YRKESHÖGSKOLAN NOVIA

Market Compliance Evaluation for MV-Switchgear Setups in Multi-Engine Power Plants

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Abstract

This thesis was commissioned by Wärtsilä Energy Business. A development group was formed to renew the Wärtsilä medium voltage specification that is used for tendering the MV-switchgear. Another task was to integrate a new concept of the single-line protection diagram showing all the power plant protection functions in a single document.

A renewal of the MV-specification was realized necessary as Wärtsilä had entered more markets which have broadened the technical requirement aspect. What should be implemented as standard features when tendering the switchgear and what could be included as options have been analyzed.

The updated protection scheme was made only for projects included in this thesis, but it was agreed to implement it in future projects with more complex medium voltage setups.

The framework of the thesis was decided after some development meetings had been held and the desired outcome was decided. The research was conducted using books, Wärtsilä internal documents, interviews with Wärtsilä personnel, and articles. Understanding the medium voltage system and related documentation in Wärtsilä power plants is first needed to proceed with the improvement evaluation.

The thesis objective was to present the development project in such a way that the fundamental technical shortcomings are described in depth, and the possible new configurations are evaluated against the previous setup and market requirements.

Language: English

Key Words: Wärtsilä, medium-voltage, switchgear, engine power plant

EXAMENSARBETE

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Titel: Utvärdering av marknadsöverensstämmelse för mellanspänningsställverk i flermotoriga kraftverk

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Datum: 15.03.2023 Sidantal: 36 Bilagor: 4

Abstrakt

Detta examensarbete gjordes på uppdrag av Wärtsilä Energy Business. En utvecklingsgrupp bildades för att förnya Wärtsiläs mellanspännings-specifikationer som används vid upphandling av mellanspänningsställverk. En annan uppgift var att integrera ett nytt koncept av skyddsdiagrammet som visar alla kraftverkets skyddsfunktioner i ett dokument.

En förnyelse av MV-specifikationen har ansetts nödvändig eftersom Wärtsilä har gått in på fler marknader, vilket i sin tur har breddat de tekniska kraven. Det har analyserats vad som bör införas som standardfunktioner vid anbudsgivning av ställverk och vad som kan inkluderas som tillval.

Det uppdaterade skyddsdiagrammet hade endast tagits fram för de projekt som ingår i denna avhandling, men man kom överens om att införa det i framtida projekt med mer komplexa mellanspänningsuppställningar.

Avgränsningen för avhandlingen beslutades efter att några utvecklingsmöten hållits och det önskade resultatet fastställts. Forskningen har genomförts med hjälp av böcker, interna dokument från Wärtsilä, intervjuer med Wärtsiläs personal och artiklar. En förståelse för mellanspänningssystemet och tillhörande dokumentation i Wärtsiläs kraftverk är först nödvändig för att kunna gå vidare med utvärderingen av förbättringar.

Syftet med avhandlingen var att presentera utvecklingsprojektet på ett sådant sätt att de grundläggande tekniska bristerna beskrivs ingående och att möjliga nya konfigurationer utvärderas i förhållande till den tidigare installationen och marknadens krav.

Språk: engelska

Nyckelord: Wärtsilä, mellanspänning, ställverk, motorkraftverk

OPINNÄYTETYÖ

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Nimike: Monimoottoristen voimalaitosten keskijännitekytkinlaitosten markkinoiden vaatimustenmukaisuuden arviointi

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Tiivistelmä

Tämän opinnäytetyön tilasi Wärtsilä Energy Business. Kehitysryhmä perustettiin uudistamaan Wärtsilän keskijännitespesifikaatiot kilpailutuksessa käytettävää keskijännitekojeistosta. Toisena tehtävänä oli integroida uusi konsepti yhden linjan suojauskaaviosta, jossa kaikki voimalaitoksen suojaustoiminnot esitetään asiakirjassa.

