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Technical Report TA User Project

vIED

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Abbreviations

DER	Distributed Energy Resource
TA	Trans-national Access
GOOSE	Generic Object Oriented Substation Event
IED	Intelligent Electronic Device

Executive Summary

The integration of Operation Technology such as Intelligent Electronic Devices (IEDs) brings added challenges for testing and operation of complex interconnected protection systems. The hardware limitations of IEDs, such as integration in existing infrastructure and reduced run time control, limit engineers and researchers to test complex protection and automation scenarios. Virtualization of these technologies allows seamless integration of software units into existing systems, which can be scaled up for large scale system testing. In this paper, the operation of virtual IEDs has been validated with that of physical IEDs. Two separate test platforms are used; one for the physical IED infrastructure and the other for virtual IED (vIED) infrastructure. A use case for overcurrent feeder protection using GOOSE communication has been demonstrated. The performance of circuit breaker tripping and GOOSE communication has been demonstrated and compared for both the test platforms. The vIED operational ability is validated and key insights for future work are given.

The aim of the proposed work is to validate the performance of virtual IEC 61850-based Intelligent Electronic Devices (IEDs) that have been developed and tested in a real time co-simulation platform at the The Smart Energy Simulation and Automation (SESA) Laboratory in OFFIS, with a physical hardware testing platform at the MultiPower Laboratory at VTT. The virtual IED has the ability to be scaled and integrated into further applications once validation with the hardware environment is carried out. The test results for simulation scenarios are compared with the real hardware tests and the Key Performance Indicators (KPI) are compared. The simulation and real hardware testing procedure are extracted from the ERIGrid Holistic Testing Approach (HTA). This enables the experiments to be conducted in a systematic and integrated way.

The hardware test scenarios in MultiPower Laboratory in VTT are concerned with feeder protection using high speed GOOSE communication from ABB REF615 IEDs. KPIs for the hardware are the relay tripping time, GOOSE delay and fault clearing time. The experiment specification for running the tests in the relevant Research Infrastructure (RI) is defined according to the ERIGrid Holistic Testing Approach (HTA), to consider the potential interactions and characteristics of both lab environments. The simulation scenarios involve combining the OPALRT simulator with virtual IEDs developed in OFFIS using the IEC 61850 protocol. The feeder protection scheme from the MultiPower laboratory is modelled in eMEGAsim and integrated with the vIED. The effects of tripping time, communication delay and fault clearing are investigated.

The outcome of the research is presented in a scientific paper that has been submitted to the 15th International Conference on Developments in Power System Protection (DPSP 2020). Furthermore, the developed use cases and testing strategies for hardware and virtual protection testing could be utilized in future research projects. The capability of both the MultiPower and SESA has been demonstrated, and future use cases can be implemented in these RIs.

1 General Information of the User Project

The project vIED duration was between 1.03.2019 till 1.10.2019. The project comprised of three main phases. In the first phase, the use cases were developed and background study was carried out for the virtualization, protection systems, and substation automation domains. In the second phase, the ERIGrid TA visit took place at the MultiPower laboratory. Shoaib Ansari undertook the TA visit from 31.05 till 30.06, where the testing for the hardware infrastructure is carried out and the results are compiled. For the final phase of the visit, the SESA lab is used to test the real time simulation scenarios and to compile and compare results with the MultiPower Lab results. The details of the members of the project are given below.

Prof. Dr. Sebastian Lehnhoff

Prof. Lehnhoff is an executive board member of the OFFIS Institute for Information Technology and responsible for its Energy R&D division. He is speaker of the special interest group "Energy Information Systems" within the German Informatics Society (GI) and active member of numerous committees and working groups focusing on ICT in future Smart Grids.

Sebastian Lehnhoff is dealing with research topics in the area of smart grid, and virtual power plants. His focus lies on real-time methods for safety-relevant applications, grid-oriented decentralized operation strategies as well as co-simulation and automation in complex energy systems.

Dr. Davood Babazadeh

Davood Babazadeh is an R&D manager at OFFIS Institute for information technology in Germany since 2017. He received his first master degree in energy engineering from Sharif University of Technology - Tehran in 2008. Then, he worked in industry in the field of reliability analysis in power systems for four years. He received his second master degree in electric power engineering in 2012 and afterwards his PhD from KTH Royal Institute of Technology-Sweden with the focus on distributed control of hybrid AC/DC transmission grids. In 2016, he worked as an area manager in Swedish Center for Smart Grids and Storage (SweGRIDS) in Stockholm. His areas of research are focused on Smart grid and smart city resilience and reliability, power system automation and control as well as multi-domain co-simulation testbeds.

M.Sc Shoaib Ansari

Shoaib Ansari is a scientific researcher at OFFIS Institute for information technology in Oldenburg Germany since January 2018. He received his Master’s degree in ´Electrical Engineering and Information Technology’ from Otto von Guericke University Magdeburg in 2017. His research interests are focused on Smart grid simulation test-beds, power system automation, Smart grid communications and cyber security methodologies.

Dr. Anna Kulmala

Anna Kulmala is a Senior Scientist and leads the Smart Grids substance node at VTT. She holds a D.Sc. (Tech.) degree from Tampere University of Technology and has been working in several national and European projects for more than 10 years. She has been working with several aspects of the future smart grids such as active distribution network management, distribution network planning, testing of new smart grid functionalities both in lab and in field and smart grid information exchange architectures.

M.Sc. Petra Raussi

Petra Raussi is a Research Scientist at VTT and responsible for the MultiPower power systems laboratory. She has graduated with M.Sc. (Tech.) in electrical engineering in 2018 and has participated in European and national research projects. Her research interests include automation and ICT of smart grids.

2 Research Motivation and scope

Modern substations are employing improved and more reliable control devices known as Intelligent Electronic Devices (IEDs). Integration of Operational Technology (OT) is becoming an important part of future power systems. These new digital technologies automate the process of substation protection and control, allowing for faster and more reliable protection and control schemes. For this purpose, IEC 61850 standard defines all the processes and the communications behind the phenomena of substation automation. The advantages of faster communication between IEDs, less cabling in substations and more control for the operators, are some of the reasons these technologies are being integrated with existing infrastructure [1, 2]. GOOSE communication defined in [3], can be deployed for protection applications such as overcurrent feeder protection. The fast nature of message transmission enables reverse blocking and interlocking schemes without the need for binary inputs and outputs but rather with a simplified Ethernet infrastructure. These Ethernet communications can be easily integrated with real IEDs for substation automation and with real time simulators to test real time simulation for this purpose [3].

IEDs have slowly replaced traditional electromechanical relays, with modern communication and monitoring technologies that adhere to communication standards such as the IEC 61850. However, these modern technologies bring added challenges to the existing infrastructure. As seen in December 2016, a malfunction of a packet payload caused the disconnection of a transmission substation in Ukraine [4]. Furthermore hardware limitations of IEDs, such as integration in existing infrastructure and reduced run time control, limits operators to test the security features of OT. The challenge also relies in the testing of new algorithms and cyber security mechanisms for the IEDs before field deployment [5, 6]. These challenges can be met through virtualization of OT that helps to test and validate complex protection systems before field deployment. This way, the communication infrastructure along with the power system infrastructure can be tested without the risk of malfunction or failure. Existing literature shows that virtual IED test beds have been deployed and tested. However, a complete analysis of operation, control and performance of virtual protection IEDs is missing. Real hardware testing limitations can be overcome by building a virtual platform that mimics real hardware and runs in real time. A holistic comparison of the two research infrastructures would show the advantages and drawbacks of both platforms. In this project, the performance of both real and virtual IEDs in two different research infrastructures is tested for reverse blocking schemes with GOOSE communication that conforms to the IEC 61850-8-1 standard. The novel contribution is the comparison and analysis of the GOOSE packet transmission for both the IED platforms and investigating the operational behaviour of the virtual and physical IEDs.

Virtualization of Operational Technologies (OT) is not a widely researched application area. With increasingly complex power systems integrated with ICT components, the need for real time simulation arises that is possible in a virtual environment. These simulation scenarios allow us to scale up the system by simulating multi domain systems and investigate the phenomena of real networks in a virtual environment. Finally, cyber security and malfunctions are a serious concern for future smart grids. Virtual components allow modelling attack patterns on devices or on the network which would emulate real cyber physical attacks. These environments help to test the critical and resilient performance of devices and networks in the smart grid [7, 8]. The proposed research on aspects of GOOSE communication, virtual IEDs and over current feeder protection will be beneficial for substation automation and virtualization domains. Moreover, the design of experiments using HTA will be a major advancement for future holistic testing approaches.

The results of the proposed project would give active feedback to the ERIGrid project. It would also highlight the cyber physical features of the Smart Grid Resilient Laboratory in OFFIS and the MultiPower in VTT Finland. The proposed results would help to carve out future research use cases on GOOSE delays, DOS attacks on substations and virtual substations.

2.1 Objectives

The objectives of the TA was the testing of IEDs and GOOSE communication in a real and virtual substation laboratory environment. Test cases for over current protection were conducted and it was demonstrated how GOOSE communication affects substation events. The project objectives are divided into two parts; the first one for the MultiPower Laboratory in VTT Espoo and the other for the SESA Lab in OFFIS. Finally, the comparison of both the Research Infrastructure (RI) and the Function under Test (FUT) are compared and investigated. For the MultiPower Laboratory in VTT Espoo the objectives are listed below:

- Setup the test infrastructure according to the users' needs
- Observe the system behaviour and verify the correct interconnections and measurements
- Conduct the testing and experiments according to the ERIGRid HTA
- Emulate a use case for over current protection via a load increase at the feeder
- Model the ABB REF615s logic and communication for the overcurrent scenarios
- Observe and analyse the substation events and the GOOSE communication for the scenarios tested.
- Compile the results and observe the Functions under Test (FuT)

For the SESA Lab in OFFIS the objectives are listed below:

- Setup the real time infrastructure.
- Engineer the IEC 61850 processes and create virtual IEDs.
- Mimic the real network model of VTT with the OPAL RT simulator and the virtual IEDs.
- Observe and analyse the substation events and the GOOSE communication for the scenarios tested.
- Compile the results and observe the Functions under Test (FuT).

3 State-of-the-Art/State-of-Technology

Distributed automation in power systems is becoming increasingly important for protection systems. Distribution automation allows the system to be more reliable and secure in cases of faults. With more DERs in the system, the system encounters fluctuating power flows which must be dealt with by a fast, robust and optimized protection strategy. The concepts of feeder, distance, differential, and bus bar protection are being integrated with the IEC 61850 standard. This enables substation automation to be optimized for better performance and testing [9], [10].

The IEC 61850 in recent years has been widely used by research laboratories and modern substations. Work has been done in the application of this standard for protection, control and monitoring of substations. The IEC 61850 standard comprises of a data model and communication protocols which combine together for substation automation applications. The data model comprises of a hierarchical structure which goes from a physical device all the way down to a data attribute. The physical device is the IED which measures current and voltage inputs, enables time synchronization to the measurements and issues command to other IEDs or the Human Machine Interface (HMI) for some corrective measures. These devices in the substation use effective communication protocols such as GOOSE. The GOOSE communication can transmit remote measurements such as line voltage and breaker status and can transmit commands for breaker change or load shedding. The benefit of using this messaging is the fast transmission time of less than 4ms and the reduction of hard wiring on the relays since GOOSE runs on Ethernet and a Local Area Network [11].

Existing literature works investigate the application of GOOSE messaging for protection applications. Relay characteristic changes from GOOSE have been demonstrated in [12]. This work is useful for seeing the change in overcurrent data set, in case of feeder fault. Authors in [13], test GOOSE messaging for transformer protection scenarios. The GOOSE messaging enables the circuit breaker connected to a transformer to trip in case of a distribution feeder fault. The operation of islanding and non-islanded modes and the transition between the two states using GOOSE has been carried out by [14]. References [15] and [16] show how distance relays can be configured with IEC 61850 specifications to carry out distance protection. Another application which has been tested is load shedding using GOOSE communication by authors in [17], [18] and [19]. All these recent works show the importance of GOOSE communication for protection applications.

Recent works have been more focused on testing physical hardware using GOOSE. Virtual IEC 61850 platforms are still relatively new. Virtualization is required to test large scale complex simulation, with remote measurement. In [5], open source IEDs are developed on a virtual server that tests the performance of protection related application. This work is relevant to this project but lacks a comprehensive validation of the virtual IED platform. Security mechanisms for IEC 61850 communication are also new and have been carried out by authors [9] and [20].

Existing literature shows that more research is needed in the virtualization domain. Virtual IED testing and complex substation automation simulations can help researchers and operators to investigate new ideas in this domain, and also to perform protecting testing which is limited to physical infrastructure.

4 Executed Tests and Experiments

This section aims to explain in detail the tasks and considerations leading to the successful execution of the experiments intended for this project.

4.1 Test Plan

The test plan consists of one main use case, in which different communication messages are exchanged between the Intelligent Electronic Devices (IEDs) equipped at the system under test. The objective of this use case is to determine the effect of the communication infrastructure, in particular IEC 61850 GOOSE and its adequacy to be used for power system protection purposes.

4.1.1 Use Case

This use case consists of a reverse blocking scheme between a feeder load relay and a grid relay using GOOSE messaging. The objective is to block the circuit breaker operation of the grid connection after a load increase at the feeder. This use case would emulate a situation where a fault arises on an outgoing feeder, the protection relays of both the incoming feeder and the faulty outgoing feeder start. On starting, the relay of the outgoing feeder, however, blocks the fast-acting overcurrent stage of the relay of the incoming feeder (ABB Bus bar protection). Figure 1 shows the schematic idea of this use case.

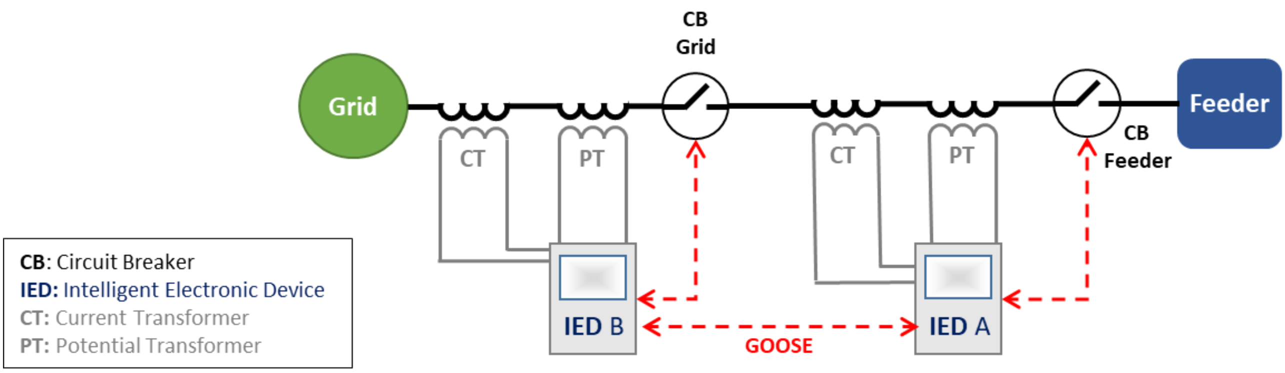


Figure 1: Schematic of the idea of Use Case 1

The use case consists on a load increase by the element “Load”, which increases the current of the feeder, surpassing the pickup value of the overcurrent protection in IED A and B. The main point of investigation is reverse blocking using GOOSE communication. A load increase at the load sends GOOSE messages from the IED A to IED B. In this case, IED A opens its circuit breaker and sends a message to IED B to block the operation of its protection. The aim is to utilize GOOSE communication to avoid the operation of the circuit breaker assigned to IED B, and therefore avoid the disconnection of the grid connection and other elements in the laboratory.

Three test cases are analysed:

1. IED A opens its circuit breaker when the load is increased and sends GOOSE message to block IED B. This is the normal operation for reverse blocking scheme.
2. The circuit breaker of the load malfunctions when there is a load increase and IED A still sends a GOOSE blocking message to block IED B.
3. IED A opens its circuit breaker through a load increase and sends message to block IED B, but the GOOSE message is impaired.

4.2 Standards, Procedures, and Methodology

For the execution of the use cases a combination of hardware, software, communication infrastructure and communication standards were used. The test infrastructure was setup and the testing was done according to the ERIGrid Holistic Testing approach. This approach allowed multiple tests to be conducted for the experimental specifications in an orderly manner. The main communication standard used in the test infrastructure was the IEC 61850 and in particular GOOSE. In this section, the ERIGrid HTA and the IEC 61850 are described in more detail.

4.2.1 HTA

The formulation of the experiments was done according the ERIGrid Holistic Testing Approach. The experiments for the test cases were conducted using this approach as shown in Figure 2 . The complete test templates are shown in the Annex in. The mapping of the holistic test to sub tests and the mapping of subtests to RI enable to investigate the interdependencies between different tests and RI. The experimental outcomes from both RIs are heavily dependent on each other and hence this approach maps the results and outcomes of both RIs for a clear comparison and validation of both the environments. The Holistic Testing Approach is useful for multi domain testing and provides a useful test case for a basic understanding of design of experiments compliant testing for protection system and substation automation [21].

