

Closed-loop Testing of Distance Relay Based on IEC 61850 and RTDS

by

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ABSTRACT

Intelligent Electronic Devices (IEDs) serve as the foundation of substation automation system. Many testing cases have discussed the performance of implementing IEC 61850 in IEDs manufactured by different vendors. However, the procedures of configuring an IED and mapping it with the power network model are not summarized. This project aims to provide the configuring procedures of a distance relay using IEC 61850 protocols, and test if the relay can correctly operate a circuit breaker modelled in Real Time Digital Simulator (RTDS). The communication between relay and circuit breaker is realized by GOOSE, SV and MMS services embedded in the GTNET card. Two testing cases are performed to illustrate that the closed-loop testing using IEC61850-configured relay is feasible in RTDS environment. The thesis is developed as guidelines for future lab work and teaching materials.

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LIST OF ABBREVIATIONS

ACSI	Abstract Communication Service Interface
CDC	Common Data Classes
CID	Configured IED Description
DDB	Digital Data Bus
FCDA	Functionally Constrained Data Attributes
Gcb/GoCB	GOOSE Control Block
GGIO	GOOSE Generic Input and Output
GOOSE	Generic Object Oriented Substation Event
ICD	IED Capability Description
IED	Intelligent Electronic Device
IID	Instantiated IED Description
MMS	Manufacturing Message Specification
OPGOOSE	Optimised Performance Goose
PSL	Programmable Scheme Logic
RTDS	Real Time Digital Simulator
SCADA	Supervisory Control and Data Acquisition
SCD	Substation Configuration Description
SCL	Substation Configuration Language
SCSM	Specific Communication Service Mappings
SED	System Exchange Description
SSD	System Specification Description
SV	Sampled Values

1

INTRODUCTION

This is an introductory chapter where the background of applying IEC 61850 in power networks is introduced to motivate the need for closed-loop testing procedures. Following this, a practical research objective is proposed. Finally, the outline of the thesis is provided.

1.1. BACKGROUND AND MOTIVATION

As the electricity demand is increasing and incorporating more renewable energy sources, the size and complexity of power systems evolve towards the smart grid. Besides, a large number of digital, integrated and multi-functional devices are installed in the power network to replace the conventional analogue single-purpose devices. These trends bring new challenges to modern substations [11]. The substation is a crucial part of the power network, where voltages are transformed from high level to low level or in the reverse direction. Measuring elements like current transformers and voltage transformers, switchgear, control/monitoring devices and other apparatus are installed in substations, resulting in a significant data stream for communication.

IEC 61850 standards are widely used in digital substations. It defines the object-oriented modelling method and enables real-time communication and information exchange among critical devices. IEC 61850 serves as the foundation of open communication and data exchange for substation automation system. Instead of traditional hardwiring equipment, the data processing and communication in IEC 61850 are realised through optic fibres via Ethernet, saving the occupied area and increasing the efficiency [13]. Substation communication system based on Ethernet has shown adequate performance in satisfying the time-critical messages compared to message transmission through cables [16] [1]. Conventionally, protective relays are installed and operate as a separate system in a substation. However, IEC 61850 has standardised the data model definition and communication protocols. It enables the coordination of Intelligent Electronic Devices manufactured by different vendors. In [6], the author investigated the benefits of implementing IEC 61850-9-2 process bus and its impact on the design of protection scheme. The GOOSE message utilisation in substation testing is elaborated in [1]. Figure 1.1 depicts the network layout of digital substations [18].

In digital substations, protective relays are modelled at the bay level connected with the process bus. Switchgear at the process level operates in response to the commands sent by relays. There is no direct wiring between the control device and the control target. The communication and signal transmission are realised through IEC 61850 protocols over the process bus. Therefore, the testing procedures of IEC 61850 configured devices are quite different from conventional hardwiring testing. Furthermore, for high voltage level substations, the testing requires large area and protection measures to ensure safety. Real Time Digital Simulator (RTDS) developed in Winnipeg, Manitoba, Canada, thus, is selected as a convenient simulation tool for digital substations.

The testing of different power devices and network setup using IEC 61850 have been discussed in recent years. A laboratory experiment evaluates the performance of GOOSE service for the communication of two SEL relays [2]. In [9], high voltage switchgear is tested using RTDS under IEC 61850 protocols. The interoperability of IEDs using IEC 61850 tools are experimentally demonstrated with wind turbines from several vendors [8]. Protection schemes based on IEC 61850 are also interested by many researchers. The testing performance of distance protection under weak-in-feed sources is investigated using GOOSE and SV services. In [3], wide-area GOOSE over Multiprotocol Label

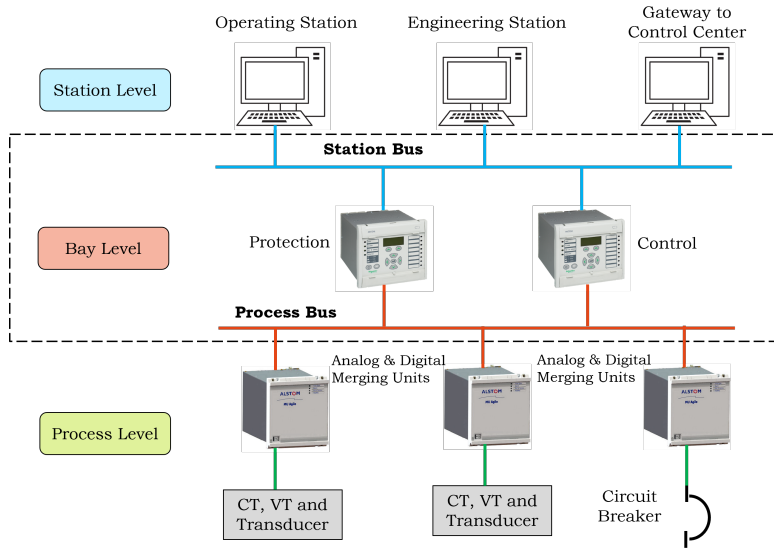


Figure 1.1: Digital substation network layout

Switching and Routable-GOOSE over IP network are deployed for the protection testing of multi-terminal lines. Klaus-Peter Brand et al. extends the application of IEC 61850 by creating new logical nodes for different protection topologies [5]. The feasibility and performance of applying IEC 61850 in power network setup and IEDs have been investigated in many cases.

However, back to the foundation of power network testing using IEC 61850, the detailed configuration procedures of IEC 61850 testing are not summarised and provided as an instruction for researchers. The motivation of this project is to elaborate the procedures of configuring an IED using IEC 61850 and perform the testing of a power network model in real-time simulators. It is expected to help subsequent researchers get familiar with the concept of IEC 61850, provide the general configuration method for IEDs and perform real-time testing in different scenarios through IEC 61850 communication protocols.

1.2. RESEARCH OBJECTIVES

The primary goal of this thesis is to summarise the procedures of configuring an external relay to control a circuit breaker using IEC 61850 protocols. The objective of the thesis is then partitioned and achieved through the following questions:

- What are the IEC 61850 standards?
- What are the suitable settings of distance relay, and how to configure it with the circuit breaker in RTDS?

- How to perform the closed-loop testing in RTDS using the configured external relay?
- What are the testing results in RTDS? Does the circuit breaker clear the fault as expected?

1.3. THESIS OUTLINE

- **Chapter 1: Introduction**

In this introductory chapter, the background of applying IEC 61850 in power networks is introduced to motivate the need for closed-loop testing procedures. Following this, a practical research objective is proposed. Finally, the outline of the thesis is provided.

- **Chapter 2: Overview of IEC 61850 System**

This chapter gives an introduction to IEC 61850 standards and the modelling method. Several specific communication protocols that are widely adopted in automated substations are explained. Manufacturing Message Specification (MMS), GOOSE (Generic Object Oriented Substation Event) and Sampled Values (SV) contribute to the three layers of intelligent substation communication system. Finally, the advantages of implementing IEC 61850 in modern substations are discussed.

- **Chapter 3: Theory of Distance Protection and Closed-loop Testing in RTDS**

In this chapter, the principle of distance protection is introduced. The time-graded distance zone settings are explained. Furthermore, the closed-loop testing in RTDS using IEC 61850 protocols is proposed as the preparation for relay configuration. The implementation of GTNETx2 card enables the communication between RTDS model and external IEDs.

- **Chapter 4: Procedures of Distance Relay Configuration**

This chapter introduces the configuration procedures of a numerical distance relay. The complete settings of relay are made in MiCOM S1 Agile. Furthermore, procedures to configure the distance relay to be mapped with the power network model built in RTDS are explained in detail. GOOSE generation and subscription, SV transmission and Programmable scheme logic are performed to achieve the communication between the external relay and the circuit breaker in RTDS model.

- **Chapter 5: Experimental Validation**

This chapter intends to verify if the distance protection can correctly operate using the relay programmed in Chapter 4. The relay is already fully configured in MiCOM S1 Agile. The communication between the relay and the circuit breaker is established through IEC 61850 protocols. Closed-loop testing of the circuit breaker on the transmission line of power network model in RTDS is performed by applying various fault types and then analysing the circuit breaker operations. Firstly, the setup of power network model is provided. Next, the testing procedures and analysing method are explained. Finally, two cases are elaborated to show the configuration is sufficient to conduct closed-loop testing in RTDS.

- **Chapter 6: Conclusion and Future Work**

The concluding chapter summarizes the project and answers the research objective proposed at the beginning of the thesis. The practical contribution of the thesis is mentioned. Furthermore, a few recommendations are provided for future work.

2

OVERVIEW OF IEC 61850 SYSTEM

IEC 61850 works for communication networks and systems in electrical substations. It is one of the most comprehensive international communication standard systems, which supports the manufacturing of electronic devices and builds the cornerstone of intelligent digital substations. As an overall and sophisticated system, IEC 61850 adopts the object-oriented modelling method to describe the electric network in a user-friendly way. Data models defined in IEC 61850 standards can be mapped and transmitted among different devices according to many protocols. Regarding the power network applications, MMS (Manufacturing Message Specification), GOOSE (Generic Object Oriented Substation Event), SV (Sampled Values) are currently implemented in automated substations all around the world. These protocols enable reliable and high-speed data transmission in the substation and make sure the power network operates in a safe, steady, and intelligent environment. This chapter gives an introduction to IEC 61850 standards and the modelling method. Several specific communication protocols which are widely adopted in digital substations are explained. Finally, the advantages of applying IEC 61850 in modern substations are discussed.

2.1. INTRODUCTION OF IEC 61850

2.1.1. THE OBJECTIVE OF IEC 61850

Signals like currents and voltages in the primary side of the electric power network are continuous analog information, which brings a lot of work in the data processing and transmission among different devices. To improve the efficiency of data processing, modern substations convert analog signals from the primary side to digital signals on the secondary side, and then the digital signal can be easily transmitted among devices through cables or fibres instead of traditional copper wires. However, the manufacturer has its own communication protocols. The devices from different vendors cannot communicate directly but have to be converted through protocol conversion devices every time. These disadvantages increase the burden of substation monitoring, protection and maintenance, and restrict the power network zone connections.

International Electrotechnical Commission (IEC) worked in three groups to respond to the above concerns from 1995. The objectives of IEC 61850 standards are to unify the communication protocols, improve the adaptability of devices from different suppliers, provide a common service for modelling data and simplify the testing procedures of equipment installed at substations. WG10 (Work Group) is responsible for the overall description and function requirements of substation data communication protocols. WG11 focuses on the definition of substation-level data communication bus. WG12 conducts the protocols regarding process-level data communication.

2.1.2. IEC 61850 DOCUMENTS

IEC 61850 standard system contains plenty of standards describing every aspect of data communication in electric power network. Documents that are frequently applied in substation communication are listed as follows. Figure 2.1 shows a basic structure of this system.

- IEC 61850-1: Introduction and overview of the system.
- IEC 61850-2: Glossary.
- IEC 61850-3: General requirements, such as quality requirements (reliability, security, availability, portability, interoperability, maintainability), environmental requirements, auxiliary services and other criterion.
- IEC 61850-4: System and project management, including engineering requirements, system life cycle, quality guarantee, etc.
- IEC 61850-5: Communication requirements for functions and device models, including the path of logical nodes and functional definitions.
- IEC 61850-6: Substation Configuration Language (SCL). It provides the language and format to represent the configuration of Intelligent Electronic Devices (IED) in substations [1]. The SCL file can be classified into different types according to the purpose of use.

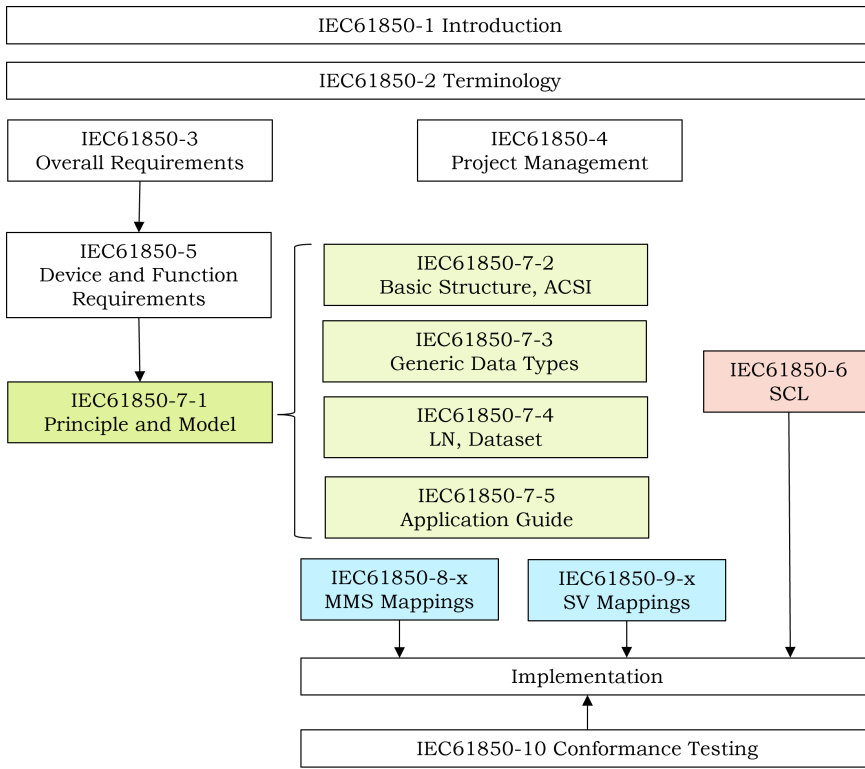


Figure 2.1: Main documents of IEC 61850

- IED Capability Description (ICD) file. It contains all the information required to make complete configuration settings of an IED.
- System Specification Description (SSD) file. This file describes the complete settings of a substation, including its single line diagram, logical nodes, data objects and functions.
- Substation Configuration Description (SCD) file. It is the file that gives the detailed configuration of a substation, both the information of SSD and ICD file are included in the SCD file.
- Configured IED Description (CID) file. This file is used to communicate between an IED and the configuration tool of this IED.
- Instantiated IED Description (IID) file. It describes the settings of one IED for a project and defines the data exchange format from an IED configurator to a system configurator.
- System Exchange Description (SED) file. This file is served as the communication tool for different projects. It defines the exchange interface between systems.

- IEC 61850-7: The basic communication structure of substations.
 - IEC 61850-7-1: This document includes the principle and model of substation communication. It is an overview of IEC 61850-7.
 - IEC 61850-7-2: Abstract Communication Service Interface (ACSI). It defines the service model, including the object and the access to the object, the process of a request being responded and what actions the service is going to achieve.
 - IEC 61850-7-3: It defines common data classes and attributes for the logical nodes in IEC 61850-7-4.
 - IEC 61850-7-4: This document defines compatible logical node classes and data objects for system functionalities.
- IEC 61850-8-1: Specific Communication Service Mappings (SCSM). It defines the mappings between abstract communication service interface and specific Manufacturing Message Specification (MMS).
- IEC 61850-9-1: Specific Communication Service Mappings (SCSM). It defines the mapping of Sampled Values in a unidirectional peer-to-peer transmission mode.
- IEC 61850-9-2: Specific Communication Service Mappings (SCSM). It defines the mapping of Sampled Values over Ethernet, which is bidirectional and more flexible.
- IEC 61850-10: Conformance testing.

2.2. MODELLING FEATURES OF IEC 61850

As an essential part of the power network, modern substations are required to achieve different functions like monitoring, control, processing and protection. IEC 61850 system intends to classify these functions, assigning specific devices and communication paths for each function. This leads to the abstract, semantic hierarchical method of modelling, in which a system is divided into layers and subsystems. This section introduces the modelling structure under IEC 61850 system.

FUNCTION

Function describes the task that automated substation system can achieve, such as monitoring the operating status of IEDs, controlling the switches, protecting the electric power network of a restricted zone. The function is defined according to the user's requirements. One function can be divided into several sub-functions, for example, "Protection Function of a transmission line" can be specified as different sub-functions, including differential protection (sub-function 1), overcurrent protection (sub-function 2), distance protection (sub-function 3). Each sub-function can be achieved with one or several logical nodes.

Table 2.1: Names of logical node groups

Logical Node Groups	
L	System Logical Node
P	Protection
R	Protection related
C	Control
G	Generic
I	Interfacing and archiving
A	Automatic Control
M	Metering and measurement
S	Sensor and Monitoring
X	Switchgear
T	Instrument Transformers
Y	Power Transformers
Z	Further power system equipment

INTELLIGENT ELECTRONIC DEVICE (IED)

Intelligent Electronic Device consists of one or more processors and is capable of receiving and sending data for information exchange. IEDs are physical devices that can perform one or more applications defined in logical nodes. An IED can be partitioned into several logical devices and logical nodes.

LOGICAL DEVICE (LD)

Logical devices are "virtual" devices, which are created for the purpose of data communication. Generally, one physical device can be abstracted into one or more logical devices. A physical device (an IED) is qualified for certain applications, but not all applications are required at the same time. In order to increase the efficiency of data communication, only the required part is abstracted as logical devices and logical nodes. Data are gathered and processed in these units.

LOGICAL NODE (LN)

A logical node, which is the smallest unit for data exchange, represents a specific use of an IED. It can perform required operations through logical connections (LC), and data exchange occurs among logical nodes under specific communication service mappings. Basically, a logical node is a container of function-related data. The name of logical nodes obeys the semantic method as shown in table 2.1. By referring to the initial character of logical node name, one can easily know the usage of a logical node [4]. For example, a logical node named "XCBR" is used for circuit breaker, "CSWI" is for switch controller.

DATA OBJECT (DO)

Data object refers to specific information, such as the status of devices, measured current/voltage values, position of switches. In object-oriented modelling, data object is described using "Class". IEC 61850-7-3 provides definitions of Common Data Classes

Table 2.2: Example of Data Object and Attributes

DPC (Double Point Control)		
Data Attributes		Type
Control and status attributes	ctlVal	Boolean
	OperTim	Timestamp
	origin	Originator
	ctlNum	INT8U
	stVal	Coded ENUM
	q	Quality
	t	Timestamp
Configuration and description attributes	stSeld	Boolean
	pulseConfig	PulseConfig
	ctlModel	ctlModels
	sboTimeout	INT32U
Substitution attributes	sboClass	SboClasses
	d	Visible string255
	subVal	Coded ENUM
	subEna	Boolean
	subQ	Quality
	subID	Visible string64

(CDC). For example, Class "Complex measured value (CMV)" is a data object defined for measurement information. Attributes of Class CMV include measured magnitude value as "cVal.mag.f", measured angle value as "cVal.ang.f", "q" for quality and "t" for timestamp. Except for measurand information, there are common data classes defined for status information, controllable status information, controllable analog information, status settings, analogue settings and description information.

DATA ATTRIBUTE (DA)

Data attributes describe the detailed information of data encapsulated in a data object. All data objects defined in IEC 61850 contain at least three data attributes which are the value, quality and timestamp. Sometimes a data object will be included as a data attribute of another data object. Class "Phase to ground related measured values of a three phase system (WYE)", as its name indicated, includes three phase measured values, and the data of each phase is defined with data object type "CMV", acting as an attribute of data object WYE. Table 2.2 shows an example of data object "Double Point Control (DPC)" and its data attributes. DPC describes the position and operation of circuit breaker and its data attributes are classified into three groups. Attribute "stVal" reflects the position of circuit breaker using a 2-bit binary integer, with "00" means the CB is in intermediate-state, "01" means Open, "10" means Closed and "11" for bad-state. For a data object named "POS" of Class DPC, if the value of "POS.stVal" equals 1, the circuit breaker is open. And if the breaker is closed, the value of "POS.stVal" will be 2.