Keskijännitekytkinmäärittelyn uudistaminen on osoittautunut tarpeelliseksi, koska Wärtsilä on tullut uusille markkinoille, mikä puolestaan on laajentanut teknisiä vaatimuksia. On analysoitu, mitkä ominaisuudet olisi toteutettava vakio-ominaisuuksina kytkinlaitteita kilpailutettaessa ja mitkä voitaisiin sisällyttää lisävarusteina.

Päivitetty suojausjärjestelmä oli tehty vain tähän opinnäytetyöhön sisältyviä hankkeita varten, mutta sovittiin, että se otetaan käyttöön tulevissa hankkeissa, joissa on monimutkaisempia keskijänniteasetelmia.

Opinnäytetyön runko päätettiin sen jälkeen, kun oli pidetty muutamia kehityskeskusteluja ja päätetty haluttu lopputulos. Tutkimus on tehty kirjojen, Wärtsilän sisäisten asiakirjojen, Wärtsilän henkilöstön haastattelujen ja artikkelien avulla. Parannusten arvioinnin aloittaminen edellyttää ensin Wärtsilän voimalaitosten keskijännitejärjestelmän ja siihen liittyvän dokumentaation ymmärtämistä.

Opinnäytetyön tavoitteena oli esitellä kehityshanke siten, että perustavanlaatuiset tekniset puutteet kuvataan perusteellisesti ja että mahdollisia uusia kokoonpanoja arvioidaan suhteessa aiempaan kokoonpanoon ja markkinoiden vaatimuksiin.

Kieli: englanti

Avainsanat: Wärtsilä, keskijännite, kojeisto, moottorivoimalaitokset

Table of Contents

Table of Figures

APPENDICES

List of Abbreviations

OEM = Original Equipment Manufacturer

GW = Gigawatt (10^9W)

kW = Kilowatt (10^3W)

EPP = Engine Power Plant

Genset = Generating set

SLD = Single-line Diagram

OP SLD = Overall Protection Single-line Diagram

EEQ = Engineered Equipment delivery

EPC = Engineering, Procurement, and Construction

AIS = Air Insulated Switchgear

GIS = Gas Insulated Switchgear

IEC = International Electrotechnical Commission

ANSI = American National Standards Institute

IEEE = Institute of Electrical and Electronics Engineers

BAA = Auxiliary Transformer Bay (switchgear, Wärtsilä abbreviation)

BAE = Generator Bay (switchgear, Wärtsilä abbreviation)

BAO = Outgoing Bay (switchgear, Wärtsilä abbreviation)

CB = Circuit Breaker

GCB = Generator Circuit Breaker

MCB = Miniature Circuit Breaker

IED = Intelligent Electronic Device

1 Introduction

Wärtsilä must enhance its medium voltage (MV) specifications to better meet market requirements. The fact that Wärtsilä has started executing projects in new markets, and that standards and grid codes are continuously updated are underlying causes. Technical shortcomings of the MV-switchgear have been the cause of difficulties in recent power plant projects in both Mexico and Germany. This development project will make the execution stage easier for both Wärtsilä and the customer while cutting down time and costs for additional engineering work.

1.1 About Wärtsilä

Wärtsilä first started its business within the sawmill industry in 1834. The first diesel engine was produced by Wärtsilä in 1942, after signing a license agreement with Friedrich Krupp in Germany. Engine production started in Vaasa, Finland in 1954. Wärtsilä is the first Finnish company to be listed on the London stock exchange in 1984. (Wärtsilä, 2022a)

Wärtsilä can be considered one of the global leaders in innovative technologies and lifecycle solutions for the energy and marine sectors. Engine production and operational service stand for the major business economy. Located in 68 countries with around 17 000 employees whom all work for the same goal towards a renewable energy future. (Wärtsilä, 2022b)

1.1.1 Marine

Sustainable marine solutions and services are another important Wärtsilä business sector. The marine business is split into different areas ranging from power generation equipment to automation and control. Wärtsilä supplies marine solutions and lifecycle services to a range of customers, such as fishing vessels, naval ships, merchant ships, and offshore platforms. (Wärtsilä, 2022b)