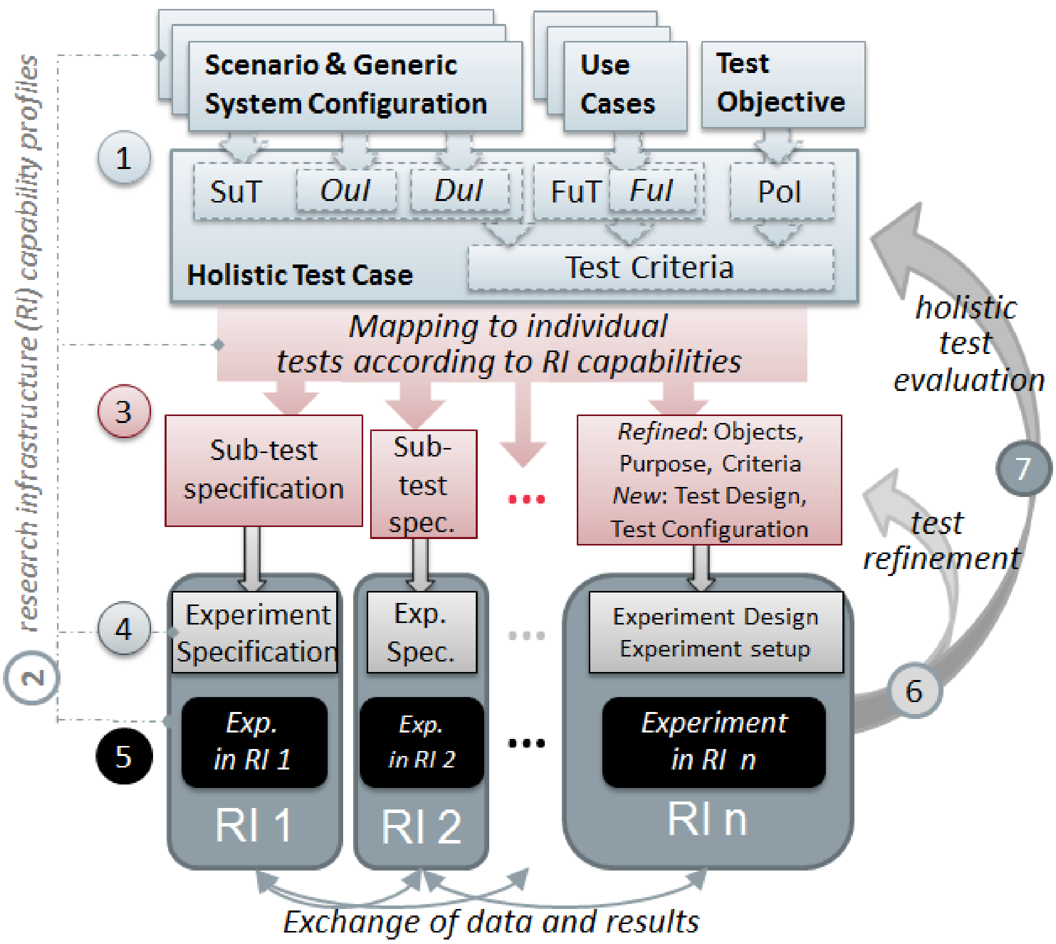


Figure 2: ERIGrid Hollistic Testing Approach Methodology [21]

4.2.2 IEC 61850

The IEC 61850 is a set of standards which was released in early 2000 to standardize substation automation. The standard has been revised and extended over the years to include features related to power system automation, in particular power system protection. The IEC 61850 is relatively new in the electricity industry and hence it is being continuously tested and implemented to ensure its commercial success. The IEC 61850 is not just a communication protocol like the 60870-5-104, as is widely perceived. On the contrary it is a much more comprehensive set of publications that define system requirements. Many international vendors are moving to standardize their equipment to comply with the IEC 61850. This interoperability helps this standard to be widely used within different substations and devices [13]. It also describes new communication models which are needed to improve the interoperability and interchangeability between power system devices [Theron]. Each part describes different structures and functions that are essential for understanding the IEC 61850 series [15]. The standard realizes the road from substation application to communication using abstract models, virtualization and mapping to OSI model [22]. The communication in IEC 61850 takes place through different technology mappings. The mapping to the physical layer is of importance for integration with other devices. The serial connection or the mapping to Ethernet allows for high speed GOOSE and sampled values mapping.

GOOSE is a method for fast transmission of real time data to IEDs. The GOOSE methodology is based on the subscriber/publisher model. Both the subscriber and publisher exchange data through a local buffer. GOOSE messages are sent sporadically with high frequency since there is no acknowledgement of GOOSE at the receiving end. Different data in the IED is grouped or configured into a data set. The GOOSE message can contain one or several data sets. Any change in these parameters trigger GOOSE messages, and a fault increases the frequency of GOOSE messages. There are several parameters in a GOOSE message which need to be configured. These include GOOSE ID, MAC address, VLAN ID, Application ID, IED name, Configuration revision, time to live (milliseconds) etc. These messages must be configured in the ICD or SCD files which is usually available within the IED. These files are then connected to a server in order for multiple devices to communicate with each other. The GOOSE control block contains the data set of a GOOSE message. It can be configured as enabled or disabled depending on whether data needs to be sent through Ethernet. The GOOSE transmission model is shown in Figure 3 [23]. T0 is the normal retransmission time when no event change occurs. This is the heartbeat of the GOOSE message. When an event occurs, T1 is a minimum retransmission time. After the new event transferred, retransmission time is increase gradually from T2, T3 back to T0. The substation events can be analyzed according to this retransmission model the time intervals can be investigated for these events [23].

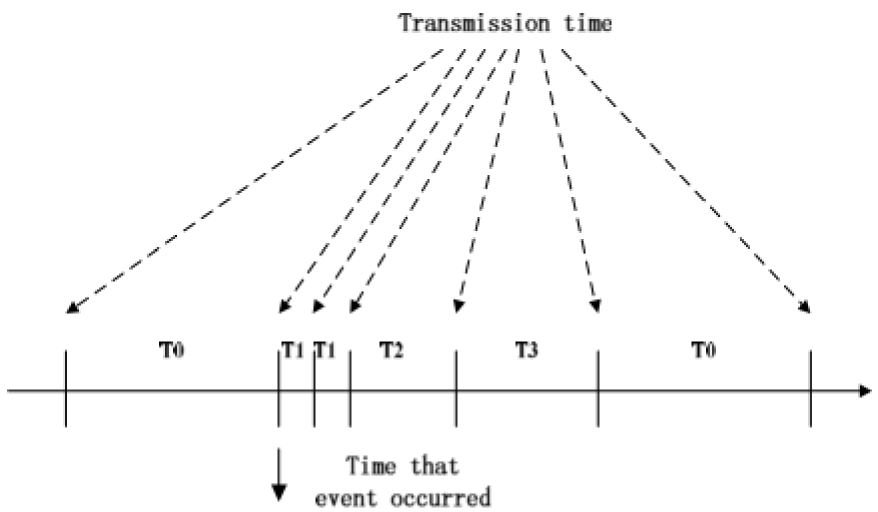


Figure 3: GOOSE transmission model

The SV communication is very fast, around 4000 samples per second. Unlike PMU protocol, the IEC 61850 does not determine real time behavior. However the fast communication enables real time data to be exchanged between different elements. GOOSE messaging occurs when an event takes place such as a change in the switch status. SVs are exchanged using the multicast and unicast mapping. With multicast addressing the values can be exchanged between various devices with the same multicast address. The sampling rate defines how often the data should be sent by the control blocks [24].

The architecture of the IEC 61850 communication system is based on digital communication with minimal copper cabling. This type of communication is vertical communication based on the publisher/subscriber model. The communication between the client/server or external devices is represented by interfaces. The interface links the process, bay and station level communication within a substation [16]. These are described below.

Process level
The process levels comprises of process function that relate to data acquisition and command exchange. These are digital and analog inputs and outputs. The elements in this level are CTs, VTs, PTs and CBs. These elements send data through the process bus to the relevant IEDs at the bay level. The Ethernet switch is the process bus.

Bay level
The bay level is a subpart of a substation which consists of a function within a bay. This could be a switch gear or a station feeder and must be configured according to the data being sent or received by the bay level.

Station level
The station level is the monitoring part of the IEC 61850 communication architecture. It can receive data, monitor it and send commands accordingly to the IED's at the process level. The station bus is the Ethernet switch which acquires data from the process level and sends it through a gateway to an external station.

Gateway
The gateway is responsible for changing the protocols to enable varied communication between devices. This is especially relevant for systems deploying IEC 61850, 104 or the DNP3 all in the same server. Further research is being done on how to bring in SCADA features in the IEC 61850.

Files and data representation
The communication and information exchange for the IED's is specified by a file format. This format allows the IED's to exchange capability description, configuration and parameters of different manufacturers in an effective way. This file format is extremely important for vendors and manufacturers to achieve interoperability between IED tools. This language is known as Substation Configuration Language and is based on XML version. The format provides data about the following:

- System specification and logical nodes allocation for the intended specifications
- Pre-configuration of the IED's
- The logical nodes
- The report and control service blocks
- MMS services and GOOSE

There are four types of SCL files; ICD, CID, SSD and SCD. Many IEC 61850 IEDs contain ICD files which are configured according to IED's capabilities and constraints. The ICD file is configured and put at the station level in a server and an SCD file is then generated back to the IEDs. This communication and file transfer is vital for efficient and error free data transmission and exchange. The SCL files contains important parameters such as a header, substation description, IED description and LNType definitions [25].

4.2.3 MuliPower laboratory infrastructure

The MultiPower laboratory at VTT Espoo was used to execute the experiments. The MultiPower laboratory is a nationwide empirical research environment and provides opportunities for testing new technical DER products and solutions in a multifunctional environment [26, 27, and 28]. The laboratory network is 400 V low-voltage network. The laboratory network is connected to 20 kV public distribution network via 0.5 MVA and 1 MVA transformers. Additionally, an islanded operation of the laboratory is possible. The laboratory includes a grid emulator Cinergia GE30PLUS, 6 kW PV emulator/DC source, 750 W PV panels, adjustable resistor loads up to 1700 kW and controllable PQ load up to 15 kW. Additionally, there is also a ready-made connection point for testing additional devices and a DC residential customer grid interface with voltage control, metering, protection and islanding. The grid emulator Cinergia GE30PLUS can alter voltage and frequency of the feed-in for testing with different grid conditions and disturbance [29].

At the Laboratory, IEC 61850 protection or control solutions and GOOSE messaging can be tested with the substation automation system, which consists of ABB COM600 substation computer and four ABB REF615 feeder protection IEDs. Regarding communication, the MultiPower laboratory has a communication emulator and is a part of the 5G pilot area as VTT is participating in 5G development [28]. Ideally, DER generation units, ICT applications for DER systems, distribution automation and devices based on IEC 61850 and malfunctions and faults could be tested at the MultiPower laboratory [28].

The test set-up to execute the experiments explained in section 4.1 is shown in Figure 4.

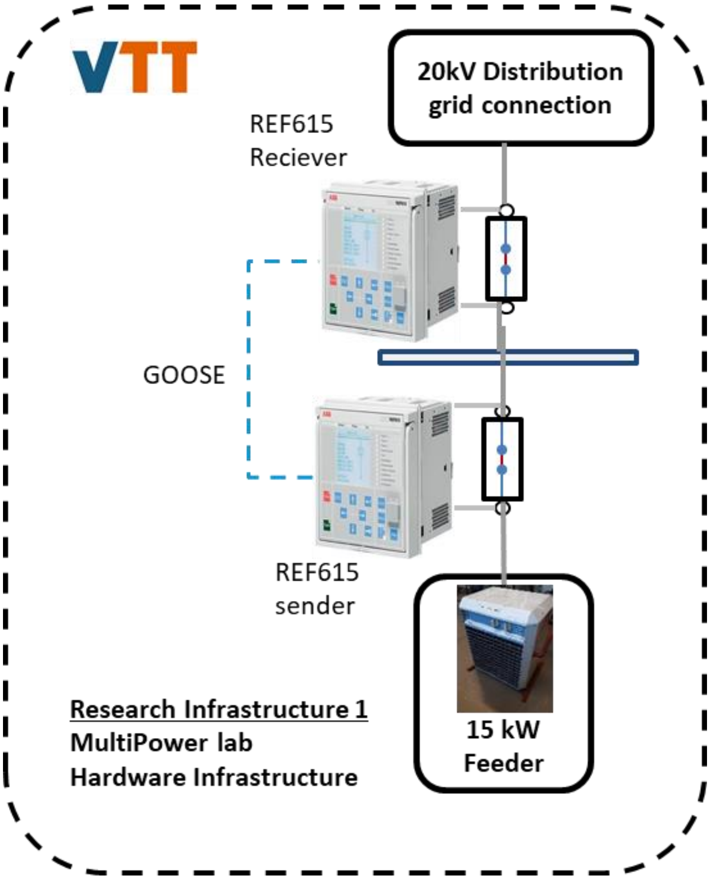


Figure 4: Schematic of the test set up in VTT Lab

The setup consists in a small low voltage level grid (400V), in which two circuit breakers are controlled by two respective ABB REF615s.

- **A** – REF615 connected to 15kW feeder load circuit breaker
- **B** – REF615 connected to circuit breaker with 20kV distribution grid connection point circuit breaker

These IEDs retrieve measurements directly from the current and potential transformers installed next to each device. The IEDs are connected one to the other through Ethernet cables and communicate using IEC 61850 protocol. Specifically, GOOSE messages are used for fast communication of commands between the IEDs.

The interconnection between the REF615s and the ICT infrastructure is shown in Figure 5. The figure shows four IEDs but in the test only IED at the feeder and the distribution grid are used.

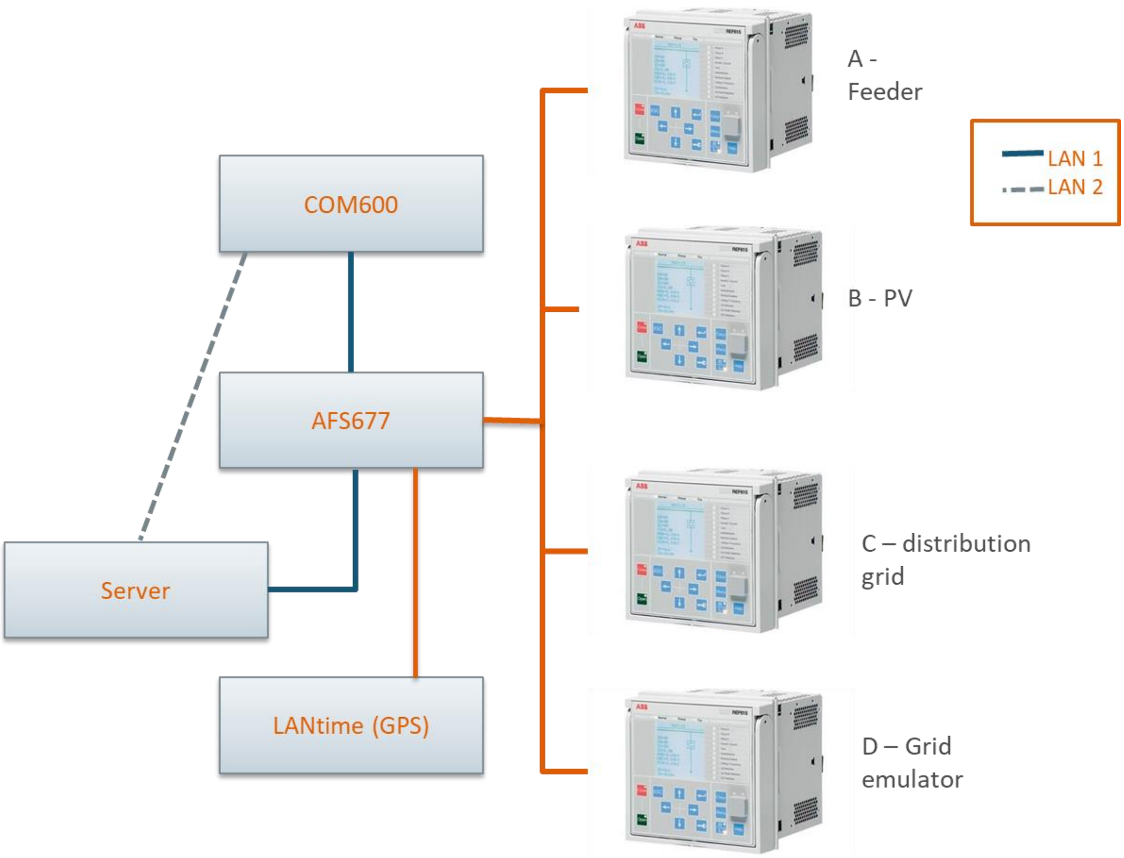


Figure 5: ICT and IED infrastructure of MultiPower Laborotary

It is noted that for simplicity and controllability purposes, a diesel generator is used as DG instead of the PV panels. This choice is done in order to have a controllable power generation in these experiments. Table 1Table 1**Error! Reference source not found.** shows the electrical characteristics of the grid emulator, the current and potential transformers, the circuit breakers, the resistive load and the distributed diesel generator used for the development of the use cases under study. The REF615s are configured with logic and communication through the ABB IED manager and the ABB substation manager. Moreover, the packets transmitted in the network are monitored through Wireshark. These software and the REF615 are described more in detail below.

