Sami Sorvala

Techno-Economic Analysis of Centralized Protection and Control Systems

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Author:	Sami Sorvala
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Supervisor:	Hannu Laaksonen
Instructor:	Kimmo Kauhaniemi, Miika Vehmasto
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ABSTRACT:

This thesis investigates the technical feasibility and economic impact of centralized protection and control (CPC) systems in medium- and high-voltage substations, especially from the point of view of the contractor. One centralized protection and control product can be capable of handling the protection and control tasks of up to 30 traditional protection relays. Centralizing protection and control functions offers several advantages, including cost savings, advanced protection functions and capabilities, and improved fault diagnostics.

The study begins with a literature review of the technologies and architectures that enable centralized protection and control schemes, such as IEC 61850 communication standards, process bus applications, redundancy protocols, and the use of intelligent electronic devices. In addition, CPC products currently available on the market are reviewed and compared, providing a foundation for the subsequent analysis. Existing literature about the economic impact of implementing centralized protection and control solutions is rather limited, but the available studies suggest that CPC systems can offer significant cost savings, reduced device counts, and simplified maintenance compared to traditional decentralized architectures.

Two case studies of real-life substation projects were carried out to evaluate the practical implications of CPC adoption. The first case study examined a large, complex 110/20 kV substation with demanding protection requirements, while the second focused on a medium-scale substation with simpler architecture. The findings indicate that while CPC systems are technically mature and feasible, their economic attractiveness depends strongly on the scale and configuration of the substation. In large-scale projects, where the protection requirements are demanding, the high costs of CPC units and integration can outweigh potential savings, whereas in smaller and simpler substations, CPC solutions can offer clear capital and operational cost advantages.

Beyond cost considerations, CPC offers several long-term operational benefits, including reduced device count, simplified maintenance and testing, and improved scalability for future system upgrades. However, challenges remain in terms of engineering complexity, training requirements in a rapidly evolving field, and integration with established practices. The results of this thesis indicate that CPC solutions are not universally optimal but can provide significant value under the right circumstances.

KEYWORDS: centralized protection, substation automation, protection relay, control system, high voltage

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TIIVISTELMÄ:

Tässä diplomityössä tutkitaan keskitettyjen suojaus- ja ohjausjärjestelmien teknistä toteutettavuutta ja taloudellisia vaikutuksia keski- ja suurjännitesähköasemilla, erityisesti urakoitsijan näkökulmasta. Yksi keskitetyn suojauksen tuote voi pystyä hoitamaan jopa 30 perinteisen suojareleen tehtävät. Suojaus- ja ohjaustoimintojen keskittäminen tarjoaa useita etuja, kuten kustannussäästöjä, kehittyneitä suojatoimintoja ja parannettua vikadiagnostiikkaa.

Tutkimus alkaa kirjallisuuskatsauksella teknologioista ja arkkitehtuureista, jotka mahdollistavat keskitetyt suojaus- ja ohjausjärjestelmät, kuten IEC 61850 -kommunikaatiostandardi, prosessiväyläsovellukset, redundanssiprotokollat ja automaatiolaitteiden käyttö. Lisäksi työssä tarkastellaan ja vertaillaan markkinoilla tällä hetkellä saatavilla olevia keskitetyn suojauksen ja ohjauksen tuotteita, mikä luo perustan myöhemmälle analyysille. Keskitettyjen suojaus- ja ohjausratkaisujen taloudellisista vaikutuksista on olemassa vain rajoitettu määrä tutkimuksia, mutta saatavilla olevat tutkimukset viittaavat siihen, että keskitetyn ohjauksen ja suojauksen järjestelmät voivat tarjota merkittäviä kustannussäästöjä, vähentää laitemäärää ja yksinkertaistaa huoltoa verrattuna perinteisiin hajautettuihin järjestelmiin.

Työssä toteutettiin kaksi tapaustutkimusta oikeista sähköasemaprojekteista. Ensimmäinen tapaus käsitteli suurta ja monimutkaista 110/20 kV sähköasemaa, jossa oli vaativat suojausvaatimukset, kun taas toinen keskittyi keskisuureen sähköasemaan, jonka arkkitehtuuri oli yksinkertaisempi. Tulokset osoittavat, että vaikka keskitetyt järjestelmät ovat teknisesti kypsiä ja toteuttamiskelpoisia, niiden taloudellinen houkuttelevuus riippuu vahvasti sähköaseman koosta ja kokoonpanosta. Suurissa ja vaativissa projekteissa keskitettyjen laitteiden ja integroinnin korkeat kustannukset voivat ylittää mahdolliset säästöt, kun taas pienemmissä ja yksinkertaisemmissa sähköasemissa keskitetyt ratkaisut voivat tarjota selkeitä etuja sekä pääoma- että käyttökustannuksissa.

Kustannustekijöiden lisäksi keskitetty suojaus tarjoaa useita pitkän aikavälin käyttökustannusetuja, kuten vähentyneen laitemäärän, yksinkertaistetun huollon ja testauksen sekä parannetun skaalautuvuuden tulevia järjestelmäpäivityksiä varten. Haasteita kuitenkin edelleen esiintyy, erityisesti suunnittelun monimutkaisuuden, nopeasti kehittyvän alan koulutustarpeiden ja olemassa olevien käytäntöjen integroinnin osalta. Työn tulokset osoittavat, että keskitetyt suojaus- ja ohjausratkaisut eivät ole universaalisti optimaalisia, mutta ne voivat tarjota merkittäviä etuja oikeissa olosuhteissa.

AVAINSANAT: keskitetty suojaus, sähköasema-automaatio, suojarele, ohjausjärjestelmä, suurjännite

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Abbreviations

7SX85	Centralized Protection and Control Unit, Siemens
A/D	Analog/Digital
BCU	Bay Control Unit
CPC	Centralized Protection and Control
CT	Current Transformer

DSO	Distribution System Operator
GIS	Gas-Insulated Switchgear
GOOSE	Generic Object-Oriented Substation Event
GPS	Global Positioning System
HMI	Human Machine Interface
HSR	High-availability Seamless Redundancy
I/O	Input/Output
IEC	International Electrotechnical Commission
IEC 61850	International Standard for Substation Communication
IED	Intelligent Electronic Device
IMU	Intelligent Merging Unit
LAN	Local Area Network
LED	Light Emitting Diode
MU	Merging Unit
MV	Medium Voltage
PMU	Phasor Measurement Unit
PRP	Parallel Redundancy Protocol
PTP	Precision Time Protocol
SCADA	Supervisory Control and Data Acquisition
SAS	Substation Automation System
SEL	Schweitzer Engineering Laboratories, Inc.
SEL-487E	Centralized Protection and Control Unit, SEL
SFP	Small Form-factor Pluggable
SNTP	Simple Network Time Protocol
SSC600	Centralized Protection and Control Unit, ABB
SV	Sampled Values
TCP	Transmission Control Protocol
TSO	Transmission System Operator
VT	Voltage Transformer

1 Introduction

Power system protection is crucial for quickly isolating faulty areas of power grids in order to ensure uninterrupted power flow and to safeguard equipment and personnel. The increasing complexity of modern power grids has increased the demand for more sophisticated protection and control methods. One way to address these demands is deploying centralized protection and control (CPC) systems. The main idea of centralized protection concept is to move the protection and control functions from multiple bay level devices to a single centralized processing unit. CPC systems are not quite a novel concept, but they are still not widely used today. However, recent advancements in computing technology and international standards have made it a feasible alternative for modern substations. CPC units can be deployed in several different architectures, depending on the components used and the requirements of the application. The main expected benefits of deploying CPC solutions are increased flexibility and performance, while reducing overall costs (ABB, 2019a, p. 1).

1.1 Background

This thesis has been conducted as a commission for VEO Oy, a Finnish energy company that delivers various electrification solutions. VEO Oy specializes in providing tailored electrification solutions for sectors such as renewable energy, hydropower, marine, and power grids, with a strong focus on enhancing efficiency, reliability, and sustainability in energy production and distribution. With decades of experience and a commitment to innovation, VEO Oy has established itself as a trusted partner in the development of modern power systems and industrial electrification projects. The company VEO Oy is a part of VEO Group, which has subsidiaries in Sweden, Norway and in the United Kingdom. The group as a whole employs approximately 500 professionals from various industries, including electrical engineering, automation, and project management. (VEO Oy, 2025).

This thesis is conducted for VEO Oy’s Power Distribution department. Typical customers include transmission system operators (TSO) and distribution system operators (DSO), both of which are essential for maintaining the reliability and efficiency of power systems. Typical project deliveries of the Power Distribution department consist of designing, testing and commissioning of substation equipment, tailored to meet the specific needs of each client and project.

This research is relevant and topical subject for VEO, as the interest towards centralized protection and control systems is increasing. The research will not only help VEO assess the technical feasibility and practical benefits of CPC systems but also provide insights into potential challenges and best practices for implementation. By addressing these factors, the findings of this thesis can support VEO in developing optimized CPC solutions for their substation projects, ultimately enhancing the performance and reliability of the power distribution networks they serve.

1.2 Research Objectives

The primary objective of this thesis is to conduct techno-economic analysis about centralized protection and control products. This thesis aims to evaluate the technical feasibility, economic benefits, challenges and advantages associated with CPC systems compared to conventional protection and control architectures. The selection of suitable CPC products on the market for the needs of the target company is explored. The main goal of this thesis is to gain answers for the following questions:

- What are the technical and economic benefits of centralized protection and control systems?
- What are the key advantages and challenges of centralized protection and control systems compared to conventional protection schemes?
- Which centralized protection products available on the market are the most suitable for VEO’s needs?

To undertake and answer these questions, this thesis follows a structured approach combining both technical analysis and economic evaluation. This research provides an in-depth study of centralized protection and control systems, not only assessing their architectural structure, functionality, and performance in substation environments, but also evaluating the economic feasibility, especially from VEO's point of view as a turnkey project provider. Two case studies about real-life substation projects are conducted to further assess their technical feasibility and cost considerations under different substation sizes and configurations.

1.3 Structure of the Thesis

The research begins by presenting a general overview of the topic and the motivation behind selecting centralized protection and control systems as the focus of this thesis. Chapter 2 introduces the technical background, including the physical hardware required to implement CPC systems, typical substation architectures, and the most relevant standards and communication protocols that enable their implementation. The chapter also highlights the fundamental differences between decentralized and centralized protection approaches, providing the foundation for the subsequent analysis.

Chapter 3 focuses on the economic perspective of CPC systems. The chapter introduces the main CPC products currently available on the market and examines their technical characteristics. Furthermore, the cost structure of centralized architectures is explained, with an emphasis on how CPC solutions differ from conventional systems in terms of capital investments and potential operational expenditure savings.

Chapter 4 is focused on two case studies based on VEO's substation projects. These case studies provide concrete examples of how CPC can be applied in practice, both in larger and smaller scale substations. The findings from these cases are then brought together in chapter 5, where they are discussed alongside the background research to evaluate both the technical and economic feasibility of CPC systems. Areas where further research could be useful are also pointed out. Finally, chapter 6 concludes the thesis by summarizing the main results and highlighting what they mean in practice.

2 Technical Analysis of Centralized Protection and Control Systems

2.1 Basics of Centralized Protection and Control Systems

Centralized protection and control systems are large entities, that consist of multiple IEDs, communication networks, and a centralized controlling unit, working together to provide coordinated monitoring, protection, and control of substation equipment. The main concept of centralized protection and control systems is that all the protection and control functions are combined into a single device. (Teoh et al., 2020) To gain a comprehensive understanding of the technical aspects of CPC solutions, the following subsections will discuss the most important hardware components of typical CPC solutions and their technical characteristics.

2.1.1 Centralized Protection Device

The main component of a centralized protection and control system is obviously the CPC device. The CPC device serves as the core unit of the whole CPC system, integrating multiple protection, control, and automation functions. For a CPC unit to be a successful solution, the computing platform, both hardware and software or firmware must be powerful and reliable. When considering CPC implementations, it is important to remember that the CPC device will be installed in a substation and must meet all the expected environmental and performance requirements for protective devices in substations. A centralized protection device must be a technologically mature and reliable solution, built on a robust and self-supervised platform. It should use tested and proven protection algorithms and offer scalability, all while being supported by hardware designed for a 20-year operational lifespan. Cyber security issues are becoming even more important when moving from decentralized systems to CPC solutions, where most of the data is digitized. (Teoh et al., 2020)

2.1.2 Merging Unit

The standard IEC 61850-9-1 defines merging unit as an interface unit that accepts CT and VT inputs, as well as binary inputs and produces multiple time synchronized digital outputs to provide data communication via the logical interfaces (ABB, 2022a). When it comes to centralized protection and control systems, merging units are the core components that make CPC systems feasible. In addition to serving as an interface between the primary equipment and the CPC unit, merging units can also manage input and output functions to process digital signals from feeders.

When the merging unit includes additional functionality, such as protection functions, it is called an intelligent merging unit (IMU). In practice, IMUs are ordinary microprocessor-based protection relays that also include process bus sending capabilities, i.e. they are IEC 61850-9-2 compatible. The main benefit of an IMU is that it can serve as a local back-up protection device of the CPC unit, in case the main CPC unit or communication network fails. (ABB, 2022a)

2.1.3 Remote I/O Unit

Sometimes in CPC applications the main CPC device does not have enough I/O to single-handedly manage all signaling and controlling functions of a substation, remote I/O units may be needed. Merging units can contain some I/O, but in some cases, the amount of I/O must be expanded by remote I/O units. Remote I/O units are typically used to monitor the status of the system, and to control circuit breakers and switches. Typically, signals are transferred between the main CPC device and remote I/O unit over Ethernet, utilizing IEC 61850. (Teoh et al., 2020) The main distinguishing feature between remote I/O units and merging units is that the remote I/O units are not IEC 61850-9-2 process bus compatible.

2.1.4 Time-Synchronization Device

Ethernet-based technology allows for software-based time synchronization with an accuracy of 1 millisecond without relying on hardware components. This level of accuracy is referred to as the basic time synchronization class in the IEC 61850 standard. A more traditional protocol, SNTP (Simple Network Time Protocol), is often used for local substation synchronization in smaller systems. However, when the SNTP server is located behind multiple Ethernet nodes, the latency increases, which reduces the synchronization accuracy. Therefore, SNTP is not an ideal solution for system-wide implementation. Normally, a GPS or equivalent time synchronization resource is required in each substation. IEEE 1588 v2 and IEC 61850-9-3 deal with these issues and makes it possible to achieve a time synchronization accuracy of 1 microsecond. This is required for a process bus system like CPC. (ABB, 2022b, p. 8)

Conventional substations with decentralized protection use electromagnetic instrument transformers for measuring electrical quantities and getting continuous analog output, then protection devices sample the analog input via A/D timing module, in which way sampling processing latency is small and relatively stable. However, the case is much different in CPC applications, where the protection and control functions rely on sampled values provided by electronic transformers and merging units, transmitting sampled data over a network. In this setup, data is sent as packets at fixed intervals, and the sampling process depends on network transmission timing, which introduces potential delays and variability. As a result, the timing characteristics of data sampling and transfer are more complex and less predictable compared to conventional substations. (Zhongqing et al., 2014).

CPC systems do not necessarily require absolute time synchronization, but only relative synchronization between the merging units and the CPC unit. As long as all the merging units are synchronized to the same source, the CPC relay and the SV streams can be aligned and used for protection. In a digital substation, with good architecture design including duplicated master clocks, it is unlikely to lose all the time masters. But if this rare situation occurs, the merging units will lose time synchronization, and protection functions must be blocked under this situation to avoid false tripping. However, the CPC unit can be designed to act as a master clock to the process bus network. In normal operations, the master clock in the CPC device is synchronized to the substation master clocks. (Teoh et al., 2020)

2.1.5 Instrument Transformers and Sensors

Instrument transformers refer to current transformers (CT) and voltage transformers (VT). These devices are needed to convert the primary currents and voltages into lower level, suitable for measuring devices. Conventional, analogue CTs and VTs are still widely used, but recent advancements in sensor technology make using non-conventional CT and VT solutions more attractive, especially in CPC applications. (Das et al., 2015.)