Wärtsilä offers pre-planned maintenance to avoid unexpected downtimes and costs, which might be important for vessels and power plants. Wärtsilä offers multiple service solutions. Apart from lifecycle services, Wärtsilä also offers OEM parts supply, technical advice, environmental solutions, field services, performance optimization, and crew training. (Wärtsilä, 2023a)

1.1.2 Energy

Wärtsilä Energy business first called Wärtsilä Power Plants initially began its engine power plant business in the 1980s as a secondary venture to its marine engines business. Over time, the business grew to become its distinct line of business. It started with the production of unique engine power plants and gradually expanded to offering more comprehensive modularized power plant solutions. In addition to providing engineered equipment deliveries (EEQ), Wärtsilä also delivers complete turnkey engineering, procurement, and construction (EPC) power plants. The engine power plant (EPP) business has had a predominant global focus throughout its history, with a particular emphasis on serving remote and isolated power grids as well as supporting factories and mines. Despite this, Wärtsilä has also built numerous power plants in developed countries. (Development Manager, Wärtsilä, 2023; Wärtsilä internal webpage, 2022a)

A future vision of the Wärtsilä Energy sector includes 100% renewable energy usage. To help achieve this goal, Wärtsilä develops sustainable technology for engine power plants and energy storage, while also increasing efficiency and reliability in all business sectors. By summing up past projects, 110 energy storage systems and 76 GW of power plant capacity have been delivered to 180 countries worldwide. (Wärtsilä, 2022b)

Like the marine sector, Wärtsilä also offers lifecycle solutions and remote support to ensure performance and reliability for the operation of Wärtsilä engine power plants. (Wärtsilä, 2023b)

1.2 Background

Current MV-specifications have been realized as outdated due to the entering of new markets and demanding customers (mostly grid owners), who require more features from the switchgear and related safety equipment. The same kind of issue is also present for the low voltage (LV) system, but this thesis only focuses on the MV-system and related documentation. The MV-specification written by Wärtsilä states what must be included when tendering the MV-switchgear. An exhaustive overview of the protection functions has been prepared to ease commissioning and discussions with the customer or other stakeholders, referred to as the overall protection single-line diagram (OP SLD). The OP SLD has been prepared for two projects, however in Microsoft Visio over AutoCAD Electrical, the latter is normally used within Wärtsilä. It is necessary to transition to AutoCAD Electrical. A cutout of the OP SLD can be seen in Appendix 2, and the original way of preparing it is shown in Appendix 3.

1.3 Objective

The main goal is to research the necessary adjustments to be made in the MV-specification, resulting in effortless tendering, and skipping extra engineering work during the switchgear purchase process. The adjustments or technical features do not necessarily need to be a standard inclusion for every project, they could also be listed as available options. Discussions with switchgear suppliers are necessary to make sure wanted changes are feasible. In the future, the goal is to do a similar development project for the LV-system and related documentation.

Another goal is to analyze the advantages and disadvantages of using the OP SLD prepared in Microsoft Visio and to consider the possibility of transitioning it to AutoCAD Electrical for Wärtsilä personnel to start implementing it in projects with more complex MV-systems.

A development team has been set up within Wärtsilä to achieve these goals. Meetings are held frequently to follow up on required tasks and to discuss the topic. Information in this thesis will in some instances refer to these meetings.

1.4 Thesis Structure

The thesis structure is as follows.

- Chapter 1 introduces the thesis subject and Wärtsilä as a company.
- Chapter 2 introduces the Wärtsilä engine power plant, its applications, and its purpose.
- Chapter 3 provides the background knowledge and information related to equipment and systems referred to in this thesis.
- Chapter 4 provides a deeper insight into the problem with concrete examples of past projects where the MV-system has been deviating.
- Chapter 5 evaluates implemented features from Chapter 4.
- Chapter 6 introduces the overall protection single-line diagram.
- Chapter 7 presents the conclusions and future work of the development project.
- Chapter 8 lists references.