Table 1: Characteristic of the devices used for the use cases

Device	Characteristics					
Grid Emulator	kVA	kW	Independent mode Arms/ch	 Adc/ch	Parallel mode Arms	 Adc
Cinergia GE7.5	7.5	6.75	±10A	±10A	30A	±30A
CTs & PTs	Primary		Secondary			
Current Transformers Grid, PV and Load Potential Transformer Grid Potential Transformer Load and PV	250A 277V 400V		5A 100V 100V			
Circuit Breakers - ABB SACE Tmax. T Generation - model PR221DS	Size [A]	In [A]	Nr. Poles	Ue [V]	Icu [kA] (380-415V AC)	
Grid: T5S 400 PV and Load: T4S 250	400 250	320 20	3 3	690 690	50 50	
Resistive Load	Type	Freq [Hz]	Un [V]	kW	power factor	
Frico Temperator 200	215B	50	380	2x7.5	1.00	
Diesel Generator	kVA	Un [V]	In [A]	cosphi	RPM	
T20FS-130	10	230/400	25.1/14.4	0.8	3000 (50Hz)	

REF615

REF615 is a member of ABB's Relion® product family and part of its 615 protection and control product series. It is a s a dedicated feeder protection IED designed for the protection, measurement and supervision of utility substations and industrial power systems. The REF is designed for applications that need overcurrent, earth fault or voltage protection. Its main applications are cable or line feeders. For the purpose of modern communications, the REF615 fully supports the IEC 61850 standard and has the capability to engineer GOOSE, MMS and Sampled Value communication. The peer- to-peer communication using GOOSE over a substation-wide switched Ethernet LAN enables sophisticated logic schemes to be introduced for substation protection and automation. Via GOOSE, complex logic schemes can be introduced over a substation wide Ethernet LAN that enables substation protection and control [30].

COM600

ABB's COM600 is a substation automation and management unit. It is possible to build a virtual substation with COM600 and run both simulations and physical power system with it. COM600 has gateway functions for mapping signals between protection and control IEDs. COM600 also contains HMI for transferring data to users and providing visualization of the substation as a single line diagram. It is also possible to access HMI remotely via web HMI. (ABB 2017, 15.) COM600 is compatible with several communication protocols and supports interoperability between different protocols. Hence, gathering data by connecting IEDs with various protocols is possible. COM600 includes web technology for displaying data and transferring data to Network Control Centre (NCC) or Distributed Control System (DCS). COM600 uses IEC 61850 SCL and IEC 61580 data modelling for communications modelling [31].

In the MultiPower laboratory, the COM600 is connected to four REF615 feeder protection IEDs, which are further connected to a PV unit, a grid emulator, the distribution grid and a movable connection point for additional devices respectively. Via REF615 devices, it is possible to cultivate data from the generation and load units and transfer the data to COM600.

ABB COM600 uses IEC 61850 in the substation structure. The substation structure is a diagram displaying the major component and connections to the components within a substation. Substation structure can be built manually, based on Connectivity packages or based on SCL files. At least gateway, substation voltage level and bay objects should be added to the substation structure. Substation structure can be built only after the communication structure has been built. Busbars, bays and connections between components can be added on Single Line Diagram (SLD) Editor. Additionally, display boxes and indicator for measurements and operational modes can be configured on SLD Editor [31]. Figure 6 presents an example of a substation structure on SLD Editor.

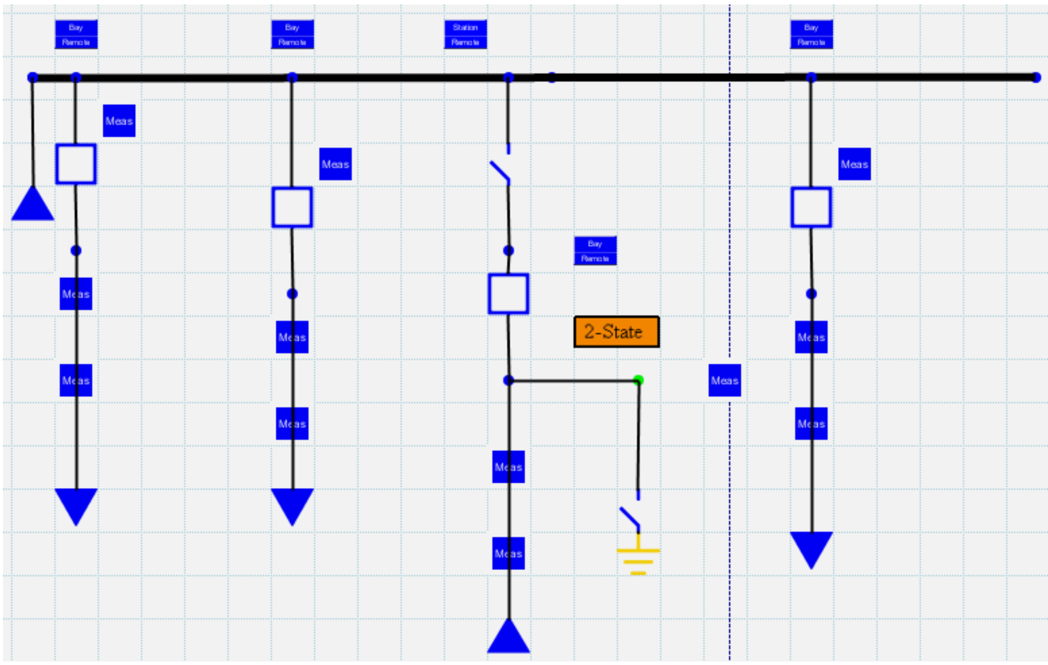


Figure 6: An example of COM600 substation structure on SLD Editor. Blue boxes are measurement displays and blue dots represent terminals

PCM600

The Protection and Control IED Manager PCM600 provides versatile functionalities for protection and control IEDs in transmission and distribution applications. The PCM600 allows the connected IEDs to be engineered for logic schemes, signal transmission, time synchronization and communication protocols. PCM600 is compliant with IEC 61850, which simplifies the IED engineering and enables information exchange with other IEC 61850 compliant tools. The hierarchical presentation model that reflects the real system topology enables efficient viewing and editing of the power system information [32]. The PCM has an application configuration tool that models the operational logic of the IED. The communication can be configured with GOOSE, SV and Client/Server communication. The signals are mapped with the signal matrix tool. Furthermore, the parameter settings allows the operator to parameterize and configure the protection and control functions.

Wireshark

Wireshark is a network packet analyzer which monitors live data network packets. The traffic between the source and destination is displayed along with the protocol which is being used. The packet payload can be examined which shows the size, parameters and time stamp of the packets. The monitored packets can be analyzed for network communications in a switched Ethernet network.

4.2.4 SESA Lab OFFIS

The Smart Energy Simulation and Automation (SESA) Lab allows real-time co-simulation of impacts on energy supply systems under realistic conditions to facilitate integration of new components into the system; to identify critical situations; and to develop any adaptations that might be required. To ease the simulation planning and execution process, SESA includes a virtualization server (VM cluster) that can provide virtual machines for software-based simulations (with the possibility of coupling with hardware-based real-time simulation and automation system in the Lab), development environments, or licensing servers for possible runtime environments.

For the test platform a real time simulator from OPAL RT is used to model the network. The network model from VTT Multi Power Lab is mimicked and run in real time on the RT LAB software eMEGASIM. The REF615 from MultiPower Laboratory are replaced with virtual IEDs that run on virtual machines and communicate with the OPAL RT simulator via Ethernet with GOOSE and UDP communication. Figure 7 shows the test platform below.

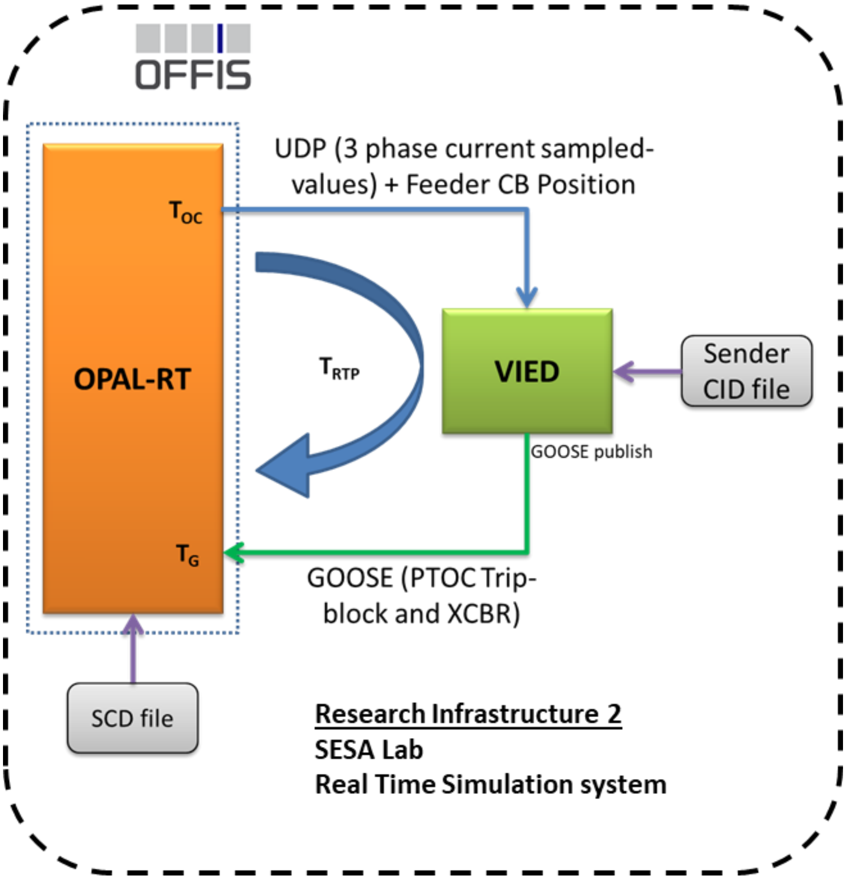


Figure 7: SESA Lab infrastructure

The network model in OPAL RT sends real time current measurements from the Feeder circuit breaker via UDP. The vIEDs export a CID file which is developed in the IEC 61850 System Configurator Tool (STS) from HELINKS. The vIEDs dynamically read the GOOSE data set and control blocks and wraps them in GOOSE messages. These messages are then published from vIED 1 and subscribed by vIED 2. Vied2 further publishes GOOSE to OPAL RT. The UDP communication delay and transmission time is not measured as the main KPI is the communication via GOOSE from vIED 1 back to the OPAL RT grid circuit breaker to see how the blocking effect takes place. The OPAL RT software RT LAB, vIEDs and the STS are explained more in detail below.

RTLAB

RT-LAB is OPAL-RT's real-time simulation software which is fully integrated with MATLAB/Simulink. It offers the most complex model-based design for interaction with real-world environments. It provides the flexibility and scalability to achieve the most complex real-time simulation applications in the automotive, aerospace, power electronics, and power systems industries. eMEGASIM software runs on the RTLAB platform. It is used to model up to 3000 nodes for distribution, transmission and microgids. The real world interaction with power electronics, software programs and controllers allow for Hardware and software in the loop testing [Web refernce].

vIED

The vIED is a console application written in C that implements its IEC61850 functionality using the open source library libiec61850 version 1.4. It consists of three integrated units: The data input, the logic and the IED server as shown in Figure 8. The data input supports the reception of data via the communication protocols UDP, MMS, Sampled Values and GOOSE and decodes the data under consideration of special properties (e.g. a transmitter-specific header with metadata). Inside the logic, the data is processed according to the desired functionality and then passed on to the IED server. The IED server loads the data model and the dynamically configures the communication parameters from the CID file. For the generation and validation of the configuration file a model generator tool provided by the libiec61850 library can be used. The data passed by the logic is assigned to the corresponding data attribute objects of the model and the server is updated. This data can be published via Sampled Values, GOOSE or MMS. In this test case, the vIED takes in the sampled UDP values and wraps them in to GOOSE control blocks. The communication parameters are dynamically set from the CID file from HELINKS and then it publishes the GOOSE messages.

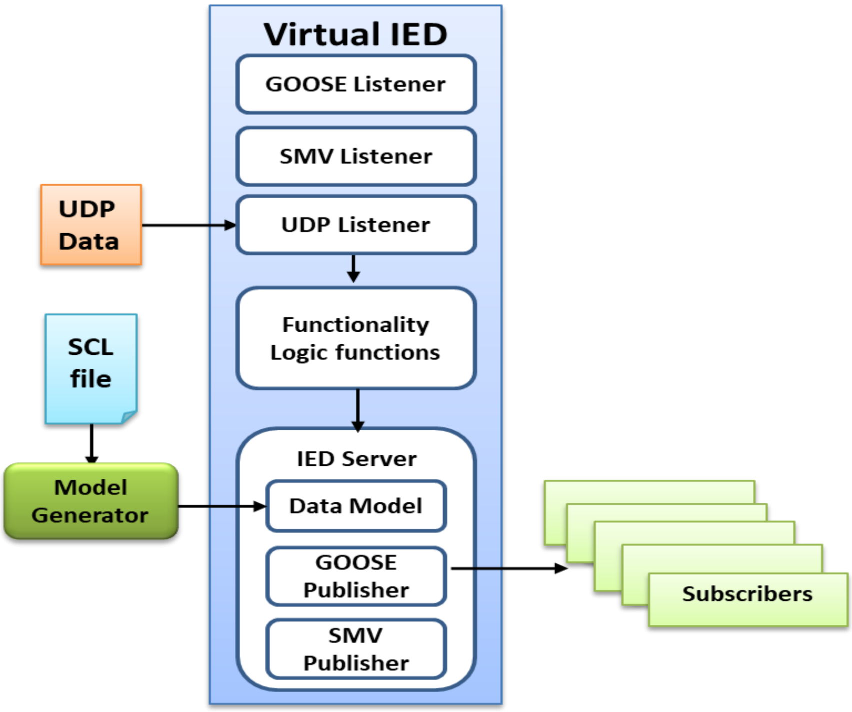


Figure 8: vIED concept and process flow

HELINKS STS

The HELINKS STS is an IEC 61850 system configuration tool that supports the top down and bottom up engineering process for substation automation. It completely implements the IEC 61850 edition 1 and 2 and allows to solve IEC61850 engineering processes with ease. It combines both the network model (Single Line Diagram) and the system integration (IED network) in a valid SCD file. These files can be exported and used accordingly.

4.3 Test Set-up(s)

For the test setup, a reverse blocking use case was performed for three different test cases for RI1. For RI 2, only the first test case is performed. The use case is tested on both RI 1 and 2 (Multi power Lab and SESA Lab OFFIS) and an analysis of both the platforms is done. The ERIGRID HTA helps in this direction as it describes the functionality and capabilities of both RIs and merges them together with the system and experiment specification.

The three test cases are listed below.

1. **Test case one:** IED A opens its circuit breaker when the load is increased and sends GOOSE message to block IED B. This is the normal operation for reverse blocking scheme. The main KPIs here are the GOOSE transmission time, current response of the feeder load and the tripping time of the circuit breaker connected to IEDA.

2. **Test case two:** IED A opens its circuit breaker through a load increase and sends message to block IED B, but the GOOSE message is impaired. The main KPIs here are the GOOSE quality status, and the tripping times of the circuit breaker connected to IEDA and IEDB.

3. **Test case three:** The circuit breaker of IED A malfunctions when there is a load increase but the GOOSE message is still published by IED A and subscribed by IED B. The main KPIs here are the GOOSE transmission time and the current response of the feeder load

4.3.1 MultiPower laboratory infrastructure

The hardware testing in the MultiPower is done in phases. Due to the complexity of the equipment, the test cases are conducted in three phases; pretesting phase, testing phase and post testing analysis. The pretesting phase is same for test case one, two and three. The testing and post testing are different for each test case.

