

Centralized Protection System in Distribution Substation

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Bachelor's thesis

Electrical Engineering

Vasa 2019



BACHELOR'S THESIS

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Specialization:	Automation
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Title: Centralized Protection System in Distribution Substation

April 27, 2019 Number of pages 32

Abstract

This bachelor's thesis was commissioned by ABB Oy, Power Grids Integration in Vaasa, Finland.

The task was to examine the centralized protection and control system and make a template configuration for a typical distribution substation. The work scope also included development of signal list, relay interface list and IP-Address list.

During the work, I've mainly worked with the PCM600 software. I've collected information about traditional relay configuration and implemented the functions for the new configuration. During the work, essential functions in the configuration were tested in the FAT area with OMICRON relay test and commissioning tool.

The result of this bachelor's thesis is a complete configuration for a whole substation. That includes configurations for SMU615, SSC600, and RIO600. Three different documents were also developed as assistance for the configuration, a signal list, a relay interface list and an IP-Address list.

Language: English	Key word: SSC600, SMU615, RIO600, configuration
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EXAMENSARBETE

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Utbildning och ort:	El- och Automationsteknik, Vasa
Inriktningsalternativ:	Automationsteknik
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Titel: Centraliserat skyddssystem i distributionsstation

27.04.2019 Sidantal 32

Abstrakt

Detta examensarbete var ett beställningsjobb av ABB Oy, Power Grids Integration i Vasa, Finland.

Uppgiften var att undersöka det centraliserade skydds- och kontrollsystemet och göra en mallkonfiguration för typiska distributionstationer. Till arbetet hörde också utveckling av signallista, relägränssnittslista och IP-adresslista.

Under arbetets gång har jag huvudsakligen arbetat med PCM600-programvaran. Jag har samlat in information om traditionella reläkonfigurationer och implementerat funktionerna för den nya konfigurationen. Under arbetets gång testades grundläggande funktioner av konfigurationen i FAT-områden med OMICRON relätestverktyg.

Resultatet av detta lärdomsprov är en komplett konfiguration för en hel elstation. Det inkluderar konfigurationer för SMU615, SSC600, och RIO600. Tre olika dokument utvecklades som stöd för konfigurationen, signallista, relägränssnittslista och IP-adresslista.

Språk: engelska Nyckelord: SSC600, SMU615, RIO600, konfiguration

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Abbreviations

ABB	Asea Brown Boveri
GOOSE	Generic Object-Oriented Substation Events
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IED	Intelligent Electronic Device
IT	Information Technology
SMV	Sampled Measured Values
WHMI	Web-based Human-machine Interface
FAT	Factory Acceptance Testing

Preface

This thesis work is the concluding part of the degree programme in electrical engineering at Novia University of Applied Sciences in Vaasa, Finland. This thesis work was done in collaboration with ABB Oy, Power Grids, Grid Integration and Digital Automation in Vaasa, Finland.

Huge thanks to everyone involved, who supported and helped with this bachelor's thesis. I would also like to thank ABB for the opportunity to write this bachelor's thesis. Thanks to my supervisors, Magnus Udd at ABB Oy and Ronnie Sundsten at Novia University of Applied Sciences. Special thanks to Andre Back and Tomi Huhtamaki for support throughout the work.

Vaasa, 29.04.2019

Evgeni Mirachytski

1 Introduction

This bachelor's thesis is about centralized protection and control system, its implementation and development for use in distribution substations. That also includes the development of configuration, documents and lists related to configuration development.

1.1 Background

Centralized protection for distribution substations is fairly new approach in distribution networks. This bachelor's thesis aims to give engineers a better picture of this solution, the limitations and advantages of the system. This bachelor's thesis with the configuration and all related documents can be used as assistance or a template for future projects with the same protection and control solution. The configuration and related documents used as a template will save time in configuration work, commission work and overall increase configuration quality.

The main task of this bachelor's thesis is to examine the centralized protection system and make a template configuration for a typical distribution substation. The configuration should be done with PCM600 and by collecting the information from inside ABB organization about traditional relay configurations and implementing the functions for the new configuration. At last, verification of the system should also be done with factory acceptance testing.

1.2 Company

The ABB Group is a multinational corporation which has its focus in power, robotics, electrical equipment, and automation technologies, serving customers with utility, industry, transport, and infrastructure globally. With its headquarters located in Zurich, Switzerland the company operates in roughly 100 countries and employs approximately 147 000 employees. The company was formed through a merger of Swedish company ASEA (Allmänna Svenska Elektriska Aktiebolaget) and Swiss company BCC (Brown Boveri & Cie) in 1988. ABB's current operations are divided into five global businesses: Electrification Products, Industrial Automation, Robotics & Discrete Automation, Motion

and Power Grids. Power Grids business is going to be divested to Hitachi in 2020. (The ABB Group, 2019a)

ABB in Finland originated from Strömberg Oy, a company founded by Axel Gottfrid Strömberg in 1889. Strömberg Oy merged with Swedish company ASEA in 1986, which merged with Swiss company BCC in 1988 forming ABB. (The ABB Group, 2019b) Today in Finland, ABB operates mainly in Hamina, Helsinki, Vaasa, and Porvoo but also has smaller offices located in approximately 20 different locations and has around 5300 employees. (The ABB Group, 2019c)

1.3 ABB Oy, Grid Integration

The ABB Grid Integration unit in Finland supplies and maintains transmission and distribution network solutions, merely put substations. ABB substations are found all over the world, from deserts and mountain ranges, offshore and metropolitan areas. (The ABB Group, 2019d)

2 Distribution substation

The distribution substations are used for conversation of the high incoming transmission voltages to distribution voltages and maintains them within specified voltage tolerances. Distribution networks are more cost-efficient and reliable, and it is uneconomical to directly connect customers to the main transmission network unless they use large amounts of power. (Sclater, N. & Traister, J.E., 2003) Transmission voltages in Finland vary from 110-400kV, having this high voltage reduces transmission losses. Distribution voltages can either be 20, 10, 1 or 0,4 kV. (Finsk Energiindustri, n.d.)

Distribution substations can be divided into two types, air-insulated and gas-insulated, they can also be indoor or outdoor. The advantages of gas-insulated substations are that they require less space and increase personal safety. Such substations generally have the necessary equipment that consists of circuit breakers, disconnectors, earthing switches, surge arresters, instrumentation, control devices and other protective apparatus. Those components provide protection and control, isolation, de-energizing and interruption of fault currents to protect other equipment and personnel. Control and protective devices include protection relays that provide fault detection, control and monitoring. Included in this category are

metering instruments, communication equipment and auxiliary power supplies. For measurements are instrumental transformers used, which reduce high voltages and currents to safe and usable values for measurements. Power transformers accomplish the conversation of transmission voltage and maintenance of specified voltage tolerance. The primary purpose of a power transformer in distribution substation is to step down the voltage for distribution purpose. (Sclater, N. & Traister, J.E., 2003)

3 Centralized protection and control

The concept of IEDs sharing information creates many possibilities with potential of better detection of fault condition and improvements in protection and dependability. These possibilities can be implemented by an architecture that includes central computing platform that collects the information. (IEEE PES Power System Relaying Committee, 2015)

A centralized protection and control (CPC) system can be characterized as a “high-performance computing platform capable of providing protection, control, monitoring, communication and asset management functions.” This type of system is based on high-speed communication and requires time-synchronized measurements. (IEEE PES Power System Relaying Committee, 2015)

CPC unit processes real-time data for protection and control by collecting data from all bays in the network, this makes the CPC unit an access point to forward data to the substation network. Additionally, CPC partially removes the functions from the bay level too station level. (IEEE PES Power System Relaying Committee, 2015)

