Cape Peninsula
University of Technology

MULTI-VENDOR BASED BUSBAR PROTECTION SCHEME FOR TRANSMISSION NETWORKS

by

LUNTU SIPHELO MGAGA

Dissertation submitted in partial fulfilment of the requirements for the degree

Master of Engineering: Electrical Engineering (Smart Grid)

in the Faculty of Engineering and the Built Enviornment

at the Cape Peninsula University of Technology

Supervisor: Dr M. Mnguni

Bellville
September 2023

DECLARATION

I, Luntu Siphelo Mgaga, declare that the contents of this dissertation represent my own unaided work, and that the thesis/dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

L. Smgaga

20/09/2023

Signed **Date**

ABSTRACT

Busbars are the common points of connection for all incoming and outgoing feeders, thus, busbars are critical components of transmission networks. The operation of busbars is affected by faults occurring on the busbar or faults that are carried through from the incoming and outgoing feeders. A fault in the incoming or outgoing feeders of a busbar can result in the system becoming unstable or experiencing a blackout, which requires a fast-operating protection scheme to quickly isolate the faulty section. This will minimize damage to faulty equipment and prevent interruption of supply in other healthy sections of the network. A busbar protection scheme must meet the basic protection requirements of the electrical system. The requirements include speed to detect and isolate faults, reliability to ensure the security of supply, sensitivity in detecting faults, and the scheme must always ensure that the power system is stable. These requirements are necessary for detecting busbar faults early, and to isolate the faulty equipment. 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 dissertation focuses on achieving interoperability between multi-vendor intelligent electronic devices “SEL and ABB”. The research study aimed to improve the performance of busbar protection schemes by introducing the IEC 61850 standard to enhance the communication system performance between the devices to reduce the fault clearance time. The research study was conducted by implementing hardware-in-the-loop (HIL) testing using a real-time digital simulator (RTDS). A laboratory-scale test bench was developed to achieve interoperability between the IEDs SEL-487B and REF615. A fault condition was simulated, and the behaviour of the protection scheme was analysed.

Keywords: IEC 61850, GOOSE, Intelligent Electronic Devices, Interoperability, Busbar differential protection scheme, Transmission, Protection relays, Real-Time Digital Simulator, Hardware-In-the-Loop.

ACKNOWLEDGEMENTS

I wish to thank:

- Dr. M.E.S Mnguni, my supervisor for the support.
- Dr. Senthil Krishnamurthy for his input
- Everyone at the Center for Substation Automation and Energy Management Systems (CSAEMS) for their inspiration.
- All my colleagues at work for their support

DEDICATION

I dedicate this dissertation to my entire family.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Term	
Busbar	A common point of connection in transmission and distribution network substations
Protection system	It is a system that safeguards equipment when there is an electrical or mechanical fault by isolating the faulty part from the healthy system.
Numerical relay	A relay with the ability to acquire instantaneous voltage and/or current samples and process them using a mathematical algorithm.
Transmission	Electricity conveyance through a transmission network
Distribution	Electricity conveyance through a distribution network
IEC 61850	International standard for substation communication and modelling
Interoperability	The ability for two or more intelligent electronic devices to communicate information and utilise that information for the proper performance of specific functions, regardless of the vendor.
Current transformer	A device that transforms the magnitude of current from one magnitude to another
Voltage transformer	A device that transforms the magnitude of voltage from one magnitude to another
GOOSE	Is a high-performance multi-cast messaging service utilized for inter-IED communications and substation event transmission.
Substation configuration description language	Is a description language for IED-related communication in electrical substations.
Peer-to-peer communication	Each layer of the Open System Interconnection reference model communicates with its peer on the destination side.

ABBREVIATIONS AND ACRONYMS

3PC	Triple Processor Cards
ACSI	Abstract Communication Service Interface
Amps	Amperes
ANSI	American National Standards Institute
CDC	Common Data Classes
CID	Configured IED Description
CPU	Central Processing Unit
CT	Current Transformer
D/A	Digital to Analog
DA	Data Attributes
DNP3	Distributed Network Protocol
DO	Data Object
DSP	Digital Signal Processors
GOOSE	Generic Object-Oriented Substation Event
GPC	Giga Processor Cards
GSSE	Generic Substation Status Event
GTAO	Giga-Transceiver Analogue Output
GTNET	Giga-Transceiver Network
GUI	Graphical User Interface
HIL	Hardware-In-the-Loop
HV	High Voltage
ICD	IED Capability Description
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Devices
IEEE	Institute of Electrical and Electronics Engineers
I/O	Input/Output
IP	Internet Protocol
kV	kilo Volts
LAN	Local Area Network
LD	Logical Device
LN	Logical Node
MMS	Manufacturing Message Specifications
OSI	Open Systems Interconnect
PD	Physical Device

pu	per unit
RSCAD	Real-time Simulation Computer-Aided Design
RTDS	Real-Time Digital Simulator
SAS	Substation Automation System
SCADA	Supervisory Control and Data Acquisition
SCD	Substation Configuration Description
SCL	Substation Configuration Language
SCSM	Specific Communication Service Mapping
SEL	Schweitzer Engineering Laboratories
SMV	Sampled Measure Value
SNTP	Simple Network Time Protocol
SSD	System Specification Description
TCP	Transmission Control Protocol
UCA	Utility Communication Architecture
VT	Voltage Transformer
VMD	Virtual Manufacturing Device
XML	Extensible Markup Language

CHAPTER ONE:
INTRODUCTION

1.1 Introduction

Transmission networks consist of large transmission lines with high voltages ranging from 765, 400, 275, and 220 kilo Volts (kV) (Smith, 1998). These lines transmit high-voltage electricity to major distribution substations where voltage is stepped down as shown in figure 1.1 below. 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.

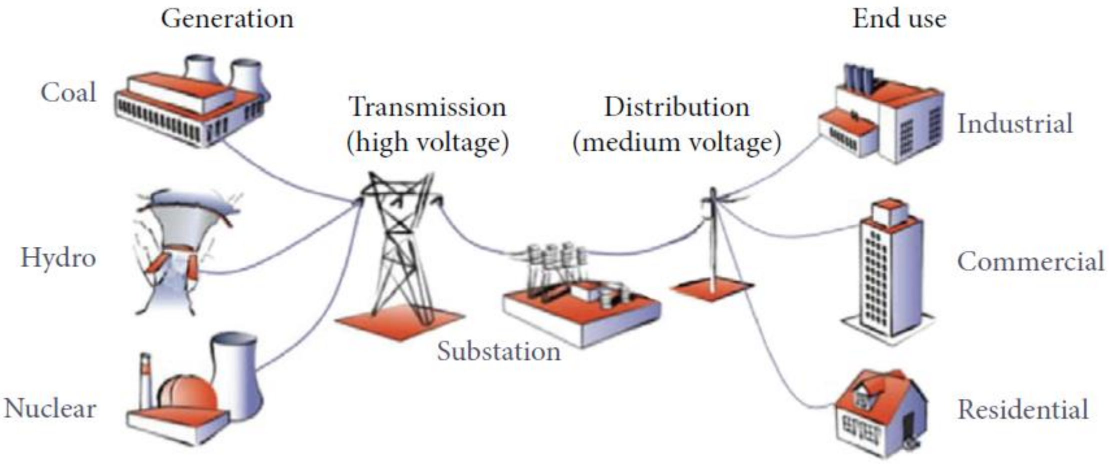


Figure 1. 1: **Elements of electrical power grid** (Smith, 1998)

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.

This chapter elaborates on the power system components, emphasising the importance of busbars in a power grid. The chapter presents an awareness of the problem in section 1.2, the problem statement in 1.3, the research aims and objectives in 1.4, the hypothesis in 1.5, the delimitation of the research in 1.6, motivation of the research project in 1.7, assumptions in 1.8, research methodology in 1.9, and section 1.10 concludes the chapter.

1.2 Awareness of the problem

Busbars are common points of connection to many electrical circuits as shown in figure 1.2 below. A single fault in a busbar can cause an interruption of supply to many circuits which can be a threat to system stability. The fault currents are high at a busbar and can cause severe damage to the network components if the fault is prolonged. Instant clearance is needed when there is a fault in the busbar which can be achieved via a reliable busbar protection scheme.

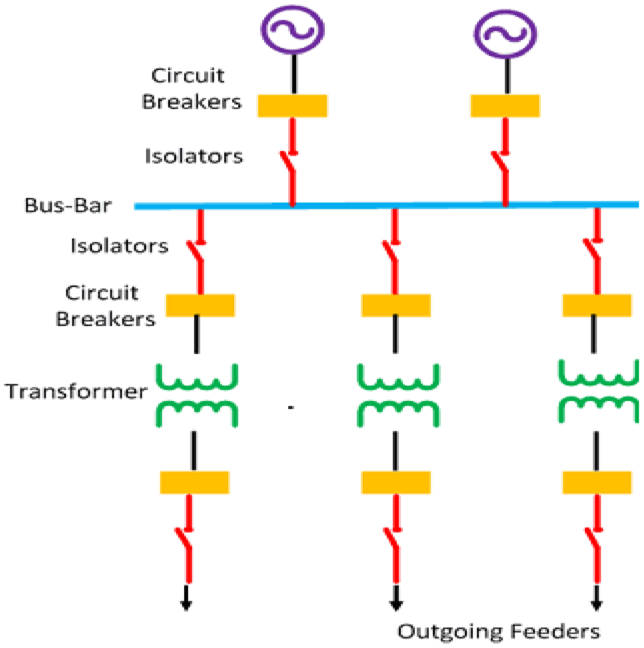


Figure 1. 2: **Single Busbar Arrangement** (Chowdhury, 2015)

For the busbar protection scheme to be reliable, it must meet the following basic requirements of an electrical protection system (Smith, 1998):

- Selection

This is the most important requirement of the protection scheme. Its function is to pinpoint the fault and disconnect only the faulty section, leaving the rest of the system intact. Correct fault selection keeps the system stable.

- Speed

A protection scheme must operate as quickly as possible to limit damage following a fault. The damage results naturally from the heat released by the fault current. Sometimes it is necessary to delay the tripping of a relay via a timer to obtain selection or discrimination.

- Sensitivity

  This is a quality that a protection scheme should have to detect small and large faults. The protection scheme must be very sensitive in detecting and isolating faulty parts.

- Reliability

  Protection must operate whenever required. It is equally important that it does not operate when there is no fault. The protection scheme must be reliable and ensure the security of the supply as well as the network equipment.

- Stability

  This is the potentiality of the protection scheme to not operate when faults occur outside the protected zone. Strictly speaking, this is a characteristic of unit systems since zones are not clearly defined in non-unit schemes.

A busbar protection scheme that is well-designed should be capable of protecting the entire busbar against all forms of failures. Line and distance protection can be employed as busbar protection, however, it is ineffective in the event of a fault in the busbar zone as the fault is cleared with a time delay. A protection scheme that malfunctions or operates slowly in the event of an internal fault may have fatal repercussions that could lead to the entire busbar getting damaged. Therefore, there is a need for dedicated busbar protection schemes that are fast against internal faults and stable against external faults (Mnguni, 2014).

1.3 Problem statement

Most busbars don’t have dedicated busbar protection schemes. In most cases, some of the dedicated busbar protection schemes that were utilised in the past used Intelligent Electronic Devices (IEDs) of the same vendor. However, they have limited functions to operate the scheme ideally or perfectly. In that case, it becomes a need to have more than one vendor of IEDs coordinate with each other for that protection scheme. The problem in utilising more than one vendor in a protection scheme is interoperability because these different vendor IEDs struggle to communicate with each other. Furthermore, interoperability between IEDs from different vendors could result in a busbar protection scheme delaying operating when clearing faults. This situation could lead to a power system becoming unstable or experiencing blackouts. By introducing an IEC 61850 standard, the problem of interoperability is accomplished, also the copper wire for communication is reduced. The problem with the copper wire is that it needs some auxiliary power to energise where the signal is going to flow when it comes to coordination, this creates a time delay in clearing faults. The IEC 61850 is a prominent standard that was specified to provide information modelling of substation automation functions. Subsequently, the standard is widely utilised to design the existing busbar protection schemes.

1.4 Research aim and objectives

1.4.1 Aim:

This research project aimed to develop a busbar protection scheme for a transmission network based on IEC 61850 standard to investigate the solutions for interoperability problems between IEDs from different vendors.

1.4.2 Objectives:

The aim of the research project mentioned above was accomplished through the following objectives:

- Literature review on the algorithms of the busbar protection schemes, IEC 61850 standard, and its solutions for achieving interoperability between multi-vendor IEDs.
- Overview of the theory of busbar protection schemes, and the communication used between the relays.
- Development of a transmission network model on the RTDS platform to be used as a case study.
- Development and implementation of a busbar protection scheme in the transmission network model on the RSCAD software environment.
- Investigation of the performance of the proposed protection scheme for various types of faults.
- Development of a hardware-in-the-loop (HIL) test bench to evaluate the proposed busbar protection scheme in RTDS using IEDs from different vendors.
- Investigation and implementation of the proposed protection scheme based on the interoperability between the IEDs.
- Development and implementation of solutions to enhance communications between the IEDs.

1.5 Hypothesis

A good dedicated busbar protection scheme should improve the stability and reliability of the transmission network. The communication between different IEDs should be improved when implementing IEC 61850 standard-based busbar protection scheme.

1.6 Delimitation of the research

The thesis focuses on the application of the IEC 61850 standard-based busbar protection schemes and the analysis of interoperability problems between IEDs from different vendors. Differential protection was studied in detail as it is the scheme of interest in this research project. Investigation of the performance of the busbar protection scheme for various types of faults is performed. The following hardware and software were used in the research test bench implementation:

- Omicron Test Universe software
- GOOSE Inspector Demo software
- DIgSILENT PowerFactory simulation software
- RTDS/RSCAD
- ABB software “PCM 600”
- SEL software “AcSELerator QuickSet and Architect”

1.7 Motivation of the research project

Transmission networks are crucial to the power grid. They supply electrical energy to distribution substations, which is where the voltage is stepped down to suit customer loads. Interruption of supply from the transmission side can cause the network to be unstable which will lead to blackouts. Busbars are essential apparatuses in the transmission network as they connect all the incoming and outgoing feeders. Hence, the dedicated protection of busbars needs high reliability and stability.

A literature survey has shown that IEC 61850-based busbar protection schemes were proposed. Their common objective was to solve the problem of interoperability between IEDs from different vendors. Interoperability affects the communication between protection devices which in turn negatively impacts the speed of the protection system. Therefore, interoperability is a significant challenge in the deployment of successful protection systems. This has motivated the decision to take on this research project to address this vital issue in power grids. The research project focuses on developing an improved modern busbar protection scheme. It also investigates interoperability between IEDs from different manufacturers and proposes solutions for improving communication between protection devices.

1.8 Assumptions

A generic Institute of Electrical and Electronics Engineers (IEEE) nine-bus system network model was used in this research project. Modifications and changes performed on the network model were carried out to achieve the objectives of the project. DIgSILENT power factory software will be used to simulate the power flow of the network. The RTDS was used to simulate the proposed busbar protection scheme in real-time. The main busbar protection relay should operate faster than the backup overcurrent protection relay. The Generic Object-Oriented Substation Event (GOOSE) messaging communication should be faster than the hardwiring communication system.

1.9 Research methodology

The focus of the thesis was to develop an IEC 61850 standard-based busbar protection scheme used at the transmission networks. The focus was to investigate the IEC 61850 standard-based solutions for interoperability problems between multi-vendor IEDs. In addition, solutions for improving the communication between the devices are proposed within the research project. The research methods used for achieving the goals of the project are as follows.

1.9.1 Literature review

A literature review is conducted on the algorithms of busbar protection schemes, the IEC 61850 standard, and the problems and solutions for achieving interoperability between multi-vendor IEDs. Information is gathered from several sources including but not limited to IEEE journals, engineering books, and the Internet.

1.9.2 Methods for protection

Differential protection is suitable for protecting a station bus as it is the ideal sensitive and reliable method. During normal conditions, the total of all quantified currents entering and leaving the bus should be zero not unless there is a fault within the protected zone. Therefore, High Voltage (HV) networks require fast fault-clearing times, and the busbar protection scheme is used to perform this function by tripping an HV circuit breaker. The type of protection used in this project is the current differential protection scheme, this principle has been used for years for the protection of transmission busbars against internal and external faults.

1.9.3 Simulation

Simulation and analysis of the current differential busbar protection scheme are done using both DIgSILENT PowerFactory software and RTDS/RSCAD platform. Configuration of protection files is done using AcSELerator QuickSet and PCM600 software. IEC 61850 GOOSE configuration is done using AcSELerator Architect.

1.9.4 Documentation methodology

The dissertation is divided into six chapters and one appendix as follows:
Chapter one: The research project is introduced in this chapter, and problem awareness and motivation of the research project are explained.

- Chapter Two: A literature review of the existing busbar protection schemes and interoperability of multi-vendor IEDs used in power system networks is presented in this chapter. Also, generations of protection relays are explained in this chapter.
- Chapter Three: A detailed theory of busbar protection schemes which are used in transmission networks, is delivered in this chapter.
- Chapter Four: Describes the load flow studies and contingency analysis of the modelled network.
- Chapter Five: The importance of the IEC 61850 standard and the interoperability between multi-vendor IEDs, Design, and implementation of the proposed protection scheme.
- Chapter Six: presents the conclusion and recommendations.
- Appendix: comprises all the figures and results which are not included in the body of this dissertation.

1.10 Conclusion

The significance of having a proper busbar protection scheme in a power system network is justified in this chapter. The software to be used to accomplish this research project is stated. The awareness of the problem, problem statement, research aim, and objectives are described in this chapter. Also included in this chapter are the hypothesis, delimitation of the research, and motivation of the research project. Lastly, this chapter explains the assumptions and the research methodology used to achieve the objectives of the research study.

The literature review of the existing busbar protection schemes used in the network is presented in the next chapter. The information is collected from conference papers, journals, and books.

CHAPTER TWO:
LITERATURE REVIEW

2.1 Introduction

The main purpose of any power system is that it should function with the highest reliability and availability as the customers expect the supply to be available continuously. A busbar is one of the most crucial elements in a power grid. It has high fault currents, and it interconnects many transmission lines and a variety of other elements. Faults on the busbar occur due to operating errors such as leaving exposed earthing cables on equipment after maintenance which creates life-threatening conditions. Therefore, the safety of personnel highly depends on the speed of the protection system.

Due to the above-mentioned facts, busbar protection requires high reliability and stability. The protection scheme needs to respond quickly to internal as well as external faults, and any maloperation of the scheme can cause a complete blackout in the power system (Mohan & Chatterjee, 2010). Protection requirements include selection, speed, sensitivity, reliability, and stability to achieve the above-mentioned tasks.

According to the literature reviewed, factors that complicate the busbar protection scheme are different busbar arrangements, current transformer saturation, speed, and stability. Researchers have made progress in designing suitable algorithms for use in microprocessor-based relays using digital technology, and these developed algorithms are based on the same principles as their equivalent electromechanical relays. Other parts of the power system have been gradually improved using digital approaches, while busbar protection has received almost no attention (Mnguni, 2014).

This chapter provides a survey of the existing literature on busbar protection in power systems. It examines and analyses various methods that have been developed and used to improve busbar protection. The aim is to look at the advantages and disadvantages of different protection schemes to develop a high-precision busbar protection scheme.

The chapter is constructed as follows, section 2.2 analyses the literature reviewed on existing busbar protection schemes from previous researchers. A discussion of reviewed literature is presented in section 2.3. Section 2.3 presents the conclusion of the chapter.

2.2 Reviewed literature on existing papers for busbar protection schemes

A literature review was conducted using the following points:

- Different protection schemes applied on busbars which were:
    a. System protection schemes used to protect busbars.
    b. Frame earth protection scheme.
    c. Differential protection scheme.
    d. Phase comparison protection scheme.
    e. Directional blocking protection scheme.

- Communication protocols used for communication between protection devices are also explained in detail in chapter 3.
- Conventional busbar protection using traditional protection devices.
- Use of IEC 61850 standard-based IEDs
- Substation communication history

Figure 2.1 below shows a graph of the number of publications reviewed from 1990 to 2022. These publications were chosen based on their relevance to power system protection, with an emphasis on the history of busbar protection techniques.

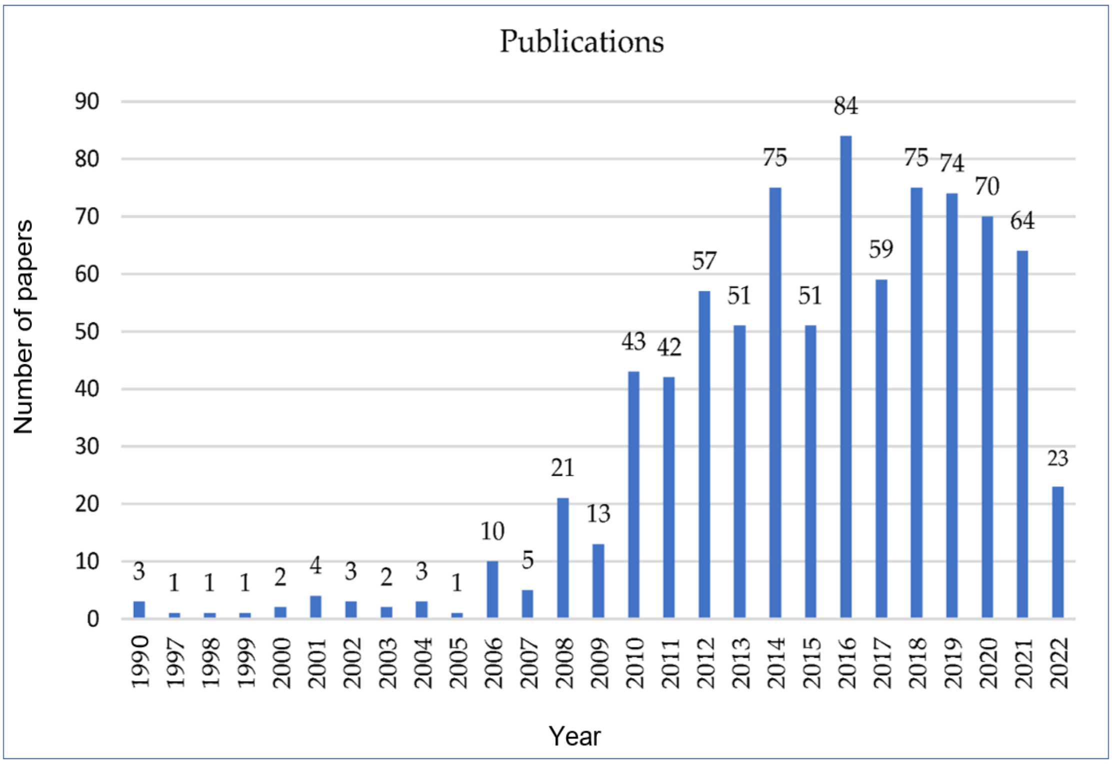


Figure 2.1: Busbar protection schemes

According to the graph above, from 1990 to December 2022, eight hundred and thirty-eight IEEE publications focusing on the area of busbar protection were published. The graph also illustrates that the number of articles published on busbar protection schemes virtually reaches its peak in the years 2014, 2016, 2018, 2019, and 2020. In 2010, there was an increase in the topic of implementing digital protection for busbars. As time passed, researchers remained focused on digital protection schemes for transmission busbars. Hence this thesis is concerned with enhancing the busbar protection scheme at the transmission level. The following important terms were used:

Busbar protection, differential protection, differential relay, differential protection algorithm, percentage differential, conventional bus protection, traditional busbar scheme, high impedance scheme, low impedance scheme, electromechanical schemes, digital protection schemes, IEC 61850 standard, IEC 61850 bus protection, GOOSE message, interoperability, Intelligent Electronic Devices, interlocking and blocking schemes.

2.2.1 Review and analysis of differential busbar protection schemes

(Namdari et al., 2005) proposed a Power Differential Protection (PDP) that can be used in Wide Area Protection (WAP). This PDP technique operated effectively for all types of system faults, including bad data caused by Current Transformer (CT) saturation. The main objective of this scheme is to locate and isolate the faulty sections utilising methods based on differential protection. The key disadvantage of PDP is that it cannot distinguish the faulted phase; thus, if single pole tripping is required, it cannot be utilized for primary protection and must be used for backup protection.

(Chothani & Bhalja, 2011) proposed a new differential relaying protection scheme for busbars that aimed to overcome CT saturation during severe faults. The proposed scheme was based on monitoring the difference in currents between the incoming and outgoing lines of the respective phase at a specific bus. The suggested approach provided more stability against external faults, increased sensitivity to high resistance faults, and improved reliability in distinguishing between in-zone and out-of-zone faults.

(Allah, 2014) developed a busbar protection scheme based on the alienation technique to achieve a reliable and efficient protection scheme. The technique was accurate in detecting faults, determining fault locations, identifying all types of short-circuit fault conditions in the busbar protection zone and discriminating external faults with CT saturation. The vector sum of all measured currents in and out of the bus must be equal to zero as long as there are no faults within the protected zone. When a fault occurs outside of the protected zone, the damaged circuit is energized at a considerably higher level, approaching CT saturation or with varied degrees of CT saturation, potentially resulting in huge false differential currents.

(Xu et al., 2015) evaluated the performance of busbar protection schemes for various fault scenarios. They analysed three fault scenarios using biased differential protection and fast Fourier transform algorithms. The project aimed to assess if the differential relay can make correct decisions for different fault scenarios. Simulation results demonstrated that the relay could make accurate decisions for different fault scenarios.

(Nasir et al., 2016) implemented the all-Optical Differential Protection (ODP) scheme using magneto-optic current sensors. This method of protection connected magneto-optic current sensors in series to perform differential protection functionality. The project aimed to resolve CT saturation issues which caused the relay to malfunction and perform false tripping. Simulations proved that an immediate response to an increase in differential current can be achieved using an optical system and an all-optical protection scheme provides a fast and highly discriminative fault detection system for busbar protection.

(Mourad & Shehab-Eldin, 2018) evaluated the performance of a differential protection scheme based on a new and simple transform, called Akrap. This evaluation was performed against various types of internal and external faults using the Akrap transform and the current differential protection scheme. The results demonstrated that the system worked well in terms of sensitivity and reliability. Furthermore, the technique could detect all in-zone faults, including high-resistance faults, to achieve high sensitivity, and it remained stable during out-of-zone faults, even with severe external CT saturation, for improved security.

(Jena & Bhalja, 2018) developed a generalized alpha plane-based digital differential busbar protection scheme that combines the benefits of the percentage differential and the two-restrain alpha plane algorithms. The suggested approach maps the alpha plane utilizing one cycle CT secondary current signals from bays connected to the busbar. It was observed that the proposed scheme is very sensitive to internal faults with higher stability to external faults considering the saturation condition of the current transformer.

(Jena & Bhalja, 2018) presented a new busbar differential protection scheme based on Teager Energy Operator. This technique calculates differential and restraining coefficients in a mode-segregated manner using instantaneous phase current values. Simulations demonstrated that the scheme is reliable for internal faults and retains stability against external faults with the CT saturation taken into consideration.

(Makwana et al., 2020) discussed the principles of high-impedance differential busbar protection, bus wire supervision, and associated auxiliary relays needed to complete standard schemes such as zone In/Out switches, zone indication relays, DC supply supervision, etc. This was done based on the comparison of modern numerical protection schemes and conventional electromechanical schemes. The simulation results proved that protecting with a digital signal processor-based scheme has many advantages over traditional electromechanical schemes used for high-impedance busbar protection.

The review of the papers based on the above terms is shown in Tables 2.1 and 2.2. The comparison of the reviewed papers is conducted using the following criteria:

- Author(s) of the paper and year published
- Aim of the paper
- Protection method used
- System layout
- Hardware/software used
- Advantages/Challenges
- Outcomes/Achievements

Table 2.1: Differential busbar protection schemes

Paper	Aim of the paper	Method of protection used	System structure	Hardware/Software used	Advantages/Challenges	Achievements
(Namdari et al., 2005)	To develop a power differential protection (PDP) that can be used in wide area protection (WAP).	Power Differential protection method	Single busbar arrangement with two outgoing circuits	MATLAB and PSCAD/EMTDC software	The fundamental drawback of PDP is its inability to identify the faulty phase; as a result, if only a single pole must be tripped, it can only be used as backup protection and cannot serve as the primary form of protection.	The PDP technique operated effectively for all types of system faults, including poor data induced by CT saturation.
(Chothani, 2011)	To present a new differential protection scheme for the busbar to overcome early and severe CT saturation during major faults.	Current Differential protection method	Single busbar arrangement with two incoming lines and two outgoing lines	PSCAD software	The primary disadvantages of this scheme are that it needs more maintenance and that it is susceptible to failure due to a large number of contacts in series with the trip circuit.	The suggested approach offered more stability against external faults, increased sensitivity to high resistance faults, and improved reliability in distinguishing between in-zone and out-zone faults. Furthermore, the suggested approach aimed to overcome early and severe CT saturation during major faults.
(Chothani, 2014)	To implement a new dual slope differential relay scheme to protect the busbar against faults for various busbar arrangements	Current Differential protection method	Single busbar, One and a half breaker, and Double busbar arrangements	PSCAD/EMTDC software	The advantage of the scheme is that it uses Fast Fourier Transform (FFT) techniques to eliminate noise and unwanted harmonics in the system.	The proposed scheme could detect all types of in-zone failures and maintain stability against all types of out-zone faults. Furthermore, the scheme tripped within 20ms for the majority of the internal faults.
(Allah, 2014)	To develop a protection scheme for busbars based on the alienation technique	Alienation coefficients calculation method for current signals	Single busbar arrangement with one incoming line and two outgoing lines.	MATLAB software	All 10 types of fault conditions in the busbar protection zone can be accurately identified. This method took about 10ms to clear faults, so it is a fast method. It is a highly reliable protection method that can be implemented using a digital protective relay.	Simulation results showed that the algorithm used correctly detected faults, determined fault locations, selected faulty phases, and discriminated external faults with CT saturation.

Paper	Aim of the paper	Method of protection used	System structure	Hardware/Software used	Advantages/Challenges	Achievements
(Xu, Li and Wen, 2015)	To evaluate the performance of busbar protection schemes for different scenarios of faults.	Three fault scenarios were analysed using a biased differential protection algorithm and a fast Fourier transform algorithm	Double busbar arrangement with two outgoing feeders.	PSCAD and MATLAB software	Possible asynchronous data problems between current transformers were not analysed.	Results simulated proved that the relay could make correct decisions for various scenarios of faults.
(Nasir et al., 2016)	To implement the all Optical Differential Protection (ODP) scheme utilising magneto-optic current sensors.	Current Differential protection method	Single busbar arrangement	MATLAB/SIMULINK software	The advantage of the scheme is that it doesn't require complex signal processing, it only utilises a series connection of optical models.	Simulation results proved that an optical system could respond immediately to an increase in differential current, and an all-optical protection strategy provides a quick and highly discriminative fault detection solution for busbar protection.
(Mourad & Shehab-Eldin, 2018)	To evaluate the differential busbar protection scheme's performance based on the Akrap transform technique.	The performance of the suggested method was assessed for various fault types of internal and external faults utilizing Akrap transformation and current differential protection techniques.	Single busbar arrangement with four outgoing lines	EMTP software	The method has the benefit of not being impacted by fault conditions such as the location of the fault, resistance of fault, start time, or type of fault. Furthermore, load switching does not affect it.	The findings demonstrated that the system performed well in terms of sensitivity and dependability. Furthermore, the technique could detect all in-zone faults, including high-resistance faults, in order to achieve high sensitivity, and it remained stable during out-zone faults, even with severe external CT saturation, for improved security.
(Jena & Bhalja, 2018)	To develop a generalized alpha plane-based digital differential busbar protection scheme that combines the benefits of the percentage differential and the two-restrain alpha plane algorithms.	The suggested approach maps the alpha-plane utilizing one-cycle CT secondary current signals from bays connected to the busbar.	Single busbar arrangement with one incoming line and two outgoing lines	PSCAD software	The scheme was found to have a fast response time (5 ms), hence it was considered to be on par with the modern busbar protection schemes.	It was observed that the proposed scheme is very sensitive to internal faults with higher stability to external faults considering the saturation condition of the current transformer.
(Jena and Bhalja, 2018)	To present a new differential busbar protection algorithm based on Teager Energy Operator	This scheme calculates differential and restraining coefficients in a mode-segregated manner using instantaneous phase current values.	Double bus single breaker arrangement	PSCAD software	The scheme provided high-speed protection to the busbar.	Simulations showed that the scheme is reliable for internal faults and retains stability against external faults with the CT saturation taken into consideration.

Paper	Aim of the paper	Method of protection used	System structure	Hardware/Software used	Advantages/Challenges	Achievements
(Makwana et al., 2020)	This paper discusses the fundamentals of high-impedance differential bus protection, bus wire supervision, as well as the corresponding auxiliary relays needed to complete standard schemes such as zone Input/Output switches, zone indicator relays, and DC power monitoring.	Comparison between modern numerical protection schemes and conventional electromechanical schemes	Double busbar arrangement	Real-Time Digital Simulator (RTDS)	Digital protection schemes can enable event and fault recording, metering, self-monitoring, and SCADA communication. To identify potentially harmful open circuit events in current transformers, both current and voltage monitoring mechanisms are included in the same relay.	The results proved that protecting with a digital signal processor-based scheme has many advantages over traditional electromechanical schemes used for high-impedance busbar protection.

(Namdari et al., 2005) proposed a power differential protection based on wide area protection to enhance the reliability of the protection system. The main purpose of WAP was to identify and isolate faulty sections using differential protection techniques. The fundamental concept outlined in the article was based on traditional differential protection. This scheme was developed for the 275kV Northern Ireland Electricity (NIE) network and the simulation of the grid was done using PSCAD software. All internal and external faults were modeled using MATLAB software, which eliminates the influence of discrete calculations related to digital measurement and protection. The results simulated showed that the proposed algorithm performs well in all type of faults and maintain stability when there is no fault. However, the processing time of the simulated network and algorithm implementation was about 20 seconds on a modern 2.8GHz PC using PSCAD software. The processing time of 20 seconds is very slow for protecting a busbar. Busbar protection necessitates a high-speed relaying scheme as it connects many incoming and outgoing circuits.

(Chothani & Bhalja, 2011) introduced a new differential relay scheme for busbar protection. The suggested technique was based on the differential between the incoming and outgoing line currents at a specific bus. This scheme was thoroughly tested and modelled on a 230 kV Indian power transmission network using PSCAD software. The suggested approach offered more stability against external faults, increased sensitivity to high-resistance faults, and improved reliability in distinguishing between in-zone faults and out-zone faults. The authors also observed that the relay’s operating time was less than 20 ms after the fault has occurred. Furthermore, the proposed technique was able to avoid early and severe CT saturation during severe faults. The relay response time for this scheme is faster than the previous scheme explained above. The operating time of 20ms for a relay is a reasonable time for detecting a busbar fault. However, simulations were not conducted using real-time data which is more accurate when doing fault simulations.

(Allah, 2014), developed another way of protecting a busbar against all types of faults, using the alienation coefficient technique. This method does require any additional equipment as it relies only on three-phase current measurements of all feeders connected to the protected bus. The proposed methodology was used on a portion of Egypt's 500 KV network. It was implemented using the MATLAB software package and was observed to be accurate in identifying faults within a busbar-protected zone. Furthermore, this method was observed to be fast in detecting faults as it took about 10ms. However, it is still difficult to conclude and say the scheme is the best as no real-time simulator software was used.

(Mourad & Shehab-Eldin, 2018), presented an Akrap transform technique that makes use of a differential busbar protection scheme. This technique combines the benefits of both the differential algorithm and the Akrap transform. The Akrap transform was used to extract the incoming fault signal waves. It was applied to both the sum of currents entering and leaving the busbar. The studied network was modelled for a 230 kV network using the EMTP software. It was observed by the authors that this scheme is immune to CT saturation, as it makes ultrafast decisions before saturation exists. Additionally, it was observed that the average fault detection time is 0.1ms. The technique also satisfies the requirements for fast speed, sensitivity to high-resistance faults, reliability in distinguishing between in-zone and out-zone faults, and avoidance of early major CT saturation effects.

Authors, (Jena & Bhalja, 2018), developed an alpha-plane algorithm using a digital differential busbar protection scheme. This technique combined the benefits of the percentage differential and two-restrain alpha-plane algorithms. The suggested approach maps the operational points on a complex alpha plane using a cycle CT secondary current signal from each bay connected to the busbar. The suggested concept was tested and simulated on a 400 kV Indian power station using PSCAD software. The suggested scheme's performance was evaluated on a large number of examples with considerable variations in system and fault parameters. A lab prototype of the proposed bus protection scheme was built to confirm the validity of the suggested method. CT secondary current signals were recorded using the prototype during internal and external faults with CT saturation. The comparison of simulation and prototype data clearly showed the benefits of using the suggested approach concerning increased sensitivity during internal faults and improved stability during external faults. The proposed technique has a fast response time (about 5 ms) and can thus be compared to modern busbar protection schemes.

Different algorithms for protecting a bus were proposed in the literature above. However, the majority of the proposed methods are only capable of providing calculation-based protection. Also, a disappointing aspect of these protection techniques is that very few have been implemented using a Real-Time Digital Simulation (RTDS) platform, which is more accurate as simulations are performed using real-time data. Furthermore, none of them have taken into account the physical protective device test that complies with IEC 61850. Therefore, drawing a conclusion that these algorithms have been properly implemented and tested is difficult. As a result, the proposed research focuses on the design and implementation of protective systems in real-time simulation, with physical devices integrated. Furthermore, the proposed method uses microprocessor-based protection devices that comply with the IEC 61850 standard to offer adaptive protection features for busbars. The IEC 61850 communication method used allows for fast communication between IEDs. The use of the current IEC 61850 GOOSE model which uses Logical Nodes (LNs) allows the protection scheme to reduce hardwiring while providing a fast communication network between the IEDs. The existence of these LNs between multi-vendor protection IEDs enables communication between these devices. The proposed algorithm uses an RTDS device with its RSCAD software.

2.2.2 Review and analysis of the IEC 61850 standard communication used in the busbar protection scheme

The IEC 61850 standard specifies an internationally recognized technique of local and wide-area data communications for substations. It includes built-in capabilities for data sharing and high-speed control through a communication network, removing the need for most hardwiring. The standard can be applied for communication between primary equipment, bay-level devices, and station-level computers. It also enables the interlocking and inter-tripping of protection relays. The convenience of Ethernet is combined with security, which is critical in substations. Intelligent Electronic Devices (IEDs) can send and receive GOOSE messages, automatically send fault records, and enable communication with IEC 61850 substation masters over Local Area Networks (LAN). LAN cable reduces costs by eliminating traditional hardwiring (Baningobera, 2018).

(Saleem & Nordstr, 2010) described the mapping between multi-agent system architectures using IEC 61850 standard for substation automation. The mapping was based on a use-case-driven methodology in which multi-agent systems defined the need for information exchange. Incorporating IEC 61850 communication principles has been demonstrated to improve the use of multi-agent systems for power system control and protection.

(Muthu & Chidambaram, 2010) challenged the existing specifications developed in power utilities by decreasing the number of protective IEDs needed to perform the necessary protection functions required by current industry practice. This will make it easier to access the protection systems' overall architecture and result in considerable cost savings. This can be accomplished by activating the necessary protection features on each bay IED. This was done by comparing the new protection control system design with a traditional system. The proposed protection system architecture was proven to reduce the number of devices while providing optimal availability.

(Tanaka et al., 2012) described a peer-to-peer connection between Merging Units (MUs) and IEDs for securing the Sampled Value (SV) messages of 32 bays on the process bus. The sampling timing of each MU was controlled from the IED via a 1 Pulse Per Second (PPS) signal that is independent of the Global Positioning System (GPS) time stamp signal, ensuring busbar protection lockout even in the event of GPS clock failure. It was discovered that the proposed system is dependable, has a long lifespan, is interoperable, and is simple to maintain.

(Apostolov, 2014) investigated the impact of the IEC 61850 standard on busbar protection in transmission and distribution substations. This was done by comparing conventional bus differential protection with IEC 61850 bus differential protection. The study demonstrated that bus protection with IEC 61850 communication standard offers several key benefits over traditional bus differential protection systems e.g. less wiring, less installation, less maintenance, and reduced commissioning costs.

(Yang et al., 2014) investigated, assessed, and maximised the level of security, reliability, and operation speed of the protection devices used in a mesh substation. This was done by designing and testing the performance of a prototype multi-vendor protection scheme based on the process bus used in mesh substations. It was observed that instant interoperability between many providers is not ideal and is currently ineffective in some combinations of vendors.

(Arnold et al., 2015) evaluated the performance of IEC 61850 communication devices concerning speed, security, and reliability. The study used IEDs from various vendors which were configured for a Permissive Overreaching Transfer Trip (POTT) communication scheme. This scheme used conventional proprietary protocols and IEC 61850 GOOSE messages based on a hardware-in-the-loop (HIL) system with RTDS. The obtained findings proved the IEC 61850-based scheme to be reliable, quick, and secure as compared to the traditional scheme.

(Jamborsalamati et al., 2016) presented a flexible HIL platform for testing and validating protection schemes based on IED intelligence. The platform contained RTDS which enables power system simulations of contingencies in real-time and offers plug-and-play deployment for IED integration in protection schemes. The results showed that the

IEDs were communicating successfully with each other in both peer-to-peer and client-server modes, allowing a comprehensive protection scheme to be implemented.

(Kumar et al., 2021) implemented a practical block busbar protection (BBP) system for a single busbar scheme and tested it in the lab with sampled values (SV) and GOOSE to demonstrate its dependability and technological advancement. This experiment was conducted on three scenarios in a simulated substation network relevant to the process plant industry. Moreover, this lab-based experiment of utilising multi-vendor IEDs examined the performance of Ethernet and Fibre Optics (FO) based process bus networks to confirm the overall busbar protection scheme performance. Lastly, a comparison was made between digital and traditional protection schemes, as well as recommendations for future applications. In a digital protection system, it was found that GOOSE and SV offer better operational solutions because of their quicker communication, less wiring, and constant IED monitoring.

(Sastromiharjo et al., 2022) 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.

(Kumar et al., 2022) investigated the performance of the IEC61850 standard in a digital busbar protection scheme. This was done by comparing digital Substation Automation Systems (SAS) with traditional protection schemes. Experiments showed that interlocking and blocking schemes have significant technical advantages over traditional protection schemes with flexible diagnostics and reduced engineering work.

A summary of the reviewed papers relating to IEC 61850 standard communication used in busbar protection schemes is presented in Table 2.2 below. The objectives of the papers and the methods used are also discussed.

Table 2.2: **busbar protection schemes using IEC 61850 standard communication**

Paper	Aim of the paper	Method of protection used	System structure	Hardware/Software used	Advantages/Challenges	Achievements
(Saleem & Nordstr, 2010)	To describe the mapping between multiagent-based architectures using IEC 61850 standard for substation automation.	The mapping is according to a use-case-driven methodology, in which the multi-agent system defines the need for information exchange.	10 X Single busbar arrangements	Hardware: ▪ 5 X Distributed Generators ▪ 7 X physical relays ▪ 1 X Transformer ▪ 6 X Loads	The benefits mentioned include enhanced interoperability between low-level devices as well as the possibility of economic and operational improvements that are not available with more conventional methods that need significant copper connections.	It was proven that the use of multiagent systems for control and protection in electrical networks could be enhanced by including IEC 61850 communication principles.
(Muthu & Chidambaram, 2010)	This document challenged the existing specifications developed in utilities by decreasing the number of protective IEDs needed to perform necessary protection functions required by current industry practice. In this case, the whole design of the protection system will be more easily accessible, and considerable savings may be realized.	A comparison between the conventional system and the new protection and control system architecture	Double busbar configuration with two outgoing feeders	Hardware: 1. 10 X Bay unit supplier 1 2. 10 X Bay unit supplier 2 3. 1 X Central unit supplier 1 4. 1 X Central unit supplier 2 5. Integrated disturbance recorder	The proposed system has the following advantages: ▪ Fast fault clearance and reliable fault isolation are provided via a decentralized system of individual bay units within the bay. ▪ Halving the number of IEDs overall. This results in lower costs for things like copper wire, spare parts, hardware, engineering, commissioning, and maintenance. ▪ Reduction in the number of CT core requirements ▪ Reduction in the project's overall cost and completion time.	It was proven that the proposed protection system architecture reduces the number of devices while providing optimal availability.

Paper	Aim of the paper	Method of protection used	System structure	Hardware/Software used	Advantages/Challenges	Achievements
(Tanaka et al., 2011)	This paper aimed to describe a peer-to-peer connection between merging units (MUs) and IEDs for securing the sampled value (SV) messages of 32 bays on the process bus.	The sampling timing of each MU is controlled from the IED by a 1 pulse per second (PPS) signal that is independent of the time stamp signal generated by GPS, preventing bus protection lockout in the event of GPS clock failure.	Double bus configuration	Hardware: ▪ 2 X Merging Units ▪ 2 X Intelligent Electronic Devices	The advantage is that this method applies to the voltage selection scheme (VSS) as well, not just busbar protection.	It was observed that the proposed system is reliable, has a long lifespan, is interoperable, and is simple to maintain.
(Apostolov, 2014)	To investigate the impact of the IEC 61850 standard on substation's busbar protection for transmission and distribution networks	Comparisons between conventional bus differential protection and IEC 61850-based busbar differential protection.	Single busbar arrangement with four outgoing lines	Six multi-vendor IEDs/Conventional bus differential protection relay	The advantage of distributed bus protection based on peer-to-peer communication is that it provides fast fault-clearing time for sub-transmission and transmission bus faults with no additional protection equipment required.	The study proved that bus protection with IEC 61850 communication standard offers several significant benefits over traditional bus differential protection systems e.g. wiring is reduced, installation, maintenance, and commissioning costs. Furthermore, it allows easier adaptation to changes in substation bus configurations and virtually eliminates CT saturation and open circuits.
(Yang et al., 2014)	This project's main goal was to investigate, evaluate, and maximise the level of security, reliability, and operation speed of the protections utilised in a mesh substation.	Design and performance test of a multi-vendor prototype protection scheme based on the process bus used in mesh substations.	Double busbar configuration	SVScout EV and Wireshark software	Instant interoperability between several providers is not ideal and is currently ineffective in some vendor combinations.	Possible causes of relay malfunctioning were identified and corrected.

Paper	Aim of the paper	Method of protection used	System structure	Hardware/Software used	Advantages/Challenges	Achievements
(Arnold et al., 2015)	This article aimed to evaluate the performance of IEC 61850 standard-based devices concerning speed, security, and reliability.	The study used IEDs from several vendors configured for the POTT communication method utilizing traditional proprietary protocols and IEC 61850 GOOSE messages based on a HIL system with RTDS.	Single busbar arrangement with a single transmission line	RSCAD/RTDS software	IEC 61850's benefits include i)a significant decrease in project costs due to utilising less copper wiring for devices connected; ii) improved safety and isolation of live equipment and wiring; iii) less maintenance and reconfiguration; and iv) interoperability between same vendor devices as well as seamless interoperability between multi-vendor devices.	The findings proved the IEC 61850-based scheme to be reliable, quick, and secure as compared to the traditional scheme.
(Jamborsalamati et al., 2016)	To present a flexible HIL platform for testing and validating protection methods based on IED intelligence.	The platform includes RTDS for simulating power system contingencies in real-time and provides plug-and-play deployment for integrating IEDs to implement protection schemes.	Double busbar arrangement with three outgoing feeders	RTDS software	The advantage of developing such a platform is to enable close-to-the-field validation of distributed protection methods that integrate communication.	The results showed that the IEDs were communicating successfully with each other in both peer-to-peer and client-server modes, allowing a comprehensive protection scheme to be implemented.