Figure 2.2 gives a description of the interrelationship of functions, IEDs, logical devices

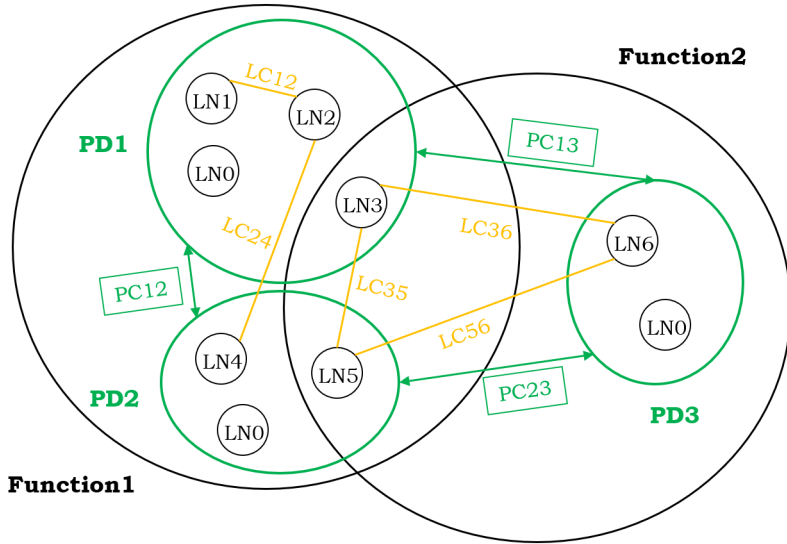


Figure 2.2: The Interrelationship of functions, physical devices, logical nodes and their connections

and logical nodes. The achievement of a function requires one or several physical devices/IEDs and these IEDs are connected through copper wires or fibers (Physical Connection). One or more logical devices and logical nodes are abstracted from a single IED according to user's data exchange requirements. The communication among different logical nodes is realized by mappings (Logical Connection). And below the logical node, there are several data objects and their attributes representing the actual values of variables in power network.

In the case of distance protection, the function can be described as "Trip and reclose internal faults on the protected transmission line". This function should include at least two IEDs: the distance relay and the circuit breaker. The relay needs to receive measured values from the power network to decide whether there is an internal fault and sends trip or reclose commands to the circuit breaker. Hence, logical nodes associated with circuit breakers and switch controllers are required to exchange information between the two IEDs. The actual values of power system variables are represented as data attributes and encapsulated in data objects ready to be transmitted. The communication services are introduced in the next section.

2.3. SPECIFIC COMMUNICATION SERVICE MAPPINGS

2.3.1. MANUFACTURING MESSAGE SPECIFICATION (MMS)

Manufacturing Message Specification (MMS) defined by ISO/IEC is widely adopted in the engineering field. It unifies the communication settings of different IEDs and im-

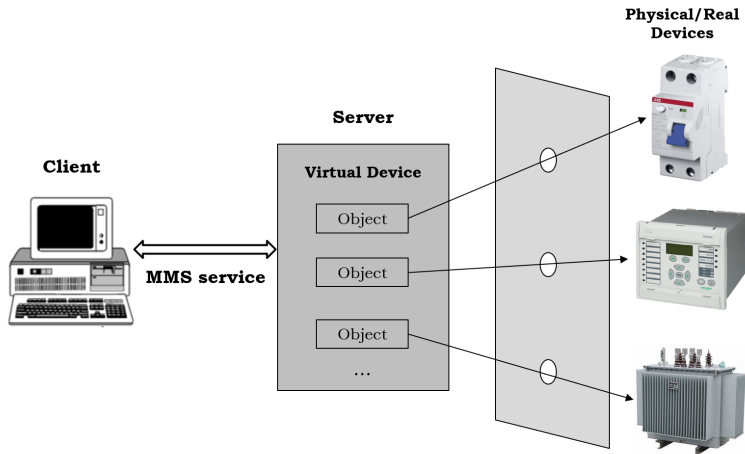


Figure 2.3: Client-Server communication service

proves the interoperability of devices from different vendors [20]. The objective of MMS is to implement Client-Server service among IEDs. One IED can be seen as a server that contains all the data required by the function and is prepared to receive requests from another IED. While the other IED, acting like a client that initiates the communication, can have access to read the data and send requests to the server. Once the request-response link is established, the involved IEDs are able to communicate and report information. When the system is running in steady state, the packaged data in the server is not changed and no request is initiated by the client; When there is an event introduced into the system, data exchange between the server and client is carried automatically. Real devices can be a server and a client at the same time. A controller is the client of its controlled object and the server to other controllers at higher level. MMS serves for the communication between station level and bay level in substations. In most applications, the physical device is abstracted into virtual devices as indicated in figure 2.3.

2.3.2. GENERIC OBJECT ORIENTED SUBSTATION EVENT (GOOSE)

GOOSE (Generic Object Oriented Substation Event) is another communication service for different IEDs defined in IEC 61850, which replaces the traditional hardwired connection between two IEDs, and the inputs and outputs are in binary instead of analog. There are at least one GOOSE sending IED and one or more GOOSE receiving IEDs to achieve communication demands; thus, GOOSE service can be seen as a Publish-Subscribe model.

Under the Publish-Subscribe model, the sending IED sends GOOSE messages as a publisher in low level of communication stack and these messages are broadcasting to all IEDs in the same network. Some of these messages can be moved to the front of the queue to be sent out ahead of other messages by assigning higher priority to those GOOSE messages. When the publishing IED outputs messages in the network, the subscrib-

ing IEDs retrieves GOOSE messages and get the required data. Unlike the Client/Server model, GOOSE service does not build a stable connection between sending and receiving IEDs and cannot provide feedback information to ensure the message has been received. Therefore, to increase the success probability of data transmission, the publisher sends GOOSE messages with an incremental sequence number. The sequence number continues increasing until the status of system is changed. Then the sequence number will be cleared to zero and start a new round.

2.3.3. SAMPLED VALUES (SV)

As its name indicates, SV (Sampled Values) serves to transmit measured values of the power system. There are many devices implemented in power system to sample the real-time data of voltages, currents, frequency and other variables. These measured or sampled values from primary side are analog signals, which should be converted to digital signals before processing [17]. As shown in figure 2.4, IEC 61850-9-2 specify the mappings of sampled values, defining a common interface for data transmission between process level and bay level in substations.

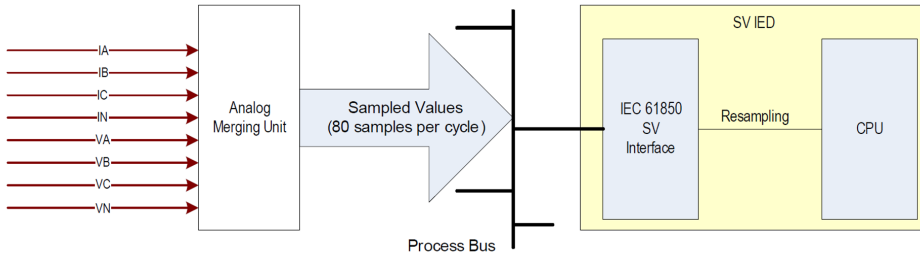


Figure 2.4: Data sampling using IEC 61850-9-2

2.4. ADVANTAGES OF IEC 61850

Compared with traditional control and communication systems, modern substations built on IEC 61850 bring many advantages in practical applications and gradually replace the conventional setup. Firstly, in IEC 61850 system, data are packaged in the hierarchical structure. This structure leads to the concise, understandable and function-driven installation of modern substations. Unlike the traditional data processing that all data are placed together, IEC 61850 encapsulates the data according to function requirements. All the related data are selected in advance and transmitted in groups among different devices, reducing the possibility of data missing and avoiding the waste of data transmission capacity.

Furthermore, IEC 61850 enables data transmission over Ethernet. In conventional substation setup as figure 2.5 shows, power network components like CTs, VTs, CBs, relays and other control blocks are connected by parallel copper wires. This hardwired setup increases the construction cost dramatically as the electricity demand grows rapidly and more feeders are added to the substation. Besides, the maintenance of copper wires is

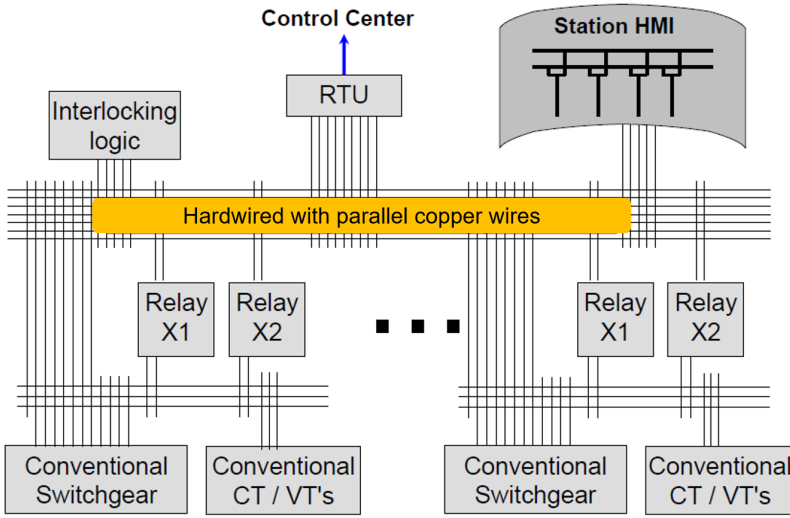


Figure 2.5: Conventional substation setup

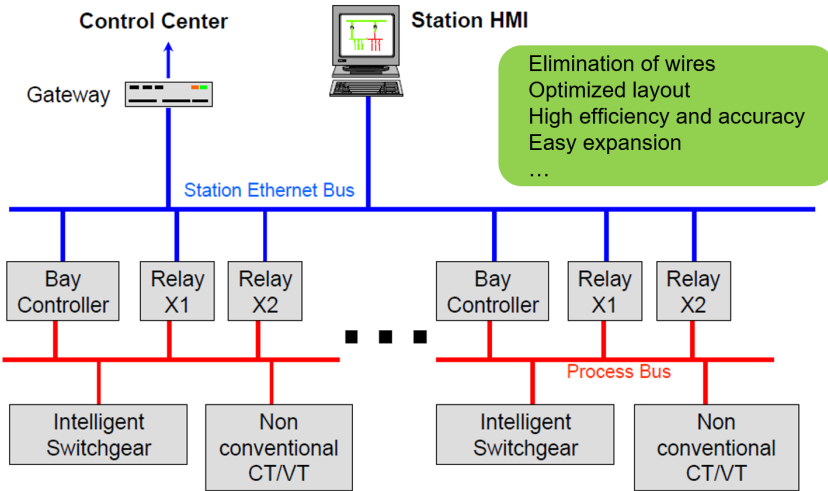


Figure 2.6: Intelligent substation setup

also expensive, requiring large floor area and clean environment [15]. These problems are solved in modern substations with IEC 61850 applied. As shown in figure 2.6, the structure of intelligent substations is divided into three levels: the process level, the bay level and the station level. All the measuring devices and switchgear are connected to

a process bus where all the power system real-time data are collected and transmitted to the higher level. Next, the data are processed and exchanged among different control blocks in the bay level, then uploaded to the station bus and known by the operating staff. Using Ethernet transmission can eliminate the wiring and increase the speed and accuracy of data transmission [19]. The IEC61850-based substation is easy to expand because new devices are connected to the common communication bus instead of hard-wiring with all the related devices.

In conclusion, IEC 61850 is indispensable in the construction of intelligent digital substations and device manufacture, and is proved to be effective and satisfied in substation applications and maintenance.

3

THEORY OF DISTANCE PROTECTION AND CLOSED-LOOP TESTING IN RTDS

Distance protection is implemented in almost every power network. It can protect the most part of transmission line instantaneously and the whole line with allowable time delay. Distance protection is also performed as backup protection for busbar and adjacent transmission line. The accurate circuit breaker operation depends on the characteristics and settings of distance relay. In this chapter, the principle of distance protection is introduced. The time-graded distance zone settings are explained. Furthermore, the closed-loop testing in RTDS using IEC 61850 protocols is proposed as the preparation for relay configuration.

3.1. PRINCIPLE OF DISTANCE PROTECTION

The principle of distance protection is to calculate the impedance seen from a relay point using measured voltages and currents from power network as shown in figure 3.1. The impedance of a transmission line normally is proportional to its length, but when a fault occurs to the system, the fault current increases rapidly and the voltage of busbar will drop to lower value, resulting in an abnormal small calculated impedance value. So if the voltage and current at the relay point can be measured, the impedance is calculated either in the forward direction of the line or in the reverse direction behind the relay point. This calculated impedance is then compared with a pre-defined value called “Reach Point” to decide whether there is a fault. If the calculated impedance is smaller than the Reach Point, the relay detects an internal fault and sends a trip command to the circuit breaker to disconnect the fault part from the power system.

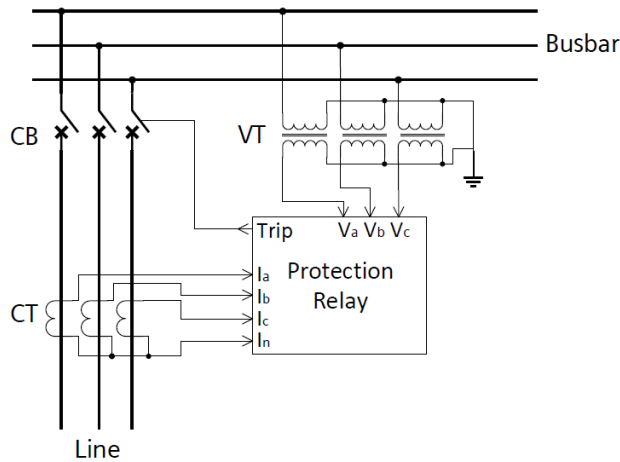


Figure 3.1: Distance relay installation in three-phase system

3.2. DISTANCE MEASURING ZONES

To achieve proper coordination of distance protection relays at different segments of the transmission line, the reach settings and operating times must be chosen with reasonable verification. Fundamental distance protection contains three zones, which are the instantaneous directional protection Zone 1 and one or more zones with time delay [10]. Digital/numerical relays can have up to five or six protection zones for more complex settings such as protection in the reverse direction and backup protection for busbar/adjacent lines. To find out the appropriate zone settings, not only the targeted line will be considered, but its adjacent transmission lines should be taken into account because the fault current varies according to network connections. The typical zone reach coordination of distance protection is presented in figure 3.2.

ZONE 1 PROTECTION SETTING

Since the impedance value is not directly measured from the power system but a calculated value from the measured results of CT and VT, the accuracy cannot be guaranteed and errors will present in the measurement. Therefore, the distance relay operates in several stages to make sure the correct operation of circuit breakers. Commonly, the under-reaching stage, also called Zone 1, protects 85%-90% of the line. The 10%-15% security margin ensures that the relay will only trip internal faults with no time delay, and external faults will not lead to a maloperation.

ZONE 2 PROTECTION SETTING

The rest part of the line is protected by the over-reaching stage which generally covers 120% of the transmission line. Besides, Zone 2 must be graded with time delay to achieve the selectivity of distance protection. With proper time delay, the relay can cut internal faults on the 10%-15% part left by Zone 1, and will not trip external faults on its over-reaching part of the adjacent line (the external fault will be cleared instantaneously by the Zone 1 protection of the adjacent line before the time-delayed Zone 2 protection). For electro-mechanical protection, the grading time is 400-500ms and 200-300ms in the case of analogue static and numerical protection [22].

ZONE 3 PROTECTION SETTING

Zone 3 protection usually can cover the entire length of adjacent lines and busbar if needed. Zone 3 is graded with a longer time delay compared with Zone 2 to achieve absolute selectivity.

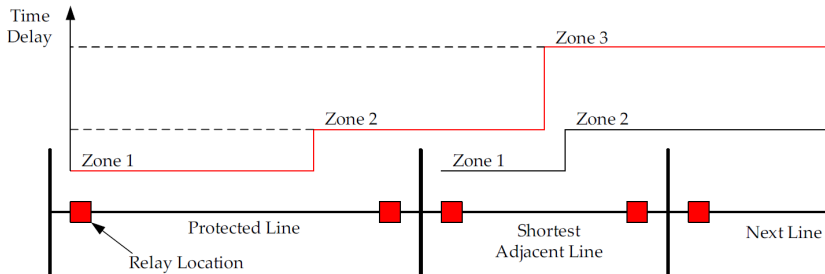


Figure 3.2: Typical time-graded distance zones

3.3. CLOSED-LOOP TESTING

3.3.1. REAL-TIME DIGITAL SIMULATION

The power network model is simulated in Real Time Digital Simulator (RTDS), which is capable of simulating realistic power system events. The typical timestep of electromagnetic transient phenomena is 2~50 μ s and the frequency range is 0~3kHz. The RTDS can provide high-frequency sampling and ensure the accuracy of testing results. Besides, RTDS allows closed-loop testing and supports different communication protocols. As figure 3.3 shows, the testing of power network model continues after the action of protection or control devices, showing a dynamic response of the system.

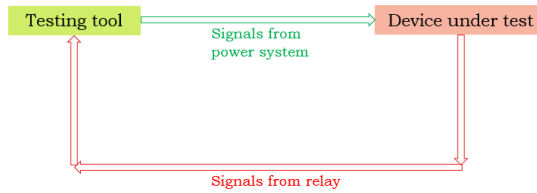


Figure 3.3: Device under closed-loop testing

3.3.2. GTNETx2 CARD

GTNETx2 card supports real-time communication with the simulator via Ethernet. It allows to configure the GTNET module with different communication protocols. The GTNETx2 card has two modules for each application, providing more communication connection choices and more flexible data exchanges. As figure 3.4 shows, each module on GTNETx2 card can be connected to the RTDS simulator using optic fibers. For the communication with external IEDs, the module has one Ethernet port connected to the Ethernet Switch. And by proper mappings, the GTNET module can exchange messages with external IEDs.

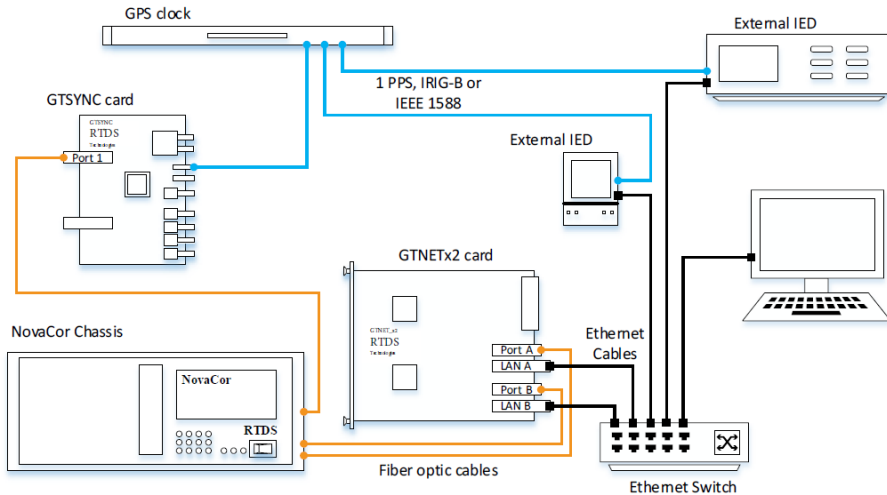


Figure 3.4: Communication setup of GTNETx2 module to RTDS and external IEDs

In this case, GTNET-SV and GTNET-GSE module are enabled to perform the testing. Figure 3.5 shows the two components in RTDS model. The GTNET-SV block supports IEC 61850-9-2 for SV communications and MMS client-server service. The GTNET-GSE block provides GOOSE configuration using SCL files.

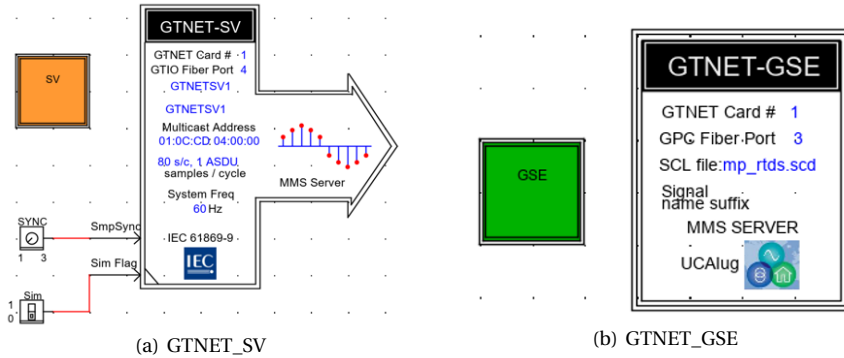


Figure 3.5: GTNET modules

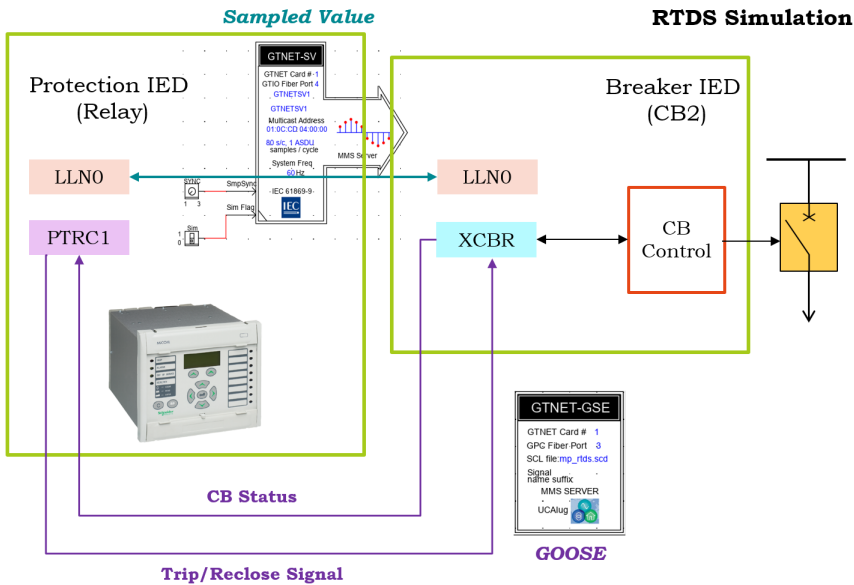


Figure 3.6: The testing setup using GTNET modules

The closed-loop testing of a circuit breaker in RTDS based on IEC 61850 can be illustrated using figure 3.6. One IED is the circuit breaker built in RTDS and the other IED is a distance relay. CTs and VTs in RTDS measure the currents and voltages during simulation, and these measured signals are transmitted to the external relay after configuring the GTNET-SV block. Logical nodes as the smallest data exchange unit between the relay and the CB are correctly mapped in the configuration. The logical node *LLNO* in both IEDs communicates through the GTNET-SV block. Logical Node *XCBR* contains the status information of the CB in RTDS and Logical Node *PTRC* of the relay includes con-

trol signals, and these signals are published and subscribed as GOOSE messages using GTNET-GSE block. When the relay receives real-time data from the RTDS, the internal logic of the relay will process these data and decide whether there is a fault on the line. If the relay sees a fault, it will send a trip signal to the CB via the GOOSE service. And the status of the CB is also transmitted as GOOSE messages to the relay. Therefore, the scheme is capable of performing the closed-loop testing.