The interface of both conventional and non-conventional instrumental transformers with different types of substation protection, control, monitoring and recording equipment is through a Merging unit. The merging unit can be considered the analog input module of a conventional protection or other multifunctional IEDs. (IEEE PES Power System Relaying Committee, 2015)

3.1 Communication

The development of centralized substation protection and control is possible based on the IEC 61850 standard. The standard improves functionality and reduces the cost of centralized substation protection and control system. IEC 61850 defines various ways for data exchange

between IEDs that can be used for different forms of protection and control. (IEEE PES Power System Relaying Committee, 2015)

For time-critical event such as the protection of the equipment, messages known as Generic Object-Oriented Substation Events (GOOSE) are used. GOOSE is used in substation networks for fast horizontal communication, for direct data exchange. According to IEC 61850-8-1, GOOSE shares information from one device to one or several devices using Ethernet communication. (ABB Oy, 2019h)

Furthermore, the IEC 61850 also defines the transmission of Sampled Measured Values within the substation automation system protocol known as IEC 61850-9-2 Process bus. Process bus is used for distributing process data from the primary circuit to all process bus compatible IEDs. The merging unit is the critical element of the process bus, it gathers information, such as phase voltages and currents from instrumental transformers. The merging unit then digitizes the information to data packets, and with the help of time synchronization it sends time-stamped data packets through process bus network to a CPC unit. The data can then be processed by CPC unit to perform different protection, automation, and control functions. (ABB Oy, 2019h)

IEEE 1588 Standard offers high accuracy clock synchronization for interconnected systems. In this scenario, the merging unit sample current and voltage value and timestamp them using the IEEE 1588 synchronized timers. The CPC unit processes these values and reconstructs the status of the grid using these values, and the CPC unit can then apply these values to any protection and control action. An IEEE 1588 infrastructure requires Master clock equipment to provide clocking reference, and Slave clocks to synchronize with Master clock. Additionally, all networking equipment should support IEEE 1588-time synchronization in order to maintain the same level of accuracy in the whole network. (IEEE PES Power System Relaying Committee, 2015) (ABB Oy, 2019h)

Centralized protection and control require reliable, secure communication infrastructure. There are several existing standard redundant protocols used in substation communication that provides network fault detection, isolation, and recovery. Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR) considered being the best-standardized option available for centralized protection and control communication architectures. These redundancy protocols provide zero second recovery time and zero packet loss. The basic principle of HSR/PRP protocol is that the source node packets are

duplicated and are sent in redundant directions, to both LANs in case of PRP and across the ring with HSR. The first packet that reaches the destination will be accepted, and the duplicated packet will be rejected. These networks also support IEEE 1588 clock synchronization. (IEEE PES Power System Relaying Committee, 2015)

3.2 System architectures

A complete system would consist of merging units utilized in every feeder, interfacing with the CPC unit over a single IEC 61850 network. Every merging unit multicasts SMV values and GOOSE messages to CPC unit, but also receives GOOSE messages from CPC unit. The system should include time synchronization via IEEE1588v2 GPS master with any merging as backup time master, this ensures high accuracy measurements and control. Also, COM600 can be added to the system, as it includes ease of use functionality to enhance redundant operation. A laptop or PC working station is required for substation human-machine interface. (ABB Oy, 2019a) (IEEE PES Power System Relaying Committee, 2015)

Additionally, such system can implement redundant Ethernet communication. Ethernet network redundancy can be achieved by using the parallel redundancy protocol, where each node is attached to two independent networks operated in parallel. Two CPC units can be used at substation level to enhance the reliability and availability of the entire system further. Additional GPS master clock also increases the reliability of sustaining accurate time synchronization in the whole substation. Both architectures are shown in Figure 1. (ABB Oy, 2019a) (IEEE PES Power System Relaying Committee, 2015)

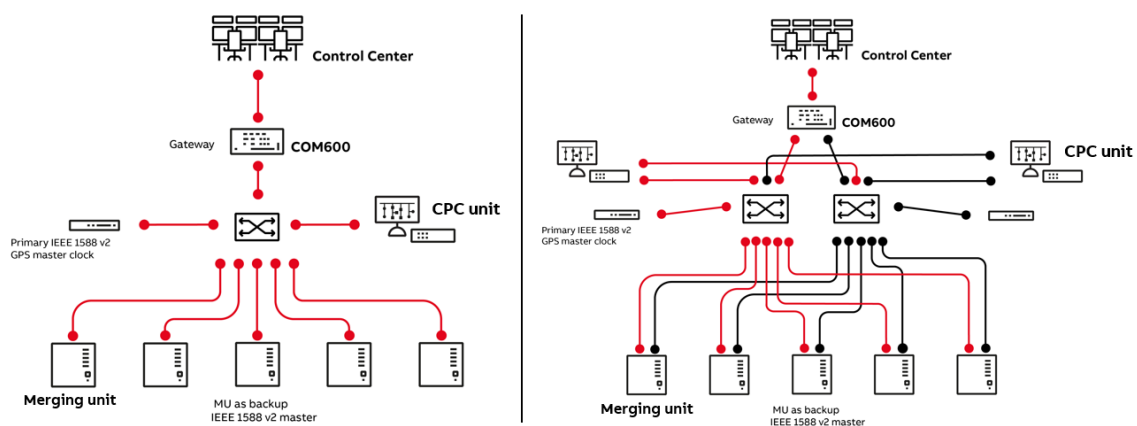


Figure 1 Example solutions of centralized protection and control system (ABB Oy, 2019a)

4 SSC600

Smart substation Control and Protection (SSC600) is a smart substation device that provides protection, control, measurement and supervision of substations and its equipment. SSC600 centralizes a wide range of protection and control functionality in one device at the substation level. Combined with Region series IEDs and with communication, interoperability based on IEC 61580 standard it creates a complete solution. (ABB Oy, 2019a)



Figure 2 SSC600 (ABB Oy, 2019a)

The device offers different base protections which consists of different types and stages of overcurrent, earth fault, voltage, and frequency protection. Fault recorder and switchgear control are also included in base protection. Additionally, the device provides protection for transformers, machines, feeders, interconnection and protection against arc with light detecting devices at the bay level. (ABB Oy, 2019a)

The SSC600 integrates functionalities for control of circuit breaker, motor-operated disconnector or circuit breaker truck and earthing switch. For each primary device taken into use, two physical binary inputs and outputs are required in the bay level IED. This device also offers on-load tap changer control for tap changers position indication, voltage regulation, and line drop compensation. The control functionality is available via the WHMI or by means of remote control. (ABB Oy, 2019a)

The device supports several communication protocols including IEC 61850 Edition 1, Edition 2 and IEC 61850-9-2 LE. Implementation of IEC 61850 allows communication of monitoring, control, and operational information. IEC 61850-8-1 GOOSE profile allows the device to receive and send binary and analog signals to other devices, and this enables secure transfer of binary and analog signals over the station bus. The measurements of voltages and currents are received as sampled values using the IEC 61850-9-2 LE protocol. Process bus

uses IEEE 1588 Precision Time Protocol for high accuracy time synchronization. (ABB Oy, 2019a)

Access to control and monitoring functionalities in this device is available via a web-based human-machine interface (WHMI). WHMI gives easy access to control, valuable information and visualization to view and monitor processes on substation level. WHMI features user-configurable single line diagram which indicates positions of associated primary equipment, enables control of controllable objects, displays measurements, and other relevant information. WHMI can be accessed locally, by connecting the laptop to the device via the local WHMI port, or remotely by accessing over LAN/WAN. (ABB Oy, 2019a)