Paper	Aim of the paper	Method of protection used	System structure	Hardware/Software used	Advantages/Challenges	Achievements
(Kumar et al., 2021)	To implement a practical block busbar protection (BBP) algorithm for a single busbar arrangement and test it in the laboratory using Sampled Values and GOOSE to demonstrate its dependability and technological advancement.	This experiment was conducted for three scenarios in a simulated substation network relevant to the process plant industry. Furthermore, the performance of Ethernet and fiber optics (FO) based process bus networks was examined in this lab-based experiment utilizing multi-vendor IEDs to confirm the overall performance of the busbar protection scheme. Lastly, it made a comparison between digital and traditional protection schemes, as well as recommendations for future applications.	Single busbar configuration with a single incoming line and three outgoing feeders	IED scout, SV scout, test universe, S1 Agile, Essergy, and Wireshark software.	Digital protection in a busbar protection scheme has the advantages of being easily configurable and extendable.	It was found that GOOSE and SV offer better operational solutions in a digital protection system as a result of faster communication, less wiring, and constant IED supervision.
(Sastromiharjo et al., 2022)	To implement a busbar protection scheme using IEC 61850 GOOSE message.	Comparison between traditional busbar schemes (high impedance and low impedance types) and IEC 61850 GOOSE message-based busbar protection schemes.	Double busbar arrangement with one incoming line and three outgoing lines.	GOOSE messaging busbar protection utilises main protection unit (MPU) and backup protection unit (BPU) relays in each bay to tripping and blocking logic.	The proposed protection scheme has the following benefits: ▪ Increase the distribution of electrical energy with greater reliability. ▪ Prevent pervasive interference. ▪ Cost-effectiveness ▪ Increase competence	It was observed that GOOSE busbar protection is quick in locating busbar faults. This takes about 100 ms. This increases the dependability of the busbar protection system and reduces the risk of widespread failures and power outages.

Paper	Aim of the paper	Method of protection used	System structure	Hardware/Software used	Advantages/Challenges	Achievements
(Kumar et al., 2022)	This study investigated the performance of IEC 61850 when used in a digital busbar protection scheme.	Comparison between digital SAS and traditional protection schemes.	Double busbar arrangement with one incoming feeder and three outgoing feeders	This scheme uses Four IEDS with the same vendor.	The use of GOOSE and SV has numerous advantages, including less copper wiring, a smaller footprint for the automation panel, and a smaller trench size.	Experiments showed that interlocking and blocking schemes have considerable engineering advantages over traditional protection schemes, with flexible diagnostics and less engineering work.

(Muthu & Chidambaram, 2010), developed an article that challenges the current utility technical requirements by reducing the number of protective IEDs necessary to achieve the protection and control functions. They mentioned that by doing so, the total protection system structure will be more accessible, and significant cost reductions may be realized. This is accomplished by activating the necessary protection features in each Bay IED. The busbar central unit IED performs the busbar protection function based on the primary system data provided by each bay IED. They also observed that utilities are not fully utilising the multifunctional capabilities of numerical relays in the application of protection and control schemes. This is due to a long-standing history of allocating distinct IEDs for main 1 & 2 functions. Furthermore, bay control functions are always kept separate from protective systems. However, as reliability improves, protection and control features such as breaker fails, overcurrent, synchronization, and auto-reclose delays are combined as integrated features of bay control IEDs. Also, busbar protection is generally a stand-alone system utilising either the high-impedance principle or the low-impedance principle. The authors also mentioned that multi-object capabilities in IEDs can be used to maintain high network reliability while increasing availability and optimizing cost-effectiveness. It also offers enhanced power quality monitoring, measurement, fault logging, event logging, fault location, and communication capabilities to meet your automation needs. Furthermore, the IEC61850 standard guides and governs the interoperable communication exchange of IEDs from various product manufacturers.

(Yang et al., 2014), developed a prototype protection scheme based on the IEC61850-9-2 process bus for use in the mesh corners of UK transmission substations. Extensive testing was performed with traditional hardwired relays and IEC61850-9-2-based relays. Results showed that their operational performance is compatible. Multi-vendor prototype Merging Units (MUs) were connected to the process bus to evaluate interoperability and time offset. They also discovered that misconfigurations in the process bus can confuse the relay, resulting in unacceptable operational delays. This should be avoided before commissioning the system to ensure the reliability of the protection system. Moreover, they state that instant interoperability between several providers is not ideal and is currently not functional in other vendor combinations. Hence, this research study focuses on investigating interoperability problems between IEDs from different manufacturers.

(Arnold et al., 2015), evaluated the performance of IEC 61850 standard-based devices concerning speed, security, and reliability. The research was carried out using different vendor IEDs configured for a POTT communication scheme with traditional proprietary protocols and the IEC 61850 GOOSE messages, which were based on HIL simulations with RTDS. The acquired findings confirmed the reliability and security of the IEC 61850-based POTT communication scheme with quicker operating times when compared to the traditional POTT communication scheme. The IEC 61850 standard offers several advantages for substation automation, and the results gathered to prove that the IEC 61850 standard operated as planned. As a result, it may be confidently utilized in the future as a standard for power system automation, not simply substation automation.

(Kumar et al., 2021), 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. 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.

The literature above is mainly about comparing traditional busbar protection schemes with digital busbar protection schemes. All the authors above are stating that IEC 61850-based protection schemes have several benefits over traditional protection schemes. As a result, the deployment of IEC 61850-compliant protective IEDs is the solution for reliable power system protection. The IEC 61850 communication standard facilitates the development of new protection and control applications. It successfully promotes interoperability between IEDs from diverse suppliers in the substation. This is essential for interlocking, protection, and control activities at the substation level, as well as improving the efficiency of digital relays. Furthermore, the IEC 61850 protocol offers a novel approach to substation automation that will result in significant cost savings and performance advantages for electrical power systems.

The following section presents the remarks and observations made from the reviewed literature above.

2.2 Remarks and Observations

Based on the literature review that was conducted, the following observations were made:

- Interoperability between different-vendor IEDs negatively affects the performance of busbar protection schemes.
- CTs saturation also affects the performance of busbar protection schemes negatively due to the maloperation of relays.
- Interoperability challenges arise at various levels of the design and development process associated with implementing automation software modules, including modeling and notation, information exchange formats, and adaptation of defined software interfaces to developing communication standards in energy systems.
- The lack of Substation Automation System (SAS) experts is a challenge that users and vendors must cope with today.

2.3 Discussion of the reviewed literature

The various traditional busbar protection techniques are examined in the literature review. 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 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, including packet loss/delay, malformed packets, and data desynchronization, among others. These issues are significant and deserve consideration in future studies. Hence, this dissertation is focusing on investigating the communication challenges of different vendor IEDs and coming up with possible solutions to overcome the problem.

According to (Baningobera, 2018), 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). (Apostolov, 2014) stated the benefits of using peer-to-peer communication for bus protection which are:

- It allows for fast fault clearance for transmission bus faults without additional protection equipment needed.
- It replaces a high or low-impedance transmission bus protection device and, in some instances, eliminates the need for current transformer addition or replacement.

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). In this dissertation, 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. Also, its capability of high-speed fault clearing time.

(Yang et al., 2014) investigated the performance of a multi-vendor prototype protection scheme based on the process bus used in mesh substations. Their findings were that instantaneous interoperability of different vendor IEDs in real-time is not ideal and is currently ineffective in some vendor combinations. They identified malfunctioning relays which they state that it is most likely a compatibility or timing issue between the two IEC 61850 implementations. Also, their tests demonstrated that if the process bus is misconfigured, there is a possibility of confusing the relay, resulting in unacceptably delayed operation. To ensure the reliability of the protective scheme, this must be prevented before system commissioning. This was a good investigation conducted by the authors (Yang et al., 2014). However, the only problem with this investigation 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, (Baningobera, 2018), 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.

This research focuses on investigating IEC 61850 standard-based solutions for interoperability issues of multi-vendor IEDs as stated by the authors 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.

2.4 Conclusion

The literature review presented several busbar protection techniques. Different algorithms of conventional busbar protection schemes were analysed and compared with IEC 61850 bus protection schemes. Based on the reviewed literature, IEC 61850 standard protection schemes have several advantages over conventional protection schemes. The advantages of IEC 61850 include: i) significant cost savings due to reduced use of hardwiring; ii) improved safety and isolation of live equipment and wiring; iii) less maintenance and reconfiguration; and iv) seamless interoperability between multi-vendor devices. However, it was observed from the literature that interoperability between multivendor IEDs is not always seamless or instantaneous. It was also observed that conventional systems respond slower to faults because they use parallel wiring as compared to the single Ethernet wire of the proposed digital busbar scheme. In the recommended digital approach, data packets move across Ethernet cables, but voltage and current signals move through different nodes and terminals in conventional cabling, which results in quality loss. On the other hand, with the widespread deployment of IEC 61850 in the future SAS faces several challenges such as a lack of practical experience, cyber threats, and communication-related problems. These challenges deserve attention as they negatively impact the performance of the power system protection schemes. Furthermore, it was observed from the reviewed literature that these communication-related issues arise when two or more multivendor IEDs are put together in one scheme to communicate with one another. This is one of the things that triggered this research study. This dissertation is focusing on investigating interoperability issues between IEDs from different manufacturers for IEC 61850-based differential busbar protection scheme at the transmission level. Some of the remarks were done in section 2.2 based on the observations made from the reviewed literature.

Chapter three presents the theoretical background of busbar protection and IEC 61850 communication protocol.

CHAPTER THREE

THEORETICAL BACKGROUND OF BUSBAR PROTECTION AND IEC 61850 COMMUNICATION PROTOCOL

3.1 Introduction

A busbar is a vital part of a power system, as it serves as a connection point for many circuits including transmission lines, generation, and loads. A single fault on the busbar can cause damage that is equivalent to many faults on the network happening at the same time (Hejazi, 2004). This is because of the large currents usually drawn by the busbar due to the many circuits connected to it. Busbars are often left unprotected because of the assumption that they are very reliable, therefore, they do not need special protection. There were concerns that a dedicated protection scheme for a busbar might cause it to malfunction which will negatively affect the entire power system. Additionally, it was assumed that backup protection would be adequate to protect the buses. However, due to issues like loss of loads and lengthy delays in clearing faults, it is necessary to use a dedicated busbar protection scheme (Mnguni, 2014).

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 chapter focuses on busbar protection schemes at the transmission level. The chapter describes the currently used busbar protection schemes, along with their operation. Information about digital busbar schemes is also included in the chapter.

This chapter gives a theoretical background of busbar protection and communication protocol. Different types of existing busbar protection schemes and equipment used for the protection schemes are explained in section 3.2. The digital busbar protection scheme is also covered in section 3.3. Section 3.4 explains the IEC 61850 standard and interoperability of Intelligent Electronic Devices. Also covered in section 3.5 in this chapter is the IEC 61850 standard basic approach. Section 3.6 describes the IEC 61850 communication stack and IEC 61850 Substation Configuration Language Files are presented in 3.7. Sections 3.8 and 3.9 explains the benefits of using the IEC 61850 standard and the Virtualization model. IEC 61850 object models are also covered in section 3.10. Sections 3.11 and 3.12 gives the discussion and conclusion.

3.2 Busbar protection schemes

Several protection schemes have been devised for busbars including the following (NPAG, 2011):

a. System protection schemes used to cover busbars.
b. Frame earth protection scheme.
c. Differential protection scheme.
d. Phase comparison protection scheme.
e. Directional blocking protection scheme.

In the above busbar protection schemes, (a) is only used in small substations, (d) and (e) has become obsolete. Therefore, in this chapter, a detailed theoretical background will be presented only for protection schemes (b) and (c).

3.2.1 System protection used to protect busbars

Busbars are inherently protected in systems where overcurrent protection or a distance protection system is applied. In general, overcurrent protection is meant to be used as a backup measure in relatively simple distribution networks. While distance protection is often implemented as a backup to cover busbar faults in transmission networks. Both of these protection methods are slow and only intended to limit damage to busbars (NPAG, 2011).

3.2.2 Frame earth protection

In the past, frame leakage protection has been used for busbars. Frame leakage configurations come in a few variations, offering a wide range of busbar protection capabilities. There are still many configurations that are operational today, and frame leakage may prove to be an ideal solution in some situations. Despite this, the need to insulate switchboard frames, and the availability of alternative configurations such as numerical protection relays, have played a part in the decline of frame leakage protection applications (Lackovic, 2012a).

3.2.3 Frame earth protection “for single busbar”

In this scheme, the short-circuit current circulating from the switchgear frame to the earth is measured. A CT is located on the earthing conductor and its reading is used to activate an instantaneous relay as presented in Figure 3.1 below. The connection of any other type of earth to a structural steelwork is completely not allowed. In this way, the CTs and the main earth connection are ensured not to be shunted, as that could cause changes in the effective setting, which may cause maloperation. It is necessary to insulate the entire switchgear, generally by placing it on concrete (Hejazi, 2004).

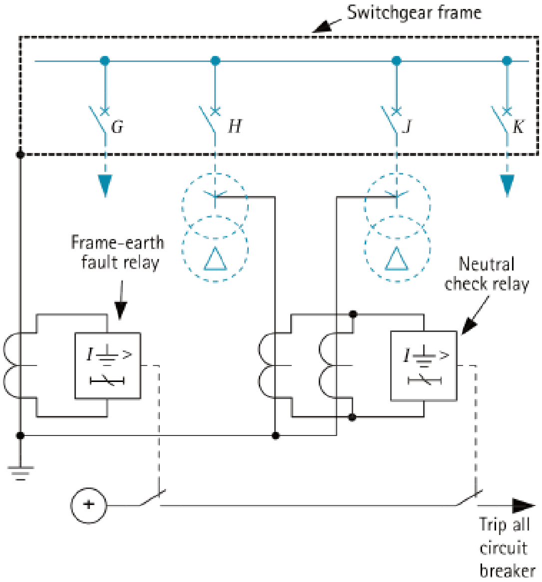


Figure 3.1: **Single zone frame earth protection** (Hejazi, 2004).

It is crucial that the impedance between the frame and ground not be excessively high, to prevent the frame's potential from exceeding a certain threshold. This also ensures that the current carried is not too small to be detected by the relay.

3.2.4 Frame earth protection “sectioned busbars”

This arrangement consists of one busbar split into two sections using one section circuit breaker as seen in Figure 3.2 below. This is accomplished by dividing the frame into sections, with each section having a separate CT, relay, and dedicated earth conductor. Only the faulted zone should be isolated for a busbar fault (NPAG, 2011).

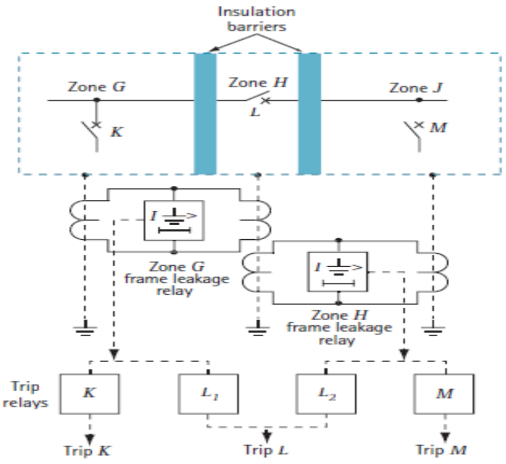


Figure 3.2: **Three zone frame earth scheme** (NPAG, 2011).

3.2.5 Frame earth scheme “double busbar substation”

In general, it is not practical to separate the metal enclosures of the main busbar from the auxiliary busbar. Thus, the protection of dual busbar systems is generally organized similarly to single busbar systems, but with the option to trip circuits connected to the auxiliary bus for any fault that occurs. This can be seen in Figure 3.3 below (Lackovic, 2012a).

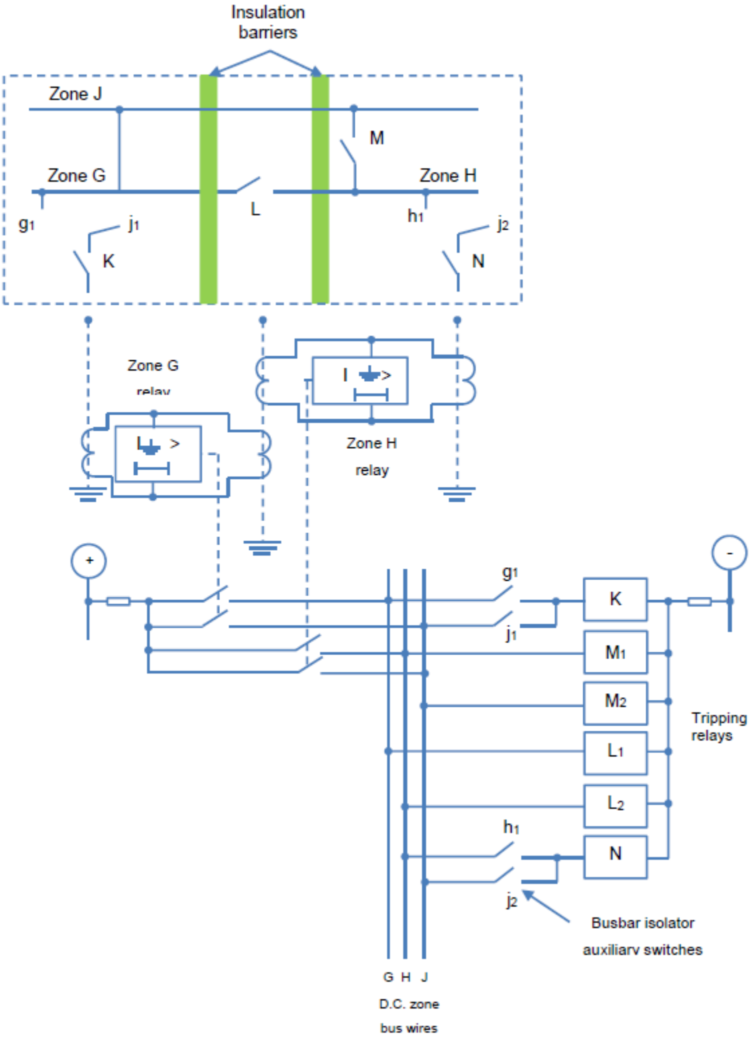


Figure 3.3: **Frame earth scheme, double busbar substation** (Lackovic, 2012a).

3.2.6 Frame earth protection “check system”

It is recommended to provide a check system for all other equipment, except for small types of equipment. It is there to provide security in a system against operating errors caused by human or mechanical shock. In the case of faulty low voltage (LV) wiring, the check system shall not allow the current from passing through the switchgear frame and reaching the earth. A useful check is performed by the relay energized through system neutral current. If not performed, there should be a short time delay in the operation of frame-earth relays (Hejazi, 2004).

3.2.7 Differential protection scheme

This is the most used protection scheme on transmission busbars. 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 (Chowdhury, 2015). 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 Figure 3.4 below (Hejazi, 2004). The CTs terminals are connected such that the currents on their secondary side cancel each other out during external faults and normal loading conditions.

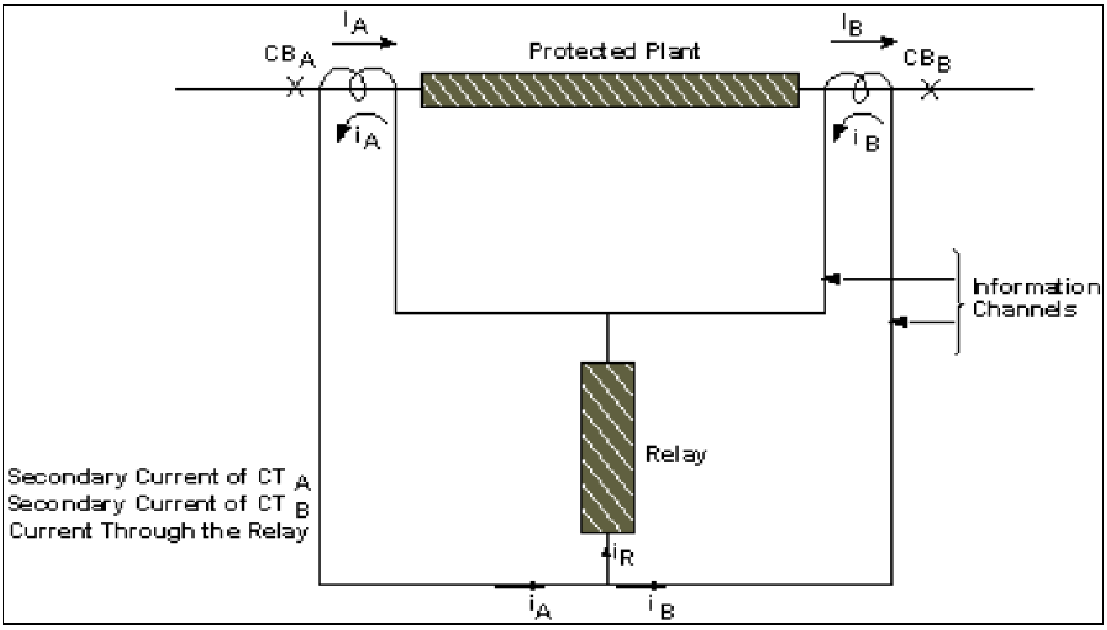


Figure 3.4: **Schematic wiring diagram of a circulating current differential protection** (Hejazi, 2004).

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 value of current flow through the relay. If this current is above a pre-set value, the relay will trip breakers ‘A’ and ‘B’.

This scheme can be applied using numerous methods. It can be implemented using one relay with CTs connected in parallel which can be used to protect a busbar from earth faults. Moreover, phase fault protection can also be added to this system by connecting CTs in each phase with a 3-phase relay as shown in Figure 3.5 below. For the scheme to function effectively, phase and earth-fault settings must be configured identically (Mnguni, 2014).

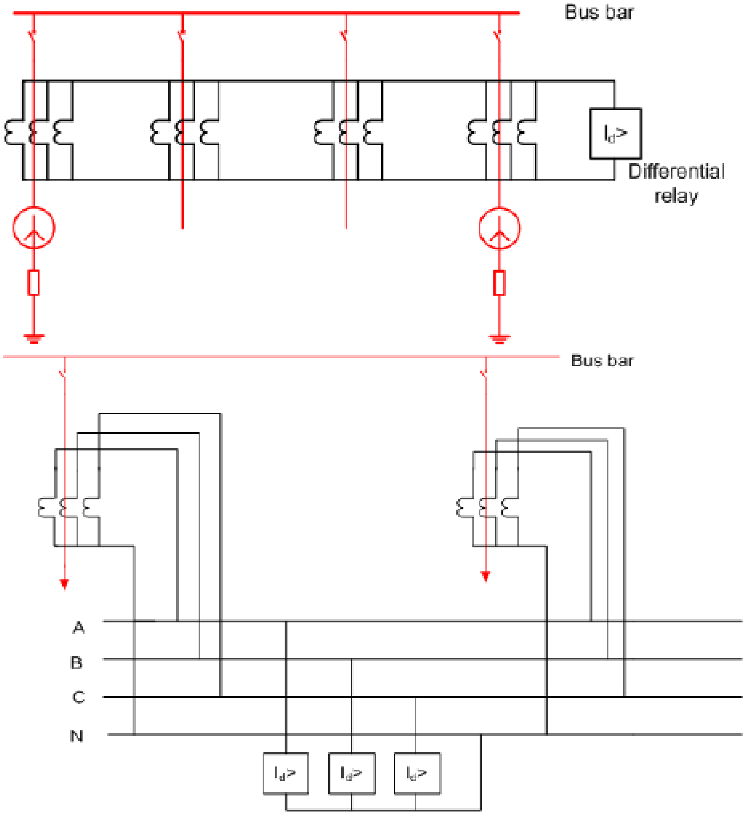


Figure 3.4: **Basic circulating current scheme** (Mnguni, 2014).

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. 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 case of a bus fault, a voltage-limiting varistor must be used to absorb energy (Mnguni, 2014).

- 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. 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 (Mnguni, 2014).

- Differential protection scheme for sectionalized busbars

  This scheme requires separate circulating currents for the divided buses. Zones are there for dividing sections and are configured such that they overlap the switches across the sections so that the entire network is protected, as seen in Figure 3.6 below (Mnguni, 2014).

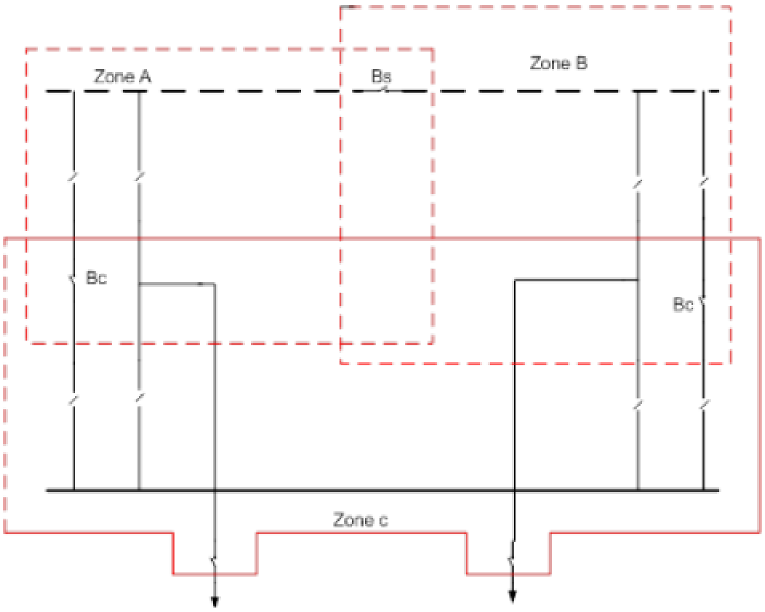


Figure 3.5: **Protection zones for sectionalized buses** (Mnguni, 2014)

Dual busbar layouts are maintained as separate zones. Overlap of zones occurs where the busbars are coupled. In this scheme, an isolator switch is located between the buses. An appropriate zone must be linked to the switch through early-make and late-break auxiliary contacts. In this way, the auxiliary contacts operate before the main contacts of the isolator switch. To open the auxiliary switches, the main contacts of the isolator must be opened first. On the transfer operation, two secondary circuits are connected in parallel and linked via isolators.

3.2.8 Equipment used for protection schemes

A protection scheme may consist of CTs, Voltage Transformers (VTs), circuit breakers, batteries, and relays (Newelani, 2000).

- Current and voltage transformers

Relays are energized by currents and voltages associated with the apparatus or the network being protected. These currents and voltages are not applied directly to the relay but are first reduced to suitable levels through CTs and VTs. The standard full-load secondary current ratings of relays or measuring equipment are rated to either 5 or 1 amperes (Amps). Thus, for primary circuits rated at 1200, 200, and 100 Amps, the CTs would have ratios of 1200/5, 200/5, and 100/5 respectively, or 1200/1, 200/1, and 100/1 Amps. The standard secondary interphase voltage is 110 V. Consequently, for primary circuits rated 275, 88, and 11 kV, the VTs would have ratios of 275kV/110V and 11kV/110V respectively (Aylward, 1997).

- Protective relays

A protective relay is a device that detects and responds to abnormal situations in a power system. It controls a circuit breaker, which isolates the faulty part of the system with minimal service disruption. There are four generations of protective relays mentioned as follows (Reimert, 2006).

- First-generation – Electromagnetic relays

The first generation of protective relays was the electromechanical relay. Its disadvantages were that it was slow, and it had too many moving mechanical parts.

- Second-generation – Static relays

Unlike electromechanical relays, the static relay has no moving parts. It has a faster response speed, decreased noise during operation, and a longer lifespan compared to an electromechanical relay. All the functions that were achieved earlier by the electromechanical relay were better performed by the static relay.

- Third-generation – Digital relays

Static and electromechanical relays were replaced by digital relays. All the measured analog quantities used in static relays are converted into digital signals by the digital relays. One of the advantages of digital relays is that they are accurate and implement more complex functions. Their main disadvantage is that they have a short lifetime due to the continuous development of new technologies. Moreover, staff needs to be taken to special training before operating a digital system due to its complexity.

- Fourth-generation – Numerical relays

Static and electromechanical relays are hardwired relays. They have fixed wiring, and their settings can be changed manually. Numeric relays are relays that can be programmed to set specific characteristics and behaviour. Given their advanced technology, they can be seen as natural developments of digital relays. One of their advantages is that it furnishes an easy interface with digital communication equipment. Their disadvantages include cyber vulnerability since they rely on non-proprietary software.

- Circuit breakers

A breaker is a device designed to either make or break the current under normal and fault circumstances. A fault condition arises when the circuit experiences an excessive current flow. A circuit breaker must be able to make and break the current associated with the type of fault that is occurring on the system, or it must be able to withstand it for a short period without being damaged. To do this, it must be fast in operating to minimize the damage in a circuit, it must have an arc-extinguishing medium, and it must be robust.

The following section explains how the CTs must be connected in relation to the circuit breakers in the power system.

3.2.9 Current transformer location

Ideally, the different discriminating zones and their circuit protection schemes should overlap each other. A circuit breaker should be overlapped by the zones so that it protects both zones. For this configuration, CTs are required on both sides of the circuit breaker as presented in Figure 3.7(a) below, which is feasible for many switchgear types but not for all. However, as seen in Figure 3.7(b) below, when both CTs are connected on the same side of the circuit breaker, it will create an overlap in protection zones at the CTs, but a short-circuit between the CT and the circuit breaker cannot be completely isolated (Lackovic, 2012b).

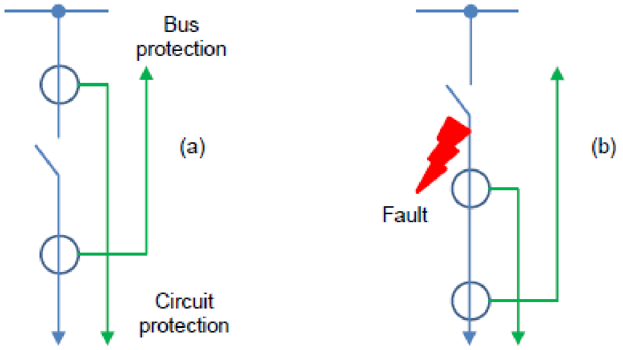


Figure 3.6: (a) Current transformers located on both sides of the circuit breaker

(b) Current transformers located on one side of the circuit breaker (Lackovic, 2012b).

The following section presents the application of digital busbar protection.

3.3 Digital busbar protection

The application of digital protection to busbars has been slower than the application of protection functions. However, static technology is still used in bus protection, but digital technology has matured to the point that it can now be considered for bus protection. Through digital technology, protection relays were able to communicate with various units via multiple pathways. The diagram shown in Figure 3.8 below illustrates how the measured values are distributed and processed; each feeder has its Processing Unit (PU) that collects information about the current, voltage, circuit breakers, and isolators. For communication, data is transmitted via high-speed fibre optics to a Central Processing Unit (CPU). In large substations, multiple CPUs are necessary, while in small substations, units are co-located (Mnguni, 2014).

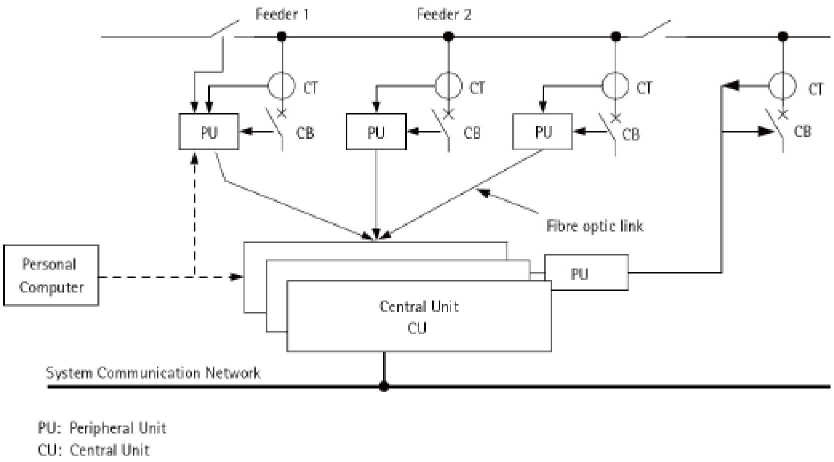


Figure 3. 8: Architecture for digital relay protection (Mnguni, 2014).

The CPU performs the necessary functions for protection INCLUDING the following protection functions:

- Backup overcurrent protection.
- Breaker failure.
- Dead zone protection.
- A disturbance recording is provided for monitoring of switchgear such as circuit breakers and isolators.

The following section explains the IEC 61850 standard structure and provides information on the interoperability of IEDs.

3.4 IEC 61850 standard and interoperability of Intelligent Electronic Devices

The IEC 61850 is a communication standard which was specified by the International Electrotechnical Commission (IEC) in the year 2003 for Substation Automation Systems (SAS). 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 providing interoperability. between IEDs from different vendors.

3.4.1 Overview and scope of IEC 61850

The IEC 61850 standard has 10 main parts as shown in Figure 3.9 below, which deal with different segments of the substation communication network (Saeed, 2015).

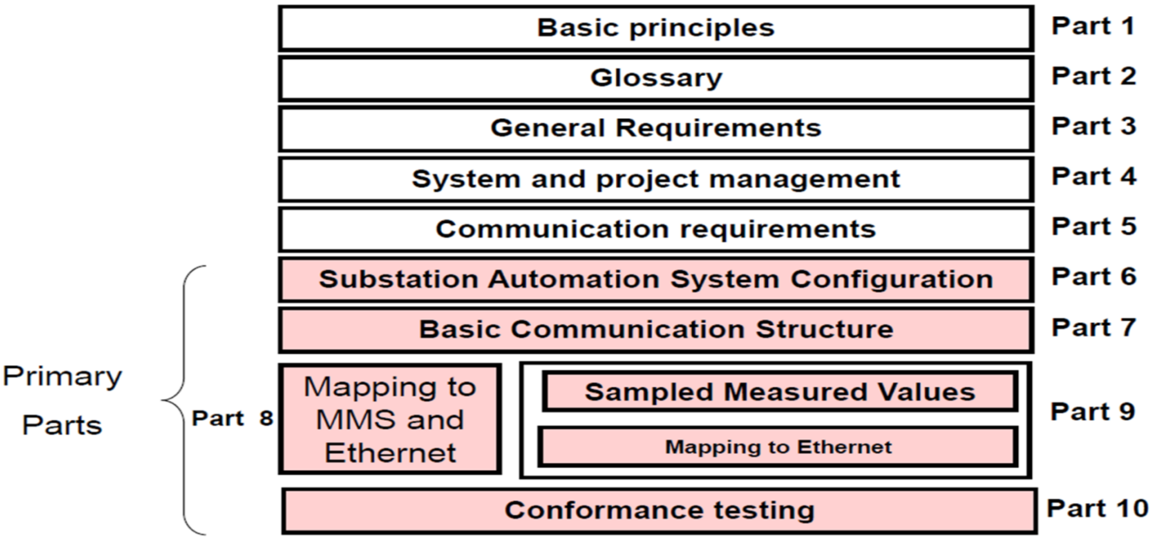


Figure 3.9: **IEC 61850 standard parts** (Saeed, 2015).

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.

Parts 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 (Saeed, 2015):

- 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.

3.5 IEC 61850 basic approach

Generally, the SASs performs functions such as data monitoring, switch control, and protection. These functions are broken down into sub-functions or low-level functions in IEC 61850 standard. The IEDs must be installed in the substation to perform each sub-function. A single IED can perform one or several sub-functions (Saeed, 2015). The sub-functions communicate with one another in substations through local area networks (LANs). The IEC 61850 standard defines specific syntax and semantics for communication between sub-functions. This standard provides all the information required by every substation. The sub-functions are allocated at three levels, namely process level, bay/unit level, and station level. The functions in these levels are explained in detail in the section below (Saeed, 2015).

3.5.1 IEC 61850 standard architecture

The IEC 61850 standard defines substation automation with three different levels as seen in Figure 3.10 below (Saeed, 2015):

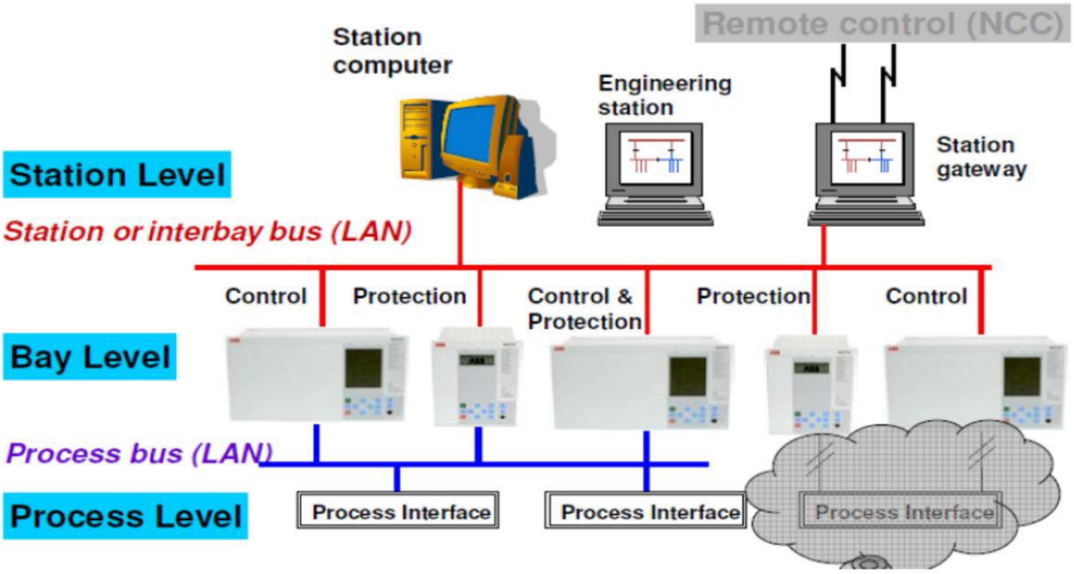


Figure 3.10: **IEC 61850 architecture** (Saeed, 2015).

- Process level

It has functions that interact with the process which are usually binary and analog inputs/outputs including data acquisition and issuing of commands. This level has instruments which are VTs, CTs, power transformers, circuit breakers, and isolators.

They are the primary instruments of the power system network. They send data to the IEDs in the ‘Bay Level’ through the interfaces and the process bus Ethernet connection. The functions for this level are mostly applied in the bay-level IEDs.

- Bay level

  This is the high-voltage switching part in a substation where power lines and transformers are connected to the substation busbar. The IEDs at this level decide which actions to be done when they receive data from the process-level instruments.

- Station level

  This level provides monitoring of the power network. It also sends commands to the IEDs for the desired network configuration.

In this research project, the proposed busbar protection scheme is implemented at the station level.

3.6 IEC 61850 communication stack

The IEC 61850 standard communication profiles are very significant. Several protocols make up these communication profiles. Part 8-1 describes the mapping of communication services to the Manufacturing Message Specifications (MMS) over Ethernet (Mguzulwa, 2018). The mapping of communication services is depicted in Figure 3.11 below. When messaging types have similar performance requirements, they are grouped and mapped to one protocol (Saeed, 2015).

Time-critical messages are mapped together to GOOSE including type 1 and 1A messages. Additionally, they are directly mapped to Ethernet to reduce processing time incurred by network and transport layers protocols. Raw messages are mapped to SMV protocol which was created to convey raw data such as type 4 messages. Similarly, these messages are mapped directly to Ethernet to accomplish time-critical performance. Type 6 messages maintain the synchronization of time and are mapped to the Simple Network Time Protocol (SNTP). Types 2, 3, and 5 messages are for supporting core IEC 61850 services and are mapped to MMS.

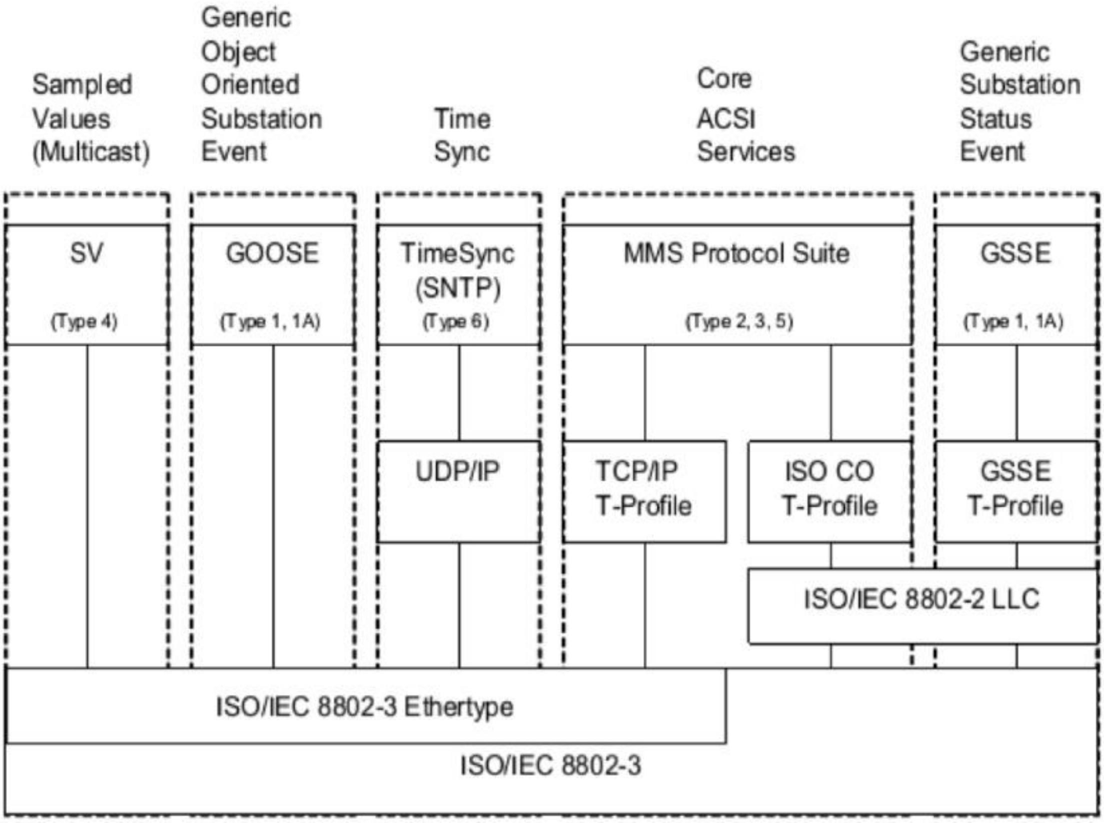


Figure 3.11: **IEC61850 overview of functionality and profile** (Saeed, 2015).

Figure 3.12 below describes the Specific Communication Service Mapping (SCSM) of IEC 61850 data models to the layers of the Open Systems Interconnect (OSI) communication model (Mnguni, 2014).

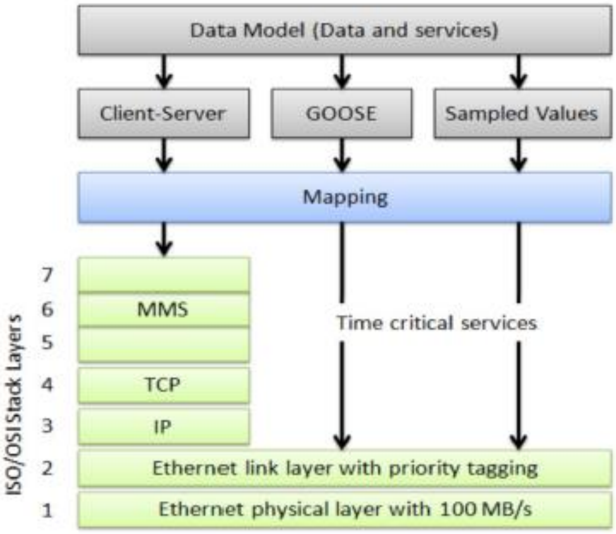


Figure 3.12: **Mapping IEC 61850 to the OSI stack** (Saeed, 2015).

The IEC 61850 standard was created to avoid interoperability issues between different vendor devices. The approach taken to achieve interoperability is through the separation of the domain-related models from protocols, for both data and communication services. The OSI seven-layer stack is responsible for coding and decoding information into bit strings for communication over a serial link. This stack comprises MMS, Transmission Control Protocol (TCP), Internet Protocol (IP), and Ethernet layers. Only time-critical services, as seen in Figure 3.12, are directly mapped to the Ethernet link layer. The MMS application layer is mapped to all other services.

There are three communication profiles offered by IEC 61850 which are:

- Client-server communication
- GOOSE messages
- SMVs

In this research project, the GOOSE messaging communication protocol will be utilized as it is the fast communication method for IEDs.

3.6.1 GOOSE communication protocol

GOOSE is a communication method used as a replacement for hardwired control signal communication between IEDs for protection and interlocking purposes. Therefore, it is faster, more reliable, and more sensitive (Baningobera, 2018). It is used to distribute time-critical data such as switchgear status to IEDs. As well, GOOSE messages are used to broadcast control commands and blocking signals. This method uses the publisher/subscriber communication principle where both sending and receiving IEDs use a local buffer for data exchange (Saeed, 2015). It is the responsibility of the communication system to update the local buffers of the subscribers. The procedure is controlled by the Generic Substation Status Event (GSSE) control class in the publisher devices. The GOOSE messages contain information that allows the receiving devices to know not only when a status has changed but also when it last changed. Consequently, the receiving device can set local timers which are linked to a certain event. GOOSE communication is reliable and suitable for real-time protection functions (Gholizadeh, 2016).

3.7 IEC 61850 Substation Configuration Language Files

The SCL was developed based on the eXtensible Markup Language (XML) to enable the interchange of configuration data among different tools from multiple vendors. The SCL files are divided into four types, as illustrated in figure 3.13 below (Koshiishi et al., 2012):

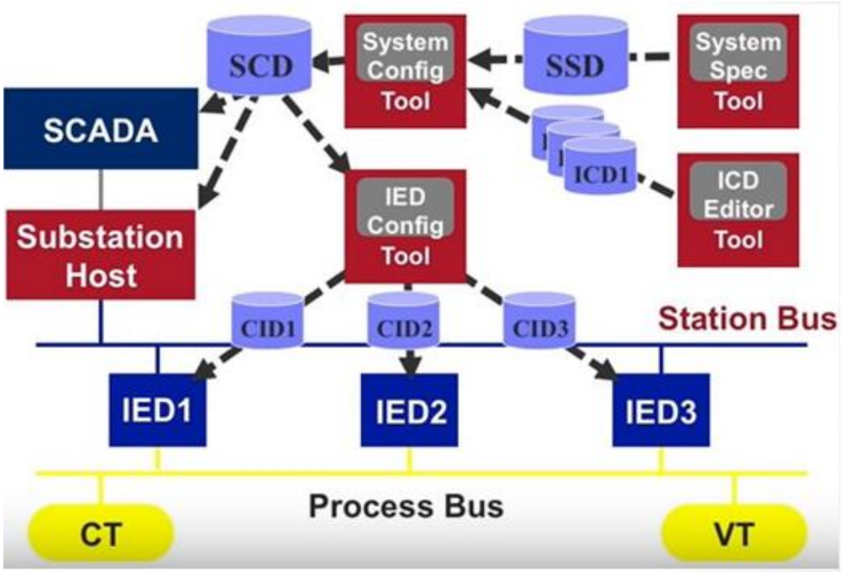


Figure 3.13: **SCL files** (Koshiishi et al., 2012).

1. **IED Capability Description (ICD) file** – provides information on LNs and GOOSE support, as well as IED capabilities.
2. **System Specification Description (SSD) file –** LNs and substation diagrams are described in this file.
3. **Substation Configuration Description (SCD) file –** carries information on all IEDs, communication configuration data, and substation descriptions.
4. **Configured IED Description (CID) file –** describes and contains address information for a single instantiated IED within the project.

The main function of SCL is to ensure interoperability between multi-vendor IEDs and the station computer. This is because each IED is configured by an individual configuration tool provided by its vendor. The ICD files are imported into IEC 61850 system configuration tools, which allows for the configuration of GOOSE messages by designating the publishers as "senders" and the subscribers as "receivers". The system configuration tool then creates the SCD file. It includes a description of GOOSE messages and a Single-Line Diagram (SLD) of the station. Each IED configuration tool must be able to import the SCD file and retrieve the required information for the IED. It must be able to combine all data into one SCL file to send it to another IED or a station computer (Koshiishi et al., 2012).

The SCL file is one of many benefits of the IEC 61850 standard, some of these benefits are stated in the section below.