4

PROCEDURES OF DISTANCE RELAY CONFIGURATION

This chapter introduces the configuration procedures of a numerical distance relay. The complete settings of relay are made in MiCOM S1 Agile. Furthermore, procedures to configure the distance relay to be mapped with the power network model built in RTDS are explained in detail. GOOSE generation and subscription, SV transmission and Programmable scheme logic are performed to achieve the communication between the external relay and the circuit breaker in RTDS model.

4.1. INTRODUCTION OF DISTANCE RELAY P446

MiCOM P446 relay gives high performance in distance protection. Figure 4.1 shows the actual relay involved in the testing. It can be adopted at all voltage levels in all applications, trip genuine line faults in less than one cycle to ensure high-speed fault clearance, provide five zones of protection and each zone allows mho or quadrilateral characteristics to be selected independently for phase and ground faults. As figure 4.2 indicates, P446 relay provides Zone 1, Zone 2, Zone 3, Zone 4 and Zone P (reverse) in both mho and quadrilateral characteristics, which enables flexible zone settings for different fault types and increases the selectivity of distance protection. Besides, the relay can perform overcurrent protection, voltage protection, broken conductor, thermal overload and high speed breaker failure as the backup of distance protection. Another advantage of P446 relay is the dual breaker autoreclose, which allows two breakers to reclose in a leader-follower scheme.

4



Figure 4.1: MiCOM Alstom Distance Relay P446

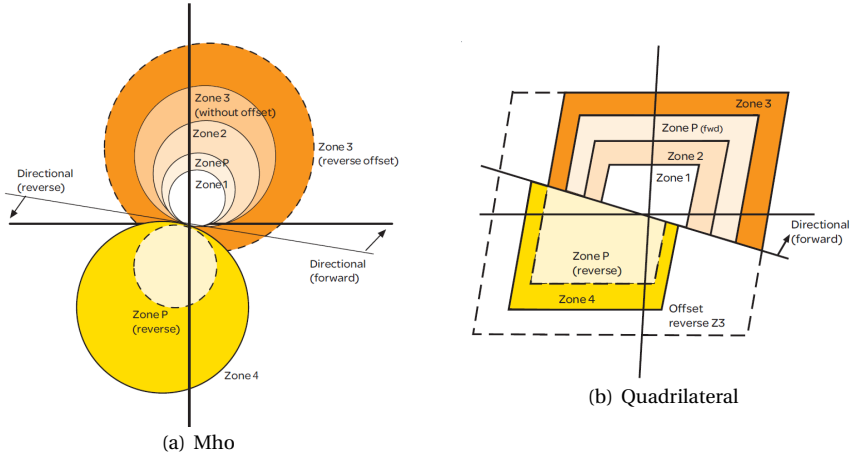
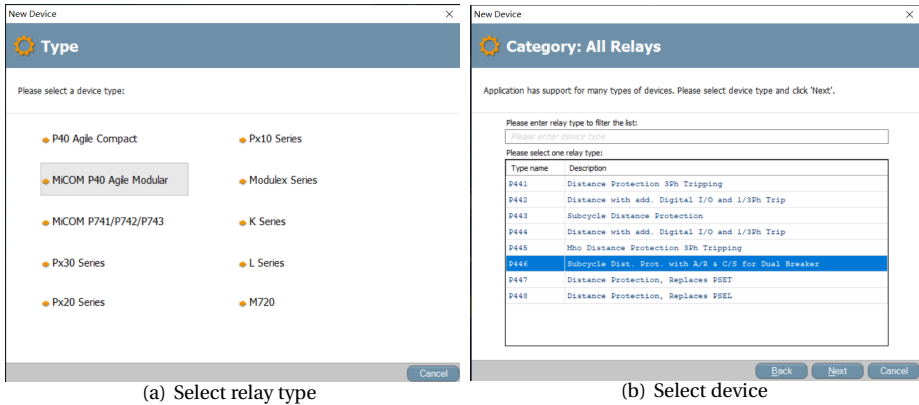
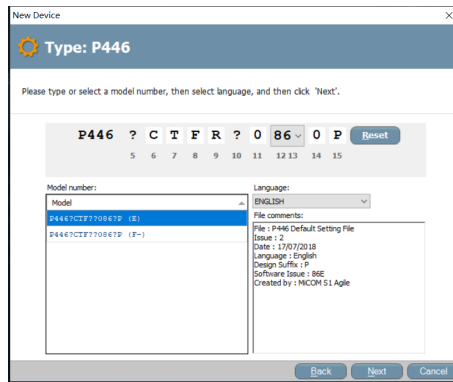


Figure 4.2: Mho and quadrilateral characteristics of distance protection zones in P446 relay



(a) Select relay type

(b) Select device



(c) Enter device model number

Figure 4.3: Select Device Model

To start the relay configuration, firstly a new system is created at the interface. Secondly, new devices or new substations can be created. In this case only a new device P446 relay is introduced into the system. Next, select a device type and enter the model number of the target device according to device instructions as shown in figure 4.3. The relay type is *MiCOM P40 Agile Modular* and the complete model number in this case is *P4469CTF7R0860P*. Then a new device P446 relay is created on the right pane with essential folders. To make the distance protection functional, the configuration in folder **Settings**, **MCL 61850** and **PSL** are elaborated in next sections.

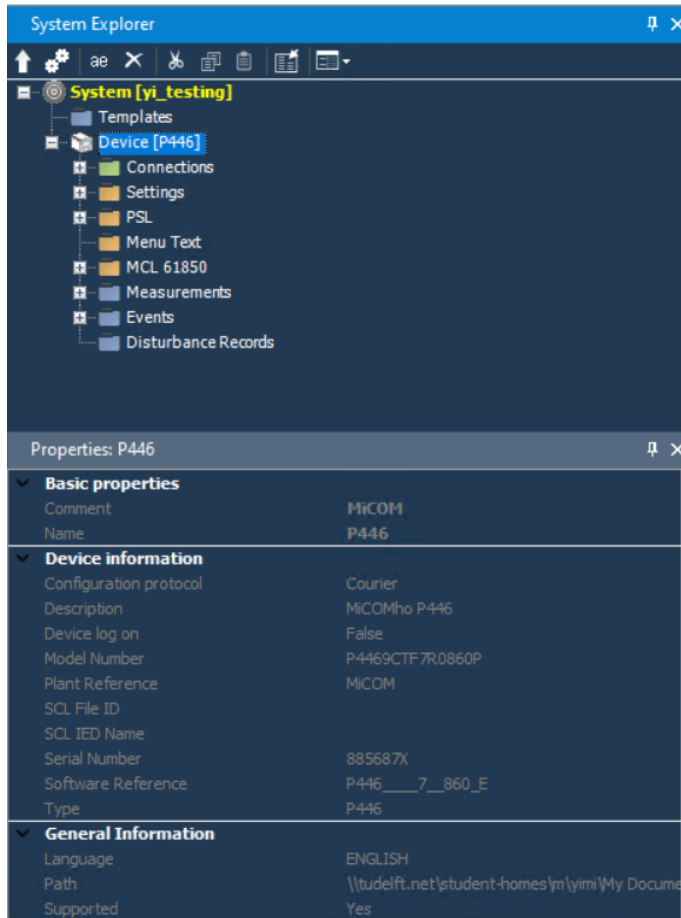


Figure 4.4: Device configuration interface

A complete device configuration menu should appear at the right pane of the interface as shown in figure 4.4 after finishing device selection. Below the Device menu, the green sub-menu *Connections* is created to establish the connection between the software and the physical device. The yellow sub-menu, *Settings*, *PSL*, *MCL 61850* are the main part of relay configuration, defining protection functions, internal logic of relay and communication mappings with external IEDs. The blue sub-menu *Measurements* and *Events* are used for real-time testing to check if the relay can monitor the power network variables and provide records for network events.

4.2. SETTINGS

This file works for the general settings of relay. After creating a new *.set* file, all settings of the relay are listed in different categories as figure 4.5 shows, and parameters are filled by default. To realize the closed-loop testing of CB in RTDS, *System Data*, *CB Control*, *Configuration*, *CT and VT ratios*, *IEC 61850-9.2LE* and *Groups* need to be correctly set according to distance protection requirements of the model in RTDS. Parameters not mentioned in the following sections are conserved as default values.

The screenshot shows the MICOM S1 Agile V2.1.2 software interface. The main window is titled 'Quick Connect...' and contains a list of settings categories. The categories are listed in a table with columns for Name, Value, Address (C.R), and User note. The categories include SYSTEM DATA, CB CONTROL, DATE AND TIME, CONFIGURATION, CT AND VT RATIOS, RECORD CONTROL, DISTURB RECORDER, MEASURE 1 SETUP, COMMISSION TESTS, CB MONITOR SETUP, OPTO CONFIG, CONTROL INPUTS, CTRL I/P CONFIG, IEC 61850-9.2LE, IEC 61850 CONFIG, SECURITY CONFIG, CTRL I/P LABELS, Group 1, GROUP 1 LINE PARAMS..., GROUP 1 DISTANCE SETUP, GROUP 1 DIST. ELEMENTS, GROUP 1 SCHEME LOGIC, GROUP 1 OVERCURRENT, GROUP 1 AIDED DEF, GROUP 1 POWER DWIN..., GROUP 1 CB FAIL & P..., GROUP 1 SUPERVISION, GROUP 1 SYSTEM CHECKS, GROUP 1 AUTORECLOSE, GROUP 1 INPUT LABELS, and GROUP 1 OUTPUT LABELS.

On the right side, there is a 'System Explorer' pane showing a tree view of the system structure. The tree view includes: System [y10930], Templates, Device [P446], Connections, Settings, temp, test_CB2, test_ym, PSL, Menu Text, MCL 61850, Measurements, Events, and Disturbance Records. Below the System Explorer, there is a 'Properties: test_CB2.set' pane showing the basic properties and general information for the selected file.

Properties: test_CB2.set

- Basic properties**
 - Comment: test_CB2.set
- General Information**
 - Creation date: 06/10/2021 16:40:53
 - Data Model File Path: C:\PROGRAMDATA\GE\MICOM S1
 - File is hidden: No
 - File is read-only: No
 - File present on disk: Yes
 - Last modified: 11/11/2021 16:07:40
 - Model Number: P4469CTF700860P
 - Path: C:\Users\JP\Documents\GE S1 Agi
 - Settings template: 906231B
 - Size: 906231B
 - Type: P446

Figure 4.5: The interface of Setting file

SYSTEM DATA

Frequency: 60Hz.

The nominal frequency of electric power network is 50/60 Hz. In this case, the parallel line model simulates at 60Hz in RTDS. The GSE and SV module on GTNETx2 card using IEC 61850 protocols also follow the system frequency.

Name	Value	Address (C.R)	User note
SYSTEM DATA			
Language	English	00.01	
Password	*****	00.02	
Sys Fn Linko	0	00.03	
Description	MiCOMho P446	00.04	
Plant Reference	MiCOM	00.05	
Model Number	P4469CTF7R0860P	00.06	
Serial Number	123454A	00.08	
Frequency	60 Hz	00.09	
Comms Level	2	00.0A	
Relay Address	1	00.0B	
Plant Status	0000001000000010	00.0C	
Control Status	0000000000000000	00.0D	
Active Group	1	00.0E	

Figure 4.6: Parameter settings of System Data

CB CONTROL

CB control by: Local.

The device provides three CB control methods (local, remote and opto) and their combinations. For the control of a single circuit breaker, "Local control" can satisfy most circumstances including control with IED menu and hotkeys. "Remote control" is applied in Supervisory Control and Data Acquisition (SCADA) communication. For applications that require push buttons or other external signals to control operations of CB, "Opto-inputs control" is selected to enable connections and mappings of these extra signals using relevant DDBs in relay's logic.

CB1 Status Input: 52A 3 pole.

This parameter reflects the status monitoring method of relay to the CB. CB can transmit their status (Open/Closed) values to the control equipment such as relays through auxiliary contacts. "52A" means auxiliary contacts follow the status of CB, while "52B" is for contacts that are in opposition to the status of CB. Referring to the MMS configuration from RTDS (figure 4.7(b)), the relay uses 3-pole operation, which means the relay has the ability to trip single phase when fault occurs, while 1-pole operation always trips three phases with no discrimination. In practice, three-pole tripping circuit breakers are installed at high voltage level power systems for large capacity transmission as they are expensive and bulky compared with 1-pole circuit breakers. If single-phase fault happens to the system, 3-pole operation CB will trip only the fault phase and the other two phases can still transmit power to users. While for 1-pole operation, the CB will always trip three phases, thus 1-pole operation is adopted at low voltage level and small capacity transmission to minimize the impact of power supply interruption.

In the case of 500kV parallel line protection, the generator sends approximately 320MW active power at the initial, as the main protection of high voltage level transmission line, the choice of 3 pole operation is reasonable.

Name	Value	Address (C.R)	User note
SYSTEM DATA			
CB CONTROL			
CB Control by	Local	07.01	
Close Pulse Time	250.0 ms	07.02	
Trip Pulse Time	100.0 ms	07.03	
Man Close Delay	10.00 s	07.05	
CB Healthy Time	5.000 s	07.06	
Check Sync Time	5.000 s	07.07	
CB mon LO reset	No	07.08	
Ret CB mon LO by	CB Close	07.09	
CB mon LO RetDly	5.000 s	07.0A	
Autoreclose Mode	No Operation	07.0B	
AR Status	Out of Service	07.0E	
CB1 Status Input	52A 3 pole	07.11	
CB Status Time	5.000 s	07.7F	
CB2 Status Input	52B 1 pole	07.80	
CTRL CB2 Lead	No Operate	07.81	
Reset AROK Ind	No	07.82	
Reset CB1 LO	No	07.83	
Reset CB2 LO	No	07.84	
CB1 Total Shots	0	07.85	
CB1 SUCC SPAR	0	07.86	
CB1SUCC3PARShot1	0	07.87	
CB1SUCC3PARShot2	0	07.88	
CB1SUCC3PARShot3	0	07.89	
CB1SUCC3PARShot4	0	07.8A	
CB1 Failed Shots	0	07.8B	
Reset CB1 Shots	No	07.8C	

(a) Parameter settings of CB Control

_rtds_GTNET_GSE_v6.def						
GOOSE Output Quality, Test, NdsComm Bitmap Enables						
GOOSE Input Quality, Test, NdsComm Bitmap Enables						
TX 5 Output Signal Names/Types			RX/TX 1 Input Signal Names/Types			
TX 5 Output Retransmit Curve			RX/TX 1 Output Signal Names/Types			
Output Deadband Parameters			RX/TX 1 Output Retransmit Curve			
CONFIGURATION		GOOSE Configuration		MMS Configuration		
Name	Description	Value	Unit	Min	Max	
nXCBRLoc	XCBR/XSW Local/Remote Switch Signal Name	LocRem		0	0	
nMtlLev	Bay Mode of Switching Authority Signal Name	MtlLev		0	0	
nCSWLoc	Bay Local Control Behaviour Signal Name	CSWLoc		0	0	
nCSWLocSta	Bay Control Authority st Station Signal Name	CSWLocSta		0	0	
nCSWOpnCmd	Bay Control Open Command Signal Name	CSWOpnCmd		0	0	
nCSWclsCmd	Bay Control Close Command Signal Name	CSWclsCmd		0	0	
TrMod	Three or Single Pole Operation	3Pole		0	1	
nXCBRPosA	XCBR A phase Signal Name	PosA		0	0	
nXCBRPosB	XCBR B phase Signal Name	PosB		0	0	
nXCBRPosC	XCBR C phase Signal Name	PosC		0	0	
nCILOEnaOpnCmd	CILO DOI EnaOpn Command	CILOEnaOpn		0	0	
nCILOEnaClsCmd	CILO DOI EnaCls Command	CILOEnaCls		0	0	
nTX1LLN0Mod	RX/TX1 LLN0 Mod Name	TX1LLN0Mod		0	0	
nTX2LLN0Mod	RX/TX2 LLN0 Mod Name	TX2LLN0Mod		0	0	
nTX3LLN0Mod	RX/TX3 LLN0 Mod Name	TX3LLN0Mod		0	0	
nTX4LLN0Mod	RX/TX4 LLN0 Mod Name	TX4LLN0Mod		0	0	
nTX5LLN0Mod	RX/TX5 LLN0 Mod Name	TX5LLN0Mod		0	0	
nLGOSLLN0Mod	LGOS LLN0 Mod Name	LGOSLLN0Mod		0	0	
nSynPrg	Sync-in-progress output signal name	SynPrg		0	0	

(b) RTDS GTNET_GSE MMS configuration

Figure 4.7: Settings of CB Control

CONFIGURATION

Name	Value	Address (C.R)	User note
CONFIGURATION			
Restore Defaults	No Operation	09.01	
Setting Group	Select via Menu	09.02	
Active Settings	Group 1	09.03	
Save Changes	No Operation	09.04	
Copy From	Group 1	09.05	
Copy To	No Operation	09.06	
Setting Group 1	Enabled	09.07	
Setting Group 2	Disabled	09.08	
Setting Group 3	Disabled	09.09	
Setting Group 4	Disabled	09.0A	
Distance	Enabled	09.0B	
Directional E/F	Enabled	09.0C	
Overcurrent	Enabled	09.10	
Neg Sequence O/C	Disabled	09.11	
Broken Conductor	Disabled	09.12	
Earth Fault	Disabled	09.13	
SEF/REF Prot'n	Disabled	09.15	
Residual O/V NVD	Disabled	09.16	
Thermal Overload	Disabled	09.17	
PowerSwing Block	Enabled	09.18	
Volt Protection	Disabled	09.1D	
Freq Protection	Disabled	09.1E	
df/dt Protection	Disabled	09.1F	
CB Fail	Disabled	09.20	
Supervision	Enabled	09.21	
System Checks	Enabled	09.23	
Auto-Reclose	Enabled	09.24	
Input Labels	Visible	09.25	
Output Labels	Visible	09.26	
CT & VT Ratios	Visible	09.28	
Record Control	Visible	09.29	
Disturb Recorder	Visible	09.2A	
Measure't Setup	Visible	09.2B	
Comms Settings	Visible	09.2C	
Commission Tests	Visible	09.2D	
Setting Values	Secondary	09.2E	
Control Inputs	Visible	09.2F	

Figure 4.8: Settings of Configuration

Setting Group: *Select via menu.*

The relay provides two manners to select active setting group, *select via menu*, or *select via PSL*. The device can enable at most four setting groups in a file, but only one group will be activated and dominate the protection function at one time. If "Select via menu" is chosen, users can set the Group using Active Settings or with the hotkeys. If "Select via PSL" is selected, the setting group is selected by DDB signals (Boolean value) in PSL. *Select via menu* is chosen in this case for convenience.

Enable Setting Group: *Group 1* is enabled.

One setting group can satisfy the distance protection reach requirements of the parallel line model in RTDS. If reach requirements are changed, for example, the transmission line is replaced by new construction or a load with large in-feed fault current is connected to the bus, then the rest three groups can be enabled and set to provide alternative relay settings.

Protection Function Selection: Enable the corresponding protection function according to power network requirements.

In this case, *Distance* (the main protection), *Overcurrent* (back-up protection), *System Check* (monitor the voltages on both side of the circuit breaker and perform a synchronisation check for autoreclosing on parallel connection) and *Auto-reclose* (to deal with instantaneous faults) are enabled. The rest functions are kept as default.

Setting Values: *Secondary*.

The reach of each distance protection zone can be set using primary or secondary values. The conversion of primary and secondary values depends on CT and VT ratios.

CT AND VT RATIOS

Name	Value	Address (C.R)	User note
CT AND VT RATIOS			
Main VT Primary	500.0 kV	0A.01	
Main VT Sec'y	110.0 V	0A.02	
CB1 CS VT Prim'y	500.0 kV	0A.03	
CB1 CS VT Sec'y	110.0 V	0A.04	
CB2 CS VT Prim'y	110.0 V	0A.05	
CB2 CS VT Sec'y	110.0 V	0A.06	
Phase CT Primary	600.0 A	0A.07	
Phase CT Sec'y	1.000 A	0A.08	
SEF CT Primary	1.000 A	0A.0B	
SEF CT Secondary	1.000 A	0A.0C	
MComp CT Primary	1.000 A	0A.0D	
MComp CT Sec'y	1.000 A	0A.0E	
CS Input	AN	0A.0F	
CT1 Polarity	Standard	0A.11	
CT2 Polarity	Standard	0A.12	
SEF CT Polarity	Standard	0A.13	
M CT Polarity	Standard	0A.14	
CB1 CS VT PhShft	0 deg	0A.21	
CB1 CS VT Mag	1.000	0A.22	
CB2 CS VT PhShft	0 deg	0A.23	
CB2 CS VT Mag	1.000	0A.24	

Figure 4.9: Parameter settings of CT and VT ratios

Main VT Primary and Secondary: *500kV / 110V*.

