Development of an IEC 61850 Standard-Based Busbar Protection Scheme

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Abstract – *Communication systems of intelligent electronic devices play a huge role in the performance of busbar protection schemes. They determine the effectiveness of the protection scheme in terms of detecting and isolating busbar faults. A literature survey has revealed that multiple proposed algorithms of busbar protection schemes have encountered a common problem of achieving interoperability between intelligent electronic devices produced by different vendors. This affects the performance of busbar protection schemes. This paper focuses on achieving interoperability between IEC 61850 standard-based multi-vendor intelligent electronic devices "SEL and ABB". This improves the performance of busbar protection schemes between multi-vendor devices, and at the same time increases the operational reliability. The investigation is conducted using a current differential busbar protection algorithm. The study is performed by implementing Hardware-In-The-Loop (HIL) testing using a Real-Time Digital Simulator (RTDS). A laboratory-scale test bench is developed to achieve interoperability between the Intelligent Electronic Devices (IEDs) SEL-487B and REF615. A fault condition is simulated, and the behaviour of the protection scheme is analysed. The hardware-in-the-loop results demonstrate the benefit of the proposed technique.*

Keywords: *Busbar differential protection scheme, GOOSE, Hardware-In-the-Loop, IEC 61850, real time digital simulator*

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I. Introduction

Transmission networks consist of large transmission lines with high voltages ranging from 220 to 765 kV [1]. These lines transmit high-voltage electricity to major distribution substations where voltage is stepped down as shown in Fig. 1. The transmission network consists of major components including busbars, transformers, circuit breakers, and overhead lines or cables. These components are essential and costly, hence, they must be protected. Busbars are crucial elements in a power grid, they are used to connect multiple electrical circuits. They have high fault currents, and the damage will be considerable if the fault is left for a long time. Delayed tripping is a significant problem in the coordination of protection schemes because it will result in several lines feeding into the busbar tripping simultaneously at remote ends which will cause partial blackouts. Hence, busbars require a high-speed protection scheme that will respond quickly in detecting and isolating faults.

The various traditional busbar protection techniques were examined in the previous studies. Protection engineers are under a great deal of pressure because of the speed, stability, security, and dependability of digital algorithms for busbar protection schemes. The creation of algorithms that are appropriate for protecting these busbars has received little attention, and the field of digital busbar protection at a distribution level has been given little attention as compared to the transmission level. As a result, busbar faults are cleared by backup relays resulting in longer fault clearing times due to time coordination between distribution feeder relays and transformer relays. This becomes a serious power quality issue because of the lengthy duration of voltage sags. The transmission level was the focus of the majority of busbar protection techniques devised by earlier researchers. This is a result of their high cost and implementation complexity. Another observation is that everyone has been focused on resolving the Current Transformer (CT) saturation problems. No previous algorithm proposed has inherent resilience to CT saturation. The algorithm's stability during fault instances is supplied by using unique techniques such as special circuitry, two algorithms functioning simultaneously, and the selection of a constraint factor. The added circuitry increases the complexity of the protection scheme, which raises the likelihood of improper operations due to component malfunction. The total cost rises as the number of components increases.

Methods based on IEC61850 overcome the primary issue with traditional methodologies, which is CT saturation. However, the new challenges now with the IEC 61850 standard are communication-related problems of multi-vendor Intelligent Electronic Devices (IEDs) [2], including packet loss/delay, malformed packets, and data desynchronization, among others. These issues are significant and deserve consideration in future studies. Hence, this paper is focusing on investigating the communication challenges of different vendor IEDs and coming up with possible solutions to overcome the problem.

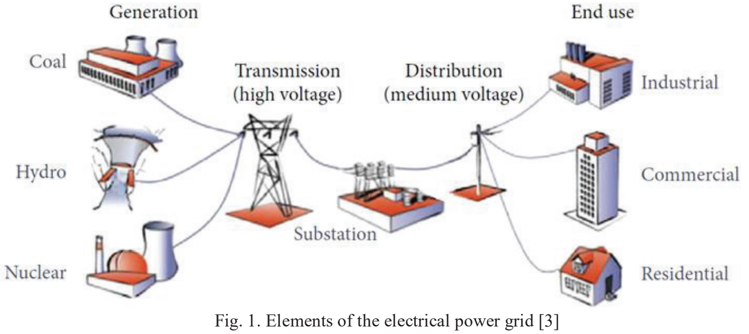

Fig. 1. Elements of the electrical power grid [3]

According to [4], IEC 61850 standard has established two types of communication models based on peer-to-peer communication. These models are Sampled Values (SV) and Generic Object-Oriented Substation Events (GOOSE). Reference [5] stated the benefits of using peer-to-peer communication for bus protection which are:

- GOOSE and SV packet messages flow without delay.
- All sensor signals are sent across the LAN, which can be expanded depending on the topology chosen.
- Inherent supervision features can be utilized to detect impending faults and so take appropriate action to avert potential consequences.
- Can continue to operate until human intervention is arranged

IEC 61850 has superb features such as high priority, tremendous flexibility, and a dependable mechanism for the substation's fast transmission events (trip commands, alarms, or indications) [6]-[7]. In this paper, the investigation is conducted using the GOOSE communication method because of the significant advantages it has. One of them is its flexibility to adapt to topology changes in the substation [8]. Also, its capability of high-speed fault clearing time [9]-[10].