3.8 The IEC 61850 standard benefits

The IEC 61850 specifies GOOSE messaging which is a peer-to-peer communication protocol that satisfies the stringent communication requirements within substation protection systems. It is a fast and reliable protocol for exchanging data between IEDs and other devices. The IEC 61850 has defined LNs that allow standardized interconnection of IEDs from multiple vendors for Substation Automation Systems. In addition, when using IEC 61850, wiring is reduced between devices and that simplifies engineering and operations processes (Chen, 2016).

3.9 Virtualization model

The basis of the IEC 61850 standard is achieving interoperability between IEDs from various manufacturers. Different Physical Devices (PDs) exchange data based on standardized information models and communication services, allowing interoperability between them. Virtualization refers to the ability to represent any PD in a virtual world. The virtualized model of the IEC 61850 standard is achieved through mapping to MMS where Virtual Manufacturing Device (VMD) model is used, as shown in figure 3.14 below (Saeed, 2015). One of the core functions of the IEC 61850 standard is to break down PDs into small entities which are called LNs.

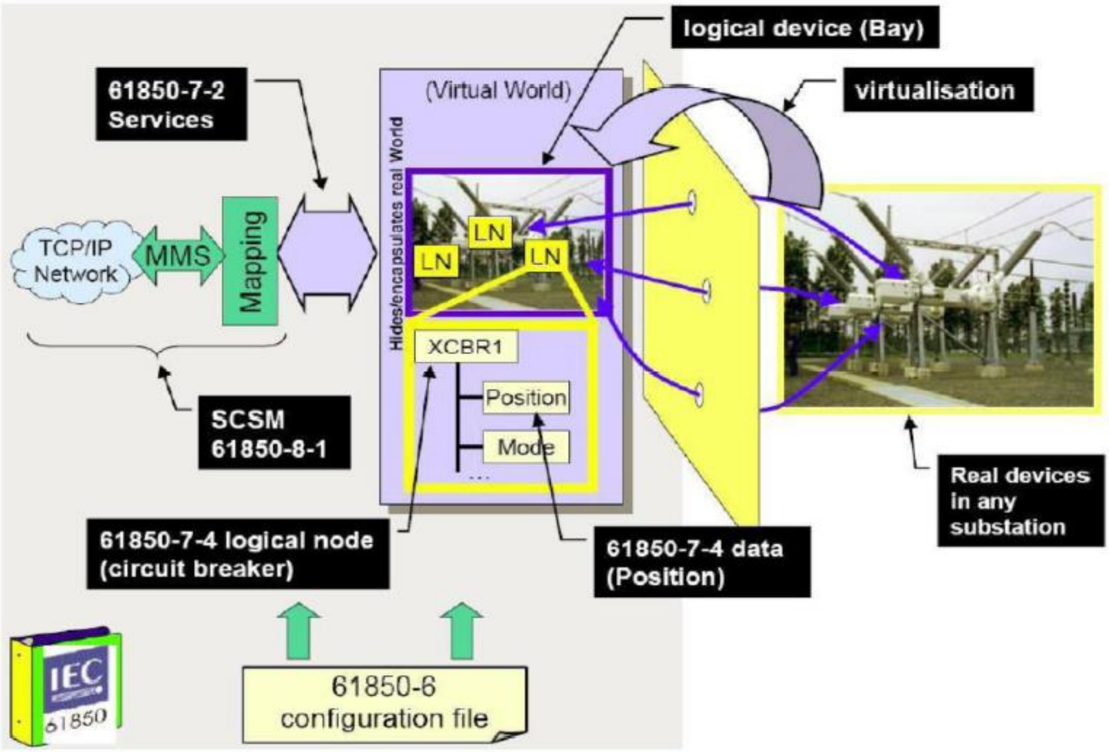


Figure 3.14: **Real World versus Virtual World** (Saeed, 2015).

The LNs are built by combining similar functions performed by multiple devices, and multiple LNs make up an LD. Virtualized representations of LDs are not necessarily representative of one PD. It mostly represents different LNs from different PDs. The LDs are not distributed and are usually implemented in one IED.

3.10 IEC 61850 object models

The IEC 61850 standard enables interoperability by defining functions as blocks which are referred to as object models as noted in figure 3.15 below.

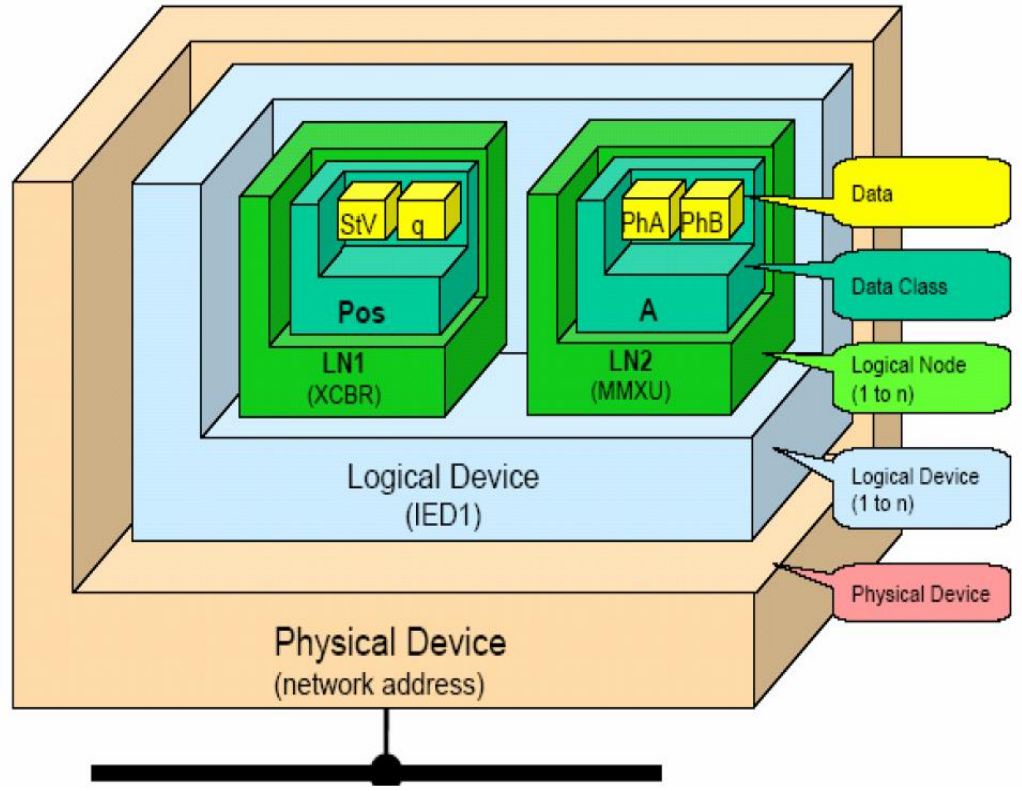


Figure 3.15: **Logical and Physical Devices** (Saeed, 2015).

According to (Mguzulwa, 2018), the model in figure 3.15 above, is a standard object modelling for all SASs. It consists of LDs, LNs, and Data Attributes (DAs). The model enables interoperability across devices from various vendors. However, the major challenge in realizing interoperability is that vendors have different interpretations of the IEC 61850 standard, which is the key motivation for this research study. The standard itself does not define how information should be interpreted, which causes incompatibility in the information exchange among IEDs from different vendors. (Saeed, 2015) has stated that the LNs are fundamental for information exchange inside SASs to accomplish interoperability.

3.10.1 Physical devices

The PD, also known as a server, represents the top tree structure of the object model in IEC 61850, as shown in figure 3.16 below. An electrical network comprises one or more IEDs that can connect and exchange information using a unique IP address.

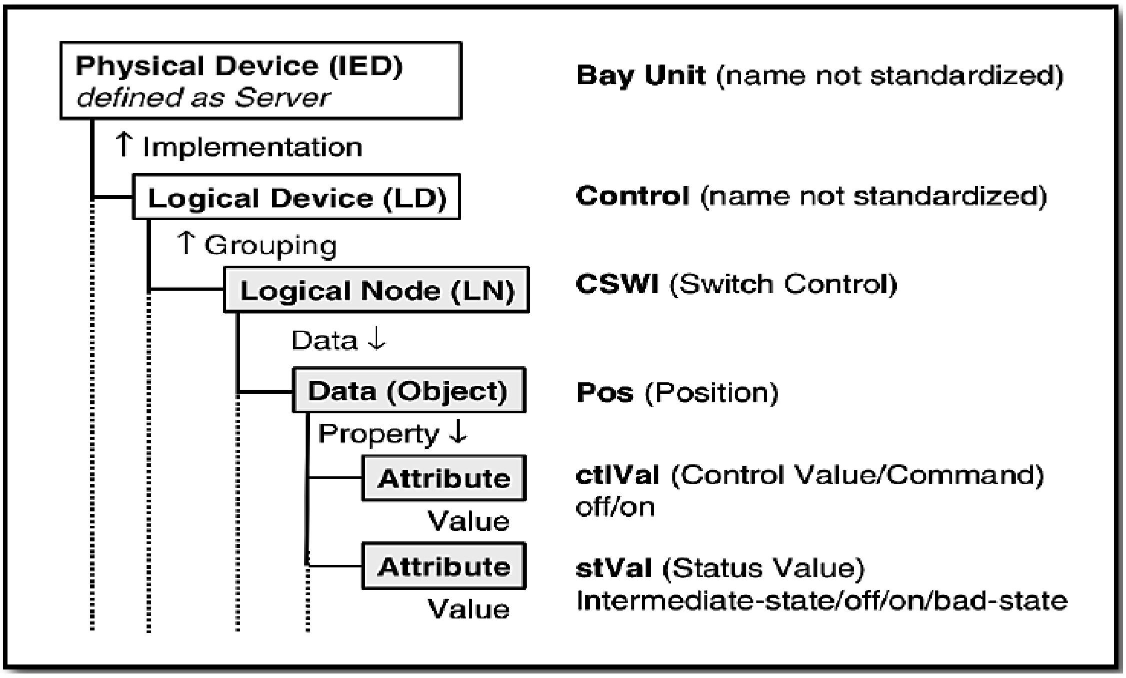


Figure 3.16: **IEC 61850 object model** (Nomandela, 2021).

3.10.2 Logical devices

The LD is located inside the PD and is regarded as the main entity of the object model. An LD consists of a group of LNs according to the outputs required by a certain device in the network. It is significant to understand that an IED has only one LD and does not involve LNs from other devices. It is also compulsory that each device must contain three LNs at least, as illustrated in figure 3.17 below. The relationship between common LNs is exposed to 'LLN0 and LPHD' corresponding to logical and physical devices, respectively (Saeed, 2015).

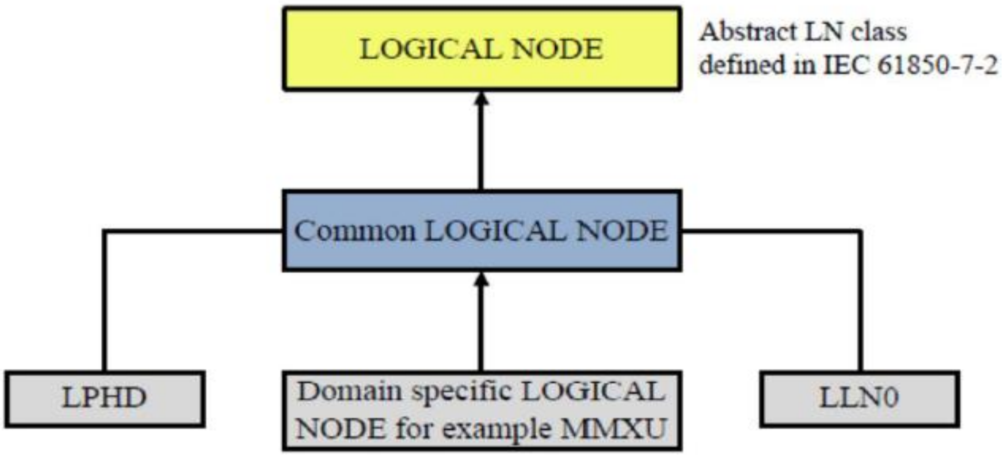


Figure 3.17: **Relationships of LNs** (Saeed, 2015).

3.11 Discussion

Various busbar protection schemes were discussed. According to the literature, the most common technique used for transmission busbar protection is differential protection. High and low impedance schemes were also discussed. The downside of using these schemes is that they require additional circuitry, which increases the complexity of the scheme. This also increases inaccuracy protection and low stability due to the multifunctionality of its components. In addition, some circuits connected to the busbar may have undersized current transformers. This poses a risk of CT saturation and threatens the safety of busbar protection. Digital busbar protection was also discussed. Its advantage is that data is transmitted over high-speed fiber to the central processing unit (CPU). Hence, this study also focuses on deploying a digital busbar protection scheme. It was also observed that the following factors are possible contributing factors to interoperability issues of multivendor IEDs. They are as follows:

- IEC 61850 standard defines several information models “logical nodes” and communication services for the realization of a specific function.
- According to the standard, each logical node contains several mandatory and optional signals.
- There are some parts of the standard, where logical nodes are not clearly defined for the realization of specific functions.
- The existing IEC 61850 data models do not give a complete representation of all protection settings currently employed by each manufacturer, causing IED suppliers to choose proprietary file formats.
- The data model needs to be extended in the future to cover all protection functions.

That is the reason why interoperability issues of multivendor IEDs will be looked at in this dissertation.

The following section concludes the chapter.

3.12 Conclusion

This chapter provided a theoretical background on the protection functions of busbars, their types, and their applications in a transmission environment. A theoretical explanation of the aspects of busbar protection study that need to be understood in order to use various schemes is provided. The theory of generations of protective relays was discussed in this chapter. Information on the IEC 61850 standard and interoperability of multi-vendor IEDs was also presented. IEC 61850 standard communication profiles were discussed as well in this chapter. Theory on the IEC 61850 communication stack and IEC 61850 Substation Configuration Language Files was also provided. The benefits of using the IEC 61850 standard, Virtualization model, and IEC 61850 object models were discussed as well.

The theory covered in this chapter confirms what the authors were saying in the literature review in chapter 2. IEC 61850 standard-based bus protection schemes are the future, it has several significant advantages over traditional bus differential protection devices, reduced copper wiring, installation, maintenance, and commissioning costs, ease of adaptation to changing bus configurations in the substation, and the practical elimination of CT saturation.

It is also clear from the theory covered in this chapter that the solution to interoperability problems for multi-vendor IEDs is the utilisation of the IEC 61850 standard. This standard satisfies the stringent communication requirements within substation protection systems, as it uses a GOOSE messaging peer-to-peer communication protocol. This is a fast and reliable protocol for data exchange between IEDs and other devices.

The next chapter discusses the load flow studies and contingency analysis of the modelled network. They are crucial in the planning, designing, and operation stages of the power system networks.

CHAPTER FOUR

LOAD FLOW STUDIES AND CONTINGENCY ANALYSIS OF THE MODELLED NETWORK

4.1 Introduction

Load flow is the terminology used for the power flow from one source or more to the loads where energy is consumed (McFadden, 1980). The direction and the amount of power flowing in the path or branch can be shown in the single-line diagram map, which is a simplified model of a balanced 3-phase power system network. The power flows directly to the loads in the radial network with no parallel paths. However, it is rare to find a power system network with no parallel paths nowadays due to the complexity of modern power networks. The power flow in the network is divided into branches based on their respective impedances until a voltage balance is reached according to Kirchhoff's law (Ratshitanga, 2018).

The flow of power will remain balanced as long the network configuration stays unchanged. It will only change if the network configuration is modified or generation is shifted, and load requirements are adjusted. It changes each time when a power-consuming device is switched on or off. Load flow analysis is significant in power systems' planning, designing, and operation stages. It determines the steady-state performance of the power system. The power flow analysis focuses on the calculation of power flow and voltages of the power system at the nodes or branches. (Ratshitanga, 2018) has stated that for the power flow to be deemed successful it must meet the following requirements:

- Generation to supply the load and network losses to be considered.
- Voltage magnitudes of buses to remain close to rated values.
- Operation of generators to stay within specified power limits.
- No overloading of transformers, transmission lines, and cables.

Load flow studies are done to assess the technical capability of a power network under steady-state or fault conditions. The software that is used in this chapter for power flow calculations is DIgSILENT PowerFactory software. It is a computer-aided software engineering tool used for the analysis of the transmission and distribution of electrical networks. It was designed to solve power system modelling and simulation problems (Ratshitanga, 2018).

The chapter is structured as follows, load flow studies are introduced in section 4.1, and transmission network modelling is presented in section 4.2. Contingency analysis of the used IEEE nine bus system is outlined in section 4.3. Load flow calculations of the modified IEEE nine bus network are exhibited in section 4.4 Discussion of the results in section 4.5 and the conclusion in section 4.6.

4.2 Transmission network modelling of the IEEE nine bus system.

This chapter presents an IEEE nine bus power system model, the selected network for the research project. A load flow analysis on the network model was performed using DIgSILENT PowerFactory software to examine the system's steady state performance. Such analysis is required throughout transmission network planning, control, and operation. This load flow calculation focuses on finding the magnitude voltage (V) of the node, and voltage angle, as well as the active (P) and reactive (Q) power flow on all branches. The method used to perform these load flow calculations in a balanced network is the Newton-Raphson method.

The chosen IEEE nine bus system consists of 3 transformers, 3 loads, 9 busbars, 6 lines, and 3 synchronous machines as shown in Figure 4.1 below.

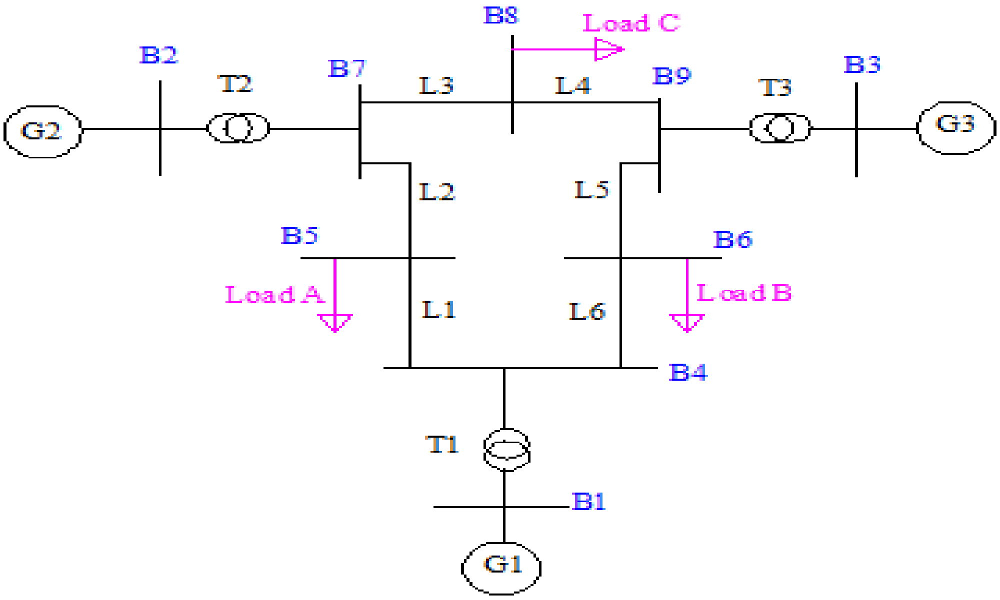


Figure 4.1: **Single-line diagram of the chosen IEEE nine bus network** (Abul et al., 2019).

The next section explains the contingency analysis which is done to evaluate the consequences of power system failures that could arise in the near future. It is also an important exercise to do in order to identify the critical busbar of the IEEE nine bus power system.

4.3 Contingency analysis of the IEEE nine bus system using DIgSILENT Power Factory

The network behaviour must always be analysed for both normal and abnormal conditions. Contingency analysis is the term related to abnormal conditions of the system (DIgSILENT, 2018). Contingency analysis is done to assess the security degree of an electrical power system (Gonzalez-Longatt & Rueda, 2014). It becomes a crucial problem for the daily operation of power system networks if the contingency cases are not investigated. A criterion that is commonly used is evaluating the contingencies for a single outage of any equipment including generators, transformers, and transmission lines, and assessing the post-contingency state of the power system network. This is recognized as the ‘n-1’ contingency case. Another criterion is estimating the contingencies of a double outage of any system element and evaluating the post-contingency state of the system. This is said to be the ‘n-2’ contingency case. Both cases were analysed in this research study to evaluate the post-contingency state of the network after an outage of one or two system elements. Additionally, they were analysed to assess the most crucial busbar in the IEEE nine bus system. The results for both contingency cases “n-1 and n-2” are presented in sections 4.3.1 and 4.3.2.

4.3.1 Contingency case for ‘n-1’

The n-1 contingency case was performed on the network model to assess the worst violated components in the power network. According to IEEE standard 141-1993, the busbar voltages must not exceed the maximum voltage limit of 1.05 per unit (pu) and must not violate the minimum voltage limit of 0.95 pu with a +/-5% tolerance limit (Cooper, 1988). As seen in table 4.1 below, it is evident from the analysis results that, the minimum voltage limit of 0.9 pu is violated under the ‘n-1’ contingency case. Busbar 6 was discovered as the worst violated busbar in terms of minimum voltage limit when transformer 1 ‘T1’ is out of service. It was violated with 19.1% “0.759 pu” which was outside the 5% limit as per IEEE standard 141-1993 (Cooper, 1988). Another thing that was observed is the loading of generators and transformers. The loading limit for generators and transformers was 75% according to the network and grid planning standard (Dedekind, 2019). It is evident from the results shown in table 4.2 below that, the loading limits were violated. Transformer 2 ‘T2’ is the worst violated apparatus in terms of loading limit when ‘T1’ is out of service. It is 79% loaded and which is more than the 75% loading limit.

Table 4.1: Contingency analysis report (n-1): worst voltage violations “Min. voltage”.

	Component	Voltage Min. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Contingency Number	Contingency Name	Base Case and Post Voltage [0.759 p.u. - 1.040 p.u.]
1	Bus 6	0.759	-0.254	1.013	10	T1	🟥🟩
2	Bus 5	0.765	-0.230	0.996	10	T1	🟥🟩
3	Bus 1	0.768	-0.272	1.040	7	G1	🟥🟩
4	Bus 4	0.768	-0.258	1.026	10	T1	🟥🟩
5	Bus 3	0.831	-0.194	1.025	10	T1	🟥🟩
6	Bus 9	0.841	-0.191	1.032	10	T1	🟥🟩
7	Bus 8	0.873	-0.143	1.016	10	T1	🟥🟩
8	Bus 7	0.927	-0.099	1.026	10	T1	🟥🟩

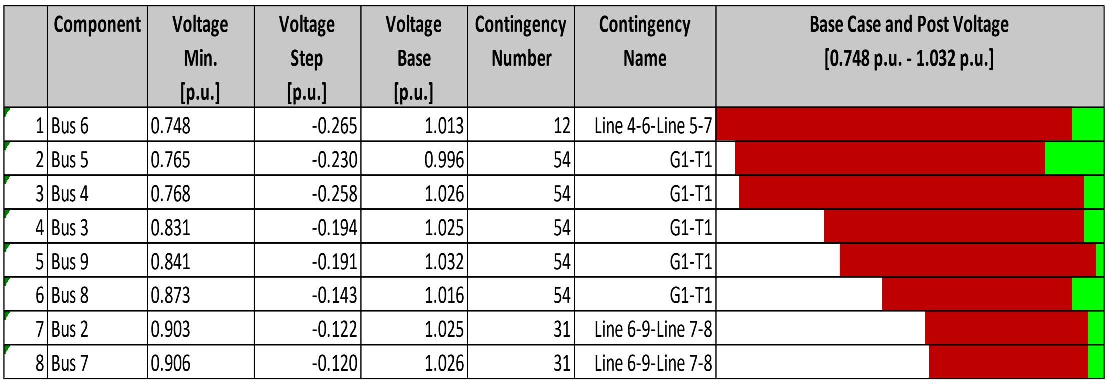
Table 4.2: Contingency analysis report (n-1): Worst loading violations.

	Component	Loading Continuous [%]	Loading Short-Term [%]	Loading Base Case [%]	Contingency Number	Contingency Name	Base Case and Continuous Loading [0 % - 149 %]
1	T2	149.0	149.0	79.6	10	T1	🟩🟥
2	T1	93.5	93.5	29.5	8	G2	🟩🟩▨

4.3.2 Contingency case for ‘n-2’

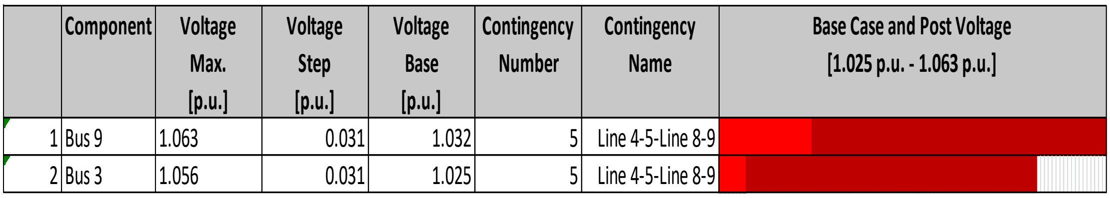
The ‘n-2’ contingency case was performed to assess the worst violated components in the power network. Based on the contingency analysis reports shown in tables 4.3 and 4.4 below, the minimum and maximum voltage limits were violated. All the busbar voltages are below the minimum voltage limit of 0.95 pu in table 4.3. The worst violated busbar in terms of minimum voltage limit is busbar 6 which was violated with the value of 0.748 pu. This case happened when lines 4-6 and 5-7 are out of service. It can be seen that two busbars are affected in terms of the maximum voltage limit which are busbars 9 and 3 as shown in table 4.4. The busbar with the worst violated voltage is busbar 9 and is violated with the value of 1.063 pu when lines 4-5 and 4-9 are out of service. The contingency analysis report for worst loading violations was generated and the results are shown in table 4.5 below. As mentioned in section 4.3.1, the loading limit for generators and transformers is 75%. There are 3 components with loading violations which are ‘T1’, ‘T2’, and ‘T3’. The transformer with the worst violated loading limit is ‘T3’ with a loading of 79.6%. That is the post-contingency state when generator 1 ‘G1’ and ‘T1’ are out of service.

Table 4.3: Contingency analysis report (n-2): worst voltage violations "Min. voltage".



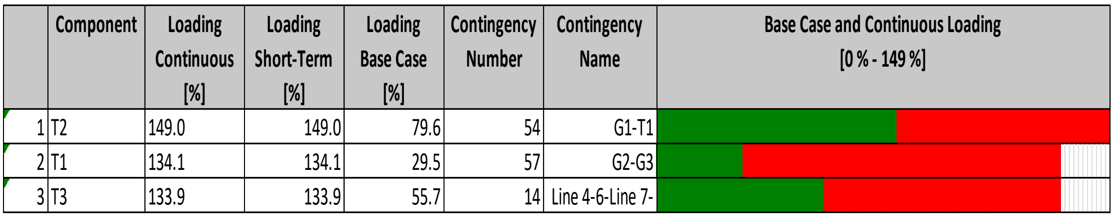
	Component	Voltage Min. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Contingency Number	Contingency Name	Base Case and Post Voltage [0.748 p.u. - 1.032 p.u.]
1	Bus 6	0.748	-0.265	1.013	12	Line 4-6-Line 5-7	🟥🟩
2	Bus 5	0.765	-0.230	0.996	54	G1-T1	🟥🟩
3	Bus 4	0.768	-0.258	1.026	54	G1-T1	🟥🟩
4	Bus 3	0.831	-0.194	1.025	54	G1-T1	🟥🟩
5	Bus 9	0.841	-0.191	1.032	54	G1-T1	🟥🟩
6	Bus 8	0.873	-0.143	1.016	54	G1-T1	🟥🟩
7	Bus 2	0.903	-0.122	1.025	31	Line 6-9-Line 7-8	🟥🟩
8	Bus 7	0.906	-0.120	1.026	31	Line 6-9-Line 7-8	🟥🟩

Table 4.4: Contingency analysis report (n-2): worst voltage violations "Max. voltage"



	Component	Voltage Max. [p.u.]	Voltage Step [p.u.]	Voltage Base [p.u.]	Contingency Number	Contingency Name	Base Case and Post Voltage [1.025 p.u. - 1.063 p.u.]
1	Bus 9	1.063	0.031	1.032	5	Line 4-5-Line 8-9	🟥🟥
2	Bus 3	1.056	0.031	1.025	5	Line 4-5-Line 8-9	🟥🟥

Table 4.5: Contingency analysis report (n-2): worst loading violations.



	Component	Loading Continuous [%]	Loading Short-Term [%]	Loading Base Case [%]	Contingency Number	Contingency Name	Base Case and Continuous Loading [0 % - 149 %]
1	T2	149.0	149.0	79.6	54	G1-T1	🟩🟥
2	T1	134.1	134.1	29.5	57	G2-G3	🟩🟥
3	T3	133.9	133.9	55.7	14	Line 4-6-Line 7-	🟩🟥

Based on the contingency analysis cases "n-1 and n-2" explained in section 4.3 above, busbar 6 was found to be the most crucial busbar of the network, therefore, it is chosen to implement the protection scheme in this research project. The data of the IEEE nine bus system needed for the preparation of load flow calculations are provided in the appendix. The performed load flow calculations are described in the next section to assess the steady-state operation of the chosen network.

4.4 Load flow calculations of the modified IEEE nine bus system using DIgSILENT PowerFactory

Load flow calculations are performed to evaluate the steady-state operation of an electrical power system network. They are used to assess if the system voltages remain within acceptable limits of +/-5% as per IEEE standard 141-1993 under normal and contingency conditions (Cooper, 1988). They evaluate if generators, transformers, and transmission lines are not overloaded. Lastly, load flow calculations are necessary for the planning of an existing power network and its future growth. Figure 4.2 below shows that the load flow calculations performed on DIgSILENT are successfully executed and that the network is balanced. The results from the simulation prove that the voltages on busbars are operating within an acceptable range and that there is no overloading of equipment such as transformers and transmission lines. The busbar highlighted in red in Figure 4.2 below is the modified busbar in the IEEE nine bus network and is the focus area for this research project. It was chosen based on the contingency analysis explained in section 4.3 above.

Busbar 6 is modified by introducing two section breakers “refer to figure 4.1” and splitting the busbar into two sections “NorthBus and SouthBus” as shown in figure 4.2 below. The existing load ‘load b’ which is connected to bus 6 is then equally divided into two loads “load 1 and load 2”. This is done so that when there is a fault on busbar 6, only one load is disconnected. This means that the supply will only be interrupted to half of the load connected to busbar 6 during a fault condition.

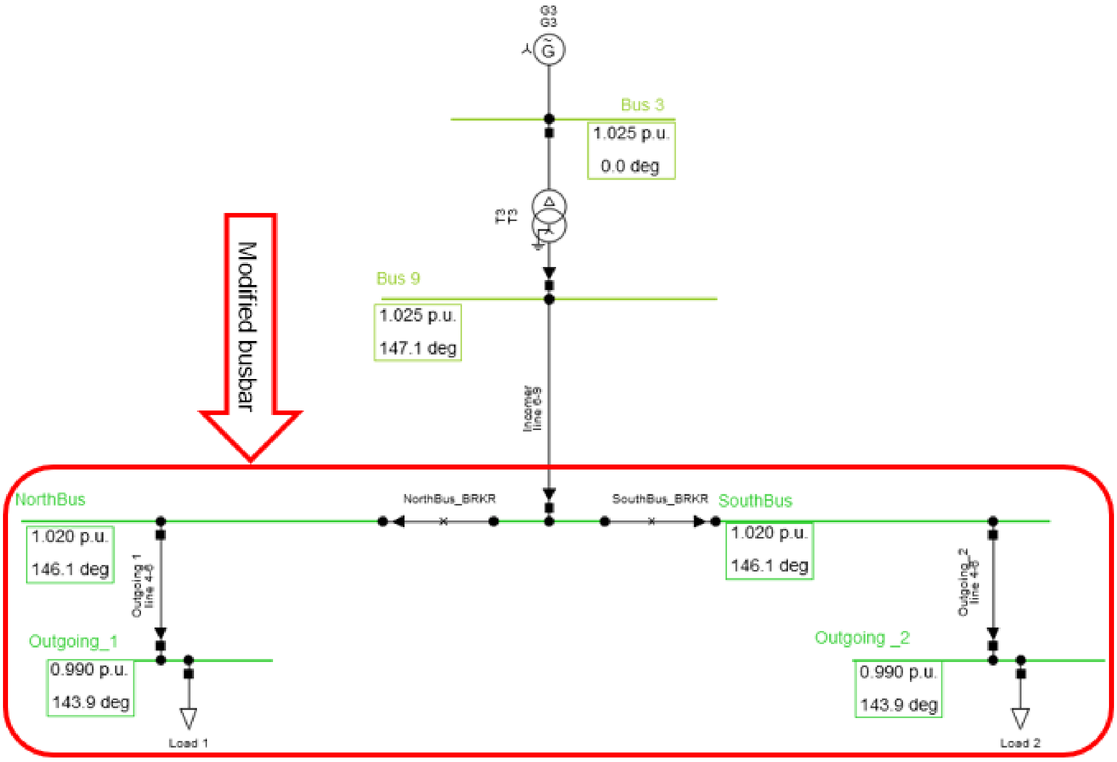


Figure 4.2: **Single line diagram of the load flow simulation for the studied transmission system network.**

The waveforms shown in figure 4.3 below represent 3-phase voltages after the load flow is successfully executed. Where red colour represents phase A, yellow represents phase B, and blue represents phase C. These waveforms were captured during the steady-state condition in the transmission network. Table 4.6 below shows load flow results for different voltage levels in the network from bus 1 up to load bus 2. Table 4.7 below shows that the load flow results for bus voltages are operating within an acceptable range of +/-5% as per IEEE standard 141-1993 voltage regulation (Cooper, 1988).

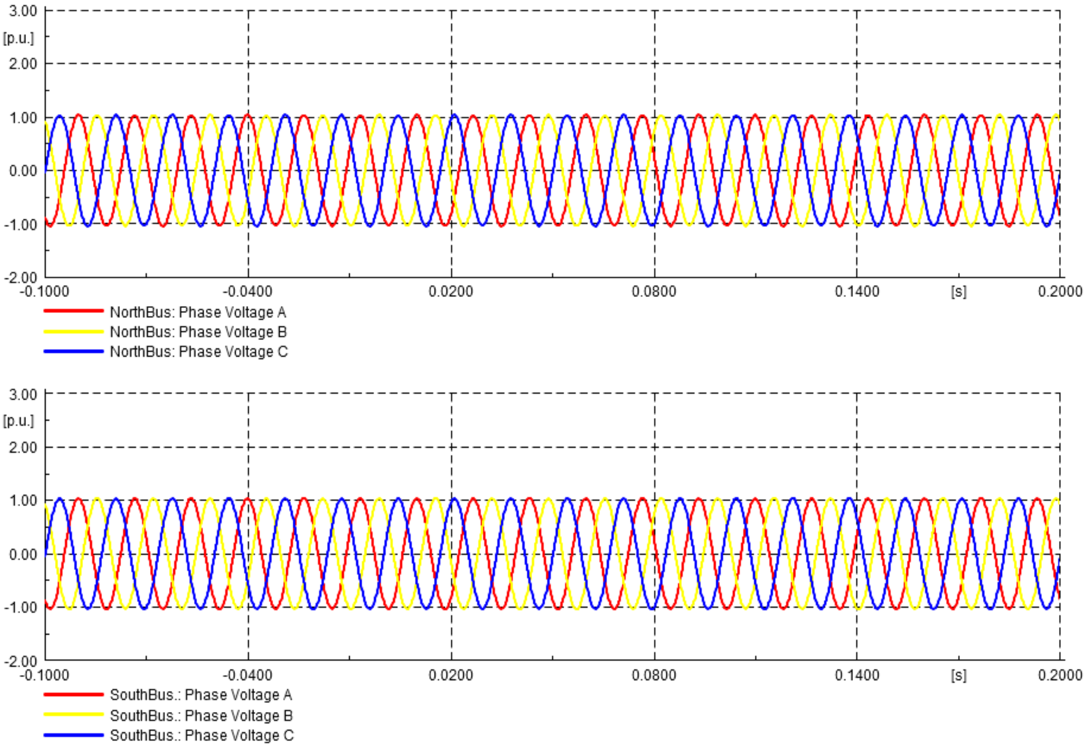


Figure 4.3: **Simulated three-phase voltages for the chosen busbar network.**

According to (YUN, 2015), a three-phase system is considered balanced or symmetrical if the three-phase voltages and currents have the same magnitude and are phase shifted by 120° with regard to each other; if any or both of these conditions are not met, the three-phase system is called non-balanced or asymmetrical. Voltage imbalance is a recognized power quality criterion that signifies the phase voltages have different magnitudes or the phase differences between consecutive voltages are less than 120° in a three-phase system.

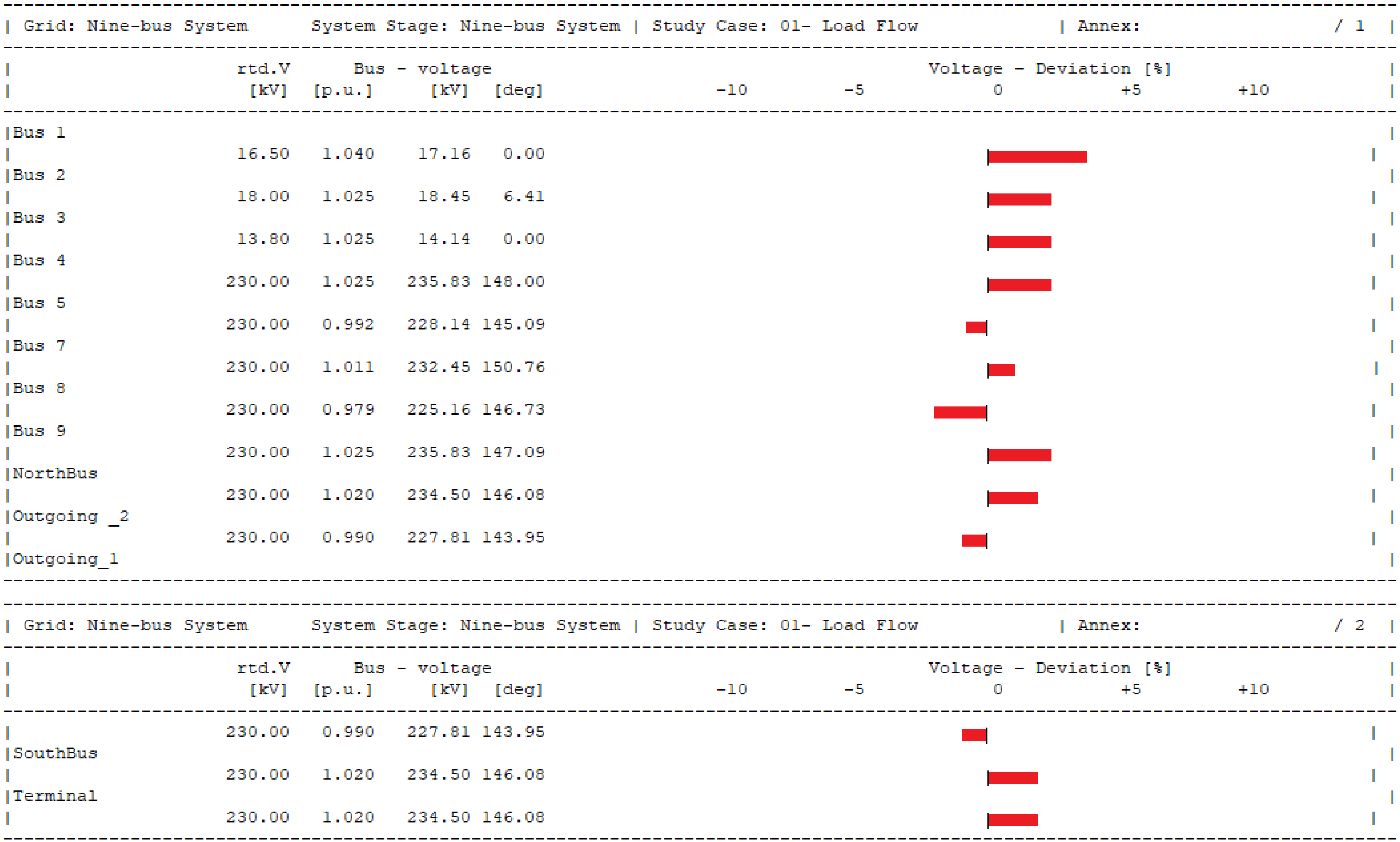
The simulation results shown by the waveforms in figure 4.3 above prove that the three-phase system is balanced or symmetrical. The magnitudes of voltages at bus 6 are equal with a phase shift of 120 degrees.

Table 4.6: Load flow results for different voltage levels in the network.

Name	Grid	Nominal L - L Volt.	V(actual)	V (pu)	V (angle)
		kV	kV	pu.	deg
Bus 1	Nine - Bus System	16.5	17.16	1.04	0
Bus 2	Nine - Bus System	18.0	18.45	1.025	9.3
Bus 3	Nine - Bus System	13.8	14.14	1.025	4.7
Bus 4	Nine - Bus System	230.0	235.83	1.025	148.0
Bus 5	Nine - Bus System	230.0	228.14	0.992	145.1
NorthBus	Nine - Bus System	230.0	234.50	1.020	146.1
SouthBus	Nine - Bus System	230.0	234.50	1.020	146.1
Bus 7	Nine - Bus System	230.0	232.45	1.011	150.8
Bus 8	Nine - Bus System	230.0	225.16	0.979	146.7
Bus 9	Nine - Bus System	230.0	235.83	1.025	147.1
Load 1	Nine - Bus System	230.0	227.81	0.990	143.9
Load 2	Nine - Bus System	230.0	227.81	0.990	143.9

The results from table 4.7 show the voltage profile of the IEEE nine bus system. All the busbars are operating within the maximum voltage limit of 1.05 pu and the minimum voltage limit of 0.95 pu.

Table 4.7: Load flow results for bus voltages in the network.



```
------------------------------------------------------------------------------------------------------------------------------
| Grid: Nine-bus System      System Stage: Nine-bus System | Study Case: 01- Load Flow             | Annex:                / 1  |
------------------------------------------------------------------------------------------------------------------------------
|                     rtd.V       Bus - voltage                                Voltage - Deviation [%]                       |
|                      [kV]  [p.u.]       [kV]   [deg]            -10          -5            0           +5          +10       |
------------------------------------------------------------------------------------------------------------------------------
|Bus 1                                                                                                                       |
|                     16.50   1.040     17.16    0.00                                                                       |
|Bus 2                                                                                                                       |
|                     18.00   1.025     18.45    6.41                                                                       |
|Bus 3                                                                                                                       |
|                     13.80   1.025     14.14    0.00                                                                       |
|Bus 4                                                                                                                       |
|                    230.00   1.025    235.83  148.00                                                                       |
|Bus 5                                                                                                                       |
|                    230.00   0.992    228.14  145.09                                                                       |
|Bus 7                                                                                                                       |
|                    230.00   1.011    232.45  150.76                                                                       |
|Bus 8                                                                                                                       |
|                    230.00   0.979    225.16  146.73                                                                       |
|Bus 9                                                                                                                       |
|                    230.00   1.025    235.83  147.09                                                                       |
|NorthBus                                                                                                                    |
|                    230.00   1.020    234.50  146.08                                                                       |
|Outgoing _2                                                                                                                 |
|                    230.00   0.990    227.81  143.95                                                                       |
|Outgoing_1                                                                                                                  |
------------------------------------------------------------------------------------------------------------------------------
------------------------------------------------------------------------------------------------------------------------------
| Grid: Nine-bus System      System Stage: Nine-bus System | Study Case: 01- Load Flow             | Annex:                / 2  |
------------------------------------------------------------------------------------------------------------------------------
|                     rtd.V       Bus - voltage                                Voltage - Deviation [%]                       |
|                      [kV]  [p.u.]       [kV]   [deg]            -10          -5            0           +5          +10       |
------------------------------------------------------------------------------------------------------------------------------
|                    230.00   0.990    227.81  143.95                                                                       |
|SouthBus                                                                                                                    |
|                    230.00   1.020    234.50  146.08                                                                       |
|Terminal                                                                                                                    |
|                    230.00   1.020    234.50  146.08                                                                       |
------------------------------------------------------------------------------------------------------------------------------
```

The following section provides points of discussion on the simulation and load flow results.

4.5 Discussion of Results

One of the analyses of power system security assessment is contingency analysis. A power system is operationally secure if blackouts or equipment damage are unlikely. The analysis of the contingency cases “n-1 and n-2” were performed using DIgSILENT PowerFactory software. These contingency cases were executed to evaluate equipment loading and assess busbars with voltage violation limits. These studies are a major activity to understand which busbar is critical in the power system network. Additionally, these contingency analyses assist in strengthening the initial basic power system planning. NRS048 standard stipulates that transmission busbars should operate at a range of 0.95 to 1.05 pu. If the voltage at the buses falls below 0.95 pu, it is said to have a low voltage. If the bus voltage exceeds 1.05 pu, It is regarded as a busbar with a high voltage problem. Based on the simulation results in Tables 4.1 and 4.3 above, the busbar with the worst voltage violations for both n-1 and n-2 contingency cases is busbar 6. The minimum voltage limit of 0.95 pu was violated in both contingency cases as the voltages were 0.759 pu and 0.748 pu. The simulation results proved that busbar 6 is the critical busbar as it experienced the worst voltage violations after contingency cases were performed. Hence, it was a chosen busbar to protect in this research protect. System security entails methods that are specifically designed to survive in imminent disruption scenarios (contingencies) without jeopardizing safety, dependability, or customer service. According to authors (MOLLA & BASU, 2020), if violations or faults continue in a system, the system might become unstable and later on experience blackouts. Hence, it is critical to have a power system that is safe, dependable, continuous, and economical to operate. Severe contingencies must first be identified, and then fast, secure, dependable, and continuous operation is required. Part of the power system analysis involves load flow studies.

Load flow simulations were done using DIgSILENT and the results were analysed. The simulation studies were performed to assess the stability of the IEEE Nine-bus system during normal operating conditions. It is evident from the simulation results in Table 4.7 above that the network is stable. The voltages at busbars are all within the voltage deviation of +/-5%.

4.6 Conclusion

Two contingency cases were investigated in this chapter. The ‘n-1’ contingency case assesses the state of the power system network after a single outage of any component. The ‘n-2’ contingency case evaluates the post-contingency state of a power system network after a double outage of any system element. The study network was chosen based on the simulation results from both contingency cases. The contingency analysis reports “for both n-1 and n-2 cases” obtained from DIgSILENT simulations show that the most crucial busbar of the IEEE Nine-bus network is busbar 6. Hence it was the chosen busbar for this research project. Protection settings and interoperability testing were demonstrated using busbar 6.

Load flow simulations were also performed in this chapter using DIgSILENT PowerFactory software. They were performed to assess if the system voltages would remain within acceptable limits of +/-5% as per IEEE standard 141-1993 under normal and contingency conditions. The simulation results proved that the network is stable as the system voltages were within the acceptable limits of +/-5%.

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. In order to achieve interoperability between multi-vendor IEDs, the next chapter 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.

CHAPTER FIVE

IMPLEMENTATION OF IEC 61850 STANDARD BASED MULTI-VENDOR IEDs FOR BUSBAR PROTECTION SCHEME

5.1 Introduction

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. (Mnguni, 2014) 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 protecting 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.

Therefore, the main objective of this thesis was to achieve interoperability between IEDs (SEL-487 and ABB 615) that were used in the proposed busbar protection scheme. This chapter 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 was 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 was used as the main differential protection device and ABB REF615 IED as the backup protection device. These two protection devices had to be interoperable with each other, meaning they had to communicate with each other without any problems. The scheme was 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 were performed to verify the effectiveness of the scheme. The first case study was when the internal faults were simulated, and the blocking signal was 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 were simulated on the nine-bus power network modelled in Real-Time Digital Simulator (RTDS), and a Hardware-in-the-loop was the proposed test bench used to validate the proposed busbar protection scheme.