Rogowski coils are used for current measurement purposes, and they operate on the same principle as conventional iron-core CTs. The primary difference between Rogowski coil and conventional CT is that Rogowski coil windings are wound over a non-magnetic air core, instead of over an iron core. Thanks to the air core design, Rogowski coils are linear, and they cannot saturate unlike iron-core CTs. However, the mutual coupling between the primary conductor and the secondary winding in Rogowski Coils is much smaller compared to iron-core CTs. Therefore, Rogowski Coil output power is small, so it cannot drive current through low-resistance burden like CTs are able to drive. In general, Rogowski Coil current sensors have performance characteristics that are favorable when compared to conventional CTs, such as their linear response, wide frequency range and immunity to saturation. Unlike with conventional CTs, open secondary circuit does not cause damage when using Rogowski coils. (Kojovic et al., 2010)

Optical instrument transformers are an alternative to conventional solutions. Optical CTs have several advantages when compared to conventional iron-core CTs. The performance of optical CTs are generally not affected by ambient temperatures, unlike conventional CTs. Optical CTs also cannot saturate like iron-core CTs, because the measuring systems of optical CTs are based on the Faraday effect. Typically, optical CTs are also lighter and smaller than equivalent iron-core CTs. Electrical safety is also improved, when the measurement data is transmitted via fiber-optic. (Kucuksari et al., 2010)

For voltage measurement purposes, there are also alternatives to the conventional VTs. There are solutions that are based on optical measurement principles. In addition to optical VTs, there are capacitive voltage sensors, that are based on the principle of capacitance, where the high-voltage conductor and a secondary electrode form a capacitor. The voltage applied across the conductor induces an electric field, which varies with the voltage, and this change in capacitance is measured by the sensor. A voltage divider circuit within the sensor scales down the high voltage to a measurable level, which is then digitized for processing. One of the key advantages of capacitive voltage sensors is their galvanic isolation, which provides high-voltage safety while preventing electrical interference. The digital data output from these sensors can be integrated into modern digital substations. (Johansen, N.D.)

There are also variants of instrument transformers that combine current and voltage measurements into a single unit. These combined current and voltage transformers or sensors are an ideal solution for applications with limited space, as they reduce the need for multiple separate devices, thus optimizing the physical form of substations or electrical installations.

2.2 Relevant Standards and Protocols

A crucial factor shaping the feasibility and widespread adoption of centralized protection and control systems is their compliance with industry standards. This subsection of the thesis provides information about the most important industry standards related to centralized protection and control systems.

2.2.1 IEC 61850

IEC 61850 is a global standard for substation automation, which enables seamless communication and interoperability between IEDs in CPC systems. It defines a common data model, real-time communication services, and standardized configuration methods to ensure efficient protection, monitoring, and control of power systems. By utilizing IEC 61850, CPC solutions can achieve high-speed data exchange, precise synchronization, and scalable system integration, all of which enhance the reliability and flexibility of modern substations. IEC 61850 is very extensive standard, and every part of it is absolutely necessary. However, presenting it comprehensively would be irrelevant for this thesis. Instead, the most important parts of the standard, related to CPC systems are presented. The main goal of the standard is to achieve interoperability among the IEDs in the substation automation system, promoting operation in multi-vendor environments. Table 1 presents the scope of the first version of IEC 61850 standard in general.

Table 1. IEC 61850 scope (Mekkanen, 2019, p. 3, modified).

Part	**Definitions**
IEC 61850-1	*Introduction and Overview:* it provides an introduction to IEC 61850 and general overview to all parts.
IEC 61850-2	*Glossary:* it defines specific terms used in SAS.
IEC 61850-3	*General Requirements:* it defines quality requirements based system operation.
IEC 61850-4	*System and project management:* it specifies engineering service requirements.
IEC 61850-5	*Communication requirements for functions and device models:* it defines the virtualizations aspect and its performance requirements.
IEC 61850-6	*Configuration language for communication in electrical substations:* it specifies a file format for describing system configuration and relation between devices.
IEC 61850-7	*Basic communication structure for substation and feeder equipment:*
IEC 61850-7-1	*Principles and Models:* it defines the communication and information model principles also mapping scheme.

IEC 61850-7-2	*Abstract Communication Service Interface (ACSI):* it defines the cooperation of various devices.
IEC 61850-7-3	*Common Data Classes (CDC):* it defines the common attribute type and common data classes related to substation applications.
IEC 61850-7-4	*Compatible logical nodes and data classes:* it specifies the data classes with regard to syntax and semantics.
IEC 61850-8	*Specific Communication Service Mapping (SCSM)*
IEC 61850-8-1	*Mapping to MMS (ISO/IEC 9506-1 & 2) and to (ISO/IEC8802-3):* it describes the communication mapping for the entire system.
IEC 61850-9	*Specific Communication Services Mapping (SCSM)*
IEC 61850-9-1	*Sampled values over serial unidirectional multi-drop point-to-point link:* it describes the point-to-point unidirectional communication mapping services.
IEC 61850-9-2	*Sampled values over ISO/IEC 8802-3:* it describes the SCSM for bus-type.
IEC 61850-9-3	*Precision Time Protocol profile for power utility automation*
IEC 61850-10	*Conformance testing:* it specifies the implementations conformance testing techniques and the declaring performance parameters measurements techniques.

The part 9-2 of IEC 61850 standard is absolutely central for this thesis. IEC 61850-9-2 Ethernet-based communication network is also known as the process bus. The part 9-2 of the standard defines different ways to structure the process bus communication. This part of the standard also defines that the analog, high-voltage signal must be sampled, digitized and transmitted via process bus through specific messages, called Sampled Values (SV). These samples are performed in a synchronous way according to a time base defined, or by the IEEE 1588 v2 protocol. The standard IEC 61850-9-2 is very flexible and comprehensive, but also complex. It allows for different data models and configurations. (Igarashi et al., 2015) As the full standard is complex and not very user-friendly, there is a guideline called IEC 61850-9-2LE (Light Edition) that is a simplified implementation guideline that improves interoperability between different manufacturers' IEDs. A standard SV-message according to IEC 61850-9-2LE contains four current measurements and four voltage measurements in one dataset. The IEC 61850-9-2LE guideline defines two sampling rates: 80 samples per cycle (for protection purposes) and 256 samples per cycle (for measurement purposes, such as PMU). (Teoh et al., 2020) In 50 Hz grids, it is equivalent to 4 kHz sampling rate for protection purposes and 12.8 kHz sampling rate for measurement purposes.

2.2.2 IEEE 1588 v2, Precision Time Protocol

As time synchronization is highly important in CPC systems, IEEE 1588 v2 standard is needed for the devices in CPC architecture to maintain time synchronism. IEEE 1588 v2, also referred as Precision Time Protocol (PTP) is a protocol designed to synchronize real-time clocks in the nodes of a distributed system that communicates using a network. Thanks to this standard, sub-microsecond accuracy of hardware time stamping can be achieved. In substation environments, PTP is necessary to synchronize clocks between IEDs accurately. PTP devices periodically exchange messages for synchronization purposes, and the underlying algorithm takes into account network propagation delay, and other variables. One of the key reasons why PTP achieves very high synchronization accuracy is the active involvement of network switches during the process. In typical substation applications, every switch along the path of synchronization measures path delay of every link, and the time the data packet spends inside the switch. These accumulated delays are written into the correction field, which allows time clients to calculate the time offset very precisely. (Moxa, 2023) Nowadays, the use of PTP is adopted by the standard IEC 61850-9-3 (Falk, 2018, p. 94).

Three types of clocks are defined for the PTP standard: Ordinary clock, transparent clock, and boundary clock. These clocks work together to distribute highly accurate synchronization messages. Ordinary clocks are single port devices that support PTP. They maintain a time scale in the PTP domain. They can also be configured to work as a master clock or just a slave clock. Switches and routers in the network can act as a transparent clock. The role of transparent clocks is to measure the switching delay and add this information to the PTP message. The operating principle of boundary clocks is similar to transparent clocks. Boundary clocks normally act as a network switch, but they are equipped with a local oscillator. The difference is that transparent clocks transport only network packets and mark them with timestamps, while boundary clocks act as an intermediary clock between the grandmaster and slave clocks. (BitStream, 2020).

In general, the IEEE 1588 v2 synchronization process consists of two steps. The first step is to establish a master-slave hierarchy by deciding the role and state of each port of all ordinary clocks and boundary clocks. The second step is that the grandmaster clock starts synchronizing the slave clocks. To establish a master-slave hierarchy, it is necessary to decide which node is the grandmaster clock for the entire system. One technical advantage of IEEE 1588 v2 is that it allows the use of multiple master clocks on the same network, so the failure of one clock does not lead into a synchronization failure. An example network utilizing PTP is presented in Figure 1. (BitStream, 2020).

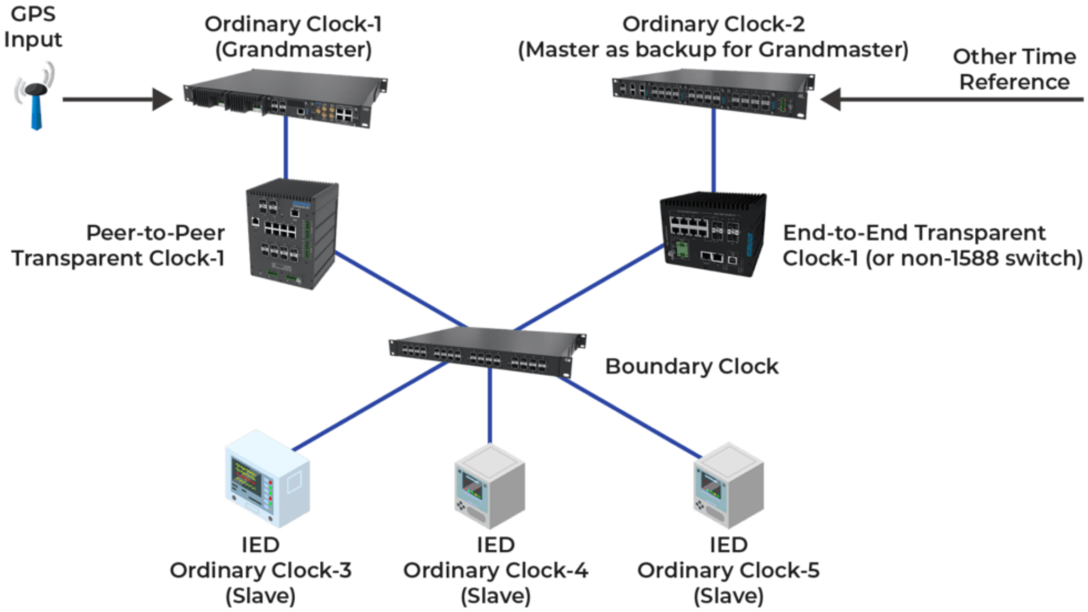


Figure 1. IEEE 1588 v2 clock network (BitStream, 2020, modified).

2.2.3 IEC 62439-3

IEC 62439-3 is an international standard that specifies two redundancy protocols — Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR). For the IEC 61850-9-2 process bus it is required to have a communication recovery time of zero. To address such a need, the use of the standard IEC 62439-3 is mandated in the standard IEC 61850. (Valtari, 2020) In centralized protection and control systems, redundancy is a key concern to keep the centralized protection unit operational and reliable. Redundancy ensures continuous system performance even in the event of component failures, network disruptions, or planned maintenance activities.

HSR utilizes a ring structure where all IEDs in the ring have two network interfaces. These network interfaces each transmit identical data frames in opposite directions around the ring. Instead, PRP uses two independent LANs, sending identical packets on both paths – providing higher reliability with no recovery time. (TTTech Industrial, N.D.) Figure 2 presents an example network with both protocols utilized.

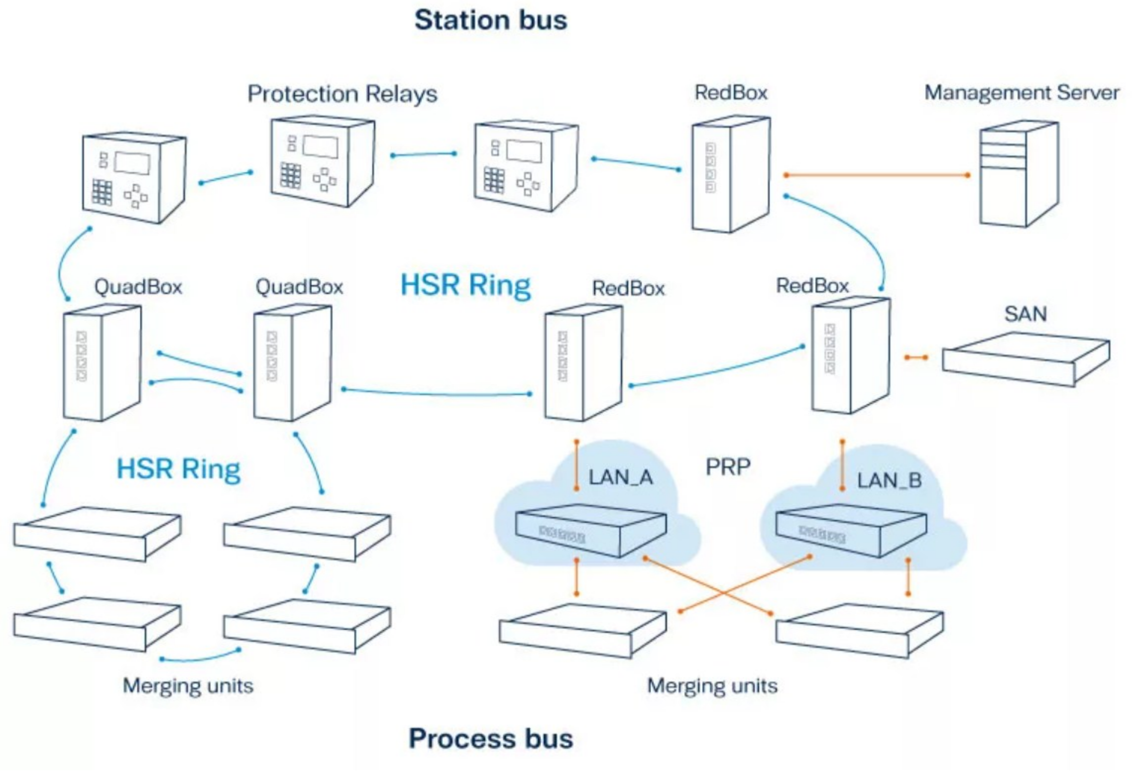


Figure 2. Combined PRP/HSR network (TTTech Industrial, N.D.).

When choosing between HSR and PRP, the decision should be guided by the specific project’s requirements, as the project will determine how the benefits and limitations of each option are prioritized. Generally, PRP is more expensive, but also more flexible than HSR. Both methods provide zero recovery time with no packet loss. For small, simple, and low-cost applications HSR can be a good choice. Low capital costs and the simplicity of the network are the advantages in this situation. However, PRP is a better fit in complex substations, where the size of the system is large. With HSR, maintenance and testing is difficult, as isolating a device breaks the ring. Maintenance is easier with PRP solutions, which decreases the operational costs of the PRP system. (Hunt et al., 2015)

2.2.4 IEC 62351

IEC 61850 is a prevalent standard for smart grid communication, but it was not designed with cybersecurity considerations as a primary objective. IEC 62351 is a standard that extends the IEC 61850 by comprehensive security measures. IEC 62351 was published to implement encryption tunnelling and network monitoring to prevent and detect attacks targeting power system communication networks. Implementation of this standard can significantly improve the security of power systems if applied comprehensively. The standard IEC 62351 offers many recommendations to further improve the cybersecurity of the substation automation system, but its use is not mandated in the IEC 61850 standard. (Hussain et al., 2020)

As centralized protection schemes employ more and more digitized data, cybersecurity is becoming even more important. For example, the standard IEC 62351 offers role-based access control that allows only authorized personnel or applications to access or modify protection and control settings. In addition, the standard includes mechanisms to ensure data integrity and support reliable time synchronization. The standard also defines certificate management processes that ensure secure device authentication and prevent external devices from interfering with CPC communication network. (Hussain et al., 2020) The implementation of cybersecurity improvements from IEC 62351 is highly recommended, although not mandatory.