Referring to the RTDS model, Capacitive Voltage Transformer (CVT) is installed on the line side of CB2. As the main VT, the primary input voltage is the nominal line voltage which is 500kV, and the secondary voltage is 110V.

Phase CT Primary and Secondary: *600A / 1A*.

The ratio of current transformer installed on the transmission line in RTDS model is 600. Thus the CT primary value is set to 600A, and the secondary value is 1A.

CS VT: CS VTs are provided by the device to perform system synchronisation check. For a single CB, the relay compares two voltage inputs from the line side and the bus side using *CB1 CS VT*. For a dual circuit breaker scheme (one-and-a-half breaker installation or ring/mesh bus) that requires three VT signal inputs, *CB1 & CB2 CS VT* settings are needed.

SEF CT: This CT setting is used to configure Sensitive Earth Fault protection.

IEC 61850-9-2LE

Name	Value	Address (C.R)	User note
IEC 61850-9.2LE			
Physical Link	Copper	18.01	
AntiAlias Filter	Enabled	18.02	
Synchro Alarm	No SYNC CLK	18.03	
SV Test Mode	Disabled	18.04	
Merge Unit Delay	0 s	18.05	
VT Switch Mode	Disabled	18.06	
LN Count	1	18.11	
LN1 Name	0000MU0101	18.12	
IA1 IB1 IC1	LN1	18.31	
IA2 IB2 IC2	Unused	18.32	
INoen	Unused	18.33	
IM	Unused	18.34	
VA VB VC	LN1	18.35	
Voc1	Unused	18.36	
Voc2	Unused	18.37	
Trust Quec Data	000000	18.43	
Looc Rate Level	10.00 %	18.44	
SAV Absence	000000001	18.51	
SAV No SmpSynch	000000000	18.52	
SAV Test	0000000000000	18.53	
SAV Questionable	0000000000000	18.54	
SAV Invalid	0000000000000	18.55	
Frame Loss Data		18.70	
Frame Loss Rate	Enabled	18.71	
LN1 LossRate Sec	0 %	18.72	

(a) Parameter settings in IEC 61850-9-2LE

_rtds_cti_GTNET_SV_v6.def					
SV-1 CHANNEL SCALING		SV-1 CHANNEL OFFSET		SV-1 CHANNEL DELAYS	
SV-1 OUTPUT IEC 61850 CONFIG			SV-1 SIGNAL NAME/FORMAT		
CONFIGURATION		MMS SERVER ADDRESS		MMS CONFIGURATION	
Name	Description	Value	Unit	Min	Max
APPID	APPID (hex) 0x4000□0x7FFF	4000		4000	7FFF
VLANPRI	VLAN priority	4		0	7
VLANID	VLAN ID (hex) 0x000□0xFFFF	000		000	FFF
LDpre	LDName prefix (4-30 characters)	0000			
LDsuf	LDName suffix (eg. 1)	1		1	99
MACH	Output multicast address (eg. 01:0C:CD)	01:0C:CD		0	0
MACL	Output Multicast address (eg. 04:00:00)	04:00:00		0	0
INCSSF	Include sample sync field in message	CC			
INCSR	Include sample rate field in message	FALSE		0	0
CONFREV	ConfRev (hex) 0x00000001□0xFFFFFFFF	1		1	FFFFFFFF
sLevel	Voltage Level	500kV		0	0
sBay	Bay	5L1		0	0
nChan	Number of voltage and current channels	8		1	24
Tx1isRoutable	Whether or not to publish a routable stream	NO		0	1
Tx1MmulticastIP	Multicast IP address destination	224.168.1.10		0	0

(b) RTDS GTNET_SV Output

Figure 4.10: Settings of IEC 61850-9-2LE

Physical Link: *Copper.*

The relay and the circuit breaker compiled on RTDS rack are connected through copper wire. Another choice is *Optic fiber.*

LN Count: *1.*

According to the power network model, only one LN of CB2 is needed to realize the data communication requirement between the relay and the CB through SV service.

LN1 Name: *0000MU0101.*

Go to RTDS and open the GTNET-SV block (figure 4.10(b)). LD name has the fixed format of ppppMUss01 (for SV-1) and ppppMUss02 (for SV-2) as GTNET-SV can publish two independent SV messages at the same time. In this case, only the first SV module is activated. The prefix and suffix can be found in the "SV-1 Output IEC 61850 Config" of which the prefix is "0000" and the suffix is "01". By setting this parameter, logical nodes of the relay in MicOM and the CB in RTDS are mapped through this unique name.

GROUP 1

This category defines specific values of parameters that are related to the protection function enabled in *Configuration* category.

Line parameters

Line parameters are set according to practical power networks. The information in table 4.1 of the protected line can be found in RTDS model.

Table 4.1: Line Parameters of Transmission Line 1

Line Parameters	Values
Frequency	60.00 Hz
Length	97 km
Primary Line Impedance (positive sequence)	1.54 + j33.36 ohms (33.40/_87.35 degree)
Primary Line Impedance (zero sequence)	35.36 + j104.74 ohms (110.56/_71.34 degree)
CT ratio	600/1A
VT ratio	500/0.11kV

The residual compensation factor k_{ZN} is configured with amplitude $k_{ZN} Res Comp$ and angle $k_{ZN} Res Angle$. For hybrid circuits or dissimilar construction where line impedance changes between segments, the residual compensation factor can be applied independently to certain protection zones in *Dist.Elements*. In the case of a uniform transmission line, a common k_{ZN} factor is set for all protection zones.

$$k_{ZN} = \frac{Z_0 - Z_1}{3Z_1} \quad (4.1)$$

Thus,

$$k_{ZN} = \frac{110.56\angle 71.34^\circ - 33.40\angle 87.35^\circ}{100.20\angle 87.35^\circ} = 0.79\angle -22.69^\circ \quad (4.2)$$

Name	Value	Address (C.R)	User note
GROUP 1 LINE PARAMETERS			
Line Length	97.00 km	30.01	
Line Impedance	4.410 Ohm	30.03	
Line Angle	87.00 deg	30.04	
kZN Res Comp	790.0e-3	30.05	
kZN Res Angle	-23.00 deg	30.06	
Mutual Comp	Disabled	30.07	
Phase Sequence	Standard ABC	30.0B	
CB1Tripping Mode	3 Pole	30.0C	
CB2Tripping Mode	3 Pole	30.0E	
Line Charging Y	2.000 mS	30.10	
Main VT Location	Line	30.12	

Figure 4.11: Line parameters

Therefore set:

$$kZN \text{ Res Comp} = 0.79$$

$$kZN \text{ Res Angle} = -23.00 \text{ deg}$$

Distance Setup

Select the *Setting Mode*, *Distance Characteristics* and *Active Protection Zones*.

Numerical relays like P446 have up to five zones of distance protection, but not all zones are necessary to be involved in testing. *Distance Setup* is used to select zones that will be involved in specific distance protection cases. P446 relay provides two setting modes, *Simple* or *Advanced*. "Simple mode" selects zones and sets the reach of each zone in percentage. Actual values of zone reach impedances will be automatically calculated using line parameters and filled in the next sub-menu *DIST.Elements*. This mode is suitable for most cases. "Advanced mode" is recommended for power networks in which the protected line and its adjacent lines have different construction. This mode enables individual zone impedances, residual compensation settings and operating current thresholds for every active zone in order to fit the requirements of dissimilar installation.

P446 relay provides both mho and quadrilateral characteristics for phase and ground fault zones. Mho characteristics for phase fault zones and quadrilateral for earth fault zones are recommended for short line applications. For series compensated lines, mho characteristics are suitable for both phase and earth faults. For open delta voltage transformer applications, mho is selected for phase fault protection. Earth fault distance elements are disabled and "Directional Earth Fault" is activated to realize the protection. Generally, mho characteristics are recommended for line protection, and quadrilateral characteristics are preferred in cable applications [7].

In the case of 500kV parallel line distance protection, TL1 is uniform and in medium length. Thus Mho characteristics are selected for both phase and earth fault zones [21]. Four zones are enabled for the protection (Zone 1, Zone 2, Zone 3 and Zone 3 reverse). Using *Simple* setting mode, distance protection is configured by the following steps.

- Set *Zone x Ph Status* and *Zone x Gnd Stat.* to "Enabled".
- Set *Zone x Ph Reach* and *Zone x Gnd Reach* to "the percentage of the line length".

The reach of Zone 1 is set to 85% of the whole length, 120% for Zone 2, 200% for Zone 3 (forward) and 10% for Zone 3 (reverse). Leave the rest zones disabled.

Name	Value	Address (C.R)	User note
Group 1			
GROUP 1 LINE PARAMETERS			
GROUP 1 DISTANCE SETUP			
Setting Mode	Simple	31.0C	
PHASE DISTANCE		31.10	
Phase Charc.	Mho	31.11	
Zone 1 Ph Status	Enabled	31.20	
Zone 1 Ph Reach	85.00 %	31.21	
Zone 2 Ph Status	Enabled	31.30	
Zone 2 Ph Reach	120.0 %	31.31	
Zone 3 Ph Status	Enabled	31.40	
Zone 3 Ph Reach	200.0 %	31.41	
Zone 3 Ph Offset	Enabled	31.42	
Z3Ph Rev Reach	10.00 %	31.43	
Zone P Ph Status	Disabled	31.50	
Zone 4 Ph Status	Disabled	31.60	
GROUND DISTANCE		31.70	
Ground Charc.	Mho	31.71	
Zone 1 Gnd Stat.	Enabled	31.80	
Zone 1 Gnd Reach	85.00 %	31.81	
Zone 2 Gnd Stat.	Enabled	31.90	
Zone 2 Gnd Reach	120.0 %	31.91	
Zone 3 Gnd Stat.	Enabled	31.A0	
Zone 3 Gnd Reach	200.0 %	31.A1	
Zone3 Gnd Offset	Enabled	31.A2	
Z3Gnd Rev Reach	10.00 %	31.A3	
Zone P Gnd Stat.	Disabled	31.B0	
Zone 4 Gnd Stat.	Disabled	31.C0	
Digital Filter	Standard	31.D0	
CVT Filters	Disabled	31.D1	
Load Blinders	Disabled	31.D3	
Dist. Polarizing	1.000	31.D7	
DELTADIRECTIONAL		31.E0	

Figure 4.12: Distance Setup (Using Simple setting mode)

DIST. Elements

If *Advanced* setting mode is chosen in *Distance Setup*, the reach points of distance protection zones can be calculated and set independently in this menu. Otherwise, the *DIST. ELEMENTS* settings will be grey and values are filled automatically by the software. For cross-reference, the reach impedances are calculated as follows. Since the line impedances extracted from RTDS are primary values while the configuration is set based on secondary values. The impedance values should be converted from primary to secondary firstly.

$$Z_{sec} = Z_{prim} \cdot \frac{I_{prim}/I_{sec}}{U_{prim}/U_{sec}} \quad (4.3)$$

$$I_{prim}/I_{sec} = 600/1$$

$$U_{prim}/U_{sec} = 500/0.11$$

In the case of parallel distance protection, Zone 1 is set to protect 85% of the transmission line. Overreaching Zone 2 covers 120% of the entire length. Zone 3 plays as backup protection with 200% of the protected line length in the forward direction and 10% in the reverse direction [21].

Thus,

$$\begin{aligned}
 Z1.reach &= Zline_{sec} \times 85\% = 33.4 \times \frac{600/1}{500/0.11} \times 85\% = 3.747 \text{ Ohms} \\
 Z2.reach &= Zline_{sec} \times 120\% = 33.4 \times \frac{600/1}{500/0.11} \times 120\% = 5.291 \text{ Ohms} \\
 Z3.reach &= Zline_{sec} \times 200\% = 33.4 \times \frac{600/1}{500/0.11} \times 200\% = 7.497 \text{ Ohms} \\
 Z3.REV.reach &= Zline_{sec} \times 10\% = 33.4 \times \frac{600/1}{500/0.11} \times 10\% = 441 \text{ mOhms}
 \end{aligned}
 \tag{4.4}$$

4

Name	Value	Address (C.R)	User note
Group 1			
GROUP 1 LINE PARAMETERS			
GROUP 1 DISTANCE SETUP			
GROUP 1 DIST. ELEMENTS			
Phase Distance		32.01	
Z1 Ph. Reach	3.749 Ohm	32.02	
Z1 Ph. Angle	87.00 deg	32.03	
Z1 Sensit. Iph>1	75.00 mA	32.09	
Z2 Ph. Reach	5.292 Ohm	32.10	
Z2 Ph. Angle	87.00 deg	32.11	
Z2 Sensit. Iph>2	75.00 mA	32.17	
Z3 Ph. Reach	8.820 Ohm	32.20	
Z3 Ph. Angle	87.00 deg	32.21	
Z3' Ph Rev Reach	441.0 mOhm	32.22	
Z3 Sensit. Iph>3	50.00 mA	32.28	
Ground Distance		32.50	
Z1 Gnd. Reach	3.749 Ohm	32.51	
Z1 Gnd. Angle	87.00 deg	32.52	
kZN1 Res. Comp.	790.0e-3	32.55	
kZN1 Res. Angle	-23.00 deg	32.56	
Z1 Sensit Ignd>1	150.0 mA	32.5B	
Z2 Gnd. Reach	5.292 Ohm	32.60	
Z2 Gnd. Angle	87.00 deg	32.61	
kZN2 Res. Comp.	790.0e-3	32.65	
kZN2 Res. Angle	-23.00 deg	32.66	
Z2 Sensit Ignd>2	150.0 mA	32.6B	
Z3 Gnd. Reach	8.820 Ohm	32.70	
Z3 Gnd. Angle	87.00 deg	32.71	
Z3' Gnd Rev Rch	441.0 mOhm	32.72	
kZN3 Res. Comp.	790.0e-3	32.75	
kZN3 Res. Angle	-23.00 deg	32.76	
Z3 Sensit Ignd>3	50.00 mA	32.7C	

Figure 4.13: Dist. Elements (Using Advanced setting mode)

Scheme Logic

The time-grading scheme of distance protection is configured in this menu. Zone 1 is the instantaneous protection zone. Zone 2 operates with a 200ms time delay and 400ms is set for Zone 3. The time delay settings in Zone 2 and Zone 3 are in accordance with CB1 installed at the opposite end of the protected line. Thus, the clearance of internal faults using the two circuit breakers is coordinated.

Name	Value	Address (C.R)	User note
Group 1			
GROUP 1 LINE PARAMETERS			
GROUP 1 DISTANCE SETUP			
GROUP 1 DIST. ELEMENTS			
GROUP 1 SCHEME LOGIC			
BASIC SCHEME		34.01	
Zone1 Tripping	Phase And Ground	34.08	
tZ1 Ph. Delay	0 s	34.09	
tZ1 Gnd. Delay	0 s	34.0A	
Zone2 Tripping	Phase And Ground	34.10	
tZ2 Ph. Delay	200.0 ms	34.11	
tZ2 Gnd. Delay	200.0 ms	34.1C	
Zone3 Tripping	Phase And Ground	34.18	
tZ3 Ph. Delay	400.0 ms	34.19	
tZ3 Gnd. Delay	400.0 ms	34.1A	
ZoneP Tripping	Phase And Ground	34.20	
tZP Ph. Delay	400.0 ms	34.21	
tZP Gnd. Delay	400.0 ms	34.22	
Zone4 Tripping	Phase And Ground	34.28	
tZ4 Ph. Delay	1.000 s	34.29	
tZ4 Gnd. Delay	1.000 s	34.2A	
AIDED SCHEME 1		34.40	
Aid. 1 Selection	Disabled	34.41	
AIDED SCHEME 2		34.60	
Aid. 2 Selection	Disabled	34.61	

Figure 4.14: Settings of Scheme Logic

Autoreclose

Name	Value	Address (C.R)	User note
GROUP 1 AUTORECLOSE			
Num CBs	CB1 Only	49.50	
AR Mode	AR 3P	49.51	
AR Shots	1	49.59	
Multi Phase AR	Allow Autoreclose	49.5C	
CB IC Time	5.000 s	49.60	
CB IC MemoryTime	500.0 ms	49.61	
DT Start by Prot	Protection Reset	49.62	
3PDTStart WhenLD	Disabled	49.63	
DTStart by CB Op	Disabled	49.64	
3P AR DT Shot 1	300.0 ms	49.68	
3P AR DT Shot 2	60.00 s	49.69	
3P AR DT Shot 3	60.00 s	49.6A	
3P AR DT Shot 4	60.00 s	49.6B	
3PAR ReclaimTime	180.0 s	49.6E	
AR CBHealthyTime	5.000 s	49.6F	
AR CheckSyncTime	5.000 s	49.70	
Z1 AR	Initiate AR	49.72	
Dist Aided AR	Initiate AR	49.74	
Z2T AR	Initiate AR	49.75	
Z3T AR	Block AR	49.76	
ZPT AR	Block AR	49.77	
Z4T AR	Block AR	49.78	
DEF Aided AR	Block AR	49.79	
Dir Aided AR	Block AR	49.7A	
TOR AR	Block AR	49.7B	
I>1 AR	No Action	49.7C	
AR SYS CHECKS		49.85	
CB1L SC all	Disabled	49.86	

Figure 4.15: Autoreclosure

Autoreclosure is applied in Zone 1 and Zone 2 protection. Most faults do not last long

and are self-clearing if isolated. Approximately 80%-90% faults on transmission lines are transient. As Zone 1 and Zone 2 have covered the whole length of the protected line, initiating autoreclosing in the two protection zones is sufficient to deal with most internal faults.

4.3. IED CONFIGURATOR (MCL 61850)

This section describes procedures to map the external distance relay P446 with the virtual circuit breaker in RTDS. In IEC 61850 system, function-related data are packaged in logical nodes and transmitted through specific protocols. Menu "MCL 61850" is created to configure signal inputs and outputs between relay and CB. The configuration starts with the IP address check, then select relevant signals as datasets, and finally match the GOOSE publishing and subscribing between circuit breaker in RTDS and relay in MiCOM S1 Agile.

4

4.3.1. COMMUNICATIONS

Firstly, to realize data communication, the IP address of relay and CB should be matched correctly. Figure 4.16 indicates the required information. Check the MMS server address in the GTNET_SV module and make the first three numbers of relay's IP address the same as RTDS GTNET alias. Considering the IP address should be unique, the fourth number is set different to avoid conflict.

4.3.2. DATASET DEFINITIONS

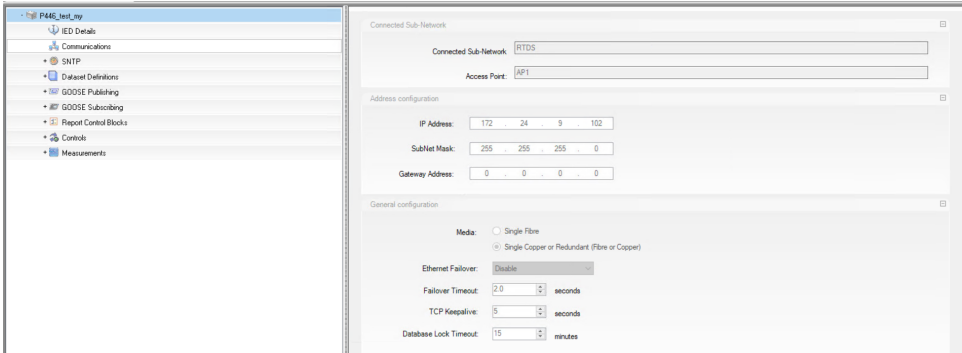
Dataset definitions are used to create a group of data required by protection function as a data object and then exchange among logical nodes under IEC 61850 protocols. This configuration tool supports two types of dataset definition: *Dataset* and *OPGOOSE dataset*. There is no significant difference between the two definitions except OPGOOSE (Optimised Performance Goose) dataset has higher processing priority in IEDs. Signals such as tripping or blocking commands that require high-speed GOOSE transmission can be selected into the OPGOOSE dataset.

To define a dataset:

1. Right click *Dataset Definitions*, click "Add Dataset/OPGOOSE Dataset".
2. Name the new dataset and check the location to which logical node the dataset belongs.
3. Select items to be added in the dataset. The list of Functionally Constrained Data Attributes (FCDA) can be viewed in a flat or hierarchical list, showing the tree structure of data arrangement in IEC 61850 system. An indicator on the right side shows the GOOSE capacity of a single dataset.

Regarding this protection case, there are two basic requirements: trip the CB when fault is detected and reclose the CB after the transient fault is cleared. Therefore, two datasets are created. The first OPGOOSE dataset selects Tr (fast protection tripping) and Op (in case the CB needs manual operation) signals, including attributes of general 3 phases, phase A, phase B, phase C, quality and timestamp for both manners. The second dataset

contains autoreclose signals. It is noticed that only one OPGOOSE dataset can be created in one logical node, thus the selection of signals to be transmitted with high speed should be considered.