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

The chapter is structured as follows:

The functions and components of the Real-Time Digital Simulator (RTDS) are presented in section 5.2. The advantages of using RTDS are discussed in section 5.3. Implementation of the Hardware-in-the-Loop testing using the IEC 61850 standard is presented in section 5.4. The results are discussed in section 5.5. Section 5.6 concludes the chapter.

5.2 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. 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 (Baningobera, 2018).

The RTDS employs a unique hardware design for parallel computing, which is organized into racks. 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. 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. The hardware of RTDS is shown in Figure 5.1 below.

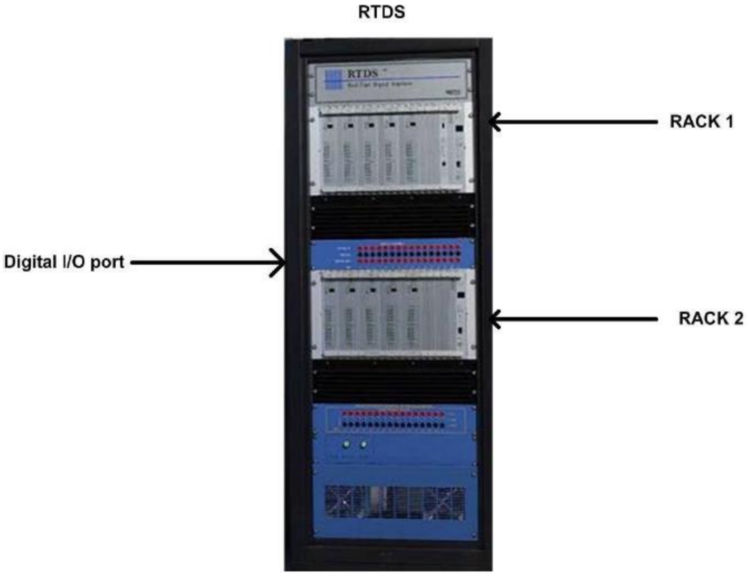


Figure 5.1: **RTDS hardware** (Baningobera, 2018).

The racks are positioned on the RTDS cubicle as shown in Figure 5.1 above. 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 RSCAD software package provides an innovative and simple Graphical User Interface (GUI) to the RTDS hardware. The software includes numerous modules that allow users to create, simulate, and analyse the simulation results on RTDS. Users can simulate electrical systems using components from graphical power and control system libraries. The RSCAD software allows a detailed definition of electrical system components parameters (Baningobera, 2018).

The next section of the chapter explains the advantages of using RTDS for testing.

5.3 Advantages of using RTDS

The RTDS simulates the power system network and produces the required voltages and current signals using Digital to Analog (D/A) converters and amplifiers as seen in Figure 5.2 below whereby the blue lines indicate inputs, whilst the red lines indicate outputs. The RTDS exchanges the status of the circuit breakers as well as the trip and recloses signals with under-test IEDs, using a binary input/output (I/O) interface. The

RTDS sends low-level signals to the amplifier, which amplifies the signals to a level that is compatible with IED's input circuits. One amplifier can generate only one group of voltage and current signals, which limits the capacity of the RTDS system for relay testing. As a result, only a limited number of relays may be connected to the RTDS system at any given moment (Chen, 2016).

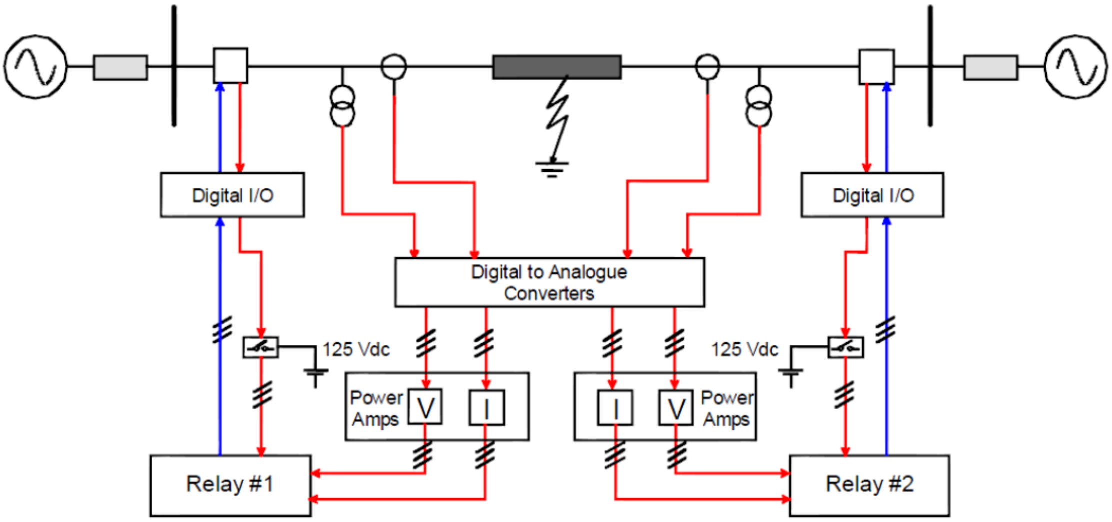


Figure 5.2: **Analog signals in a substation environment** (Chen, 2016).

The key benefit of using RTDS to test IEC 61850 systems is that analog and binary signals can be replaced by Ethernet as shown in Figure 5.3 below. All the hardwiring can be replaced by a single Ethernet cable usually connected between the simulator and the station bus LAN where the protection IEDs are connected. GOOSE messaging communication is fast as compared to hardwiring, its transfer of trip time is 3-10 milliseconds (ms) (Nomandela, 2021).

The GTNET card provides real-time communication via Ethernet from and to the simulator. Different firmware versions are utilized to support various communication protocols including IEC 61850 GOOSE messaging, SMV, Playback, and the Distributed Network Protocol (DNP3).

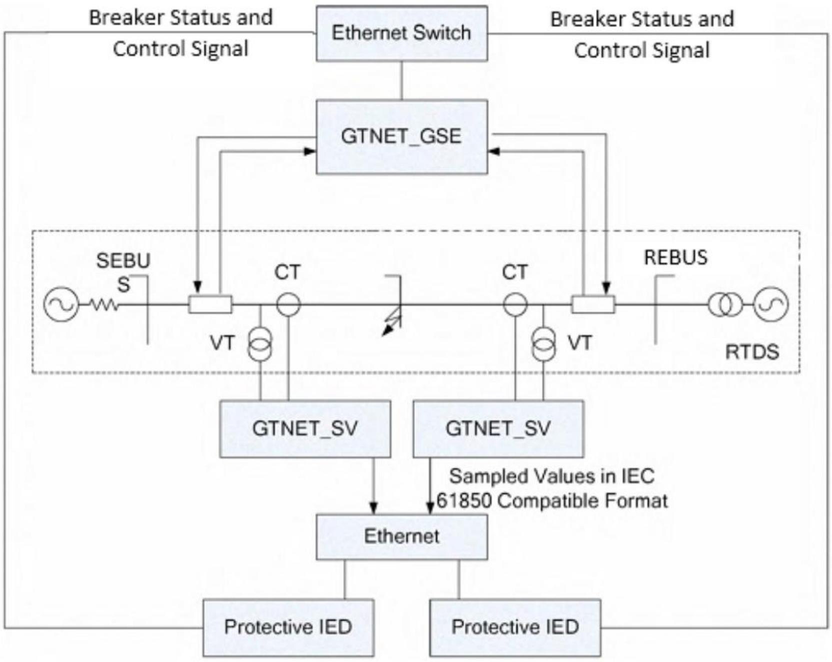


Figure 5.3: **RTDS system using GTNET** (Chen, 2016).

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

5.4 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. 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. 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 (Baningobera, 2018).

To achieve the HIL simulation in this research project, SEL-487B and REF615 IEDs were configured and interfaced with RTDS through three omicron amplifier devices, two CMS 156 and one CMS 356. The function of these amplifiers is explained in detail in section 5.4.3 below.

5.4.1 The setting of the power network model for the testbed

Busbar 6 from the IEEE nine bus system was chosen for this research project based on the contingency studies which were presented in Chapter 4. It is a single busbar arrangement configuration that consists of two bus sections namely ‘NorthBus’ and ‘SouthBus’ as shown in Figure 5.4 below. These bus sections are separated by two bus section breakers which split the busbar into two sections. The busbar is fed by a single incoming transmission line connected to busbar 9. There are also two outgoing transmission lines connected to busbar 6, namely ‘outgoing 1’ and ‘outgoing 2’. ‘Outgoing 1’ is connected to ‘NorthBus’ and supply ‘load 1’. ‘Outgoing 2’ is connected to ‘SouthBus’ and feeds into ‘load 2’. There are four Current Transformers used in this network, two located on the busbar and the other two located on the outgoing feeders. The purpose of these CTs is to measure current entering and leaving the busbar to enable the differential protection scheme, and to monitor fault currents in the system. There is a certain criterion to be followed to select the CTs.

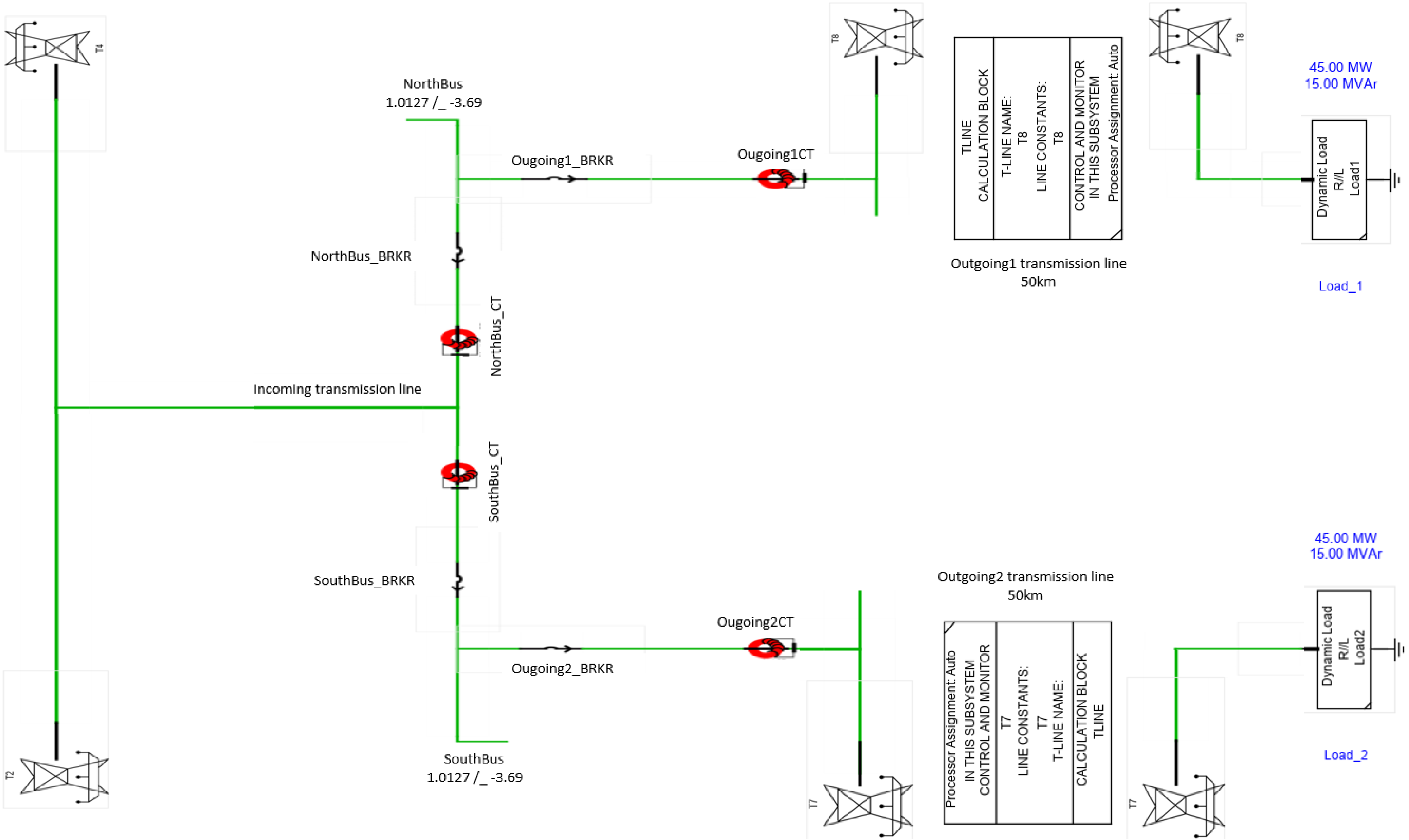


Figure 5.4: Modelled power network in RSCAD software environment.

The following section explains the criteria to be used when selecting a CT.

- The CT selection

The selection of CTs was done correctly to achieve proper current measurement in the network and retain the accuracy of differential protection calculations. The CT primary rating should range from 120% to 150% of the rated current of the object. The aim is to choose a CT with a large number of turns to keep the secondary current as small as possible to avoid CT saturation. Therefore, 150% of the rated current of the busbar was used as written in Equation 5.1 below.

$$CTPrimaryTurns = 150\% * I_{rated} \tag{5.1}$$

Where ‘$\boldsymbol{CTPrimaryTurns}$’ stands for CT turns ratio and ‘$\boldsymbol{I_{rated}}$’ is the rated current measured while the system is operating under steady-state conditions. The load current values of the system must be known to determine the CT turns ratio values. As a result, currents were measured from the system under normal load conditions, and the results are shown in Table 5.1 below. The values recorded in this table represent currents monitored in the branches supplying the system's protected busbar.

Table 5.1: Branch currents measured at the busbar.

Branches	Primary currents (kA)
INorthBus_BRKR	0.1244
ISouthBus_BRKR	0.1244
ILoad1	0.1244
ILoad2	0.1244

Busbar 6 has four branch currents, namely ‘INorthBus_BRKR’, ‘ISouthBus_BRKR’, ‘ILoad1’, and ‘ILoad2’. The current values are the same in these branches. It is required for parallel connected CTs to be configured with the same turns ratio, this is for the accuracy of differential protection calculations. The CT turns ratios are calculated based on the rated current of the protected object. The CT ratio is calculated using the formulas in Equations 5.2 and 5.3 below. In terms of the CT ratio standard, the calculated turns ratio is equal to 400.

$$NorthBus_{CTPrimaryTurns} + SouthBus_{CTPrimaryTurns} = 150\% * 0.2488\ kA \tag{5.2}$$

$$NorthBus_{CTPrimaryTurns} + SouthBus_{CTPrimaryTurns} = 373.2\ A \tag{5.3}$$

The following section discusses the basic operation of the busbar protection scheme using IEC 61850 standard.

5.4.2 The operation of the busbar protection scheme using IEC 61850

In the implemented protection scheme, both IEDs are located at the busbar and communicate using IEC 61850 GOOSE messages. When a busbar internal fault occurs, the main protection IED “SEL-487B” operates and sends a GOOSE message to block the backup IED “REF615”. This is done to block the backup ABB IED from unnecessarily tripping when the main SEL- 487B IED has already cleared the fault. The SEL-487B IED operates on differential elements and the REF615 IED operates on overcurrent elements. A laboratory-scale test bench was developed to implement this protection scheme. The RSCAD software was used to simulate the power network as shown in Figure 5.5 below. The key objective in this implementation is to achieve interoperability between these two IEDs from different vendors, thereby, improving the performance of the busbar protection scheme.

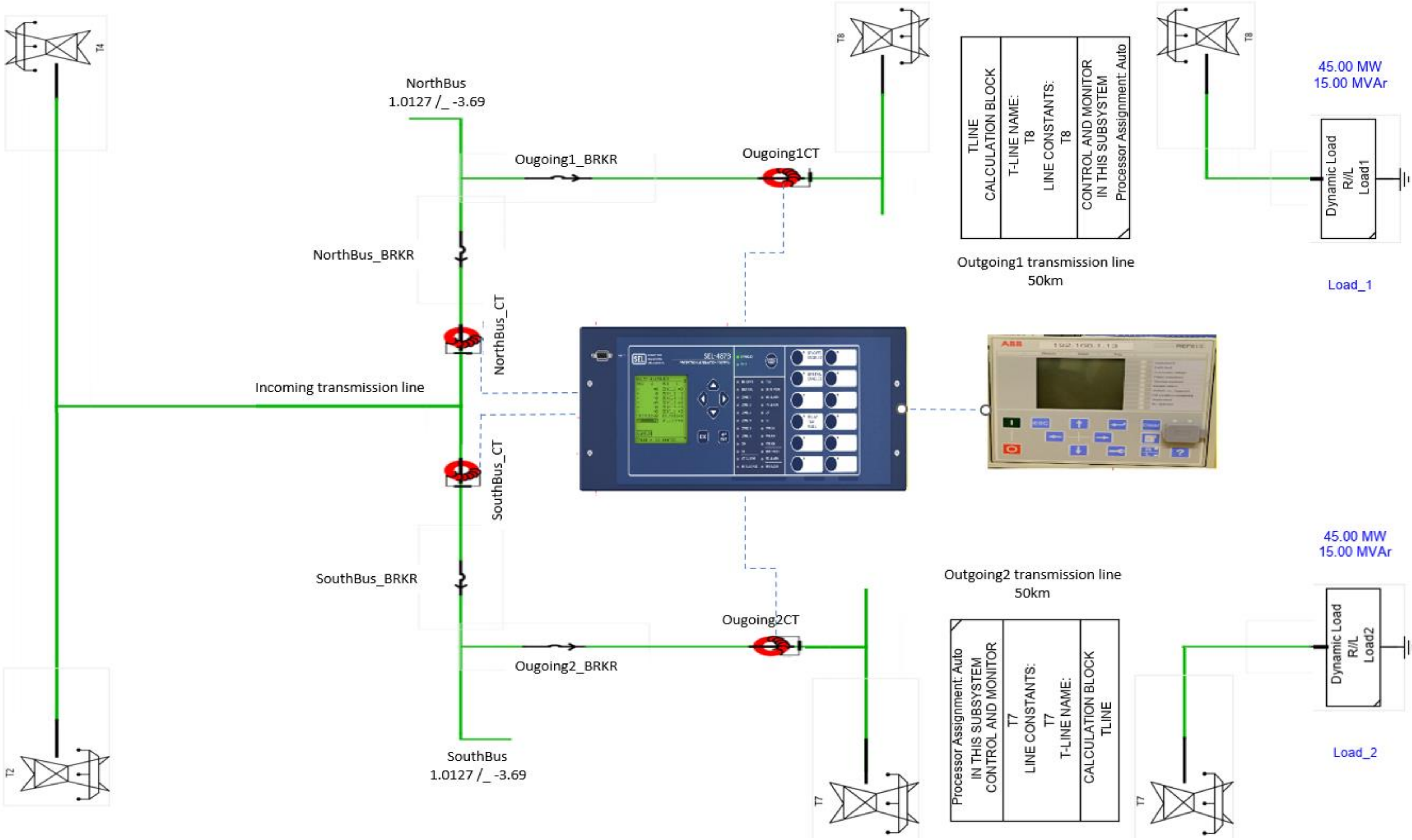


Figure 5.5: RSCAD modelled network for the lab-scale test bench

5.4.3 Development of the lab-scale test bench used for the busbar protection scheme

A lab-scale test bench was 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 was simulated, and the behaviour of the protection scheme was analysed. The test bench shown in Figure 5.6 below was developed to conduct all the experiments of the research project.

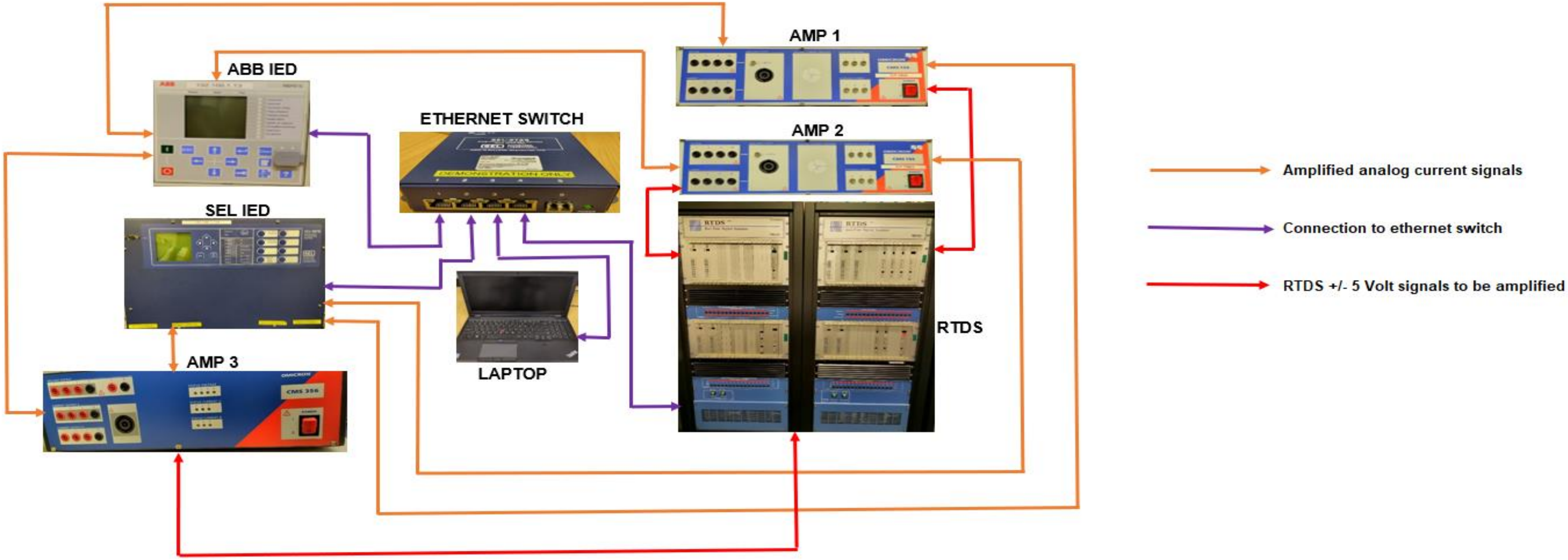


Figure 5.6: Developed lab-scale test bench.

The components that were used to construct the lab-scale test bench are as follows:

- SEL Ethernet switch
- ABB REF615 IED
- SEL-487B IED
- Omicron CMS 156 and 356 amplifiers
- RTDS/RSCAD
- Lenovo laptop
- SEL AcSELerator QuickSet software
- SEL AcSELerator Architect software
- ABB PCM600 software

- GOOSE Inspector Demo

The following sections provide a function of each component.

- SEL Ethernet switch

Ethernet switches link many devices together by physically connecting them to the same network. Coaxial, fibre, and LAN cables are used to connect devices to the Ethernet switch. In this thesis, the LAN cable was used to connect the IEDs, RTDS, amplifiers, and Lenovo laptop to the same network.

- SEL-487B and REF615 IEDs

The SEL-487B is set as the main differential protection relay and REF615 as the backup overcurrent protection relay. These IEDs are both compliant with the IEC 61850 standard and are used for protection, control, and monitoring.

- CMS 156 & 356 amplifiers

The RTDS devices generate +/-10 Volts using twelve 16-bit gigabit transceiver analog output (GTAO) cards. The analog outputs of the GTAOs are sampled every microsecond, and the card’s output channels are updated simultaneously. The GTAO card is accessible as a draft component in RSCAD. Omicron amplifiers are used in conjunction with the RTDS to amplify the +/-10 Volts signals generated by the 16-bit GTAO cards to suit external IEDs.

- Lenovo laptop

Software used in this study is all installed in this Lenovo personal computer including RSCAD, AcSELerator QuickSet, AcSELerator Architect, and PCM600.

- AcSELerator QuickSet software

  This software is used to configure SEL-487B IED properties and differential protection settings.

- AcSELerator Architect software

  AcSELerator Architect software is used to configure the SCL file of the SEL-487B relay.

- PCM600 software

  Protection and control IED manager (PCM600) software is compliant with the IEC61850 standard. It enables information exchange (interoperability) between IEC61850-compliant IEDs which are SEL487B and REF615 protection IEDs.

- GOOSE Inspector Demo

  GOOSE Inspector Demo software is used to monitor GOOSE messages published by the IEDs on the network.

5.4.4 Practical implementation of the proposed main busbar protection using the test bench

The flow chart shown in Figure 5.7 below, provides the guidelines for the practical implementation of the proposed main busbar protection using the test bench

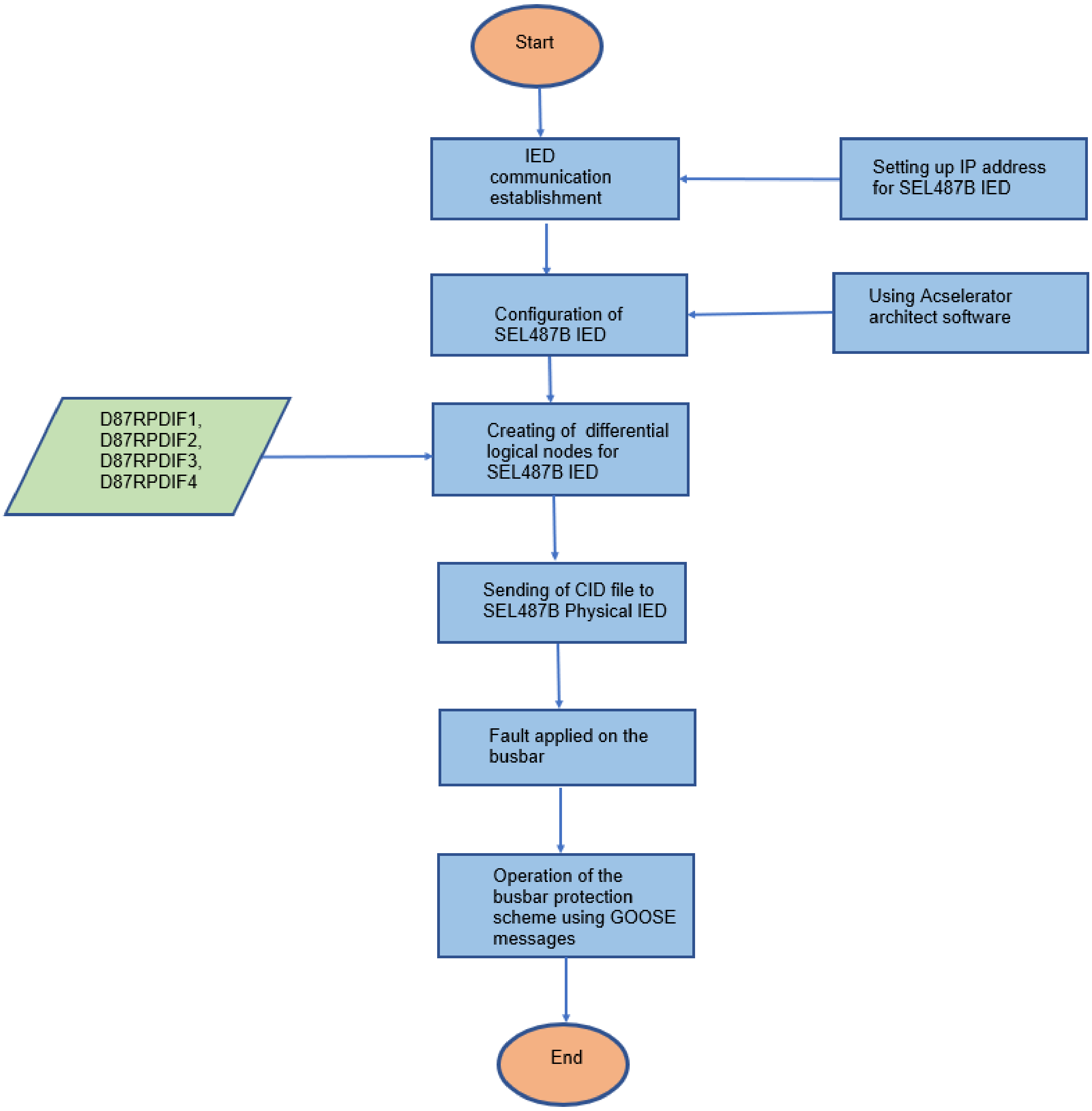


Figure 5.7: Flow chart for SEL487B IED practical experiment

The application of the busbar protection scheme between IEDs was done using the GOOSE messaging communication protocol to test for interoperability.

5.4.4.1 Configuration of SEL-487B IED for GOOSE messaging using AcSELerator Architect software

This section deals with the creation of Logical Nodes (LNs), which are used to transport data with status events over Ethernet. The RTDS utilizes a Giga-Transceiver Network (GTNET) card to send status event messages for protection and control from physical IEDs to RTDS as shown in Figure 5.8 below.

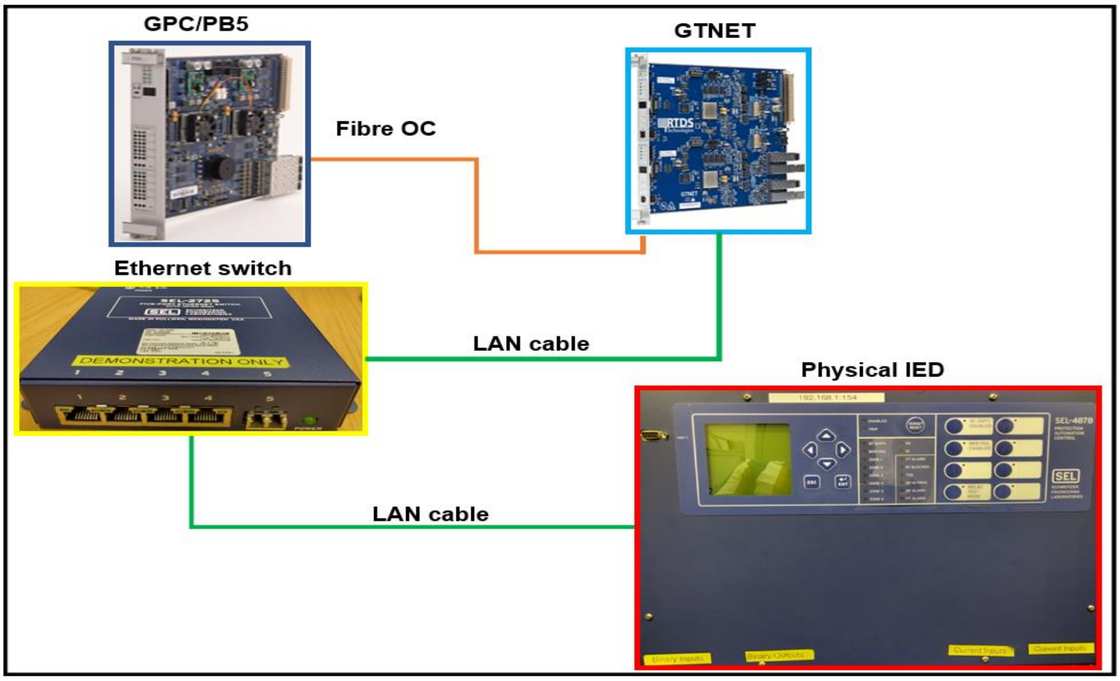


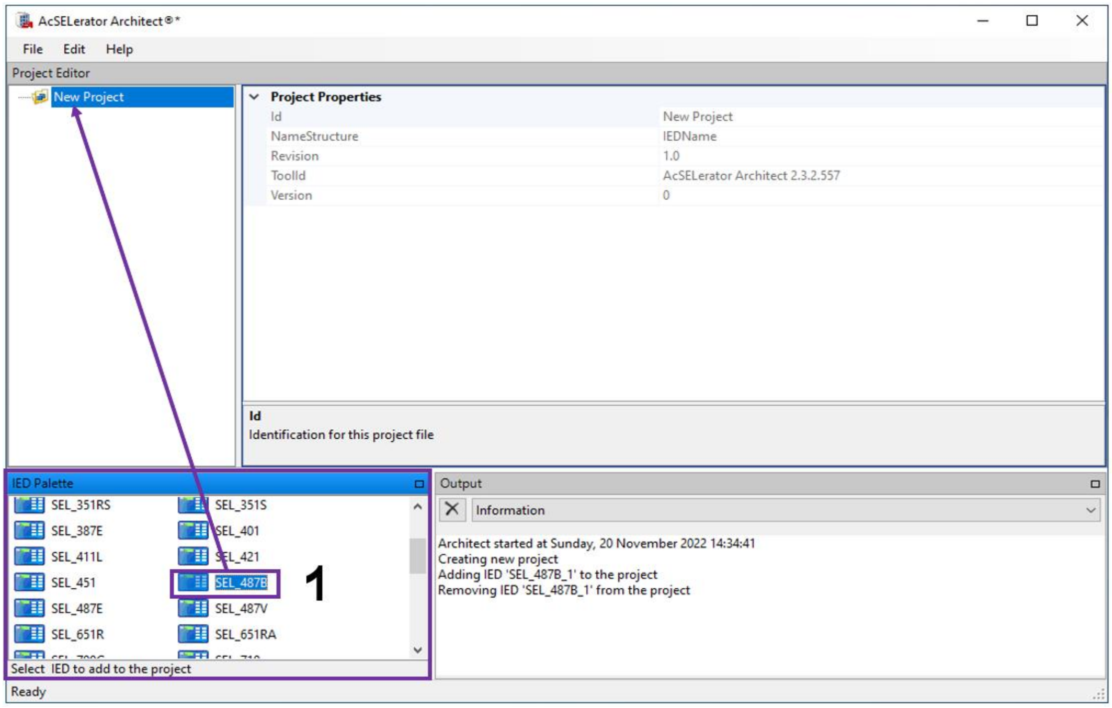
Figure 5.8: HIL interface between SEL-487B IED and RTDS using IEC 61850 standard

Figure 5.8 above shows the HIL interface between the physical IED (SEL-487B) and RTDS. It is necessary to use LNs that correspond to the American National Standards Institute (ANSI) relay word bits to publish the status events via Ethernet. Table 5.3 below shows the corresponding LNs that were used.

Table 5.2: List of LNs corresponding to IED word bits.

Primitive Name	Logical Nodes	Data Attributes	Comments
87Z1	D87RPDIF1	Str.general Str.q Str.t Op.general Op.q Op.t	Zone1 instantaneous and restraint differential elements picked
87Z2	D87RPDIF2	Str.general Str.q Str.t Op.general Op.q Op.t	Zone2 instantaneous and restraint differential elements picked
87Z3	D87RPDIF3	Str.general Str.q Str.t Op.general Op.q Op.t	Zone3 instantaneous and restraint differential elements picked
87Z4	D87RPDIF4	Str.general Str.q Str.t Op.general Op.q Op.t	Zone4 instantaneous and restraint differential elements picked

The LNs listed in Table 5.2 above, were used to configure the Configured IED Description (CID) file for the SEL-487B relay using AcSELerator Architect software to configure datasets that are sent via GOOSE to trip the circuit breakers in RTDS. The steps to be followed when configuring this file are described in the following discussion. The IED palette labelled ‘1’ in Figure 5.9 below shows the list of the IEDs available in the AcSELerator Architect software database. The selected IED is dragged and dropped into the new project folder as shown in the figure.



Id	New Project
NameStructure	IEDName
Revision	1.0
ToolId	AcSELerator Architect 2.3.2.557
Version	0

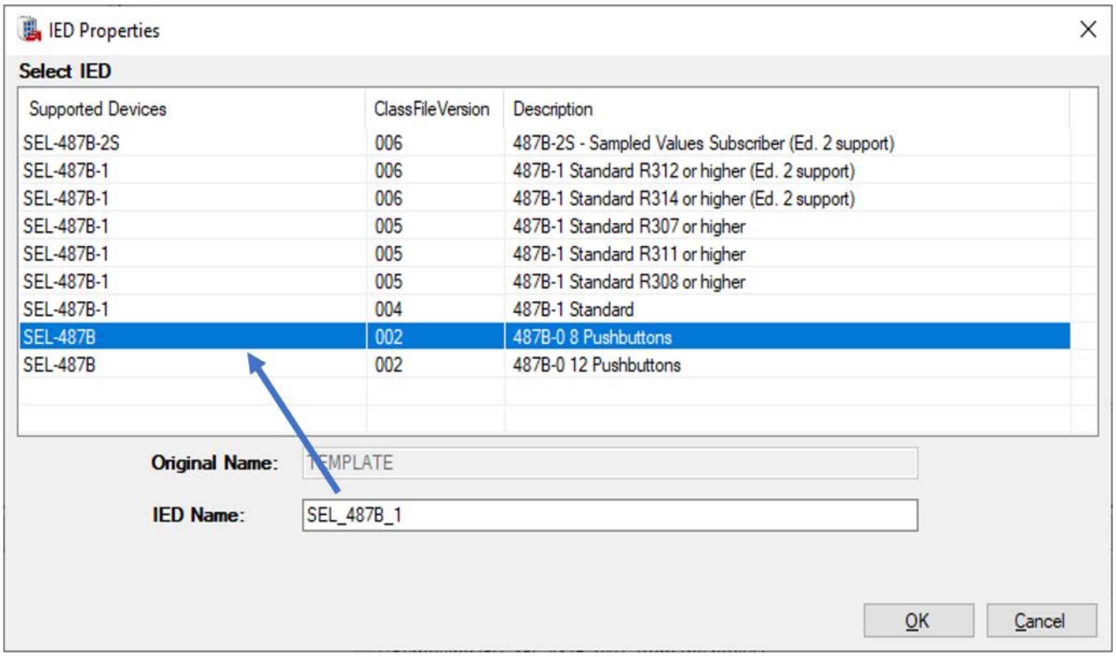
Id
Identification for this project file

Select IED to add to the project

```
Architect started at Sunday, 20 November 2022 14:34:41
Creating new project
Adding IED 'SEL_487B_1' to the project
Removing IED 'SEL_487B_1' from the project
```

Figure 5.9: Selected IED for the project.

As soon as the IED is dropped into the new project folder, a dialog box appears with class file version information and a description of the IED as shown in Figure 5.10 below. The IED used for this research project uses the specifications highlighted in blue.



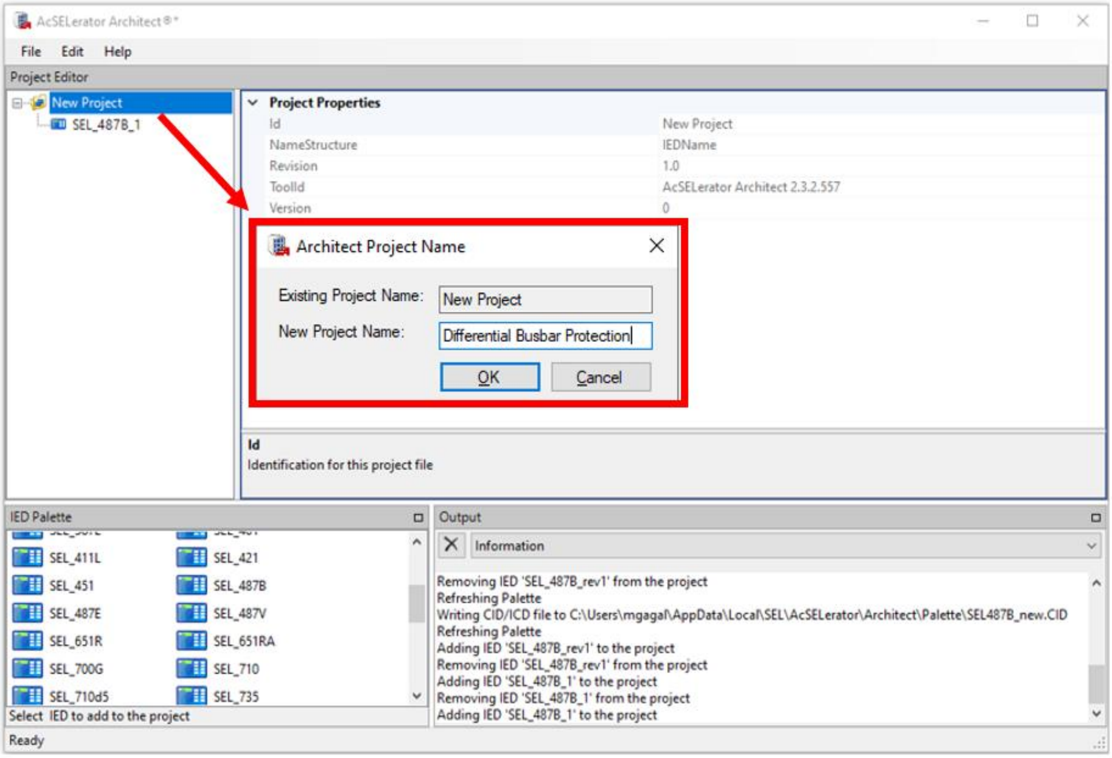
Supported Devices	ClassFileVersion	Description
SEL-487B-2S	006	487B-2S - Sampled Values Subscriber (Ed. 2 support)
SEL-487B-1	006	487B-1 Standard R312 or higher (Ed. 2 support)
SEL-487B-1	006	487B-1 Standard R314 or higher (Ed. 2 support)
SEL-487B-1	005	487B-1 Standard R307 or higher
SEL-487B-1	005	487B-1 Standard R311 or higher
SEL-487B-1	005	487B-1 Standard R308 or higher
SEL-487B-1	004	487B-1 Standard
SEL-487B	002	487B-0 8 Pushbuttons
SEL-487B	002	487B-0 12 Pushbuttons

Original Name: TEMPLATE

IED Name: SEL_487B_1

Figure 5.10: Selected IED specifications.

The next step is to rename the new project as shown in Figure 5.11 below.



Id	New Project
NameStructure	IEDName
Revision	1.0
ToolId	AcSELerator Architect 2.3.2.557
Version	0

Existing Project Name: New Project

New Project Name: Differential Busbar Protection

Id

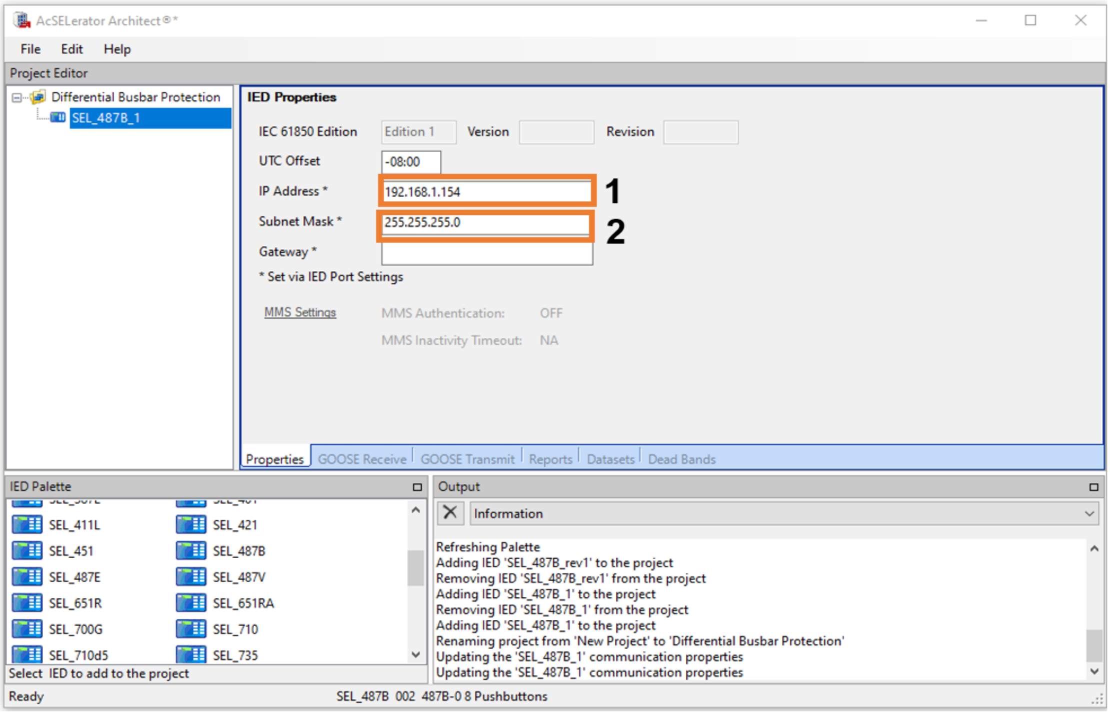
Identification for this project file

Select IED to add to the project

```
Removing IED 'SEL_487B_rev1' from the project
Refreshing Palette
Writing CID/ICD file to C:\Users\mgagal\AppData\Local\SEL\AcSELerator\Architect\Palette\SEL487B_new.CID
Refreshing Palette
Adding IED 'SEL_487B_rev1' to the project
Removing IED 'SEL_487B_rev1' from the project
Adding IED 'SEL_487B_1' to the project
Removing IED 'SEL_487B_1' from the project
Adding IED 'SEL_487B_1' to the project
```

Figure 5.11: Renaming of the project.

The next step is to define IED communication properties as shown in Figure 5.12 below. This includes configuring the IP, Subnet Mask, and Gateway addresses which are used to establish communications with the IED.



IEC 61850 Edition: Edition 1 Version Revision
UTC Offset: -08:00
IP Address *: 192.168.1.154
Subnet Mask *: 255.255.255.0
Gateway *:
* Set via IED Port Settings

MMS Authentication: OFF
MMS Inactivity Timeout: NA

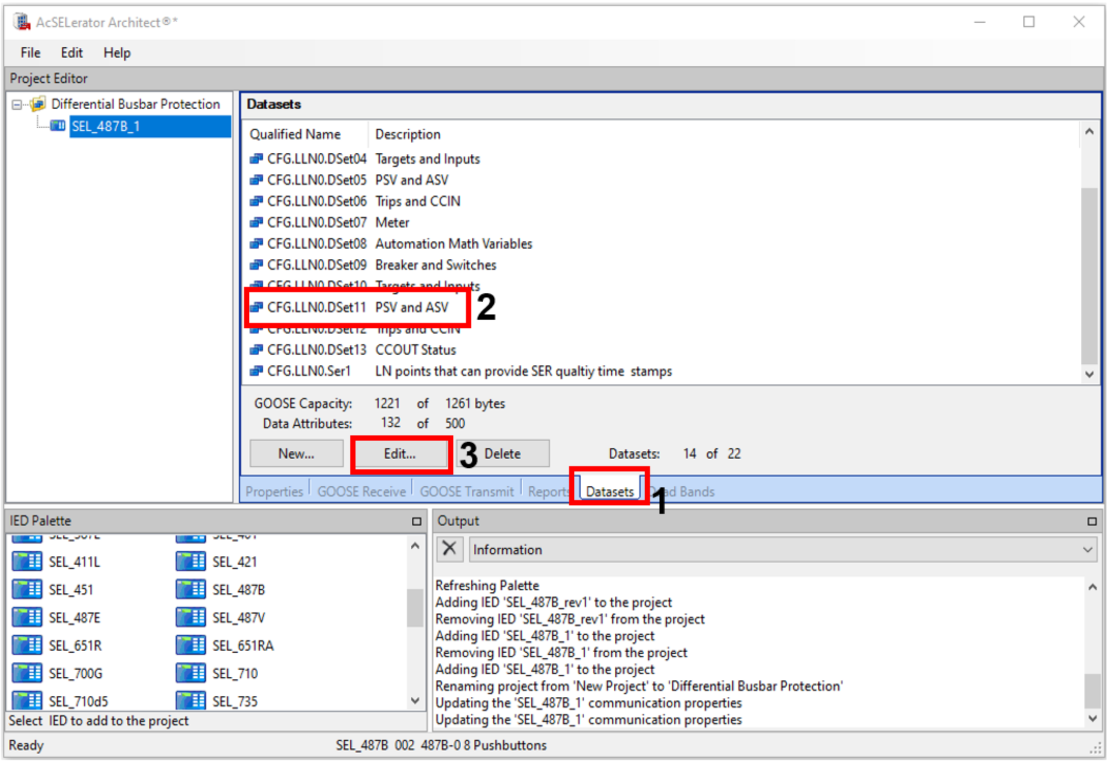
Select IED to add to the project

```
Refreshing Palette
Adding IED 'SEL_487B_rev1' to the project
Removing IED 'SEL_487B_rev1' from the project
Adding IED 'SEL_487B_1' to the project
Removing IED 'SEL_487B_1' from the project
Adding IED 'SEL_487B_1' to the project
Renaming project from 'New Project' to 'Differential Busbar Protection'
Updating the 'SEL_487B_1' communication properties
Updating the 'SEL_487B_1' communication properties
```

Ready SEL_487B 002 487B-0 8 Pushbuttons

Figure 5.12: Configuring IED properties

The next step is to define the datasets that will be published via GOOSE as shown in Figure 5.13 below.