Reference [11], looked at implementing a practical Block Busbar Protection (BBP) scheme for a single busbar scheme and tested it in the laboratory, relying on sampled values and GOOSE to verify its dependability and technological advancement. This experiment was conducted for three scenarios in a simulated substation network relevant to the process plant industry. The software used to perform this experiment were IED Scout, test universe, S1 Agile, Essergy, and Wireshark software. Additionally, this lab-based experiment using IEDs from different vendors evaluated the performance of Ethernet and Fibre Optics-based process bus networks to validate the overall performance of BBP protection. The conclusion was to compare digital and traditional protection systems and provide recommendations for future applications. GOOSE and SV have been observed to provide a better operational solution in digital protection systems due to quicker communication, less wiring, and constant monitoring of IEDs. Digital protection, including BBP schemes, has the advantage of being easily configurable and scalable. These schemes provide faster operation and fewer diagnostic efforts. This was a good investigation conducted by the authors. However, the only problem with this experiment is that simulation studies were not performed using Real-Time Digital Simulator (RTDS) software. RTDS offers one of the most advanced and efficient means available for testing protection systems. The simulation is performed in real-time on a power system model, so protective devices can be connected in open-loop or closed-loop mode. The technique of real-time simulation is useful for validating the protection algorithms and testing simulations on various fault types that may occur in an actual power system network. The author in [4], states that testing numerical relays with a real-time digital simulator (RTDS) improves reliability and achieves maximum performance and functionality when applied to power transmission systems.

Authors of [12], also implemented a busbar protection scheme using the IEC 61850 GOOSE message. They did a comparison between traditional busbar schemes and IEC

61850 GOOSE message-based busbar protection schemes. It was observed that GOOSE-based busbar protection locates busbar faults quickly. This takes roughly 100 milliseconds compared to conventional busbar protection schemes which normally take about 20 seconds. This improves the busbar protection system's reliability and lowers the possibility of widespread failures and power outages. This was also a good investigation by the authors. However, a time delay of 100ms to clear busbar faults is a bit long. By the time the fault is cleared there will already be considerable damage to the equipment. Busbars require a protection scheme with high-speed fault-clearing time as they connect multiple circuits. Author [13], stated that high-speed protection schemes should at least clear faults within 40 milliseconds.

Authors of [14], investigated the usage of the slope degree of the grey incidence analysis model to develop a busbar protection algorithm. A grey-based busbar protection criterion has been created to examine the similarity of the superimposed currents detected by surrounding CTs inside the busbar protection zone. If each of the superimposed currents is the same, it is inferred that the fault is internal; if not, it is concluded that the fault is external. The authors' technique was proven to be able to distinguish between internal and external faults with accuracy in each of the simulated scenarios. Furthermore, the outcomes showed that the protection indices of the suggested scheme, such as security, dependability, sensitivity, and selectivity, are adequate for a variety of fault-related conditions, such as fault type, fault resistance, fault inception angle, simultaneous faults, evolving faults, faults during transformer energization, CT saturation, normal operating switching, and white noise. This was another good investigation conducted by the authors, however, the problem is that simulations were not performed using real-time data as MATLAB software was used for this experiment, and not Real-Time Digital Simulator (RTDS) software. Another observation is that this proposed scheme uses a hardwired approach which is less flexible as compared to IEC 61850 standard-based GOOSE protocol. Furthermore, the proposed scheme relies on additional Current Transformer (CT) circuitry in order to operate adequately. This increases the complexity of the protection scheme, thereby increasing the chance of incorrect operations due to component malfunction.

Authors of [15], presented the design and testing of a digital substation test platform that incorporates devices from different vendors. They observed that connecting many IEDs made by various suppliers and complying with the IEC 61850 standard is not an easy operation. They discovered that differences in device edition, device firmware, and ethernet switch due to its multivendor approach are contributing factors to interoperability issues. As a result, they emphasized the importance of grasping the fundamentals of the IEC 61850 standard, as well as each IED's setup tools in order to minimize IEC 61850 difficulties throughout the protection scheme setting process.

This paper focuses on investigating IEC 61850 standard-based solutions for interoperability issues of multi-vendor IEDs as mentioned by authors [3]-[15] above. It becomes a necessity for enhancement of the performance of protection devices within a busbar protection scheme. Simulation studies will be performed using a Real-Time Digital Simulator (RTDS) based on the reasons stated above. The high-speed GOOSE communication method will be applied for communication between IEDs. This communication mechanism will assist in eliminating the problem of using hardwire for communication. A major focal point of the research is highlighting the significance of achieving seamless compatibility among various devices from different vendors. This interoperability is crucial in ensuring that utilities and municipalities receive optimal value for their investments. By addressing the need for effective interoperability, the study aims to enhance the overall efficiency and cost-effectiveness of the system.

The paper is structured as follows: Section II presents the theoretical background of busbar protection and IEC 61850 communication protocol. Section III presents an implementation of IEC 61850 standard-based multi-vendor IEDs for busbar protection. Section IV presents the development of the lab-scale test bench used for the busbar protection scheme. Section V presents a discussion of the results obtained. Section VI concludes the paper.

II. Theoretical Background of Busbar Protection and IEC 61850 Communication Protocol

It is essential to provide a sensitive, reliable, and high-speed bus protection scheme to minimize damages to the system, and equipment, and to keep the service at maximum capacity. A literature review has shown that the most sensitive and reliable way to protect a station busbar is through differential protection. This paper focuses on busbar protection schemes at the transmission level. The next section describes the currently used busbar protection schemes.

A. Busbar Protection Schemes

Several protection schemes have been devised for busbars including the following [16]:

1. System protection schemes are used to cover busbars.
2. Frame earth protection scheme.
3. Differential protection scheme.
4. Phase comparison protection scheme.
5. Directional blocking protection scheme

In this paper, a detailed theoretical background will be presented only for differential protection schemes.

