devices, helping to ensure that the devices can communicate effectively and reliably. The development of the GOOSE communication protocol based on interoperability involves the identification of requirements and specifications, the development of the communication architecture and interfaces, and testing and validation.

A. Monitoring of GOOSE Messages Results

Programs that track IEC 61850 GOOSE messages via the network can stay updated on the message attributes when GOOSE is being broadcast. Wireshark and GOOSE Inspector are two such software. After successfully sending the settings file to the IEDs, the GOOSE Inspector software was used to confirm whether the IED was publishing GOOSE messages. Fig. 9 shows the GOOSE Inspector Demo with the packet data, a Detailed View of the MiCOM-P645, and the GOOSE Monitor window.

On the GOOSE Monitor window (Zone F) in Fig. 9, the indication is defined by different colour being:

- Dark Orange indicates at least one error, but warnings may be pending.
- Mustard yellow indicates at least one warning but no pending error.
- Green indicates no error or warnings.

GOOSE messages are forced to be transported when the data attribute trigger changes. After that, the data sets will be copied into the buffer that will be transmitted. The real value will also be included in the buffer and transmitted as a message. GOOSE messages will then be delivered to the subscriber.

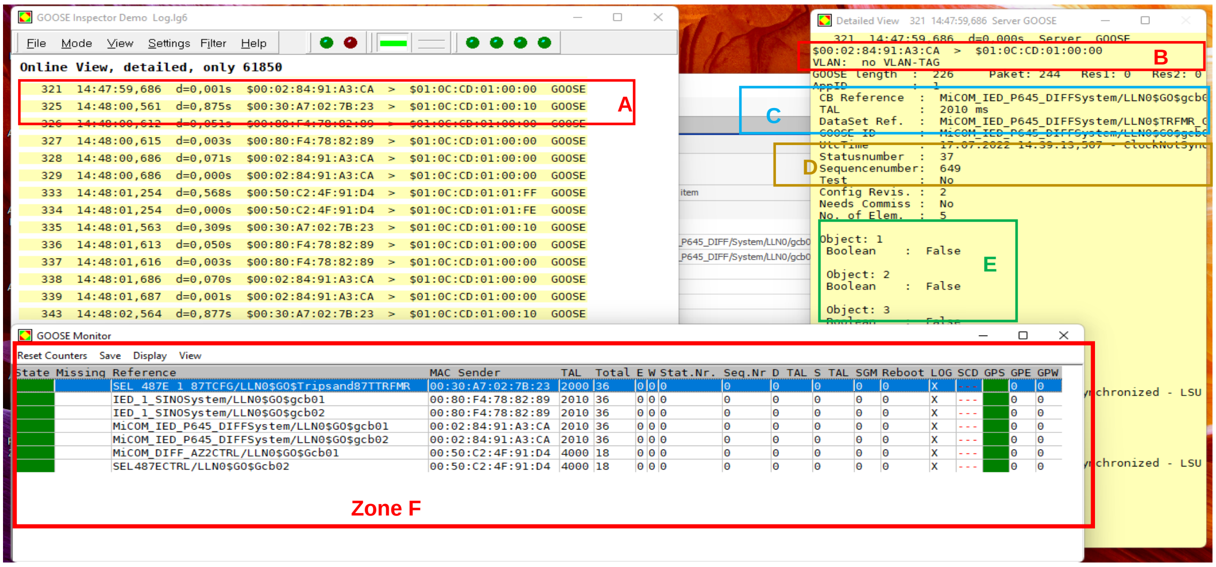

Fig. 9. GOOSE Inspector Demo, Detailed View, and GOOSE Monitor window.