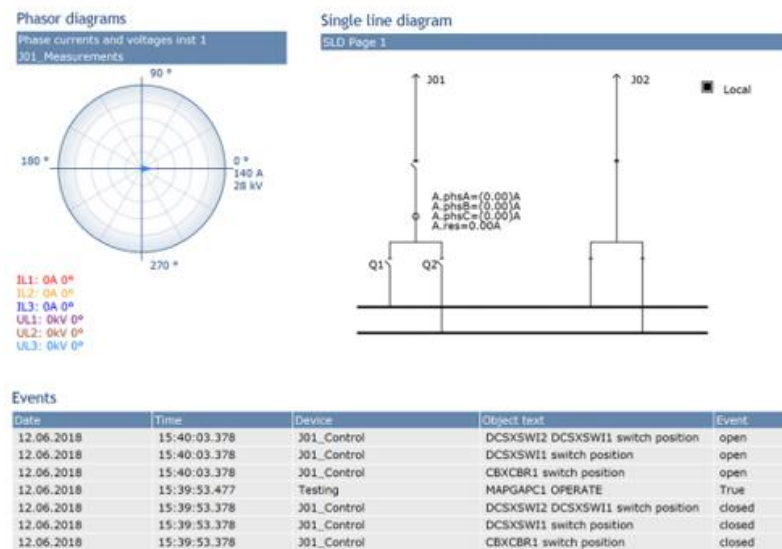


Figure 3 Measurements, SLD and Events in SSC600 WHMI

5 SMU615

SMU615 is a member of ABB's Relion product family, and this merging unit has a standard digital interface which makes it possible to connect ABB sensors and conventional instrument transformers for measurement of current and voltage signals. SMU615 by itself does not have any protection functions and it is not designed to make trip decisions. Trip decision is made by another device, but the opening of circuit breaker is performed by SMU615. The device also integrated functionalities for the control of circuit breaker, motor-

operated disconnect or circuit breaker truck and earthing switch by mean of remote-control commands. (ABB Oy, 2019b)

SMU615 fully supports IEC 61850 standard for communication, and this includes process bus according to IEC 61850-9-2 LE with IEEE 1588 v2 time synchronization. SMU615 measures currents and voltages and sends them as sampled measured values over the Ethernet using the IEC 61850-9-2 LE protocol. Additionally, SMU615 can send and receive binary or analog signals via Ethernet using the IEC 61850-8-1 GOOSE profile. (ABB Oy, 2019b)

SMU615 also utilizes web-based human-machine interface for access to system supervision, measurements, events, and parameters. WHMI gives easy access to valuable information and visualization to view and monitor processes on the bay level. (ABB Oy, 2019b)



Figure 4 Substation merging unit SMU615 (ABB Oy, 2019b)

5.1 Inputs and outputs

Depending on the option selected, the merging unit can consist of analog inputs with three-phase currents inputs, one residual-current input, and three-voltage inputs. Both phase-to-phase voltages and phase-to-earth can be connected. However, phase-to-earth should be used for the calculation of residual voltage. The merging unit can also feature three light detection channels for arc fault detection in circuit breaker, busbar, and cable compartments. The detection of an arc fault is sent to another device where the tripping decisions are made. All

inputs or outputs are freely configurable with the signal matrix or application configuration in PCM600. (ABB Oy, 2019b)

6 RIO600

The purpose of RIO600 is to expand the I/O of protection and control units or provide I/O for SSC600 and COM600, this also gives the flexibility of I/O assignments, decreases and simplifies wiring inside the substation, improves functionality and performance. RIO600 uses Ethernet-based IEC 61850 international standard for horizontal communication, GOOSE communication. The signals can be transmitted within the switchgear and to the higher-level automation system. Similarly, signals from the higher-level automation systems can be transferred to the RIO600 via connected protection relays. The unit also supports Modbus TCP-based communication, which is used in many different applications. (ABB Oy, 2019d)

6.1 Modules

The modular design of RIO600 makes it possible to install specific module configurations required for various systems. The device offers full flexibility, and it can include up to 40 inputs or outputs and connect several different types of modules. The modules can be stacked to achieve the required configuration, the minimum configuration required is a power supply module, a communication module, and an input/output module. (ABB Oy, 2019d)

Binary input module can be used for receiving signals from primary equipment, various devices or secondary systems. The binary output modules can be used to send out control signals to equipment. The RTD/mA module can be used for supervision, control, and different monitoring applications. The module supports 5 different RTD sensors which give the possibility to receive temperatures from various devices. The mA input is a 0 - 20mA configurable input, the current input can also be linearly scaled for various applications and with analog output module, an external device can be controlled. Additionally, other modules can be added such as sensor input module with combined three-phase current and voltage signals, a smart control module which enables control of disconnecter, circuit breaker, earthing switch, and three-position switch. (ABB Oy, 2019d)



Figure 5 Remote I/O unit RIO600 (ABB Oy, 2019d)

7 Cybersecurity

Cybersecurity refers to technologies, processes, and practices designed to protect devices, networks, and data from attacks, damages and unauthorized access. Critical infrastructures like electrical distribution and transmission network together with an appliance of the communication network require cybersecurity. Several cybersecurity standards can be followed, the most applicable and referred ones are ISO 2700x, IEC 62443, IEEE P1686 and IEC 62351. Besides standardization, there are also several government-initiated requirements and practices. Such standards and requirements are equipped with cybersecurity mechanisms, which enable the design, development and continual improvement of security for control systems such as distribution automation applications. (ABB Oy, 2019e)

Improvement of cybersecurity can be achieved by following several hardening rules, from just changing the default passwords to encrypting the communications. It is essential to recognize all parts in the systems, system communication links and also removing all unnecessary communication links and checking that communication link from the substation to upper-level system uses encryption and authentication. Separating networks, separating public network from the automation network and improving the system security by removing all unused processes, communication ports, and services. It is also essential to have backup available from all relevant parts, storing and having them up-to-date. Lastly, using firewalls and antivirus software in workstations. (ABB Oy, 2019e)

8 PCM600

Protection and Control IED Manager (PCM600) is a software which manages the IED protection, control and monitoring applications, at all voltage levels. The software has individual tool components to perform different task, functions and even control the whole station. PCM600 is compliant with IEC 61850, which simplifies information exchange and IED engineering with other IEC 61850 compliant tools. PCM600 software can interact directly with IEDs over fast and reliable TCP/IP via LAN or WAN, or directly through the front communication port. With established communication to IEDs it is possible to read or write configurations and parameters to IEDs. A typical project contains plant structure with one or several IED objects, IED object contains engineering data created or modified using different tool components. (ABB Oy, 2019f)

8.1 Tool components

In this subchapter, all essential tool components needed for making a configuration are presented. The availability of the tool components depends on IED and installed connectivity package.

Application Configuration enables the presentation of the signal flow from input to output. It is used for the configuration of the IEDs, mainly to create, adapt and modify configurations. Before writing the configuration to an IED, it can be validated to ensure that the configuration does not contain errors. Further, the signals can be on-line monitored which enables real-time validation. (ABB Oy, 2019f) Figure 6 is showing an example of measurement page and functions in SSC600 application configuration.