A-1 Differential protection scheme

This is the most used protection scheme on transmission busbars [17]. This type of protection scheme applies Kirchhoff's current law which states that the current entering a node is exactly equal to the current leaving the node [18]-[19]. The two currents are equal when the system is normal but as soon as the system is abnormal "fault occurring" they become unequal. This research study focuses on the current differential protection schemes as they are ideal, sensitive, and reliable for protecting a transmission busbar.

The basic operation of differential busbar protection is explained in the section below.

- *Operation*

  For the protection scheme to be effective, the protected plant must be situated between two CTs and circuit breakers as seen in Fig. 2 [20]. The CTs terminals are connected such that the currents on their secondary side cancel each other out during external faults and normal loading conditions.

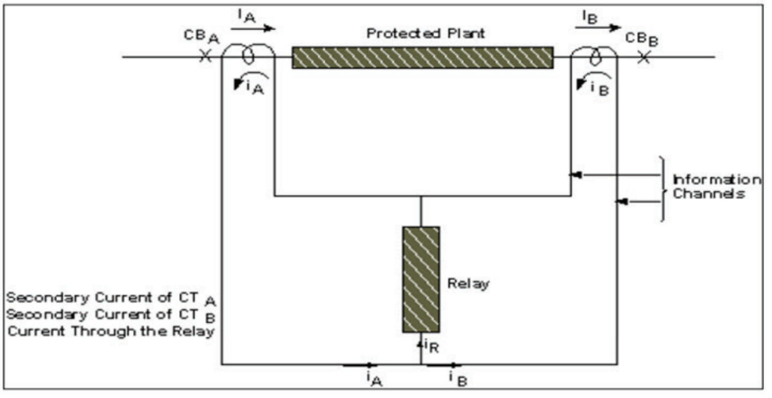

Fig. 2. Schematic wiring diagram of a circulating current differential protection [20]

The current flowing at any time through the relay is $i_R=I_A-I_B$. During external faults and normal loading, assuming the same CT behaviour at both sides, $I_A=I_B$, therefore $i_A=0$. During an internal fault, i_B flows in the reverse direction, and thus $i_R=i_A-(-I_B)=i_A+i_B$. Therefore, a definite number of currents flow through the relay. If this current is above a pre-set value, the relay will trip breakers 'A' and 'B'.

Differential protection has several types as explained in the following sections.

- *High-impedance differential scheme*

  This scheme has been used for more than fifty years due to its robustness, speed, and security. It uses the voltage measured across differential junction points. The used CTs must have low secondary leakage impedance [18]. This arrangement is vital for external faults when the CTs become saturated, and the voltages do not increase above a certain threshold. This is due to the CT having a lower impedance path than the protection relay's input impedance. A disadvantage of this scheme is its requirement for dedicated CTs which incurs additional costs. In the case of a bus fault, a voltage-limiting varistor must be used to absorb energy [21].

- *Low-impedance differential scheme*

  This scheme does not require a dedicated CT. It can handle significant CT saturation caused by external faults and provides fast-tripping [22]. Ever since the introduction of microprocessor-based relays, this protection scheme is becoming increasingly popular with protection engineers due to its advanced algorithms for percent differential protection [21]. Low impedance bus differential protection scheme is selected due to its ability to work well with microprocessor-based relays.

B. IEC 61850 Standard and Interoperability of Intelligent Electronic Devices

The IEC 61850 is a communication standard that was specified by the International Electrotechnical Commission (IEC) in the year 2003 for Substation Automation Systems (SAS) [23]. The standard is regarded as a potential solution to perform effectively in the interchange of information in real time. One major motivation for using the standard is to provide interoperability between IEDs from different vendors [24].

B-1 Overview and scope of IEC 61850

The IEC 61850 standard has 10 main parts as shown in Fig. 3, which deal with different segments of the substation communication network [25].

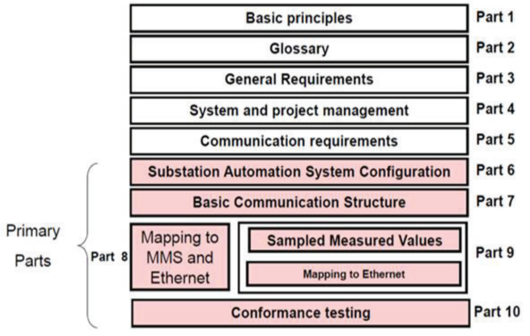

Fig. 3. IEC 61850 standard parts [25]

Parts 1 and 2 are introductory to the standard series and include a glossary of terms and their definition in accordance with power utility automation systems. Part 3 deals with general requirements for substation communication including the following:

- Quality requirements
- Environmental conditions
- Auxiliary services

Part 4 and 5 describe in detail the communication requirements for a specific function. Part 6 focuses on the Substation Configuration Language (SCL); which allows IEDs from multiple vendors to exchange information compatibly. Part 7 is the most important and deals with basic information and communication structures for substation and feeder equipment. Part 7 consists of the following sections [25]-[26]:

- IEC 61850-7-1 principles and models
  This is an introductory part of modelling methods; it also includes information models and communication services used.
- IEC 61850-7-2 Abstract Communication Service Interface (ACSI)
  This part deals with abstract service definitions as well as the methodology of client-server communications. The modelling and exchange of information in IEDs can be done through pre-defined functions.
- IEC 61850-7-3 Common Data Classes (CDCs)
  This part defines CDCs in detail and describes information such as status information, controllable analog set point information, and measured and controllable status information.
- IEC 61850-7-4 Compatible Logical Node (LN) classes and data classes
  This part deals with the definition of LNs classes and data classes. The LNs and Data Objects (DOs) are responsible for developing communication in IEDs and describing them according to their class of origin.