(a) MCL-Communications

_rtds_ctl_GTNET_SV_v6.def					
SV-1 CHANNEL SCALING		SV-1 CHANNEL OFFSET		SV-1 CHANNEL DELAYS	
SV-1 OUTPUT IEC 61850 CONFIG			SV-1 SIGNAL NAME/FORMAT		
CONFIGURATION		MMS SERVER ADDRESS		MMS CONFIGURATION	
Name	Description	Value	Unit	Min	Max
Sip1	MMS IP Address 1	172		0	255
Sip2	MMS IP Address 2	24		0	255
Sip3	MMS IP Address 3	9		0	255
Sip4	MMS IP Address 4	182		0	255
Sport	MMS Port Number	102		0	65535

(b) GTNET_SV MMS Server Address

Figure 4.16: Establish the communication

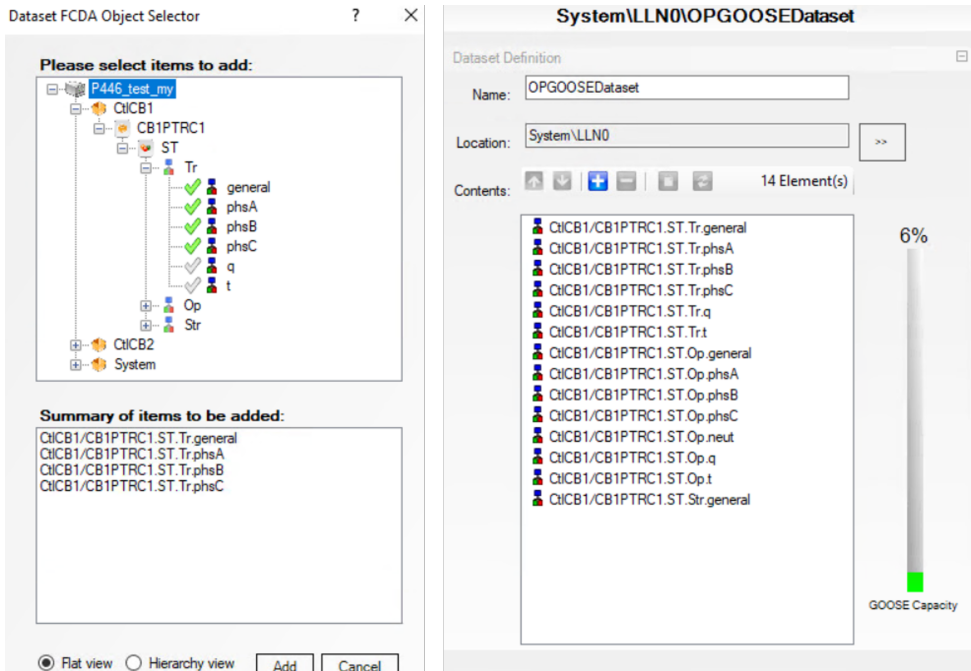


Figure 4.17: OPGOOSE Dataset (For Tripping)

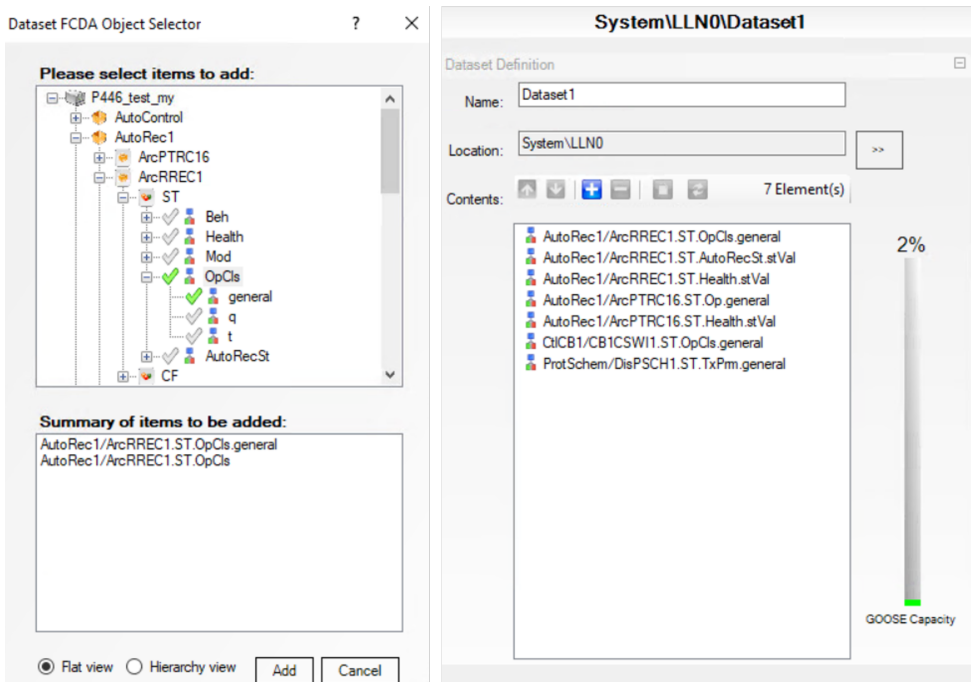


Figure 4.18: Dataset1 (For Autoreclose)

Figure 4.17 displays the OPGOOSE dataset and figure 4.18 is the Dataset1. By defining datasets, signals are packaged in groups and ready to be published from relay to circuit breaker.

4.3.3. GOOSE PUBLISHING

GOOSE publishing and subscribing manage GOOSE schemes among different IEDs. Tripping and reclosing messages should be sent from relay to the CB, which is the GOOSE publishing of relay. Status messages of CB are sent from CB to the relay as the GOOSE subscribing. Figure 4.19 displays the configuration interface.

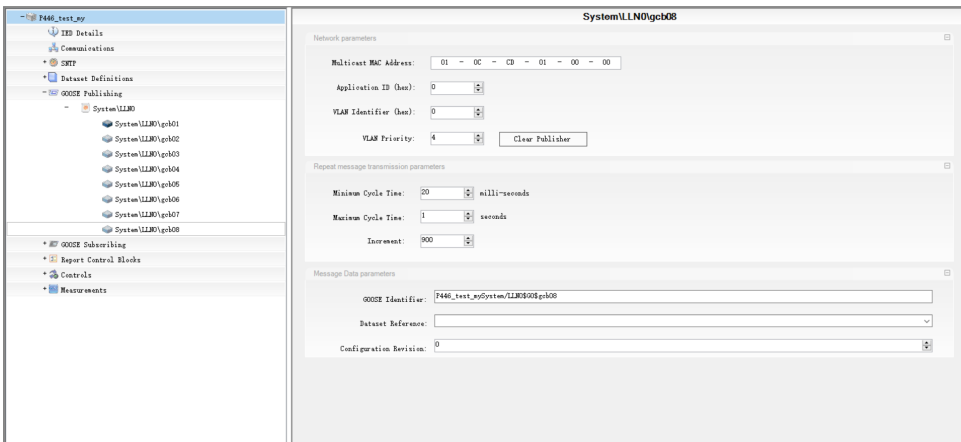


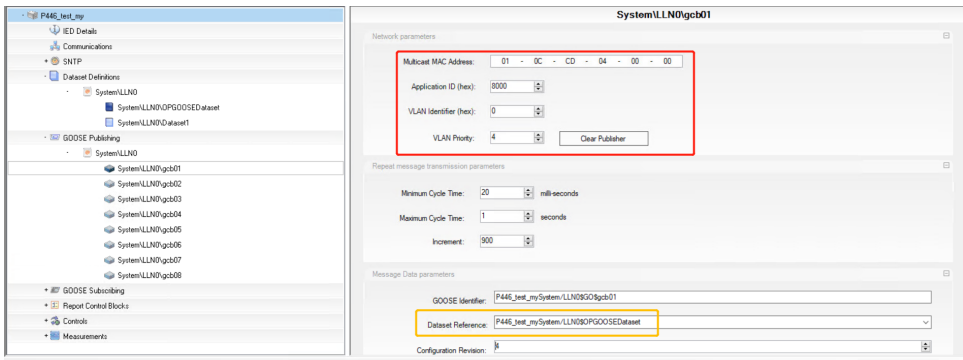
Figure 4.19: GOOSE Publishing Configuration

GOOSE publishing in the relay is configured following these steps:

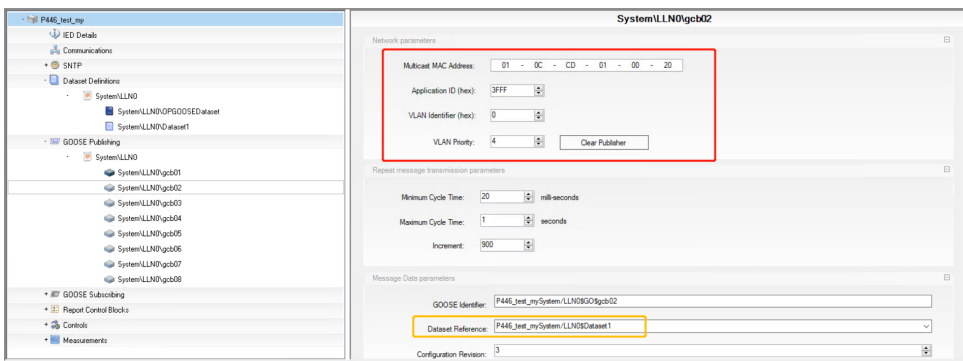
1. Click **GOOSE Publishing** on the left pane to expand the hierarchical structure of IEC 61850.
2. Select a **GOOSE Control Block (Gcb)** and start configuration.
3. Enter Network parameters according to the SCL file in GTNET-GSE section of the connected IED to which the *Gcb* publishes GOOSE messages.
 - **Multicast Mac Address.** This address is configured with the IED to which the relay publishes GOOSE messages. The first four octets (01-0C-CD-01) are defined by IEC 61850 standards and filled by default. The rest octets are taken from the configured SCL file in the connected IED's GTNET_GSE module.
 - **Application ID.** The AppID has a setting range of 0000 to 3FFF using hexadecimal notation. AppID is also found from the SCL file in GSE section.
 - **VLAN Identifier.** VLAN (Virtual LAN) is specified as a hexadecimal number with a range from 0000 to 4095 [12]. VLAN is known from the SCL file of the connected IED's GSE section. The default number is 0 if no VLAN is used.

- **VLAN Priority.** The setting range of VLAN priority is from 0 to 7, indicating the priority level of specific GOOSE messages published on VLAN. If no VLAN is used, the default value is 4.
4. Check Repeat message transmission parameters. These parameters are configured from SCL file of the connected IED's GSE module in RTDS.
 - **Minimum Cycle Time.** Due to the publish-subscribe characteristic of GOOSE service, the sending end keeps publishing GOOSE messages at a fixed rate without confirming that the message has been received. The Minimum Cycle Time ranged from 1 to 50 milliseconds represents the time interval between the first change-driven message being transmitted and its first repeat transmission.
 - **Maximum Cycle Time.** This parameter setting ranges from 1 to 60 seconds. It represents the time of a quiescent "no change" state between repeat message transmissions.
 - **Increment.** This parameter determines the rate at which the repeat message transmission intervals step up from the Minimum Cycle Time to the Maximum Cycle Time. The higher the number, the fewer the repeat messages, and therefore the less time it takes to reach the Maximum Cycle Time. This setting is not taken from SCL file. It is specific in MCL with a setting range of 0 to 999 and has no units.
 5. Match GOOSE data messages.
 - **GOOSE Identifier.** It configures the 64 character GOOSE Identifier (GoID) of the published GOOSE message that is configured in SCL file. The initial character must be alphabetic (a to z or A to Z), while the rest of the name can be either alphanumeric or the underscore symbol. The GOOSE Identifier must be unique for the entire system. This setting is taken from the LN0/GSE Control section of the configured SCL file.
 - **Dataset Reference.** It assigns which dataset to be included in the publishing of this GOOSE control block. Only the dataset that defined in the same logical node with the Gcb will be displayed at the interface. If the dataset definition does not exist or is too large to be published in a GOOSE message, a warning appears.
 - **Configuration Revision.** It displays the configuration revision of the published GOOSE message. Suppose the dataset reference or dataset contents are changed. In that case, the Configuration Revision must be incremented to allow other peers to listen to the published GOOSE messages and identify the configuration change. This setting has a range of 0 to 4294967295.

Figure 4.20 shows the configuration of this distance protection case. *Gcb01* refers to the OPGOOSE dataset for tripping and *Gcb02* refers to the Dataset1 for autoreclosure.



(a) Publish OPGOOSE dataset



(b) Publish Dataset1

Figure 4.20: GOOSE Publishing of the relay

4

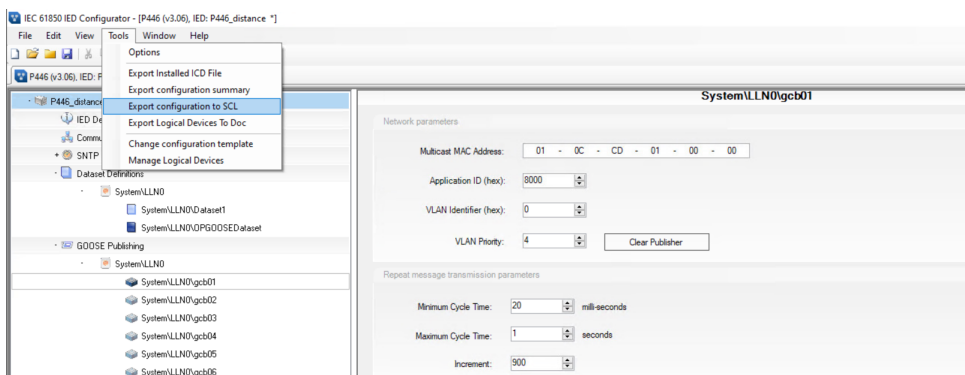
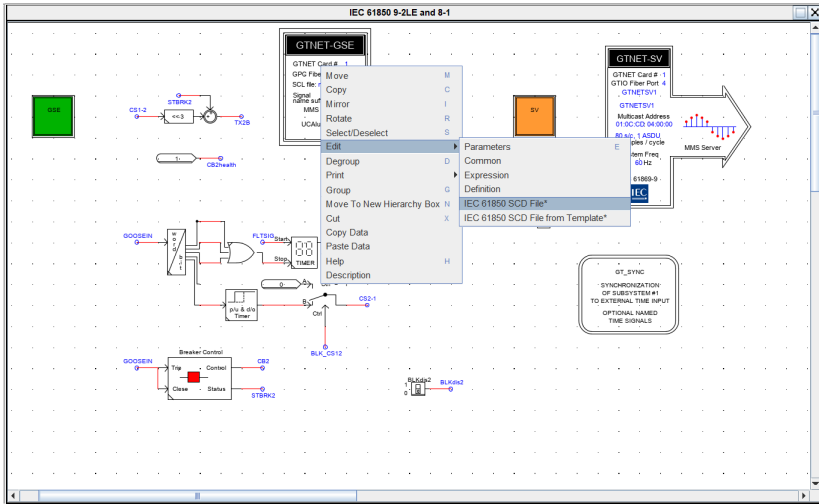


Figure 4.21: Export as SCL file

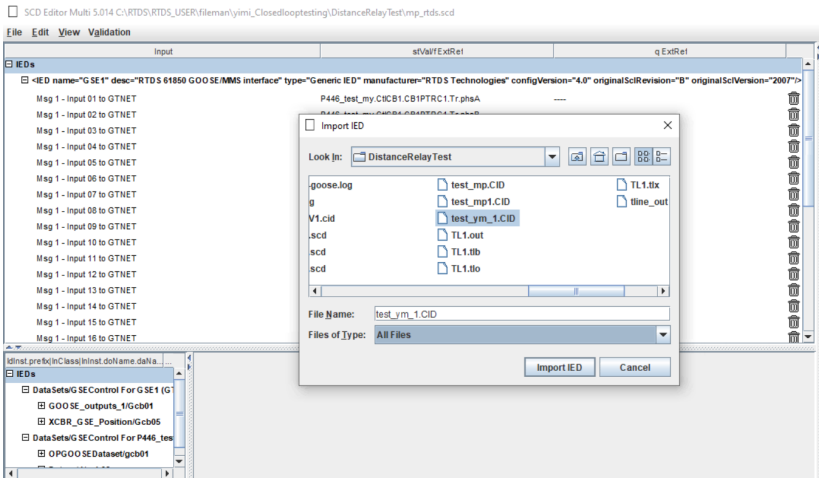
After finishing the configuration in *MiCOM SI Agile*, as figure 4.21 shows, open *tools* on

the top menu and choose "Export configuration to SCL file", which will be the GOOSE inputs of CB in RTDS.

The GOOSE publishing of relay is the message received by the virtual CB in RTDS. Therefore, signal mappings are carried out in RTDS to establish effective communication. The configuring procedures in RTDS are provided as follows.



(a) Open SCD file in RTDS



(b) Import CID file from relay configuration

Figure 4.22: SCD Editor in RTDS

Firstly, right click the GTNET_GSE block, choose "IEC 61850 SCD file" and import the SCL file created in relay's IED configurator to the RTDS model as shown in figure 4.22.

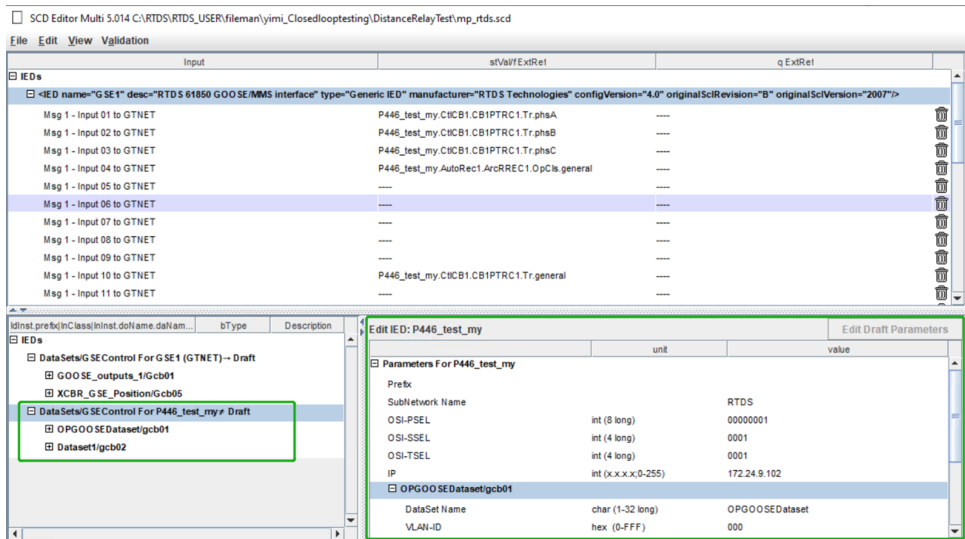


Figure 4.23: The interface of SCD Editor

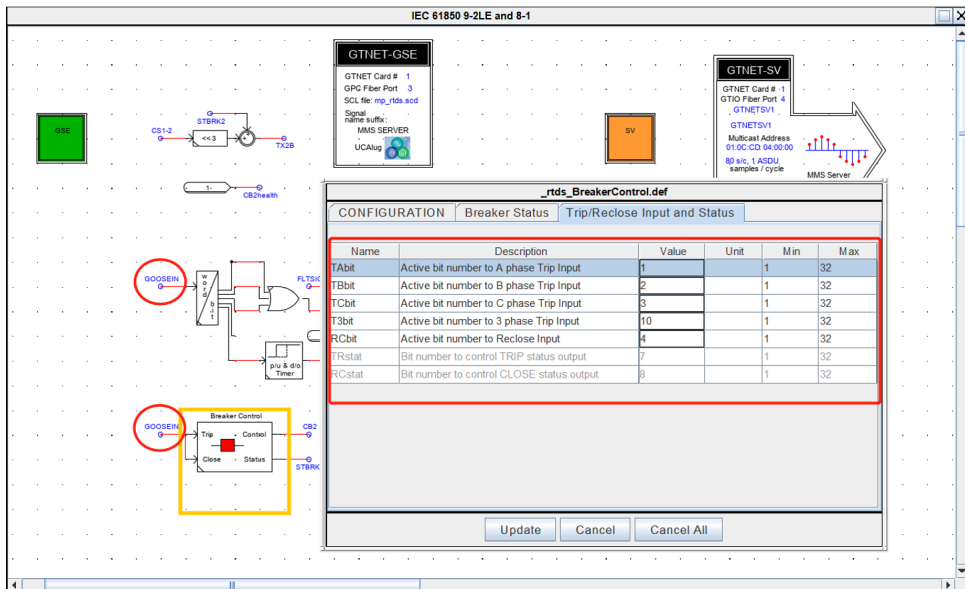


Figure 4.24: Breaker Control Block

After importing the SCL file, Datasets/GSE control from the external IED P446 relay are

displayed in the IED list as figure 4.23 shows. Next, drag and drop the corresponding GOOSE signals from relay to the "Msg inputs to GTNET". There are up to 32 inputs to the GTNET in RTDS. In this case, all GOOSE inputs of the GTNET are gathered as a combined signal **GOOSEIN**. Using word to bit converter, an integer word is converted to multiple logical signals. Thus it can be seen which GOOSE input signal belongs to which position. Referring to the Breaker Control Block in figure 4.24, the trip and reclose inputs of CB are coded with unique values from 1 to 32. This input value of "Msg to GTNET" in RTDS should match the GOOSE publishing signal from the external relay as shown in table 4.2. Drag the corresponding signal listed in IEDs from relay's GOOSE publishing to the Msg inputs of CB.