2 Engine Power Plant

An EPP produces electrical energy by running one or multiple internal combustion engines and generators, together often called gensets. The Wärtsilä gensets come in standard packages which range from 4 000 – 20 000 kW (Wärtsilä, n.d. a). An example can be seen in Table 1, which shows the rated power output of the Wärtsilä 31 genset in different configurations. An EPP can also be set up to heat district water, utilizing the heat produced by the engines. These plants are known as combined heat and power (CHP). Larger plants may consist of tens of gensets and output several hundred thousand kW. (Haga, 2011)

Table 1 Wärtsilä Genset 31 (Wärtsilä, 2022; Wärtsilä, n.d.)

Wärtsilä Genset 31, Rated powers				
Engine type	60 Hz		50 Hz	
	590 kW/cyl, 720 rpm		610 kW/cyl, 750 rpm	
	Mechanical power (kW)	Electrical power (kW)	Mechanical power (kW)	Electrical power (kW)
8V31	4 720	4 530	4 880	4 685
10V31	5 900	5 665	6 100	5 855
12V31	7 080	6 800	7 320	7 030
14V31	8 260	7 930	8 540	8 200
16V31	9 440	9 060	9 760	9 370
20V31 (EPP)	11 800	11 377	12 200	11 777

Defined Wärtsilä 31 genset configurations in Table 1 column "Engine type" include 8-20 cylinders, V-line formed, and 310 mm cylinder bore (defined by 12V31, etc.). Smaller cylinder setups are generally used in marine solutions and vice versa for power plant setups as seen in Table 1 (20-cylinder setup for engine power plants). (Wärtsilä, 2023c; Wärtsilä 2022)

In comparison, the wind power park in Märkenkall, Korsholm (Finland) equipped with 15x GE 158 wind turbines at 5500 kW each, generates a total of 82500 kW (max. production). (OX2, 2021)

One of the main advantages of EPPs is that they are flexible. In a closed-loop cooling system using radiators, the water losses are minor. This means that the plant could be placed in a desert or other areas where there is limited access to water. This makes it possible to build them almost anywhere, preferably close to main consumers such as industrial areas to minimize transmission losses. (Haga, 2011)

Wanted output power of the plant can be achieved by installing as many gensets as needed. If needed at a later stage, the output power can be increased by adding more gensets. A heat recovery steam generator (HRSG) can also be retrofitted at a later stage. An HRSG utilizes the heat caused by the combustion process of the engine to drive a steam turbine which then drives a generator to produce additional electricity thus improving total plant efficiency. (Haga, 2011)

As we rely more on variable renewable energy sources like wind and solar to minimize the use of fossil fuels, there is a need to stabilize the grid at certain times like when there is no wind, or it is cloudy. Variable renewable energy sources are unreliable and thus need to be backed up during peak demand, making the EPP a solution. In a variety of scenarios, from base load to peak loads, the EPP can reach full load and help with stabilizing the grid in a matter of minutes. (Haga, 2011)

2.1 Wärtsilä EPP Overview

The standard Wärtsilä EPP setup is tailored depending on the project if needed.

Figure 1 and Appendix 4 illustrate the main components of a typical Wärtsilä EPP.