4.3.1.1 Test case1

Pretesting phase

For the pretesting phase the following steps and procedures are followed

1. Setup the test infrastructure as shown in Fig x
2. Loading the .ICD files for IED A and B
3. Modelling the logic schemes in PCM600
4. Configure the IEC 61850 GOOSE communication and signal transmission for IED A and B
5. Modelling the GOOSE reception quality with alarms and a control strategy
6. Testing the IEDs for measurements and alarm signals

The test setup for this test case is shown in xx. The infrastructure is setup to test reverse blocking scheme using GOOSE communication. 1. IED A opens its circuit breaker when the load is increased and sends GOOSE message to block IED B. This is the normal operation for interlocking scheme. The parameters which are used for this test case are shown in Table 2.

Table 2: Parameters used for the test case

Primary current	250A
Secondary current	5A
Primary voltage	20kV
Secondary voltage	0.4kV
xIn	0.06
Current pickup	15A
Load increase to	15kW

Before the test is performed, some measurements of the system are noted. The primary current of the CT for the feeder circuit breaker is 250 A while the secondary current is 5A. The xIn parameter is configured in the IED and this parameter is the pickup value at which the overcurrent function starts to operate. The secondary voltage of the system is 0.4kV.

After these measurements are noted, the next step is to configure the IEC 61850 GOOSE communication and the logic schemes for IEDs in PCM 600. The first step is to load the .ICD files in both the IEDs with the correct IP configuration. The GOOSE communication is configured in IED A and then the signals are mapped into IED B. The properties of the GOOSE communication are shown in Table 3 below. The MAC address, App ID and the time is configured according to IEC 61850 8-1. The max time of 1000ms is configured which is the GOOSE heartbeat. Hence a GOOSE message is sent after every one second under normal operation. The Min time is the transmission time under a GSE. This means that the average GOOSE time under a substation event should be less than 4ms. The logical nodes are configured as well and shown in Table 4. The logical node PTOC belongs to the LD0 logical group. Its general start operation (general) is selected along with the quality. The XCBR belongs to the CTRL group. The data attributes of status value of circuit breaker (stVal) and the quality is selected. These data attributes are wrapped in a GOOSE control block and are transmitted from IED A to IED B.

Table 3: GOOSE parameters for REF615

APP ID	0001
MAC Address	01-0C-CD-01-00-01
Max time	1000ms
Min time	4ms

Table 4: Logical nodes used for the test case

Logical Device	Logical Node	Data attribute
LD0	PTOC	Str
LD0	PTOC	quality
CTRL	XCBR	stVal
CTRL	XCBR	quality

After this validation is done, the logic model for the receiver REF615 IED B is modelled. The logic structure of the REF615 has two main functions; PHLPTOC and XCBR. The PHLPTOC operates the overcurrent protection once the pickup value xIn is met. It also blocks the PTOC operation for an upstream IED via a GOOSE message. Figure 9 shows the PCM model for the PHLPTOC start and the GOOSE quality logic. The 3I> op is the notation for overcurrent operation for PHLPTOC. The operate initiation is done through GOOSE as can be seen in GOOSESERV_BIN. The IED A sends this GOOSE message and the receiver PHLPTOC is modelled to operate on the subscription of this message. The XCBR is also modelled which gives the status of the circuit breaker throughout the overcurrent test. The PCM block for GOOSE quality logic is also modelled. This block ensures that the incoming GOOSE messages have ‘good’ quality. If the quality is bad then IED B changes its parameter settings to group 2 and the overcurrent blocking would not work. Alarms for the GOOSE quality are also modelled. LED10 lights up in case the PHLPTOC operates. LED 11 would light up when the GOOSE reception quality is bad. A control strategy of the GOOSE quality is shown in Figure 10.In case of any GOOSE communication misconfiguration or error, the alarm LED 11 lights up. This control strategy ensures GOOSE supervision between the IEDs. Shows this control strategy in a flow chart.

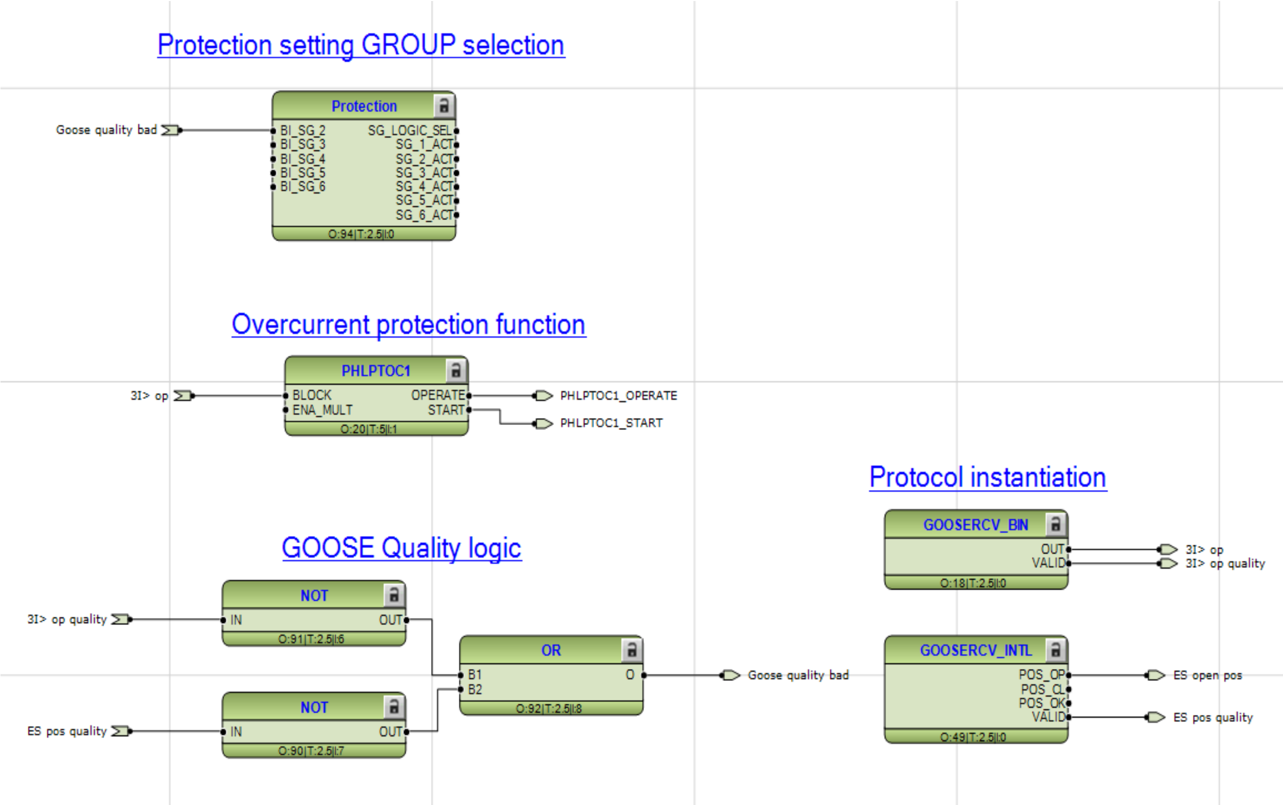


Figure 9: PCM Logic model for protection and GOOSE

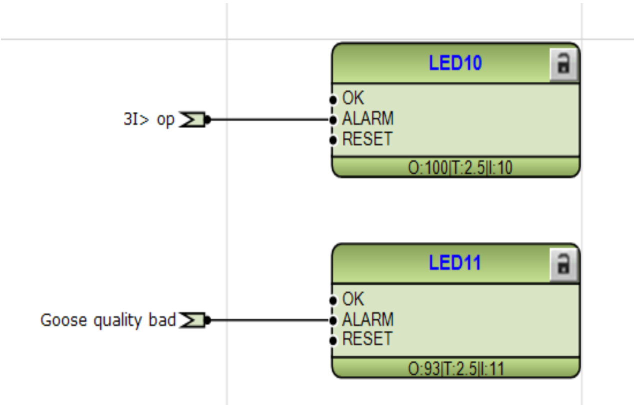


Figure 10. Alarms modelling for PTOC start and GOOSE quality

After the modelling and communciation, two test runs are performed to check that the GOOSE quality and alarms are properly working. In the first test the system is under normal operation and no substation event has happened. Under normal operation and measurement the IED A HMI can be seen in Figure 11. In Figure 12, three phase currents are seen on the local HMI. The values are lower than the pickup current value defined in tablex and hence no alarm is activated. The GOOSE configuration is also ok since the LED 11 is also not activated. In the second test GOOSE communication is disabled in the PCM600. As seen Figure 13 in the alarm LED lights up for 'No GOOSE communication'. Figure 14 shows the two tests which were performed to check and validate the GOOSE communciation and alarm LEDs for normal operation.

Figure 11: Normal operation for IED A

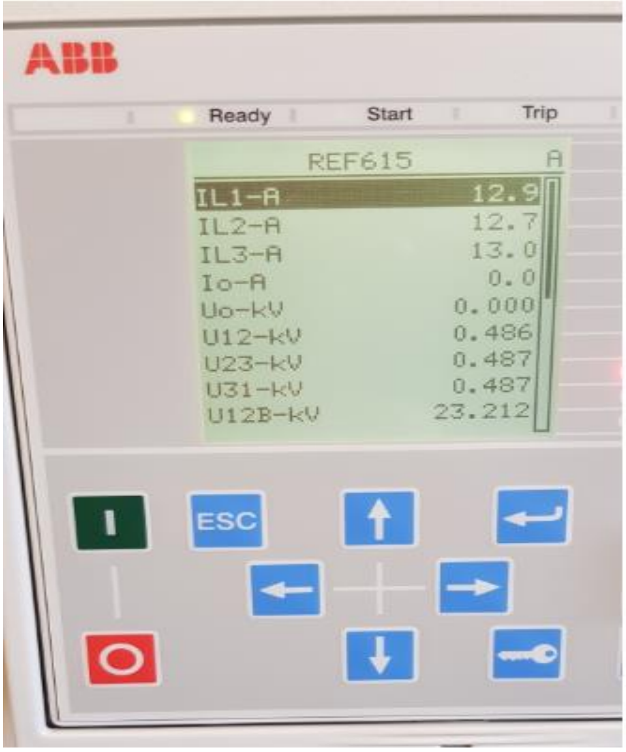


Figure 12: Three phase current measurements for feeder load

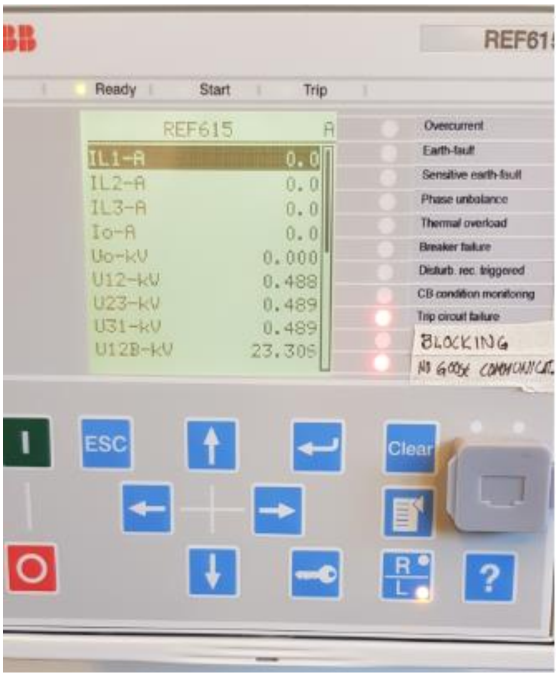


Figure 13: No GOOSE communication alarm

Table 5: Initial tests performed to test and validate GOOSE and alarms

Test no	Description	Result
1	Normal operation of system with no load increase	Circuit breaker for IED 1 is closed and no alarms are seen. GOOSE communication is also ok
2	GOOSE communication failure	The LED 9 and 11 light up showing that GOOSE communication has failed.

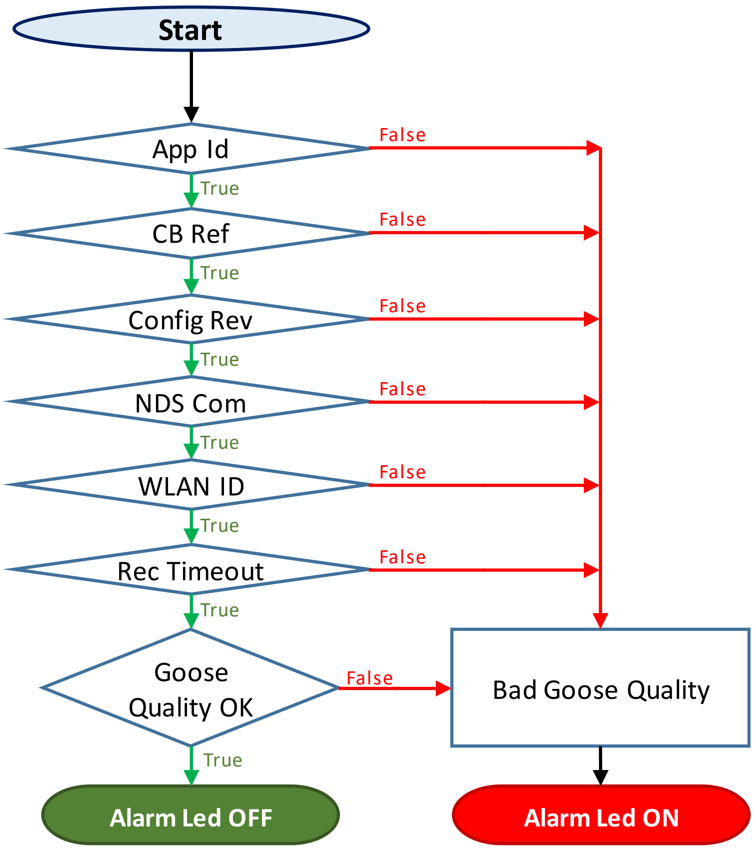


Figure 14: Flow Chart of the GOOSE Logic

Operational testing

After pretesting, the infrastructure is ready and has been validated for the reverse blocking test. For the test, the IEDs are loaded in PCM600. After that the feeder load is turned on by one step. This step is normal operation and the current measurements are below 15A. After noting this the feeder load is switched to the next step and immediately the circuit breaker for IED A is tripped while IED B circuit breaker remains closed. The next section shows the results for the current measurements and the GOOSE communication for this test.

Post Testing

Once the test is done, a systematic procedure is followed for analysing the results. These are listed below

- The blocking operation is verified in the WHMI
- The Wireshark packets are saved in PCAP and CSV files
- The tripped circuit breaker is reclosed for further testing
- The logic models for the IEDs are exported as SCD files

4.3.1.2 Test case 2

Pretesting

The pretesting procedure is repeated as in test case 1. An additional step of removing the Ethernet cable from IED B is performed.

Operation testing

The same steps are repeated and the feeder load is stepped up to the maximum. The circuit breakers for both IEDA and IEDB are now tripped and the grid connection point is lost. The post testing steps of test case one are repeated.

4.3.1.3 Test case 3

Pretesting

For this case, circuit breaker failure is tested. For this purpose, the trip function of the IEDA is turned off in PCM600. This ensures that the circuit breaker would never trip and not act on any protection setting.

Operational testing

The same steps are repeated and the feeder load is stepped up to the maximum. The circuit breakers do not trip and there is very high current in the system. Once the post testing steps are performed, the feeder load is switched one step down so that the high currents do not affect the laboratory equipment.

4.3.2 SESA Lab OFFIS

The experiments conducted in SESA Lab comprises of four phases: offline modelling in eMESASIM, IEC 61850 engineering, real time simulation, and post-test analysis. For this test platform, only test case one was tested. The main KPI here is to see the performance of GOOSE messages from vIEDs to OPAL RT for the controlling of the grid circuit breaker.

The offline modelling for the network model was done in eMEGASIM. The model is created to mimick the real behaviour of a micro grid at the MultiPower lab. The outgoing feeder or load is modelled such that after a time delay an overcurrent fault is triggered. This is done by having a load increase at the feeder. A switch is placed which can choose 9kW or 15kW load. Here it is assumed that in the first step under normal operation the load is 9kW. The over current fault is emulated by switching to 15kW where the threshold of 15A is met. Figure 15 shows this process. The switching time is modelled as 100ms after which the switch would change from 9KW to 15KW.