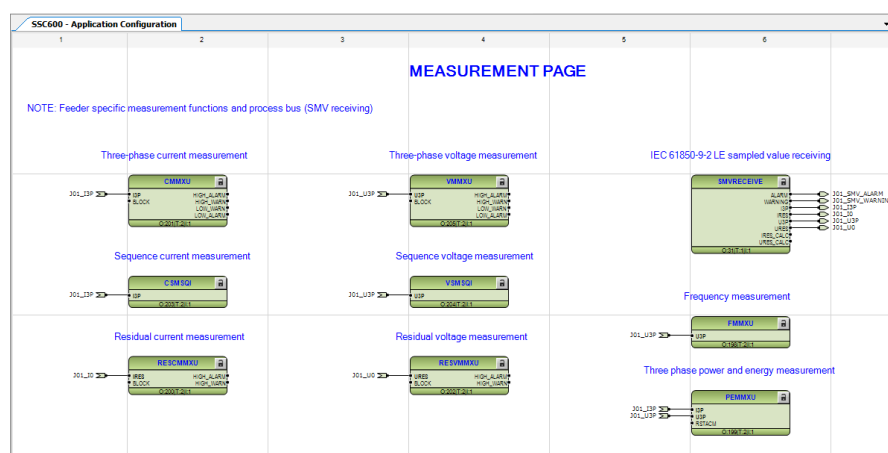


Figure 6 Application configuration in PCM600

Parameter Settings are used for parameterizing the IEDS and viewing the parameter data. The parameters can be stored either in the tool or stored in both the tool and the IED. Parameters can also be written to EIDs from PCM600 or read from IEDs to PCM600. Besides, the parameters can be exported or imported, and this is often done for tests with Omicron. (ABB Oy, 2019f) Figure 7 is showing an example of parameter setting in SSC600 configuration.

SSC600 - Parameter Setting					
Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
DEFHPDEF: 1					
Settings					
Operation		on			
Setting Group 1					
Start value		0.50	xIn	0.10	40.00
Start value Mult		1.0		0.8	10.0
Directional mode		Forward			
Operating curve type		IEC Def. Time			
Operate delay time		200	ms	40	200000
Characteristic angle		-90	deg	-179	180
Max forward angle		80	deg	0	180
Max reverse angle		80	deg	0	180
Min forward angle		80	deg	0	180
Min reverse angle		80	deg	0	180
Voltage start value		0.200	xUn	0.010	1.000
Setting Group 2					
Start value		0.10	xIn	0.10	40.00
Start value Mult		1.0		0.8	10.0
Directional mode		Forward			
Operating curve type		IEC Def. Time			
Operate delay time		40	ms	40	200000
Characteristic angle		-90	deg	-179	180
Max forward angle		80	deg	0	180
Max reverse angle		80	deg	0	180
Min forward angle		80	deg	0	180

Figure 7 Parameter settings in PCM600

Graphical Display Editor is used for configuration of the IED display or WHMI. The graphical display can consist of one or several pages, where the actual display configuration is made. Display configuration is made by dragging predefined graphical symbols from a library, and those symbols can be directly connected to the application configuration. (ABB Oy, 2019f)

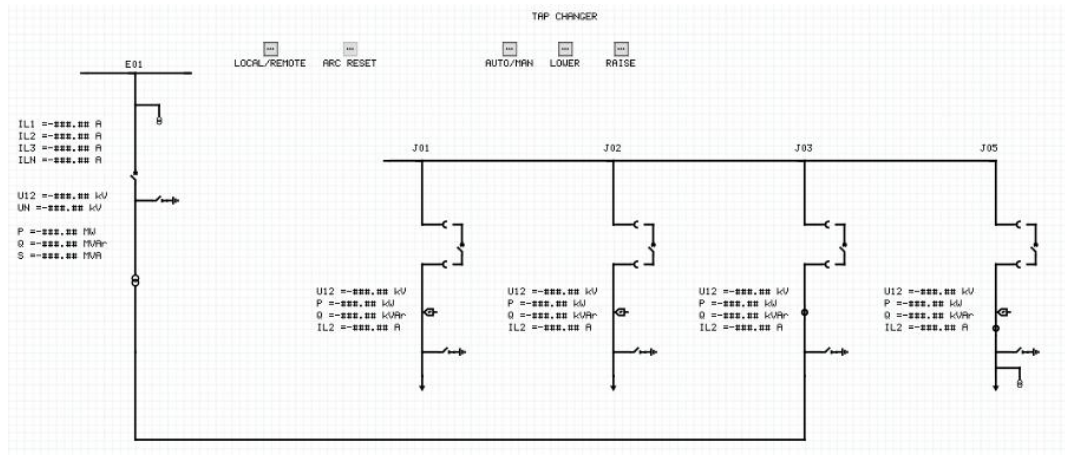


Figure 8 Graphical Display Editor in PCM600

IEC 61850 configuration is used for viewing or engineering of datasets and dataflow of client-server, process-bus and GOOSE communication. IEC 61850 configuration tool is showing all available IEDs that can receive datasets and created datasets that can be sent to IEDs. In GOOSE communication relays exchange data, for example, indications, interlocking or blocking information between IEDs. Process-bus communication sends and receives sampled values of analog neutral and phase currents in addition to the voltages. The neutral voltage is calculated when there is no physical neutral voltage input available. Client-server communication is for communication with MicroSCADA and COM600s, which can use the client definitions directly. All data in IEC 61850 configuration are sent in the form of datasets. For example, as shown in Figure 9, the position indication of the circuit breaker, disconnector, and earthing switch are sent to SSC600 within a dataset. (ABB Oy, 2019f)

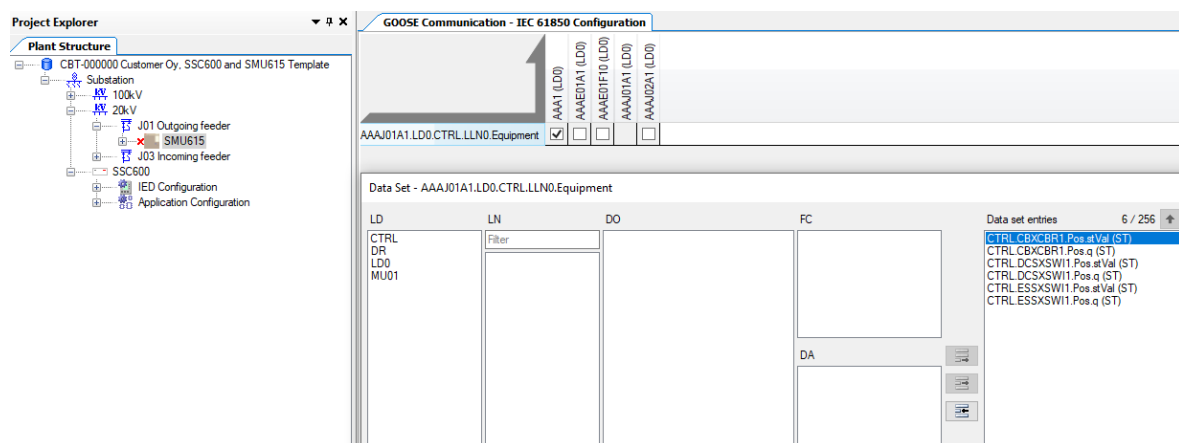
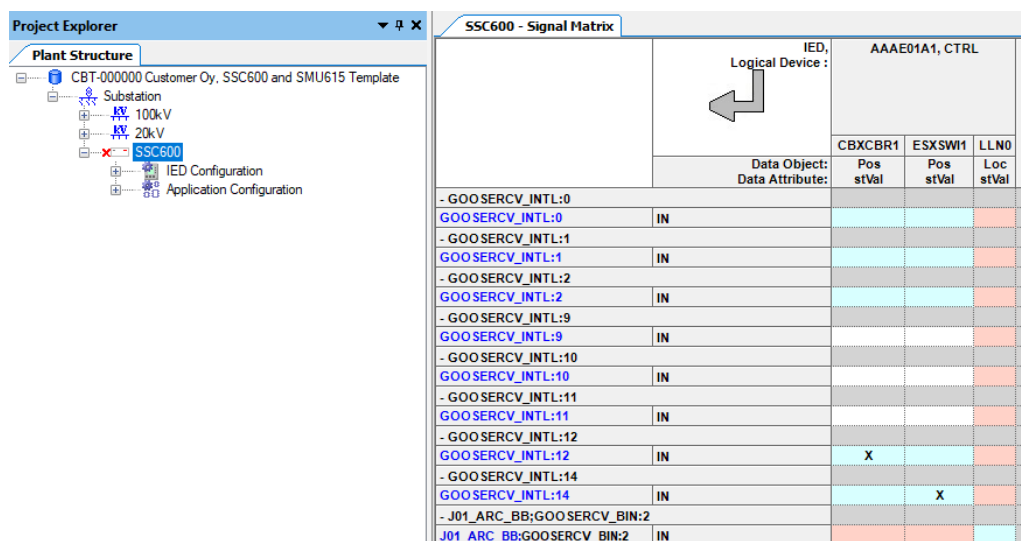