Qualified Name	Description
CFG.LLN0.DSet04	Targets and Inputs
CFG.LLN0.DSet05	PSV and ASV
CFG.LLN0.DSet06	Trips and CCIN
CFG.LLN0.DSet07	Meter
CFG.LLN0.DSet08	Automation Math Variables
CFG.LLN0.DSet09	Breaker and Switches
CFG.LLN0.DSet10	Targets and Inputs
CFG.LLN0.DSet11	PSV and ASV
CFG.LLN0.DSet12	Trips and CCIN
CFG.LLN0.DSet13	CCOUT Status
CFG.LLN0.Ser1	LN points that can provide SER qualtiy time stamps

GOOSE Capacity: 1221 of 1261 bytes
Data Attributes: 132 of 500

Datasets: 14 of 22

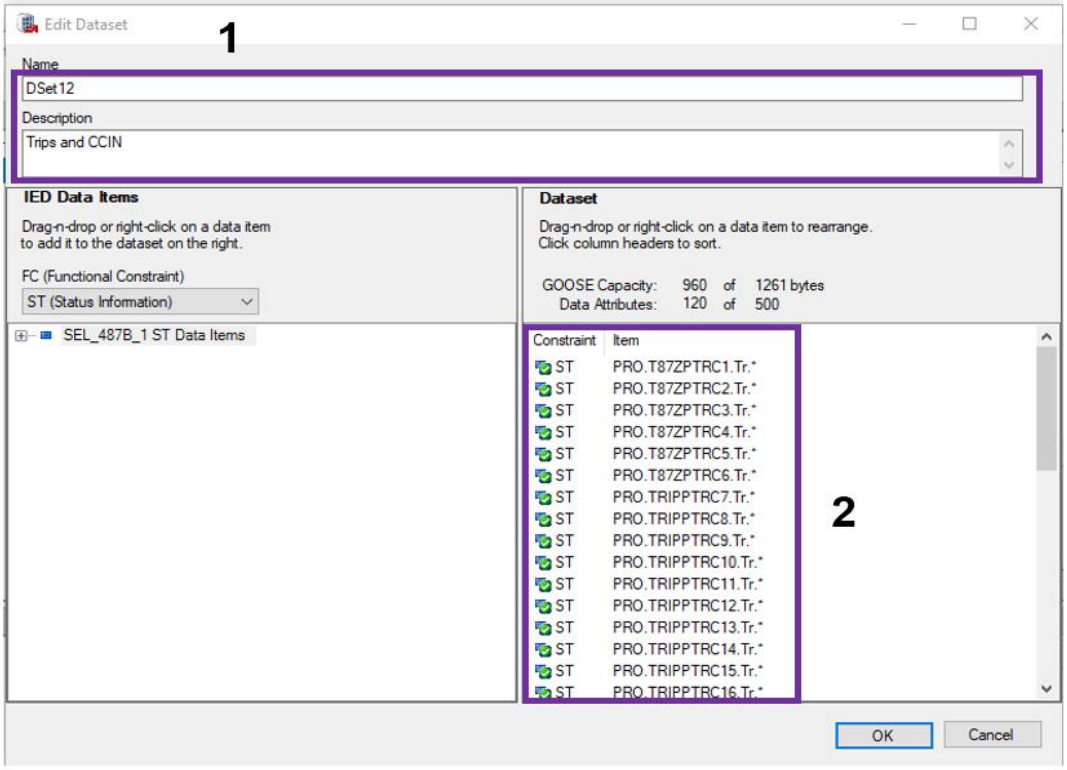
Select IED to add to the project

```
Refreshing Palette
Adding IED 'SEL_487B_rev1' to the project
Removing IED 'SEL_487B_rev1' from the project
Adding IED 'SEL_487B_1' to the project
Removing IED 'SEL_487B_1' from the project
Adding IED 'SEL_487B_1' to the project
Renaming project from 'New Project' to 'Differential Busbar Protection'
Updating the 'SEL_487B_1' communication properties
Updating the 'SEL_487B_1' communication properties
```

Ready SEL_487B 002 487B-0 8 Pushbuttons

Figure 5.13: Defining datasets.

When the ‘Edit’ button is clicked, the dialog box seen in Figure 5.14 below appears showing the default dataset defined in SEL-487B IED highlighted in zone 2. This dataset is deleted as only the differential elements are used for this protection scheme. Furthermore, the dataset name and description can be configured as highlighted in zone 1 in the figure.



Name: DSet12

Description: Trips and CCIN

Drag-n-drop or right-click on a data item to add it to the dataset on the right.

FC (Functional Constraint): ST (Status Information)

SEL_487B_1 ST Data Items

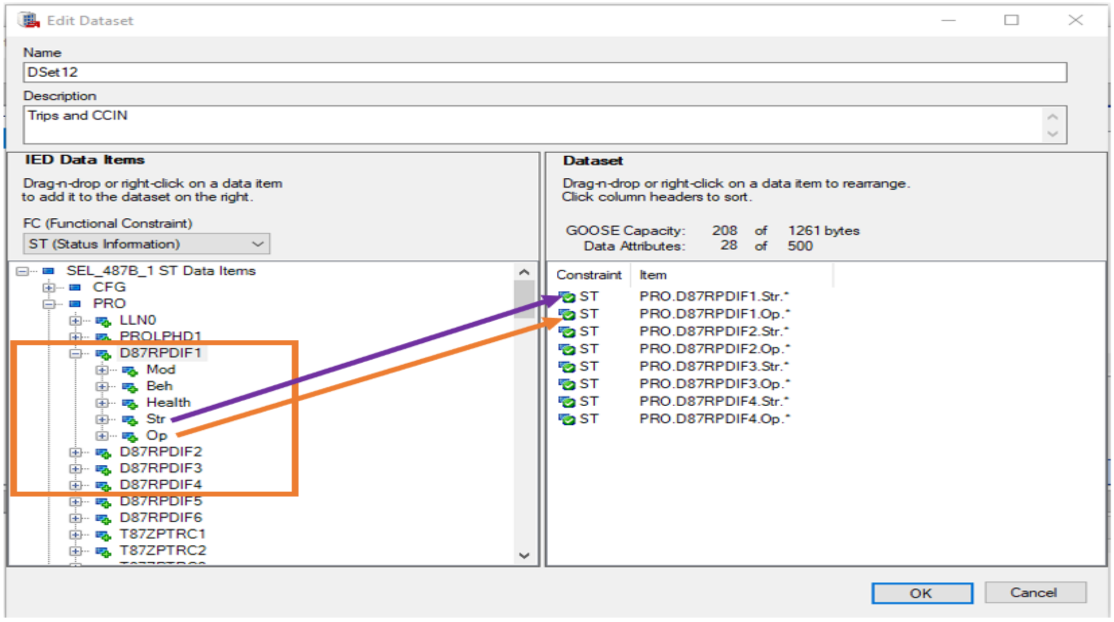
Drag-n-drop or right-click on a data item to rearrange. Click column headers to sort.

GOOSE Capacity: 960 of 1261 bytes
Data Attributes: 120 of 500

Constraint	Item
ST	PRO.T87ZPTRC1.Tr.*
ST	PRO.T87ZPTRC2.Tr.*
ST	PRO.T87ZPTRC3.Tr.*
ST	PRO.T87ZPTRC4.Tr.*
ST	PRO.T87ZPTRC5.Tr.*
ST	PRO.T87ZPTRC6.Tr.*
ST	PRO.TRIPPTRC7.Tr.*
ST	PRO.TRIPPTRC8.Tr.*
ST	PRO.TRIPPTRC9.Tr.*
ST	PRO.TRIPPTRC10.Tr.*
ST	PRO.TRIPPTRC11.Tr.*
ST	PRO.TRIPPTRC12.Tr.*
ST	PRO.TRIPPTRC13.Tr.*
ST	PRO.TRIPPTRC14.Tr.*
ST	PRO.TRIPPTRC15.Tr.*
ST	PRO.TRIPPTRC16.Tr.*

Figure 5.14: Default datasets.

The next step is to drag and drop the datasets that were indicated in Table 5.2 as shown in Figure 5.15 below.



Name: DSet12

Description: Trips and CCIN

Drag-n-drop or right-click on a data item to add it to the dataset on the right.

FC (Functional Constraint): ST (Status Information)

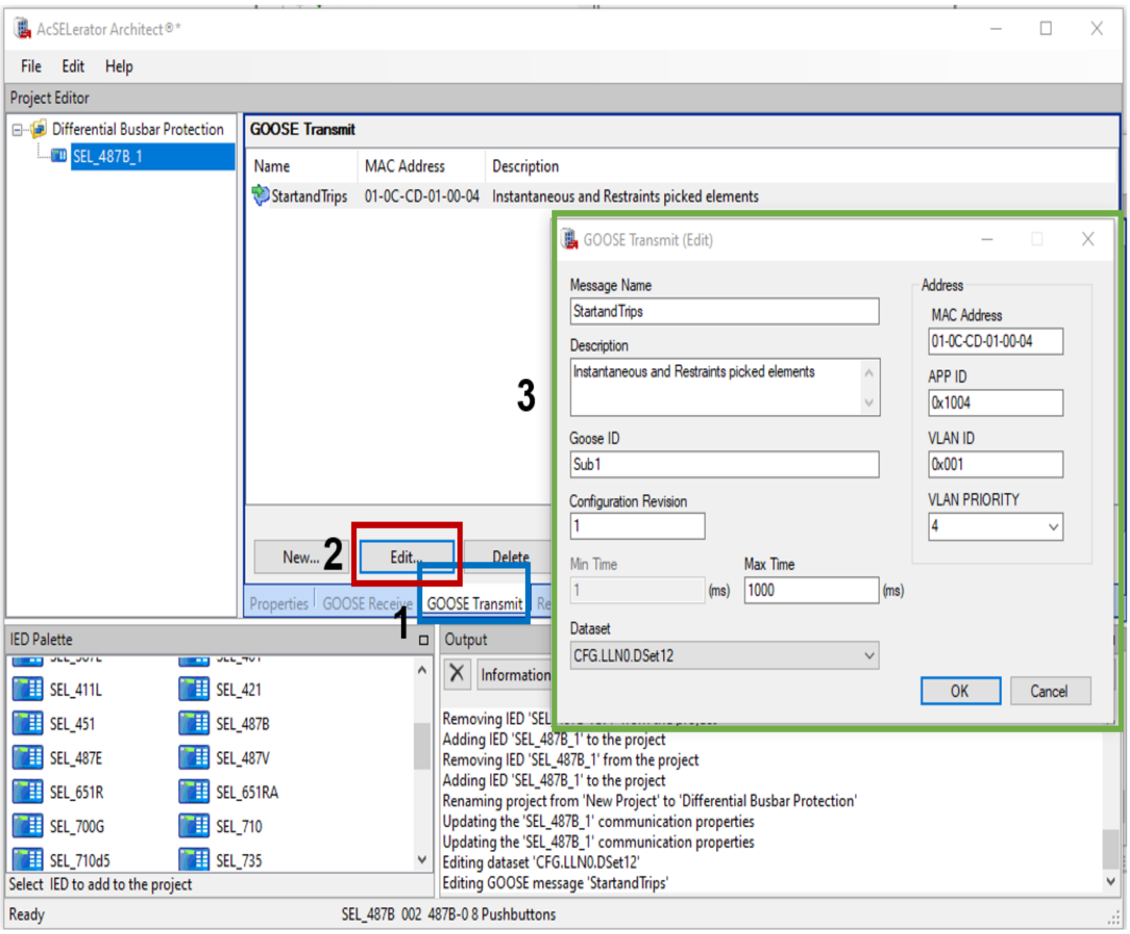
Drag-n-drop or right-click on a data item to rearrange. Click column headers to sort.

GOOSE Capacity: 208 of 1261 bytes
Data Attributes: 28 of 500

Constraint	Item
ST	PRO.D87RPDIF1.Str.*
ST	PRO.D87RPDIF1.Op.*
ST	PRO.D87RPDIF2.Str.*
ST	PRO.D87RPDIF2.Op.*
ST	PRO.D87RPDIF3.Str.*
ST	PRO.D87RPDIF3.Op.*
ST	PRO.D87RPDIF4.Str.*
ST	PRO.D87RPDIF4.Op.*

Figure 5.15:Defined datasets.

The defined datasets are configured for GOOSE transmission by navigating to the 'GOOSE Transmit' tab and editing or creating a new dataset. Upon clicking 'Edit', a window is prompted to enable configuring the name and the description of the GOOSE messages to be transmitted. Furthermore, the Mac address, APP ID, and VLAN ID details can also be configured as shown in Figure 5.16 below.



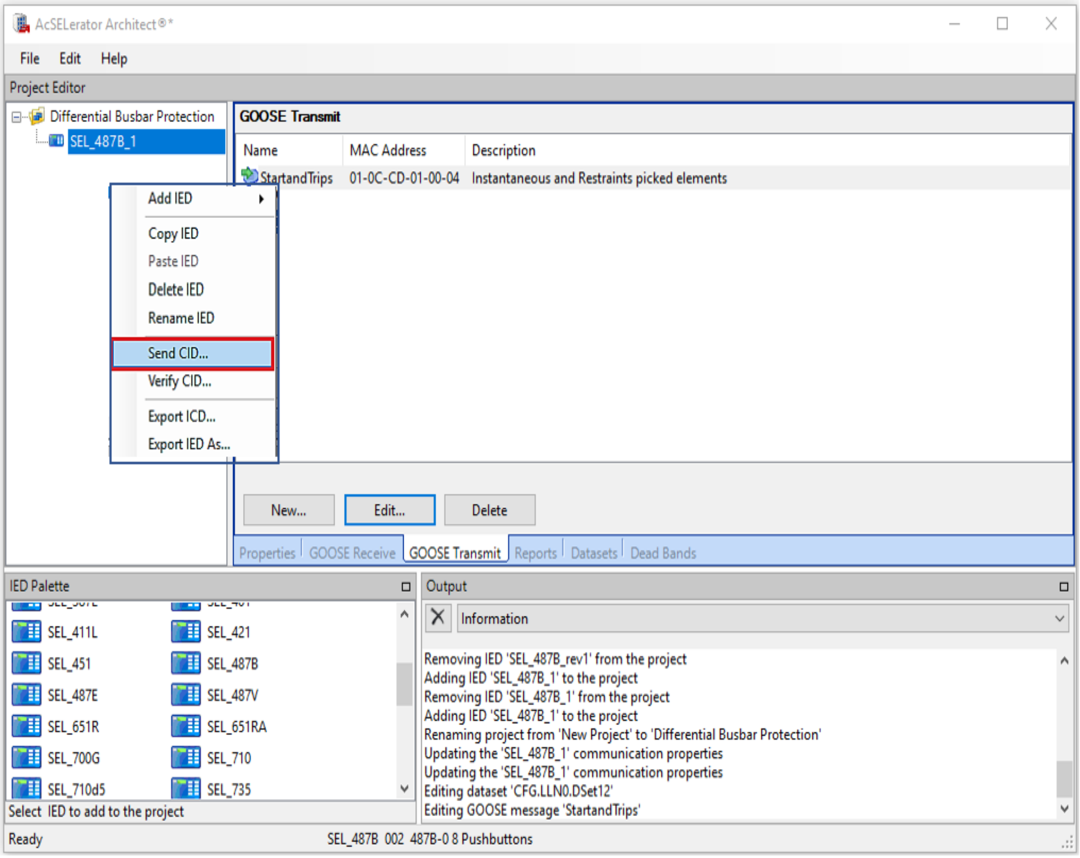
Name	MAC Address	Description
StartandTrips	01-0C-CD-01-00-04	Instantaneous and Restraints picked elements

Message Name: StartandTrips
Description: Instantaneous and Restraints picked elements
Goose ID: Sub1
Configuration Revision: 1
Min Time: 1 (ms)
Max Time: 1000 (ms)
Dataset: CFG.LLN0.DSet12
MAC Address: 01-0C-CD-01-00-04
APP ID: 0x1004
VLAN ID: 0x001
VLAN PRIORITY: 4

```
Removing IED 'SEL
Adding IED 'SEL_487B_1' to the project
Removing IED 'SEL_487B_1' from the project
Adding IED 'SEL_487B_1' to the project
Renaming project from 'New Project' to 'Differential Busbar Protection'
Updating the 'SEL_487B_1' communication properties
Updating the 'SEL_487B_1' communication properties
Editing dataset 'CFG.LLN0.DSet12'
Editing GOOSE message 'StartandTrips'
```

Figure 5.16: **Configuration of GOOSE message to be transmitted.**

The configuration is complete and the Substation Configuration Description (SCD) file is saved as a Configured IED Description (CID) file and sent to the IED in use for execution as shown in Figure 5.17 below. Before sending the CID file to the IED, the LAN connection to the IED must be verified by pinging the IP address of the physical IED command prompt window.



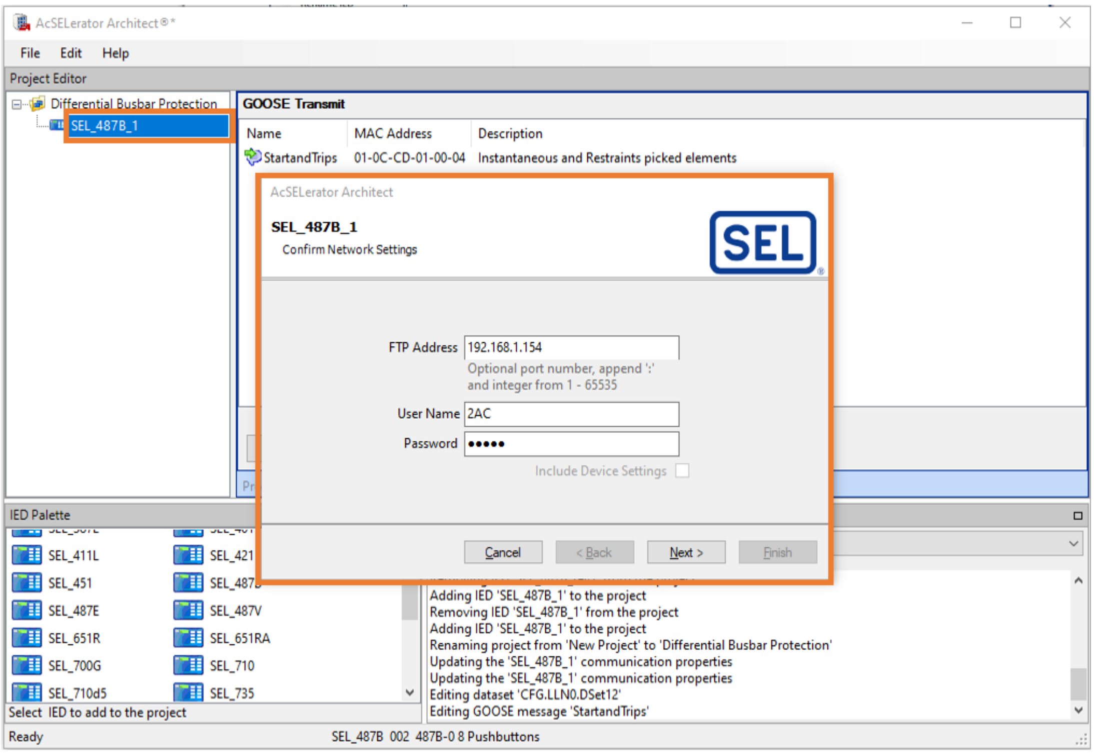
Name	MAC Address	Description
StartandTrips	01-0C-CD-01-00-04	Instantaneous and Restraints picked elements

```
Removing IED 'SEL_487B_rev1' from the project
Adding IED 'SEL_487B_1' to the project
Removing IED 'SEL_487B_1' from the project
Adding IED 'SEL_487B_1' to the project
Renaming project from 'New Project' to 'Differential Busbar Protection'
Updating the 'SEL_487B_1' communication properties
Updating the 'SEL_487B_1' communication properties
Editing dataset 'CFG.LLN0.DSet12'
Editing GOOSE message 'StartandTrips'
```

SEL_487B 002 487B-0 8 Pushbuttons

Figure 5.17: **Sending of CID file to the SEL-487B IED**

As soon as you click on ‘Send CID’, a dialog box prompts to configure network settings as shown in Figure 5.18 below.



Name	MAC Address	Description
StartandTrips	01-0C-CD-01-00-04	Instantaneous and Restraints picked elements

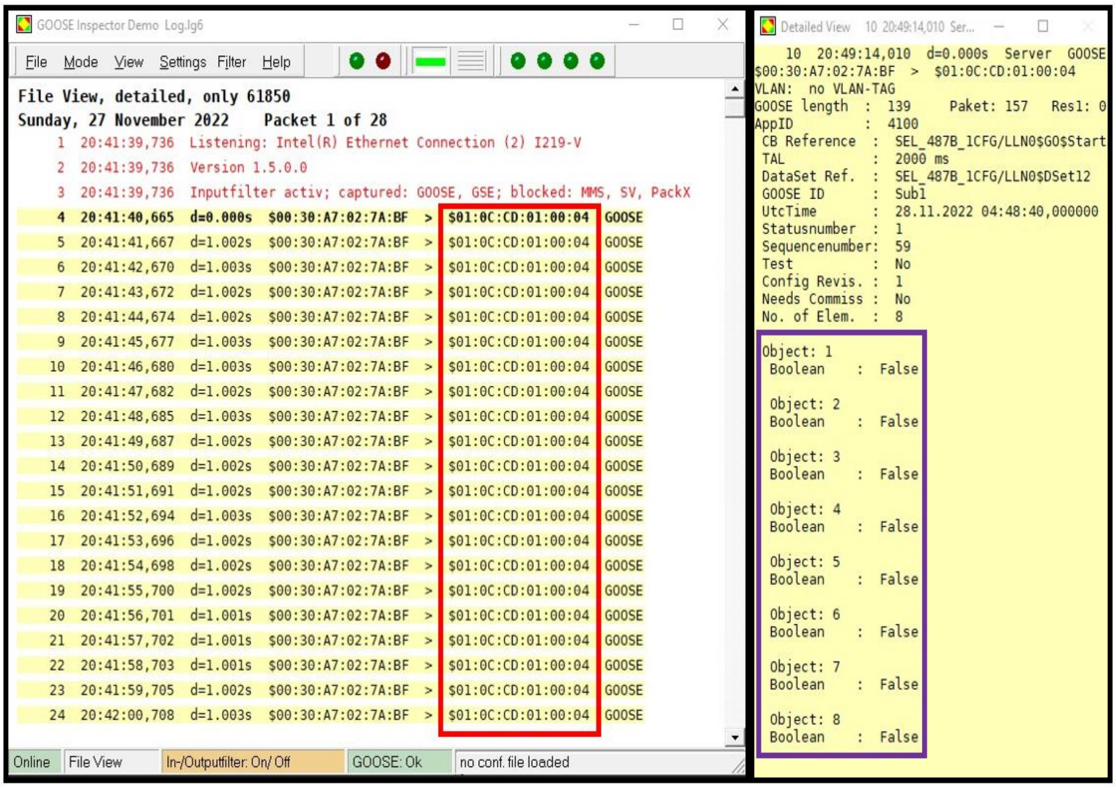
FTP Address 192.168.1.154
User Name 2AC
Password •••••
Include Device Settings ☐

```
Adding IED 'SEL_487B_1' to the project
Removing IED 'SEL_487B_1' from the project
Adding IED 'SEL_487B_1' to the project
Renaming project from 'New Project' to 'Differential Busbar Protection'
Updating the 'SEL_487B_1' communication properties
Updating the 'SEL_487B_1' communication properties
Editing dataset 'CFG.LLN0.DSet12'
Editing GOOSE message 'StartandTrips'
```

SEL_487B 002 487B-0 8 Pushbuttons

Figure 5.18: **Confirmation of network settings for the SEL-487B IED**

Once the above was done, there was a need to monitor the GOOSE information. In this case, GOOSE Inspector Demo software was used to monitor GOOSE messages published by the SEL-487B IED to verify the configuration as seen in Figure 5.19 below. The IED is identified by its MAC address highlighted in red and the eight Boolean datasets highlighted in purple that were configured for this relay are shown as objects 1 to 8 in the GOOSE Inspector software.



```
File View, detailed, only 61850
Sunday, 27 November 2022    Packet 1 of 28
    1  20:41:39,736  Listening: Intel(R) Ethernet Connection (2) I219-V
    2  20:41:39,736  Version 1.5.0.0
    3  20:41:39,736  Inputfilter activ; captured: GOOSE, GSE; blocked: MMS, SV, PackX
    4  20:41:40,665  d=0.000s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
    5  20:41:41,667  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
    6  20:41:42,670  d=1.003s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
    7  20:41:43,672  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
    8  20:41:44,674  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
    9  20:41:45,677  d=1.003s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   10  20:41:46,680  d=1.003s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   11  20:41:47,682  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   12  20:41:48,685  d=1.003s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   13  20:41:49,687  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   14  20:41:50,689  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   15  20:41:51,691  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   16  20:41:52,694  d=1.003s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   17  20:41:53,696  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   18  20:41:54,698  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   19  20:41:55,700  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   20  20:41:56,701  d=1.001s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   21  20:41:57,702  d=1.001s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   22  20:41:58,703  d=1.001s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   23  20:41:59,705  d=1.002s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
   24  20:42:00,708  d=1.003s  $00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04  GOOSE
```

```
   10  20:49:14,010  d=0.000s  Server  GOOSE
$00:30:A7:02:7A:BF  >  $01:0C:CD:01:00:04
VLAN:  no VLAN-TAG
GOOSE length  :  139     Paket: 157   Res1: 0
AppID         :  4100
 CB Reference  :  SEL_487B_1CFG/LLN0$GO$Start
 TAL           :  2000 ms
 DataSet Ref.  :  SEL_487B_1CFG/LLN0$DSet12
 GOOSE ID      :  Sub1
 UtcTime       :  28.11.2022 04:48:40,000000
 Statusnumber  :  1
 Sequencenumber:  59
 Test          :  No
 Config Revis. :  1
 Needs Commiss :  No
 No. of Elem.  :  8

Object: 1
 Boolean    :  False

 Object: 2
 Boolean    :  False

 Object: 3
 Boolean    :  False

 Object: 4
 Boolean    :  False

 Object: 5
 Boolean    :  False

 Object: 6
 Boolean    :  False

 Object: 7
 Boolean    :  False

 Object: 8
 Boolean    :  False
```

Figure 5.19: **SEL487B Publishing GOOSE messages**

The GOOSE configuration settings done above are for the main protection relay "SEL-487B" which operates on differential elements. Based on the information displayed in Figure 5.19 above, SEL-4878B IED configuration settings were complete as the IED was able to publish GOOSE messages. The GOOSE message published by this IED will be used as a blocking signal at a later stage to block ABB REF615 backup protection IED from operating unnecessarily. The GOOSE settings for REF615 IED are explained step by step in the following section.

5.4.5 Practical implementation of the proposed backup busbar protection using the test bench

The next step is to configure GOOSE messages for the ABB REF615 relay which operates on overcurrent and is a backup protection to SEL-487B. The HIL interface for this relay is shown in Figure 5.20 below.

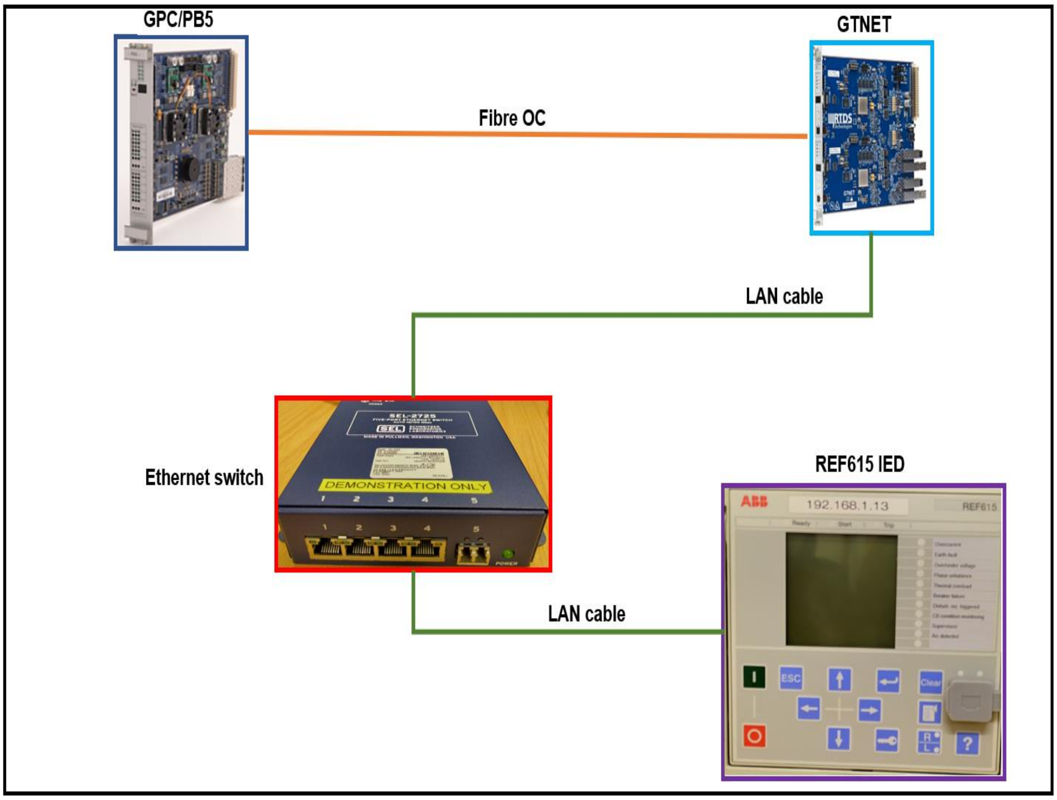


Figure 5.20: HIL interface of REF615 IED with RTDS

The configuration settings for this backup relay are done using the PCM600 configuration software from ABB as described in the following section.

The flow chart in Figure 5.21 below gives guidance for implementing the proposed backup busbar protection using the test bench.

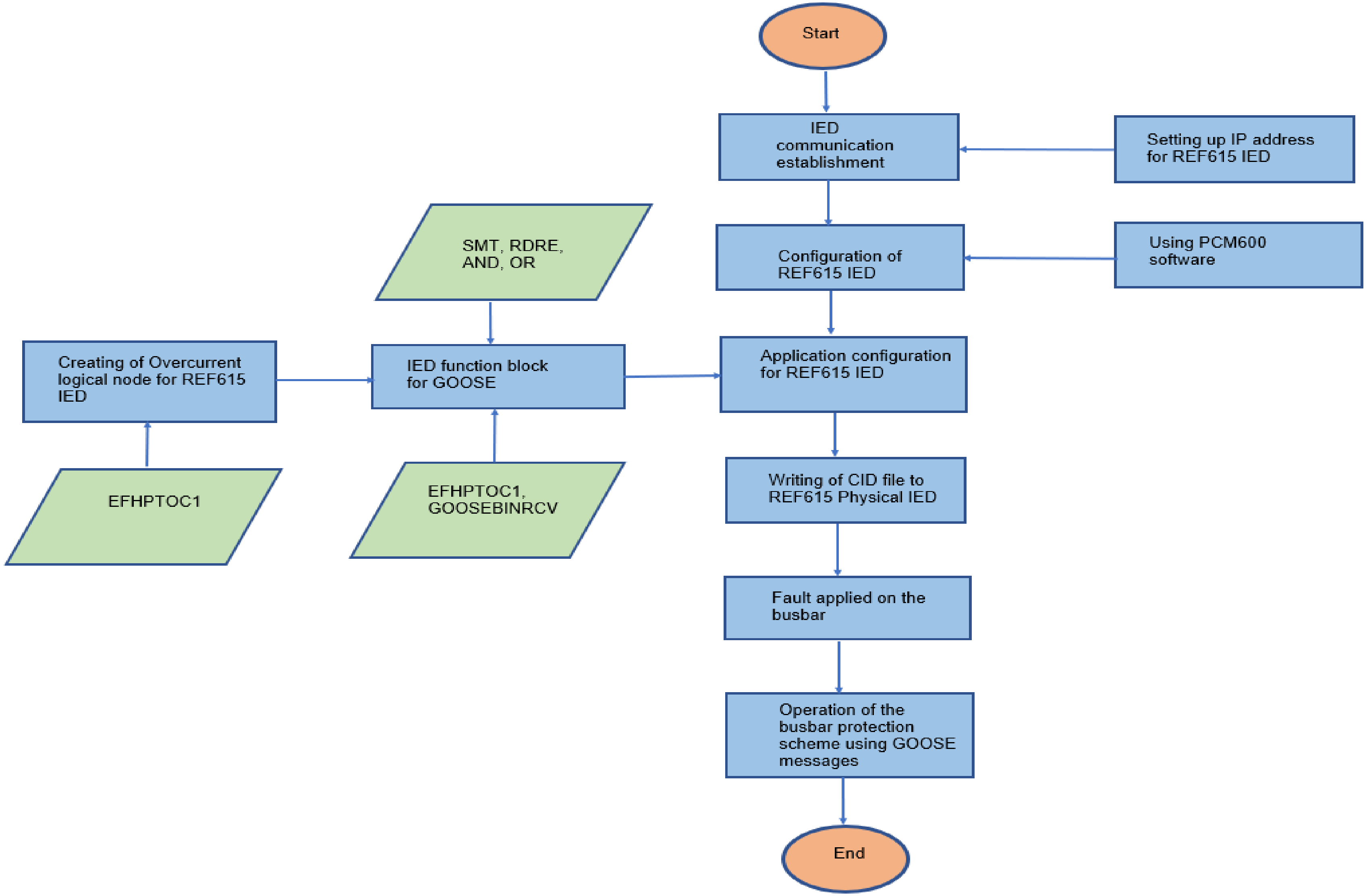


Figure 5.21: Practical experiment flow chart for REF615 IED

5.4.5.1 Configuration of GOOSE messages for REF615 IED using PCM600 software

The PCM600 Protection and Control IED Manager tool offers comprehensive functionality for the whole life cycle of all Relion® protection and controls IED applications at all voltage levels. This user-friendly tool assists in managing protection and control equipment, from application and communication configuration through disturbance management and automatic disturbance reporting. It is designed to connect with IEDs through quick and reliable TCP/IP over corporate LAN or WAN, or directly through the communication port on the front of the IED as shown in Figure 5.22 below. With a single command, the PCM600 utility may read and write all configuration and setup data from an IED (ABB, 2007).

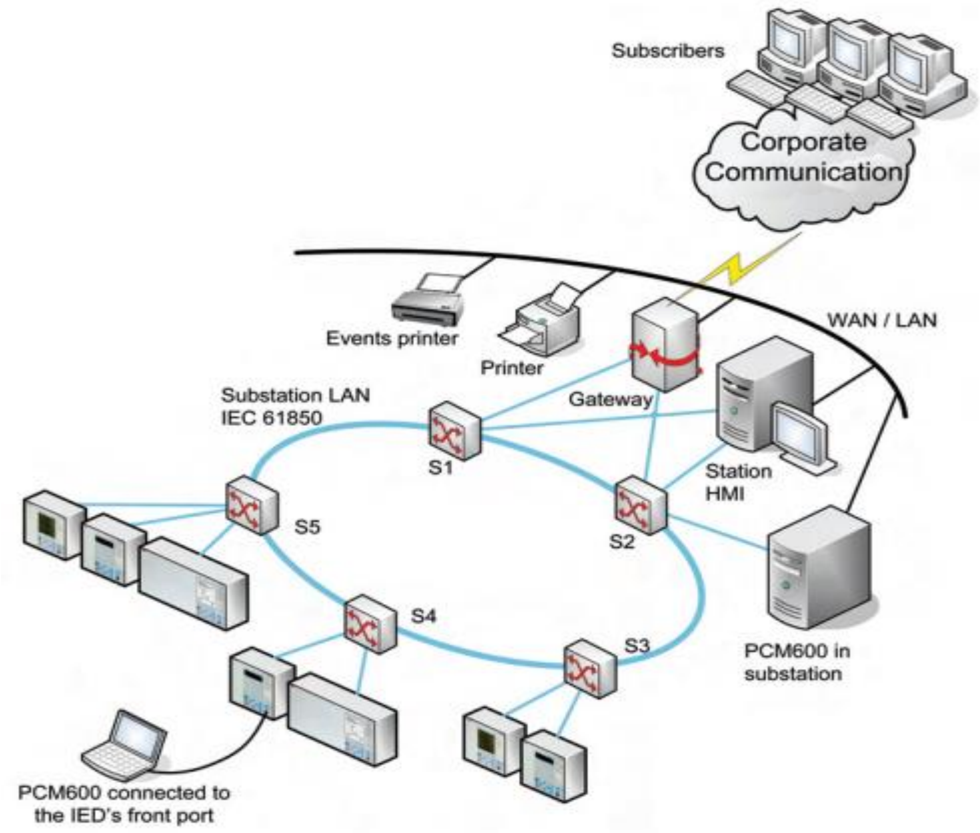


Figure 5.22: **PCM600 connected to IEDs locally or remotely** (ABB, 2007).

PCM600's user interface, workflow, and IEC 61850-based data model are all developed with the same concept as the Relion® protection and control IEDs, guaranteeing a smooth and seamless interaction between the tool and the IEDs. PCM600 also encrypts projects and data developed with previous versions of the PCM600 tool, allowing for complete backward compatibility (ABB, 2007).

In the main menu of PCM600 software, there is a window defined as a plant structure. That is where the new project is created and the name of the project is defined. The name for this project is “Backup protection relay” as shown in Figure 5.23 below.

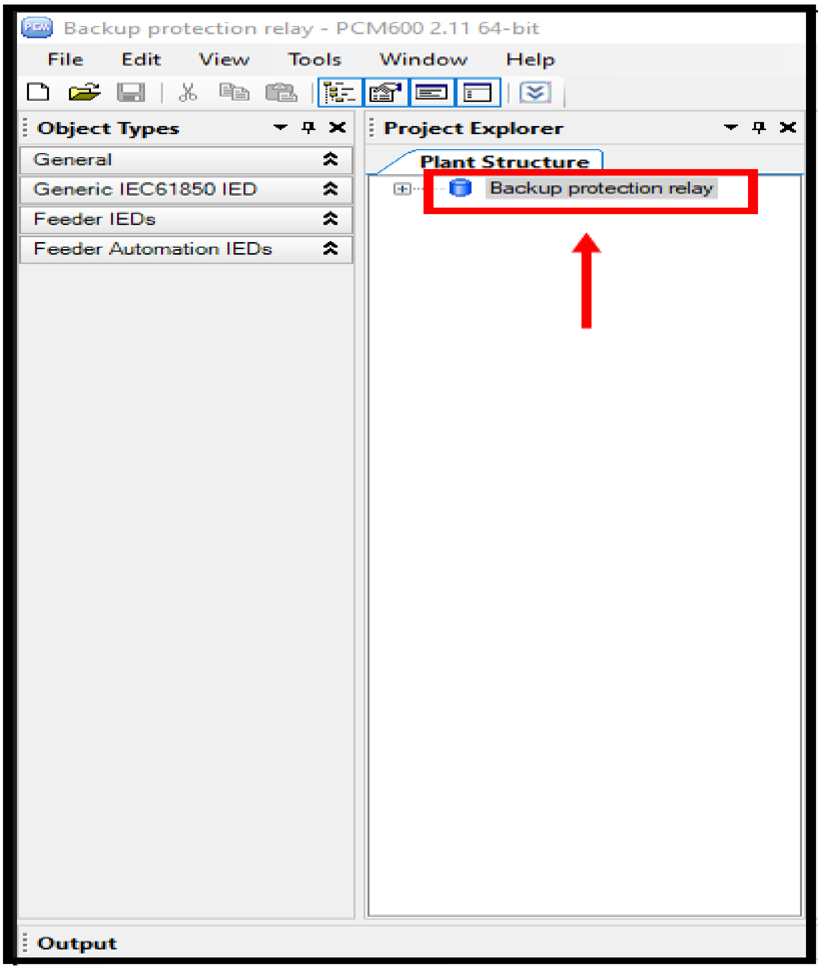


Figure 5.23: **Project naming in PCM600**

The plant structure window makes it easy to identify each IED by its name and to know where it is located in the substation. This structure is divided into five levels, as follows:

- Project Centre
- Substation
- Voltage level
- Bay level
- IEDs

The REF615 device was inserted into the bay level as shown in Figure 5.24 below.

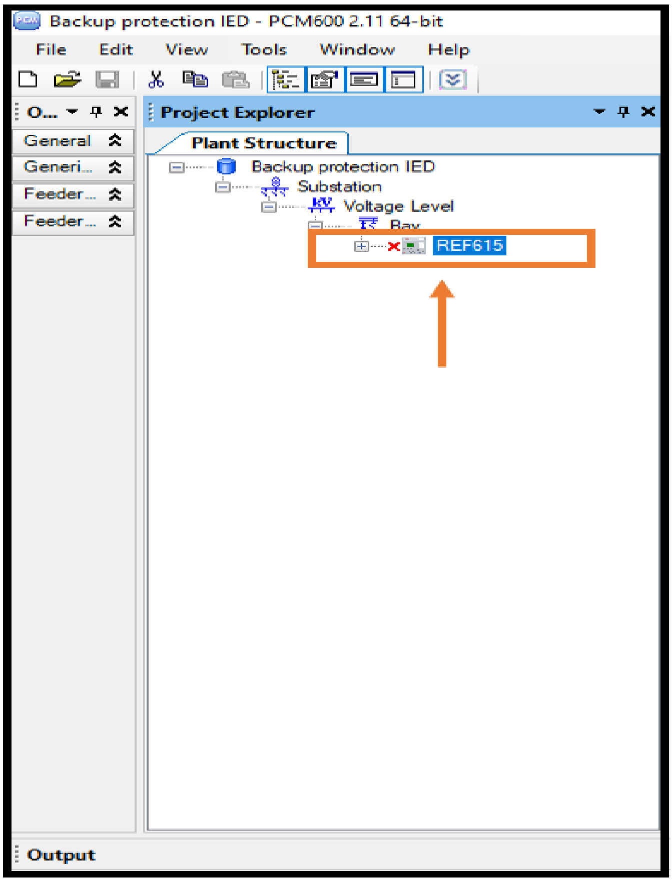
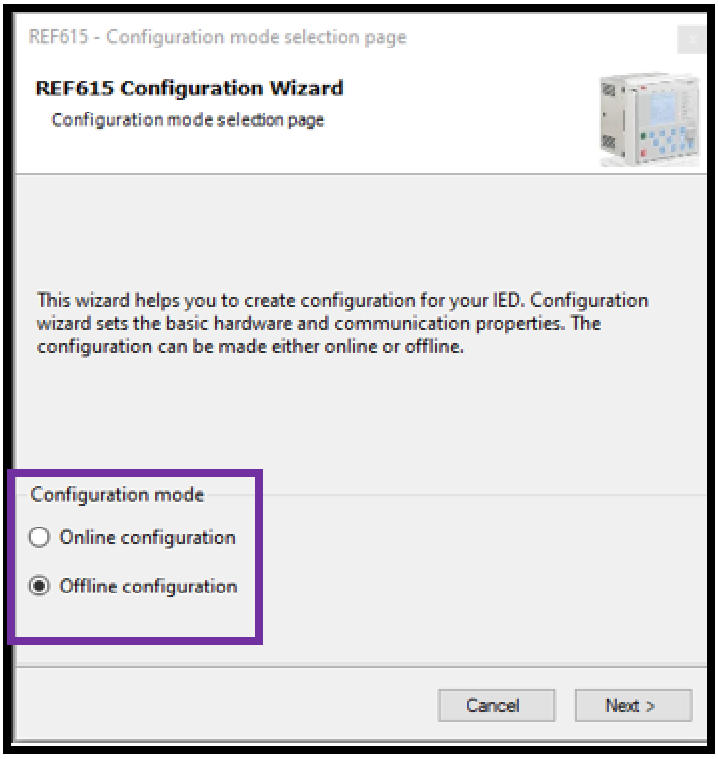


Figure 5.24: IED inserted in bay level

As the IED is inserted, a dialog box appears with two modes of configuring the IED "online/offline" as shown in Figure 5.25 below.


REF615 - Configuration mode selection page

REF615 Configuration Wizard

Configuration mode selection page

This wizard helps you to create configuration for your IED. Configuration wizard sets the basic hardware and communication properties. The configuration can be made either online or offline.

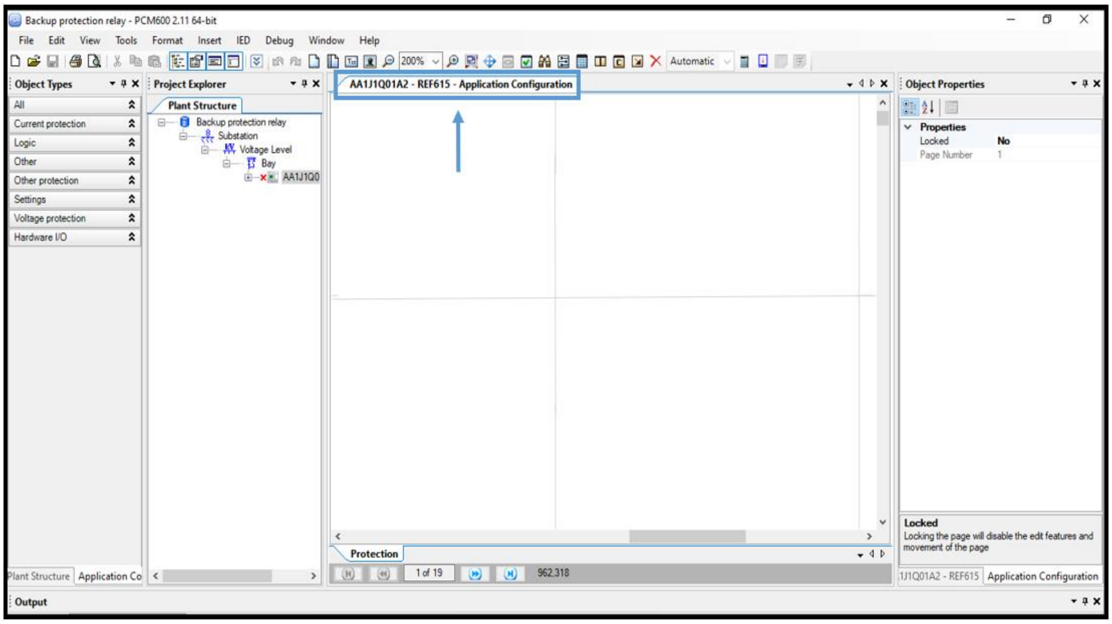
Configuration mode

○ Online configuration

● Offline configuration

Figure 5.25: Configuration modes.

Online mode is when communication is established between physical IED and the PC hosting PCM600 software. In this mode, data can be read straight from the IED. Offline mode is when there is no communication established between the IED and the PC hosting PCM600 software. In this case, the configuration is done and the settings are tested at a later stage in the online mode. After the IED is inserted in the bay level the next step was to configure the IED using the ‘Application Configuration’ tool as shown in Figure 5.26 below.