The remainder of the standard parts includes parts 8-1 which focus on mapping of communication services from parts 7-2 except the model for transmission of Sampled Measured Values (SMV). The purpose of parts 9-1 is to map the core elements of the model for the transmission of SVMs. Furthermore, parts 9-2 present the model for the transmission of SVMs as well as the model for GOOSE. Lastly, part 10 defines engineering tools and the conformance testing procedure of devices.

The IEC 61850 communication standard allows status information to be shared over a single ethernet connection for subscription by other field devices such as circuit breakers. To achieve interoperability between multi-vendor IEDs, the next section implements, configures, and tests the IEC 61850 standard Generic Substation Event (GSE) control model Generic Object-Oriented Substation Event (GOOSE), which provides a means of communication within the developed busbar protection scheme.

III. Implementation of IEC 61850 Standard Based Multi-Vendor IEDs for Busbar Protection Scheme

Traditional protection busbar protection schemes use copper hardwiring to transmit signals from relays in the sending end to the relays in the receiving end. However, this type of communication method poses an additional delay when these devices transmit signals to one another. Reference [21] stated that this delay is caused by the on/off switching of auxiliary power to energise the path where the signals must flow from the sending to the receiving device. Based on the above reason, digital protection schemes are recommended due to their high communication speed compared to traditional schemes. The IEC 61850 is the most prominent standard for power systems communications due to its top performance in the exchange of information between Intelligent Electronic Devices (IEDs). In most cases, these protection schemes use IEDs from different vendors. Therefore, there will be a situation where they need to communicate with each other to complete the operation of the scheme. Now, there are interoperability issues when it comes to the coordination of different IEDs. The IEC 61850 standard satisfies a variety of communication requirements of power systems including interoperability between IEDs from different vendors [27].

Therefore, the main objective of this paper is to achieve interoperability between IEDs (SEL-487 and ABB 615) that are used in the proposed busbar protection scheme. This section covers the development of a laboratory-scale test bench of HIL simulation of a proposed differential busbar protection scheme using IEC 61850 standard communication. This is done to investigate the impact of introducing IEC 61850 GOOSE to improve the performance and reliability of the busbar protection scheme. An SEL-487B IED is used as the main differential protection device and ABB REF615 IED as the backup protection device. These two protection devices must be interoperable with each other, meaning they must communicate with each other without any problems. The scheme is designed in a manner that only the main SEL-487 IED operates when busbar internal faults are simulated (when the fault is directly at the busbar), and the backup ABB REF 615 IED must only pick up the fault and not operate, allowing the SEL-487 IED to operate and open the circuit breaker. This is accomplished by configuring the SEL-487 IED to send a blocking signal to the ABB REF 615 IED.

Two test case studies are performed to verify the effectiveness of the scheme. The first case study is when the internal fault is simulated, and the blocking signal is sent from SEL-487B IED to ABB REF615 IED using IEC 61850 GOOSE messaging communication protocol. The second case study includes not sending the blocking signal which will allow the backup ABB REF615 IED to operate during a fault simulation. These experiments are simulated on the nine-bus power network modelled in Real-Time Digital Simulator (RTDS), and a Hardware-in-the-loop is the proposed test bench used to validate the proposed busbar protection scheme.

The following section presents an overview of the RTDS/RSCAD platform, which is used to execute real-time digital simulations of the IEEE nine-bus power system network model.

A. Functions and components of real-time digital simulator (RTDS)

The RTDS is a device used for the modelling and simulation of power system networks in real time to examine the dynamic behaviour of a power system in a transient state [28]-[29]. It is used to evaluate the reliability of protection schemes by simulating various fault scenarios on a power system. Real-time simulation of fault conditions increases the accuracy of protection schemes analysis since simulations are closer to real-world scenarios [4].

The RTDS as shown in Fig. 4 employs a unique hardware design for parallel computing, which is organized into racks [30]. It is made up of several different cards, such as Triple Processor Cards (3PC), Giga Processor Cards (GPC), and Giga-Transceiver Analogue Output (GTAO) cards [31]-[32]. Each processor card of the RTDS hardware consists of digital signal processors (DSP). The analog channel outputs that are provided by the GTAO cards can be utilized to connect external devices and carry-out HIL testing [33].

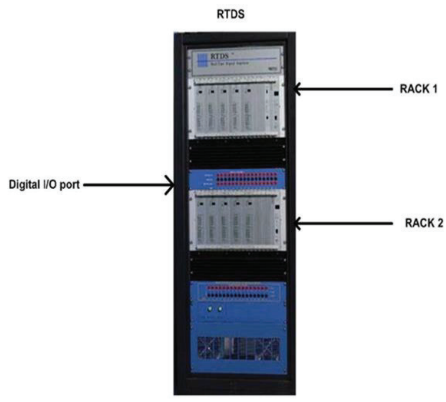

Fig. 4. RTDS hardware [4]

The racks are positioned on the RTDS cubicle as shown in Fig. 4. The feedback signals from IEDs can be connected to the RTDS using the input/output channels on the front panel. The RTDS is used in many applications including the following:

- Runtime simulations
- Closed-loop testing of protective equipment, such as relays
- Closed-loop testing of control equipment such as exciters, voltage regulators, and power system stabilisers
- HIL applications

The next section elaborates on the implementation of the HIL testing using the RTDS and implementing the IEC 61850 standard.