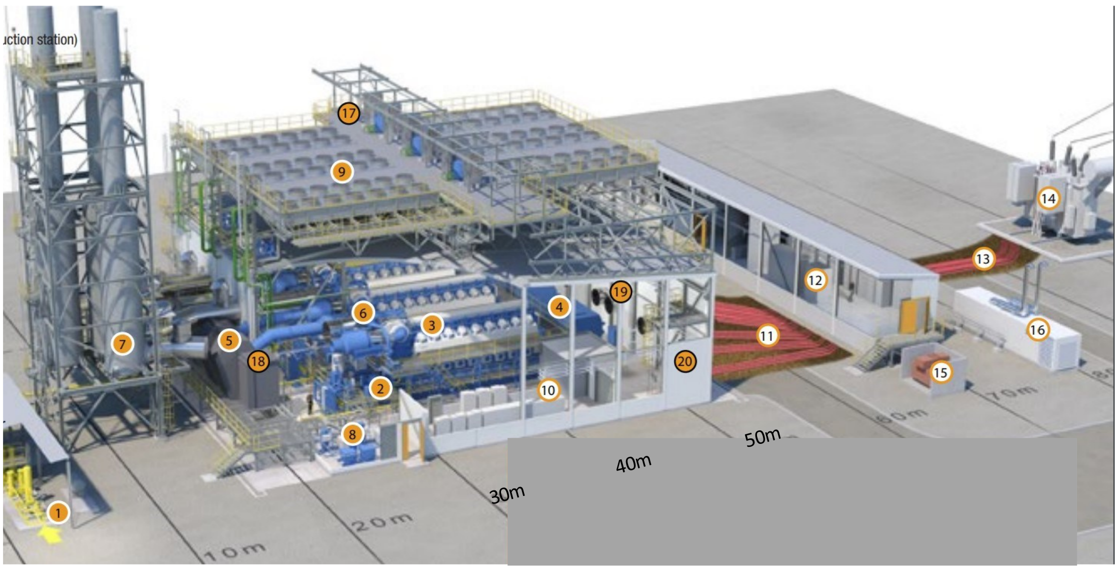

Figure 1 Typical 50 MW power generation plant (Wärtsilä, 2016)

2.2 Main Mechanical Components

Referring to Figure 1, the equipment is as follows:

1. Fuel inlet (natural gas, liquid fuels, or both if dual fuel engines).

2. Auxiliary modules, control various engine processes such as lubrication oil, fuel supply pressure, and temperature.

3. Wärtsilä engine.

4. Generator.

5. Intake air filter, providing filtered air for combustion and turbocharger.

6. Exhaust gas module, where equipment such as a ventilation fan or branch pipe is fitted.

7. Exhaust gas stack.

8. Starting air unit, Wärtsilä engines are started by a compressed air supply. Electrically driven piston air compressors are used to fill starting air bottles which can be used to start an engine three times without refilling.

9. Radiation units, where the closed loop water circulates.

(Wärtsilä, 2016)

2.3 Main Electrical Components

Referring to Figure 1, the equipment is as follows:

10. Low voltage switchgear, provides country-specific low voltage levels to auxiliary items such as cooling radiators, starting air compressors, DC-system, control, and monitoring.

11. Generator cables, connects the Wärtsilä generator to the medium voltage switchgear.

12. Medium voltage switchgear, distribution to the auxiliary transformer, and step-up transformer. Provides safety and fault protection.

13. Cables connected between the MV-switchgear and step-up transformer.

14. Step-up transformer connected to the electrical grid.

15. The auxiliary transformer supplies the LV-switchgear.

16. Black start unit, connected directly to LV-switchgear providing electrical power for needed equipment to get the plant running in case of a power outage in the electrical grid. Usually sized to achieve startup of one genset.

(Wärtsilä, 2016)

3 Medium Voltage Distribution System and Related Documentation

By using a higher level of voltage in distribution systems it is possible to lower the costs due to less need for copper and minimizing transmission power losses. Assuming a power demand (P), there will be a lower current (I) flowing in the line the higher the voltage (V). (Pacuku, 2016)

Standards have been established for voltage levels so that manufacturers can focus on developing appropriate equipment (Pacuku, 2016). ANSI C84.1-2020 - *Electric Power Systems Voltage Ratings (60 Hz)* defines the voltage classes for 60 Hz systems as follows: "Medium Voltage (MV): A class of nominal system voltages greater than 1000 volts and less than 100 kV." (American National Standards Institute)