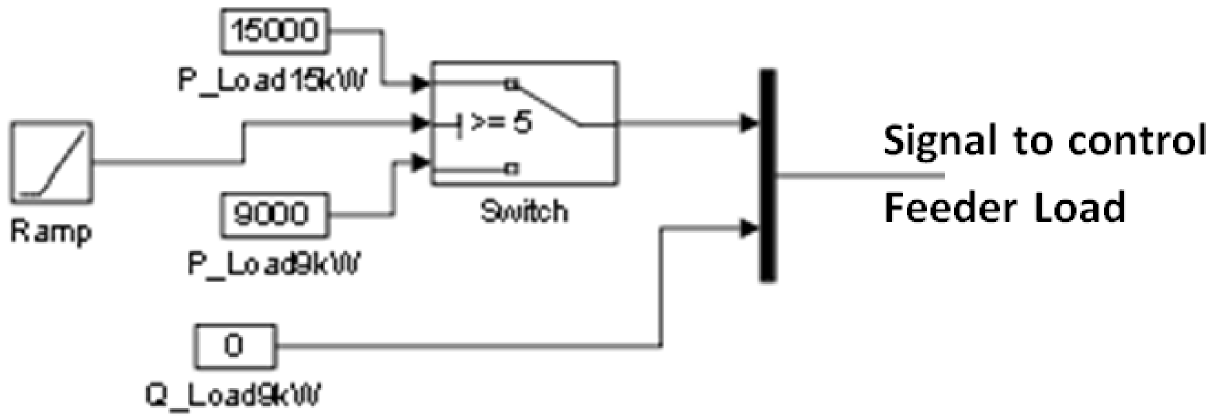


Figure 15: Switching load model in eMEGASIM

The respective three phase feeder currents of the load are sent to VIED 1 via UDP protocol. This is shown in Figure 16. The OpAsyncSend block can send measurements via UDP or TCP protocol to a valid IP address and port number. Here UDP protocol is selected and the IP and port of the VM running vIED 1 is selected.

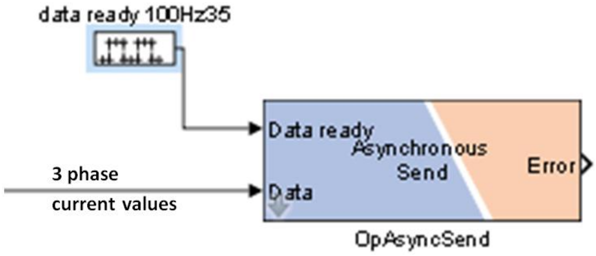


Figure 16: OpAsyncSend model to transmirt 3phase current values via UDP

VIED 1 receives the UDP values and converts them to GOOSE. It sends PTOC start (overcurrent) and XCBR (breaker position) status value to VIED via GOOSE protocol. When the emulated fault in the model causes the feeder current to rise above a set threshold, PTOC value of 1 is sent. Upon subscribing to this message VIED publishes a breaker control signal which is subscribed by the GOOSE subscriber block in the RT LAB model. This is shown in Figure 17. GOOSE_subscribe1 block receives the input signal from vIED and sends the Boolean value of the PTOC to control the grid circuit breaker. The subscriber block is configured using a Configured IED Description (CID) file generated using Helinks STS software. The complete communication process and the engineering files input between the OPAL simulator and the vIED is shown in Figure 7.

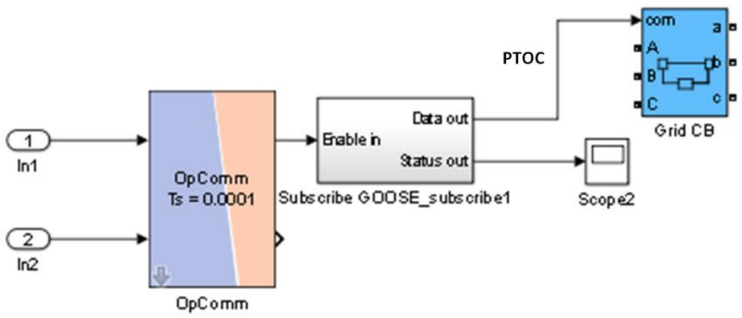


Figure 17: Circuit breaker control through GOOSE subscriber block

The IEC 61850 engineering process is designed in the HELINKS STS. In the HELINKS STS, the single line diagram of the MultiPower lab is modelled with the protection functions. These protection functions are defined for PTOC and XCBR. The communication model is then designed for the system integration. This communication model consists of the virtual IEDs and the GOOSE communication between them. Both these processes are compiled to create the SCD files which are needed for GOOSE publishing and subscribing. Figure 18 shows the engineering workflow in HELINKS STS. For the test case, three CID files are exported for the platform.

- CID file publisher for vIED1
- CID file for subscribing and publishing for vIED2
- CID file for subscribing for OPAL

With the completion of the modelling and engineering process, the platform is ready for real time simulation. The models and files are uploaded in the RT LAB platform. The simulation is run and the test case for reverse blocking is simulated. The RT LAB runs and in tandem the vIED is also started. The vIED GUI is shown in Figure 19. The vIED shown in the figure imports a valid SCD file. The internal program of the vIED dynamically reads the SCD file and the control block which it needs to send or receive. Hence any valid SCD file with a control block reference can be exported in the vIED and it can start the communication process. It also has an input control which in this case is UDP communication with a valid port. The threshold value of the input current which is15 has been programmed for this specific test case. Once the threshold is met, the vIED transmits GOOSE communication for a GSE event and the icon of the PTOC becomes true. The GSE event here is the start of the PTOC function. For future testing purposes, the logic for vIED can be added and modified for other protection functions and applications.

The GOOSE packets from vIEDs are transmitted back to OPAL where the packet reception is verified by a counter. The communication between the vIEDs is captured in Wireshark as GOOSE packets. The results for the GOOSE communication packets, transmission time and the network response of the system are shown in the next section for results.

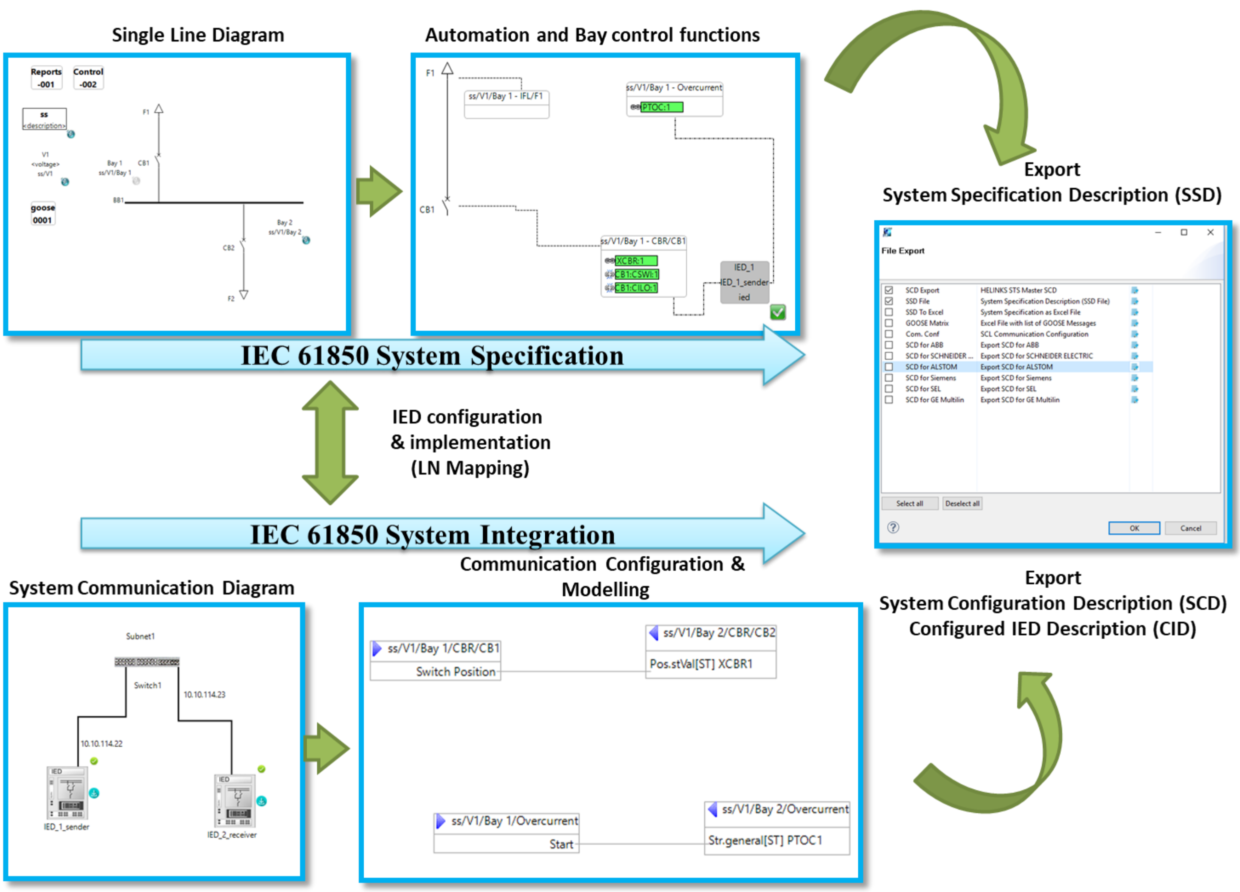


Figure 18: Engineering workflow for importing SCD files

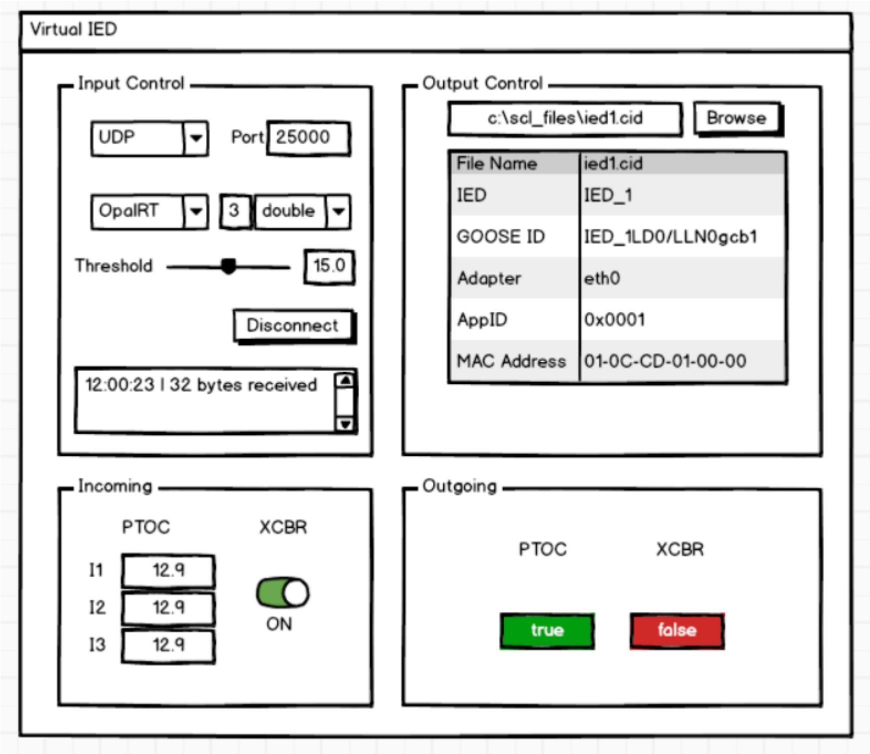


Figure 19: vIED GUI

5 Results and conclusion

The results for all the three test cases for MultiPower and the SESA lab are documented in the following subsections. Finally there is a comparison of the results and conclusions about the comparison of the two platforms are given in the subsection below.

5.1 VTT Laboratory infrastructure

The results were compiled for the current measurements, the events list and the Wireshark packet sniffer. The results are shown below for each test case.

5.1.1 Test case one

For test case one the current response of the feeder load is shown in Figure 20 . The interconnection is made for the test setup and the current measurements for normal system operation are noted. The feeder load is then increased to the maximum and the currents on the three phases become 25 A. The PTOC threshold is met and the GOOSE messages are sent with a PTOC Boolean of true. After a time of 46ms the circuit breaker trips and the current goes to zero. For the grid IED the circuit breaker operation is shown in Figure 20. After 120 ms when the GOOSE message is sent the receiver IED blocks the circuit breaker from tripping.

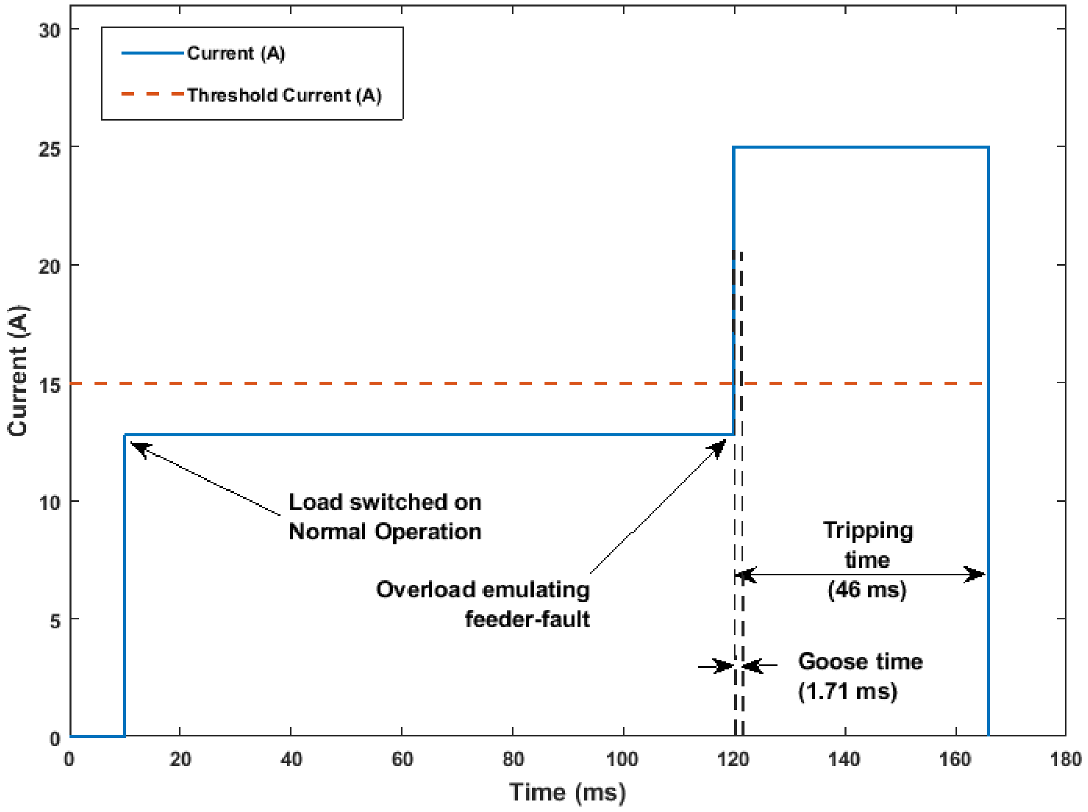


Figure 20: Current response of the feeder loa

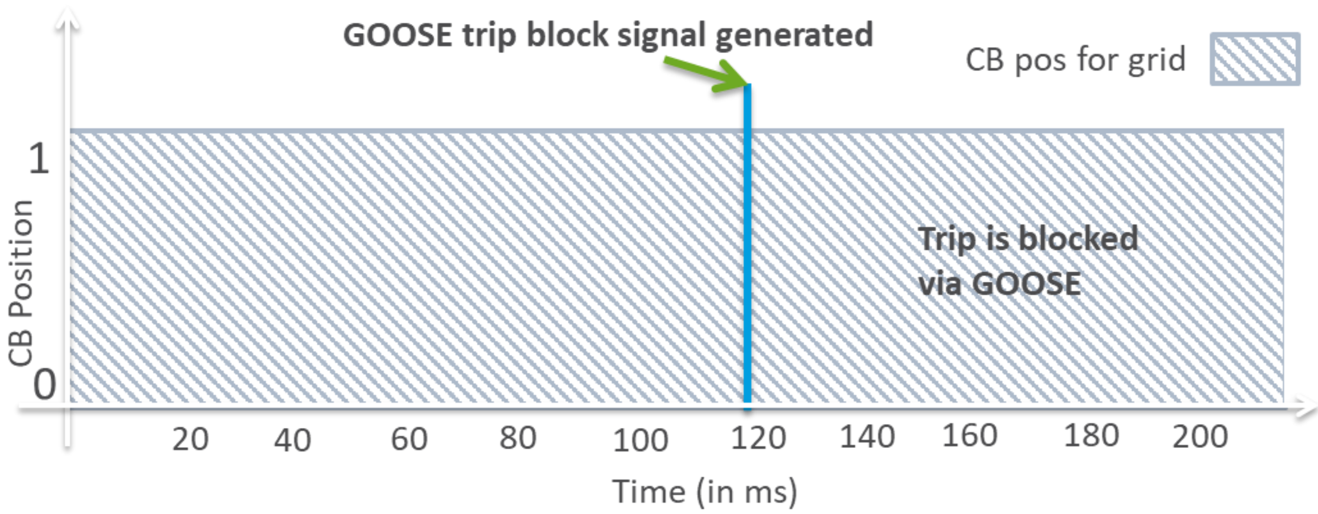


Figure 21: Circuit breaker operation for grid IED

Figure 22 shows a screenshot of the events list from PCM600 WHMI for the feeder IED A. The green circle shows the start of the PHLPTOC operation when the threshold is met. After 46ms the CBXCBR1 position is open. To verify the GOOSE communication and the Ethernet communication Figure 23 shows the output messages which are sent by the sender IED.