B. Implementation of the Hardware-In-the-Loop testing using IEC 61850 standard

Real-time simulations are important in studying a power system because they provide an accurate estimation of the system's response to transient conditions [34]. They also help in enhancing the quality of the protection system. The most effective testing methods for any protective device are real-time open-loop and closed-loop testing [35]. The following functions can be accomplished using real-time closed-loop testing:

- Communicating with one or more protective relays
- Connecting the power system and the protective relays to determine the exact interaction
- Making the real-time simulation more efficient

HIL testing is one of the most significant approaches that fall under closed-loop and open-loop testing. It is used to analyse the nonlinear and dynamic behaviour of physical devices and to assist in developing and validating a model to govern the physical devices. Complex real-time systems are being developed and tested using the HIL simulation. The major goal of HIL simulations is to give developers a practical platform to create a test bench for putting protective relays to the test in a real-time simulation environment. The control algorithm allows signals to flow via the sensors and actuators in the protective system. The virtual power system is connected to the actual physical devices in a HIL simulation [4].

To achieve the HIL simulation in this paper, SEL-487B and REF615 IEDs are configured and interfaced with RTDS through three omicron amplifier devices, two CMS 156 and one CMS 356.

IV. Development of Lab-Scale Test Bench Used for Busbar Protection Scheme

A lab-scale test bench is developed to achieve interoperability between SEL-487B and REF615 IEDs. This is done to improve the performance of the differential busbar protection scheme by implementing IEC 61850 standard which serves as a communication platform between these two IEDs. A fault condition is simulated, and the behaviour of the protection scheme is analysed. The test bench shown in Fig. 5 is developed to conduct all the experiments of the research project. The next step is to observe how the busbar protection scheme operates when there is a fault using GOOSE communication. Operation of the bus protection scheme adopts GOOSE communication. The fault simulations are done on the 'NorthBus' to evaluate the behaviour of the proposed protection scheme and there was no need to implement the repetition for SouthBus as both bus sections are the same.

A. Test Case 1: GOOSE Blocking Signal Applied

A single phase to ground fault is applied at the 'NorthBus' section of the busbar as shown in Fig. 6. In a case where there was an internal fault in the busbar, both SEL-487B and REF615 IEDs pick up the fault. The REF615 has a time delay before it operates so that it can monitor if the SEL-487B also pick-up and operate. The SEL-487B is the primary protection IED for the busbar and it operates on differential elements. The REF615 is the backup protection IED for the busbar and it operates on an overcurrent element. As soon as SEL-487B picks up a fault in the busbar, it operates instantaneously. Immediately when it operates, it publishes a GOOSE message to the GTNET card in RTDS to open the virtual circuit breakers 'NorthBRKR' and 'Outgoing1_BRKR'. At the same time, it sends a start signal to the binary input of the 'GOOSERCVBIN' function block in PCM600. The GOOSE signal from the binary output of the 'GOOSERCVBIN' function block is sent to the logic gates. The output signal generated from the logic gates is called 'GOOSE_BLOCK' and it is sent to the block input of the 'EFHPTOC1' function block. Consequently, blocking the 'EFHPTOC1' function from operating. Fig. 7 represent the flow chart of the steps that were followed to achieve interoperability between the two IEDs.

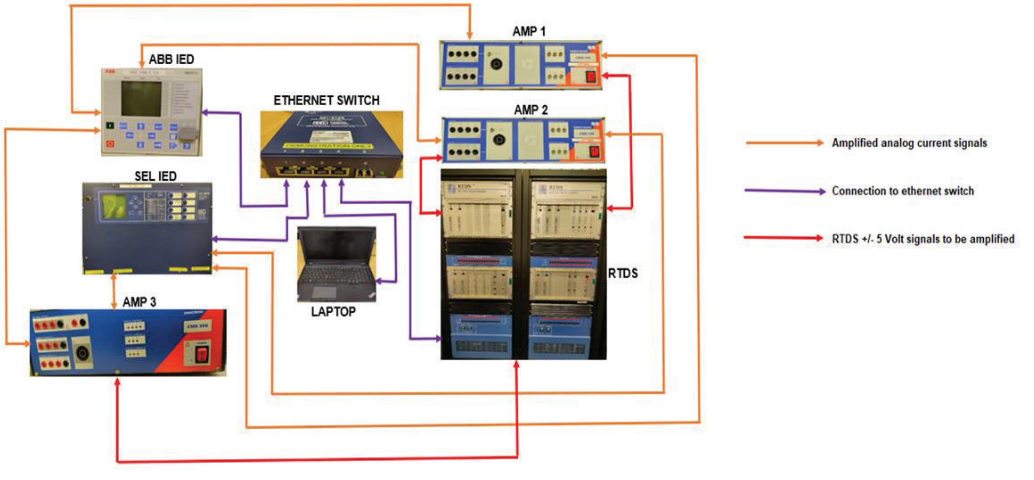

Fig. 5. Developed lab-scale test bench.