Figure 9 IEC 61850 configuration example in PCM600

Signal Matrix is used to create connections between source and target IEDs. Signal matrix is mainly used for GOOSE signal input engineering but can also be used for making connections between input and output signals to function blocks. Signal matrix is showing all available signals that are received by the IED and available function blocks that can receive the signal. For example, as shown in Figure 10, the position indication of circuit breaker and earthing switch are sent from a merging unit and received by GOOSERCV_INT 11 and 12 in SSC600, SSC600 can then use those signals.



IED, Logical Device : AAAE01A1, CTRL		CBXCBR1	ESXSW1	LLN0
Data Object: Data Attribute:		Pos stVal	Pos stVal	Loc stVal
- GOOSERCV_INTL:0				
GOOSERCV_INTL:0	IN			
- GOOSERCV_INTL:1				
GOOSERCV_INTL:1	IN			
- GOOSERCV_INTL:2				
GOOSERCV_INTL:2	IN			
- GOOSERCV_INTL:9				
GOOSERCV_INTL:9	IN			
- GOOSERCV_INTL:10				
GOOSERCV_INTL:10	IN			
- GOOSERCV_INTL:11				
GOOSERCV_INTL:11	IN			
- GOOSERCV_INTL:12				
GOOSERCV_INTL:12	IN	X		
- GOOSERCV_INTL:14				
GOOSERCV_INTL:14	IN		X	
- J01_ARC_BB;GOOSERCV_BIN:2				
J01_ARC_BB;GOOSERCV_BIN:2	IN			

Figure 10 Signal Matrix example in PCM600

9 OMICRON

OMICRON is a company that serves the electrical power industry with products, services, diagnostics and monitoring for testing purposes. OMICRON CMC 356 tool and test sets were used to verify configuration functionality. (OMICRON, 2019a)



Figure 11 Universal relay test and commissioning tool CMC 356 (OMICRON, 2019b)

9.1 Test Universe

The OMICRON Test Universe is a software for testing protection and measurement devices. It consists of Windows-based software and provides flexible and adaptable testing applications. This software allows full control of the OMICRON tools for testing. The tests can be performed individually, or in series, OMICRON also provides different templates for testing. (OMICRON, 2019d)

OMICRON Control Center (OCC) provides the execution of test modules as a test plan. It allows a single test to contain all data related to the test. This includes Hardware Configuration, Test Objects, test parameters (e.g., nominal values and tolerances), test results and assessments. After being set up, the tests will be performed sequentially, and the results will be summarized in a test report. (OMICRON, 2019c)

10 Configuration functions

In this chapter, all active protection, control, and communication functions used in the configuration are presented although there are a lot more functions available, which are inactive in this configuration.

10.1 Communication functions

10.1.1 SMV function blocks

SMV function blocks are used for receiving and sending the sampled values of currents and voltages. The SMV sender function adds the sampled value control block and the related data set into the sending devices configuration. The SMV receive function is used for activating the SMV receiving functionality. In the parameters of SMV receive, the sender's id should be specified. Further, nominal values of primary currents and voltages should also be specified in SMV receive function. (ABB Oy, 2019g) Figure 12 is showing SMV functions blocks in PCM600.



Figure 12 SMV function blocks, in PCM600

10.1.2 GOOSE function blocks

GOOSE function blocks are used for receiving incoming GOOSE data and connecting it to application configuration. The input data for GOOSE function blocks are configured in the IEC 61850 configuration in PCM600. An example of IEC 61850 configuration for GOOSE functions is shown in Figure 10 and explained in Chapter 8.1. There are several types of GOOSE functions for different applications. (ABB Oy, 2019g) Figure 13 is showing GOOSE functions blocks in PCM600 that are used in this thesis configuration.

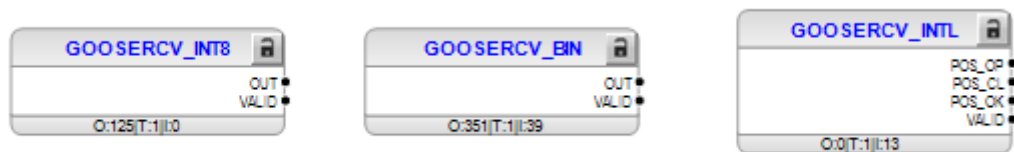


Figure 13 GOOSE function blocks, in PCM600

10.2 Control functions

10.2.1 Circuit breaker, disconnector and earthing switch control

These functions are intended for circuit breaker, disconnector, and earthing switch control. The functions execute commands, evaluate block conditions and different supervision conditions. The execution commands are performed only if all conditions indicate that a switch operation is allowed. These functions can have different identifications depending on which standard is defining them. Different identifications of these functions are shown in Table 1. (ABB Oy, 2019g) Figure 14 is showing circuit breaker, disconnector and earthing switch control functions blocks in PCM600.

Function description	IEC 61850 Identification	IEC 60617 Identification	ANSI/IEEE C37.2 device number
Circuit breaker control	CBXCBR	I<->O CB	I<->O CB
Disconnecter control	DCXSWI	I<->O DCC	I<->O DCC
Earthing switch control	ESXSWI	I<->O ESC	I<->O ESC

Table 1 Circuit breaker, disconnector and earthing switch control functions identification (ABB Oy, 2019g)

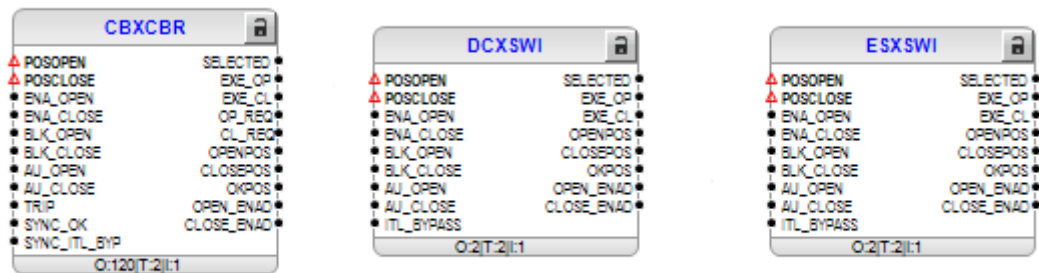


Figure 14 Circuit breaker, disconnector and earthing switch control function blocks, in PCM600

10.2.2 Tap changer control with voltage regulator

The tap changer control with voltage regulator is designed to provide the voltage regulation of power transformers with on-load tap changers in a substation. This function provides manual and automatic voltage control for the power transformer, by utilizing raise and lower signals from the function to the on-load tap changer. The measured voltage is typically from the secondary side of the power transformer. The measured current is used for overcurrent blocking, to compensate the voltage drop and for calculation in several operation modes. (ABB Oy, 2019g)

Manual raising and lowering commands can be given either via configuration itself, WHMI or remote commands. Automatic voltage regulation is designed to maintain secondary voltage stable, by calculating desired secondary voltage and comparing it to the measured voltage. The difference between desired and measured secondary voltage is the regulating process error, and the error limit can be defined. Once the regulating process error exceeds the predefined limit, the function sends either raise or lower command to the tap changer. It is also possible to block the function with an external signal or with supervision functionality

of the function. (ABB Oy, 2019g) Different identifications of the function are shown in Table 2. Figure 15 is showing the tap changer control with voltage regulator functions block in PCM600.