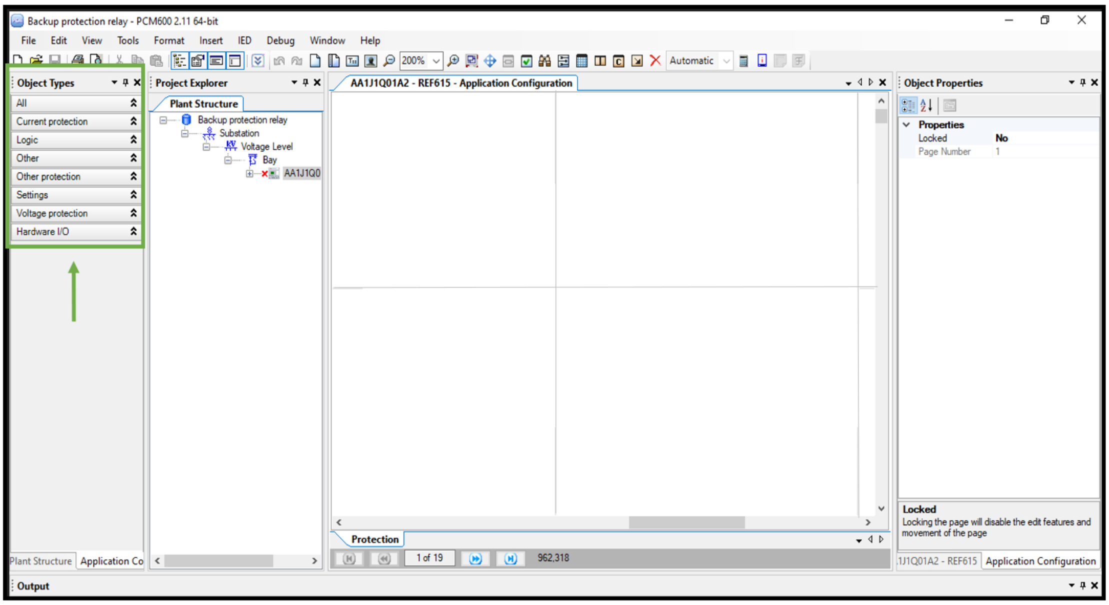


Locked No
Page Number 1

Locked
Locking the page will disable the edit features and movement of the page

Figure 5.26: **‘Application Configuration’ tool**

The configuration of IEDs is done by using function blocks which are the main elements of the ‘Application Configuration’ tool. These function blocks are found under ‘Object Types’ as highlighted in Figure 5.27 below.



Locked No
Page Number 1

Locked
Locking the page will disable the edit features and movement of the page

Figure 5.27: **Function blocks.**

The main function blocks used in this implementation are as follows:

- Earth fault overcurrent protection function block
- Trip logic function blocks
- Disturbance recorder function block
- Measurement function blocks
- Earth fault overcurrent protection function block

The earth fault overcurrent protection function block is shown in Figure 5.28 below. It is a non-directional earth fault protection, high-stage function block, and is used for monitoring ground faults in the system. The function is activated when the residual current exceeds the set limit. It has a definite time characteristic, which means that it starts working after a predetermined amount of time and stops working when the fault current stops flowing. Whenever there is an earth fault in the busbar, the earth fault protection will operate, to prevent damage to the busbar.

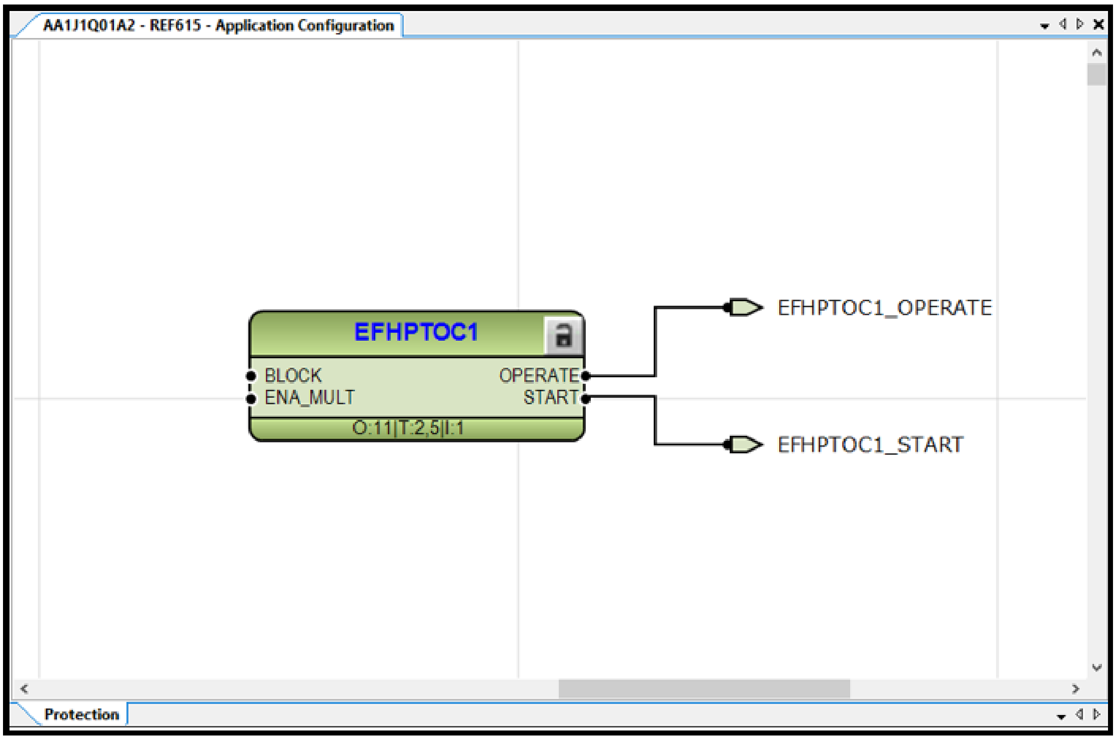


Figure 5.28: **Earth fault overcurrent function block**

A module diagram shown in Figure 5.29 below can be used to describe how EFPTOC works.

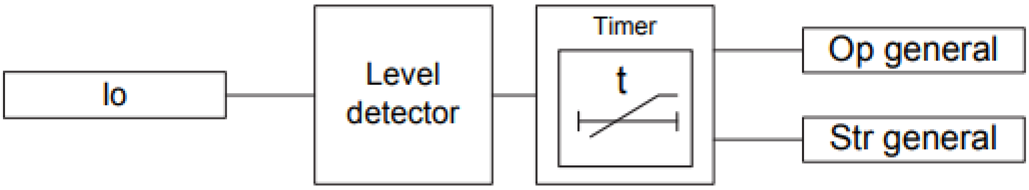


Figure 5.29: **Functional module diagram** (ABB, 2022).

The following sections provide explanations for each module on the diagram:

- Level detector

The Start value setting and the fundamental component of residual currents are compared. The Level detector sends an enable signal to the timer module if the measured value is greater than the Start value setting. For fault detection, either the direct measured residual current or the calculated residual current can be used. The Io signal Sel, which can be found in the general parameter setting, can be used to set the selection (ABB, 2022).

An absolute hysteresis setting can be used to prevent unwanted oscillations at the Str general and Op general outputs when the input current is slightly above or below the start value setting. After exiting the hysteresis range, the start condition must be met again, otherwise, the signal returns to the hysteresis range.

- Timer

Str general output is activated when the timer is activated. The time characteristic is based on a definite time. When the operating timer reaches the value set by the operating delay time, the Op general output is activated. If the fault disappears before the module becomes operational, the reset will take place immediately and the Str general output is deactivated (ABB, 2022).

- Disturbance recorder function block

The START and OPERATE outputs from Figure 5.28 above are connected to the disturbance recorder as shown in Figure 5.30 below. Also, the ‘GOOSE_BLOCK’ output signal from Figure 5.58 is connected to the disturbance recorder. These output signals trigger the disturbance recorder to record events before, during, and after a disturbance in the system.

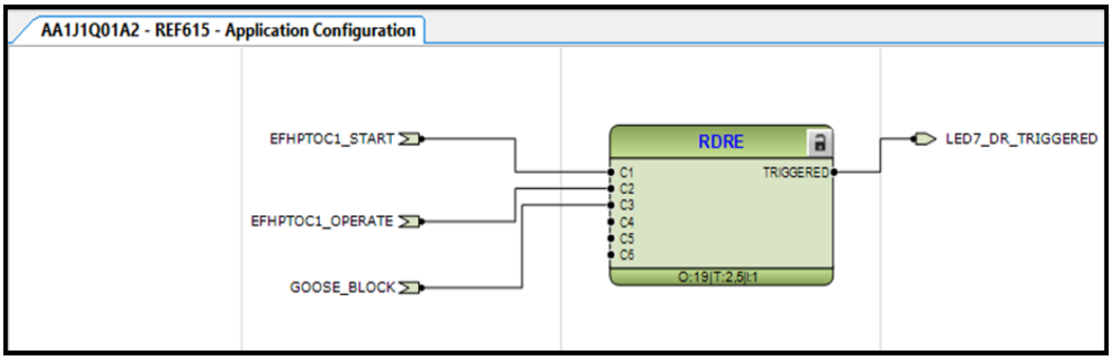


Figure 5.30: Disturbance recorder function block

The next step was to configure the IEC 61850 standard information models for this backup protection IED by configuring its CID file. This includes creating LNs and datasets which carry status event information to trip the virtual circuit breakers in RTDS.

5.4.5.2 Configuration of LNs for REF615 in PCM600

To start IEC 61850 configuration, click on ‘Tools’ then ‘IEC 61850 Configuration’ as shown in Figure 5.31 below.

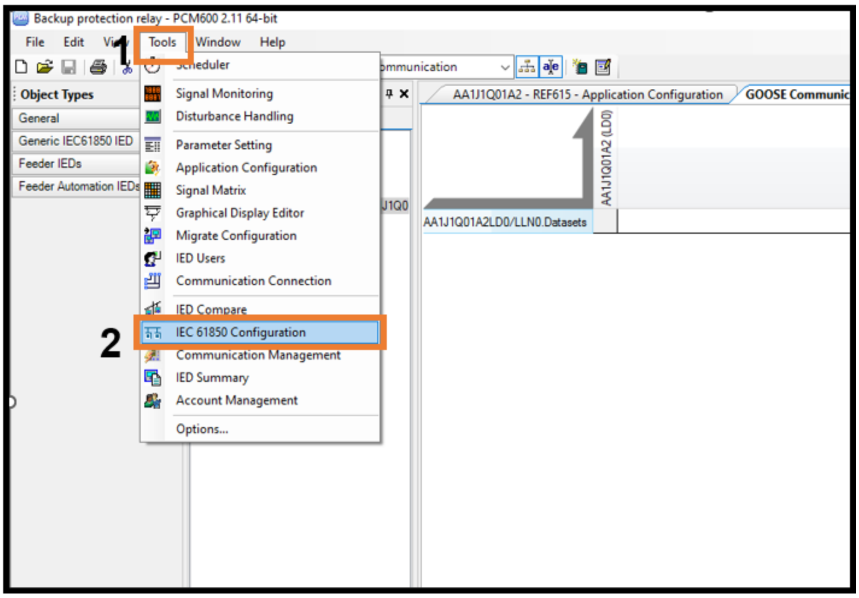
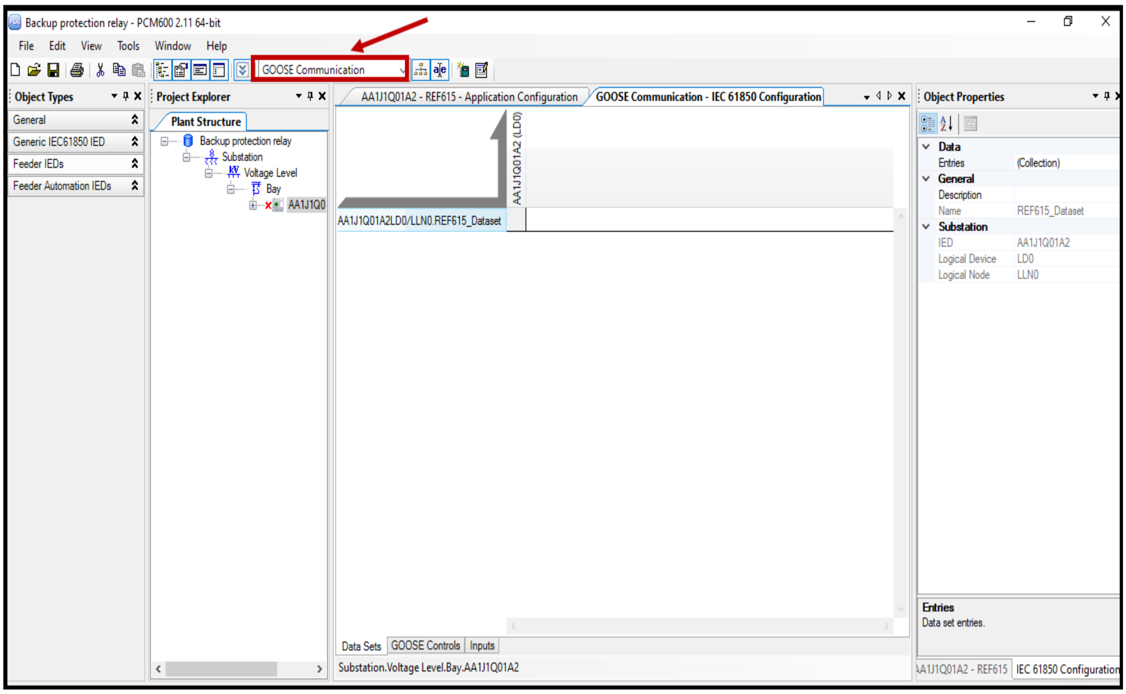


Figure 5.31: IEC 61850 configuration

After clicking on ‘IEC 61850 Configuration’, a window appears showing the type of communication mode as highlighted and shown in Figure 5.32 below.



Data
Entries (Collection)
General
Description
Name REF615_Dataset
Substation
IED AA1J1Q01A2
Logical Device LD0
Logical Node LLN0

Figure 5.32: **GOOSE communication mode**

The next step was to create a new dataset by right-clicking anywhere on the blank space and selecting 'New' as shown in Figure 5.33 below.

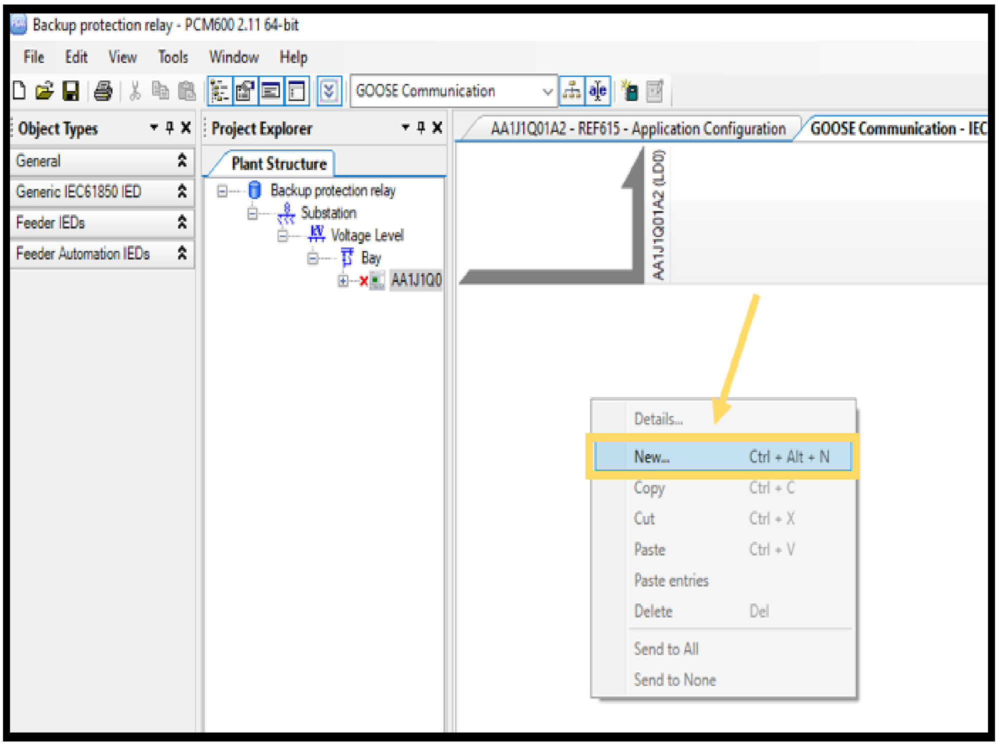
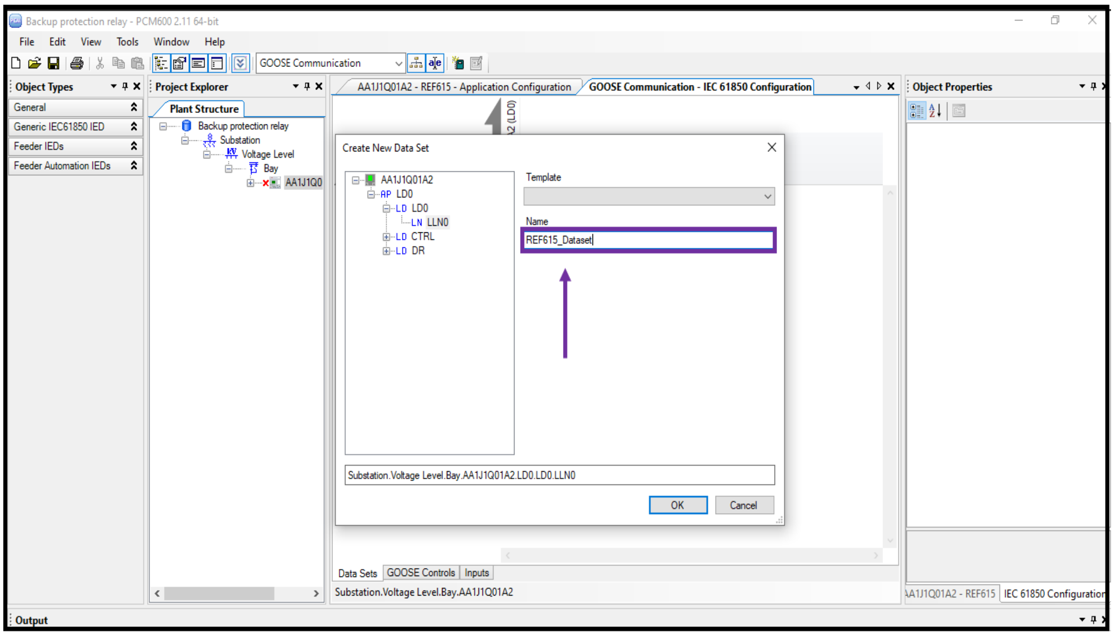


Figure 5.33: **Creating a new dataset**

Next, a window prompts as shown in figure 5.34 below, that allows for defining the dataset name 'REF615_Dataset'.



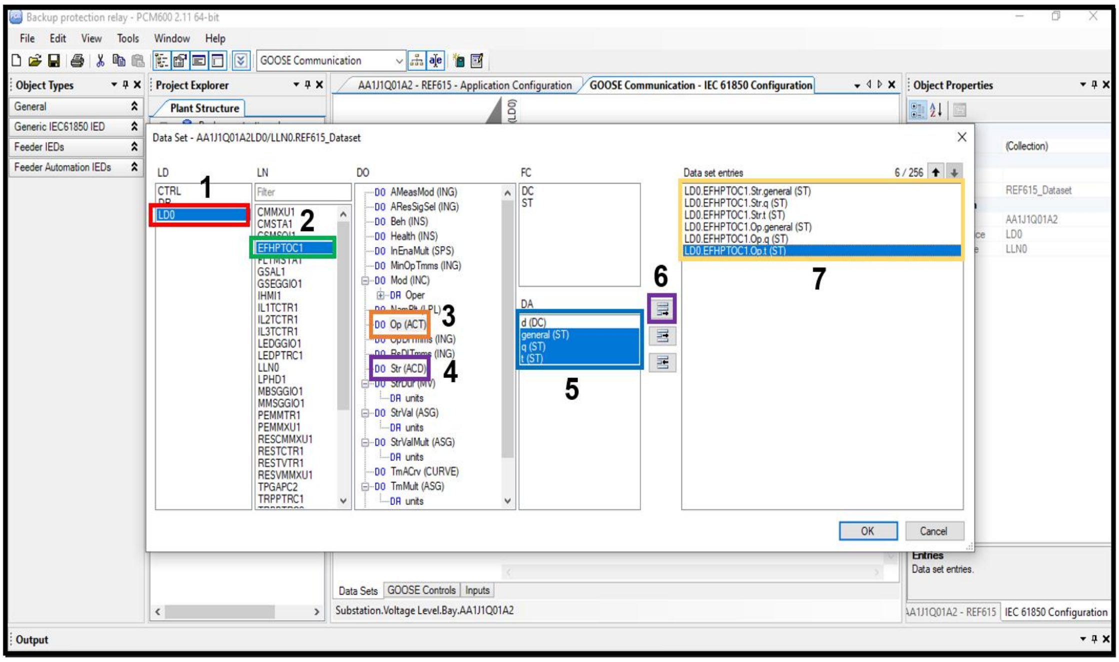
Name: REF615_Dataset

Substation.Voltage Level.Bay.AA1J1Q01A2.LD0.LD0.LLN0

Substation.Voltage Level.Bay.AA1J1Q01A2

Figure 5.34: ABB Dataset naming

As soon as the dataset name were defined, a window appears where LNs containing datasets and DAs to be published are created. For this project, a non-directional earth fault overcurrent protection LN is used. It was chosen based on the reviewed literature which states that most of the faults happening in the network are ground faults. The steps to follow when creating these datasets are indicated by steps 1 to 7 as shown in Figure 5.35 below



Data Set - AA1J1Q01A2LD0/LLN0.REF615_Dataset

Data set entries 6 / 256

LD0.EFHPTOC1.Str.general (ST)
LD0.EFHPTOC1.Str.q (ST)
LD0.EFHPTOC1.Str.t (ST)
LD0.EFHPTOC1.Op.general (ST)
LD0.EFHPTOC1.Op.q (ST)
LD0.EFHPTOC1.Op.t (ST)

Substation.Voltage Level.Bay.AA1J1Q01A2

Figure 5.35: Configuring LNs and datasets for REF615

After defining the datasets successfully, the next step was to generate the GOOSE control block. This control block was mapped to the publishing IED at a later stage. The steps to generate this GOOSE control block are shown in Figure 5.36 below. The first step was to click on ‘GOOSE Controls’, then right-click anywhere in the window to create a new control block.

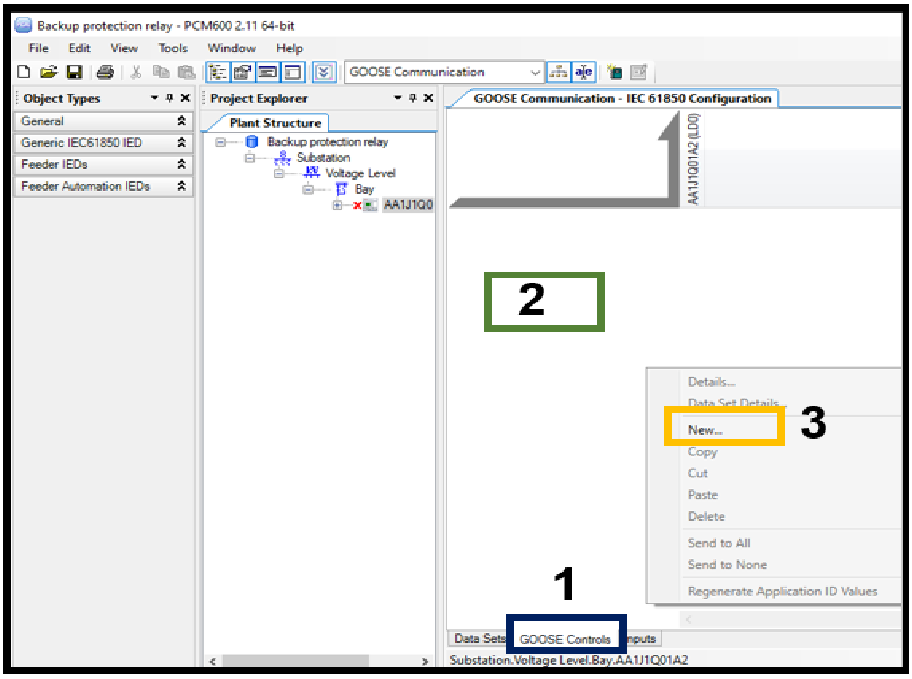
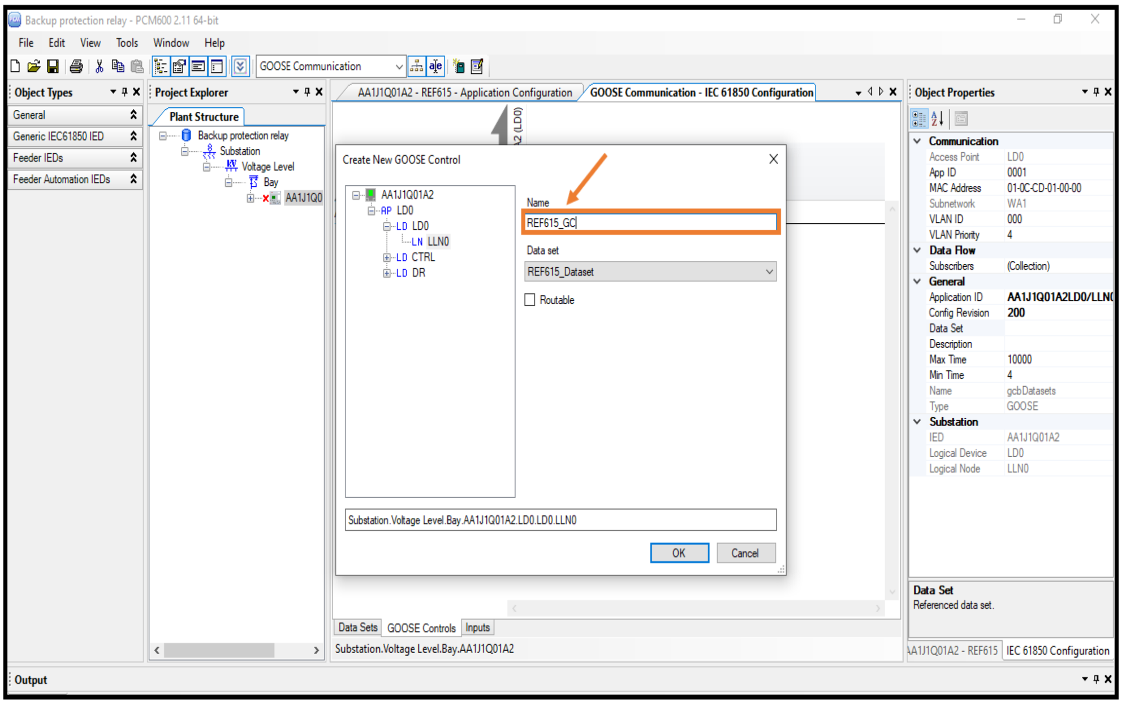


Figure 5.36: Generating GOOSE control block

Next, the window shown in Figure 5.37 below appears. This was where the GOOSE control block name was defined as ‘REF615_GC’.



Create New GOOSE Control

Name: REF615_GC

Data set: REF615_Dataset

☐ Routable

Substation.Voltage Level.Bay.AA1J1Q01A2.LD0.LD0.LLN0

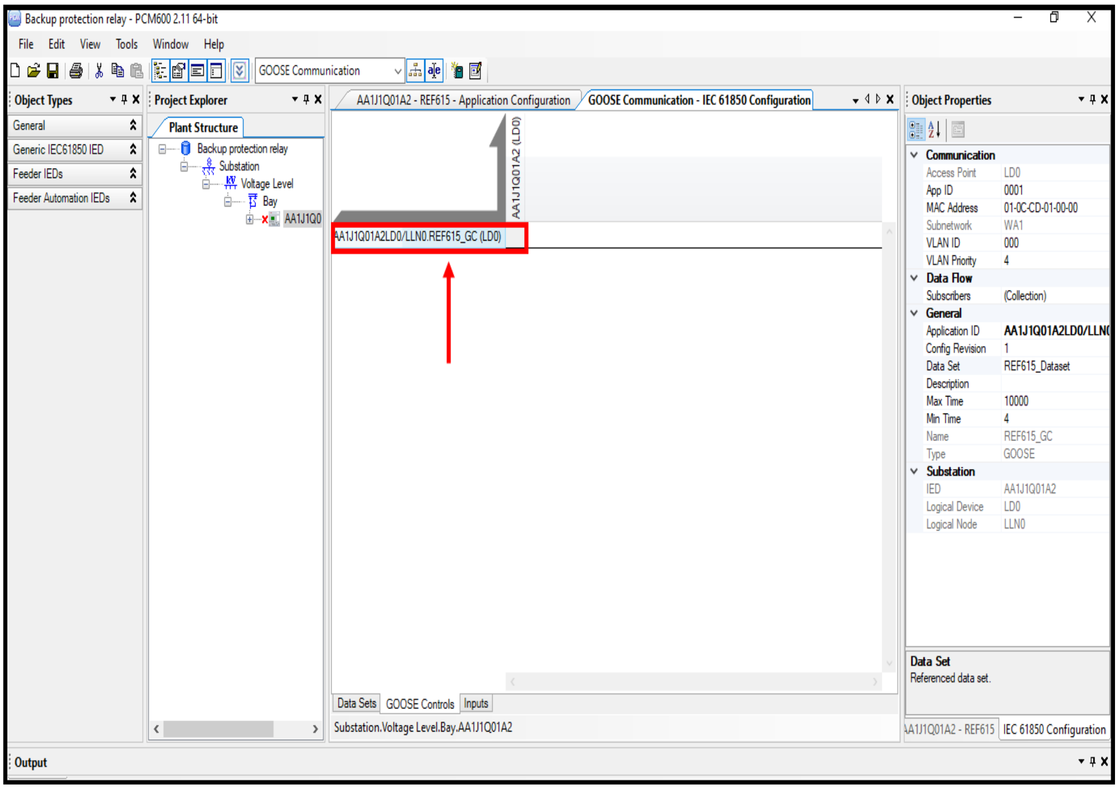
Substation.Voltage Level.Bay.AA1J1Q01A2

Communication	
Access Point	LD0
App ID	0001
MAC Address	01-0C-CD-01-00-00
Subnetwork	WA1
VLAN ID	000
VLAN Priority	4
Data Flow	
Subscribers	(Collection)
General	
Application ID	**AA1J1Q01A2LD0/LLN**
Config Revision	**200**
Data Set	
Description	
Max Time	10000
Min Time	4
Name	gcbDatasets
Type	GOOSE
Substation	
IED	AA1J1Q01A2
Logical Device	LD0
Logical Node	LLN0

Data Set
Referenced data set.

Figure 5.37: GOOSE control block name defined

After successfully creating the GOOSE control block, it will appear as shown in Figure 5.38 below.



Communication	
Access Point	LD0
App ID	0001
MAC Address	01-0C-CD-01-00-00
Subnetwork	WA1
VLAN ID	000
VLAN Priority	4
Data Flow	
Subscribers	(Collection)
General	
Application ID	**AA1J1Q01A2LD0/LLN**
Config Revision	1
Data Set	REF615_Dataset
Description	
Max Time	10000
Min Time	4
Name	REF615_GC
Type	GOOSE
Substation	
IED	AA1J1Q01A2
Logical Device	LD0
Logical Node	LLN0

Figure 5.38: GOOSE control block generated.

The next step is to save the SCD file as a CID file and to write it to the REF615 IED as shown in Figure 5.39 below. Before that, the connection of the PC with the IED must be verified by pinging its IP address.

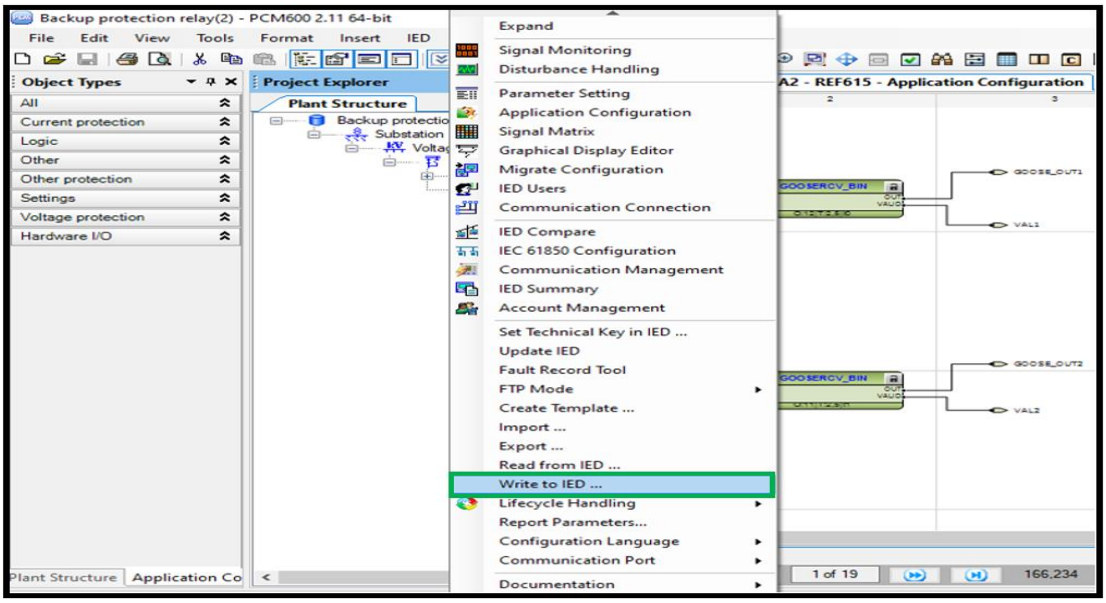
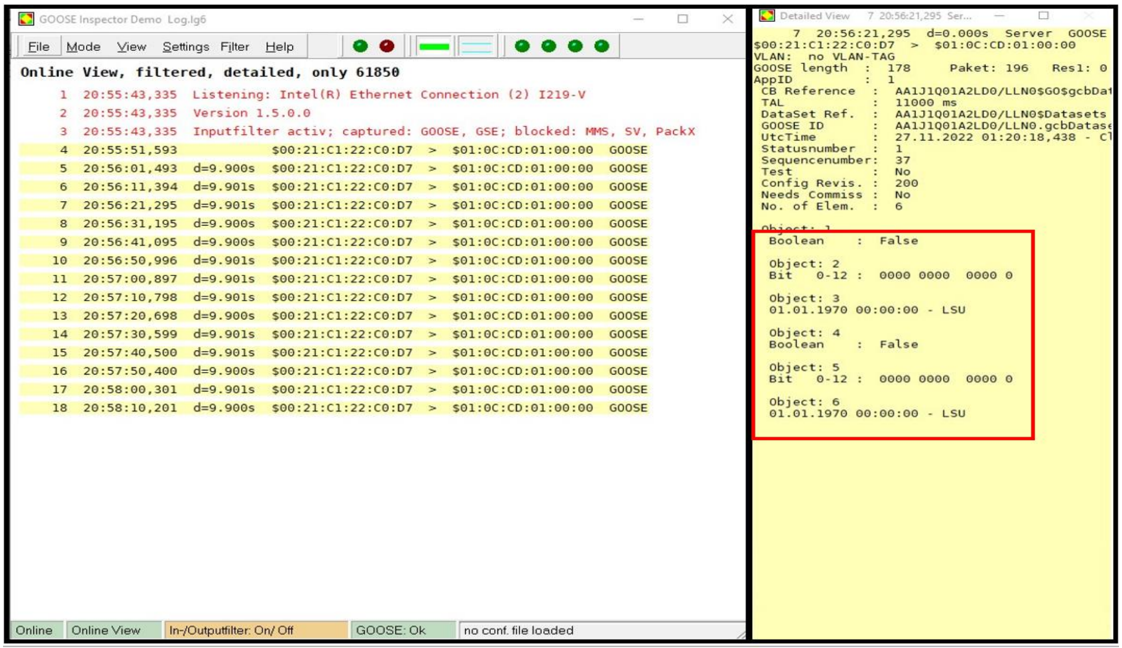


Figure 5.39: Writing the CID file to the physical IED.

As soon as the CID file was written successfully to the IED, the next step was to verify the configuration by monitoring GOOSE messages published by the REF615 IED. This was accomplished by using GOOSE Inspector Demo software. If the IED is publishing GOOSE, it will be identified by its Object Boolean highlighted in red in Figure 5.40 below.



```
Online View, filtered, detailed, only 61850
     1  20:55:43,335  Listening: Intel(R) Ethernet Connection (2) I219-V
     2  20:55:43,335  Version 1.5.0.0
     3  20:55:43,335  Inputfilter activ; captured: GOOSE, GSE; blocked: MMS, SV, PackX
     4  20:55:51,593             $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
     5  20:56:01,493  d=9.900s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
     6  20:56:11,394  d=9.901s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
     7  20:56:21,295  d=9.901s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
     8  20:56:31,195  d=9.900s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
     9  20:56:41,095  d=9.900s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
    10  20:56:50,996  d=9.901s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
    11  20:57:00,897  d=9.901s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
    12  20:57:10,798  d=9.901s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
    13  20:57:20,698  d=9.900s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
    14  20:57:30,599  d=9.901s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
    15  20:57:40,500  d=9.901s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
    16  20:57:50,400  d=9.900s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
    17  20:58:00,301  d=9.901s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
    18  20:58:10,201  d=9.900s  $00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00  GOOSE
```

```
      7  20:56:21,295  d=0.000s  Server  GOOSE
$00:21:C1:22:C0:D7  >  $01:0C:CD:01:00:00
VLAN:  no VLAN-TAG
GOOSE length  :  178     Paket: 196   Res1: 0
AppID         :  1
 CB Reference  :  AA1J1Q01A2LD0/LLN0$GO$gcbDa
 TAL           :  11000 ms
 DataSet Ref.  :  AA1J1Q01A2LD0/LLN0$Datasets
 GOOSE ID      :  AA1J1Q01A2LD0/LLN0.gcbDatas
 UtcTime       :  27.11.2022 01:20:18,438 - C
 Statusnumber  :  1
 Sequencenumber:  37
 Test          :  No
 Config Revis. :  200
 Needs Commiss :  No
 No. of Elem.  :  6

 Object: 1
  Boolean     :  False

  Object: 2
  Bit   0-12 :  0000 0000  0000 0

  Object: 3
  01.01.1970 00:00:00 - LSU

  Object: 4
  Boolean     :  False

  Object: 5
  Bit   0-12 :  0000 0000  0000 0

  Object: 6
  01.01.1970 00:00:00 - LSU
```

Figure 5.40: **REF615 IED Publishing GOOSE messages**

The CID files were configured and saved for both IEDs. They were imported into the SCD Editor tool of the GTNET component in RSCAD to complete the configuration. The datasets containing status event information and the OPERATE signal were mapped to the corresponding circuit breakers. These configurations are described in detail in the following section.

5.4.6 Configuration settings of GTNET-GSE component in RTDS

The GTNET component aims to connect a physical device to virtual RTDS circuit breakers so that the circuit breaker can recognize commands and operate accordingly when a status event is shared by the GOOSE publishing IEDs. The GTNET card is configured using GTNET-GSE v5 component from the master library in RSCAD. The GTNET-GSE v5 can simulate up to 4 soft IEDs to perform its functions and it is configured using the embedded SCD Editor tool. The tool was launched by following the steps shown in Figure 5.41, and Figure 5.42 below.

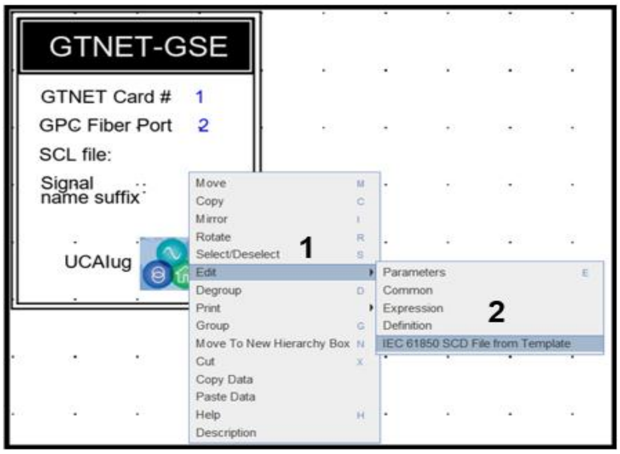
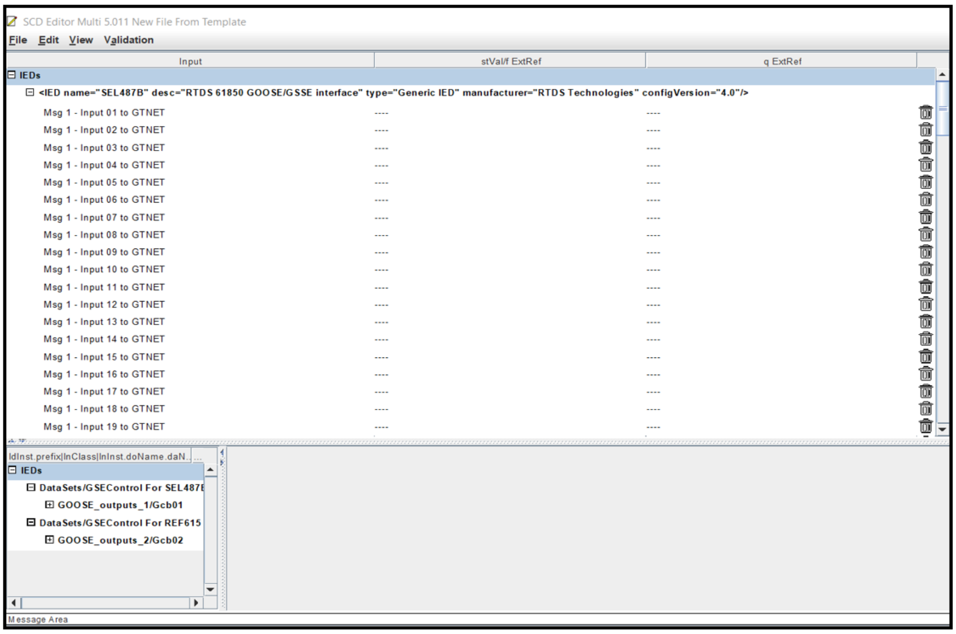


Figure 5.4121: Launching SCD Editor tool to configure GTNET-GSE v5 component



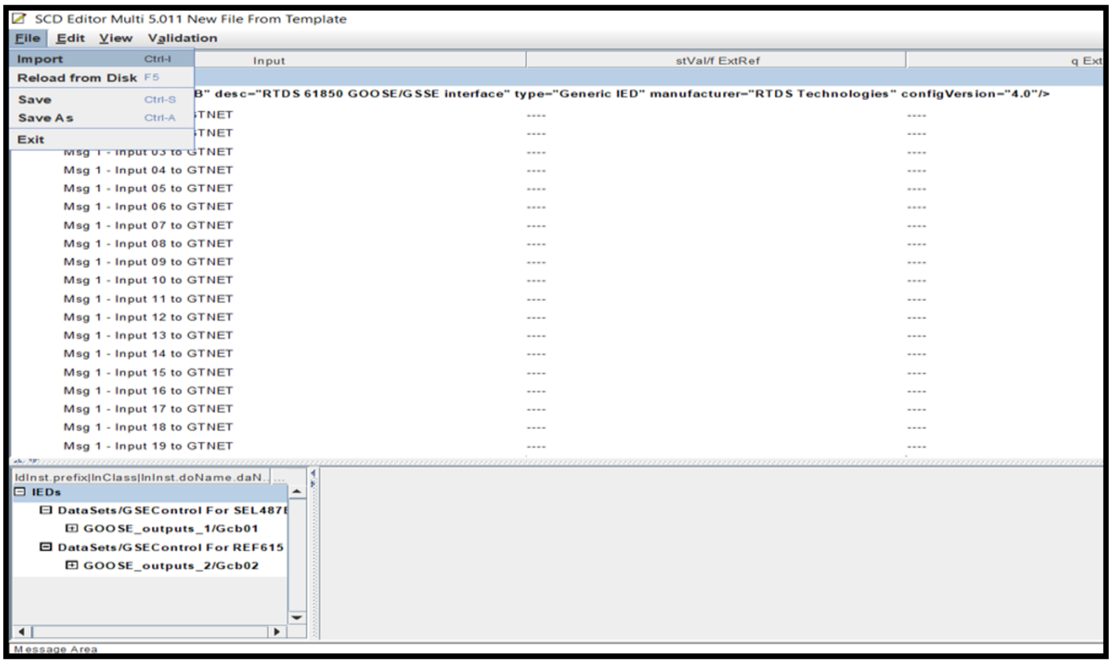
Input	stVal/f ExtRef	q ExtRef
⊟ IEDs		
⊟ <IED name="SEL487B" desc="RTDS 61850 GOOSE/GSSE interface" type="Generic IED" manufacturer="RTDS Technologies" configVersion="4.0"/>		
Msg 1 - Input 01 to GTNET	----	----
Msg 1 - Input 02 to GTNET	----	----
Msg 1 - Input 03 to GTNET	----	----
Msg 1 - Input 04 to GTNET	----	----
Msg 1 - Input 05 to GTNET	----	----
Msg 1 - Input 06 to GTNET	----	----
Msg 1 - Input 07 to GTNET	----	----
Msg 1 - Input 08 to GTNET	----	----
Msg 1 - Input 09 to GTNET	----	----
Msg 1 - Input 10 to GTNET	----	----
Msg 1 - Input 11 to GTNET	----	----
Msg 1 - Input 12 to GTNET	----	----
Msg 1 - Input 13 to GTNET	----	----
Msg 1 - Input 14 to GTNET	----	----
Msg 1 - Input 15 to GTNET	----	----
Msg 1 - Input 16 to GTNET	----	----
Msg 1 - Input 17 to GTNET	----	----
Msg 1 - Input 18 to GTNET	----	----
Msg 1 - Input 19 to GTNET	----	----

ldInst.prefix|lnClass|lnInst.doName.daN...

⊟ IEDs
  ⊟ DataSets/GSEControl For SEL487B
    ⊞ GOOSE_outputs_1/Gcb01
  ⊟ DataSets/GSEControl For REF615
    ⊞ GOOSE_outputs_2/Gcb02

Figure 5.42: SCD Editor tool in RTDS

The next step was to import the CID files of both physical IEDs into the SCD editor. Steps to import the files are shown in Figure 5.43 below.



SCD Editor Multi 5.011 New File From Template

B" desc="RTDS 61850 GOOSE/GSSE interface" type="Generic IED" manufacturer="RTDS Technologies" configVersion="4.0"/>

Input	stVal/f ExtRef	q Ext
TNET	----	----
TNET	----	----
Msg 1 - Input 03 to GTNET	----	----
Msg 1 - Input 04 to GTNET	----	----
Msg 1 - Input 05 to GTNET	----	----
Msg 1 - Input 06 to GTNET	----	----
Msg 1 - Input 07 to GTNET	----	----
Msg 1 - Input 08 to GTNET	----	----
Msg 1 - Input 09 to GTNET	----	----
Msg 1 - Input 10 to GTNET	----	----
Msg 1 - Input 11 to GTNET	----	----
Msg 1 - Input 12 to GTNET	----	----
Msg 1 - Input 13 to GTNET	----	----
Msg 1 - Input 14 to GTNET	----	----
Msg 1 - Input 15 to GTNET	----	----
Msg 1 - Input 16 to GTNET	----	----
Msg 1 - Input 17 to GTNET	----	----
Msg 1 - Input 18 to GTNET	----	----
Msg 1 - Input 19 to GTNET	----	----

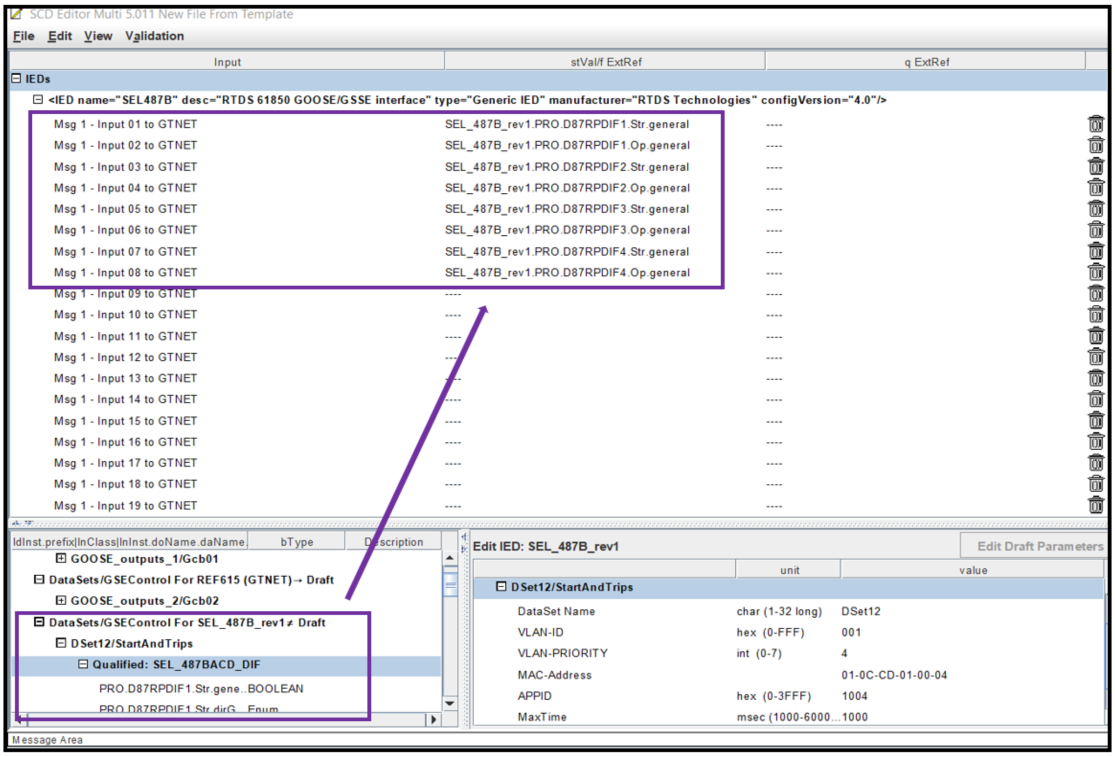
ldInst.prefix|lnClass|lnInst.doName.daN...