28.06.2019	11:15:29.652	CBXCBR1	POSITION	open
28.06.2019	11:15:29.661	Voltage (3UB,VT)	WARNING	True
28.06.2019	11:15:29.634	TCSSCBR2	ALARM	False
28.06.2019	11:15:29.631	PHLPTOC1	OPERATE	L1,L2,L3
28.06.2019	11:15:29.631	TRPPTRC2	TRIP	True
28.06.2019	11:15:29.631	TRPPTRC1	TRIP	True
28.06.2019	11:15:29.606	PHLPTOC1	START	L1,L2,L3
28.06.2019	11:14:56.659	TCSSCBR2	ALARM	True
28.06.2019	11:14:53.659	TCSSCBR2	ALARM	False
28.06.2019	11:14:26.715	GNRLLTMS1	Synch status	Up
28.06.2019	11:14:26.715	GNRLLTMS1	Synch source	SNTP primary
28.06.2019	11:14:25.465	TCSSCBR2	ALARM	True
28.06.2019	11:14:22.670	Ethernet supervision	CHLIV	True
28.06.2019	11:14:22.480	VMMXU1	HIGH_WARN	True
28.06.2019	11:14:22.480	VMMXU1	HIGH_ALARM	True
28.06.2019	11:14:14.164	Security application	Administrator access	Configuration change

Figure 22: Screenshot of the events list from PCM600 WHMI for the feeder IED A

Parameter Setting

Parameter Name	IED Value	New Value	Unit	Min.	Max.	Step
Reset counters	False	False				
Received msgs	0	0		0	10000000	1
Transmitted msgs	235	235		0	10000000	1
State changes	0	0		0	10000000	1
SeqNum changes	0	0		0	10000000	1
Test msgs	0	0		0	10000000	1
State warnings	0	0		0	10000000	1
Seq. warnings	0	0		0	10000000	1
Recv. timeouts	0	0		0	10000000	1
ConfRev errors	0	0		0	10000000	1
NdsComm errors	0	0		0	10000000	1
Dataset errors	0	0		0	10000000	1

Figure 23: Output messages sent by the sender IED in PCM600

For the receiver grid IED Figure 24 shows that the PHLPTOC operation for the IED has been blocked. The circuit breaker for the IED does not trip and it is blocked from a GOOSE message from the sender IED.

Parameter Setting

Parameter Name	IED Value	New Value	Unit	Min.	Max.	Step
TRPPTRC1	off	off				
TRPPTRC2	off	off				
SSCBR1	on	on				
INRPHAR1	on	on				
EFIPTOC1	on	on				
EFHPTOC1	on	on				
EFLPTOC1	on	on				
EFLPTOC2	on	on				
PHIPTOC1	on	on				
PHHPTOC1	off	off				
PHLPTOC1	blocked	blocked				
PHLPTOC2	off	off				
T1PTTR1	on	on				
CCBRBRF1	on	on				
NSPTOC1	on	on				
NSPTOC2	on	on				
PDNSPTOC1	off	off				
TCSSCBR1	on	on				
TCSSCBR2	on	on				

Figure 24: PHLPTOC blocked for receiver IED B

For the in depth GOOSE analysis, Wireshark packets are deciphered. Figure 25 shows how the st number value of the GOOSE increases for each state change. The st number is 1 when the IEDs are loaded in PCM 600 with a default data set of XCBR as 1 and PTOC as false. With a load increase, the threshold value is met and PTOC becomes true for feeder IED and the st num increases to 2. After 46ms when the circuit breaker opens, the state number increases again as the default XCBR value is now changed. Finally when the current goes to zero, the PTOC resets and there is an increment in the st number. For the receiver IED, the circuit breaker remains closed through the test phase as can been seen in the diagram. Table 6 shows how the GOOSE st number corresponds with the GSE events for this test case.

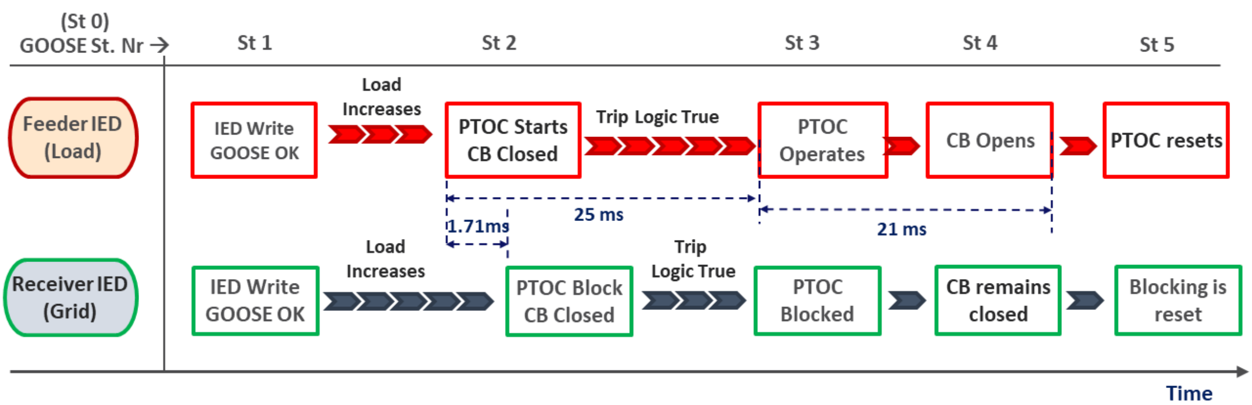


Figure 25: Relation of stNum with GSE for sender and receiver IEDs

Table 6: Relation of stNum with GSE

St num	GSE event
1	IEDs are loaded with default data set
2	PTOC becomes true
3	Circuit breaker opens
4	Current goes to zero and PTOC is reset
5	PTOC resets

The Wireshark streams are analysed for the GOOSE transmission time, payload and the stNum change. Figure 26 shows the wireshark packets which are transmitted for test case. The packets which have a PTOC of true and an stNum of 2 are highlighted. These are packets 1525, 1526, 1527 and 1528. The source MAC address is of the REF615 sender IED while the destination is the GOOSE destination address as specified in table x.

Figure 27 shows the payload of packet 1525. The first two highlighted parts show the st num and the packet number. The third highlighted part shows the payload for CBXCBR position. The value 80 shows that the circuit breaker is closed. The Boolean True shows that the PTOC is on. This verifies that the GOOSE communication adheres to the events of the PCM as shown in figure x. The state number changes and payload change also show how GOOSE packets can be analysed and deciphered for GSE events.

The GOOSE transmission time is measured by analysing the Wireshark packets. The average time of these packets is calculated and is taken as the GOOSE transmission time for the blocking operation. This was calculated to be 1.71ms as shown in equation x.

$$t_t = \frac{(0.329+2.326+2.477)}{3} \text{ ms} = 1.71 \text{ ms}$$

The area of investigation is the time it takes for GOOSE to be transmitted after st num change from 1 to 2 i.e PTOC Boolean change from false to true. Figure 28 shows the packets and the time delay between the packets for stNum change of 1 to 2.

goose

No.	Time	Source	Destination	Protocol	Length	Info
798	11.098138	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
869	11.998096	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
930	12.898087	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
990	13.798081	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1061	14.698077	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1124	15.598065	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1193	16.498052	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1259	17.398044	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1332	18.298038	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1392	19.198019	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1451	20.098028	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1524	20.998019	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1525	21.067855	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1526	21.068184	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1527	21.070550	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	
1528	21.073027	AbbOy/Me_26:f6:06	Iec-Tc57_01:00:01	GOOSE	165	

Figure 26: Wireshark packets for stNum = 2 for test case one

```
> Frame 1525: 165 bytes on wire (1320 bits), 165 bytes captured (1320 bits) on interface 0
> Ethernet II, Src: AbbOy/Me_26:f6:06 (00:21:c1:26:f6:06), Dst: Iec-Tc57_01:00:01 (01:0c:cd:01:00:01)
v GOOSE
    APPID: 0x0001 (1)
    Length: 151
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  v goosePdu
      gocbRef: AA1N1Q03A1LD0/LLN0$GO$g_cntl1
      timeAllowedtoLive: 1100
      datSet: AA1N1Q03A1LD0/LLN0$DATASET1
      goID: AA1N1Q03A1LD0/LLN0.g_cntl1
      t: Jun 28, 2019 10:15:29.606386363 UTC
      stNum: 2
      sqNum: 0
      test: False
      confRev: 400
      ndsCom: False
      numDatSetEntries: 4
    v allData: 4 items
      v Data: bit-string (4)
          Padding: 6
          bit-string: 80
      > Data: bit-string (4)
      v Data: boolean (3)
          boolean: True
      > Data: bit-string (4)
```

Figure 27: Payload of packet 1525 in Wireshark

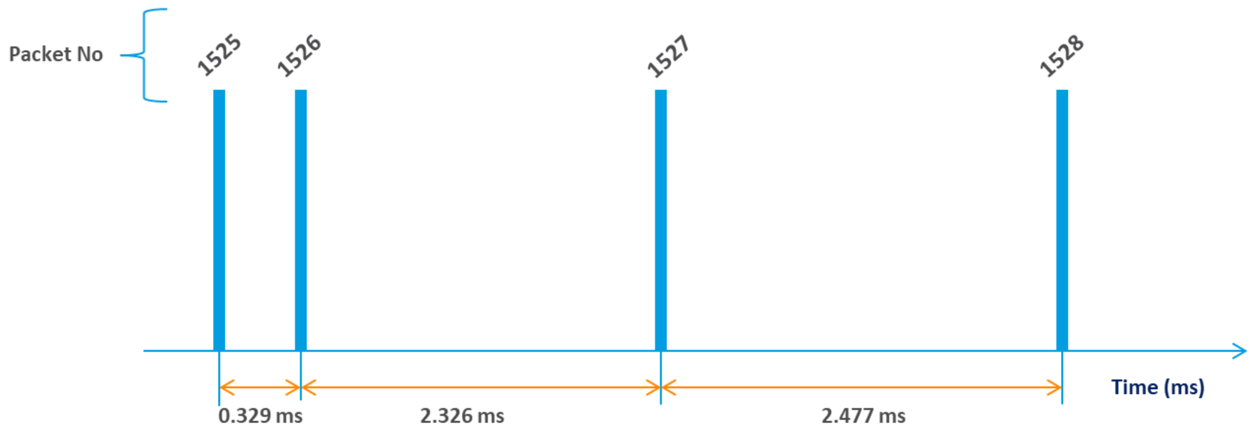


Figure 28: Transmission of GOOSE packets for stNum =2

5.1.2 Test case two

For test case two, the main KPI is to see how GOOSE communication failure affects GSE for blocking operation. Before testing the Ethernet cable for IED B is taken out. The current response of the feeder load is same as for test case one in Figure 20. The important thing to analyse is the response of the grid IED B and how it reacts to a load increase without GOOSE communication. Figure 29 shows the response of the circuit breaker for IED B. After 120 ms the over load takes place but since there is no Ethernet cable connected to the IED, there is no GOOSE message reception. The grid IED B trips after 43ms. The sender IED trips in 47ms. Figure 30 and Figure 31 show the PCM events for the sender and receiver IED. For the receiver IED, the highlighted part in blue shows that Ethernet supervision is off and the GSEGGIO alarm is true which means that the input and output Ethernet measurements are malfunctioned. The IED changes to active group 2 as this was the logic configured in Figure 9. The logic changes the active protection settings group from 1 to 2 if there is a GOOSE communication failure. Table 7 also shows the tripping time for the grid and receiver IED. The PHLPTOC for the feeder IED A starts 3ms before the grid IED. These 3 milliseconds would have been sufficient time for the blocking message to be sent if there was GOOSE communication. However without GOOSE the circuit breakers for both IEDs A and B trip in 47ms and 43ms respectively.

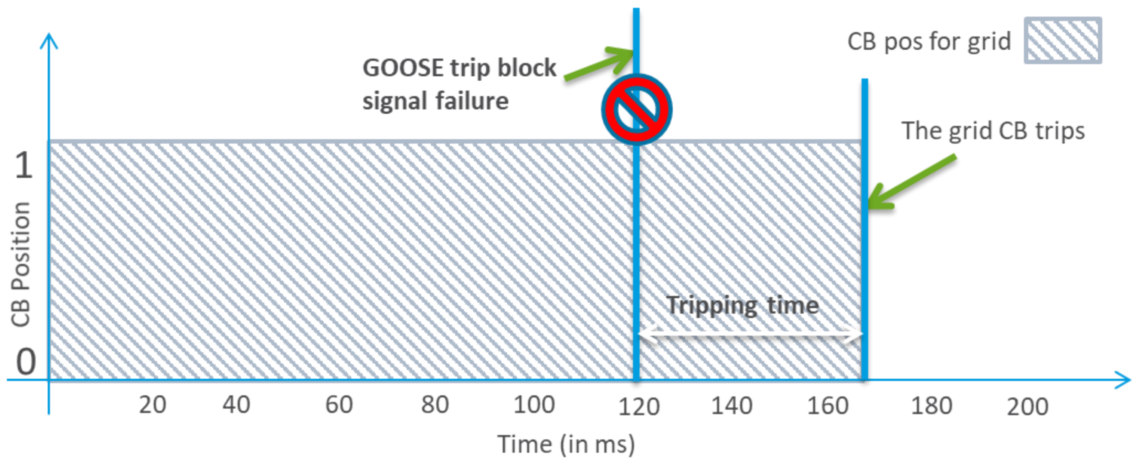


Figure 29: Circuit breaker operation for grid IED

27.06.2019	10:59:02.375	CBXCBR1	POSITION	open
27.06.2019	10:59:02.384	Voltage (3UB,VT)	WARNING	True
27.06.2019	10:59:02.359	TCSSCBR2	ALARM	False
27.06.2019	10:59:02.357	PHLPTOC1	OPERATE	L1,L2,L3
27.06.2019	10:59:02.357	TRPPTRC2	TRIP	True
27.06.2019	10:59:02.357	TRPPTRC1	TRIP	True
27.06.2019	10:59:02.332	PHLPTOC1	START	L1,L2,L3

Figure 30: PCM600 events for sender IED A

27.06.2019	10:59:02.376	CBXCBR1	POSITION	open
27.06.2019	10:59:02.356	TCSSCBR2	ALARM	False
27.06.2019	10:59:02.354	PHLPTOC1	OPERATE	L1,L2,L3
27.06.2019	10:59:02.354	TRPPTRC2	TRIP	True
27.06.2019	10:59:02.354	TRPPTRC1	TRIP	True
27.06.2019	10:59:02.329	PHLPTOC1	START	L1,L2,L3
27.06.2019	10:58:52.511	Protection LLN0	Active group	2
27.06.2019	10:58:52.509	GSEGGIO1	ALARM	True
27.06.2019	10:58:33.671	Ethernet supervision	CHLIV	False

Figure 31: PCM600 events for receiver IED B

Table 7: Comparison of tripping time IED A and IEDB

IED / Function	**Feeder IED A**	**Grid IED B**
PHLPTOC start (ms)	117	120
CB open (ms)	164	163
Tripping time (ms)	47	43

5.1.3 Test case three

For test case three it is assumed that there is a circuit breaker switching failure for the feeder IED A. The tripping function of the feeder IED A is switched off from the PCM600. The current response of the feeder current is shown in Figure 32 . Once the feeder overload takes place the threshold value of 15A is met and the GOOSE messages are transmitted to block the grid IED B. The test case is very similar to test case one except that there is no tripping of the feeder circuit breaker which is assumed to be failed. This scenario causes high currents in the system which can lead to other protection issues. The GOOSE transmission time and current response of the feeder load are the main KPI for this test case. The events from the PCM600 for both sender and receiver IEDs are shown in Figure 33 and Figure 34. In Figure 33, it can be seen that the PHLPTOC operates but does not enable the CBXCBR to open. For the grid IED, the PHLPTOC is blocked from operation. This is verified in Figure 35 that shows the WHMI screenshot of the blocking operation for grid IED B.