IEC does not state a clear voltage range for MV-systems, but mentions in IEC 62271 - *High-voltage switchgear and controlgear* the following:

> "For the use of this document, high-voltage is defined as the rated voltage above 1000 V. However, the term medium voltage is commonly used for distribution systems with voltages above 1 kV and generally applied up to and including 52 kV." (International Electrotechnical Commission, 2021)

Two standards are usually recognized as international standards, ANSI and IEC. There are however more regional-specific standards for example SFS (Finnish), IS (Indian), BS (British), etc. Wärtsilä mainly refers to the IEC standard, but with exceptions also to the ANSI

standard.
(Wärtsilä internal webpage, 2022)

According to Schneider Electric (2022), medium voltage networks generally do not exceed 35 kV for financial and technical reasons.

In modern project delivery, the MV-system in Wärtsilä engine power plants typically operates within the range of 10 – 20 kV (as shown in Table 2), according to Development Manager, Wärtsilä (2022).

Table 2 Available standard generator voltages (Wärtsilä internal document, 2023)

Available standard generator voltages	
50 Hz	**60 Hz**
6.0 kV	6.6 kV
11.0 kV	13.8 kV
15.0 kV	

An important aspect when reaching higher voltage levels is safety. One of the core apparatuses in the electrical network providing safety features and distribution control is the switchgear.

3.1 Switchgear

A switchgear controls and distributes electrical energy. There are two main categories of switchgear:

- Air Insulated Switchgear (AIS)
- Gas Insulated Switchgear (GIS)

(Jacobsson et al., 2016)

Some of the main tasks of the switchgear include operating circuit breakers, automatic disconnecting caused by faults, monitoring of electrical energy, and remote communication. Functionality may vary depending on the business segment, an electricity production facility switchgear might differ from a substation switchgear setup. (Jacobsson et al., 2016)

Multiple cubicles allow for multiple configurations in terms of distribution. A cubicle could be set up as an incomer cubicle feeding the horizontal busbar in the switchgear, or vice versa a cubicle could energize an external circuit by connecting the circuit to the horizontal busbar. A cubicle design from ABB can be seen in Figure 2. All cubicles do not control an ingoing/outgoing circuit but might just be included to have metering or protection apparatuses installed or connecting the busbar. (Csanyi, Electrical Engineering Portal, 2019)

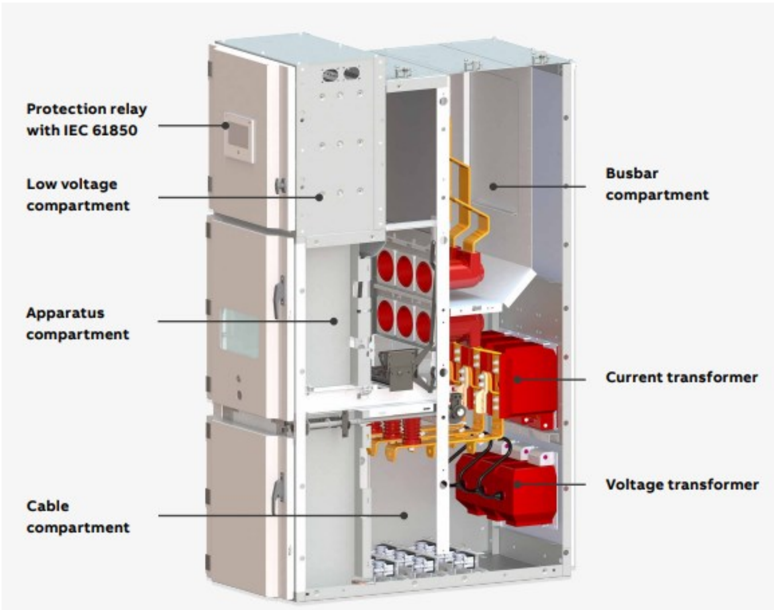

Figure 2 ABB UniGear ZS1 Cubicle (ABB, 2021)

Figure 3 represents an example electrical overview of a Wärtsilä EPP with three gensets connected to the MV-switchgear.