2.3 Architectural Design of Centralized Protection and Control Systems

The structure of centralized protection and control systems can be tailored, depending on the needs of each application. Deciding on the protection and control architecture for a substation project depends upon many parameters, such as protection philosophy, defined specifications for the project, time critical applications for protection and control, or redundancy requirements at the physical, functional or communicational level. Traditionally, the protection and control functions have been distributed in multiple bay-level numerical protection relays, but in the CPC principle, all the safety critical intelligence is stored into one device. (ABB, 2019a, p. 6) However, it is important to recognize that not all CPC device manufacturers support every possible substation architecture. Therefore, it is necessary to evaluate the needs of the project before selecting the product supplier. Figure 3 represents three common substation architecture alternatives for protection schemes.

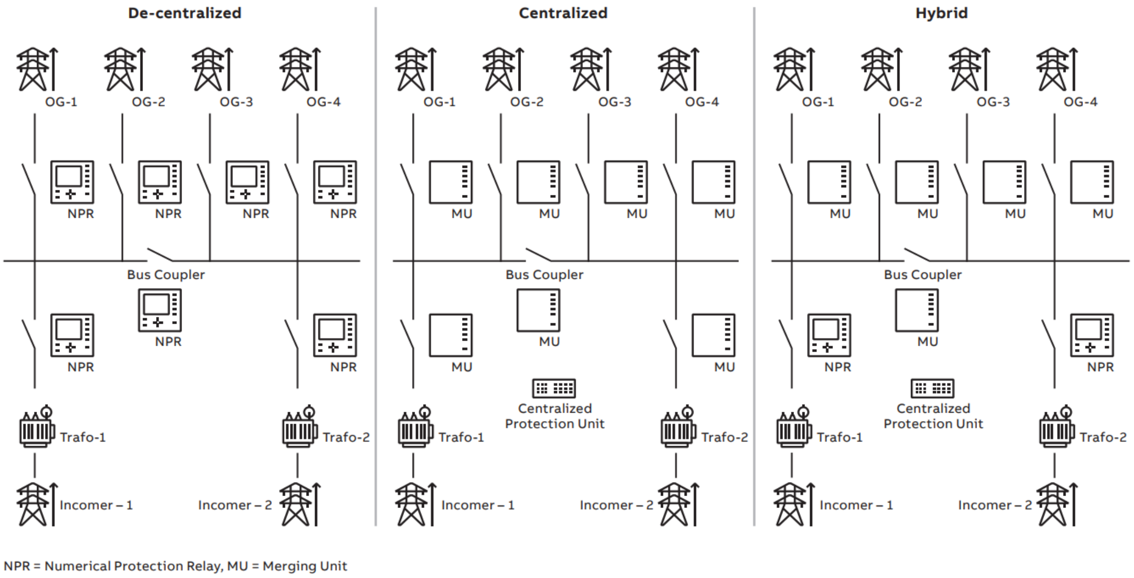


Figure 3. Centralized protection and control architecture alternatives (ABB, 2019a).

On the left side of Figure 3, there is presented the conventional, decentralized protection architecture. Each bay or cubicle has their own, dedicated numerical protection relay working independently. This is the most widely used protection approach to date.

In the middle of the figure, there is presented the fully centralized substation protection architecture. This architecture employs one centralized protection unit, which stores all the critical functions. The merging units collect CT and VT measurements, and transfer them into digital form as sampled values data, which are then subscribed by the centralized protection unit.

Finally, on the right side of the figure, the hybrid architecture is represented. In this approach, there is a mixed selection of numerical protection relays, which can operate independently, and merging units. In this configuration, the numerical protection relays can have some back-up protection functions, in case the CPC unit fails. This adds to the reliability of the protection system.

In addition to these alternatives presented in Figure 3, some CPC product manufacturers support the option to hardwire binary and analog signals from multiple bays into one centralized device, forming centralized protection scheme. A simplified diagram of this kind of architecture is presented in Figure 4.

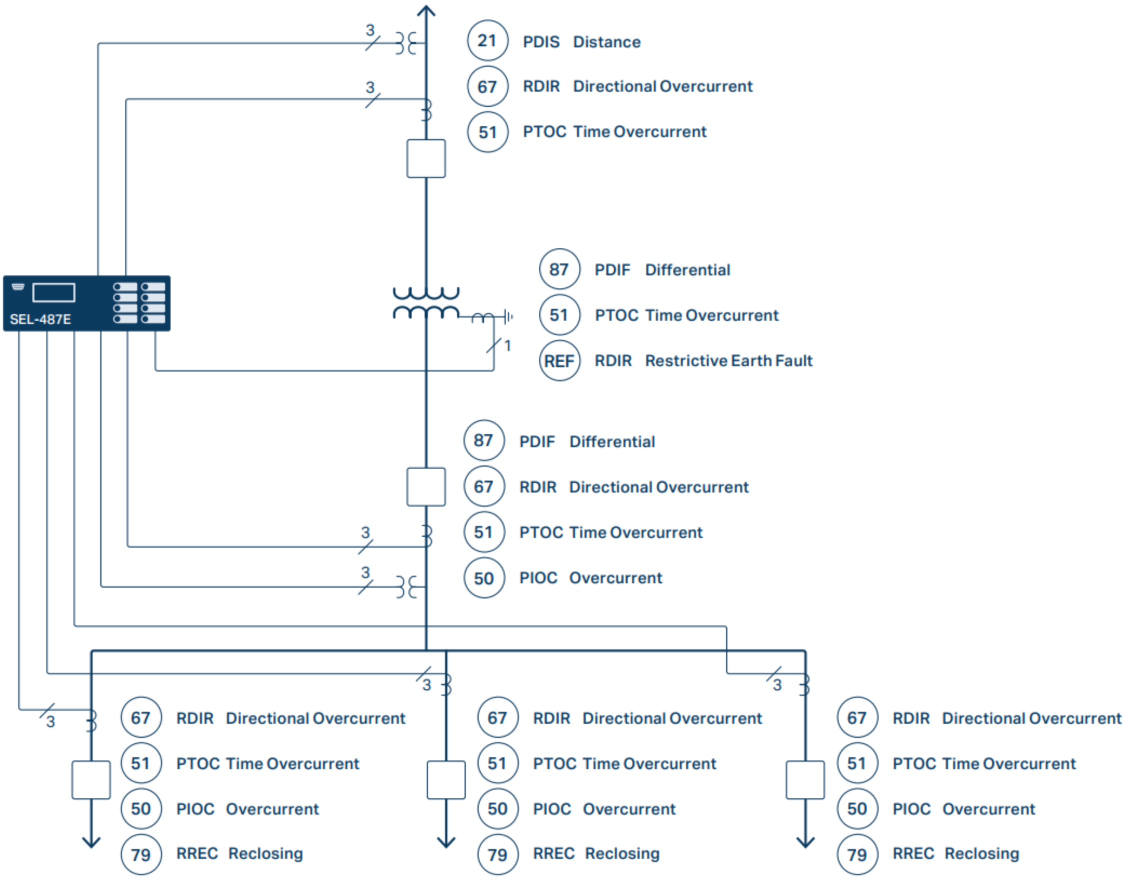


Figure 4. Hardwired centralized protection scheme (Schweitzer Engineering Laboratories, 2024).

These four aforementioned substation architectures are the most widely used alternatives to date. However, these diagrams presented only provide simplified principles of each alternative. Redundancy should be considered depending on the needs of the specific project. Often it is advantageous to use two CPC devices, to keep the other device running while, for example, updating the firmware of the other device. A more detailed approach to an example centralized protection solution utilizing two CPC devices and PRP based redundancy is presented in Figure 5.

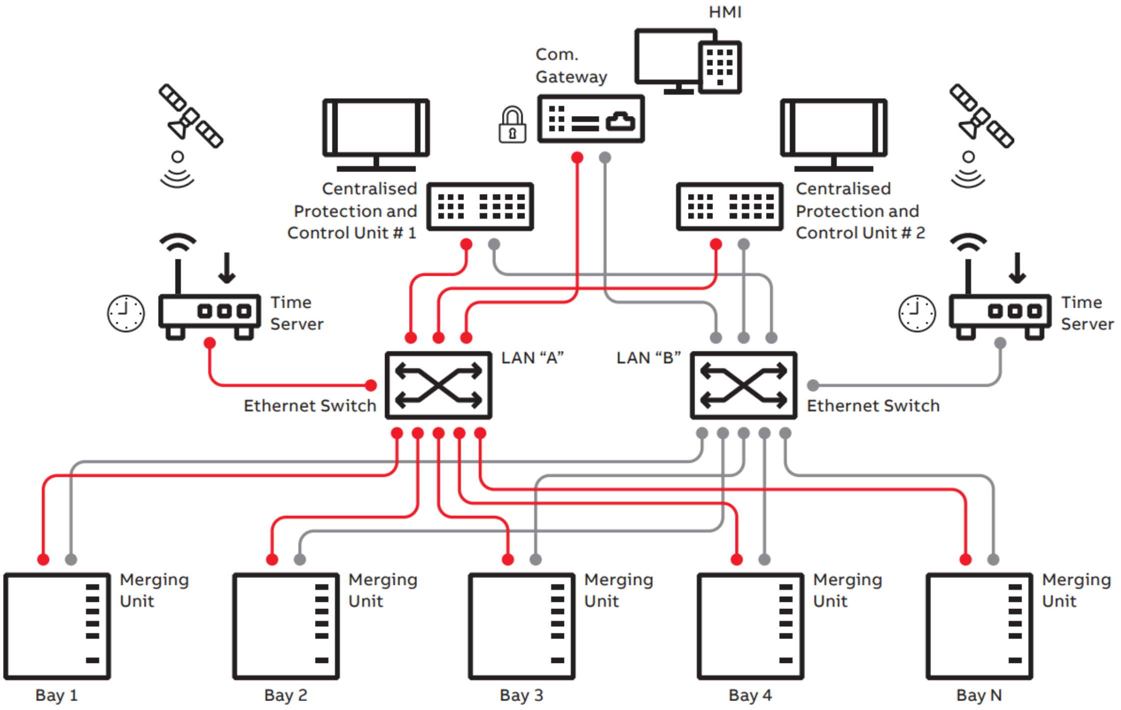


Figure 5. Detailed diagram of a CPC solution utilizing PRP based communication redundancy (ABB, 2019a, p. 7).

Whenever designing a new substation and selecting suitable substation architecture, the limitations of the communication network should be considered. Typically, the most common options for communication network speed are 100 Mb/s or 1 Gb/s in substation networks. If the substation becomes large and the number of SV streams is increased, the process bus bandwidth might become saturated, leading to increased latency, potential packet loss, and reduced performance of protection and control functions. It should be verified that the network is capable of handling all the data streams before executing the project. In their text Junior et al. (2020) have tested the bandwidth limitations of the IEC 61850-9-2 process bus. During their excessive testing, they found that the maximum estimated value of merging units publishing SV streams in one 100 Mb/s network is 19. However, the tests in their paper have been done in 60 Hz grid. In 50 Hz grids, the maximum number of merging units could be a bit higher due to the sampling frequency. In 1 Gb/s networks, they found that the maximum number of merging units is increased to 103 in 60 Hz grids. Therefore, going for 1 Gb/s network should be a safe choice even for larger substations. When needed, Junior et al. (2020)

have concluded an equation (1) to calculate the maximum number of merging units for the network:

$$n_{MUmax} = \frac{\Delta t_{SV}}{t_{Transm}} \tag{1}$$

Considering,

$$\Delta t_{SV} = (\frac{s_{Rate}}{n_{ASDU}})^{-1} \tag{2}$$

$$t_{Transm} = \left(\frac{L_{frame}}{BW_{net}}\right) + t_{SW} \tag{3}$$

where n_{MUmax} is the maximum number of MUs on the network, Δt_{SV} is the transmission period between SV frames, t_{Transm} is the total transmission time of a SV frame, s_{Rate} is the sampling rate of SV frames, n_{ASDU} is the number of Application Service Data Units, L_{frame} is the SV frame length in bits, BW_{net} is the bandwith of the network, and t_{SW} is the latency of the ethernet switch.

2.4 Benefits and Possibilities of Centralized Protection and Control

The centralized architecture of protection and control systems offers some major advantages over decentralized protection and control architecture. One of the most notable advantages of CPC systems is the simplification of system architecture. In conventional implementations, it is required to have multiple protection relays, control devices, and hardwired connections, which can lead to complicated system configuration. By consolidating protection and control functions into a centralized system, the need for excessive hardware and hardwired connections is reduced. Thus, it leads to a reduced number of devices to keep in inventory – as in decentralized protection schemes, it is required to have specific devices for each protection application. In CPC systems, typically it is enough to have suitable devices to replace the CPC units and the merging units in the case of hardware failure. (Ladd et al., 2024)

Another major benefit of CPC systems is the reduced complexity of protection settings and software. In CPC solutions, there will be a reduction in the number of setting templates that are required. Reduction in setting templates will also lead to reduced commissioning time. Additionally, the time spent on engineering is reduced, as there is fewer devices to configure. Interrelay wiring can be eliminated, and communication between IEDs can be simplified, depending on the application. (Ladd et al., 2024)

Cost savings are one of the most essential benefits of implementing CPC solutions. Combining functions of several IEDs into one single hardware allows for more efficient use of the processing power and cost savings can be achieved by reducing the number of hardware components used. Although cost savings are important, CPC systems must maintain the stability and reliability provided by conventional solutions. It is essential to find a balance between reducing costs and preserving the critical performance required for power system operation. (Teoh et al., 2020)

2.5 Limitations and Challenges of Centralized Protection and Control

Many of the aforementioned benefits can sound tempting, but they might introduce new technical challenges that should be considered before proceeding with the CPC system. Ladd et al. (2024) state in their text that one challenge that might be faced when deploying CPC system is having multiple setting groups. For any new designs, often multiple setting groups are needed for feeders, regardless of whether CPC is used or not. When using CPC, there is a higher chance to misconfigure settings, due to the fact that the relay logic can be more complex. A mistake in CPC configuration can also affect not only one feeder, but multiple feeders. Therefore, it is important to carefully configure the setting groups of the CPC unit correctly, avoiding any additional human errors.

When using a redundant two-CPC unit approach, careful consideration is needed to determine how to implement control functions within the primary and secondary CPC units. Some control functions, such as pure control, like reclosing and capacitor controls, can be implemented on the primary CPC unit and not the secondary CPC unit. With this kind of approach, the secondary CPC unit will mainly be used for redundant purposes only. Certain functions, such as operating and tripping through SCADA, must be implemented in only one CPC unit – most likely the primary CPC unit. However, relying on a single CPC unit for control introduces new challenges. For instance, if the primary CPC unit fails, power system operators may be unable to open or close switching devices as needed. To address this, a backup or bypass control mechanism would need to be implemented to ensure continued operation in the event of a primary CPC unit failure. (Ladd et al., 2024)

Operator interface needs to be considered before deploying a CPC system. Traditionally, system operators have performed many of their job functions on the front of the individual protection relays. These functions can include tasks such as opening or closing breakers, enabling or disabling autoreclosing function, or even reading the protection relay event list. The shift towards centralized protection devices requires an HMI to perform many of the local operating functions, that are integrated into traditional decentralized solutions. Also, the HMI of the CPC solution can introduce some additional challenges. In case of an emergency, there is no button on the front of the relay panel to quickly open a breaker. HMIs nowadays tend to require passwords and screen navigation skills, which makes the process slower. (Ladd et al., 2024)

Many of these challenges mentioned earlier can be overcome by proper engineering – including rigorous system design, thorough validation, and careful implementation of protection and control logic. In addition to solid engineering work, coordinated training of technicians and operators is essential to ensure they fully understand the new system’s architecture, functionality, and operational procedures. Furthermore, extensive testing and validation help to mitigate the risks associated with transitioning from decentralized protection to CPC-based approach.