- ⊟ IEDs
  - ⊟ DataSets/GSEControl For SEL487E
    - ⊞ GOOSE_outputs_1/Gcb01
  - ⊟ DataSets/GSEControl For REF615
    - ⊞ GOOSE_outputs_2/Gcb02

Message Area

Figure 5.43: Importing the CID files from the physical IEDs

The CID file for the primary protection IED “SEL-487B” was imported first. The Data Attributes contained in the dataset for status sharing were mapped to the digital inputs of the GTNET as shown in Figure 5.44 below.



SCD Editor Multi 5.011 New File From Template

⊟ IEDs

⊟ <IED name="SEL487B" desc="RTDS 61850 GOOSE/GSSE interface" type="Generic IED" manufacturer="RTDS Technologies" configVersion="4.0"/>

Input	stVal/f ExtRef	q ExtRef
Msg 1 - Input 01 to GTNET	SEL_487B_rev1.PRO.D87RPDIF1.Str.general	----
Msg 1 - Input 02 to GTNET	SEL_487B_rev1.PRO.D87RPDIF1.Op.general	----
Msg 1 - Input 03 to GTNET	SEL_487B_rev1.PRO.D87RPDIF2.Str.general	----
Msg 1 - Input 04 to GTNET	SEL_487B_rev1.PRO.D87RPDIF2.Op.general	----
Msg 1 - Input 05 to GTNET	SEL_487B_rev1.PRO.D87RPDIF3.Str.general	----
Msg 1 - Input 06 to GTNET	SEL_487B_rev1.PRO.D87RPDIF3.Op.general	----
Msg 1 - Input 07 to GTNET	SEL_487B_rev1.PRO.D87RPDIF4.Str.general	----
Msg 1 - Input 08 to GTNET	SEL_487B_rev1.PRO.D87RPDIF4.Op.general	----
Msg 1 - Input 09 to GTNET	----	----
Msg 1 - Input 10 to GTNET	----	----
Msg 1 - Input 11 to GTNET	----	----
Msg 1 - Input 12 to GTNET	----	----
Msg 1 - Input 13 to GTNET	----	----
Msg 1 - Input 14 to GTNET	----	----
Msg 1 - Input 15 to GTNET	----	----
Msg 1 - Input 16 to GTNET	----	----
Msg 1 - Input 17 to GTNET	----	----
Msg 1 - Input 18 to GTNET	----	----
Msg 1 - Input 19 to GTNET	----	----

ldInst.prefix|lnClass|lnInst.doName.daName | bType | Description

- ⊞ GOOSE_outputs_1/Gcb01
- ⊟ DataSets/GSEControl For REF615 (GTNET)→ Draft
  - ⊞ GOOSE_outputs_2/Gcb02
- ⊟ DataSets/GSEControl For SEL_487B_rev1≠ Draft
  - ⊟ DSet12/StartAndTrips
    - ⊟ Qualified: SEL_487BACD_DIF
      - PRO.D87RPDIF1.Str.gene..BOOLEAN
      - PRO.D87RPDIF1.Str.dirG...Enum

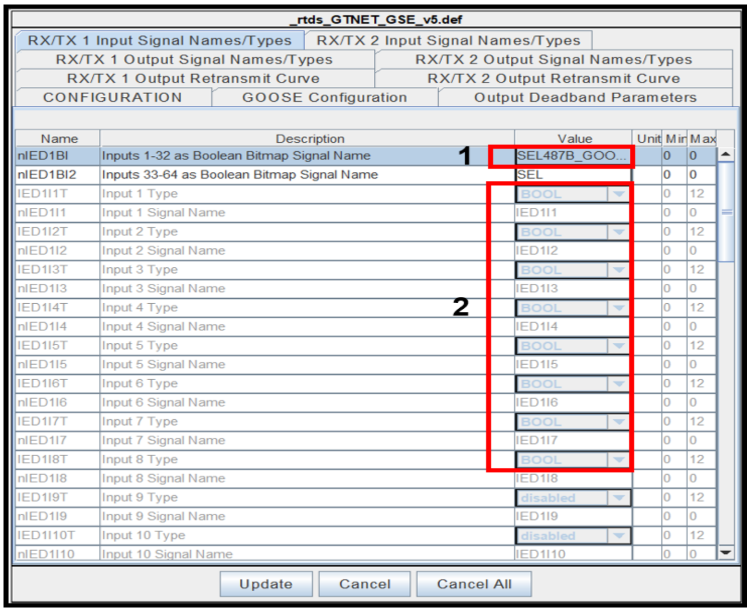
Edit IED: SEL_487B_rev1

	unit	value
⊟ DSet12/StartAndTrips		
DataSet Name	char (1-32 long)	DSet12
VLAN-ID	hex (0-FFF)	001
VLAN-PRIORITY	int (0-7)	4
MAC-Address		01-0C-CD-01-00-04
APPID	hex (0-3FFF)	1004
MaxTime	msec (1000-6000...	1000

Message Area

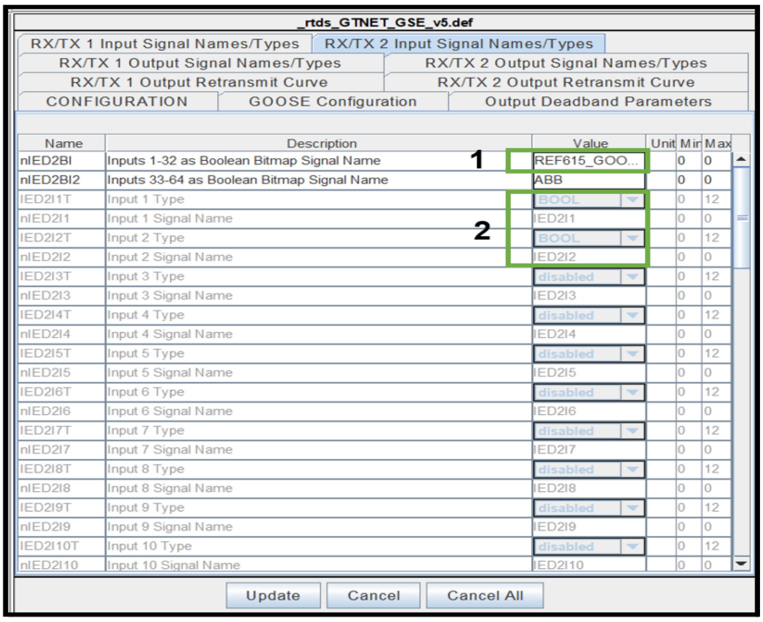
Figure 5.44: Mapping of GOOSE dataset published by SEL-487B to the GTNET IED.

The same steps of importing the CID file were followed for the backup protection IED “REF615”. The main aim of importing these CID files and mapping the datasets was to interface physical IEDs to virtual circuit breakers in RTDS. This was done to ensure that whenever the physical IED is publishing GOOSE messages, the virtual circuit breakers in RTDS receive those messages. The GTNET GSE v5 parameters configuration windows are shown in Figures 5.45 and 5.46 below. The 'SEL-487B_GOOSE' and 'REF615_GOOSE' are words containing the incoming GOOSE datasets from the external IEDs. The eight DAs from SEL-487B and two DAs from REF615 that were mapped to the GTNET in the previous steps, are highlighted in the figures showing their Boolean data type 'BOOL'.



Name	Description	Value	Unit	Min	Max
nIED1BI	Inputs 1-32 as Boolean Bitmap Signal Name	SEL487B_GOO...		0	0
nIED1BI2	Inputs 33-64 as Boolean Bitmap Signal Name	SEL		0	0
IED1I1T	Input 1 Type	BOOL		0	12
nIED1I1	Input 1 Signal Name	IED1I1		0	0
IED1I2T	Input 2 Type	BOOL		0	12
nIED1I2	Input 2 Signal Name	IED1I2		0	0
IED1I3T	Input 3 Type	BOOL		0	12
nIED1I3	Input 3 Signal Name	IED1I3		0	0
IED1I4T	Input 4 Type	BOOL		0	12
nIED1I4	Input 4 Signal Name	IED1I4		0	0
IED1I5T	Input 5 Type	BOOL		0	12
nIED1I5	Input 5 Signal Name	IED1I5		0	0
IED1I6T	Input 6 Type	BOOL		0	12
nIED1I6	Input 6 Signal Name	IED1I6		0	0
IED1I7T	Input 7 Type	BOOL		0	12
nIED1I7	Input 7 Signal Name	IED1I7		0	0
IED1I8T	Input 8 Type	BOOL		0	12
nIED1I8	Input 8 Signal Name	IED1I8		0	0
IED1I9T	Input 9 Type	disabled		0	12
nIED1I9	Input 9 Signal Name	IED1I9		0	0
IED1I10T	Input 10 Type	disabled		0	12
nIED1I10	Input 10 Signal Name	IED1I10		0	0

Figure 5. 45: GTNET input signals from the SEL-487B relay



Name	Description	Value	Unit	Min	Max
nIED2BI	Inputs 1-32 as Boolean Bitmap Signal Name	REF615_GOO...		0	0
nIED2BI2	Inputs 33-64 as Boolean Bitmap Signal Name	ABB		0	0
IED2I1T	Input 1 Type	BOOL		0	12
nIED2I1	Input 1 Signal Name	IED2I1		0	0
IED2I2T	Input 2 Type	BOOL		0	12
nIED2I2	Input 2 Signal Name	IED2I2		0	0
IED2I3T	Input 3 Type	disabled		0	12
nIED2I3	Input 3 Signal Name	IED2I3		0	0
IED2I4T	Input 4 Type	disabled		0	12
nIED2I4	Input 4 Signal Name	IED2I4		0	0
IED2I5T	Input 5 Type	disabled		0	12
nIED2I5	Input 5 Signal Name	IED2I5		0	0
IED2I6T	Input 6 Type	disabled		0	12
nIED2I6	Input 6 Signal Name	IED2I6		0	0
IED2I7T	Input 7 Type	disabled		0	12
nIED2I7	Input 7 Signal Name	IED2I7		0	0
IED2I8T	Input 8 Type	disabled		0	12
nIED2I8	Input 8 Signal Name	IED2I8		0	0
IED2I9T	Input 9 Type	disabled		0	12
nIED2I9	Input 9 Signal Name	IED2I9		0	0
IED2I10T	Input 10 Type	disabled		0	12
nIED2I10	Input 10 Signal Name	IED2I10		0	0

Figure 5.46: GTNET signals defined for REF615 relay

The differential and overcurrent OPERATE signals from the external IEDs are received by the circuit breakers through a word-to-bit converter as shown in Figure 5.47 below.

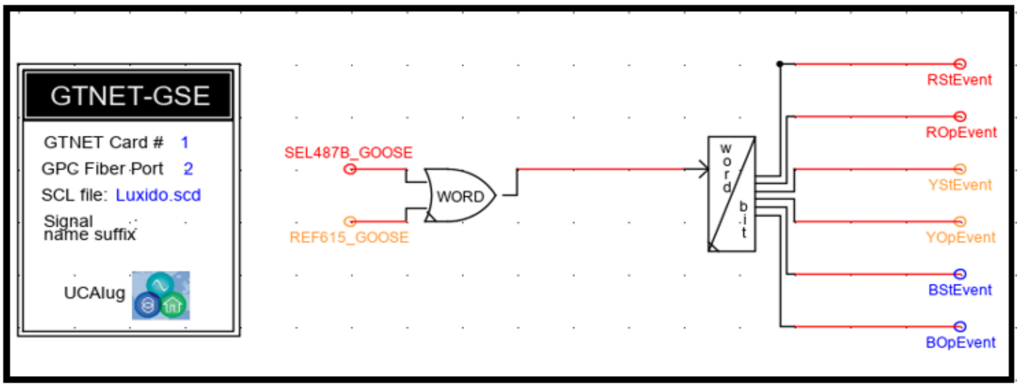


Figure 5.47: GTNET interfaced with a word to bit converter

The output signals (ROpEvent, BOpEvent, and BOpEvent) from the word to bit converter are then inputted to the S-R flip flop of the circuit breaker logic as shown in Figure 5.48 below. This is done to trigger the circuit breakers to operate accordingly whenever the GOOSE message containing the status event is published by the external IEDs.

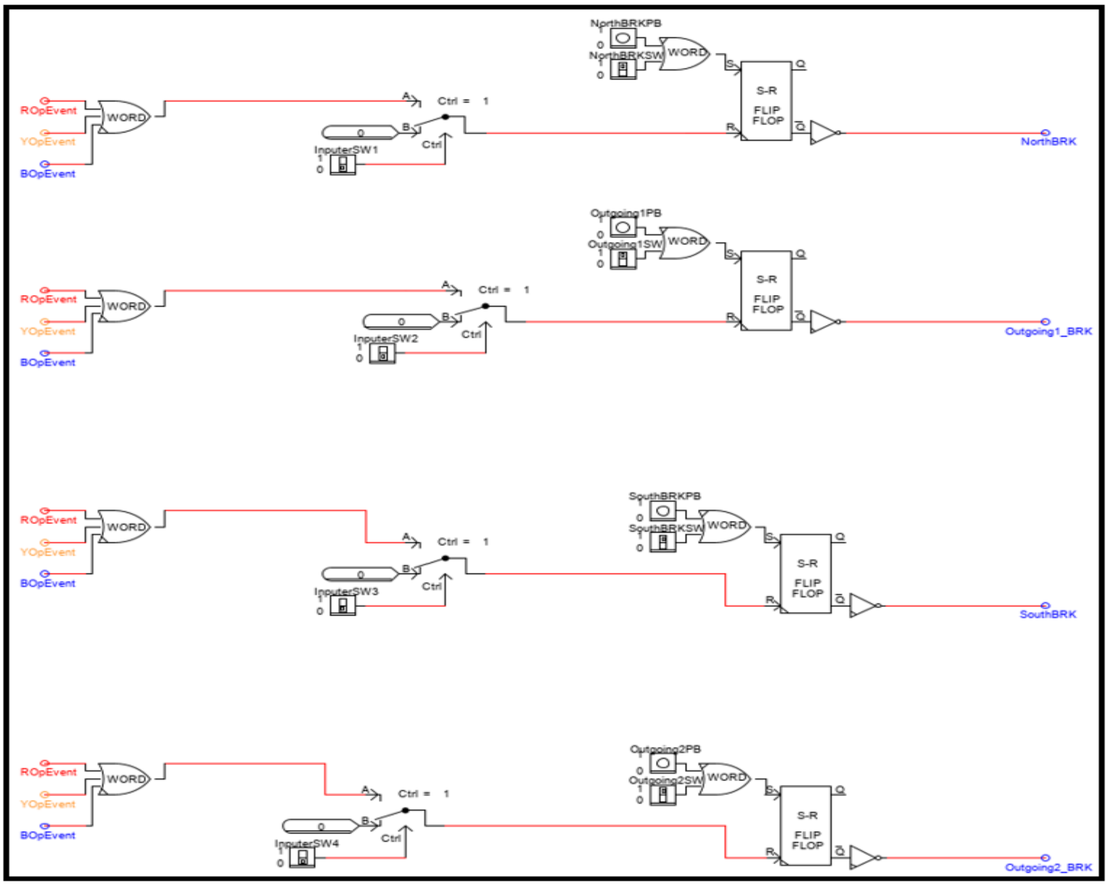


Figure 5.48: Circuit breaker control logic

The next step was to evaluate interoperability between the IEDs SEL-487B and REF615. The evaluation was performed by simulating a fault on the busbar and only the primary protection IED "SEL-487B" should OPERATE. The backup protection IED "REF615" should only pick up the fault, assert the 'Start' indicator LED on the front panel, and not OPERATE. This will be achieved through the implementation of a GOOSE signal-blocking scheme using the IEC 61850 standard. Whenever there is a fault on the busbar, the SEL-487B relay must send a GOOSE blocking signal to block the REF615 relay from operating. The only time the backup protection IED will operate is when the main protection IED is malfunctioning.

Two test case studies were performed to validate the proposed protection scheme. The first case was when the GOOSE blocking signal was applied. The second case was when there is no GOOSE blocking signal applied. The Hardware-In-the-Loop testing approach with RTDS was used to evaluate for interoperability as shown in Figure 5.49 below. The software that was used to configure this blocking scheme was PCM600 software.

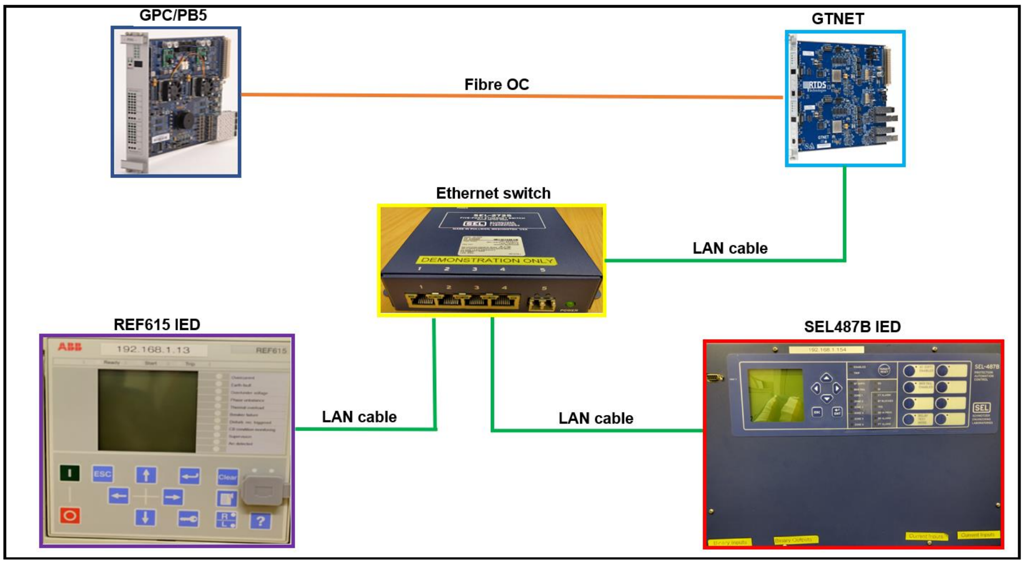


Figure 5.49 HIL interface of SEL-487B and REF615 IEDs with RTDS.

5.4.7 Implementation of GOOSE message blocking scheme using IEC61850 standard

Configuration of CID files of both SEL-487B and REF615 IEDs were described in sections 5.4.4 and 5.4.5 The next step was to import the CID file for SEL-487B into PCM600 software. This was where the mapping of GOOSE messages between the two IEDs was done. For this implementation, the SEL-487B was publishing the blocking signal to REF615. The steps followed to achieve interoperability between the two IEDs are shown in the flowchart in Figure 5.50 below.

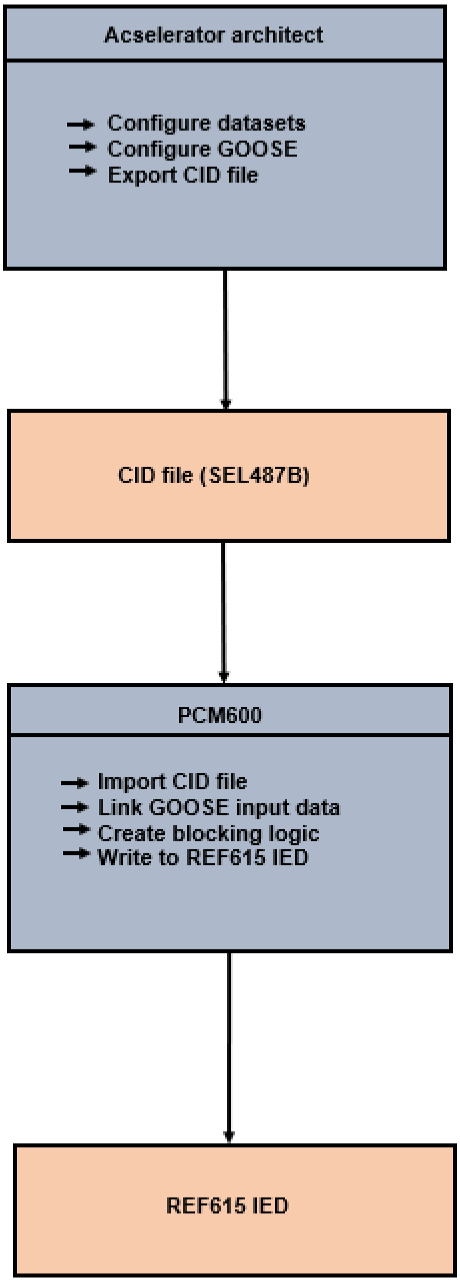


Figure 5.50: Flow chart algorithm for the GOOSE-based blocking scenario

The first step was to import the CID file of SEL-487B which was configured in AcSELerator Architect software, in the PCM600 software as shown in Figure 5.51 below.

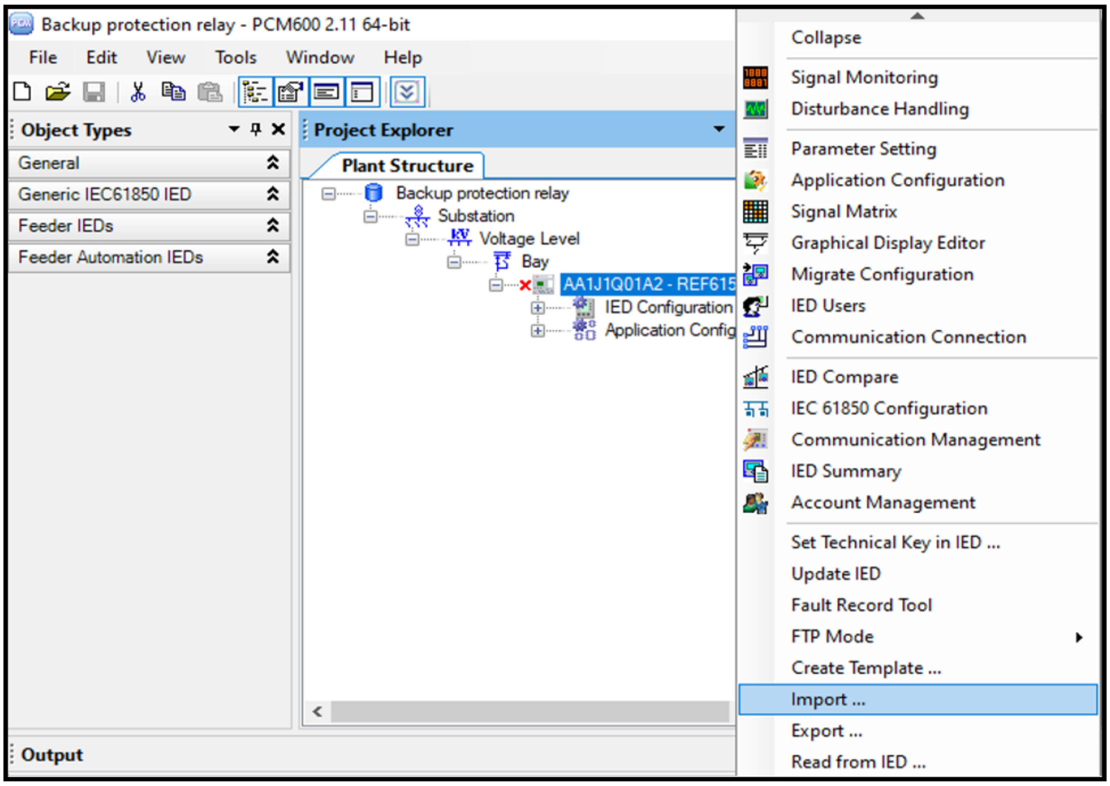
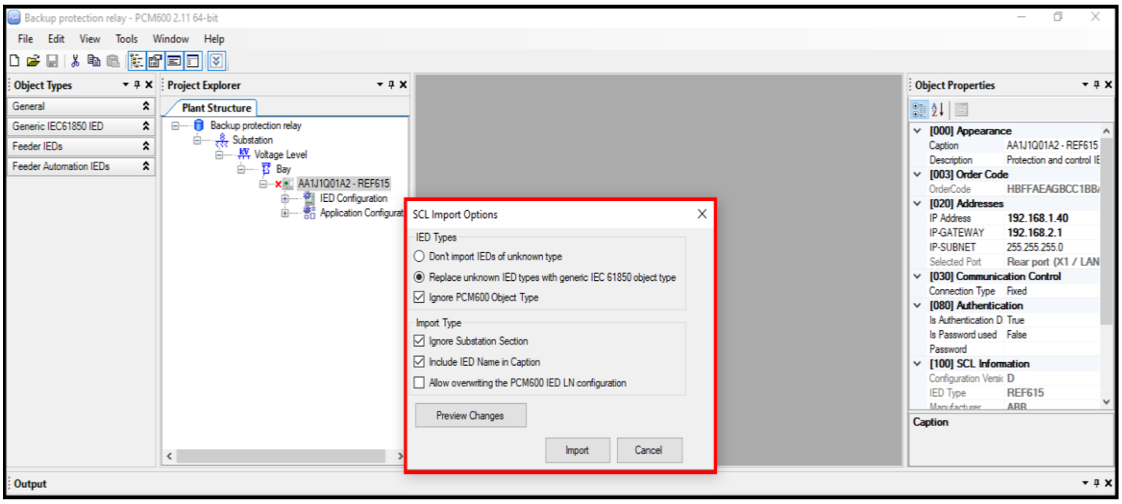


Figure 5.51: Importing the SEL-487B CID file in PCM600

After clicking 'Import' as shown in Figure 5.51 above, a window appears with multiple import options as shown in Figure 5.52 below. the selected options in the figure are used when importing a different-vendor IED in PCM600.



SCL Import Options

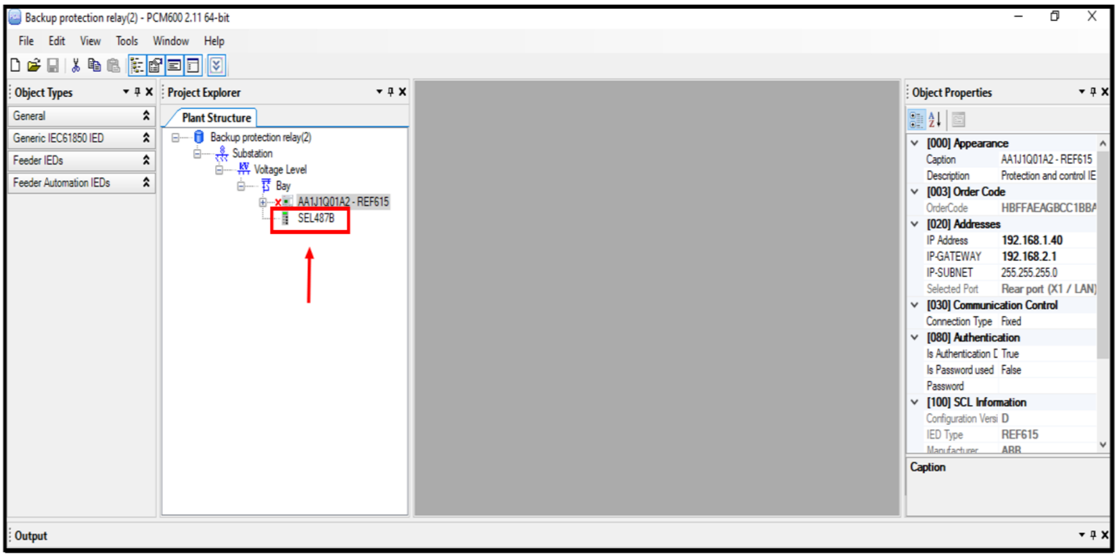
IED Types
○ Don't import IEDs of unknown type
● Replace unknown IED types with generic IEC 61850 object type
☑ Ignore PCM600 Object Type

Import Type
☑ Ignore Substation Section
☑ Include IED Name in Caption
☐ Allow overwriting the PCM600 IED LN configuration

[000] Appearance
Caption AA1J1Q01A2 - REF615
Description Protection and control IE
[003] Order Code
OrderCode HBFFAEAGBCC1BB
[020] Addresses
IP Address 192.168.1.40
IP-GATEWAY 192.168.2.1
IP-SUBNET 255.255.255.0
Selected Port Rear port (X1 / LAN
[030] Communication Control
Connection Type Fixed
[080] Authentication
Is Authentication D True
Is Password used False
Password
[100] SCL Information
Configuration Versic D
IED Type REF615
Manufacturer ABB
Caption

Figure 5.52:SCL files import options

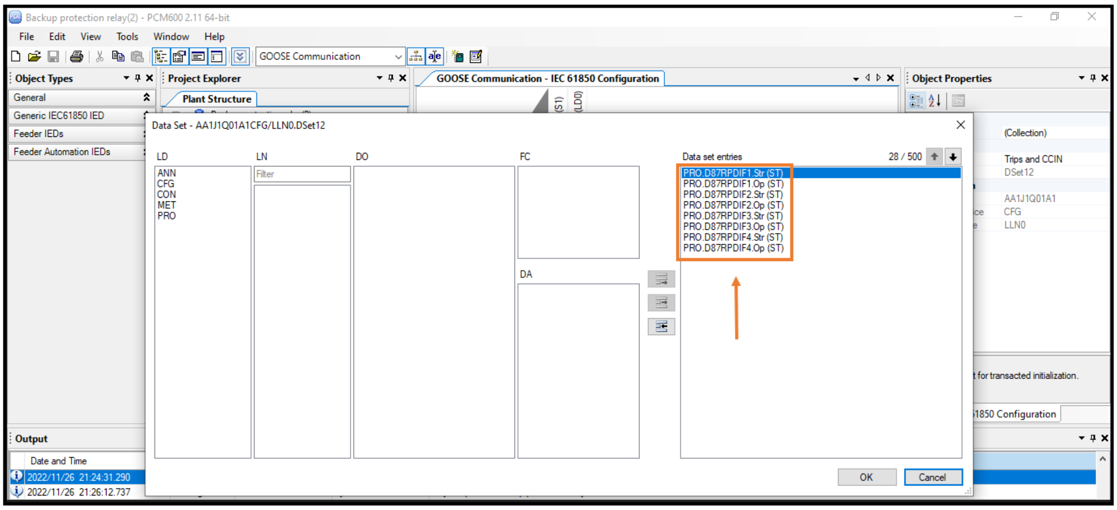
Once the CID file is imported successfully, it will appear as a generic IED as seen in Figure 5.53 below.



[000] Appearance	
Caption	AA1J1Q01A2 - REF615
Description	Protection and control IE
[003] Order Code	
OrderCode	HBFFAEAGBCC1BBA
[020] Addresses	
IP Address	192.168.1.40
IP-GATEWAY	192.168.2.1
IP-SUBNET	255.255.255.0
Selected Port	Rear port (X1 / LAN)
[030] Communication Control	
Connection Type	Fixed
[080] Authentication	
Is Authentication D	True
Is Password used	False
Password	
[100] SCL Information	
Configuration Versi	D
IED Type	REF615
Manufacturer	ABB

Figure 5.53: SEL487B CID file imported successfully.

The next step was to verify the datasets contained in the CID files of both IEDs as shown in figures 5.54 and 5.55 below.



Data Set - AA1J1Q01A1CFG/LLN0.DSet12

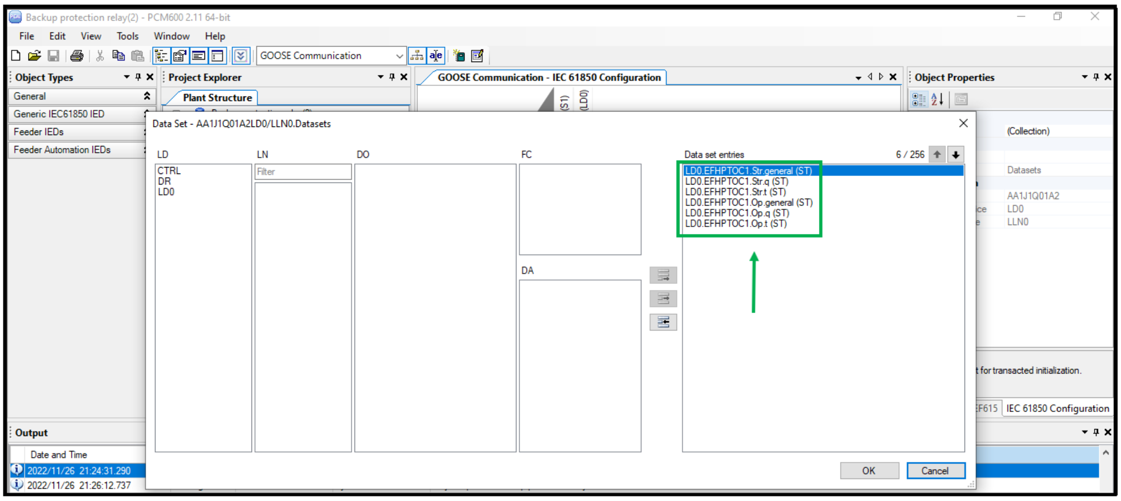
LD: ANN, CFG, CON, MET, PRO

Data set entries 28 / 500

PRO.D87RPDIF1.Str (ST)
PRO.D87RPDIF1.Op (ST)
PRO.D87RPDIF2.Str (ST)
PRO.D87RPDIF2.Op (ST)
PRO.D87RPDIF3.Str (ST)
PRO.D87RPDIF3.Op (ST)
PRO.D87RPDIF4.Str (ST)
PRO.D87RPDIF4.Op (ST)

2022/11/26 21:24:31.290
2022/11/26 21:26:12.737

Figure 5.54: Datasets of the SEL487B IED



Data Set - AA1J1Q01A2LD0/LLN0.Datasets

LD: CTRL, DR, LD0

Data set entries 6 / 256

LD0.EFHPTOC1.Str.general (ST)
LD0.EFHPTOC1.Str.q (ST)
LD0.EFHPTOC1.Str.t (ST)
LD0.EFHPTOC1.Op.general (ST)
LD0.EFHPTOC1.Op.q (ST)
LD0.EFHPTOC1.Op.t (ST)

2022/11/26 21:24:31.290
2022/11/26 21:26:12.737

Figure 5.55: Datasets of the REF615 IED

The next step is to link the datasets of SEL-487B to REF615. This is done by clicking on the highlighted box in Figure 5.56 below. These datasets were linked so that they can be available in the signal matrix for mapping.

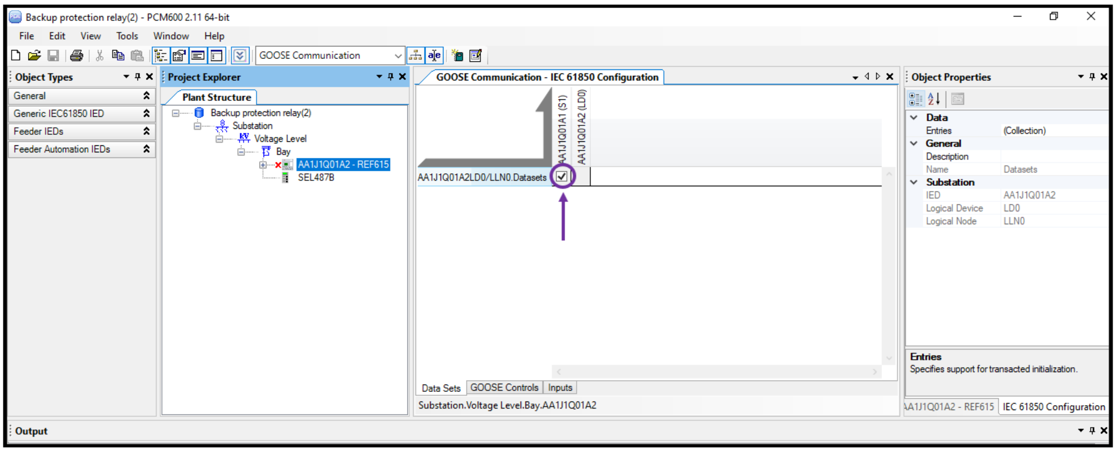
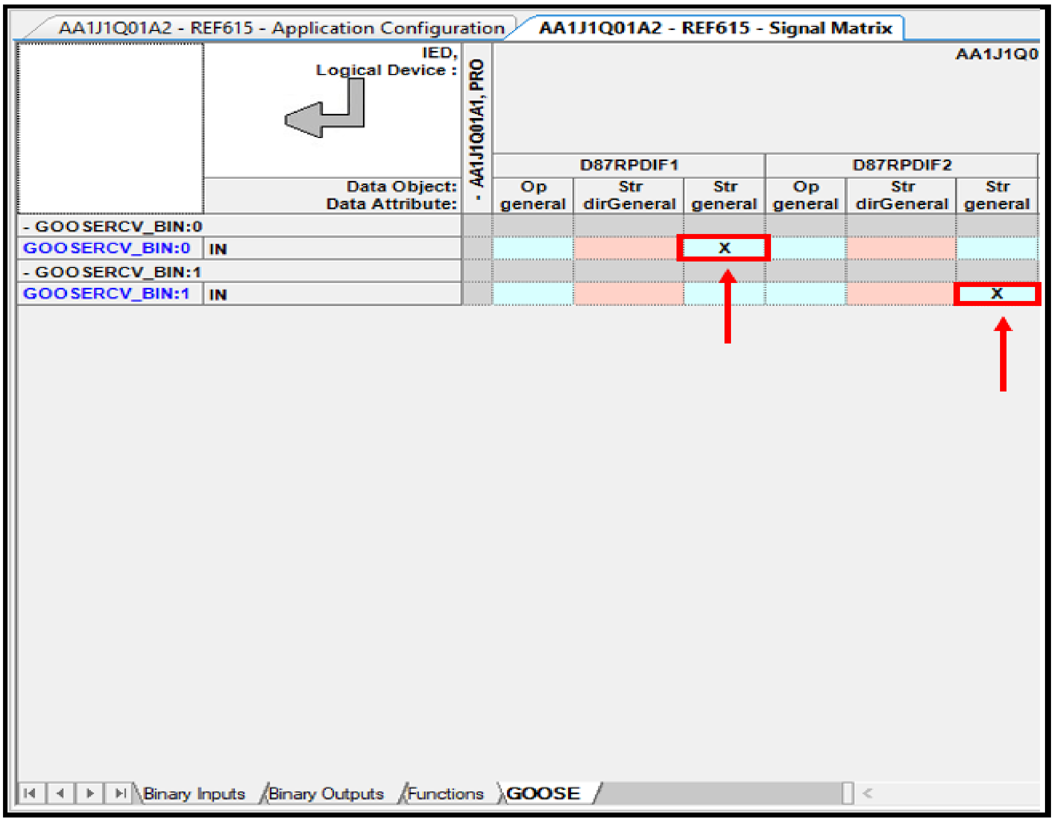


Figure 5.56: Linking datasets of SEL-487B to REF615

The tick inside the highlighted box in Figure 5.56 above, confirms that the datasets are linked. The next step is to map the dataset signals of SEL-487B to the GOOSE receive function block of REF615. The function of the GOOSE receive function block is to link the dataset signals of the SEL-487B relay to the dataset signals of the REF615 relay. In this case, the ‘START’ signals of differential elements 1 and 2 of SEL-487B, as highlighted in Figure 5.57, were mapped to the GOOSE receive function block of REF615. This is done so that whenever there is a fault on the busbar and SEL-487B picks up the fault. The pick-up signal “START” from SEL-487B is sent to the GOOSE receive function block of REF615 and the output signal from this function block is used to block REF615 from tripping. However, the REF615 IED must also pick up the fault and assert the “Start” indicator LED but must not trip.



			AA1J1Q0					
	IED, Logical Device :	- AA1J1Q01A1, PRO	D87RPDIF1			D87RPDIF2		
	Data Object: Data Attribute:		Op general	Str dirGeneral	Str general	Op general	Str dirGeneral	Str general
- GOOSERCV_BIN:0								
GOOSERCV_BIN:0	IN				X			
- GOOSERCV_BIN:1								
GOOSERCV_BIN:1	IN							X

Figure 5.57: Mapping of datasets signals

The logic created for this GOOSE-based blocking scheme is shown in Figure 5.58 below. The output signals from the GOOSE receive function block labelled ‘1’ in Figure 5.58, are connected to the inputs of the logic gates labelled ‘2’. The output signal from the logic gates is the one that does the blocking as it is connected to the block input of the earth fault overcurrent function block ‘EFHPTOC1’ labelled ‘3’. This is to block the REF615 from sending a trip to the circuit breakers as the output from this earth fault overcurrent function block is connected to the circuit breakers.

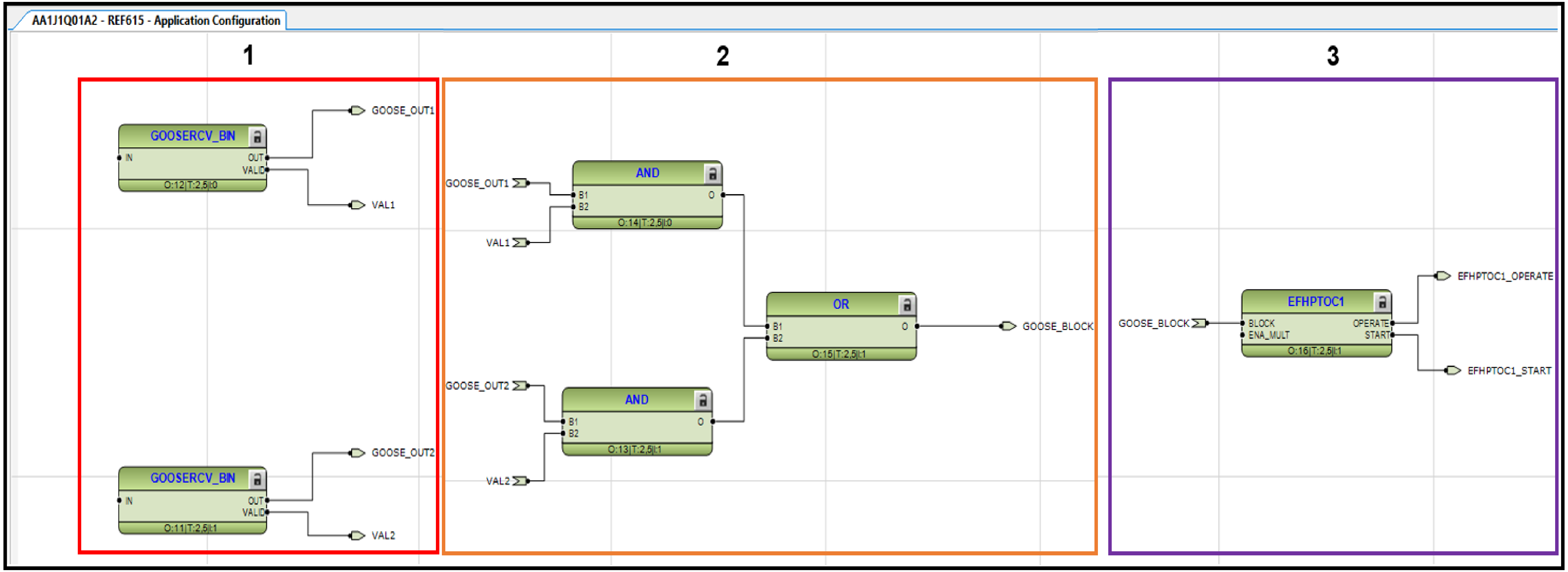


Figure 5.58: GOOSE blocking logic

The next step was to observe how the busbar protection scheme operates when there is a fault using GOOSE communication.

5.4.8 Operation of the bus protection scheme using GOOSE communication

The fault simulations were 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.

- **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 Figure 5.59 below. 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.

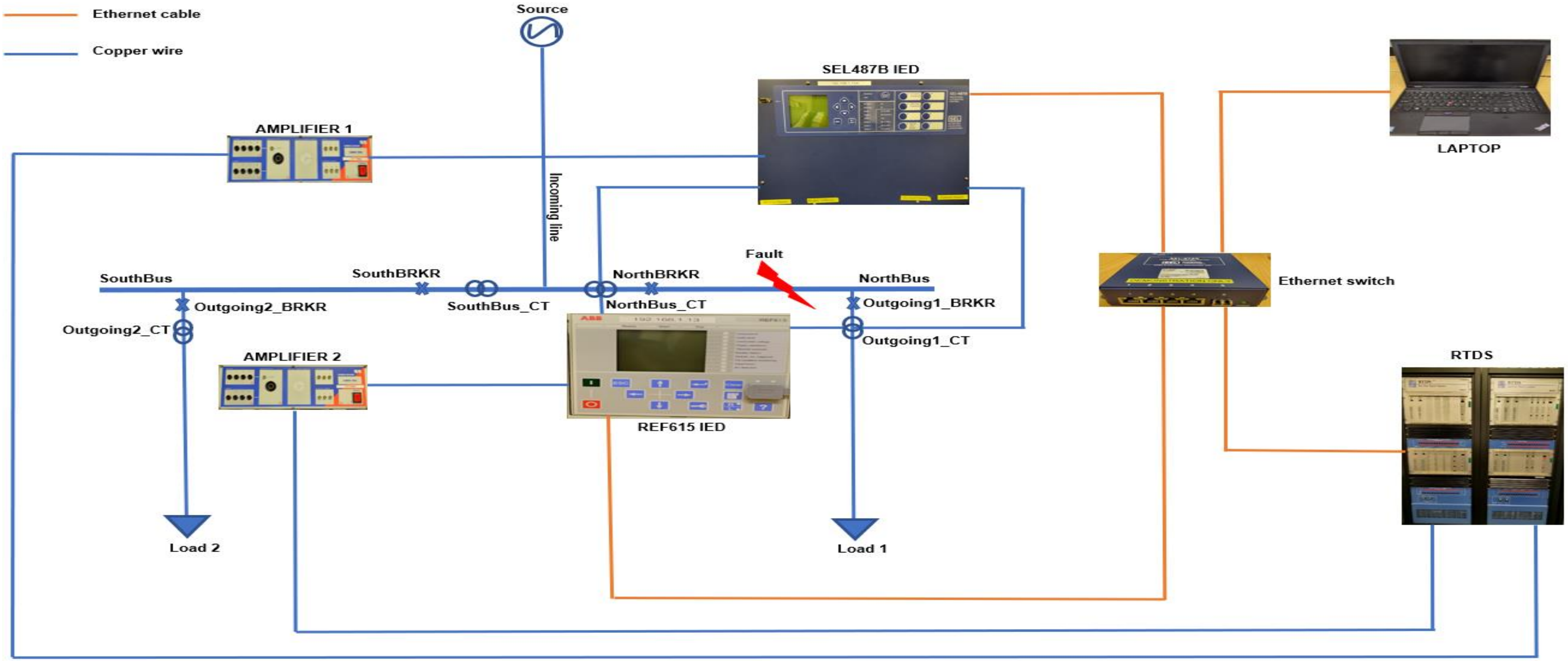


Figure 5.59: A single phase to ground fault simulated on the NorthBus section

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

- **Results of the practical experiment in test case study 1**

A busbar internal fault was simulated at the NorthBus section using RTDS software. A single phase to ground fault was simulated on the red phase and initiated after 2.69 seconds as shown in Figure 5.60. The fault was cleared at 2.73 seconds as shown in figures 5.61 and 5.62. The total fault duration is 0.04 seconds (40 milliseconds), it was cleared after this time and the busbar was isolated from the rest of the system. The response of the IED was 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 Figures 5.60, 5.61, and 5.62 were obtained through RTDS runtime when the power system simulation was in progress.