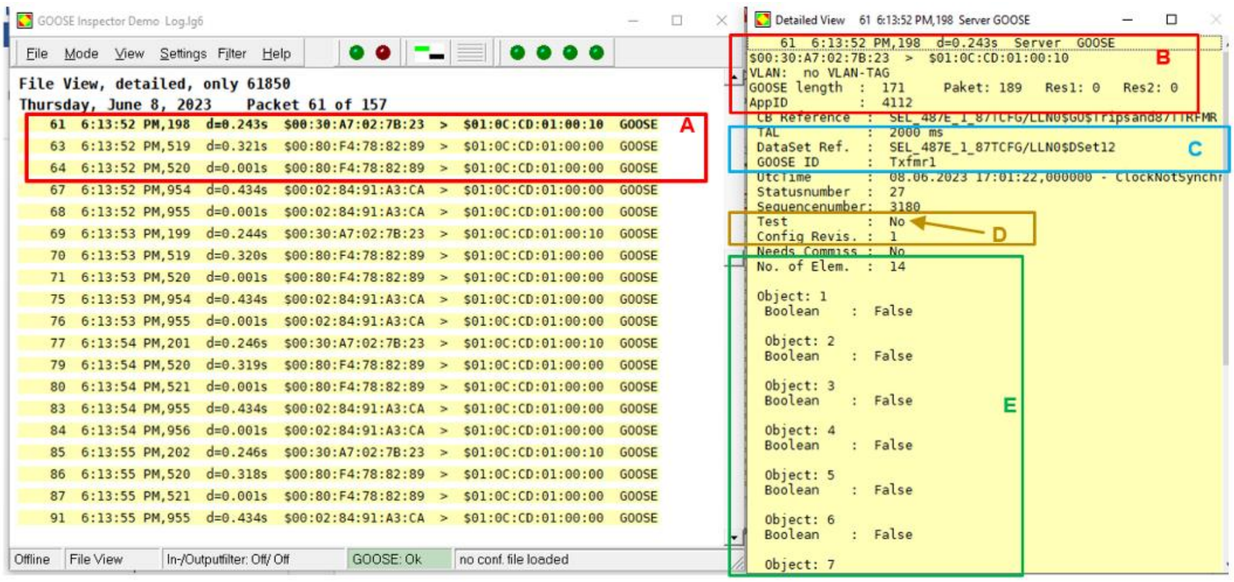

Fig. 10. GOOSE message datasets for SEL-487E during normal operation with no fault present.

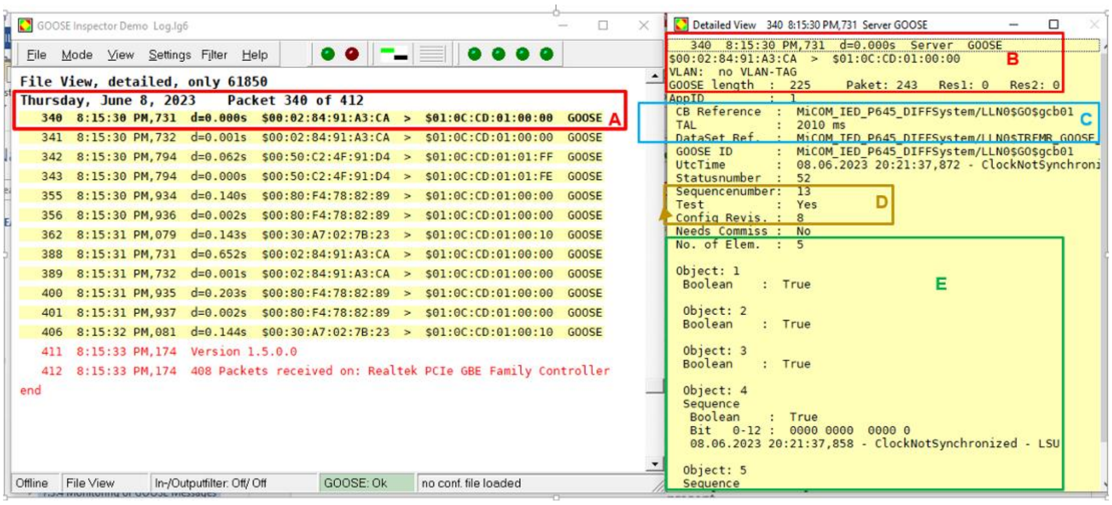

Fig. 11. GOOSE message datasets for MiCOM-P645 during the fault (GOOSE trip).