3 Economic Analysis of Centralized Protection and Control Systems

3.1 Available CPC Products on the Market

This chapter and its subsections present an overview of some of the most well-known CPC products and solutions that are currently available on the market. However, it is worth noting that the CPC market is evolving quickly. As a result, new products and updated versions of existing products are frequently introduced. For this thesis, some background investigation and exploration were carried out, what are the CPC products that could be integrated into VEO's projects. It was determined that currently there are three manufacturers offering suitable CPC solutions for VEO's needs: ABB, Siemens and Schweitzer Engineering Laboratories. In the following sections of this paper, the key features, capabilities and applications of the CPC solutions from these manufacturers are discussed, providing an understanding of the options available today.

3.1.1 ABB

ABB launched its centralized protection and control unit, SSC600, at the end of the year 2018. Since then, the product has received various updates, making it to meet demanding requirements today. One SSC600 device can handle the tasks of up to 30 protection relays. The SSC600 device always comes with a redundant power supply. The device can be configured to meet the requirements of the specific project – there are multiple options for communication ports, power supplies, and protection packages. SSC600 does not really have local HMI – instead, a web HMI can be established, where all the measurements, signals and alarms of the substation can be monitored and managed. (ABB, 2019b) The SSC600 device itself does not have binary or analog I/O – therefore the hardwired centralized protection scheme is not available for SSC600.

In addition to the physical form of the SSC600 device, ABB offers a software-based solution for CPC applications, called SSC600 SW. The virtualized product enables end users to use the hardware of their choice and gain access to the same proven protection and control functionality as the SSC600 device offers. SSC600 SW is distributed as a virtual machine which can be installed to KVM or VMware hypervisors. The computing hardware for SSC600 SW is freely selectable, it just needs to fulfill the minimum requirements. (ABB, 2025)

ABB is also manufacturing their own merging units, called SMU615. It is equipped with all the capabilities that merging units usually have, such as measuring current and voltage signals from both conventional and non-conventional CTs and VTs, IEC 61850 capability, and binary I/O as well. It also supports IEEE 1588 v2 time synchronization. SMU615 provides no protection functionality, thus it cannot be used as a backup protection device. The local HMI of the device is very simple, as it only provides a communication port, 11 programmable LEDs and a push-button to clear the LEDs. (ABB, 2023)

Additionally, ABB has released a product for expanding the digital and analog I/O of their Relion-series protection and control relays, called RIO600. This device can act as an expansion unit, or as a standalone device for grid automation applications. RIO600 is a great fit for decreasing the number of hardwired signals by digitizing them. RIO600 supports both, Edition 1 and Edition 2 versions of the IEC 61850 standard. RIO600 can also operate using the Modbus TCP automation protocol. The device is modular, and it can be equipped with various power supply modules, communication modules and I/O modules. RIO600 supports non-conventional instrument transformers for three-phase voltage and current measurements. (ABB, 2022c)

3.1.2 Siemens

Another manufacturer offering CPC solutions is Siemens. Their CPC unit is called 7SX85, which can cover the tasks of 19 different type specific Siemens protection devices. It is capable of advanced protection functions, such as distance, feeder, transformer, machine and line differential protection. The device is recommended for small-scale substations, as it can protect up to 12 bays. The philosophy is that the 7SX85 is a universal device, where can be integrated functions from various Siemens device types. For example, if distance protection is required, which is normally offered by the device 7SA86, it can be added to the universal device 7SX85. Device specific (such as 7SA86) existing application templates and parametrizations can be migrated into the universal device 7SX85. The device 7SX85 is highly modular and can be configured to fit the specific needs of each project and application. It supports up to 443 binary inputs, 225 binary outputs and 64 analog inputs. (Siemens, 2024)

Siemens offers a slightly different approach to substation architectures compared to ABB's approach. In Siemens terminology, their centralized scheme refers to a scheme, where there are no bay-level merging units at all. Instead, circuits are hardwired to the main CPC device (7SX85), including binary I/O and analog measurements. This kind of architecture is enabled thanks to the configurability and the high number of binary and analog I/O available for the device. The other architecture Siemens is offering is called distributed scheme. This scheme utilizes bay-specific merging units to gather bay-specific data. IEC 61850-9-2 is a key enabler in this scheme, as the main CPC unit subscribes to the SV data from the bay-specific merging units. (Siemens, 2024) The operating principles of these two architectures are presented in Figure 6.

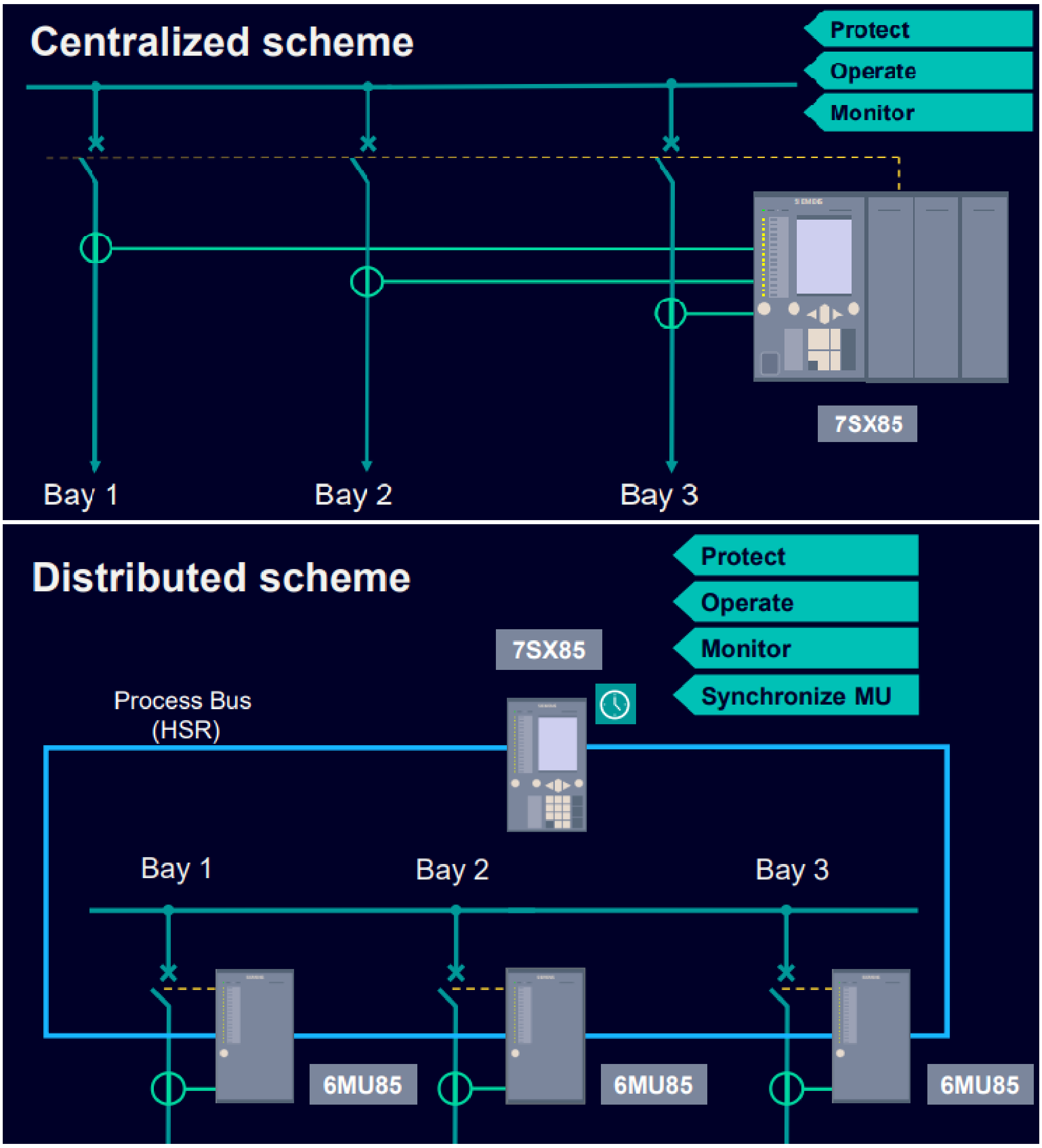


Figure 6. Principles of centralized and distributed schemes in Siemens 7SX85 (Siemens, 2024, modified).

In addition to the main CPC unit, Siemens has developed a merging unit called 6MU85. The merging unit is IEC 61850-9-2 compliant, and it has all the necessary functions that merging units shall have in CPC applications. 6MU85 may be classified as an IMU, as it has the capability to work as a backup protection device if needed. In addition to the capability of measuring currents and voltages, the device is also equipped with binary I/O. 6MU85 accepts both conventional and non-conventional CT and VT inputs. The local

HMI of the device has 16 LEDs, a push-button to acknowledge them and a communication port. It is a modular device that can be expanded with various input and output combinations. (Siemens, N.D.)

3.1.3 Schweitzer Engineering Laboratories

Schweitzer Engineering Laboratories (SEL), based in the United States, have developed their solution for centralized protection and control. The company is well known for high-reliability protection relays and cybersecurity solutions for electric power systems. Historically, SEL has been a pioneer in developing microprocessor-based protection relays and continues to be widely adopted, especially in North America. (Schweitzer Engineering Laboratories, N.D.)

Their SEL-487E protection device can handle the tasks of CPC unit. The device can simultaneously protect transformers, buses, lines, and feeders using differential, overcurrent, and distance elements. In addition to conventional hardwired CT and VT connections, SEL-487E supports IEC 61850-9-2 SV data. It can subscribe to as many as 24 SV data streams, and publish 7 SV data streams. The SEL-487E is a multi-purpose product that can be used in various different ways. The product can be used, for example, as a phasor measurement unit, transformer differential relay, or as a CPC main unit. When used as a main CPC unit, it fits the best in small substations, as the device supports up to 18 CT inputs and 6 VT inputs. The device offers flexible communications options, as small form-factor pluggable (SFP) transceivers can be used for process bus as well as station bus. All ports support 100 Mbps SFP transceivers and process bus ports support 1 Gbps transceivers. In addition to the main CPC unit, SEL has developed their own merging unit, called SEL-401 and time-synchronization device, called SEL-9524. The whole CPC scheme could be applied by using products manufactured by SEL. (Schweitzer Engineering Laboratories, 2024)

3.1.4 Comparison of CPC Manufacturers

While ABB, Siemens, and SEL all provide solutions that can be applied in centralized protection and control applications, their approaches differ in scope, maturity, and market positioning. ABB has positioned itself as a pioneer in CPC, with the SSC600 acting as a dedicated centralized protection and control unit. Siemens follows a similar path with the 7SX85 product, which integrates protection and control functions into a single device with HMI capabilities. SEL, on the other hand, has adopted a more incremental approach, enhancing its rugged and proven multifunctional relays, merging units and other products to support IEC 61850 process bus communication rather than releasing large-scale CPC platform. Table 2 presents a comparison of the main technical features of the three CPC products.

Table 2. ABB, Siemens and SEL CPC product comparison.

Feature	**ABB SSC600**	**Siemens 7SX85**	**SEL-487E**
CPC concept	Dedicated CPC unit	Multipurpose relay, can be used as CPC unit	Multipurpose relay, can be used as CPC unit
IEC 61850-9-2 compatible	Yes	Yes	Yes
Scalability	One device can handle the tasks of up to 30 relays	One device can be used to protect up to 12 bays	Only for small substations
HMI/Visualization	Web HMI (External HMI recommended)	Integrated HMI with single-line diagram display	Basic local display
Time synchronization	IEEE 1588 PTP, SNTP, IRIG-B	IEEE 1588 PTP, SNTP, IRIG-B	IEEE 1588 PTP, SNTP, IRIG-B
Redundancy options	PRP/HSR	PRP/HSR	PRP/HSR

Ideal fit	Fully digital, larger substations with full IEC 61850 adoption	Small to medium scale substations, digital or non-digital	Small substations, digital or non-digital

This comparison highlights that ABB is actively pushing the industry toward fully centralized architectures. Siemens has also established its position in CPC market. SEL maintains a hybrid, semi-centralized model that may appeal to utilities that prefer gradual adoption of CPC products. For system integrators such as VEO, this means that the choice of manufacturer depends not only on the technical performance of the product but also on the customer's readiness to adopt CPC concepts.

3.2 Cost Structure of Centralized Protection and Control Systems

The cost structure of CPC systems can vary significantly depending on the system's complexity, the hardware manufacturer, and the specific requirements of the substation project. However, the trend in CPC solutions is that the value of the product is moving towards the software, and not the hardware. The hardware choices are usually simple, but software requires extensive engineering, commissioning, and testing processes.

Previous research about the economic feasibility of CPC solutions is rather limited. However, according to the research available it is shown that CPC solutions can offer significant savings compared to decentralized solutions. In their text Sousa et al. (2017) conducted research about CPC systems in MV substations. Their research was based on seven different simulated cases, where the substation architecture was different in each case. In their calculations, they took into account two parts of the overall cost function: a capital part, which includes investments and renewals, and operational part, which includes the costs of repairs and scheduled maintenance. They found out that in every case out of the seven possible cases, the capital costs of equivalent CPC system were lower than the cost of decentralized system. The operational costs were also lower in the CPC systems in every case except one, where the system was fully redundant. In their research, they came up with the assessment of total costs presented in Figure 7.

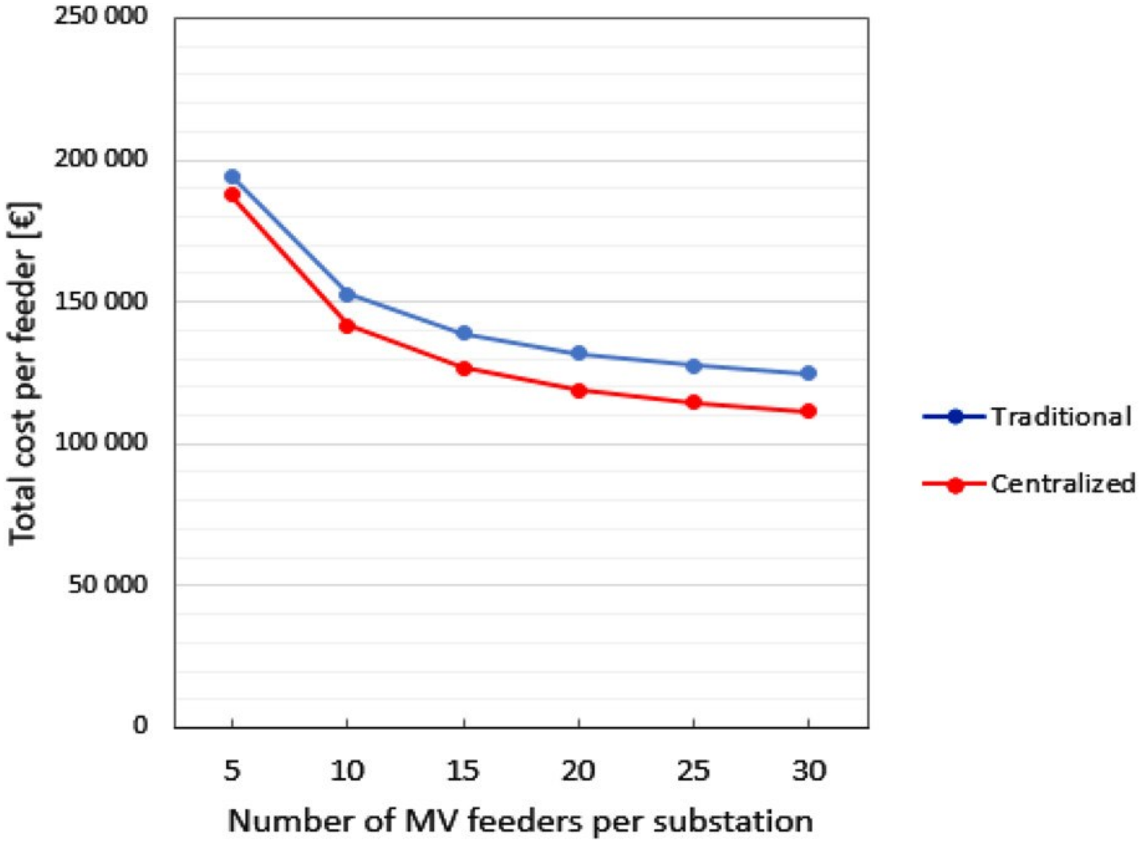


Figure 7. Assessment of total costs in traditional and centralized architectures according to Sousa et al. (2017).