Function description	IEC 61850 Identification	IEC 60617 Identification	ANSI/IEEE C37.2 device number
Tap changer control with voltage regulator	OLATCC	COLTC	90V

Table 2 Tap changer control with voltage regulator function identification (ABB Oy, 2019g)

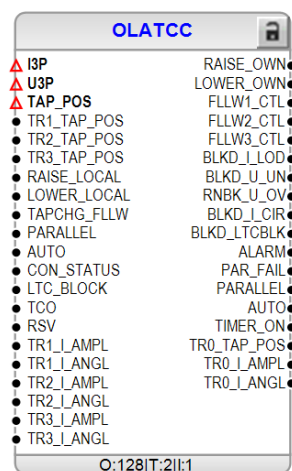


Figure 15 Tap changer control with voltage regulator function block, in PCM600

10.3 Protection functions

10.3.1 Three-phase overcurrent protection

Three-phase overcurrent protection can either be directional or non-directional, and this depends on the type of configuration or choice of protection. Directional protection can be used as non-directional protection, but non-directional protection cannot be used as directional. In short, three-phase overcurrent protection causes the relay to rapid open circuit breaker when the current exceeds a predetermined value. (ABB Oy, 2019g)

Three-phase non-directional overcurrent protection consists of three stages of protection, low, high and instantaneous. The low stage of non-directional overcurrent protection

contains several types of time-delay characteristics, high and instantaneous is commonly used for fast clearance of very high currents. (ABB Oy, 2019g) This function can have different identification depending on which standard is defining the function and what stage is used. Different identifications of non-directional overcurrent protection for each stage are shown in Table 3.

Function description	IEC 61850 Identification	IEC 60617 Identification	ANSI/IEEE C37.2 device number
Three-phase non-directional over-current protection, low stage	PHLPTOC	3I>	51P-1
Three-phase non-directional over-current protection, high stage	PHHPTOC	3I>>	51P-2
Three-phase non-directional over-current protection, instantaneous stage	PHIPTOC	3I>>>	50P/51P

Table 3 Three-phase non-directional overcurrent protection identification (ABB Oy, 2019g)

The function starts when measured phase currents exceed the predefined limit, once the current is high enough the phase selection logic detects the phase or phases in which the current exceeds the limit. The function operates if the fault current has not disappeared within either predefined time delay or current-dependent timer. There is also the possibility of blocking the function, timers and function outputs. (ABB Oy, 2019g) Figure 16 is showing the three-phase non-directional overcurrent function block in PCM600.



Figure 16 Three-phase non-directional overcurrent function blocks, in PCM600

Directional overcurrent protection consists of only two stages of protection, low and high. (ABB Oy, 2019g) This function can also have different identification depending on which standard is defining the function and what stage is used. Different identifications of directional overcurrent protection for each stage is shown in Table 4.

Function description	IEC 61850 Identification	IEC 60617 Identification	ANSI/IEEE C37.2 device number
Three-phase directional overcurrent protection, low stage	DPHLPDOC	3I> ->	67-1
Three-phase directional overcurrent protection, high stage	DPHHPDOC	3I>> ->	67-2

Table 4 Three-phase directional protection identification (ABB Oy, 2019g)

The directional calculation compares the current phases to the polarizing phases. (ABB Oy, 2019g) Suitable polarization quantities are shown in Table 5.

Polarizing quantity	Description
Pos. seq. volt	Positive sequence voltage
Neg. seq. volt	Negative sequence voltage
Self pol	Self polarization
Cross pol	Cross polarization

Table 5 Polarizing quantities (ABB Oy, 2019b)

Directional overcurrent function starts when the value of measured phase currents exceeds the set limit and the criteria of directional calculation is fulfilled. If all fault criteria are fulfilled, phase selection logic detects the phase or phases in which the measured current exceeds the limit. The function operates if the fault current has not disappeared within either predefined time delay or current-dependent timer. The function has a blocking functionality, which blocks the function itself, timers and function outputs. (ABB Oy, 2019g) Figure 17 is showing three-phase directional overcurrent function block in PCM600.

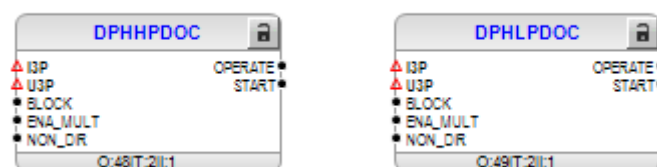


Figure 17 Three-phase directional overcurrent function blocks, in PCM600

10.3.2 Earth-fault protection

Earth fault is a fault between phase and earth. The earth-fault protection is designed for protection and clearance of earth faults in substation networks. Earth-fault protection can either be directional or non-directional, this depends on the type of configuration or choice of protection. Directional protection can be used as non-directional protection, but non-directional protection cannot be used as directional. In short, three-phase overcurrent protection causes the relay to rapid open circuit breaker when the current exceeds a predetermined value. (ABB Oy, 2019g)

Non-directional earth-fault protection consists of three stages of protection, low, high and instantaneous. Low stage of non-directional earth-fault protection contains several types of time-delay characteristics, high and instantaneous is commonly used for fast clearance of serious earth faults. (ABB Oy, 2019g) This function can have different identification depending on which standard is defining the function and what stage is used. Different identifications of non-directional earth-fault protection for each stage are shown in Table 6.

Function description	IEC 61850 Identification	IEC 60817 Identification	ANSI/IEEE C37.2 device number
Non-directional earth-fault protection, low stage	EFLPTOC	Io>	51G/51N-1
Non-directional earth-fault protection, high stage	EFHPTOC	Io>>	51G/51N-2
Non-directional earth-fault protection, instantaneous stage	EFIPTOC	Io>>>	50G/50N

Table 6 Non-directional earth-fault protection identification (ABB Oy, 2019g)

The non-directional earth-fault protection function starts as soon as the residual current exceeds the set limit. The function operates if the fault current has not disappeared within either predefined time delay or current-dependent timer. The instantaneous stage of this function operates with definite time characteristic. There is also the possibility of blocking the function, timers and function outputs. (ABB Oy, 2019g) Figure 18 is showing three-phase non-directional earth-fault function block in PCM600.



Figure 18 Non-directional earth-fault function blocks, in PCM600

Directional earth-fault protection consists of only two stages of protection, low and high. (ABB Oy, 2019g) This function can also have different identification depending on which standard is defining the function and what stage is used. Different identifications of directional earth-fault protection for each stage are shown in Table 7.