B. External Fault Simulation Results

This fault is applied on the outside of the PTRF and during this fault, no IED must trip so this means the GOOSE will be not transmitted to any. Fig. 10 shows that the status of the Boolean number is "False" in zone E before the control GOOSE message is published. For SEL-487E the Boolean datasets (indicated as Object in the software) that were set are fourteen as shown in the zone E of Fig. 10.

C. Internal Fault Simulation Results

During this fault, the protection relay must identify the fault and send a trip signal to CB to isolate the affected PTRF using the IEC 61850 GOOSE trip signal. This means the GOOSE will be transmitted to another IED to prove interoperability. Fig. 11 shows that the status of the Boolean number changes to "True" zone E when the GOOSE trip logic is published and the sequence number change. For MiCOM-P645, the Boolean datasets (indicated as Object in the software) that were set are three as shown in zone E of Fig. 11.

Overall, the results of a parallel PTRF current protection system designed for interoperability should demonstrate its ability to detect and respond to faults in a timely and efficient manner, and its ability to communicate with other devices and systems using the GOOSE protocol. This can help to ensure the reliability and stability of the power grid and prevent damage to critical equipment such as transformers.

VII. Discussion

The proposed method is an effective approach for achieving interoperability between multivendor IEDs for protection schemes in IEC 61850 devices using GOOSE messages. The method is based on analysing the communication patterns, data types, and data models used in GOOSE messages. In summary, the development of a parallel PTRF current protection system for interoperability in multi-vendor IEDs can enhance the reliability and stability of power systems, and enable effective coordination of protection functions. This can ultimately assure the safe and effective operation of power systems and increase the quality and continuity of the power supply to customers.

The summary of the achieved testing of the GOOSE Interoperability on the parallel PTRF is as follows:

- The SEL-487E identifies a fault and reacts only if the fault is internal, a GOOSE message is generated and sent to the MiCOM-P645 device; its two LEDs will illuminate, but the MiCOM-P645 relay will not trip.
- The MiCOM-P645 Identifies a fault and reacts only if the fault is internal, a GOOSE message is generated and sent to the SEL-487E device; its two LEDs will illuminate, but the SEL-487E relay will not trip.

Based on the research results, the key terms that hold significance in the investigation of interoperability are as follows:

- The evaluation of IED configuration tools, including their capability to interpret GOOSE messages, detect communication parameter modifications, IED parameters, and data type template parameters. It also verifies the import of GOOSE subscription data from other IEDs in an SCD file.
- The naming conventions and character limits for IED names to ensure interoperability. It emphasizes the importance of extending the character limit for naming conventions and suggests keeping IED names to a maximum of 8 characters or less.
- The importance of the Application Identifier (AppID) in distinguishing and identifying individual applications in GOOSE messages. It should have a unique value across the entire IEC 61850 network and cannot be edited.
- The role of Configuration Revision (ConfRev) tracks changes made to the configuration, ensuring consistency and synchronization among devices or systems. Modifying the dataset reference or contents requires incrementing the Configuration Revision.
- The Substation Configuration Language (SCL) files in achieving interoperability by facilitating the exchange of common substation files among different manufacturers. SCL is an XML-based language used to configure IEC 61850 IEDs,

enabling the exchange of common substation files among different manufacturers. IEC 61850 uses four types of SCL files: CID, ICD, SCD, and SSD.

Overall, the passage addresses various aspects related to interoperability, including IED configuration tools, naming conventions, AppID, ConfRev, and SCL files, emphasizing their significance in achieving seamless communication and system configurations. It's important to note that the specific details and organization of data within a GOOSE message may vary depending on the implementation and configuration of the IEC 61850 system being used.

A. Advantages of GOOSE Messages Over Traditional Methods in Parallel PTRF Scenario

Using GOOSE messages as a new approach in the parallel PTRF scenario offers several advantages compared to traditional methods. Table IV shows the benefits that make GOOSE messages a superior choice, enhancing the efficiency and reliability of parallel PTRF systems.