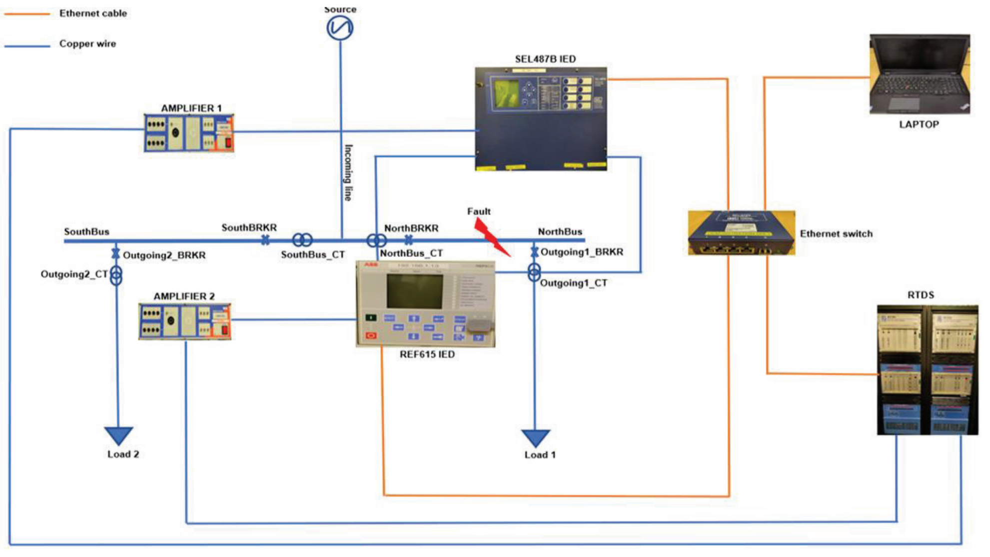

Fig. 6. A single phase to ground fault simulated on the NorthBus section

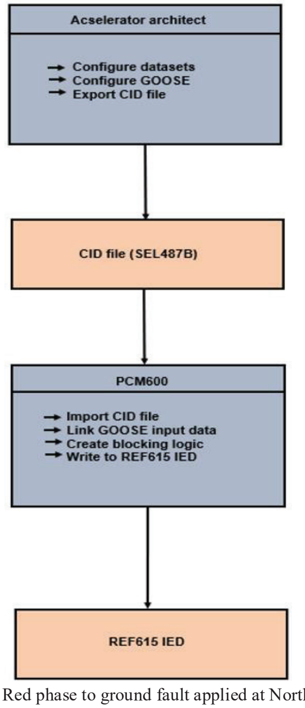

Fig. 7. Red phase to ground fault applied at NorthBus.

The results for the test case above are shown in the following section.

B. Results of the Practical Experiment in Test Case Study 1

A busbar internal fault is simulated at the NorthBus section using RTDS software. A single phase to ground fault is simulated on the red phase and initiated after 2.69 seconds as shown in Fig. 8. The fault is cleared at 2.73 seconds as shown in Fig. 9 and Fig. 10. The total fault duration is 0.04 seconds (40 milliseconds), it is cleared after this time and the busbar is isolated from the rest of the system. The response of the IED is quick to isolate the fault and operated as expected. Some of the surrounding contributions to delay in fault isolation include the speed of the breakers and the microprocessors of the IEDs. The results presented in Fig. 8, Fig. 9, and Fig. 10 are obtained through RTDS runtime when the power system simulation is in progress.

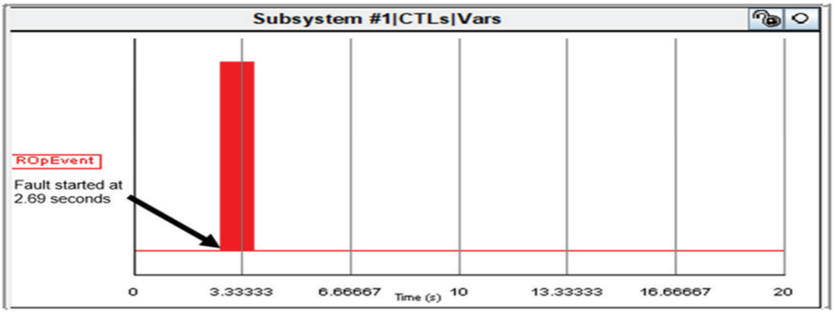

Fig. 8. Red phase to ground fault applied at NorthBus

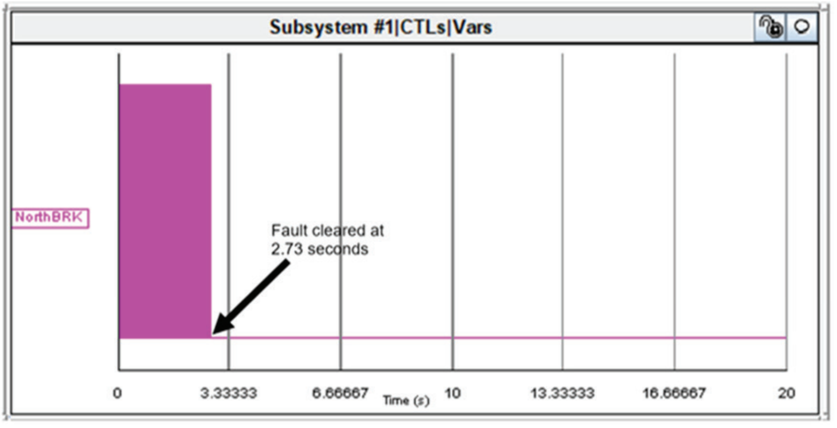

Fig. 9. NorthBRK receives a GOOSE trip signal for R-G fault at NorthBus.