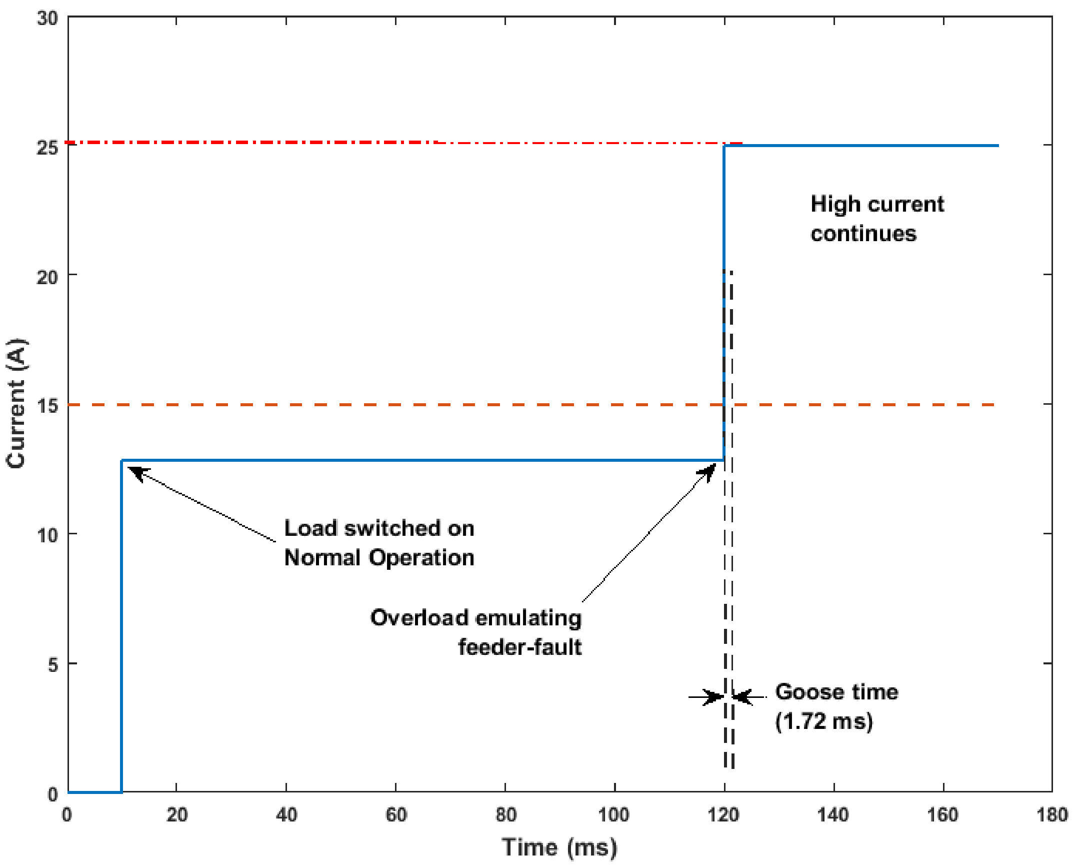


Figure 32: Current response of the feeder load

Date	Time	Device	Object text	Event
28.06.2019	11:35:20.570	PHLPTOC1	OPERATE	L1,L2,L3
28.06.2019	11:35:20.545	PHLPTOC1	START	L1,L2,L3
28.06.2019	11:35:08.893	TCSSCBR2	ALARM	True
28.06.2019	11:35:05.325	TCSSCBR2	ALARM	False
28.06.2019	11:34:35.570	Ethernet supervision	CHLIV	True
28.06.2019	11:34:29.135	GNRLLTMS1	Synch source	SNTP primary
28.06.2019	11:34:24.295	TCSSCBR2	ALARM	True
28.06.2019	11:34:21.310	VMMXU1	HIGH_WARN	True
28.06.2019	11:34:21.310	VMMXU1	HIGH_ALARM	True
28.06.2019	11:34:11.941	Security application	Administrator access	Configuration change

Figure 33: Screenshot of the events list from PCM600 WHMI for the feeder IED A

Date	Time	Device	Object text	Event
28.06.2019	11:35:20.542	PHLPTOC1	START	L2
28.06.2019	11:34:24.611	Protection LLN0	Active group	1
28.06.2019	11:34:24.609	GSEGGIO1	ALARM	False
28.06.2019	11:34:15.119	Protection LLN0	Active group	2
28.06.2019	11:34:15.119	GSEGGIO1	ALARM	True

Figure 34: Screenshot of the events list from PCM600 WHMI for the feeder IED A

Parameter Setting

Parameter Name	IED Value	New Value	Unit	Min.	Max.	Step
TRPPTRC1	off	off				
TRPPTRC2	off	off				
SSCBR1	on	on				
INRPHAR1	on	on				
EFIPTOC1	on	on				
EFHPTOC1	on	on				
EFLPTOC1	on	on				
EFLPTOC2	on	on				
PHIPTOC1	on	on				
PHHPTOC1	off	off				
PHLPTOC1	blocked	blocked				
PHLPTOC2	off	off				
T1PTTR1	on	on				
CCBRBRF1	on	on				
NSPTOC1	on	on				
NSPTOC2	on	on				
PDNSPTOC1	off	off				
TCSSCBR1	on	on				
TCSSCBR2	on	on				

Figure 35: PHLPTOC blocked for receiver IED B

For this test case, the GOOSE communication and Wireshark packets are analysed in detail like in test case one. Figure 36 shows the relationship between the GOOSE stNum and the GSE. The stNum only changes from 1 to 2 as there is only one GSE which the PTOC Boolean start. The circuit breaker position does not change throughout the test and hence there is no further stNum increment. Fig x shows the stNum events and the GSE.

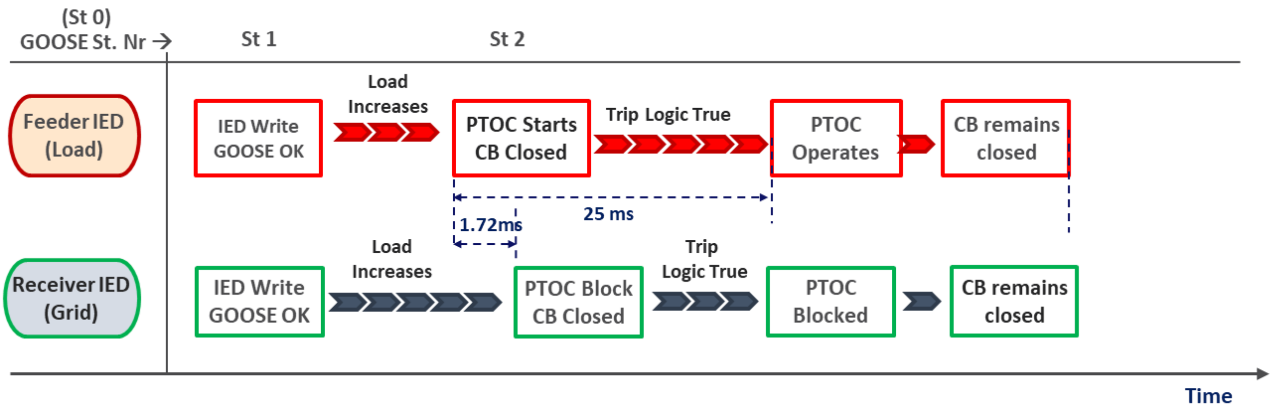


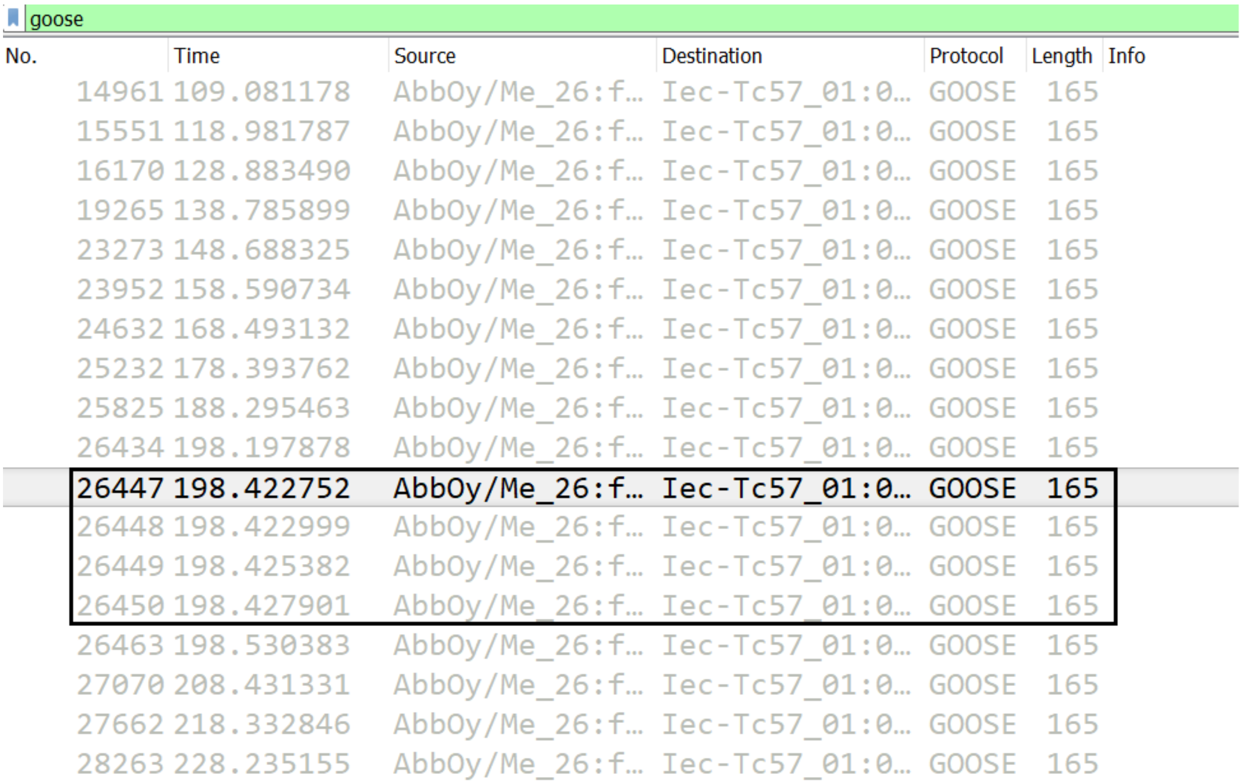
Figure 36: Relation of stNum with GSE for sender and receiver IED

Table 8: Relation of stNum with

St num	GSE event
1	IEDs are loaded with default data set
2	PTOC becomes true

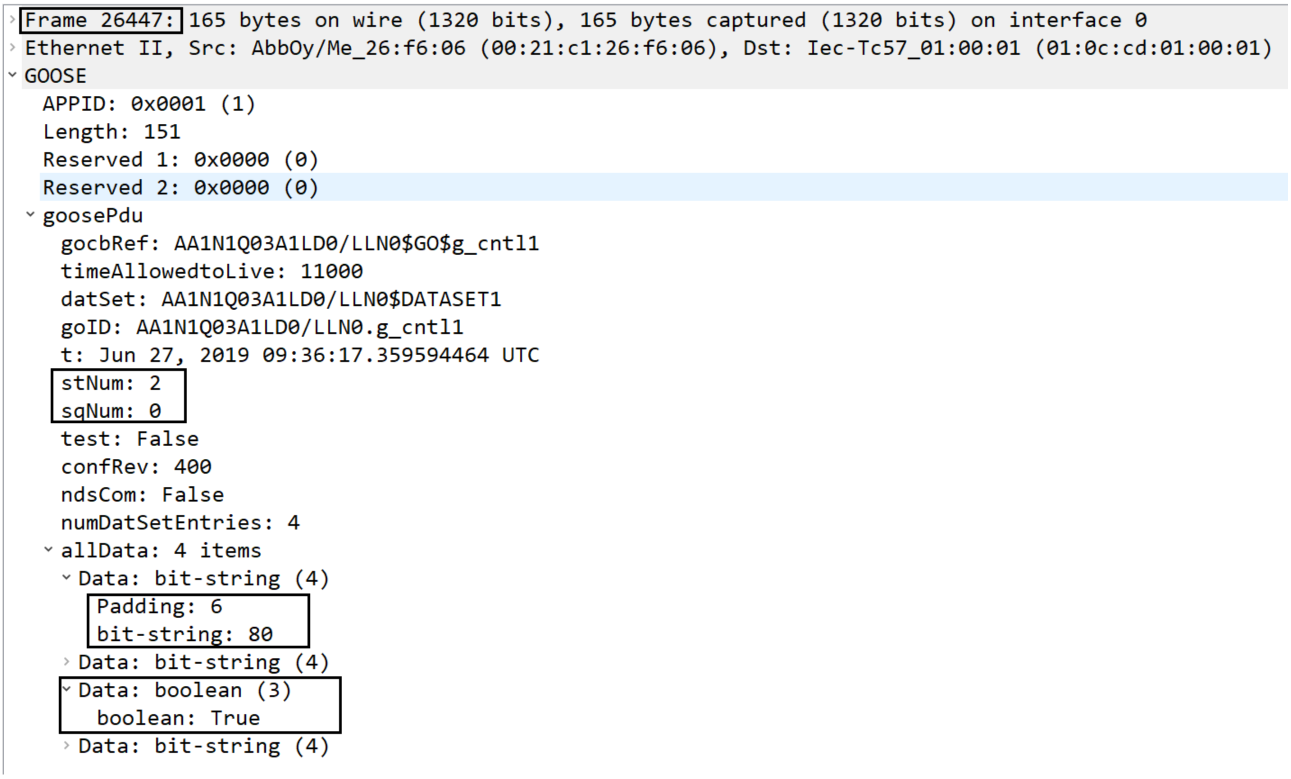
The Wireshark streams are analysed for the GOOSE transmission time, payload and the stNum change. Figure 37 shows the Wireshark packets which are transmitted for test case. The packets which have a PTOC of true and an stNum of 2 are highlighted. These are packets 26447, 26448, 26449 and 26450. The source MAC address is of the REF615 sender IED while the destination is the GOOSE destination address as specified in Table 3.

Figure shows the payload of packet 1525. The first two highlighted parts show the stNum and the packet number. The third highlighted part shows the payload for CBXCBR position. The value 80 shows that the circuit breaker is closed. The Boolean True shows that the PTOC is on. This verifies that the GOOSE communication adheres to the events of the PCM as shown in figure x. The state number changes and payload change also show how GOOSE packets can be analysed and deciphered for GSE events.


goose

No.	Time	Source	Destination	Protocol	Length	Info
14961	109.081178	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
15551	118.981787	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
16170	128.883490	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
19265	138.785899	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
23273	148.688325	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
23952	158.590734	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
24632	168.493132	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
25232	178.393762	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
25825	188.295463	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
26434	198.197878	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
26447	198.422752	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
26448	198.422999	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
26449	198.425382	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
26450	198.427901	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
26463	198.530383	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
27070	208.431331	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
27662	218.332846	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	
28263	228.235155	AbbOy/Me_26:f…	Iec-Tc57_01:0…	GOOSE	165	

Figure 37: Wireshark packets for stNum = 2 for test case three



```
> Frame 26447: 165 bytes on wire (1320 bits), 165 bytes captured (1320 bits) on interface 0
> Ethernet II, Src: AbbOy/Me_26:f6:06 (00:21:c1:26:f6:06), Dst: Iec-Tc57_01:00:01 (01:0c:cd:01:00:01)
v GOOSE
    APPID: 0x0001 (1)
    Length: 151
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  v goosePdu
      gocbRef: AA1N1Q03A1LD0/LLN0$GO$g_cntl1
      timeAllowedtoLive: 11000
      datSet: AA1N1Q03A1LD0/LLN0$DATASET1
      goID: AA1N1Q03A1LD0/LLN0.g_cntl1
      t: Jun 27, 2019 09:36:17.359594464 UTC
      stNum: 2
      sqNum: 0
      test: False
      confRev: 400
      ndsCom: False
      numDatSetEntries: 4
    v allData: 4 items
      v Data: bit-string (4)
          Padding: 6
          bit-string: 80
      > Data: bit-string (4)
      v Data: boolean (3)
          boolean: True
      > Data: bit-string (4)
```

Figure 38: Payload of packet 1525 in Wireshark

The GOOSE transmission time is measured by analysing the Wireshark packets. The average time of these packets is calculated and is taken as the GOOSE transmission time for the blocking operation. This was calculated to be 1.71ms as shown in equation x.

$$t_t = \frac{(0.247+2.383+2.519)}{3}\ \text{ms} = 1.72\ \text{ms}$$

The area of investigation is the time it takes for GOOSE to be transmitted after st num change from 1 to 2 i.e PTOC Boolean change from false to true. Figure x shows the packets and the time delay between the packets for stNum change of 1 to 2.