According to the research of Sousa et al. (2017), it is seen that the costs per feeder are inversely proportional to the number of MV feeders in a substation. Figure 7 also implies that the higher the number of MV feeders is in the substation, the higher is the difference in total cost between fully centralized and decentralized architectures. The study shows that the level of redundancy is main the main aggravating factor in the economic feasibility of the CPC systems.

Bettler et al. (2021) have also conducted some research about the economic aspects of IEC 61850-based substations. One of their studies was based on a traditional transmission substation that was built in 2018-2019. In their study, they concluded that the total cost reduction from all the materials used would have been around 300 000 $, if the substation would have been implemented with IEC 61850 based technology. However, their study did not take the labor costs into account, only the material costs were calculated.

While CPC systems require investment in training and more advanced system engineering efforts, overall operational costs are expected to be lower due to reduced device count, simplified cabling and improved scalability. Operational expenditure savings can be realized in several ways when using CPC systems. Firmware updates become more efficient, as only a single centralized device requires updating instead of dozens of individual relays. Protection testing and routine maintenance are simplified, since all functions are managed through one platform rather than distributed across multiple devices. Fault diagnostics and repair can be performed more quickly due to centralized data availability and streamlined system monitoring. Furthermore, expansions and upgrades are easier to implement in a CPC platform, as additional functions can be integrated through software and configuration changes rather than requiring extensive new hardware installations. Spare part inventory is also decreased, as there are fewer device types in the substation. (ABB, 2022a)

As this thesis is conducted from the point of view of a system integrator delivering substation projects, usually with contract pricing, it is more relevant to focus on the capital investment part of the costs, as the operational costs will be covered by the substation operator. The studies presented earlier show that the initial investment costs of CPC systems seem to be lower than the investment costs of equivalent decentralized system. However, the studies did not take into account the labor costs during the engineering and commissioning part of the project. In this thesis, two case studies will be conducted in chapter four, which will consider the costs more in-depth from the point of view of the contractor.

4 Case Studies: CPC Implementation in VEO’s Substation Projects

4.1 Case 1: Complex Large-Scale 110/20 kV Duplex Substation

4.1.1 Case Background

The first case study is focused on a 110/20 kV substation. The substation is owned and operated by a Finnish distribution system operator. The substation shall be delivered as a turnkey project, providing a complete, ready-to-operate solution for the client. As a brand-new substation, this case provides an excellent opportunity to evaluate the implementation of CPC from the initial designing stages, allowing a comparative approach to conventional protection solutions. The case study includes a comprehensive analysis of design choices, system architecture, and the integration of digital secondary systems. The case study aims to evaluate not only the technical, but also economic aspects of CPC deployment in this substation, highlighting the advantages and challenges compared to conventional protection schemes.

The substation consists of 8 bays of 110 kV gas-insulated switchgears (GIS) and 34 bays of 20 kV GIS. Both switchgears are specified to utilize duplex structure. The substation shall contain two 115/21 kV power transformers, each with a rated power of 40 MVA. The scope of the project also includes the delivery of one 110 kV reactor for reactive power compensation. Centralized earth fault current compensation is used for 20 kV network; there will be installed two Petersen-coils at the substation. Additionally, delivery of all the necessary auxiliary devices and equipment that are needed at the substation is included in the scope. The single-line diagram of the substation is provided in Appendix 1.

The substation chosen for this case study represents a typical project from VEO’s project portfolio, however, the protection schemes of the project are rather demanding. The protection and control system for the project must contain the following aspects:

110 kV:

- Differential protection for power transformers and reactor
- Overcurrent protection for power transformers and reactor as a backup function
- Voltage regulator for power transformers
- Non-directional earth fault protection for power transformers and reactor
- Distance protection for feeder bays
- Line differential protection for feeder bays
- Directional earth fault protection for feeder bays
- Overcurrent protection for feeder bays as a backup function
- Busbar differential protection and circuit breaker failure protection

20 kV:

- Overcurrent protection for 20 kV feeders
- Directional earth fault protection for 20 kV feeders
- Intermittent earth fault protection for 20 kV feeders
- Under-, over-, and residual voltage protection
- Arc flash protection
- Frequency protection
- Two setting groups for protection of the 20 kV side:
  - Setting group 1: compensated network
  - Setting group 2: isolated network

In addition to the protection capabilities, the CPC system must be capable of handling the tasks of some control and monitoring functions that are needed in the substation, such as switching operations, fault recordings, interlockings, and signal transferring to SCADA.

4.1.2 CPC System Designing Process

The initial designing process for the case was kicked off by specifying the main components for the CPC system. For this case, it was determined that the most suitable product for the main CPC unit is the ABB SSC600, due to the fact that one device can handle the tasks of up to 30 decentralized protection relays. The support for large amount of devices is seen as major advantage, to reduce the amount of main CPC units needed. However, the CPC scheme for this substation must inevitably be split into two pieces, as the substation is too large for one SSC600 device to handle. It was also specified that the primary CPC devices must have a backup device. Therefore, there will be four SSC600 devices utilized in this case, two of them are functioning as the primary protection and control device and two of them are backup devices.

In this project, the 110 kV feeder bays were required to protect with line differential protection. Since one SSC600 device is capable of providing line differential protection for up to four bays, only two SSC600 units — one primary and one backup device — were configured with line differential protection functionality (ABB, 2024). The other two devices were assigned handle other protection tasks within the substation.

In decentralized solution, redundancy protocols could have been overlooked. Due to the lack of GOOSE signals and SV streams, it would have been sufficient to use Rapid Spanning Tree Protocol (RSTP), which is significantly more affordable to implement. In CPC application, the communication network is specified to be redundant, thus PRP and HSR protocols are viable options. Initially, the intention was to use both, combination of PRP and HSR networks. However, rather quickly it turned out that it was economically not sensible to use HSR rings, as for a substation of this size, there would be a need for plenty of RedBoxes to be used. The communication ports of the merging units chosen for this application can achieve only 100 Mb/s speed, which could become a bottleneck, when the size of the HSR ring is large. Therefore, it was decided to solely go for PRP instead. Suitable ethernet switches for the communication network, Ruggedcom

RST2228 was selected for this case. One RST2228 device can be ordered with 28 SFP ports, capable of 1 Gb/s transfer speed. For a substation of this size, it was needed to have two ethernet switches for each PRP LAN – four in total.

Two grandmaster clocks are applied for this case to achieve reliable time-synchronization across the communication network. The LANTIME M3000 model from Meinberg was selected due to its proven reliability, availability of redundant modules, and VEO's prior positive experience with the product, which ensures compatibility with existing engineering practices in the company. The LANTIME M3000 model can be ordered with redundant power supplies and redundant clock modules. This achieves a good level of redundancy, thus it is debatable if it is required to have additional backup time synchronization device. However, in this project it was decided to go for the backup device to achieve that little bit of extra reliability. At least the backup device allows for convenient maintenance for the primary device; it can be easily and safely turned off, updated and reconfigured. If compared to the decentralized solution, time synchronization devices would not be required, as there would not be used GOOSE signals or SV streams. The need for time synchronization device can be seen as an additional cost to a CPC-based solution.

When it comes to merging units, it was determined that Siemens merging units are the most suitable for this case, due to their high flexibility. The 6MU85 merging units can be ordered with high amounts of I/O, which this project needs. The merging units are used to handle the tasks of the bay control units as well. In addition to controlling and measuring capabilities, it was determined that the backup protection functions are integrated into the merging units, as the 6MU85 merging units are capable of that. The bay-level devices are the key point to achieve cost reduction compared to decentralized solution. In this application, only one merging unit is needed for each bay. However, the case is different in decentralized solution. By the client, it was specified that each 110 kV bay must have many different protection functions, that typically one device cannot handle. For this substation, it would be needed to have two different devices for each

110 kV feeder bay: distance relay with bay controlling functions and line differential relay. For 110 kV transformer bays, the number of devices is also two, but the setup consists of transformer differential relay with bay controlling functionalities, and overcurrent relay as a backup protection device.

The SCADA system was specified by the client to use two remote terminal units, one as a backup. The client specified to use Siemens SICAM A8000 remote terminal units in order to set up their SCADA system. The SCADA system would be deployed with the same devices and principles, regardless of going for a CPC or non-CPC solution.

In the specifications for this project, there was a requirement that the substation should be equipped with a local HMI PC, regardless of whether a CPC or a traditional protection scheme is implemented. Therefore, the cost of deploying the HMI can be seen as a fixed cost.

The finalized system layout designed for this case is provided in Appendix 3. The final system layout is in many ways similar to the PRP-based substation architecture presented in Figure 5.

4.1.3 Calculated Materials and Resources Needed

After the designing process was completed, the materials and labor costs were to be estimated. The sales team of VEO created the offer for this project with utilizing the traditional, decentralized protection and control system. As a result of this thesis, an option that utilizes CPC products was created. Therefore, two options were considered: one based on CPC products and the other relying on conventional decentralized protection hardware. This provides a solid base to compare the differences between CPC and non-CPC implementations.

In order to conduct an objective comparison between the two substation configurations, a detailed material list was gathered for each solution. These lists focus on the components that are the most relevant to the scope of this thesis, with particular emphasis on substation automation equipment such as protection relays, merging units, communication devices, and control panels. The decentralized solution’s material composition is presented in Table 3, while the centralized protection and control setup is presented in Table 4. Presenting the material lists in this structured manner allows for a clear evaluation of the differences in device counts, hardware requirements, and system architecture between the two approaches. This also forms the foundation for the subsequent cost comparison and feasibility analysis.

Table 3. Material list for decentralized system in Case Study 1.

Item	**Description**	**Quantity**
7SD86 P1B396042	Line differential	1
7SD86 P1B397179	Line differential	1
7SD86 P1B396059	Line differential	2
7SA86 P1A671286	Distance relay, BCU	4
7UT85 P1F1165784	Transformer protection, BCU	2
7UT85 P1F1167962	Reactor protection, BCU	1
7SJ85 P1J2021416	Overcurrent relay	3
7SJ85 P1J2021430	Overcurrent relay	1
7SJ85 P1J2021423	Voltage protection relay, BCU	1
7SS85 P1E829670	Busbar protection, main unit	1
6MU85 P1M58070	Busbar protection, bay unit	8
RSG2100-R-RM-HI-HI-FX11-FX11-FX11-FX11-CG01-1FG01-FX11-FX11-TX01-TX01-XX	Ethernet switches	2
REX615B10GN+AIM16+AIM6+APP1+APP2+APP3+APP5+BIO5+BIO5+BIO5+CMP1+COM31+HMI1+PCL1+PSM4+SCT1	20 kV protection relays	36

SICAM A8000 RTU	Remote terminal unit	1
SICAM SCC HMI	HMI	1
Control panels	Control panels	16

Table 4. Material list for centralized system in Case Study 1.

Item	**Description**	**Quantity**
6MU85 P1M139199	110kV merging unit, feeder bays	4
6MU85 P1M201926	110kV merging unit, reactor bay	1
6MU85 P1M201933	110kV merging unit, transformer bays	2
6MU85 P1M201940	110kV merging unit, measuring bay	1
6MU85 P1M201957	20kV merging unit	32
6MU85 P1M201971	20kV merging unit, measuring bays	2
RST2228 6GK6222-6AB00-5FC0-Z A00+B06+C06+D06+E06+F06+G06	Ethernet switches	4
SSC600 SBAEEBANDBA1AGE16G	Main CPC unit, with line differential	2
SSC600 SBAEENANDBA1AGE16G	Main CPC unit, without line differential	2
LANTIME M3000	Time synchronization device	2
SICAM A8000 RTU	Remote terminal unit	1
SICAM SCC HMI	HMI	1
Control panels	Control panels	13

Table 5 presents a structured cost index comparison between the CPC and non-CPC implementations. Due to the confidential and volatile nature of individual equipment prices, the cost analysis is presented as a percentage-based comparison rather than absolute monetary values. Non-CPC implementation is indexed as 100 %. The table includes only the most relevant resources that have direct impact on cost or technical implementation. While the costs of IEDs, networking equipment, and control panels can be calculated accurately, labor costs, copper cabling, and operating expenses are difficult to estimate accurately. The most reasonable estimation for them has been provided. The estimations also incorporate a safety margin for engineering and testing labor, since the adoption of CPC solutions would require the contractor to adapt to new tools and processes, which could initially increase the workload and learning effort.

Data cabling and networking equipment costs are doubled in this case, when utilizing the CPC scheme, as it was needed to use PRP when utilizing CPC. The total capital costs calculated in this study include only the materials and labor directly associated with implementing the substation automation system. Broader project-related expenses, that remain unchanged regardless of the chosen substation architecture, such as civil works or site-specific construction costs, are excluded from the analysis. Operational expenditures are estimated according to the best possible judgment. The deployment of PRP in CPC application definitely does increase the operational costs, but it was determined that the increased reliability and other CPC benefits outweigh the additional operational costs related to PRP.

The total capital costs estimated include protection relays and IEDs, networking equipment, copper and data cabling, control panel materials and assembly, and labor costs related to commissioning, testing and engineering.

Table 5. Cost comparison of CPC and non-CPC solutions in Case Study 1.

Resource	**CPC cost index (Non-CPC = 100 %)**
Protection relays and IEDs	168 %
Networking equipment	200 %
Copper cabling	75 %
Data cabling	200 %
Control panels	82 %

Commissioning and testing labor	125 %
Engineering labor	125 %
Capital costs in total	126 %
Operational expenditures	90 %

4.2 Case 2: Simple Medium-Scale 110/20 kV Substation

4.2.1 Case Background

The second case study is based on a VEO's substation project, that has already been implemented with traditional protection relays. This creates a different approach to the case than in first case study, as the real materials, engineering, commissioning and testing hours spent on the project are already known. This enables a more accurate assessment of potential benefits and challenges. Additionally, the case allows for evaluation of cost savings and simplifications in system design. The project also serves as a benchmark for understanding how CPC systems would perform in small- to medium-sized substations, since this case study was performed on a relatively small substation.

The substation in this case represents a more small-scale distribution substation. In the same way as in the first case, it is a 110/20 kV substation. The substation has only one 110 kV bay, accommodating the power transformer. It has nine 20 kV bays: one incomer from the power transformer, one measuring bay, one bay for auxiliary transformer and earth fault compensation, one bay for reactive power compensation, and the rest five bays are feeders. This substation uses single busbar configuration on the 20 kV side, unlike the first case. The protection schemes of this case are remarkably less demanding than in the first case. The decentralized system of this case study is based on Arcteq protection relays. The CPC system should be equal to the already executed project, thus containing the following properties:

110 kV:

- Differential protection for the power transformer
- Overcurrent protection for the power transformer as a backup function
- Voltage regulator for the power transformer

20 kV:

- Overcurrent protection for 20 kV feeders
- Directional earth fault protection for 20 kV feeders
- Under-, over- and residual voltage protection
- Arc flash protection
- Frequency protection
- Two setting groups for protection of the 20 kV side: one for compensated network and one for isolated network.