Function description	IEC 61850 Identification	IEC 60617 Identification	ANSI/IEEE C37.2 device number
Directional earth-fault protection, low stage	DEFLPDEF	Io> ->	67G/N-1 51G/N-1
Directional earth-fault protection, high stage	DEFHPDEF	Io>> ->	67G/N-1 51G/N-2

Table 7 Directional earth-fault protection identification (ABB Oy, 2019g)

Directional earth-fault function starts once the residual current and residual voltage exceed the set limits and the angle between them is inside the set operating sector. The function operates if all criteria is still fulfilled within either predefined time delay or current-dependent timer. There are several Operation modes available for defining the operation sector, generally phase angle, IoSin and IoCos are used as operation modes. Phase angle mode allows defining desired angle and allowed deviation of the angle. Both IoSin and IoCos modes, can be used for calculating the operation current. Operation sector in IoSin and IoCos is defined by multiplying residual current with either Cos or Sin of the angle between residual current and voltage, if the value is positive the operating sector is defined as forward and reserve if negative. The function also has a blocking functionality, which blocks the function itself, timers and function outputs. (ABB Oy, 2019g) Figure 19 is showing directional earth-fault function block in PCM600.

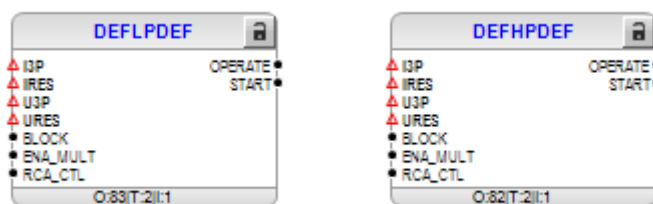


Figure 19 Directional earth-fault function blocks, in PCM600

10.3.3 Residual overvoltage protection

Residual voltage is the voltage between the grids neutral point and the earth. Residual overvoltage protects equipment from non-acceptable residual voltages. Residual overvoltage protection can have different identification depending on which standard is defining the function. Different identifications are shown in Table 8.

Function description	IEC 61850 Identification	IEC 60817 Identification	ANSI/IEEE C37.2 device number
Residual overvoltage protection	ROVPTOV	Uo>	59G/59N

Table 8 Residual overvoltage function identification (ABB Oy, 2019g)

The residual overvoltage function starts when the measured residual voltage exceeds the predefined value. The function operates if non-acceptable residual voltage hasn't disappeared within either predefined time delay. The outputs and the function itself can be blocked by function blocking functionality. (ABB Oy, 2019g) Figure 20 is showing residual overvoltage function block in PCM600.

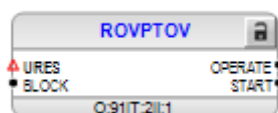


Figure 20 Residual overvoltage function block in PCM600

10.3.4 Three-phase overvoltage protection

Three-phase overvoltage protection is applied on power system elements, such as generators, transformers, motors and power lines, to protect the system from excessive voltages that could damage the insulation and cause insulation breakdown. (ABB Oy, 2019g) This function can have different identification depending on which standard is defining the function. Different identifications of overvoltage protection are shown in Table 9.

Function description	IEC 61850 Identification	IEC 60617 Identification	ANSI/IEEE C37.2 device number
Three-phase overvoltage protection	PHPTOV	3U>	59

Table 9 Three-phase overvoltage protection function identification (ABB Oy, 2019b)

Three-phase overvoltage starts when the measured three-phase voltages are higher than the set value. The function operates if the non-acceptable voltages has not disappeared within either predefined time delay or voltage-dependent timer. The function has a blocking functionality, which blocks the function itself, timers and function outputs. (ABB Oy, 2019g) Figure 21 is showing three-phase overvoltage function block in PCM600.

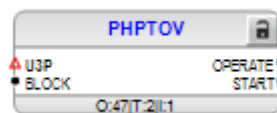


Figure 21 Three-phase overvoltage function block in PCM600

10.3.5 Three-phase undervoltage protection

Three-phase undervoltage protection is used for protection of devices that can be damaged when subjected to service under low voltage conditions. This protection prevents equipment from running under low voltage conditions which prevents overheating thus increases life time expectancy of the equipment. (ABB Oy, 2019g) This function can have different identification depending on which standard is defining the function. Different identifications of undervoltage protection are shown in Table 10.

Function description	IEC 61850 Identification	IEC 60617 Identification	ANSI/IEEE C37.2 device number
Three-phase undervoltage protection	PHPTUV	3U<	27

Table 10 Three-phase undervoltage protection function identification (ABB Oy, 2019g)

Three-phase undervoltage starts when the measured three-phase voltages are lower than the set value. The function operates if the non-acceptable voltages has not disappeared within either predefined time delay or voltage-dependent timer. The function has a blocking functionality, which blocks the function itself, timers and function outputs. (ABB Oy, 2019g) Figure 22 is showing three-phase undervoltage function block in PCM600.



Figure 22 Three-phase overvoltage function block in PCM600

10.3.6 ARC Protection

The occurrence of arc situations is a very serious fault within a power system. The impacts of an arc flash can lead to severe injuries to personnel, costly damages to equipment and long outages. The arc protection detects such situations, to be precise the function detects light and simultaneous monitors phase and residual currents to accurately make out a fault in case light is detected. (ABB Oy, 2019g) Arc protection function can have different identification depending on which standard is defining the function. Different identifications are shown in Table 11.

Function description	IEC 61850 Identification	IEC 60617 Identification	ANSI/IEEE C37.2 device number
Arc protection	ARCSARC	ARC	AFD

Table 11 ARC protection function identification (ABB Oy, 2019b)

The function starts once remote light signal is detected. The function also monitors phase and residual currents and compares them to the predefined limit. Operation of the function

depends on Operation mode, operation mode can either be “Light+current”, “Light only” or “BI controlled”. The operation is based on both current and light in “Light+current”, whenever light is detected, and one of measured currents exceed their predefined limit. On light information only in “Light only” or remotely controlled information in “BI controlled”. The block functionality of the function blocks the outputs, timers and function itself. (ABB Oy, 2019g) Figure 23 is showing arc protection function block in PCM600.

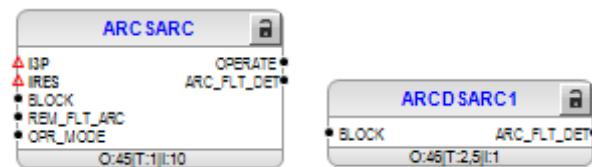


Figure 23 ARC protection function in PCM600 (Left SSC600, Right SMU615)

SSC600 itself does not have any arc light detection hardware, the phase currents and residual currents are received as SMV measurements via IEC 61850-9-2 LE and light indication as GOOSE message. (ABB Oy, 2019g)

10.3.7 Differential protection

The stabilized and instantaneous differential protection is mainly designed to protect two winding transformers in case of winding failure. The protective zone of differential protection includes the transformer, the busbar or cables between current transformer and power transformer. Short circuits and earth faults in the windings and terminals can also be detected by differential protection. It is important that the faulty transformer is disconnected as fast as possible as it can cause very serious and immediate damage. (ABB Oy, 2019g) Different identifications of stabilized and instantaneous differential protection are shown in Table 12.

Function description	IEC 61850 Identification	IEC 60617 Identification	ANSI/IEEE C37.2 device number
Stabilized and instantaneous differential protection for two-winding transformers	TR2PTDF	3dl>T	87T

Table 12 Stabilized and instantaneous differential protection identification (ABB Oy, 2019g)

Differential protection operates on the difference of incoming and outgoing currents. The functions analyses change in voltages, current and phase angles for correct tripping decision.