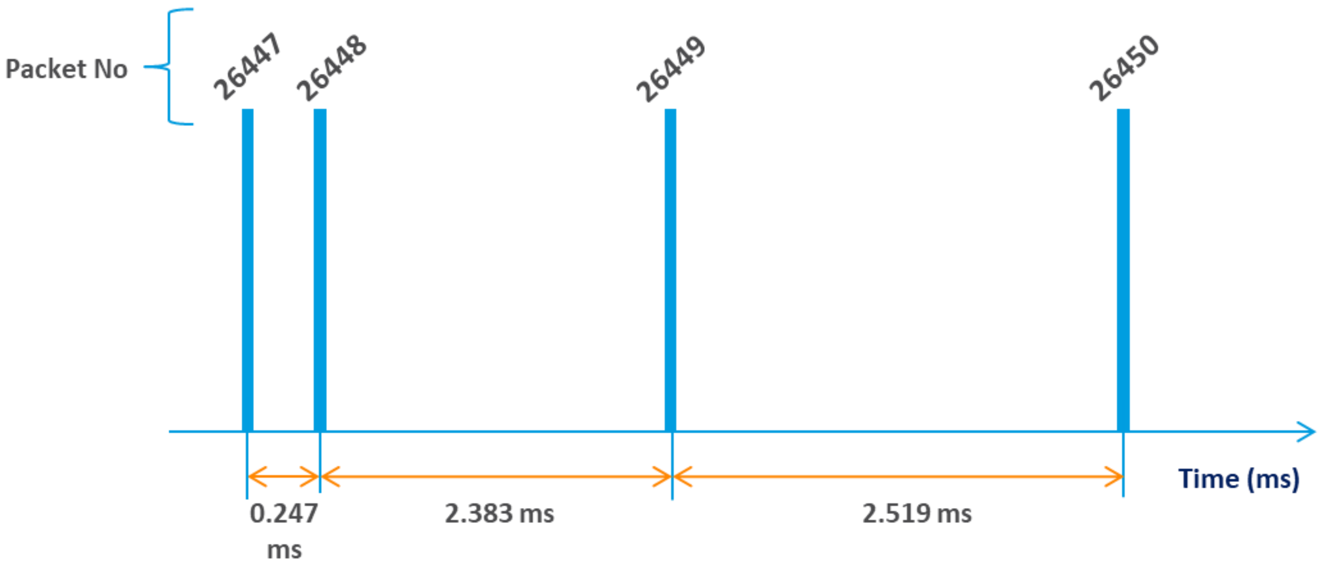


Figure 39: Transmission of GOOSE packets for stNum =2

The results from the three test cases define the operation of reverse blocking scheme, GOOSE communication failure and circuit breaker tripping failure. The KPIs of GOOSE transmission time, circuit breaking time and the current response of the feeder load are validated. Table 9 shows a comparison of GOOSE transmission and circuit breaker time for all the three test cases.

Table 9: Comparison of GOOSE transmission time and circuit breaker tripping time for all the three test cases

KPI / Test case	GOOSE transmission time (ms)	Circuit breaker trip-ping time (ms)
1	1.71	46
2	-	43ms for IED A and 47ms for IED B
3	1.72	-

5.2 SESA Lab OFFIS

The results for the SESA Lab were compiled in real time. Using the test setup at OFFIS, the network at VTT system was simulated in real time and the performance of an IEC-61850 compliant virtual IED based setup was assessed. The key parameters measured and recorded over the simulation period of 9s, the feeder load current, the CB positions and the GOOSE value and status (stNum and sqNum). In the model, at a pre-defined time an over-current situation was initiated and the time when the over-current threshold was reached was defined as the over-current time (T_{OC}). The GOOSE subscription time (T_G) is the time when the first GOOSE message after the substation event was received. The zero-current time (T_Z) is when the feeder circuit breaker is fully open, and the line currents are zero. From these times (T_{OC}, T_G and T_Z) the GOOSE round-trip time (T_{RTP}) and maximum clearing time (T_{MC}) were calculated. **Error! Reference source not found.** shows the times measurements for the round-trip time and the max clearing time. They are calculated from the equations (1) and (2).

$$T_{RTP} = T_G - T_{OC} \quad (1)$$

$$T_{MC} = T_Z - T_{OC} \quad (2)$$

For the experimental execution, after 3 seconds the feeder load is turned on. Until 8 seconds the system is under stable condition i.e. the current is below the threshold limit for PTOC which is 14.5A. At 8 seconds the overload takes place and the overcurrent threshold is met. At this overloading, the UDP messages are translated to GOOSE and wrapped in the vIED and sent back to the OPAL-RT simulator. The OPAL-RT subscribes to this message and the GOOSE stNum and the sqNum are observed. Figure 40(a) shows the current characteristics of the feeder load. It can be seen from the figure that when the threshold is met, the current goes to zero after T_{MC}. The tripping time for feeder is set to 45ms and for the grid circuit breaker to 50ms, once the overcurrent is met. The relays in the model are configured in such a way that within a 5ms interval both the feeder CB and grid CB will trip. This modelling is done to emulate a real scenario for relay protection and control. If there is no GOOSE in the system, both the circuit breakers would trip, and no blocking operation would take place. However, due to the vIED and GOOSE communication, the vIED sends a PTOC blocking message to the OPAL-RT grid circuit breaker that prevents it from tripping. This is shown in Figure 40 (b) and (c). At 8002ms a substation event (overcurrent) occurred and a GOOSE message was published by the vIED. This published message is again received by the subscriber in OPAL-RT model at 8002.6ms.

The GOOSE StNum is incremented from 1 to 2 as seen in Figure 41 (a). At this time the GOOSE sqnum becomes zero since a substation event has changed. The data set for the PTOC becomes true and verifies that the GOOSE event has taken place. **Error! Reference source not found.** shows a Wireshark screenshot of the GOOSE packet when stNum is 2 and sqnum is 0. The source MAC address which is highlighted in this figure, is that of the VM on which the vIED is running on. The destination GOOSE address is also seen as that which is configured in the CID file. The Boolean value highlighted in figure x shows that true, which means that PTOC is on.

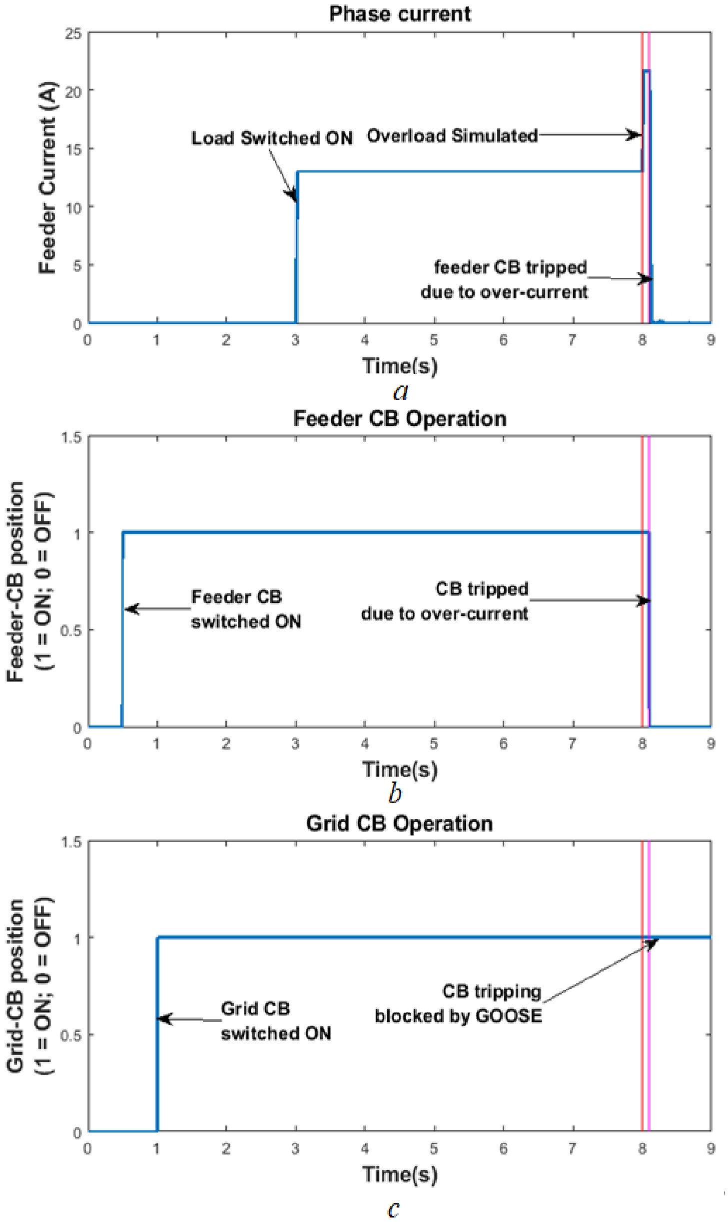


Figure 40: Real time simulation results (a) Feeder current (b) Feeder CB position (c) Grid CB position

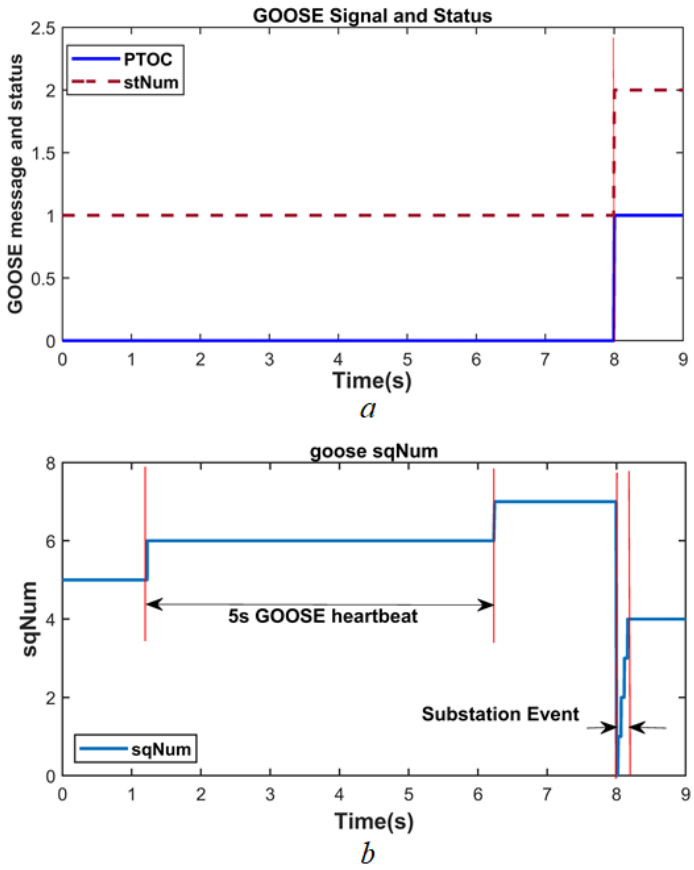


Figure 41: (a) GOOSE signal and stNum (b) sqNum

Table 10: GOOSE round trip and max clearing results

Event Annotation	***Time (ms)***
GOOSE round trip	TRTP 0.6
Maximum clearing	TMC 67.8

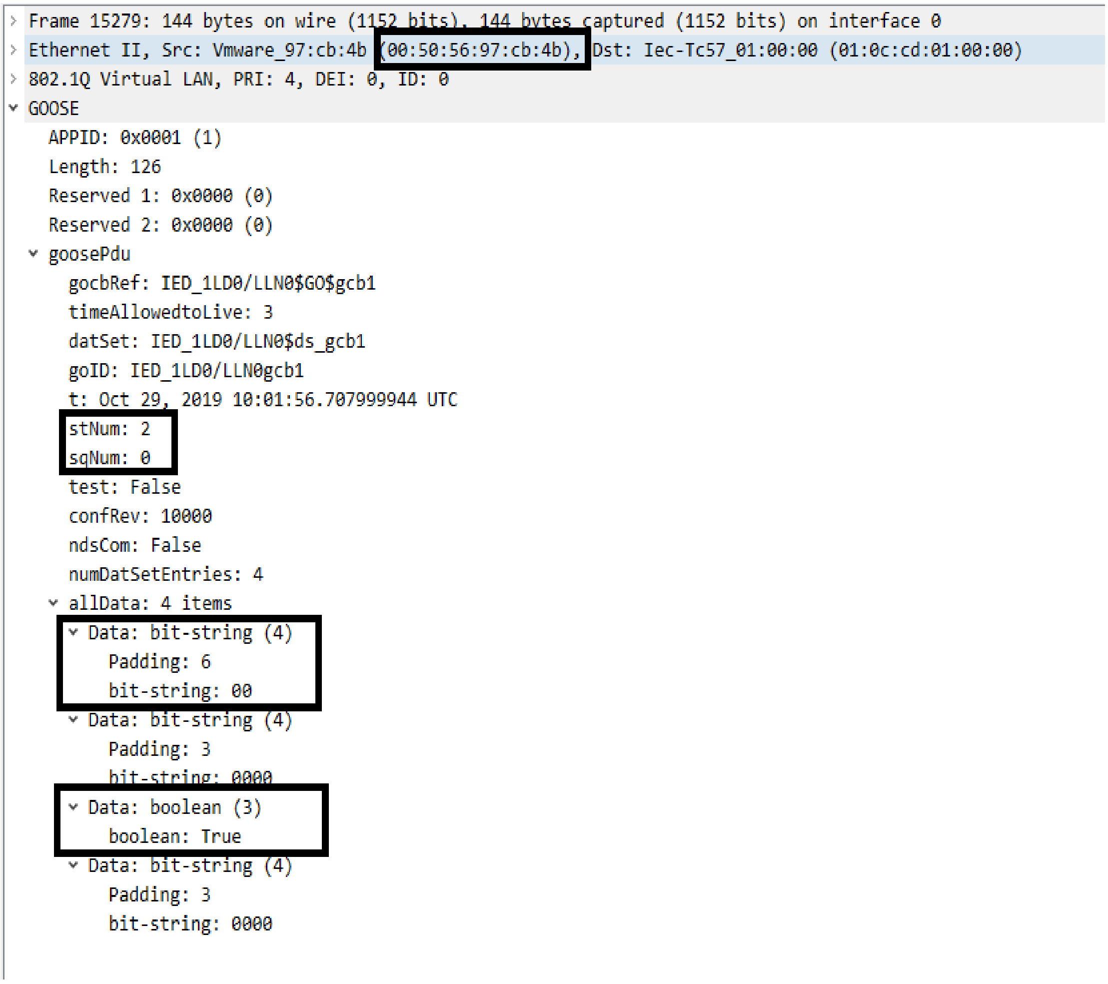


Figure 42: Wireshark packet for Stnum=2

6 Open Issues and Suggestions for Improvements

In this research work, the results for both hardware IED and real time simulation systems with vIED, are compared and analysed. The measurements for the current values, the GOOSE stNum, GOOSE sqNum and the timings of the tripping and the blocking are measured. The results for the GOOSE show that in the real time simulation, once the substation event of overcurrent occurs, the GOOSE message is faster than the ABB REF615 relays. For the hardware infrastructure, the operational time of the relays and the processing time of physical inputs of the current measurements could account for the higher GOOSE delay. In the virtual environment, the vIED runs on a VM and hence the hardware operating delays and the processing time of the relays are minimised.

The research work validates the performance of the real time simulation environment with the hardware infrastructure. The performance of the virtual environment can be further improved by having a time synchronisation PTP server for future work. Also, more complex protection scenarios can be modelled and simulated using the virtual platform and vIED can be further developed to deal with complex protection functions. The communication for Sampled Values is also incorporated in the vIED software and will be a useful feature to test current and voltage measurements for sampled value scenarios. Ongoing work is also underway to develop cybersecurity attacks for the vIED which can disrupt or attack the operating system of the vIED and can cause undesirable delays for the IEC 61850 communication. These cyber security features will help to test the security vulnerabilities for IEDs and IEC 61850.

Further suggestions are proposed for future testing and development for both the RIs. For further work in the MultiPower laboratory, the following is proposed:

- The ABB REF615s should be tested for Photovoltaic protection such as Fault-ride-through phenomena.
- Under voltage and overvoltage conditions can be emulated using the CINERGIA grid simulator. These conditions can be tested with GOOSE and Sample Value communication for voltage protection.
- The GOOSE timing delay and profiles should be further investigated using the Lanner Electronics FW-7543B-007 communication emulator at the MultiPower.
- The GOOSE quality and communication packets can also be tested using the Lanner Electronics FW-7543B-007 communication emulator.
- Distance protection should be tested using multiple loads from a distance.

For the OFFIS platform, further suggestions are proposed:

- A time synchronization protocol or server should be fully integrated for future real time simulations in SESA.
- The vIED should be further developed to incorporate more protection functionality such as voltage protection or generator protection.
- The vIED should have a fully developed simple Graphical User Interface for seamless operation.
- The communication emulator EXATA can be integrated into the existing test platform, for testing GOOSE communication properties and investing the GOOSE quality attributes.

7 Dissemination Planning

This technical report gives in depth details of the RIs and the testing which was carried out for this project. This would help future ERIGrid studies in the domain of virtualization, protection testing and IEC 61850 communication. The results and testing has also been compiled in a scientific paper which has been submitted for DPSP 2020. The result for the acceptance is still awaited.

The project has also been presented internally in OFFIS for feedback. The use cases were also presented recently in KIT for a one day workshop on real time simulation and at the ERIGrid workshop in Trondheim. The test cases would also be the basis, for future work on these RIs and would be a good reference for future scientific works.

8 References

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9 Annex

9.1 List of Figures

9.2 List of Tables