In addition to the protection capabilities, the CPC system must be capable of handling the tasks of some control and monitoring functions that are needed in the substation, such as switching operations, fault recordings, interlockings, and signal transferring to SCADA.

4.2.2 CPC System Designing Process

As the size of the substation in this case is rather small, there are more substation architecture alternatives to choose from. Siemens CPC products are better fit in small-scale applications, as they offer the capability of protecting up to 12 bays. For this case, Siemens protection relays offered the best value. As the 7SX85 device is highly modular, it can be equipped with sufficient number of modules to handle all the protection and control tasks in a substation of this size. The short product code for the device assigned for this project is P1J2259185. For the substation architecture, it was decided to apply a CPC system that utilizes conventional instrument transformers. The CPC unit is equipped with 40 current measuring inputs and 8 voltage measuring inputs. To make this case very simple and efficient, traditional copper cables are used to wire the necessary signals to the CPC unit. Therefore, IEC 61850-9-2 process bus is not needed in this project, which simplifies the engineering and commissioning processes. Time-synchronization device is neither necessary for this case.

The main CPC unit can handle all the required previously mentioned protection functions, except for the arc flash protection. Therefore, arc flash protection must be deployed as an independent system. However, in the original project, it was deployed as an independent system, meaning that it can be assumed that the arc flash protection can be deployed using the same hardware, therefore not affecting the costs of the project. In addition to that, in the project specification it was demanded that the 110 kV bay must have a backup protection device. Therefore, a simple overcurrent relay is added to the system. The same overcurrent relay that was used in the original project, is also used in the new CPC system.

The CPC system layout of this case study is presented in Appendix 5. The system layout utilizes similar centralized, hardwired protection scheme as presented in Figure 4.

4.2.3 Calculated Materials and Resources Needed

The background of this case study allows that the materials and resources used for the already executed project can be explored in-depth. The materials of the CPC system are calculated and compared to the decentralized protection system. Since the substation is relatively small, the CPC system can be implemented using a single main CPC unit with minimal additional devices. Only the components that differ between CPC and conventional non-CPC approaches are considered in this analysis.

The non-CPC system consists of multiple bay-level IEDs. For the 110 kV bay, it employs a dedicated main protection relay along with a backup protection relay. Each 20 kV bay is equipped with its own individual protection relay. In addition, an additional IED was added to the station as a binary I/O terminal, handling common alarms and station control signals. In total, the non-CPC system requires 12 IEDs, compared to the CPC implementation, which only requires two devices: the main CPC unit and a simple overcurrent relay as a backup device.

To enable a fair and structured comparison in the second case study, material lists were also compiled for both the decentralized and centralized configurations. As with the first case study, the focus was placed on substation automation equipment, including bay-level relays, communication equipment, and control panels. The material list for the decentralized configuration is presented in Table 6, while the CPC-based solution is detailed in Table 7. By presenting the lists in this way, the specific differences in device counts and hardware requirements can be clearly observed. It provides a basis for analyzing cost impacts and technical feasibility in the context of this medium-sized substation.

Table 6. Material list for decentralized system in Case Study 2.

Item	**Description**	**Quantity**
AQ-T257B-PH0AABA-BBBBBCCCI	110 kV main protection relay	1
AQ-F255A-PH0AABA-BBBCCIIAAAA	110 kV backup protection relay	1
AQ-S254A-PH8AABA-BBBBBBBBAAAAAA	Alarming device for station common alarms	1
AQ-F255A-PH0AABA-BBBCCAAAAAA	20 kV protection relay, feeder bays	7
AQ-F255A-PH0AABA-BBBCCCAAAAA	20 kV protection relay, measuring bay	1
AQ-F255A-PH0AABA-BBBBBCCCCAA	20 kV protection relay, earth fault compensation bay	1
AQ-110P devices and sensors	Arc fault protection system	1
A. Eberle REG-DPA	Earth fault compensation controller	1

ABB RTU540	Remote terminal unit	1
Siemens RSG2300	Ethernet switch	1
Communication devices	Not in scope of the contractor	1

Table 7. Material list for centralized system in Case Study 2.

Item	**Description**	**Quantity**
7SX85 P1J2259185	Main CPC unit	1
AQ-F255A-PH0AABA-BBBCCIIAAAA	110 kV backup protection relay	1
AQ-110P devices and sensors	Arc fault protection system	1
A. Eberle REG-DPA	Earth fault compensation controller	1
ABB RTU540	Remote terminal unit	1
Siemens RSG2300	Ethernet switch	1
Communication devices	Not in scope of the contractor	1

Table 8 presents a structured cost index comparison between the CPC and non-CPC implementations. In this comparison, the non-CPC implementation is indexed as 100 %, providing a clear reference point against which the CPC solution can be evaluated. The table follows the same approach as in the first case study, allowing consistency in the analysis and facilitating comparison across both cases. By using a percentage-based index rather than absolute cost values, the results remain relevant while avoiding disclosure of confidential price information. This approach highlights the relative cost differences between the two architectures and helps identify the areas where the CPC solution achieves savings, as well as where additional costs may arise.

The total capital costs estimated include protection relays and IEDs, networking equipment, copper and data cabling, control panel materials and assembly, and labor costs related to commissioning, testing and engineering.

Table 8. Cost comparison of CPC and non-CPC solutions in Case Study 2.

Resource	**CPC cost index (Non-CPC = 100 %)**
Protection relays and IEDs	74 %
Arc fault protection	100 %
Networking equipment	100 %
Copper cabling	100 %
Data cabling	25 %
Control panels	100 %
Commissioning and testing labor	85 %
Engineering labor	100 %
Capital costs in total	86 %
Operational expenditures	85 %

5 Results and Discussion

5.1 Case Study 1 Findings

The first case study represented a complex, large substation with demanding protection schemes. For this project, the IEC 61850-9-2 process bus was implemented as part of the substation communication architecture. The substation was designed with a combination of ABB and Siemens hardware. Although technically feasible, the analysis indicates that implementing CPC system in this particular case would result in significantly higher costs compared to the traditional solution. Protection relays and IEDs in total would be 68 % more expensive, and the overall capital costs would increase by 26 % while implementing CPC. However, cost alone does not provide a complete picture, as several technical and operational aspects favor CPC.

CPC system was designed to utilize PRP, while the traditional system would use a combination of RSTP and HSR. PRP is proven to be more reliable and robust. Operational expenditures are also estimated to be somewhat lower, even though the implementation PRP adds to the operational expenditures. Compared to the traditional system, the most notable cost savings in a CPC-based solution could be achieved in the control panels. In a CPC architecture, separate control panels for busbar protection would no longer be required, thereby reducing both equipment and installation costs. The reduction in the number of control panels is also seen as a reduction in operating costs.

The substation selected for the first case study was not an optimal fit for CPC implementation. Given the large size of the substation, the SSC600 was determined to be the most suitable solution, as its functionality and scalability align well with the project requirements. While a single SSC600 device is designed to manage the functions of up to 30 individual protection relays, the substation under consideration exceeded this threshold, requiring integration with 43 merging units in total. This mismatch reduces the economic efficiency of a CPC system, since the main CPC unit represents the most expensive individual component within the substation automation system. If the number of merging units was below 30 or closer to 60, the CPC system would make financially more sense, as the full potential of the SSC600 could be utilized.

From an engineering and commissioning perspective, CPC in this case would also have required more extensive system integration and testing efforts compared to the traditional design. The successful implementation of the IEC 61850-9-2 process bus requires greater training and technical expertise compared to the use of traditional analog CT and VT signal inputs. This factor, combined with the large system size, increases the capital investment costs and makes CPC less attractive for immediate implementation. The costs of the engineering and commissioning labor were estimated to be 25 % higher than in equivalent decentralized system.

Nevertheless, the case also highlights potential long-term advantages. Centralized architectures simplify protection testing, firmware management, and system diagnostics, all of which may provide lifecycle cost benefits. Moreover, CPC solutions can enhance scalability by allowing additional functions or future extensions to be implemented largely through software configuration rather than hardware installation. An additional benefit of implementing a CPC system is that it provides a centralized fault recorder, simplifying the fault diagnostics and eliminating the need for dedicated equipment.

Overall, the findings of case study 1 suggest that CPC may not be the most economically viable option for very large substations with high device counts. However, the case study provided valuable insights and information about CPC implementations in larger scale projects. The technical advantages identified — such as improved communication reliability, reduced control panel requirements, and simplified operational tasks — illustrate that CPC systems could still offer value in terms of reliability and maintainability. Operational costs could be achieved, regardless of the higher capital investment costs. These lessons emphasize that the economic feasibility of CPC systems is closely tied to substation size and architecture.

5.2 Case Study 2 Findings

The second case study examined a medium-sized 110/20 kV substation, consisting of one 110 kV feeder bay and nine 20 kV bays. Unlike the first case study, this substation is simpler in design and has less demanding protection schemes. No IEC 61850-9-2 process bus was implemented, and the system relies on conventional CT and VT wiring for measurements. The substation was designed using Siemens CPC hardware, which proved suitable for the size and scope of this project.

From an economic perspective, the implementation of CPC products in this case provides clear advantages. The capital investment costs of the protection relays and other IEDs in a CPC solution are calculated to be only 74 % of the costs for a comparable non-CPC system. The networking equipment costs remained unchanged in this case regardless of the protection architecture. Some minor cost reductions can be realized in data cabling, as the CPC system reduces the number of devices and corresponding interconnections. Copper cabling costs are unaffected due to the absence of process bus deployment in this project. The number of control panels required are also unaffected in this case. Notably, the costs of individual IEDs can be calculated accurately to provide a reliable foundation for investment estimation.

Regarding labor costs, the impact of CPC implementation is moderate. The simplified architecture reduces the number of IEDs from twelve in the non-CPC system to only two devices in the CPC configuration. This directly decreases the amount of engineering, wiring, and configuration work required. Testing efforts are also simplified, as factory and site acceptance tests become more centralized. The engineering work is estimated to be also nearly the same as in the non-CPC system, as the Siemens products are already familiar to the engineering team in this case. The costs of commissioning and testing labor was estimated to be 15 % lower than in equivalent decentralized system. Overall, the study suggests that labor effort could be slightly lower with CPC implementation, though the cost savings achieved are not as notable as in larger substations. As engineering teams gain experience with CPC products, further labor efficiencies can be expected in similar projects.

In summary, the second case study demonstrates that CPC systems can achieve notable capital savings even in medium-sized substations, while operational benefits are present but quite moderate. The simplified system architecture, reduced device count, and simplified testing provide distinct advantages, highlighting the scalability and versatility of CPC solutions for substations of varying sizes.

5.3 Technical Feasibility of CPC Systems

The literature review in chapter 2 showed that centralized protection and control technology has developed to the point where complete systems can now be reliably deployed in substations. Standards such as IEC 61850, and especially the 9-2 process bus, have provided a reliable framework for communication and interoperability, even in multi-vendor environments. At the same time, vendors have introduced products that support centralized architectures, which means CPC can no longer be considered only a theoretical approach, but one that can be put into practice.

This was also reflected in the two case studies presented in chapter 4. The first case dealt with a large and complex substation where several demanding protection schemes had to be managed. Although technically feasible, the study showed that CPC implementation in such large systems requires a high level of engineering effort and careful integration of multiple devices. The findings showed that a CPC system could be realized, but that its complexity places greater demands on design, testing, and staff competence.

The second case study examined a medium-sized substation with a simpler structure. Here the CPC solution could be applied more smoothly, as fewer devices needed to be integrated and the system architecture was more straightforward. The reduced scale made it easier to take advantage of the benefits of centralization, particularly in terms of operation and maintenance. This case suggested that CPC can be especially effective in medium-sized substations, where the relationship between the number of protection devices and the capacity of the CPC unit is more balanced.

Overall, the case studies along with the background research confirmed that CPC systems are technically feasible for both large and medium-sized substations. Larger projects present greater challenges in engineering and integration, while smaller projects tend to show clearer advantages and fewer barriers to implementation. The main obstacles are therefore not technical limitations, but instead on the economic impact of adopting CPC systems and the readiness of system integrators and operators to adjust their ways of working.

5.4 Economic Feasibility of CPC Systems

Demonstrating the economic feasibility of CPC products was one of the central objectives of this thesis. The background research conducted in chapter 3 already provided promising results that cost savings could be achieved through the case studies.

The primary interest for the contractor lies in the potential capital investment savings. From the operator’s perspective, however, operational expenditures represent a major long-term consideration. While these costs are sometimes underestimated, the potential savings achievable through CPC should be clearly demonstrated to the system operator. Making these benefits clear can strengthen the justification for transitioning towards CPC systems.

The role of the station HMI should be carefully reconsidered in CPC applications. In many cases, a HMI is not necessarily needed in decentralized solutions. When transferring to CPC-based application, oftentimes it is the case that IEDs do not have local HMI interfaces anymore. Therefore, at least in larger substations, it is recommended to add a HMI interface to the substation, which adds to the costs of the project. The Siemens 7SX85 CPC unit used in case study 2 features a display interface capable of showing the station single-line diagram. Therefore, a separate HMI is not required for that case. In case study 1, the client required a dedicated HMI for the substation, regardless of going CPC or non-CPC solution.

Redundancy requirements also play an important role in determining the overall cost structure of CPC systems. While basic configurations can provide clear cost savings, fully redundant CPC architectures may significantly increase capital and operational costs. In some scenarios, these additional costs can even outweigh the savings from simplified cabling and device reduction. This makes it important to evaluate redundancy requirements on a case-by-case basis to balance reliability standards with cost-efficiency targets.

Another important factor influencing the economic feasibility of CPC systems is personnel training and competence development. Although long-term savings can be realized through reduced device count and simplified maintenance, contractors and system operators must initially invest in building expertise with CPC-specific tools and software. These training and adaptation costs can reduce the short-term economic attractiveness of CPC solutions. However, once sufficient knowledge has been accumulated, the benefits of CPC solutions can be more consistently realized across future projects.

CPC systems also offer scalability advantages that positively affect long-term economics. Unlike decentralized systems, where expansions often require new hardware, CPC solutions enable many upgrades to be carried out through software or configuration updates. This flexibility can reduce both capital and labor costs in modernization projects, making CPC an attractive option for substations expected to serve over several decades. In addition, centralized solutions can lead to reduced spare part requirements. Since fewer device types are used in CPC architectures, operators can maintain a smaller and more standardized spare part inventory.

5.5 Limitations and Areas for Further Research

This thesis demonstrates the potential technical and economic benefits of centralized protection and control systems, but several limitations in the research process should be acknowledged. Further research on some topics is also recommended.

First, the cost analysis presented in the case studies relies on estimations to some extent rather than complete project execution data. Labor costs, copper cabling, and long-term operational expenditures are inherently site-specific and vary from one project to another. Although the best possible estimates were used to conduct a meaningful comparison, actual figures could differ in a real project implementation. The costs of IEDs and other materials, however, can generally be calculated with a high degree of accuracy, as vendor pricing is relatively consistent across projects.

Second, the scope of CPC product analysis was limited to only three vendors. While Siemens, ABB, and SEL represent major suppliers, the study did not account for the full range of vendors or the rapid pace of development in this field. There are also several semi-centralized product options available, offering intermediate solutions between fully decentralized and fully centralized architectures. Consequently, the findings should be considered more representative than comprehensive.

Third, operational benefits such as reduced downtime, faster fault diagnostics, and reduced spare part inventory and management were analyzed qualitatively, but not confirmed with field data. Further research that involves operational substations would be necessary to justify these advantages and confirm their long-term economic impact.