TABLE IV: ADVANTAGES OF GOOSE MESSAGES OVER TRADITIONAL METHODS IN PARALLEL PTRF SCENARIO

Main Keywords	Description Details
Faster Response Time	GOOSE messages enable near-instantaneous transmission, resulting in quicker communication between parallel PTRFs. This enhances system responsiveness compared to slower traditional communication methods.
Simplicity and Reduced Wiring	GOOSE messages operate over Ethernet networks, eliminating the need for dedicated wiring. This simplifies installation, reduces complexity, lowers costs, and improves system scalability.
Flexibility and Scalability	GOOSE messages support multicast communication, allowing a single message to be received by multiple devices simultaneously. This enables easy scalability without significant configuration changes, unlike traditional approaches that require manual adjustments for each new device.
Enhanced Reliability	GOOSE messages utilize multicast and redundancy mechanisms in Ethernet networks, improving system robustness and reducing communication failures compared to the traditional case with single-point links.
Reduced Configuration Effort	GOOSE messages use standardized data models and communication services defined by the IEC 61850 standard. This simplifies configuration as predefined attributes, types, and formats eliminate the need for custom mapping, saving time and reducing errors.
Enhanced Monitoring and Diagnostics	GOOSE messages carry detailed parameters, alarms, and event information, providing comprehensive monitoring and diagnostics capabilities. This surpasses the limited information available in the traditional case, enabling better analysis and troubleshooting.
Standardized Communication and Interoperability	GOOSE messages adhere to the IEC 61850 standard, ensuring standardized communication and facilitating interoperability between devices from different vendors. This seamless exchange of information is challenging in the traditional case with varying protocols and proprietary implementations

The simulation and testing of the technique in a lab-scale environment with RTDS for real-time simulation in HIL have shown promising results. However, the approach is limited to lab-scale testing and needs to be validated in real-world scenarios. Additionally, there may be other factors that affect interoperability, such as differences in device firmware or software versions. Further research is needed to address these challenges.

The primary focus of the study is on the interoperability of multi-vendor IEDs within a parallel PTRF Differential Protection system. The study extensively explores the implementation of differential current protection in this system, where the IEDs are configured to measure currents and initiate trip commands in the event of a fault. The communication between the IEDs is established using the IEC 61850 standard and GOOSE messages. While the study acknowledges the importance of signalization for other protection functions, such as overvoltage protection, it primarily emphasizes the differential current protection aspect in the parallel PTRF system. Future work is proposed to address the implementation of signalization for various protection functions beyond differential current protection.

VIII. CONCLUSION AND FUTURE WORK

For the HIL RTDS workstation, two different IEDs, and CMS omicron were used for this simulation tested in Lab. Both IEDs were set up to measure currents and send trip commands in the event of a short-circuit fault. The IEDs were set up for GOOSE communication to demonstrate the interoperability of this multi-vendor system of the parallel PTRF. The IEC 61850 standard communication was implemented using GOOSE to exchange information between these two different vendors. And it was proven that these IEDs were compatible with each other because there was no missing information when the MCL/SCL language of the MiCOM-P645 was imported to SEL-487E or vice versa.

These demonstrated the possibility of GOOSE message interoperability in a multi-vendor system.

The development of a parallel PTRF current protection system for interoperability in multi-vendor IEDs is crucial for the reliable and efficient operation of power systems. The use of a protection system designed for interoperability, with the ability to communicate with other devices and systems from different manufacturers, can enable seamless integration of different components in a substation and ensure effective coordination of protection functions.

Future work: Despite the progress achieved to date, there is a great need for further research, particularly in the area of cybersecurity, for parallel PTRF systems using multi-vendor differential protection schemes. It is important to establish security measures that ensure the reliability and resilience of the systems, effectively countering cyber-attacks. This can involve investigating techniques specific to parallel PTRSs and multi-vendor environments to detect and mitigate cyber threats. The development of secure communication protocols and robust authentication and encryption mechanisms specifically addressing the interoperability challenges of multi-vendor IEC 61850 devices in differential protection schemes is highly significant.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Ntokozo Nichol Shangase took the lead in conceptualizing the research, analysing the data, and crafting the manuscript. Mukovhe Ratshitanga and Mkhululi E. S. Mnguni played a critical role in guiding and overseeing the research, providing valuable feedback on the manuscript, and polishing it for submission. All authors gave their final approval of the manuscript.

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