The differential current can be caused by current transformer inaccuracies, variations in tap changer position, transformer no-load current and inrush current. Theoretically, in normal situations incoming and outgoing currents should be equal and differential current should be zero if the turns ratio and phase shift are correctly compensated. This function includes low biased and high instantaneous stages, low biased stage provides fast clearance of faults while remaining stable with high currents passing through the protected zone. The low biased stage operates in respect to the load current, this ensures that the differential current happened due an actual fault. There are also two stages of harmonic restraint, the second harmonic and fifth harmonic restraint. These ensure that the low biased stage does not operate due to transformer inrush current and on apparent differential current caused by harmless transformer over-excitation. The instantaneous stage provides a very fast clearance of severe faults with a high differential current, this stage is not biased in other words this stage operates once differential current exceeds the predefined limit. There are several blocking functionalities that can block one or several outputs, timers and function itself. (ABB Oy, 2019g) Figure 24 is showing stabilized and instantaneous differential protection function block in PCM600.

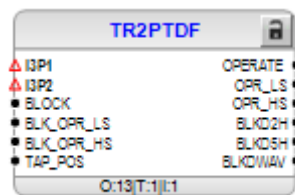


Figure 24 Stabilized and instantaneous differential function in PCM600

11 Development of configuration

In this bachelor's thesis a configuration for a whole substation was made using PCM600 software. The substation consists of one transformer feeder, two outgoing feeders, incoming feeder and reserve incoming feeder. The substation utilizes a SSC600 on substation level and SMU615 merging units in every feeder with additional SMU615 in transformer feeder configured to be used as backup merging unit. This chapter briefly describes essential functionality and logic of configuration in each device and configuration related documents.

11.1 Development of configuration related documents

Three different documents were also developed for this project. All documents are based on previously used ones.

The relay interface list which is a list of merging units analog and binary inputs and outputs. An earlier version of this list from another project was used, although several inputs and outputs were updated during the work. The IP-Address list contains IP addresses and technical keys of every device in the network. As well as subnet mask and gateway of the network. The signal list which is a list that contains the signals that are sent to, for example, surveillance center or SCADA system. The signals in signal list can vary depending on the necessity of control and monitoring. The content of this list includes signals, from which device and feeder they are taken, event and IEC 61850 designation of the signal. Earlier version of this list was edited and updated to fit this project.

11.2 Configuration of SMU615

In total, 6 configurations were made for SMU615. Standard configurations were modified to fit typical domestic projects.

The configurations for SMU615 were made so that the merging units in feeders with primary equipment receive circuit breaker, earthing switch, disconnector or circuit breaker truck and miniature circuit breaker status information as binary inputs. The positions of circuit breaker, earthing switch, disconnector or circuit breaker truck are sent as GOOSE message to SSC600, and this is mainly for visualization purposes.

The measurements are received through analog inputs and are sent to SSC600 as SMV values via process bus communication. Merging units equipped with light sensing send the light detection via GOOSE communication to SSC600 for the tripping decision. One merging unit is configured to be used as a backup unit, the backup unit receives measurements through analog inputs, various alarms as binary inputs and as GOOSE messages for physical alarm indication. The configurations for SMU615 also includes condition monitoring and supervision of circuit breaker, trip and current circuit, and fuse failure.

Tripping and start signals are received from SSC600 via GOOSE communication. Additionally, remote blocking, open and close circuit breaker signals are also received from

SSC600. The blocking signal blocks the circuit breaker from closing in case of arc detection. The tripping and start signals, as well as command signals to open and close circuit breaker, are connected to the outputs of the unit. All events are connected to disturbance recorder and all alarm, and indications are connected to LEDs.

11.3 Configuration of SSC600

SSC600 did not contain standard configuration, the configuration was built from scratch.

The configuration was built so that SSC600 receives currents and voltages from associated merging units and uses measurements to execute its functions. The device also receives primary equipment status, arc detection inputs and other feeder signals from the associated merging units. The equipment status and remote arc detected signal are received through GOOSE communication and measurements as SMV values via process bus communication. Signals like RTD measurements, mA inputs, and binary inputs are received from the remote IO unit using the GOOSE profile.

Each merging unit has its own set of protection, measurement and control functions in SSC600 configuration. Protection trip and start signals and control commands are sent to corresponding units using the GOOSE profile. Issuing of trip and start signals depends on the measurements and protection in SSC600 configuration. Protection in SSC600 configuration comprises of non-directional overcurrent, non-directional and directional earth-fault, undervoltage, overvoltage, residual overvoltage, differential and arc protection. Although there are a lot more protection functions available, earlier mentioned functions are the active ones used in this configuration. Control commands can be received as external commands or executed in WHMI. The graphical configuration was developed with the possibility to view feeder wise measurements and control primary objects like circuit breakers, disconnectors, earthing switches, and tap changer.

11.4 Configuration of RIO600

Configuration for RIO600 enables remote IO unit to receive various alarms and indications as binary and analog signals from I/O modules. These signals are sent to SSC600 via GOOSE communication, additionally RIO600 also receives tap changer control and interlocking signals from SSC600.

11.5 Testing of the configuration

The testing of the configurations were done in FAT area. The testing setup consisted of one SSC600, two SMU615 units, laptop with OMICRON Test Universe software and OMICRON commissioning tool OMICRON CMC 356. Testing templates from an older project with the same configuration but different hardware were used for testing. The whole configuration could not be tested since not all devices were available. All essential and common protection functions and their trip time were tested. The tests were performed between SSC600 and SMU615 units in transformer feeder, incoming and outgoing feeders. All units were tested one by one, and differential protection test was performed between the main merging unit in transformer feeder and merging unit in the incoming feeder.

Some minor faults were found during the testing, mostly some missing signals and incorrect parameters. The final configuration was built the same way as the tested configuration.

12 Results

The result of this bachelor's thesis is a complete configuration for a whole substation. That includes configurations for SMU615, a configuration for SSC600, and RIO600. The configurations were created with the PC600 software.

Three documents were made for this configuration, and all documents are based on previously used ones. IP-address list contains IP-addresses of all devices in a substation. Relay interface list is a list of analog inputs along with binary inputs and outputs. Lastly, the signal list, which contains client-server data signals that are sent to MicroSCADA or COM600S.

The configuration and related documents can be used for future projects with same protection and control solution. This will save time in configuration work and since this configuration is tested it'll also save time in commissioning work and overall increase configuration quality.

13 Discussion

When I summarize my thesis work, I can say that I've gained a lot of knowledge. I've learned more about substations, the communication within, new things in PCM600. I've gained more

experience in configuration making, expanding my knowledge to other solutions from traditional.

Implementation of centralized protection and control solution offers the ability to monitor and control a great variety of substation devices with one single device via HMI. Such solution increases situational awareness and gives easy access to valuable information. The advantage of only having to modify one device instead of all bay-level protection and control devices makes upgrading the entire substation system easier since needed modifications are done in one device instead of all bay-level protection and control devices. Setting up necessary bay devices separately takes more time than engineering single SSC600 device. GOOSE engineering is also reduced due to the logic being located in the SSC600 device. Additionally, usage of process bus also offers several benefits, such as simplification of wiring and flexibility in form of information exchange at process level. The accessibility of any signal on the process level opens opportunities for protection functions.

In conclusion, I am pleased with my bachelor's thesis. This template can be used as a starting point when making configuration for a substation with the same protection and control solution. Hopefully, this thesis work and configuration can help engineers to get a better picture of this solution, save time in configurations work and commissioning.

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