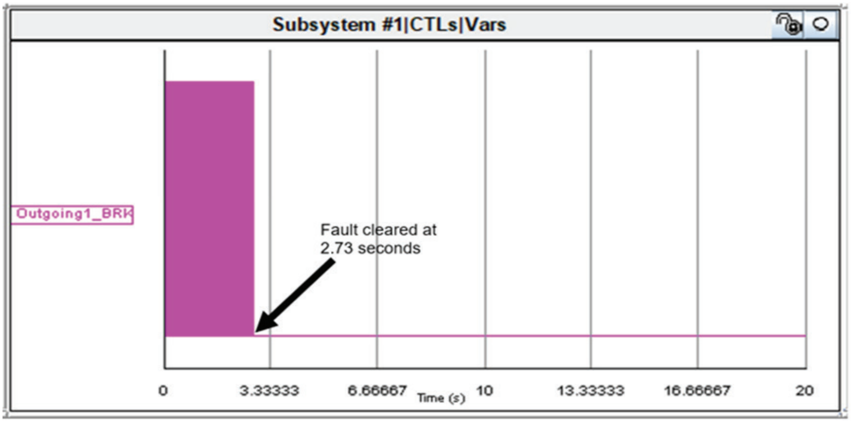

Fig.10. Outgoing1_BRK receives a GOOSE trip signal for R-G fault at NorthBus

It is also observed from the synchrowave results in Fig. 11 that the fault is in the red phase. This is confirmed by the analog signals as the current on the red phase started to rise instantaneously after the fault inception. The magnitude of current in the yellow and blue phases remained the same after initiating the fault to prove that they are not affected by the fault. It is also seen in the digital signals in Fig. 11 that the IED (SEL-487B) picks up the fault as shown by '87BTR' indicated by the red arrow, and trips instantaneously as shown by the 'TRIP01' signal shown by the green arrow. As soon as it picks up the fault, it uses that pick-up signal to send a GOOSE blocking message to REF615 IED.

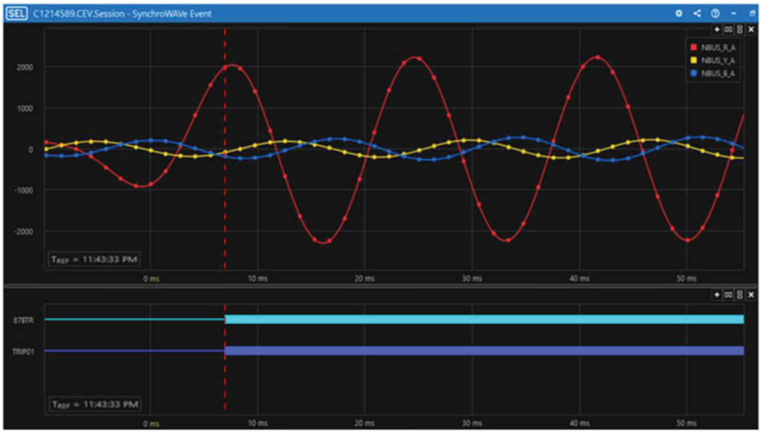

Fig.11. SEL-487B IED trips instantaneously

The analogy signals in Fig. 12 show that the three-phase system is unbalanced. The red phase current has a much higher current as compared to the yellow and blue phases. This is also confirmed by the vector diagrams in Fig. 13 as the current magnitude on the red phase (IR) is 1330.675 A, 103.853 A for the yellow phase (IY), and 138.067 A for the blue phase (IB). This proves that the fault is in the red phase. Under normal circumstances, the current magnitude on the red phase (IR) is almost the same as that of yellow phase (IY) and blue phase (IB), refer to the analog signals of Fig. 12. Furthermore, the light blue digital signal 'EFHPTOC1_START' indicated by the blue arrow in Fig. 12 also confirms that REF615 backup protection IED does see the fault. However, REF615 IED does not operate for the fault. This is because it has already received a GOOSE blocking signal sent by the main protection IED (SEL487B). This is confirmed by the 'GOOSE_BLOCK' digital signal in purple, also indicated by the orange arrow.

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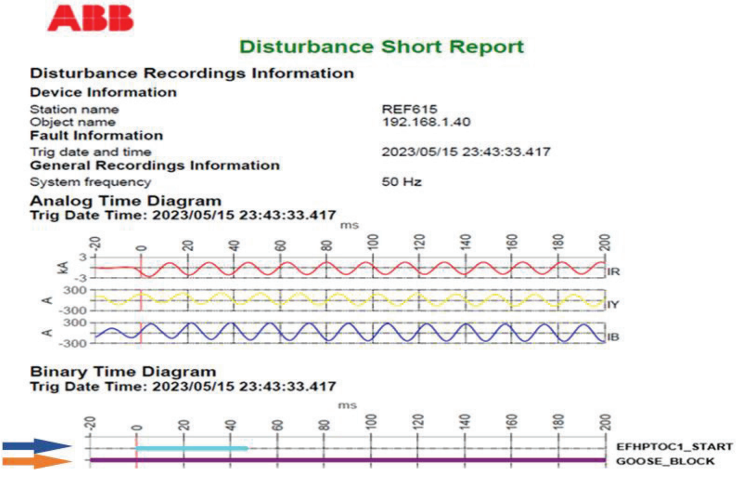

Fig. 12. REF615 IED blocked using GOOSE

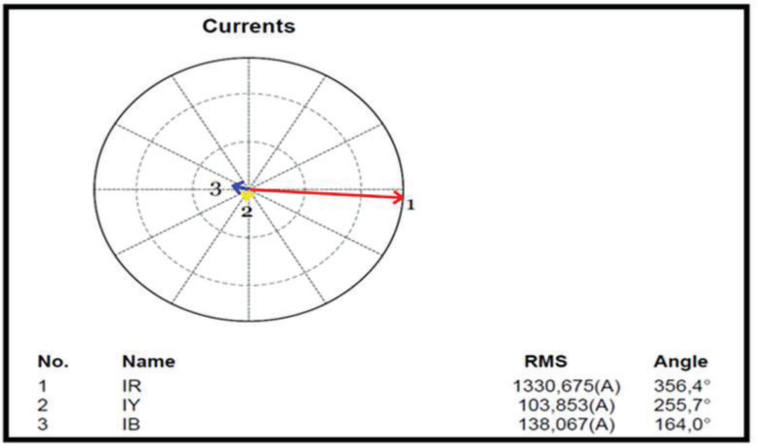

Fig. 13. Vector diagrams for REF615 IED

In test case 2 below, a redundant system is created as components inside the IEDs are prone to fail due to various reasons. In a situation like that, a backup protection IED is expected to operate thereby protecting the busbar network. SEL487B IED is disconnected from the network in the following test case. This is done to assess if the backup protection IED will be able to protect the busbar in a case where the main protection IED is faulty. Furthermore, this scenario is created to prove that the backup protection IED will operate when the GOOSE blocking signal is not applied.