Finally, cybersecurity considerations were not deeply explored. Centralizing protection and control functions into fewer devices may create new vulnerabilities that require robust protection strategies against cyberattacks. Future work should investigate the cybersecurity implications of CPC systems and assess how these risks compare to traditional decentralized architectures.

6 Conclusions

The goal of this thesis was to clarify the technical framework around CPC products, while exploring the economic benefits of CPC products. The benefits and challenges of technical implementation of CPC products were discussed thoroughly.

The research confirms that CPC systems are technically viable for both large-scale, complex substations, and smaller, simpler substations. The case studies demonstrated that CPC systems can integrate multiple demanding protection functions, control tasks, and monitoring requirements into a reduced number of devices. However, it is worth noting that these two cases represent only two individual cases, not an universal result that CPC is beneficial in small substations, and not in large substations. The outcome could be different case by case and thus should be reviewed separately.

One of the main concerns regarding CPC systems is what happens if the central unit fails. Redundant CPC units, merging units, and PRP-based communication networks can be implemented in order to maintain high reliability, even in larger substations. While CPC solutions introduce some challenges, such as the possible need for dedicated HMI, and more advanced engineering, these concerns can be mitigated in terms of careful system design, punctual testing and operator training.

From an economic perspective, CPC solutions can offer notable cost advantages. In smaller and medium-scale substations, the reduced number of devices can translate into lower capital investment and simplified maintenance, while in larger substations, the benefits may depend on careful matching of CPC capacity to substation size. The case studies also showed the importance of considering labor, cabling, and other integration costs alongside device prices to obtain a realistic assessment of CPC feasibility.

One of the interests of the target company VEO Oy was to find out the most suitable CPC products for them available on the market. As the knowledge of ABB and Siemens products is strong among the target company, those two providers were the most appealing ones. Although the focus of this thesis was mainly on ABB and Siemens, there are other CPC products on the market, such as SEL and GE. Further research and training in the company is recommended to develop expertise in these products. There are also many other vendors that offer semi-centralized protection and control solutions. CPC market is evolving fast, which means that in the future there will be even more products offered with even more functionalities.

In conclusion, CPC systems represent a significant step forward in substation automation, offering both technical and economic advantages when applied appropriately. Their adoption, when supported by proper training and clear demonstration tools, can lead to more efficient, reliable, and cost-effective operation of power systems. However, each case should be carefully reviewed and calculated before making a decision about the substation automation architecture. While not universally optimal, CPC solutions can offer remarkable value in many cases, benefiting both contractors and substation operators.

References

ABB. (2019a). *Centralized Protection and Control.* Retrieved February 23, 2025, from https://library.e.abb.com/public/6b20916a4d2e412daabb76fbada1268e/Centralized_Protection_and_Control_White_paper_2NGA000256_LRENA.pdf

ABB. (2019b). *Webinaaritallenne: SSC600 keskitetty suojaus 13.11.2019.* YouTube. Retrieved March 3, 2025 from https://www.youtube.com/watch?v=lJdkBpa29_k&ab_channel=ABBSuomi

ABB. (2022a). *Centralized protection and control – Enhancing reliability, availability, flexibility and improving operating cost-efficiency of distribution substations.* Retrieved February 26, 2025 from https://library.e.abb.com/public/6b4a135b4c0f4e7f9b4898bdfca37131/White_paper_SSC600_2NGA001420_ENa.pdf

ABB. (2022b). *Pilot Implementation of Centralized Protection and Control – SRP Experience.* Retrieved February 24, 2025 from https://library.e.abb.com/public/4821a3f38e5946bd8b86ecadea9acda7/SRP_SSC600_whitepaper_9AKK108466A9230_ENG.pdf

ABB. (2022c). *Remote I/O RIO600 Installation and Commissioning Manual.* Retrieved February 25, 2025 from https://library.e.abb.com/public/0e4a891a2281426e8f26b1d7517aae24/RIO600_instcomm_757488_ENn.pdf

ABB. (2023). *Substation Merging Unit SMU615 Technical Manual.* Retrieved February 25, 2025 from https://library.e.abb.com/public/c740efd1a4864720b1914806234b3bc9/SMU615-tech_758407_ENd.pdf

ABB. (2024). *SSC600 and SSC600 SW Technical Manual.* Retrieved February 25, 2025 from https://techdoc.relays.protection-control.abb/r/SSC600-and-SSC600-SW-Technical-Manual/1.5/en-US/Copyright

ABB. (2025). *SSC600 and SSC600 SW Product Guide.* Retrieved March 19, 2025 from https://techdoc.relays.protection-control.abb/v/u/SSC600-and-SSC600-SW-Product-Guide/1.5/en-US

Bettler, J., Silva, J., Morman, D., Abboud, R., Bowen, D., Cenzon, E. & Dolezilek, D. (2021). *Case Studies of IEC 61850 Process Bus Systems Using GOOSE and Sampled Values: Recent Installations and Research.* Retrieved April 13, 2025 from https://selinc.com/api/download/132550/

BitStream. (2020, April 2). *IEEE 1588 Time Synchronization.* Retrieved February 25, 2025 from https://bitstream.pl/en/news/ieee-1588-time-synchronization/

Das, R., Kanabar, M., Adamiak, M., Apostolov, A., Antonova, G., Brahma, S., DadashZadeh, M., Hunt, R., Jester, J., Kezunovic, M., Kockott, M., Kojovic, L., Lascu, R., Liao, Y., Luskind, Y., Madani, V., Meliopoulos, A.P., Midence, R., Myrda, P., Oliveira, A. … & Xavier, J. (2015). *Centralized Substation Protection and Control.* IEEE PES. Power System Relaying Committee. Report of Working Group K15 of the Substation Protection Committee. Retrieved February 24, 2025, from https://www.pes-psrc.org/kb/report/020.pdf

Falk, H. (2018). *IEC 61850 Demystified.* Artech House. Retrieved March 4, 2025 from https://ebookcentral-proquest-com.proxy.uwasa.fi/lib/tritonia-ebooks/detail.action?docID=5625455

Hunt, R. & Popescu, B. (2015). *Comparison of PRP and HSR Networks for Protection and Control Applications.* Retrieved March 4, 2025 from https://na.eventscloud.com/file_uploads/21893ab38e0b7ba63a8c74d922f6d07f_hun_pap.pdf

Hussain, S., Ustun, T. & Kalam, A. (2020). *A Review of IEC 62351 Security Mechanisms for IEC 61850 Message Exchanges.* IEEE Transactions on Industrial Informatics, vol. 16, no. 9. https://doi.org/10.1109/TII.2019.2956734

Igarashi, G., Santos, J.C., Junior, S.N. & Pellini, E.L. (2015). *Development of a digital optical Instrument Transformer with process bus interface according to IEC 61850-9-2 standard.* 2015 IEEE PES Innovative Smart Grid Technologies Latin America (ISGT

LATAM), Montevideo, Uruguay, 2015. https://doi.org/10.1109/ISGT-LA.2015.7381273

Johansen, P. (N.D.). *Substation monitoring and control.* Retrieved March 16, 2025 from https://jomitek.dk/downloads/Substation%20monitoring%20and%20control.pdf

Junior, P.S.P., Bernandino, R.C., Martins, C.M, Pereira, P.S. & Lourenço, G.E. (2020). *Analyzing the Limits of Data Transmission in the Process Bus.* Retrieved April 13, 2025 from https://conprove.com/artigos/analyzing-the-limits-of-data-transmission-in-the-process-bus-iec61850/#pdf

Kojovic, L., Beresh, R., Bishop, M., Javora, R., Magruder, B., McLaren, P., Mugalian, B. & Offner, A. (2010). *Practical Aspects of Rogowski Coil Applications to Relaying.* IEEE PSRC Special Report. Retrieved March 4, 2025 from https://www.pes-psrc.org/kb/report/034.pdf

Kucuksari, S. & Karady, G. (2010). *Experimental Comparison of Conventional and Optical Current Transformers*. IEEE Transactions on Power Delivery, vol. 25, no. 4 https://doi.org/10.1109/TPWRD.2010.2050010

Ladd, S., Raffield, T., Haithcox, E., Fultz, J., Shrestha, A., Chatterjee, A. & Nadkar, P. (2024). *Case Study: Designing Centralized Protection and Control Systems for a Distribution Substation at Duke Energy.* 77th Annual Georgia Tech Protective Relaying Conference. Atlanta, Georgia. Retrieved March 15, 2025 from https://selinc.com/api/download/138747/

Mekkanen, M. (2019, April 29). *Light-Weight IEC 61850 IEDs Reducing Complexity.* University of Vaasa. Retrieved March 5, 2025 from https://www.uwasa.fi/sites/default/files/2020-11/lw_iec61850_report.pdf

Moxa. (2023, December 15). *Process Bus Time Synchronization: How to Setup Precision Time Protocol (PTP).* YouTube. Retrieved February 26, 2025 from https://www.youtube.com/watch?v=tQn6qObhGrY&ab_channel=Moxa

Schweitzer Engineering Laboratories. (2024). *Centralized Protection and Control Solution Using SEL-487E.* Retrieved March 3, 2025 from https://selinc.com/api/download/136594/

Schweitzer Engineering Laboratories. (N.D.). *About SEL.* Retrieved September 20, 2025 from https://selinc.com/company/about/

Siemens. (2024). *Centralized Protection featuring SIPROTEC 7SX85.* Recorded webinar. Retrieved February 26, 2025 from https://www.siemens.com/global/en/products/energy/energy-automation-and-smart-grid/webinars/24-en/2407-protection-cpc-siprotec-7sx85.html

Siemens. (N.D.). *SIPROTEC 5 Configurator.* Retrieved February 26, 2025 from https://mall.industry.siemens.com/spicecad/sipom/#/spicecad/sipom/siprotecConfigurator

Sousa, B., Starck, J. & Valtari, J. (2017, October 1). *Viability assessment for centralised protection and control system architectures in medium voltage (MV) substations.* International Conference & Exhibition on Electricity Distribution (CIRED), 2017. https://doi.org/10.1049/oap-cired.2017.0276

Teoh, C., Hunt, R. & Lloyd, G. (2020). *A centralized protection and control system using a well proven transmission class protection relay.* 15th International Conference on Developments in Power System Protection. Liverpool, United Kingdom. https://doi.org/10.1049/cp.2020.0088

TTTech Industrial (N.D.). HSR/PRP for smart grid networks. Retrieved February 26, 2025 from https://www.tttech-industrial.com/resource-library/blog-posts/hsr-prp

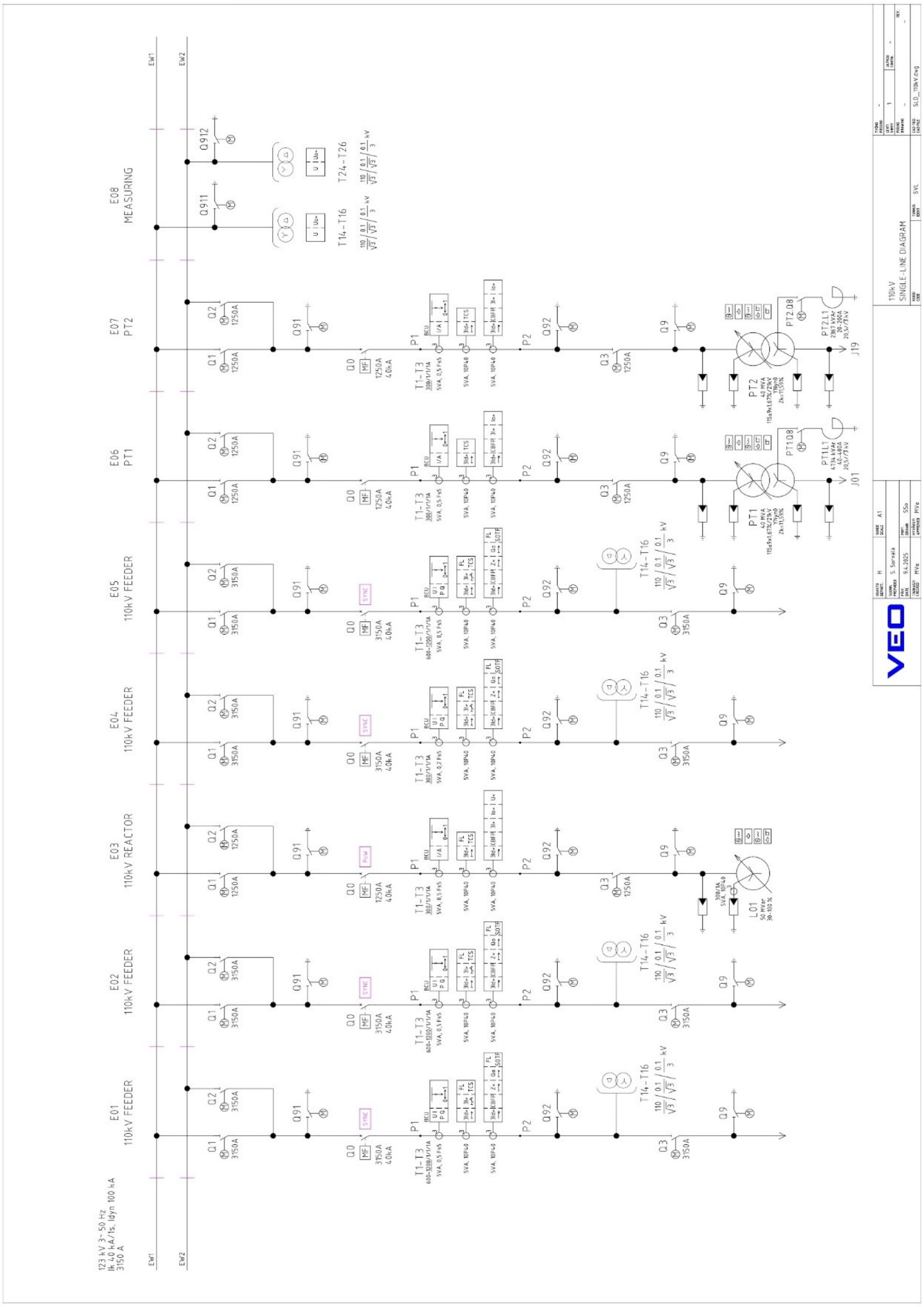
Valtari, J. (2020). *Correlation based fault management for centralized protection and control.* 2020 IEEE PES Innovative Smart Grid Technologies Europe. The Hague, Netherlands, 2020. https://doi.org/10.1109/ISGT-Europe47291.2020.9248815

VEO Oy. (2025). *Company.* Retrieved February 23, 2025, from https://veo.fi/company/