Table 4.2: GOOSE message inputs of CB and GOOSE publishing of Relay

CB Inputs value	Description	GOOSE publishing of Relay	Datasets
1	phA trip	P446_test_my.CdCB1.PTRC1.Tr.phsA	OPGOOSE
2	phB trip	P446_test_my.CdCB1.PTRC1.Tr.phsB	OPGOOSE
3	phC trip	P446_test_my.CdCB1.PTRC1.Tr.phsC	OPGOOSE
4	Reclose	P446_test_my.AutoRec1.ArcRREC1.OpCls.general	Dataset1
10	3-phase trip	P446_test_my.CdCB1.PTRC1.Tr.general	OPGOOSE

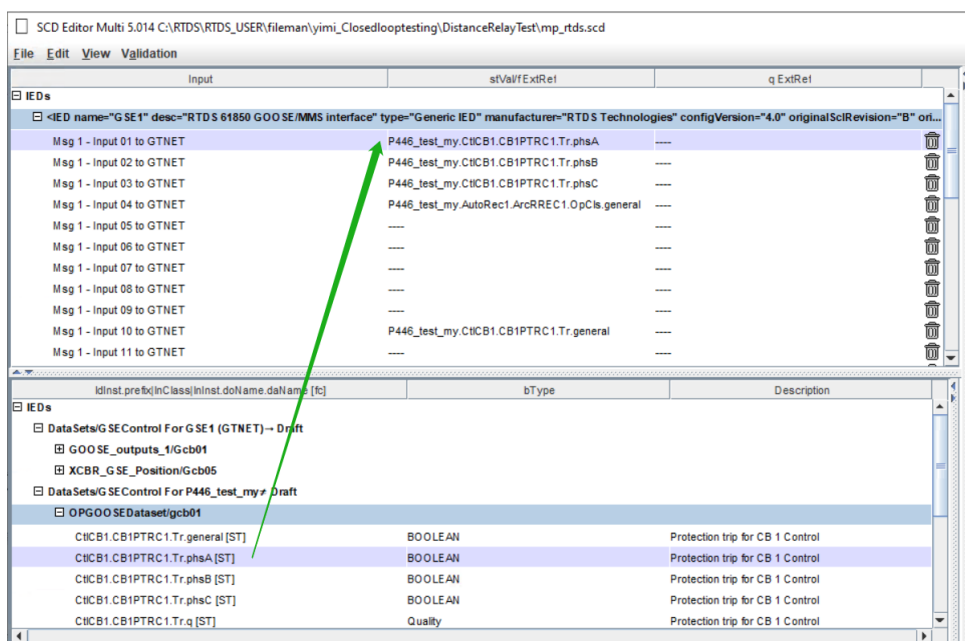


Figure 4.25: Add the GOOSE messages from relay to the corresponding CB control inputs

After configuring Msg inputs, save and compile the SCD file in RTDS. By now, GOOSE Publishing of the relay is configured with the circuit breaker under IEC 61850 protocols.

The first two GOOSE control blocks are in bold, indicating they are fully configured; otherwise, the Gcb block will be displayed as grey or regular typeface.

4.3.4. GOOSE SUBSCRIBING

GOOSE publishing configures the GOOSE control blocks and associated messages to be published to other IEDs. GOOSE subscribing displays the configuration of the relay's virtual inputs that are subscribed to posted GOOSE messages from other IEDs. The configuration interface is seen in figure 4.26.

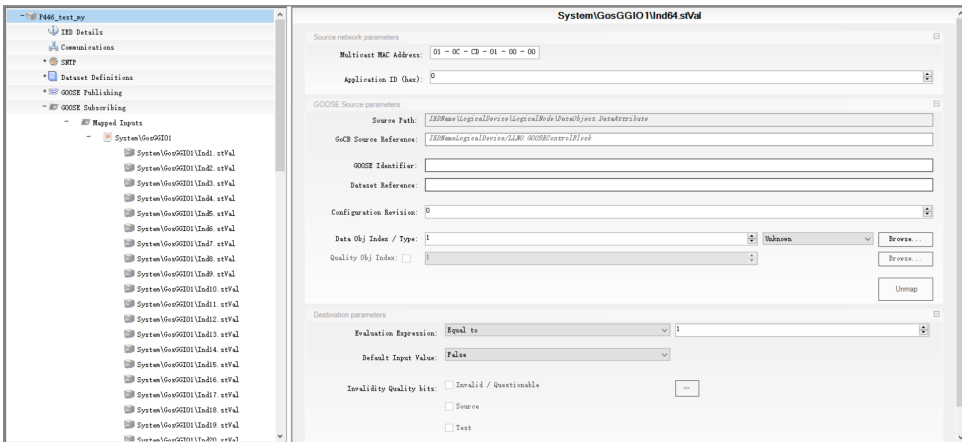


Figure 4.26: GOOSE Subscribing Configuration

GOOSE subscribing of the relay is performed as follows:

1. Click **GOOSE Subscribing**. Expand the list of **Mapped inputs**. A mapped input is the binding of two IEDs that an external value is assigned to an internal data attribute in the IED data model. On the MiCOM P446 device, a mapped input is an external signal that has been assigned to a Virtual Input in relay's Programmable Scheme Logic (see section 4.4).
2. Open the GOOSE Generic Input and Output (GGIO) logical node and configure the parameters of each input.
3. Configure source network parameters.
 - **Multicast Mac Address.** This address is in accordance with the GOOSE control block of external IEDs to which the relay is subscribed GOOSE messages. The first four octets are fixed values (01-0C-CD-01) as IEC 61850 defines. The last two octets are taken from the ConnectedAP/GSE section of the configured SCL file from the external IED.

- **Application ID.** The application ID ranges from 0000 to 3FFF in hexadecimal and is set according to the ConnectedAP/GSE section of the external IED's SCL file.

4. Configure GOOSE source parameters.

- **Source Path.** It shows where the incoming GOOSE message is taken from the external IED. It is defined in a hierarchical structure with the format of "IED Name\Logical Device\Logical Node\Data Object.Data Attribute". (For example: P446\System\GosGGIO1\Ind1.stVal.)
- **GoCB Source Reference.** This value is derived from the Inputs/ExtRef section of the selected virtual input in the configured SCL file. The general format of this reference is "IEDNameLogical Device/Logical Node.GOOSE Control block. (For example: P446XCBB/LLN0.Gcb02)
- **GOOSE Identifier.** It configures the 64 character GOOSE Identifier (GoID) of the published GOOSE message from external IEDs. This setting is taken from the LN0/GSE control section of configured SCL file.
- **Dataset Reference.** It decides which dataset of the external IED is going to be included in the published messages of GOOSE control block. Only datasets that belong to the same logical node as the GoCB can be selected in GOOSE messages.
- **Configuration Revision.** It shows the revision of GOOSE messages to which the relay is subscribed.
- **Data Obj Index / Type.** Data object index is going to be processed and assigned to relay's virtual input. It is defined inside the published GOOSE message of the configured SCL file from external IEDs. Data object type defines the specific data type of published GOOSE signals.

In practical, click the **Browse** button next to the *Data Obj Index / Type* and select the target GOOSE signal from external IEDs. Parameters above will be automatically filled using the configured SCL file.

For the testing case of P446 relay with CB in RTDS, the virtual inputs of relay are subscribed to the output signals of GTNET_GSE module. The signal name, index and data type are specified as figure 4.27 shows.

_rtds_GTNET_GSE_v6.def					
GOOSE Output Quality, Test, NdsComm Bitmap Enables			GOOSE Input Quality, Test, NdsComm Bitmap Enables		
RX/TX 1 Output Signal Names/Types			TX 5 Output Signal Names/Types		
RX/TX 1 Output Retransmit Curve			TX 5 Output Retransmit Curve		
CONFIGURATION	GOOSE Configuration	MMS Configuration	Output Deadband Parameters		
Name	Description	Value	Unit	Min	Max
IED1O1T	Output 1 Type	BOOL		0	12
nIED1O1	Output 1 Signal Name	CB2pos3ph		0	0
IED1O1B	Output 1 Boolean bitmap bit num (32..1)	1		1	32
IED1O2T	Output 2 Type	BOOL		0	12
nIED1O2	Output 2 Signal Name	CB2health		0	0
IED1O2B	Output 2 Boolean bitmap bit num (32..1)	1		1	32
IED1O3T	Output 3 Type	BOOL		0	12
nIED1O3	Output 3 Signal Name	TX2B		0	0
IED1O3B	Output 3 Boolean bitmap bit num (32..1)	1		1	32
IED1O4T	Output 4 Type	BOOL		0	12
nIED1O4	Output 4 Signal Name	TX2B		0	0
IED1O4B	Output 4 Boolean bitmap bit num (32..1)	2		1	32
IED1O5T	Output 5 Type	BOOL		0	12
nIED1O5	Output 5 Signal Name	TX2B		0	0
IED1O5B	Output 5 Boolean bitmap bit num (32..1)	3		1	32
IED1O6T	Output 6 Type	BOOL		0	12
nIED1O6	Output 6 Signal Name	TX2B		0	0
IED1O6B	Output 6 Boolean bitmap bit num (32..1)	4		1	32
IED1O7T	Output 7 Type	BOOL		0	12
nIED1O7	Output 7 Signal Name	BLKdis2		0	0
IED1O7B	Output 7 Boolean bitmap bit num (32..1)	1		1	32
IED1O8T	Output 8 Type	disabled		0	12
nIED1O8	Output 8 Signal Name	TX2B		0	0

4

Figure 4.27: Output signals of GSE

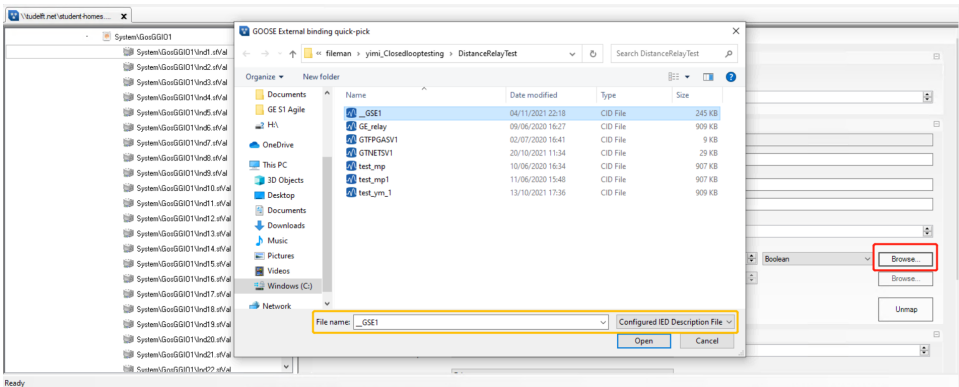


Figure 4.28: Select Configured IED Description (CID) file "_GSE1"

Click the **Browse** button and select the compiled CID file "_GSE1" of RTDS model (figure 4.28). Pick an external GOOSE binding with the virtual input of relay by showing all GOOSE Control Blocks (figure 4.29). After selecting the corresponding GOOSE message, the rest parameters are automatically configured as the example shown in figure

4.30. There are seven output signals of the logical device GSE. Thus seven inputs in the GOOSE Subscribing are fully configured and shown in bold.

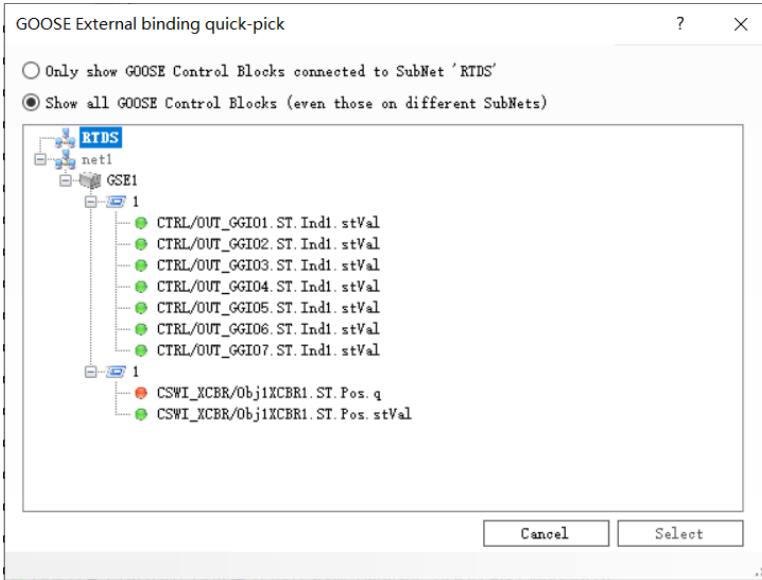


Figure 4.29: GOOSE External binding selection

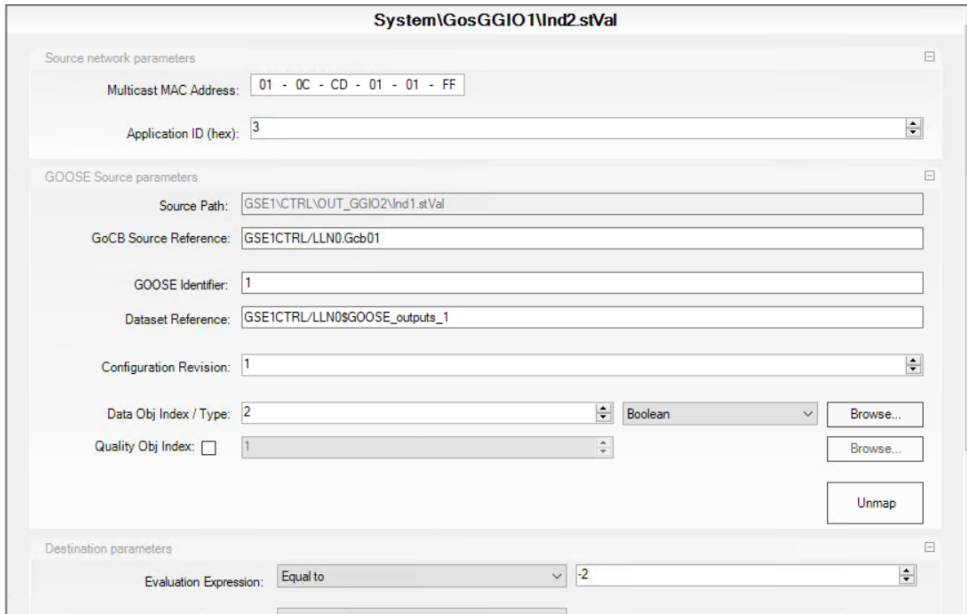
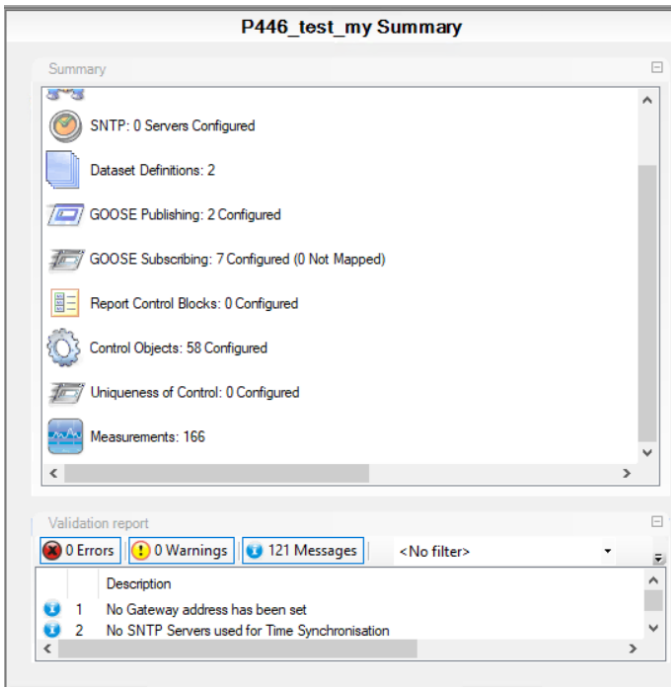
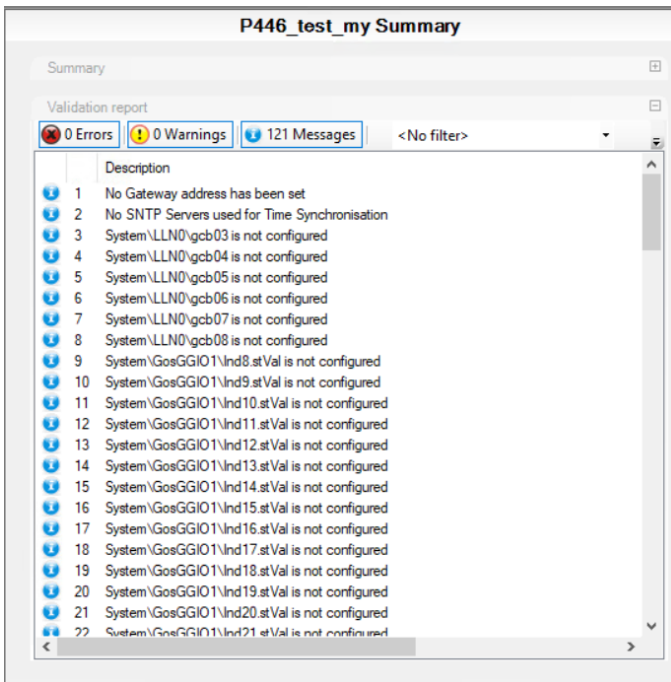


Figure 4.30: A fully configured input of relay in GOOSE Subscribing



(a) MCL Summary



(b) Validation report

Figure 4.31: Validate the configuration

By now, everything is fully configured in MCL 61850. Click "Validate Configuration" on the top pane to have an overview of the configuration. MiCOM S1 Agile provides a summary as figure 4.31 shows. Check if there are errors or warnings and fix the problem under the guidance of validation report.

4.4. PROGRAMMABLE SCHEME LOGIC

Programmable Scheme Logic (PSL) provides the possibility to edit the internal logic of distance relay. The user can introduce virtual inputs and outputs, change the existing connection of related signals and apply new attributes to some of the signal. The PSL editor makes the configuration of relay's digital inputs and outputs very flexible and adaptable to communicate with other IEDs. The scheme logic of relay can be split into two parts: the Fixed Scheme Logic (FSL) and the Programmable Scheme Logic (PSL). The FSL is built in the relay using hard coding. It is fixed and cannot be changed, while the PSL allows users to develop customized scheme to fit specific applications using the programmable logic gates and timers in the IED.

Right click the PSL folder and create a new file. The configuration interface of PSL is displayed in figure 4.32 as well as the default scheme. On the top pane, there are several signal types labelled with different colors, including Optically isolated digital inputs (Opto inputs), internal inputs and outputs, GOOSE inputs and outputs, integral tripping inputs and outputs, control inputs, LED signal, etc. The PSL editor also provides logic gates and timers. The scheme logic of relay is embedded with a concept called Digital Data Bus (DDB). All the digital inputs, outputs and internal signals are included in DDBs and every signal is coded with a unique DDB number.

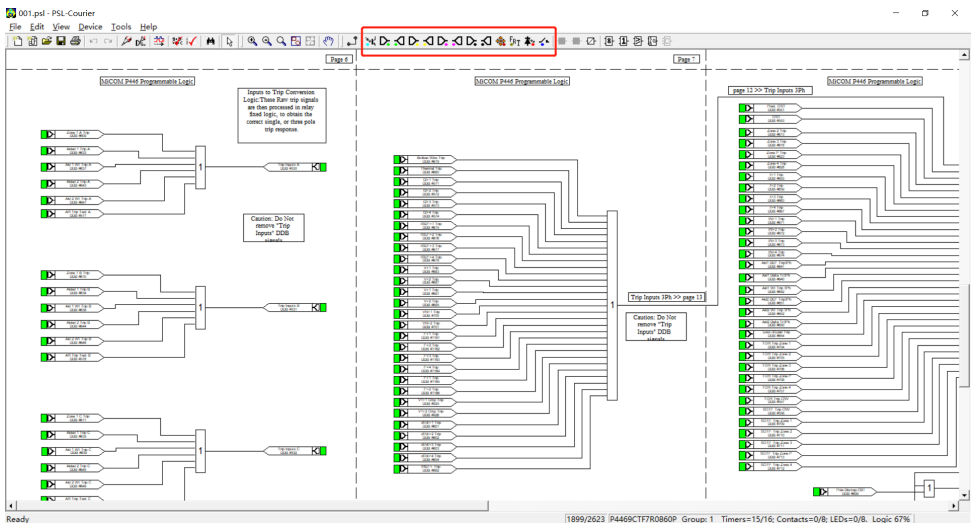


Figure 4.32: Configuration interface of PSL editor

The testing case is configured upon the IEC 61850 system where the communication between the programmable relay and virtual circuit breaker relies on the GOOSE service. Therefore, the GOOSE input and output DDBs are programmed in the PSL. For GOOSE inputs, choose the yellow input icon on the top pane. The PSL provides 64 virtual inputs.