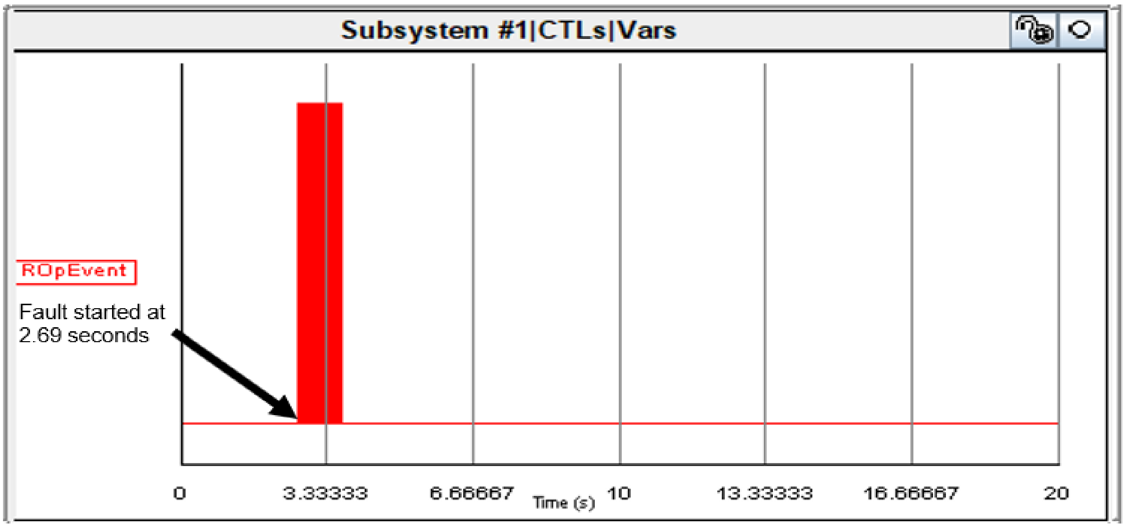


Figure 5.60: Red phase to ground fault applied at NorthBus

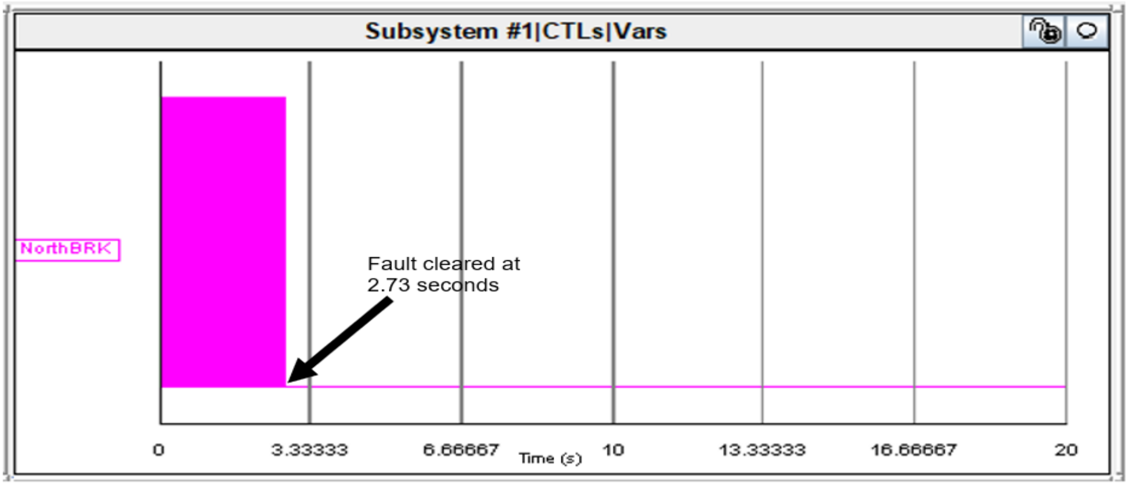


Figure 5.61: NorthBRK receives a GOOSE trip signal for R-G fault at NorthBus

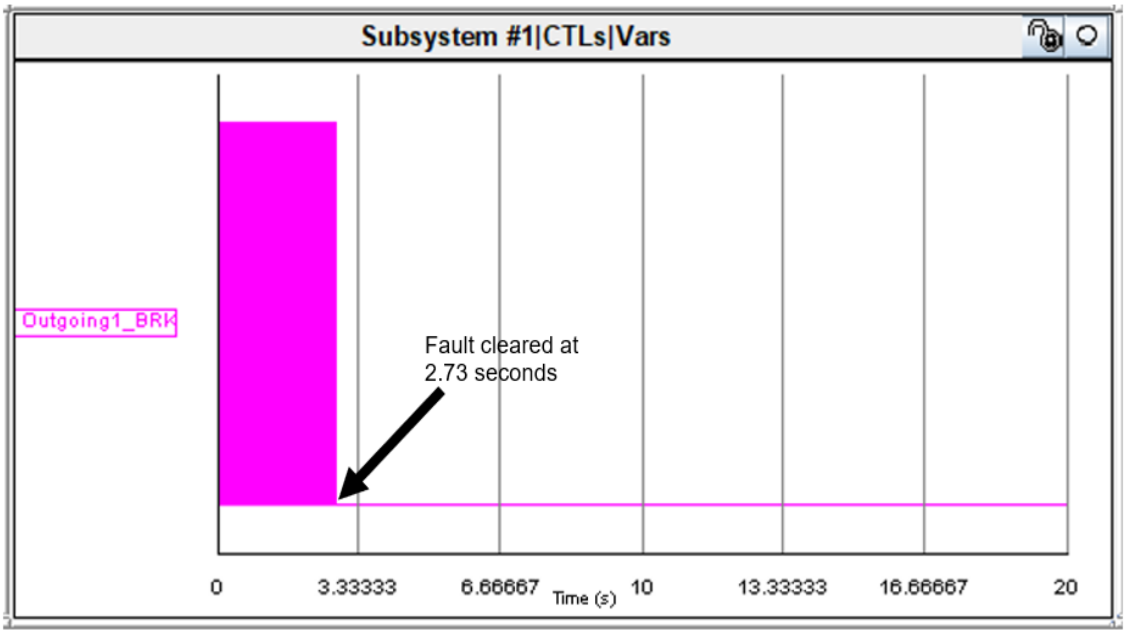


Figure 5.62: Outgoing1_BRK receives a GOOSE trip signal for R-G fault at NorthBus

It is also observed from the synchrowave results in Figure 5.63 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 were not affected by the fault. It is also seen in the digital signals in Figure 5.63 that the IED (SEL-487B) picks up the fault as shown by ‘87BTR’, and trips instantaneously as shown by the ‘TRIP01’ signal. As soon as it picks up the fault, it uses that pick-up signal to send a GOOSE blocking message to REF615 IED.

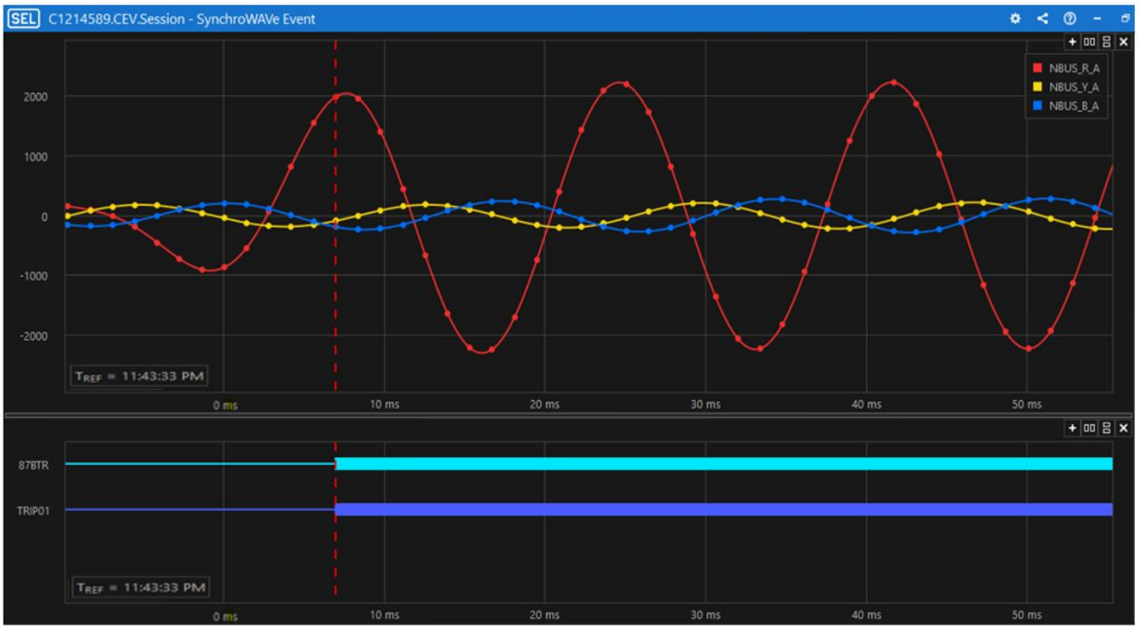
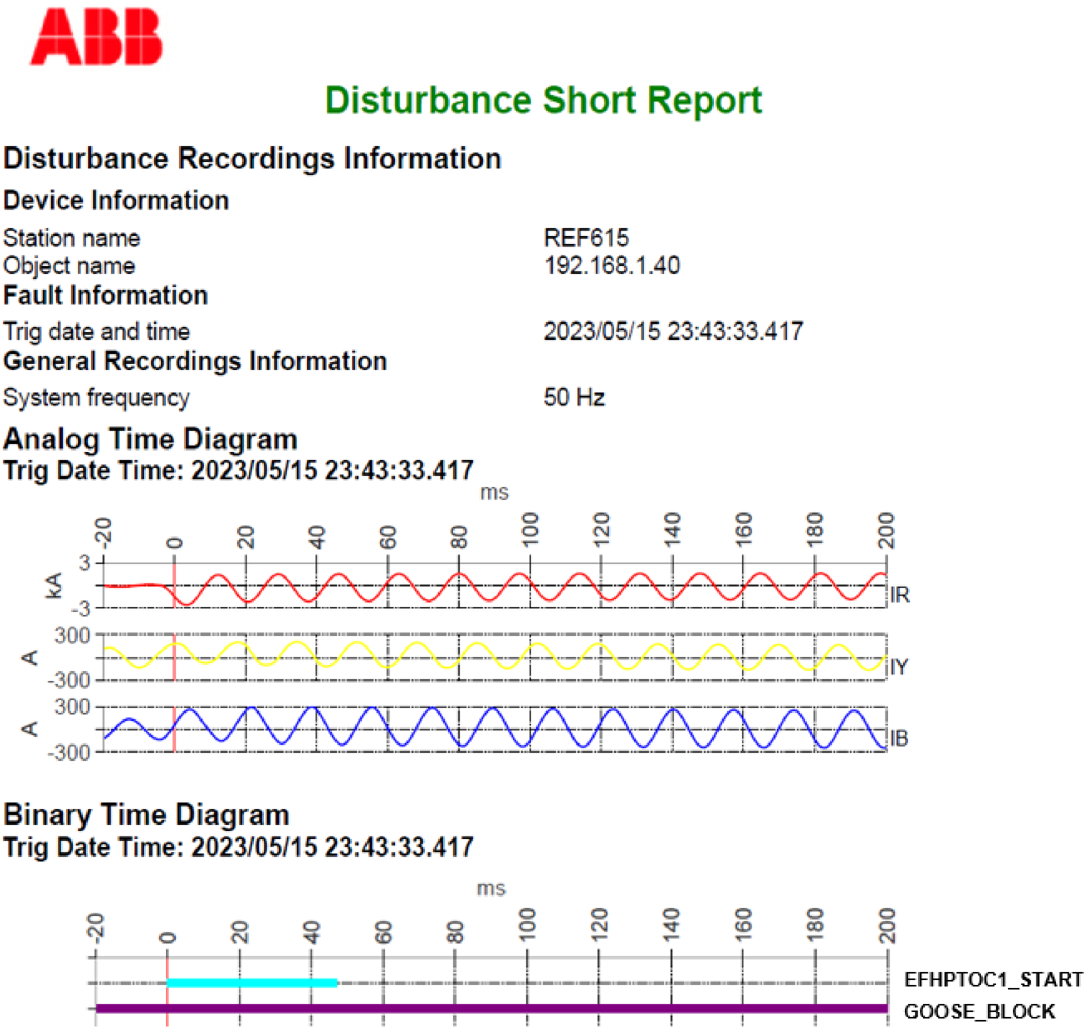


Figure 5.63: SEL-487B IED trips instantaneously

The analog signals in Figure 5.64 below 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 Figure 5.65 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. Furthermore, the light blue digital signal ‘EFHPTOC1_START’ in Figure 5.64 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.



ABB

Disturbance Short Report

Disturbance Recordings Information

Device Information

Station name	REF615
Object name	192.168.1.40

Fault Information

Trig date and time	2023/05/15 23:43:33.417

General Recordings Information

System frequency	50 Hz

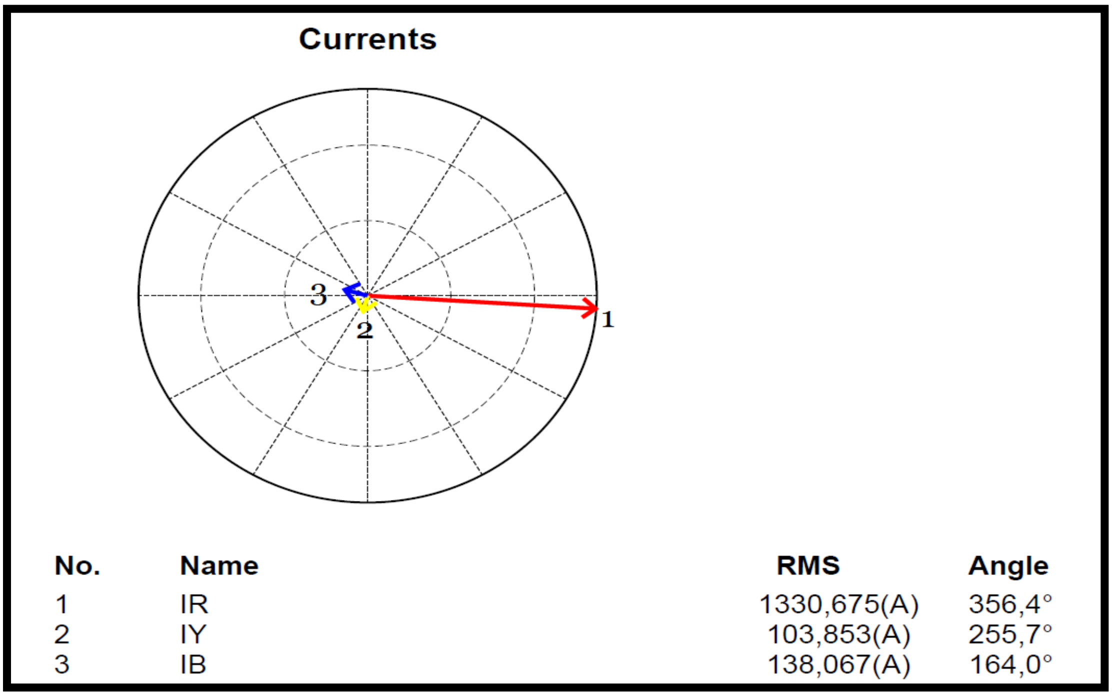
Analog Time Diagram

Trig Date Time: 2023/05/15 23:43:33.417

Binary Time Diagram

Trig Date Time: 2023/05/15 23:43:33.417

Figure 5.64: REF615 IED blocked using GOOSE



No.	Name	RMS	Angle
1	IR	1330,675(A)	356,4°
2	IY	103,853(A)	255,7°
3	IB	138,067(A)	164,0°

Figure 5.65: Vector diagrams for REF615 IED

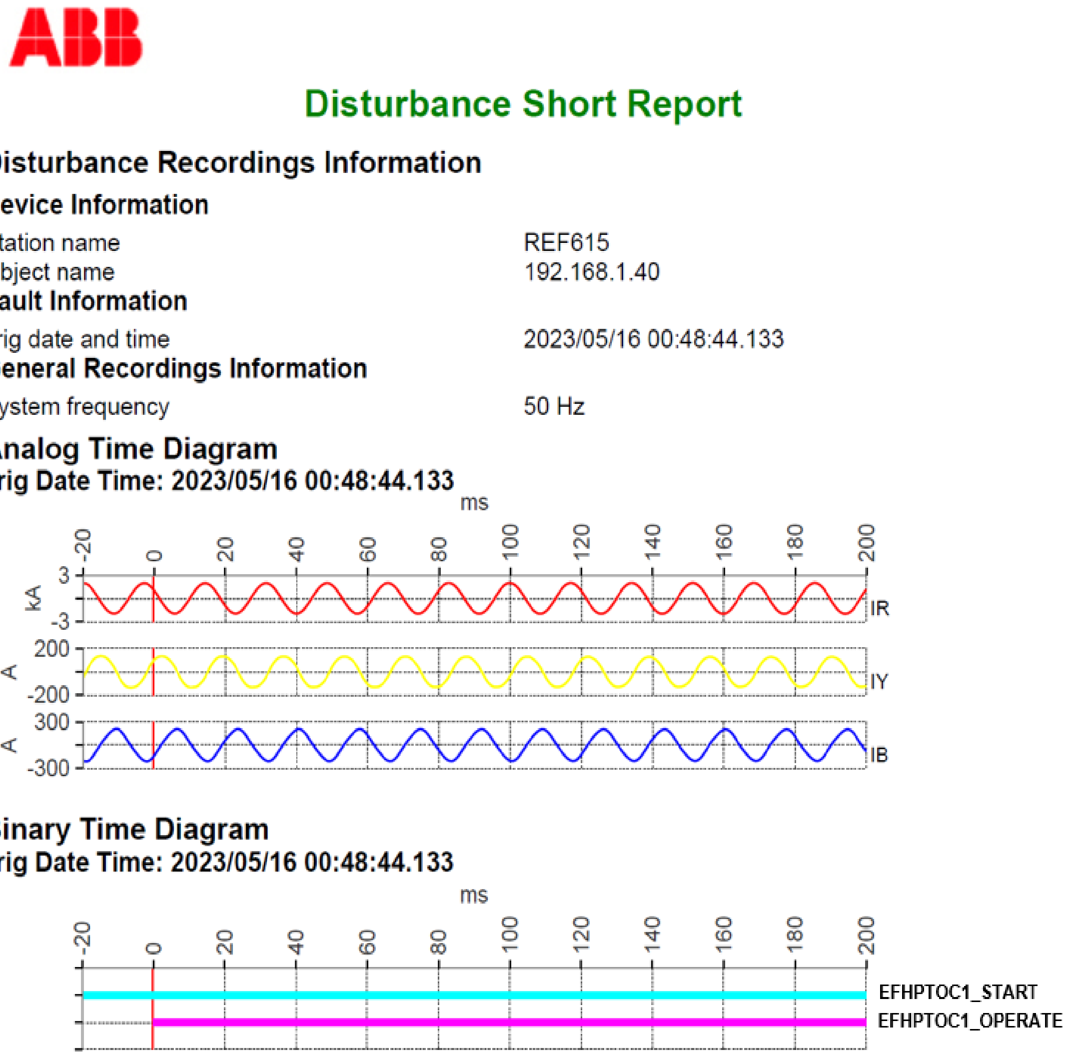
In test case 2 below, a redundant system was created as components inside the IEDs are prone to fail due to various reasons. In a situation like that, a backup protection IED is expected to operate thereby protecting the busbar network. SEL487B IED was disconnected from the network In the following test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

- **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.

- **Results for a practical experiment in test case 2**

It is observed from the analog signals in Figure 5.66 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 Figure 5.67 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 in Figure 5.66 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. It operates instantaneously after the IED has picked up the fault.



ABB

Disturbance Short Report

Disturbance Recordings Information

Device Information

Station name	REF615
Object name	192.168.1.40

Fault Information

Trig date and time	2023/05/16 00:48:44.133

General Recordings Information

System frequency	50 Hz

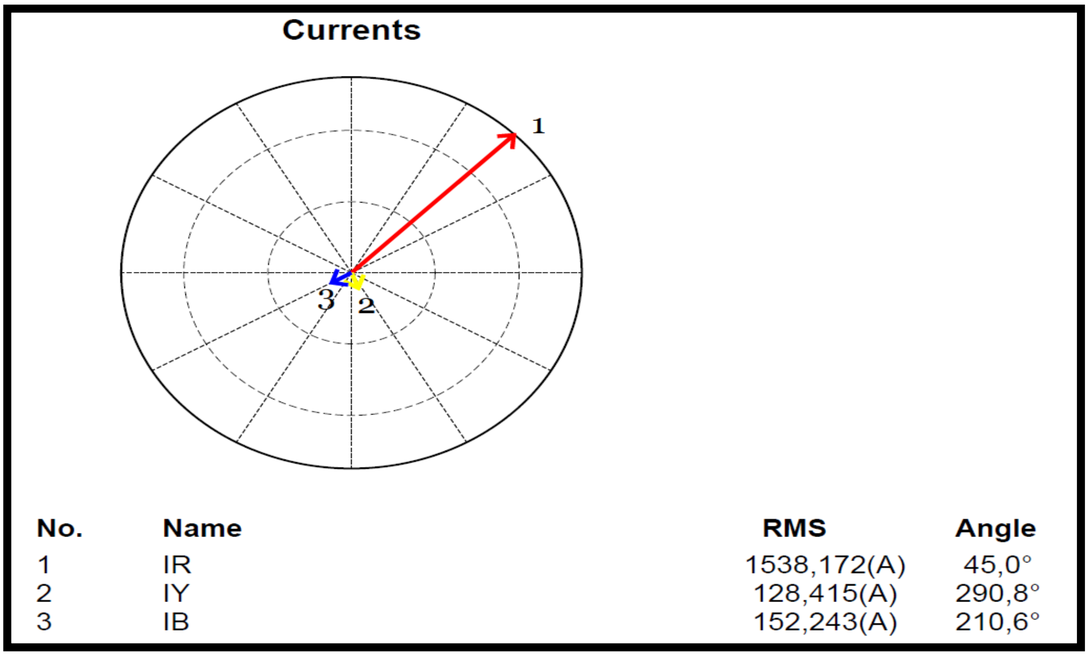
Analog Time Diagram

Trig Date Time: 2023/05/16 00:48:44.133

Binary Time Diagram

Trig Date Time: 2023/05/16 00:48:44.133

Figure 5.66: REF615 IED without GOOSE blocking.



No.	Name	RMS	Angle
1	IR	1538,172(A)	45,0°
2	IY	128,415(A)	290,8°
3	IB	152,243(A)	210,6°

Figure 5.67: **Vector diagrams for REF615 IED.**

5.5 Discussion of Results

The results obtained proved the efficacy of using of IEC 61850 standard as the interoperability between SEL-487B and REF615 IEDs was achieved. This is observed when REF615 IED was blocked from operating through the GOOSE blocking signal sent by SEL-487B IED. The results confirmed what the authors were saying in the literature review that the IEC 61850 standard is the solution for the interoperability of multi-vendor IEDs. On the other hand, it meant that the communication system between protection devices was configured successfully as the desired results were obtained. Moreover, the results proved 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 was achieved through IEC 61850 GOOSE messaging communication protocol. GOOSE signals between the two multi-vendor IEDs were linked and mapped successfully using Signal Matrix Tool (SMT) in PCM600. However, during the configuration of IEDs, the following factors that led to interoperability issues were observed:

- Version upgrade issues

If a version update is performed on the hardware or software of a single device, it may not interoperate with other devices from other vendors, necessitating the need to update the hardware or software of all devices installed in the same zone, resulting in more time, money, failures, and complexity.

- System configuration challenges

The IEC 61850 standard specifies the communication services, the IEDs model, and several common files, but not the IED or the system configuration tool. Due to the IEDs and system configuration tools produced by diverse manufacturers, the protection and integration engineer has significant difficulties while designing a single IED or even the entire system. Based on the current SAS configuration tools, the configuration work is therefore costly and time-consuming.

- Compatibility issues of IEC 61850 Editions

The release of IEC 61850 Edition 2 highlights issues with the concurrent operation of Edition 1 and Edition 2 devices in a shared substation automation system. Therefore, the system configuration must be based on Edition 1 for the integration of an Edition 2 IED into an Edition 1 environment.

- Different interpretations

Due to varying interpretations of the IEC 61850 standard, vendors have discovered that using CID or ICD files for data interchange is problematic. As a result, they have split into two groups to discuss whether the SCL file should be an ICD or CID. In other words, varying interpretations have resulted in varying implementations and problems with interoperability.

- Different Application

The standard defines standardized Logical Nodes (LNs), Data and Data Attributes (DAs), but optional LNs and generic Logical Nodes (GGIO) can also be created. This difference in the private data model included in manufactured IEDs prevents devices from communicating with each other, even if they are compliant with IEC 61850 standard.

One needs to pay full attention to the aforementioned interoperability challenges whenever doing the configuration of multi-vendor IEDS.

5.6 Conclusion

This chapter 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 chapter. 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 0.04 seconds.

IEC 61850 is widely utilized nowadays, with hundreds of substations already in service; yet this standard is accompanied by significant obstacles due to a lack of information about it. Therefore, it is important to understand the fundamentals of IEC 61850 and also learn the configuration tools of each IED to reduce IEC 61850 problems during configuration in the protection scheme. Some of the challenges of IEC 61850 were discussed. It has been found that differences in the IED's configuration tools lead to many configuration problems, such as errors when importing or exporting a file of a particular SCL type. However, the IEC 61850 standard-based busbar protection systems offer flexibility for future protection scheme development. This implies that it enables the system to be easily extended and also reconfigurable for various network topologies. Employees from utility firms working in the field of protection will utilise the test bench. It can serve as a testing ground for various schemes and the effectiveness of GOOSE communication amongst IEDs from different vendors. It will also improve the performance of future busbar protection schemes as most of the protection schemes currently have the same vendor IEDs with limited functions in some cases. Furthermore, it will improve the reliability of busbar protection schemes and also reduce the copper wire currently used for the communication of protection devices.

The next chapter presents the deliverables, conclusions, and recommendations for future developments of this project.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

A busbar is one of the most crucial elements in a power grid, it experiences high fault currents as it connects transmission lines and a variety of other elements. Consequently, busbar protection requires high speed, reliability, and stability. The protection scheme must be able to respond effectively to internal as well as external faults. Any maloperation of the protection scheme can cause a complete blackout in the power system. Ideally, differential protection is suitable for a station bus, hence, it was selected for implementation in this thesis.

This thesis focused on achieving interoperability between different-vendor IEDs, which in turn improves the performance of busbar protection schemes. A differential busbar protection scheme was implemented in a lab-scale test bench using IEC 61850 GOOSE communication protocol. A power network was modelled on RSCAD/RTDS platform, and the behaviour of the scheme was investigated through the simulation of internal busbar faults. Configurations of LNs and datasets of the IEDs under test were accomplished using AcSELerator Architect and PCM600 software. Two test cases of a GOOSE-based blocking scheme were implemented using PCM600 to test for interoperability. HIL testing was performed to test the developed busbar protection scheme.

This chapter provides an overview of the deliverables of the research project which are presented in section 6.2. Thereafter, the chapter presents academic and industrial applications in section 6.3. The future research work is proposed in section 6.4. lastly, section 6.5 outlines the publications from the research project.

6.2 Deliverables

Busbar protection schemes are very crucial at a transmission level as they interconnect multiple bulk loads and other entities in the power system. Communication between IEDs plays a big role in the performance of the busbar protection scheme. However, there are various challenges associated with interoperability between different-vendor IEDs such as dealing with different proprietary configuration tools to achieve the common objective. In this thesis, interoperability was tested using the IEC 61850 GOOSE communication protocol to send a blocking signal from an SEL-487B IED from SEL to a REF615 IED from ABB. The deliverables for this dissertation are discussed in the sections below.

6.2.1 Literature review

The literature review was conducted in Chapter 2. It analysed various busbar protection algorithms. In terms of speed, stability, security, and reliability, the digital algorithms of digital protection schemes have been reviewed. It is evident from the literature that digital protection schemes impose great weight and obligations on protection engineers. Various algorithms of conventional busbar protection schemes were analyzed and compared with IEC 61850-based busbar protection schemes. The use of protective IEDs compliant with the IEC 61850 standard has also been reviewed, and proven to be a reliable solution for protecting power systems. Based on the reviewed literature, IEC 61850 communication standard enables the development of a new class of control and protection applications and has significant advantages over traditional hardwired systems. Furthermore, the literature reveals that IEC 61850 standard ensures substation interoperability between controls and protective relays from different manufacturers. Also, according to the literature reviewed the majority of busbar protection schemes developed by previous researchers have focused on transmission level. This is due to the high cost and complexity of implementation. Literature also reveals that the main issue that appears to negatively affect the performance of transmission bus systems is communication between multivendor IEDs. Hence, it is the focus area of this research project.

6.2.2 Theoretical analysis of busbar protection schemes

The dissertation provided a theory on different busbar protection schemes in chapter three, such as frame earth protection, differential protection, phase directional protection, and directional blocking protection. It also provided the theoretical analysis of the IEC 61850 standard, focusing more on interoperability used in busbar protection schemes in a transmission network.

6.2.3 Construction of transmission network

A model of a transmission network was developed and simulated using DIgSILENT and RSCAD/RTDS software. The modelled transmission network was used to perform load flow studies which involved calculations of active (P) and reactive (Q) power flow on all branches, and the magnitudes and angles of voltage at the nodes. This was done to assess the behaviour of the network under steady-state and fault conditions. It was evident from the simulation results that the network was stable. The voltages at busbars were all within the voltage deviation of +/-5%.

6.2.4 Implementation of differential busbar protection scheme using IEC 61850

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.

6.3 Academic/Research and Industrial Application

The developed models in DIgSILENT and RSCAD software can be utilized in academia to enhance the understanding of busbar protection schemes under both normal and abnormal conditions. The implementation of the busbar protection scheme using RSCAD/RTDS and physical IEDs environments provides a standard benchmark for both academic and industrial applications. This dissertation provides a laboratory-scale test bench for implementing differential and overcurrent protection schemes for busbars using digital relays and HIL simulation. Therefore, it is recommended to implement IEC 61850 standard to achieve interoperability between IEDs from different vendors as it provides a fast and reliable GOOSE communication protocol. It will be beneficial to power utilities such as Eskom as they are currently using hardwiring protection schemes. The IEC 61850 standard is flexible as it replaces all copper wiring with Ethernet or fibre optic cables.

6.4 Future work

The research project focused on the interoperability of multi-vendor IEDs at a busbar level. It would be interesting for future research to investigate the interoperability of different-vendor IEDs across substations. In addition to SEL and ABB, the research on interoperability can be extended to include other vendors such as MICOM, and SIEMENS, to consolidate the concept and address any challenges that might face industry applications.

6.5 Publication

Luntu S. Mgaga and Mkhululi E.S. Mnguni (2023). Development of an IEC 61850 Standard-Based Busbar Protection Scheme, sent to International Journal of Electrical Engineering and Applied Sciences (IJEEAS), September 2023.

REFERENCES

ABB. 2007. *Protection and Control IED Manager PCM600*. https://www143.abb.com/SoftwareLibrary.

ABB. 2022. *Remote I/O RIO600 Installation and Commissioning Manual*. https://library.e.abb.com/public/0e4a891a2281426e8f26b1d7517aae24/RIO600_instcomm_757488_ENn.pdf.

Abul, A.R., El, F. & Nasser, S. 2019. Power System Security Assessment under N-1 and N-1-1 Contingency Conditions. *International Journal of Engineering Research and Technology*, 12(11): 1854–1863. http://www.irphouse.com.

Allah, R.A. 2014. Busbar Protection Scheme Based on Alienation Coefficients for Current Signals. , 3(4): 156–167.

Apostolov, A. 2014. The impact of IEC 61850 on transmission and distribution substations busbar protection. In *12th IET International Conference on Developments in Power System Protection, DPSP 2014*. Copenhagen, Denmark: Institution of Engineering and Technology: 1–6.

Arnold, T., Adewole, A.C. & Tzoneva, R. 2015. Performance testing and assessment of multi-vendor protection schemes using proprietary protocols and the IEC 61850 standard. In *Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE*. IEEE Computer Society: 284–290.

Aylward, A. 1997. *Basic power system protection*. https://hyperwave.eskom.co.za/.

Baningobera, B.E. 2018. *The IEC 61850 Standard-Based Protection Scheme for Power Transformers*. Cape Peninsula University of Technology. https://etd.cput.ac.za/handle/20.500.11838/2713.

Chen, X. 2016. *Performance Analysis of IEC 61850 Process Bus and Interoperability Test among Multi-Vendor System*. University of Manchester for the degree of Doctor of Philosophy. https://pure.manchester.ac.uk/ws/portalfiles/portal/60826406/FULL_TEXT.PDF.

Chothani, N. & Bhalja, B. 2011. A new differential protection scheme for busbar considering ct saturation effect. In *Canadian Conference on Electrical and Computer Engineering*. Niagara Falls, ON, Canada: IEEE: 000007–000010.

Chowdhury, M.T.K. 2015. *Implementation of Interlocking Scheme for Busbar and ARC Protection Using IEC 61850*. Tampere University of Technology. https://core.ac.uk/download/pdf/250162911.pdf.

Cooper, C.B. 1988. IEEE Recommended Practice for Electric Power Distribution for Industrial Plants. *Power Engineering Journal*, 2(2): 103.

Dedekind, K. 2019. *Network and Grid Planning Standard for Generation Grid Connection*.

DIgSILENT. 2018. *PowerFactory 2018*. https://www.digsilent.de. 19 June 2023.

Gholizadeh, N. 2016. *IEC 61850 Standard and its Capabilities*. Polytechnic University of Milan. https://www.politesi.polimi.it/bitstream/10589/123532/1/thesis.pdf.

Gonzalez-Longatt, F. & Rueda, J. 2014. *PowerFactory Applications for Power System Analysis*.

Hejazi, N. 2004. Busbar Protection. *Theory and Application of Protective Relays*.

Jamborsalamati, P., Sadu, A., Ponci, F. & Monti, A. 2016. A flexible HiL testing platform for performance evaluation of IEC 61850-based protection schemes. In *IEEE Power and Energy Society General Meeting*. Boston, MA, USA: IEEE Computer Society.

Jena, S. & Bhalja, B.R. 2018. Numerical busbar differential protection using generalised alpha plane. *IET Generation, Transmission and Distribution*, 12(1): 227–234.

Koshiishi, K., Kaneda, K. & Watabe, Y. 2012. Interoperability experience with IEC 61850- based Substation Automation Systems. In *PES T&D 2012*. Orlando, FL, USA: IEEE: 1–5.

Kumar, S., Abu-Siada, A., Das, N. & Islam, S. 2021. A Fast and Reliable Blocked Bus Bar Protection Scheme Leveraging on Sampled Value and GOOSE Protection based on IEC 61850 Architecture. In *Proceedings of 2021 31st Australasian Universities Power Engineering Conference, AUPEC 2021*. Perth, Australia: Institute of Electrical and Electronics Engineers Inc.: 5.

Kumar, S., Abu-Siada, A., Das, N. & Islam, S. 2022. Reverse Blocking Over Current Busbar Protection Scheme based on IEC 61850 Architecture. *IEEE Transactions on Industry Applications*, 59(2): 2225–2233.

Lackovic, V. 2012a. High Voltage Busbar Protection. , (877).

Lackovic, V. 2012b. Introduction to Short Circuit Current Calculations. , (877).

Makwana, S., Lloyd, G., Pal, A., Smith, B. & Teoh, C.-P. 2020. Optimizing High Impedance Busbar Protection Scheme Design Using a Numerical Relay. In *15th International Conference on Developments in Power System Protection (DPSP 2020)*. Liverpool, UK: Institution of Engineering and Technology: 1–6.

McFadden, R.H. 1980. An American National Standard IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis. *Electronics*: 1–223.

Mguzulwa, N.R. 2018. *Investigation of Interoperability of IEC 61850 Protection Functions*. Cape Peninsula University of Technology. https://etd.cput.ac.za/handle/20.500.11838/2704.

Mnguni, E.S.M. 2014. *Investigation of the application of iec61850 standard in distribution busbar protection schemes*. Cape Peninsula University of Technology. https://etd.cput.ac.za/handle/20.500.11838/1071.

Mohan, S.M. & Chatterjee, S. 2010. Busbar protection - A review. In *Proceedings - 2010 IEEE Region 8 International Conference on Computational Technologies in Electrical and Electronics Engineering, SIBIRCON-2010*. Irkutsk, Russia: 755–759.

MOLLA, B. & BASU, A. 2020. Contingency analysis of a 10-bus power system using a power world simulator.

Mourad, D. & Shehab-Eldin, E.H. 2018. Simple and adaptive busbar protection scheme considering CT saturation effect. In *2017 19th International Middle-East Power Systems Conference, MEPCON 2017 - Proceedings*. Cairo, Egyp: Institute of Electrical and Electronics Engineers Inc.: 71–77.

Muthu, K. & Chidambaram, R. 2010. Simplified Protection System Architecture Based on IEC61850 for the Next Generation IEDs. In *10th IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change*. Manchester: IET.

Namdari, F., Jamali, S. & Crossley, P.A. 2005. Power differential based wide area protection. *Electric Power Systems Research*, 77(12): 1541–1551.

Nasir, M., Dysko, A., Niewczas, P. & Fusiek, G. 2016. All-optical busbar differential protection scheme for electric power systems. *IET Conference Publications*, 2016(CP671): 1–6.

Newelani, S. 2000. *Basic Power System Protection:* https://hyperwave.eskom.co.za/.

Nomandela, S. 2021. *IEC 61850 Standard-Based Protection of the Coupling Point Between a Wind Farm and the Power Grid*. Cape Peninsula University of Technology. https://etd.cput.ac.za/handle/20.500.11838/3424.

NPAG. 2011. *Network Protection & Automation Guide Network Protection & Automation Guide Previously called Protective Relays Application Guide Network Protection & Automation Guide Network Protection & Automation Guide*. www.alstom.com/grid/contactcentre%5Cnwww.alstom.com/grid/sas.

Ratshitanga, M. 2018. *Investigation and Design of an Integrated Monitoring, Protection, and Control System of a Power Reticulation Network*. Cape Peninsula University of Technology. https://etd.cput.ac.za/handle/20.500.11838/2710.

Reimert, D. 2006. *Protective Relaying for Power Generation Systems*.

Saeed, H.A. 2015. *Implementation of IEC 61850 Based on Substation Automation Systems*. Sudan University of Science and Technology College of Graduate Studies. https://afribary.com/works/implementation-of-iec-61850-based-on-substation-automation-systems.

Saleem, A. & Nordstr, L. 2010. A Case Study of Multi-Agent Interoperability in IEC 61850 Environments. In *IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*. Gothenburg, Sweden: IEEE.

Sastromiharjo, M., Prasetia, H., Firdaus, I. & Marbun, M.P. 2022. Implementation of Busbar Protection at 150 kV Substations Based on IEC61850 Goose Message. In *Proceedings - 11th Electrical Power, Electronics, Communications, Control, and Informatics Seminar, EECCIS 2022*. Malang, Indonesia: Institute of Electrical and Electronics Engineers Inc.: 114–118.

Smith, M. 1998. *Power System Protection:* https://hyperwave.eskom.co.za/.

Tanaka, Y., Oda, S., Adachi, K. & Noguchi, H. 2012. Development of Process Bus for Busbar Protection and Voltage Selection Scheme. In *11th IET International Conference on Developments in Power Systems Protection (DPSP 2012)*. Birmingham, UK: IET.

Xu, X., Li, H. & Wen, H. 2015. Performance evaluation of busbar protection schemes under different fault scenarios. In *9th International Conference on Power Electronics - ECCE Asia: 'Green World with Power Electronics', ICPE 2015-ECCE Asia*. Institute of Electrical and Electronics Engineers Inc.: 1597–1602.

Yang, L., Crossley, P.A., Wen, A., Chatfield, R. & Wright, J. 2014. Design and performance testing of a multivendor IEC61850-9-2 process bus-based protection scheme. *IEEE Transactions on Smart Grid*, 5(3): 1159–1164.

YUN, L. 2015. *Voltage Balancing on Three-Phase Low Voltage Feeder*. Manchester: University of Manchester for the degree of Doctor of Philosophy. https://pure.manchester.ac.uk/ws/portalfiles/portal/61848917/FULL_TEXT.PDF.

APPENDIX
IEEE NINE BUS SYSTEM

A.1 IEEE nine bus power system input data

The input data of the IEEE Nine bus system for the preparation of load flow calculations are given in Table A.1 below. Table A.1 shows the magnitudes of busbar voltages in both per unit and rated values. The busbars with generators and loads are also presented in Table A.1 below:

Table A. 1:**Bus data for IEEE nine bus power system during normal operating conditions.**

Bus data							
Name	**V(pu)**	**V_{rated} (kV)**	**Angle (deg)**	**P Generator (MW)**	**Q Generator (MVar)**	**P Load (MW)**	**Q Load (MVar)**
Bus 1	1.04	16.5	0	71.6	27	-	-
Bus 2	1.03	18	9.3	163	6.7	-	-
Bus 3	1.03	13.8	4.7	85	-10.9	-	-
Bus 4	1.03	230	147.8	-	-	-	-
Bus 5	1.00	230	146	-	-	125	50
Bus 6-1	1.02	230	146.3	-	-	90	30
Bus 6-2	1.02	230	146.3	-	-	-	-
Bus 7	1.03	230	153.7	-	-	100	35
Bus 8	1.02	230	150.7	-	-	-	-
Bus 9	1.03	230	152	-	-	-	-
Load Bus 1	1.01	230	145.8	-	-	-	-
Load Bus 2	1.01	230	145.8	-	-	-	-

Table A.2 presents the generator data for the IEEE Nine bus system. Bus type, voltages, and generator power capabilities are provided.

Table A. 2: **Generator data for IEEE nine bus power system during normal operating conditions.**

Generator data				
Name	**Bus Type**	**V(pu)**	**S in MVA (minimum capability)**	**S in MVA (maximum capability)**
G1	Slack	1.040	75.58	247.5
G2	PV	1.025	163.1	192
G3	PV	1.025	85.98	128

Table A.3 presents the parameters of transmission lines for the IEEE Nine bus power system. Impedances in the polar and rectangular forms are provided in this table.

Table A. 3: **Transmission line parameters for IEEE nine bus power system during normal operating conditions.**

	Impedance - Polar Form *$Z\angle\delta$*		**Impedance - Rectangular Form** *$Z = R + jX$*	
Name	**Z1 (Ω)**	**δ**	**R1 (Ω)**	**X1 (Ω)**
Incomer_1	49.491	79.53	8.993	48.668
Incomer_2	92.266	77.079	20.631	89.93
Line 4-5	45.275	83.29	5.29	44.965
Line 5-7	86.834	78.758	16.928	85.169
Line 7-8	38.352	83.267	4.496	38.088
Line 8-9	53.693	83.267	6.295	53.323
Outgoing 1	9.898	79.53	1.798	9.733
Outgoing_2	9.898	79.53	1.798	9.733

Table A.4 presents the load demand for the IEEE Nine bus power system network.

Table A. 4: **Load demand for IEEE nine bus power system during the normal operating condition.**

Load demand			
Name	Bus number	P - MW	Q - MVar
Load A	Bus 5	125	50
Load B	Load Bus 1	45	15
Load C	Load Bus 2	45	15
Load D	Bus 8	100	35

Table A.5 presents the transformer data for the IEEE Nine bus system.

Table A. 5: **Transformer - data for IEEE nine bus power system during normal operating conditions.**

Transformer data							
Name	**HV-Side Busbar**	**LV-Side Busbar**	**HV side - kV**	**LV Side - kV**	**R - pu**	**X - pu**	**Tap Ratio**
T1	Bus 4	Bus 1	230	16.5	0.0	0.144	1.0
T2	Bus 7	Bus 2	230	18	0.0	0.125	1.0
T3	Bus 9	Bus 3	230	13.8	0.0	0.088	1.0

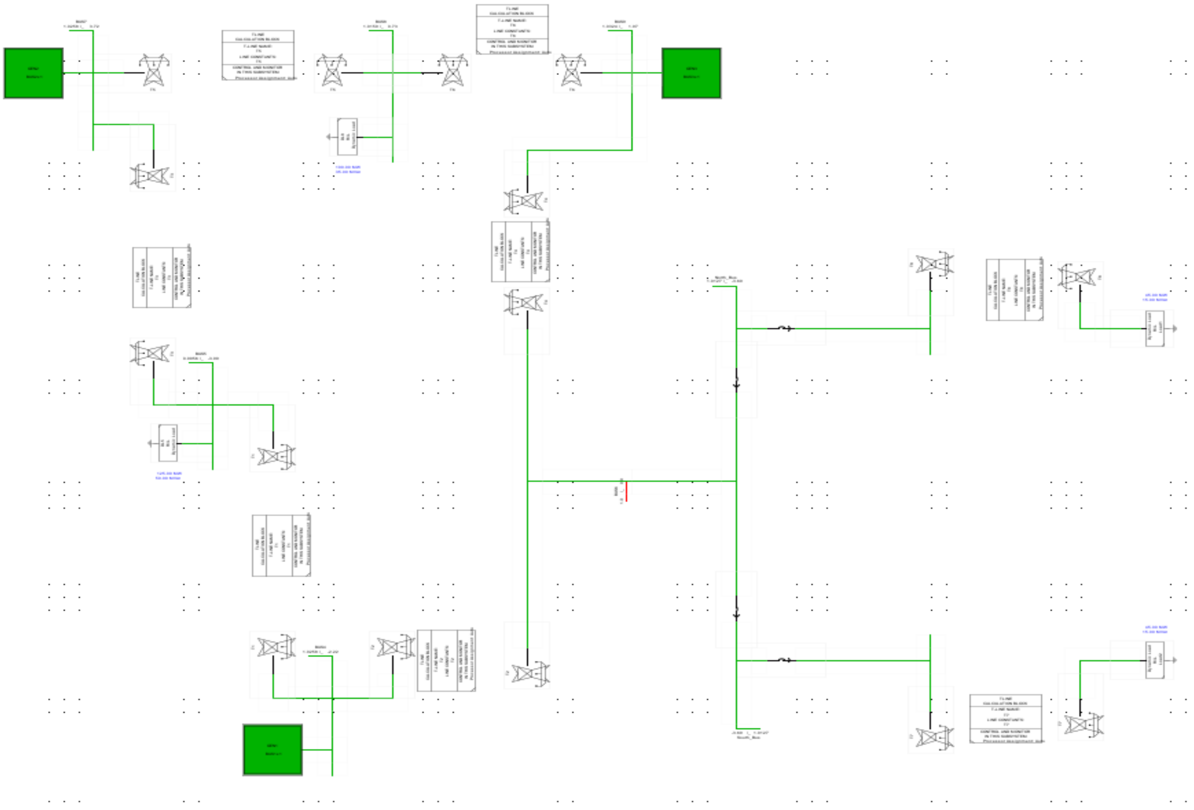


Figure A. 1: Single line diagram of IEEE nine bus system.