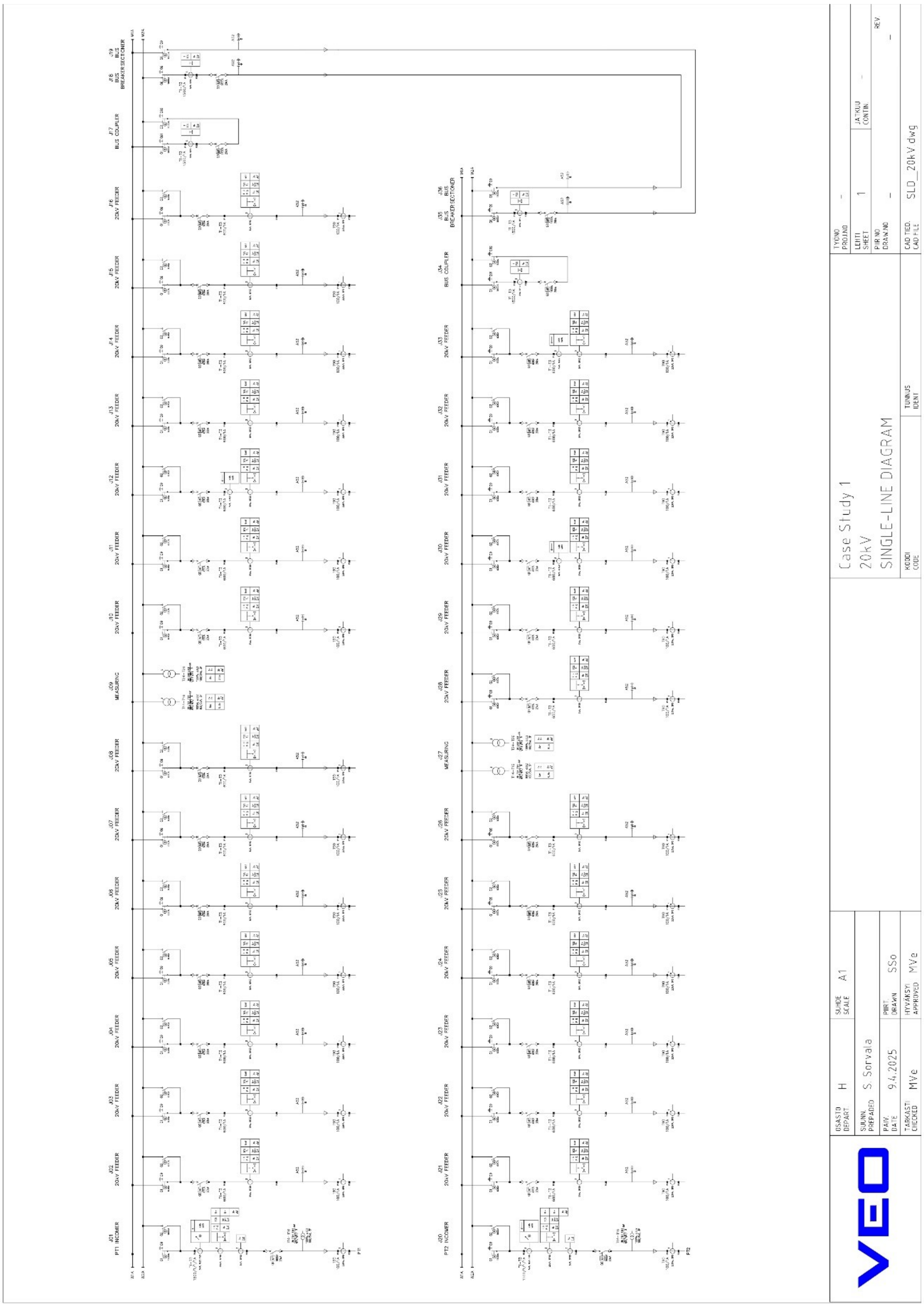
Zhongqing, L., Kaibo, L., Xiao, L. & Xianguo, J. (2014). *Sampled data synchronization scheme for relay protection in smart substation.* 2014 International Conference on Power System Technology. Chengdu, China, 2014. https://doi.org/10.1109/POWERCON.2014.6993613

Appendices

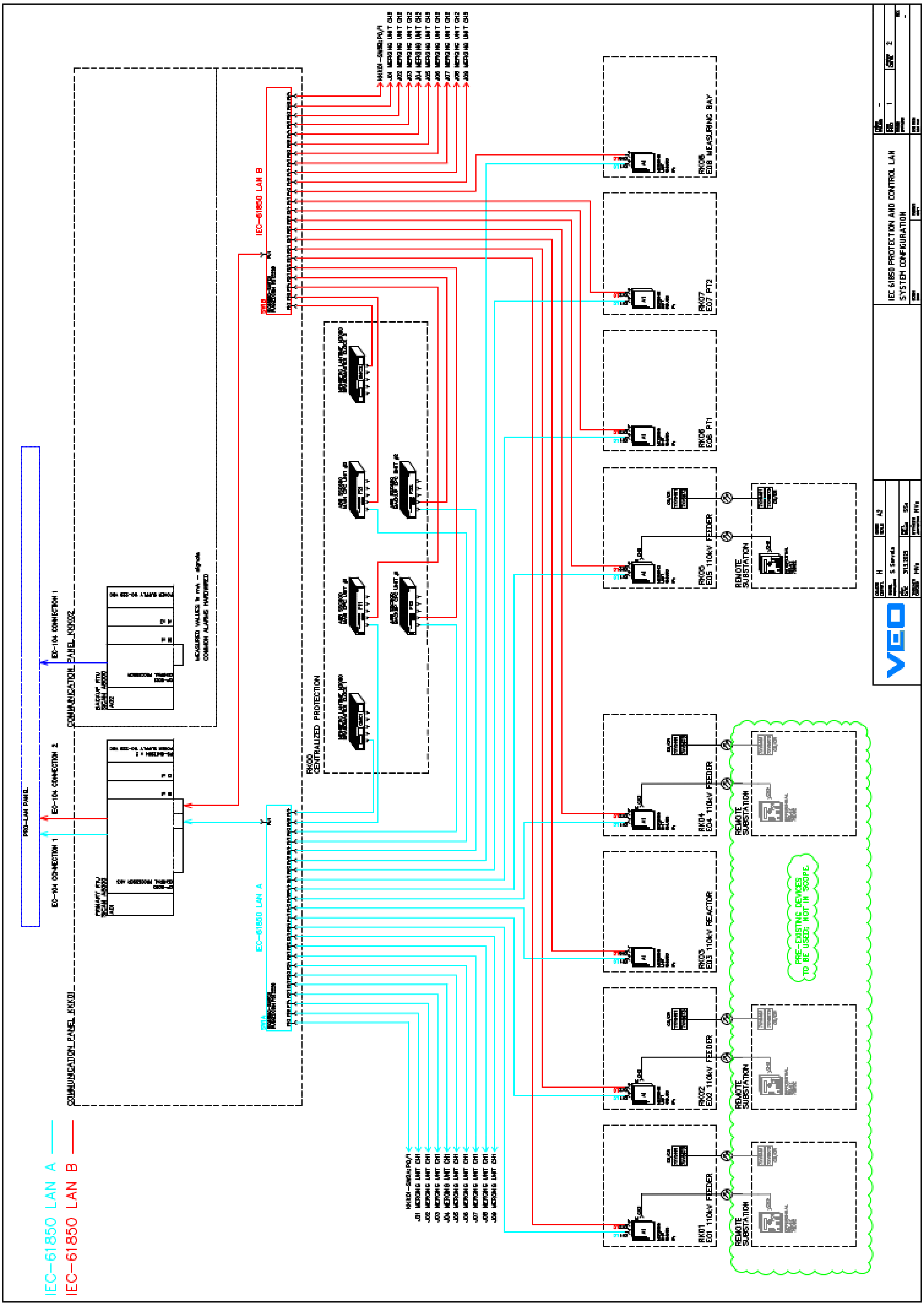
Appendix 1. 110kV Single-Line Diagram of Case Study 1.

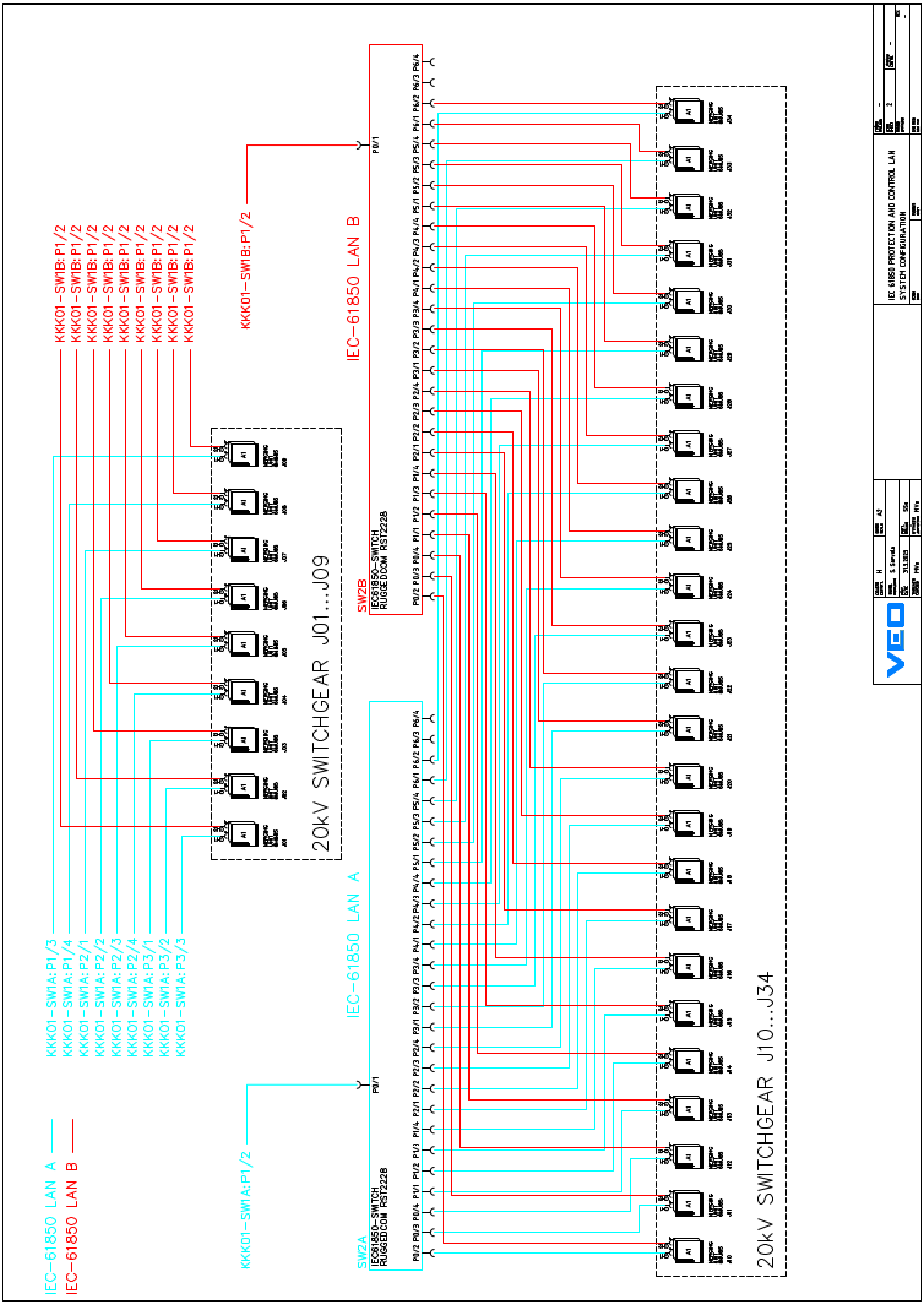


Appendix 2. 20kV Single-Line Diagram of Case Study 1.

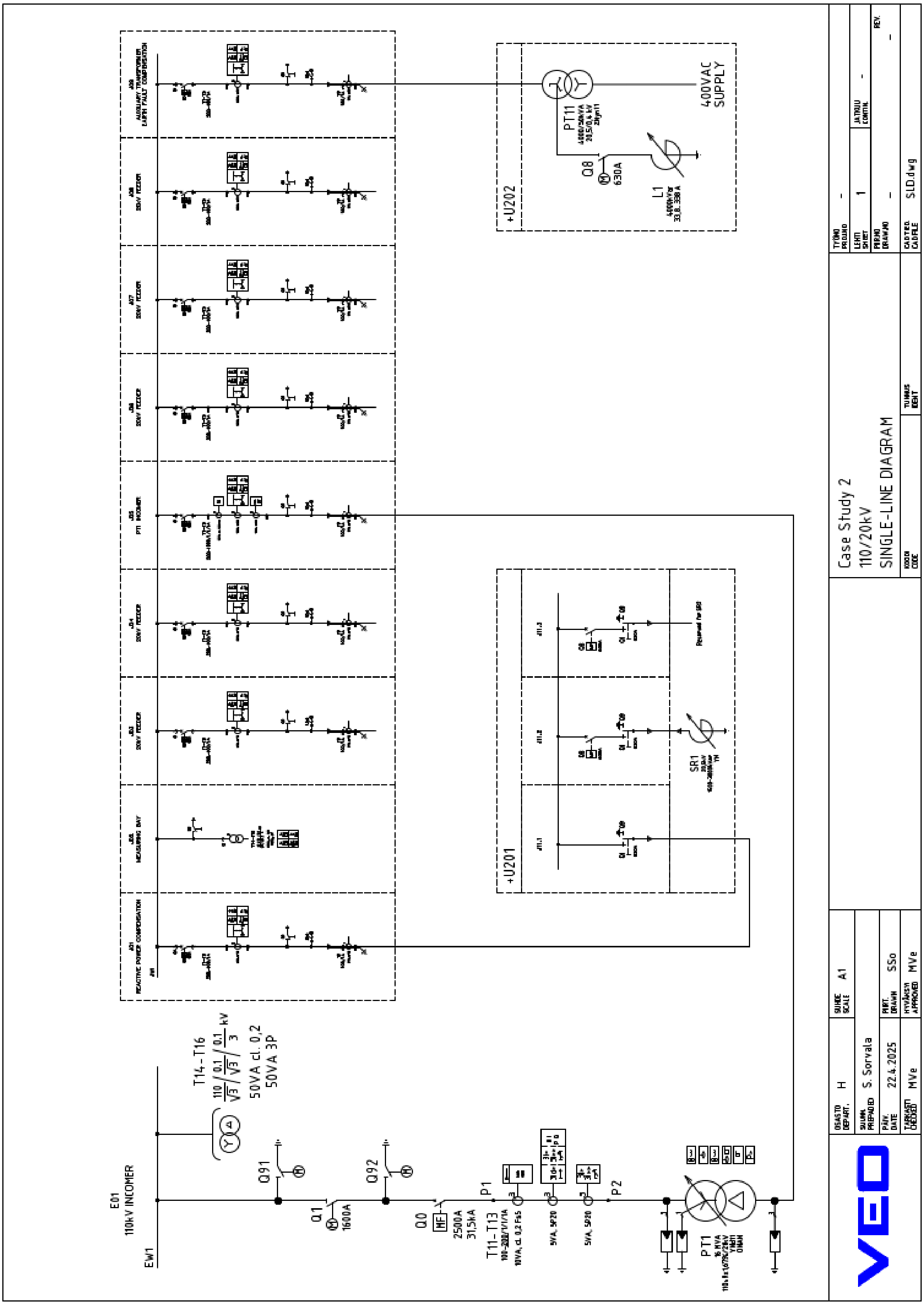


Appendix 3. Designed System Layout in Case Study 1.




IEC–61850 LAN A
IEC–61850 LAN B
KKK01–SW1A:P1/3
KKK01–SW1A:P1/4
KKK01–SW1A:P2/1
KKK01–SW1A:P2/2
KKK01–SW1A:P2/3
KKK01–SW1A:P2/4
KKK01–SW1A:P3/1
KKK01–SW1A:P3/2
KKK01–SW1A:P3/3
KKK01–SW1B:P1/2
KKK01–SW1A:P1/2
KKK01–SW1B:P1/2
20kV SWITCHGEAR J01...J09
20kV SWITCHGEAR J10...J34
IEC–61850 LAN A
IEC–61850 LAN B
SW2A
IEC61850–SWITCH
RUGGEDCOM RST2228
SW2B
IEC61850–SWITCH
RUGGEDCOM RST2228
P0/1
P0/2 P0/3 P0/4 P1/1 P1/2 P1/3 P1/4 P2/1 P2/2 P2/3 P2/4 P3/1 P3/2 P3/3 P3/4 P4/1 P4/2 P4/3 P4/4 P5/1 P5/2 P5/3 P5/4 P6/1 P6/2 P6/3 P6/4
VEO
H
A3
S. Sarvela
IEC 61850 PROTECTION AND CONTROL LAN
SYSTEM CONFIGURATION

Appendix 4. Single-Line Diagram of Case Study 2.



Appendix 5. Designed System Layout in Case Study 2.