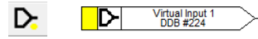


Figure 4.33: Goose input icon

Table 4.3: Mappings of virtual inputs in PSL

Virtual Inputs	GSE Output Signals	Relay's Output Signals
1	CB2pos3ph	CB1Aux 3PH(52-A)
2	CB2health	CB1 Healthy
3	TX2B	CB1Aux A(52-A)
4	TX2B	CB1Aux B(52-A)
5	TX2B	CB1Aux C(52-A)

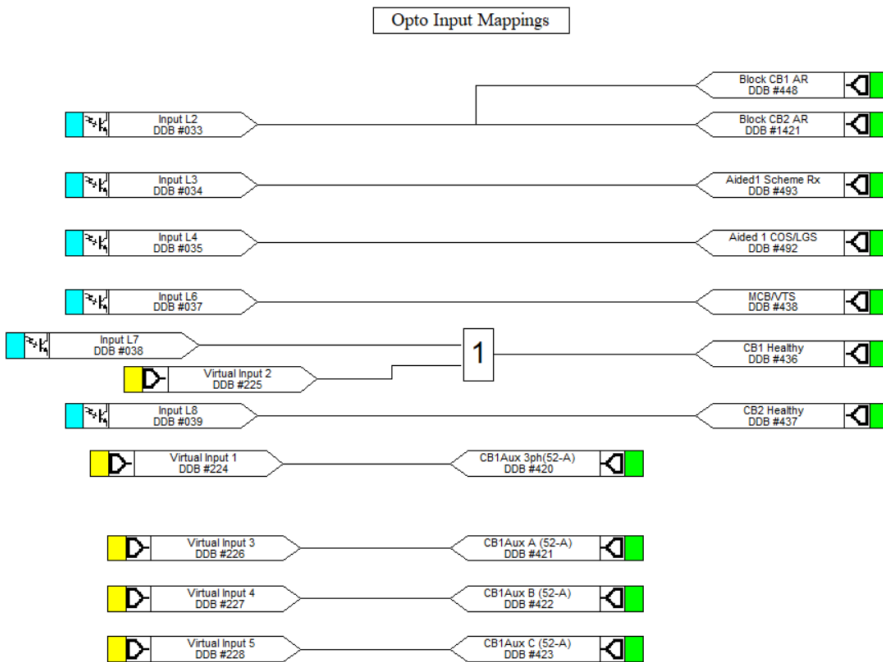


Figure 4.34: Configured PSL

Regarding the distance protection case, Virtual Input 1 equals the first subscription to GSE outputs. The first output signal in GSE section is "CB2pos3ph" (which reflects the

three phase positions of CB2). Then this virtual input should be connected to an output signal which is the "CB1Aux 3PH(52-A)" according to the settings in section 4.2. The auxiliary contact of relay is set to "52A". By connecting this virtual input to the output signal, the relay can receive GOOSE messages from RTDS and output corresponding signals. Repeat the procedures for all virtual inputs listed in table 4.3. Virtual Input 2 subscribes to the "CB2health" signal which needs to be connected to the "CB healthy" DDB in PSL. In the default scheme logic of relay, "CB healthy" is linked with Opto input 7 through hardware connections. To introduce an external signal as the input of "CB healthy", an "OR" logic gate is added to enable the GOOSE communication. Virtual Input 3-5 are subscribed to a combined signal "TX2B". "TX2B" have four binary bits. The Most Significant Bit is a carrier signal sent from the opposite terminal for Aided Directional Earth Fault (Aided DEF), and the three lower bits are assigned to reflect the status of phase A, B, C of CB2. Thus the Virtual Input 3-5 are connected to output signals of the single phase (phA, phB, phC) position separately. Figure 4.34 shows the fully configured virtual inputs in the PSL.

As explained in section 4.3, the virtual input in PSL of relay is the output signal of GSE section in RTDS. These output GOOSE messages from RTDS_GSE module are the GOOSE subscription of relay, and the GOOSE publishing of relay are mapped with inputs of CB control block of GSE section in RTDS. The mappings of bidirectional GOOSE message transmission are realized by configuring *MCL 61850*. But the internal logic are processed and achieved in PSL. Without linking the GOOSE inputs and outputs in PSL, the message cannot be correctly processed and the relay cannot obtain effective results, leading to maloperation and system failures.

4.5. CONNECTION AND MEASUREMENT

The configuration of distance relay P446 is accomplished in *MiCOM S1 Agile* and ready to control the virtual circuit breaker in RTDS based on IEC 61850 communication protocols. Before performing the testing, the last procedure is to connect the configured relay to the RTDS model.

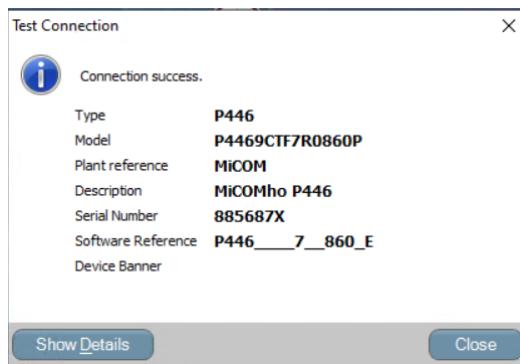


Figure 4.35: Connection Success

Firstly, check the connection between *MiCOM S1 Agile* and the physical device P446 relay. Right click "Connection" and choose "Test Connection". Successful connection notification is shown as figure 4.35. If the connection fails, follow the instruction in figure 4.36 to add a new corresponding connection through the correct port which is COM10 for this case.

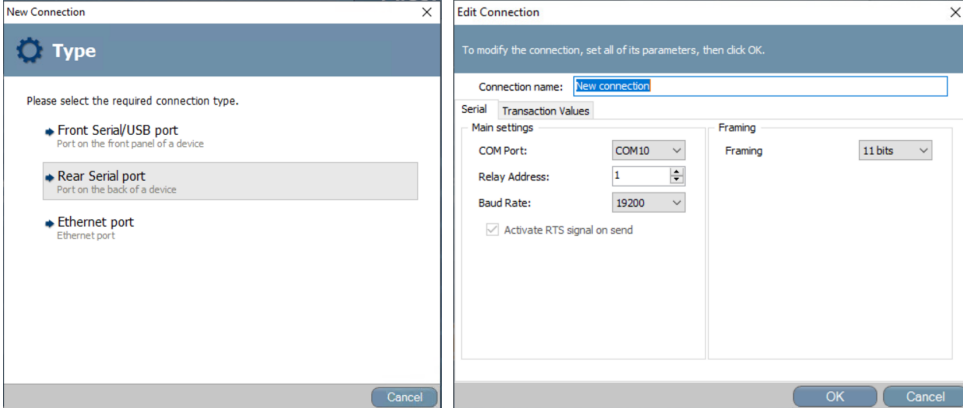


Figure 4.36: Create a new connection

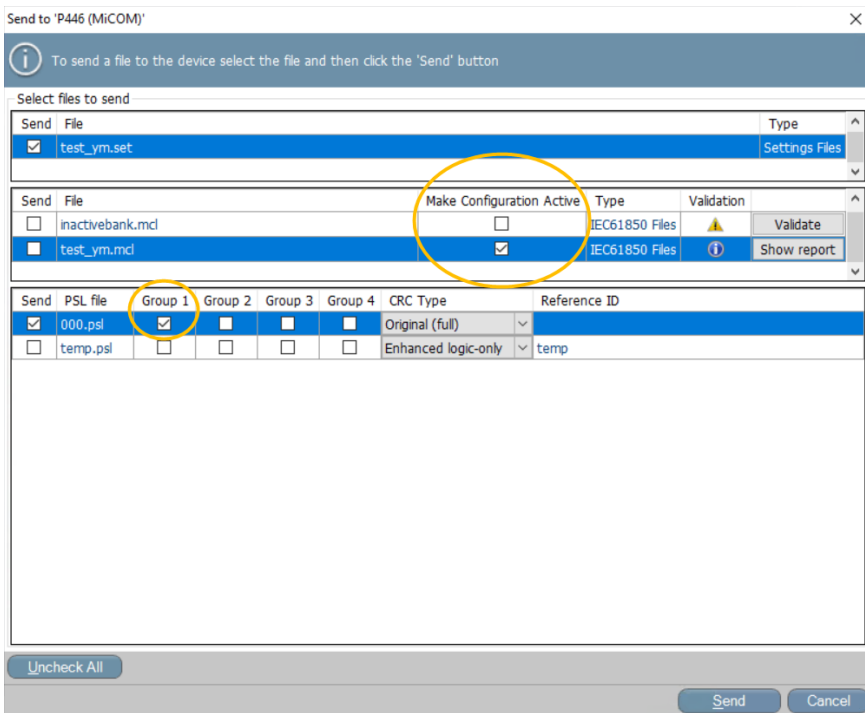
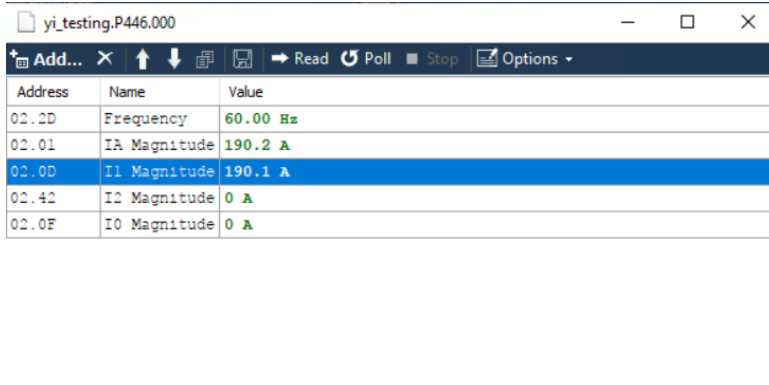


Figure 4.37: Send configured files to the physical device

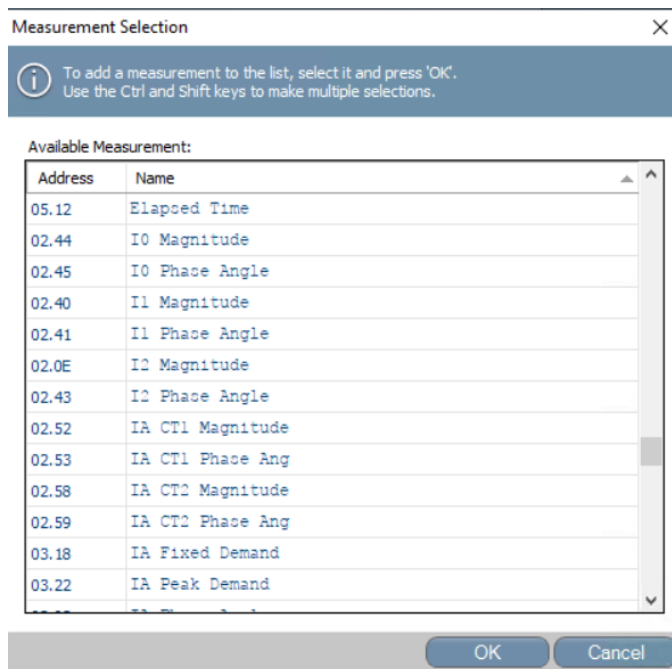
Secondly, right click the "Device" folder and choose "Send". By this step, the user can select which configured file to be activated and sent to the physical IED P446. As figure 4.37 shows, select the setting file, IEC61850 file and PSL file, then send them to the P446. It is noticed that the IEC61850/MCL file needs to be validated firstly. The Group 1 and full logic are chosen for the PSL file.



The screenshot shows a window titled "yi_testing.P446.000" with a toolbar containing "Add...", "Read", "Poll", "Stop", and "Options". Below the toolbar is a table with three columns: Address, Name, and Value.

Address	Name	Value
02.2D	Frequency	60.00 Hz
02.01	IA Magnitude	190.2 A
02.0D	I1 Magnitude	190.1 A
02.42	I2 Magnitude	0 A
02.0F	I0 Magnitude	0 A

(a) Measurement Interface



(b) Add items to be measured

Figure 4.38: Measurement Selection

Finally, *mea* file can be created to verify if the relay is measuring real-time values from RTDS. Right click the "Measurement" folder, and create a new file. The interface of *mea* file is as follows. Add the item that relay shall measure from the RTDS model as shown in figure 4.38. Then run the simulation in RTDS, it is seen that the relay can read the values of power network components, indicating a reliable communication link has been successfully built between the two IEDs through IEC 61850 configuration.

To sum up, the distance relay configuration is accomplished with the above procedures. The device is set up for closed-loop testing of a circuit breaker using IEC 61850 protocols. Therefore, not only the general distance protection elements are required in relay configuration, but the information exchange should be configured properly between the two IEDs. *MiCOM S1 Agile* provides the user-friendly configuration interface and supports the GOOSE, SV and MMS communication. Following these procedures, the testing in RTDS can be carried out successfully.

5

EXPERIMENTAL VALIDATION

This chapter intends to verify if the distance protection can correctly operate using the relay programmed in Chapter 4. The relay is already fully configured in MiCOM S1 Agile. The communication between the relay and the circuit breaker is established through IEC 61850 protocols. Closed-loop testing of the circuit breaker on the transmission line of power network model in RTDS is performed by applying various fault types and then analysing the circuit breaker operations. Firstly, the setup of power network model is provided. Next, testing procedures and analysing method are explained. Finally, two cases are elaborated to show the configuration is sufficient to conduct closed-loop testing in RTDS.

5.1. MODEL DESCRIPTION

In RTDS, a 500kV parallel line network is built. Four circuit breakers are located at the two terminals of each transmission line. CB1, CB3 and CB4 are already fully configured with distance relays in RTDS, while the control of CB2 relies on the communication with external relay P446. The RTDS model is represented by the single line diagram shown in figure 5.1.

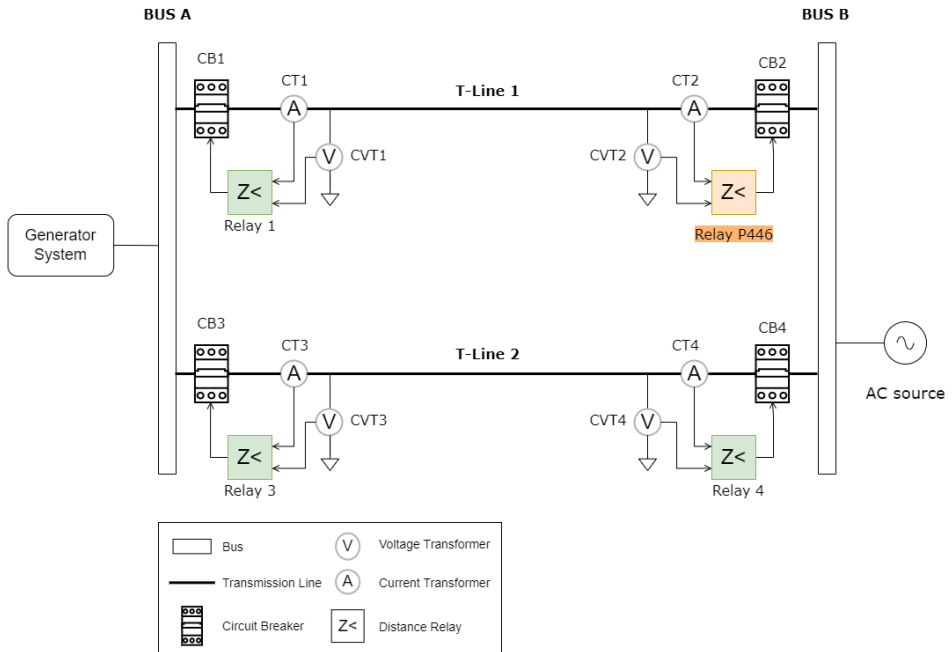


Figure 5.1: Single line diagram of modeled power system

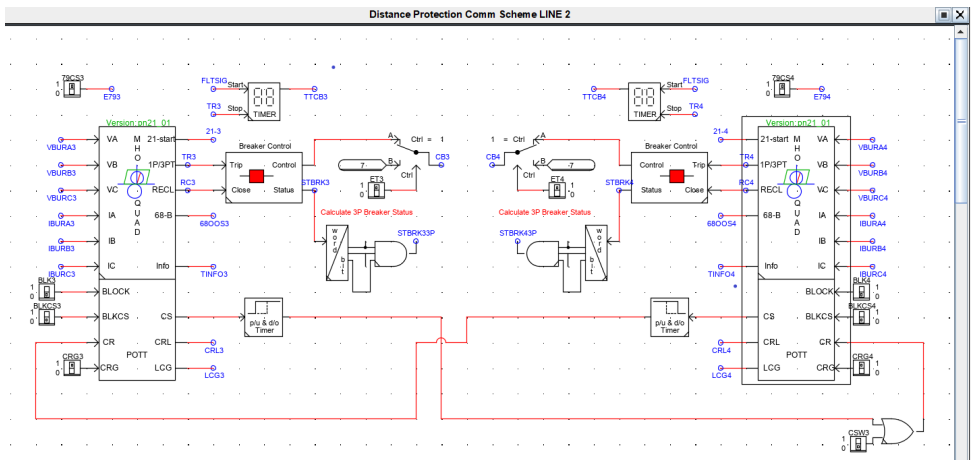


Figure 5.2: Distance protection scheme of TLine 2

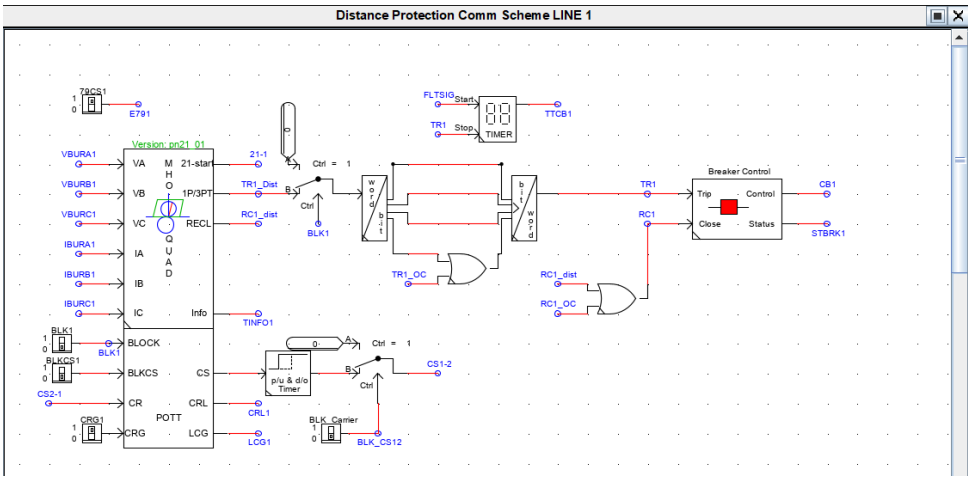


Figure 5.3: Distance protection scheme of TLine 1

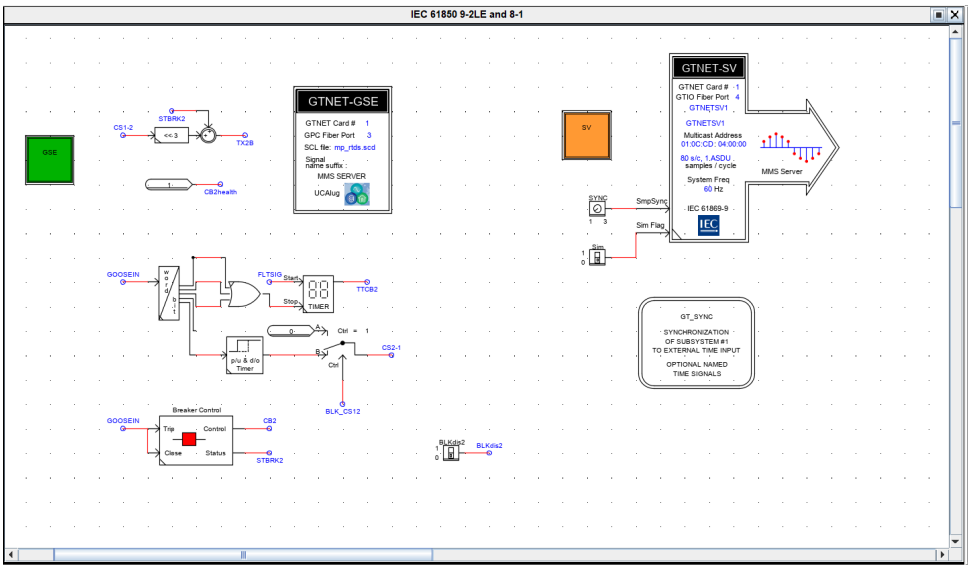


Figure 5.4: GTNET modules for distance protection with CB2

Open the "Distance Protection Comm Scheme" of TLine 1 and TLine 2 in the draft file of RTDS. The distance protection scheme of TL2 is shown in figure 5.2 as a reference. It can be seen that the internal logic is completely built in RTDS. Measured currents and voltages from CTs and VTs are processed by Multi-Function Distance Relay and the relay outputs trip/re-close signals to the CB control block. The inputs and outputs of relay and CB are completely configured within the RTDS model. While for the protection scheme of TL1 in figure 5.3, only CB1 is connected with distance relay. CB2 is not configured in

RTDS but relies on the IEC 61850 communication through the GTNET module shown in figure 5.4. Looking into the GTNET module, GSE section and SV section are activated to communicate with the external relay P446 configured in chapter 4.

5.2. TESTING PROCEDURES

The closed-loop testing of CB2 in RTDS through IEC 61850 communication with the external distance relay P446 is performed in the following steps.