C. *Test Case 2: No GOOSE Blocking Signal Applied*

In this test case, the single phase to ground fault is simulated on the red phase at the NorthBus section with SEL-487B disconnected. The results are analysed in the following section below.

D. *Results for a Practical Experiment in Test Case 2*

It is observed from the analog signals in Fig. 14 that the backup protection IED does pick up the fault on the red phase. This is observed in the current magnitude of the red phase which is much higher as compared to the other two phases (yellow and blue). This is also confirmed in the vector diagrams in Fig. 15 as the magnitude of the current in the red phase (IR) is 1538.172 A, 128.415 A for the yellow phase (IY), and 152.243 A for the blue phase (IB). Additionally, the 'EFHPTOC1_START' light blue digital signal indicated by the purple arrow in Fig. 13 confirms that the backup IED does see the fault. This time REF615 IED does operate for the fault as confirmed by the pink digital signal 'EFHPTOC1_OPERATE, also indicated by the orange arrow. It operates instantaneously after the IED has picked up the fault.

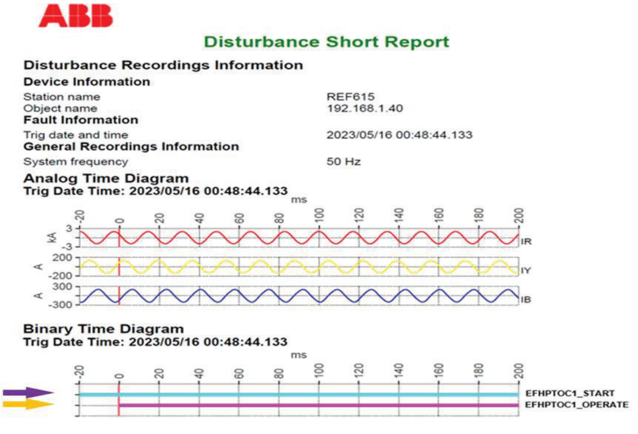

Fig. 14. REF615 IED without GOOSE blocking

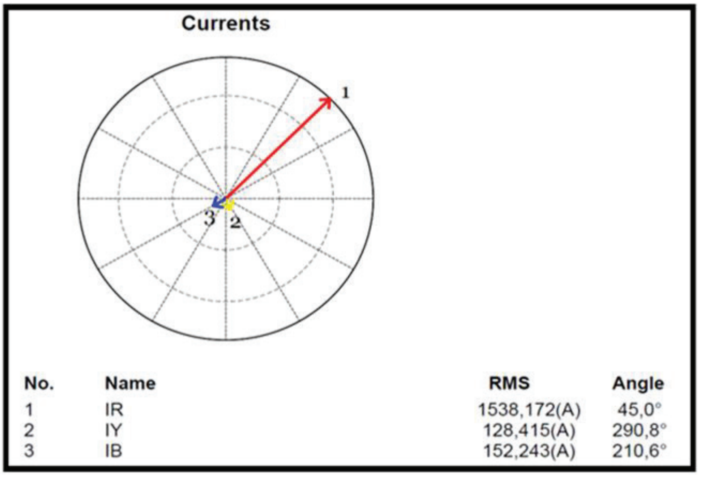

Fig. 15. Vector diagrams for REF615 IED

V. Discussion of Results

The performance of the differential busbar protection scheme was analysed for internal faults using IEC 61850 GOOSE-based blocking scheme. An IEEE nine-bus system was modelled in the RSCAD software environment. The HIL testing was developed using RTDS, SEL-487B, and REF615 IEDs. The test was conducted using two case studies. The first case study is when the GOOSE blocking scheme is applied. The second case study is when the GOOSE blocking scheme is not applied for a case where the main protection IED (SEL487B) is malfunctioning. The results obtained prove the efficacy of using of IEC 61850 standard as the interoperability between SEL-487B and REF615 IEDs is achieved. This is observed when REF615 IED is blocked from operating through the GOOSE blocking signal sent by SEL-487B IED. The results confirmed what the authors were saying in the reviewed literature that the IEC 61850 standard is the solution for the interoperability of multi-vendor IEDs. On the other hand, it means that the communication system between protection devices is configured successfully as the desired results are obtained. Moreover, the results prove that the IEC 61850 standard provides a solid solution for the interoperability challenge via its information models and communication services. As observed from the results, interoperability is achieved through IEC 61850 GOOSE messaging communication protocol.

VI. Conclusion

This paper discussed the implementation of hardware in the loop using RTDS. GOOSE configuration of IEDs was done successfully using AcSELerator Architect and PCM600 software. Interoperability between two multi-vendor IEDS was also presented in this paper. This was achieved through the GOOSE blocking method using the IEC61850 standard. Busbar internal faults were simulated and results were obtained and analysed. GOOSE communication using a LAN cable was proven to be successful as faults were cleared within 40 milliseconds as shown in Table I.

TABLE I
BUSBAR INTERNAL FAULT

Component	Fault Type	Circuit breaker fault clearance time in milliseconds (ms)
Busbar	Red phase to Ground (R-G)	40

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Conflict of Interest

The authors declare no conflict of interest in the publication process of the research article.

Author Contributions

Luntu Siphelo Mgaga conceptualized the research, performed analysis, and wrote the paper. Mkhululi E.S. Mnguni supervised the research, and reviewed, and edited the paper.

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