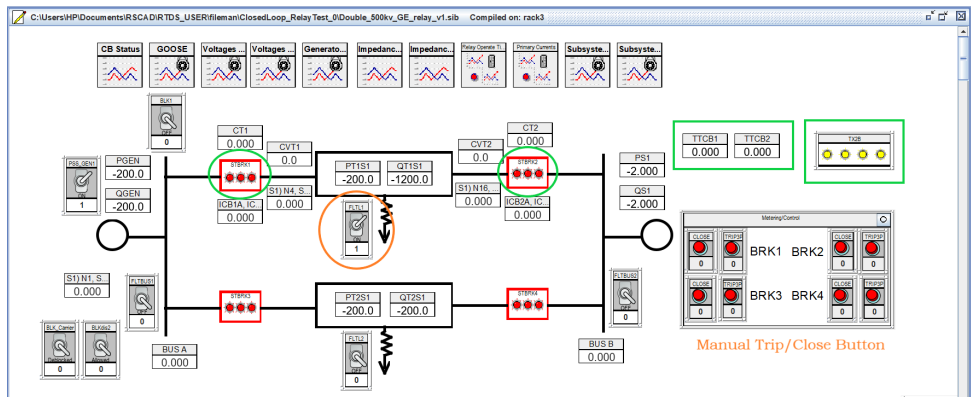


Figure 5.5: Simulation Interface

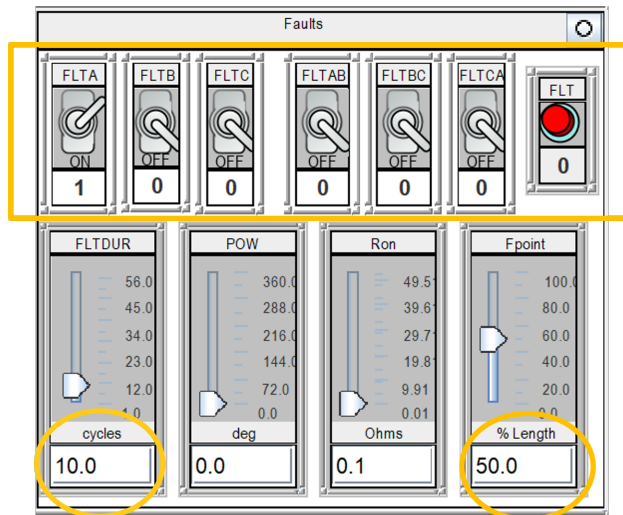


Figure 5.6: Fault type selection

1. Open the .sib file of RTDS model as shown in figure 5.5.
2. Add plots and meters to be displayed on the canvas.

3. Set *fault duration* in cycles and *fault point* in percentage of the protected line (TL1) before run the simulation as figure 5.6 indicates.
4. Start the simulation. This model is compiled on Rack 3.
5. Switch the control signal *FLTL1* from 0 to 1 to apply faults only on the tested line, and switch off the fault on TL2 (*FLTL2*), Busbar A (*FLTBUS1*) and Busbar B (*FLT-BUS2*) as figure 5.5 depicts.
6. Apply phase-to-ground fault (phA, phB, phC) and phase-to-phase fault (phAB, phBC, phCA) by pressing the red fault button as shown in figure 5.6.
7. Observe and analyze the testing results.
8. Stop the simulation. Adjust the fault point in 5% step size from 0% to 100% on the protected TL1. Repeat the fault application steps to see if the whole length of TL1 can be protected.

5.3. RESULTS AND ANALYSIS

For simple observation, operations of the four circuit breakers can be easily seen with the indicator light. During normal operation, circuit breakers are closed, the indicator light are in red color. When a fault is initiated, the CB should open the corresponding phase, the indicator light changes to green. For further analysis, the following messages marked in figure 5.5 are measured and plotted:

- Tripping time of CB1 and CB2 (TTCB1 and TTCB2). TTCB measures the time interval from a fault signal is detected to a trip signal is sent out by the relay.
- Status of CB1 and CB2 (STBRK1 and STBRK2). This integer signal reflects the three phase positions of CB. Each bit represents a single phase A, B or C.
- GOOSEIN. This combined signal shows if the model in RTDS is receiving GOOSE messages from the external relay. The lowest three bits (#0, #1, #2) represents the tripping commands of phase A, B, C sent from P446 relay. The fourth bit (#3) is for reclosing signal.
- TX2B. This is a combined signal displaying the three phase positions of CB2 using the lowest three bits (#0, #1, #2).

During normal operation, three phases of CB1 and CB2 are closed. Three phase currents and voltages are sent to the relay through GTNET_SV module, and the impedance seen by the relay is larger than the reach of protection zones. No tripping or reclosing commands are published by relay, thus no GOOSEIN message is received by the CB. In the following section, two cases are elaborated to verify the distance protection setup.

5.3.1. CASE 1: SINGLE PHASE FAULT

In this case, a fault is applied on Phase A of TL1 from 0% to 100% in a 5% step size. The testing results are listed as follows.

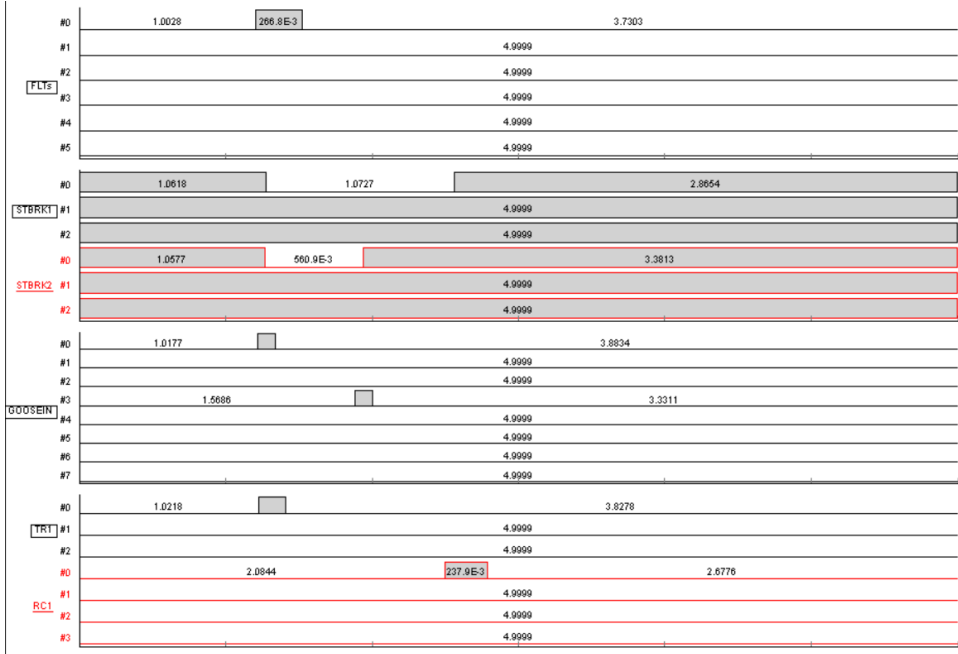
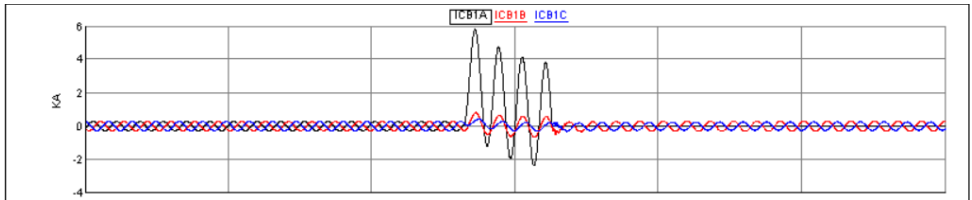
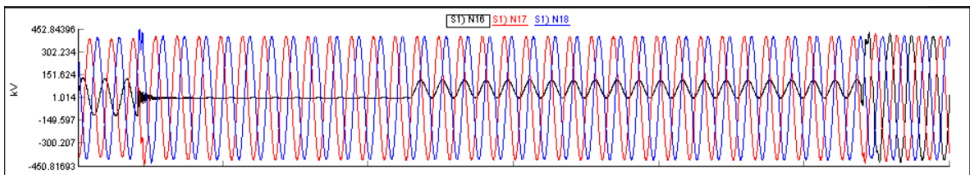


Figure 5.7: Phase A Fault



(a) Measured Currents by CT1



(b) Measured Voltages by CVT2

Figure 5.8: Measured Currents and Voltages during phase A fault

Looking into figure 5.7, *STBRK2* shows that CB2 trips the fault phase A after the fault signal (*FLT3*) is initiated, and then perform the autoreclosure on phase A. The instantaneous fault on phase A is cleared by CB1 and CB2. On the first channel (#0) of *GOOSEIN*, there is a trip message sent from the relay as the input of CB2, after that the autoreclosing message on the fourth channel (#3) is received by CB2. Figure 5.8 displays the currents measured by CT1 and the voltages measured by CVT2. When the fault is applied, the phase A current increases to a much higher value and then decays to normal value; the phase A voltage drops to zero and then recovers, indicating the fault has been cleared and the power network is back to stable operation.

Adjust the fault point on the protected line. The Tripping Time of CB1 and CB2 are listed in table 5.1.

Table 5.1: Testing Results of Phase A Fault on TL1

Fault Point (%length)	CB2 Trip PhA	CB2 Reclose PhA	TTCB1	TTCB2
0	✓	✓	0.0128	0.2172
10	✓	✓	0.0105	0.2163
20	✓	✓	0.0178	0.0170
30	✓	✓	0.0180	0.0151
40	✓	✓	0.0198	0.0151
50	✓	✓	0.0179	0.0154
60	✓	✓	0.0191	0.0165
70	✓	✓	0.0211	0.0147
80	✓	✓	0.0243	0.0154
90	✓	✓	0.2087	0.0153
100	✓	✓	0.2116	0.0163

Table 5.1 documents the testing results in 10% step size for conciseness. Using GOOSE messages, CB2 can trip and reclose for faults that are applied at every location on the protected line. It is noticed that at the initial of the line (0% to 15%), CB2 trips the fault with around 200ms time delay. This delay time conforms to the settings in P446 relay. Similarly, when the fault is applied at the end of the line from 85% to 100%, CB1 trips with a 200ms delay using Zone 2 protection.

Moreover, if we switch off the *FLTL1* and turn on the *FLTL2*, the fault will be applied on the parallel TL2. CB3 and CB4 are responsible for the protection. In this circumstance, no commands from the external relay are received by *GOOSEIN* of CB2, which proves the relay is configured correctly and will not cause a maloperation for external faults.

5.3.2. CASE 2: PHASE-TO-PHASE FAULT

In this case, L-L fault is applied on phase A and B. Similarly, the fault point is adjusted from 0% to 100% to test the whole length. The testing results are evaluated as below.

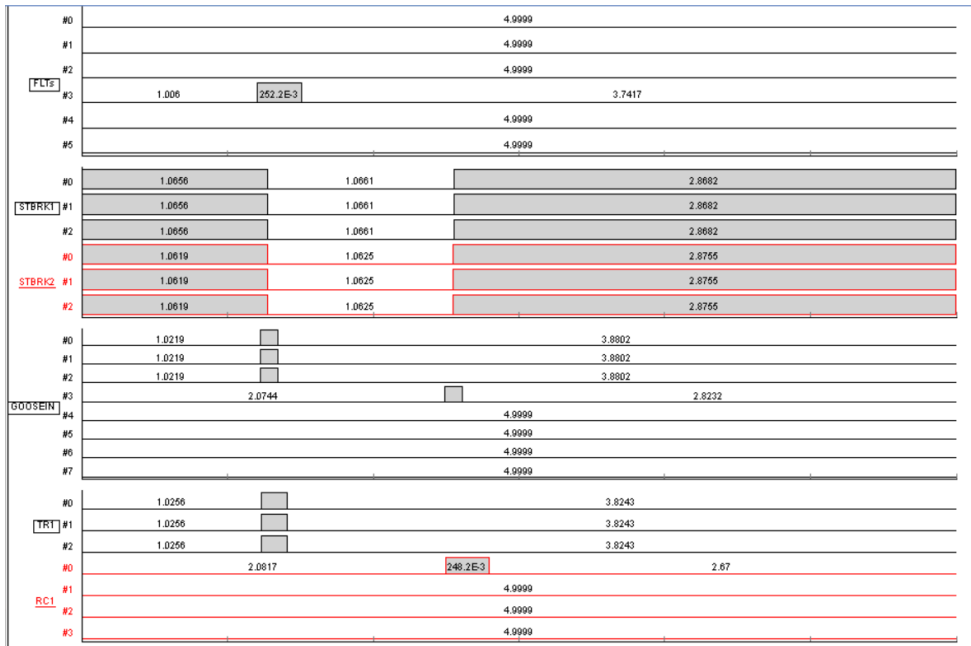


Figure 5.9: Phase AB Fault

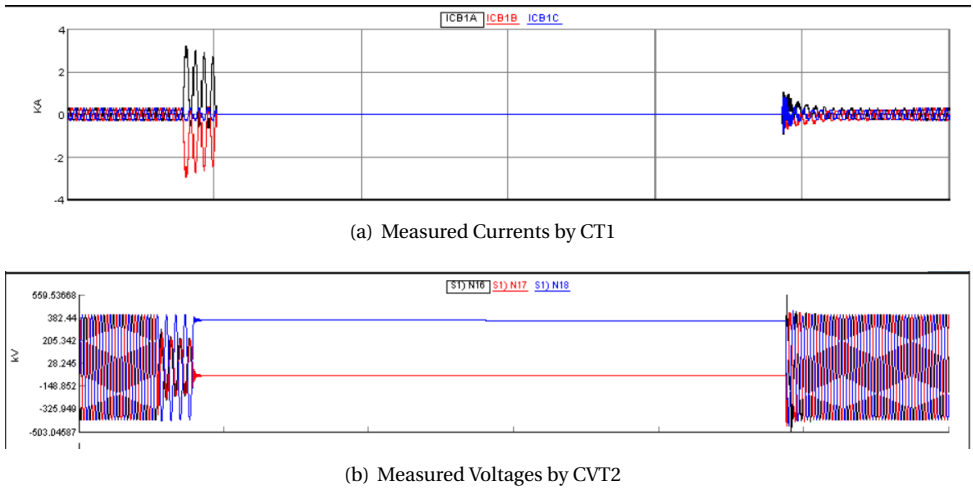


Figure 5.10: Measured Currents and Voltages during phase AB fault

Regarding figure 5.9, the first three channels of *GOOSEIN* have received tripping commands from the relay, and the fourth channel (#3) is the autoreclosing command. All the messages configured in the *GOOSE Publishing* of relay are subscribed by CB2. As a result, CB2 trips three phases and performs auto-reclosing. The measured currents and

voltages in figure 5.10 also demonstrate that the fault has been successfully cleared by CB2 and CB1. The testing results on different locations of TL1 are listed in table 5.2.

Table 5.2: Testing Results of Phase AB Fault on TL1

Fault Point (%length)	CB2 Trip 3ph	CB2 Reclose 3ph	TTCB1	TTCB2
0	✓	✓	0.0124	0.2177
10	✓	✓	0.0140	0.2128
20	✓	✓	0.0198	0.0151
30	✓	✓	0.0222	0.0163
40	✓	✓	0.0208	0.0164
50	✓	✓	0.0202	0.0164
60	✓	✓	0.0258	0.0160
70	✓	✓	0.0241	0.0178
80	✓	✓	0.0194	0.0163
90	✓	✓	0.2148	0.0157
100	✓	✓	0.2621	0.0173

It is seen that CB2 is able to cut the fault and then autoreclose for the whole length of TL1. The tripping time of CB2 in the first 15% length is around 200ms longer than CB1, indicating this line section is protected by Zone 2 of P446 relay and Zone 1 of RTDS relay. In contrast, the last 15% line section is under Zone 1 protection of P446 relay and Zone 2 of RTDS relay. This time delay coordination corresponds with the draft setting. Take CB3 and CB4 on TL2 as a comparison. The performance of IEC61850-configured relay with CB2 is as good as the built-in IEDs of RTDS.

6

CONCLUSION AND FUTURE WORK

This concluding chapter summarizes the project, answers the proposed questions at the beginning of the thesis and points out the practical contribution. Furthermore, a few recommendations are provided for future work.

6.1. CONCLUSION

As intelligent substations are incorporating a number of IEDs with various functions, the configuration of IEDs from different vendors is important for the control and communication in substations. The thesis aims to provide the guideline for closed-loop testing of IEDs using IEC 61850 standards in RTDS environment. Based on this primary goal, the thesis is organised following the research questions proposed in section 1.2.

"What are the IEC 61850 standards?"

Chapter 2 introduces IEC 61850 system in detail. Documents related to power network applications are listed and explained, providing a guide for substation operators to understand the basic concept of IEC 61850. The object-oriented modelling method elaborated in section 2.2 builds the structure of IEC 61850 data model. For the communication requirement of digital substations, specific mapping services including MMS, GOOSE and SV are illustrated in section 2.3. Furthermore, the superiority of applying IEC 61850 in digital substations are discussed compared with conventional communication system of substations.

"What are the suitable settings of distance relay, and how to configure it with the circuit breaker in RTDS?"

6

Chapter 4 explains the relay configuration in steps. Firstly, the requirements of relay are specified according to the power network setup. Parameters related to the distance protection on TL1 are calculated by hand or extracted from RTDS model, making the relay suitable for controlling the CB in RTDS. The communication link between relay and CB is configured by referring to *RTDS* and *MiCOM S1 Agile* simultaneously. The realisation of SV service is illustrated in section 4.2. Section 4.3 and 4.4 deal with the GOOSE messages.

"How to perform the closed-loop testing in RTDS using the configured external relay?"

Section 3.3 introduces RTDS simulator for closed-loop testing. The power network is already modelled mathematically in RTDS. IEC61850-based communication is realised by the network interface card: GTNETx2 card. This card allows bidirectional data flow; thus, the configured external relay P446 is connected to the network model and controls the operation of CB. The data exchange process and applied protocols are presented in section 3.3.2.

"What are the testing results in RTDS? Does the circuit breaker clear the fault as expected?"

In Chapter 5, the single line diagram of power network model is drawn. The testing steps and analysing method in section 5.2 give explicit instruction for substation operators. Two testing cases illustrated in section 5.3 prove the communication between relay and CB is effective, and the CB can clear faults with good selectivity and sufficient speed.

As shown in figure 6.1, power network model and GTNET configuration are performed

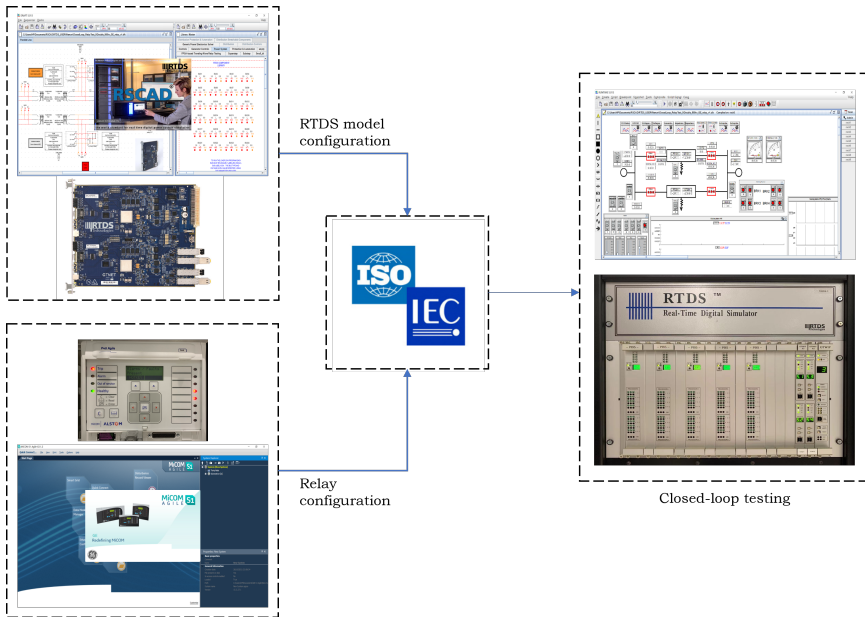


Figure 6.1: Framework of IED configuration and testing

in the draft file with software *RSCAD*. *MICOM S1 Agile* is the engineering tool for relay configuration. IEC 61850 protocols guide all the configuration. After that, the model is compiled on RTDS rack and simulates in the *sib* file of RTDS. To sum up, this project deals with distance relay testing using IEC 61850 in RTDS environment. It gives a detailed description of relay configuration, and is serviceable for lab work.

6.2. RECOMMENDATION AND FUTURE WORK

Future improvements have been stated below:

- Regarding this numerical distance relay P446, other protection functions can be enabled and set to fit more complex protection requirements, improving the selectivity of protection scheme. Besides, P446 relay is capable of dual-breaker control. The settings can be modified to incorporate a second circuit breaker, for example, CB1 on the other end of the protected line. Thus, one relay achieves the control of two circuit breakers on the same transmission line, saving the installation expense.
- For the power network testing in RTDS, other protection schemes can be created and tested by implementing more relays using IEC 61850 communication. In this project, CB2 on the one end of the transmission line is only tested for distance protection. However, CB2 is expected to cooperate with other circuit breakers and different protection schemes for the whole power network, like the protection of adjacent lines and busbar.

- Cyber attacks have become the problem that accompanied the application of IEC 61850 protocols in digital substations. Compromised GOOSE messages will mislead the operation of circuit breakers and damage the power system stability. Cyber attack against one IED may not seriously affect the system due to the N-1 criterion of power grid. However, coordinated cyber attack on multiple IEDs can cause cascading failures and lead to a blackout [14]. One measure to mitigate the influence of cyber attacks is to adopt authentication codes at the end of every GOOSE message, but it has not been widely used in substations due to the heavy computational demands.

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