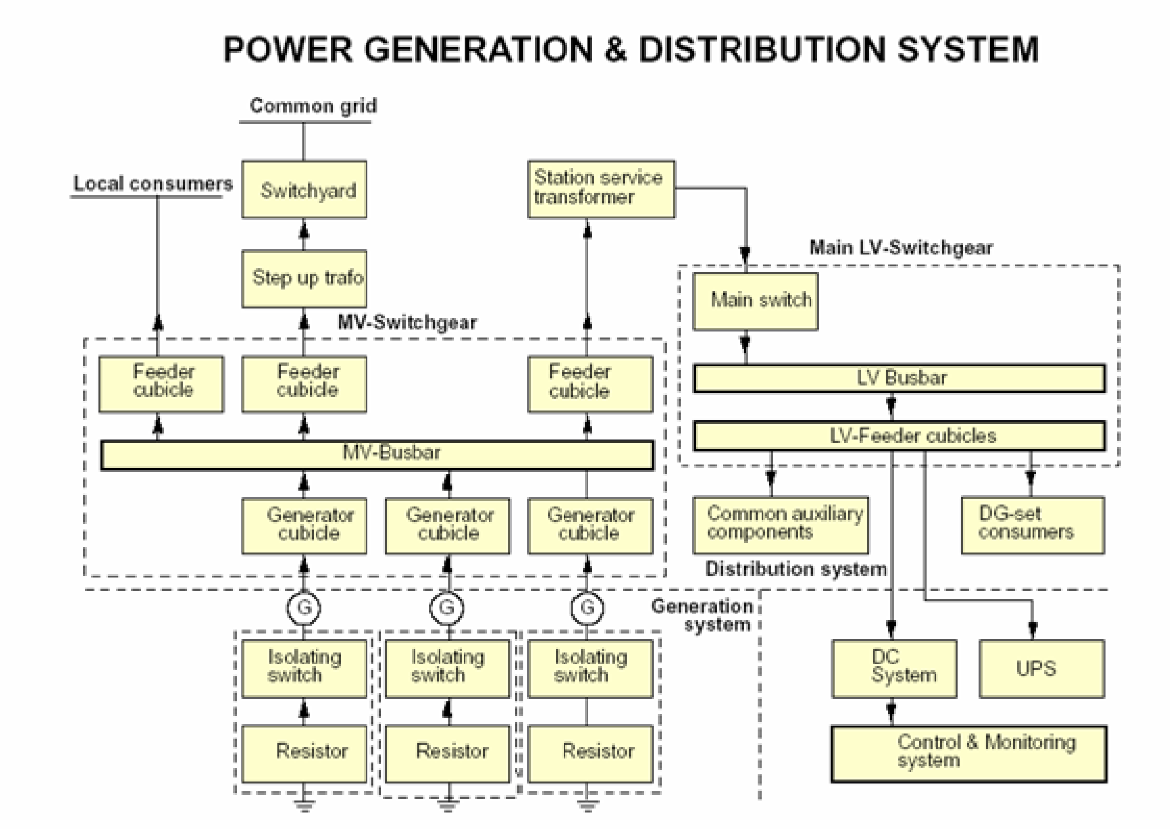

Figure 3 Power generation and distribution system (Wärtsilä, 2023)

During a meeting with the development group at Wärtsilä, it was noted that any technical improvements or changes to the MV-switchgear need to be compatible with switchgear from various Wärtsilä subcontractors.

3.2 Switchgear Protection

A protection relay can be seen as a brain of switchgear protection. For the brain to function it must read signals so it can know how to act. These signals are provided by various sensors measuring the power lines connected to the apparatus. Depending on the signal the relay will make circuit breakers open. (Costa & Sagnes, 2018)

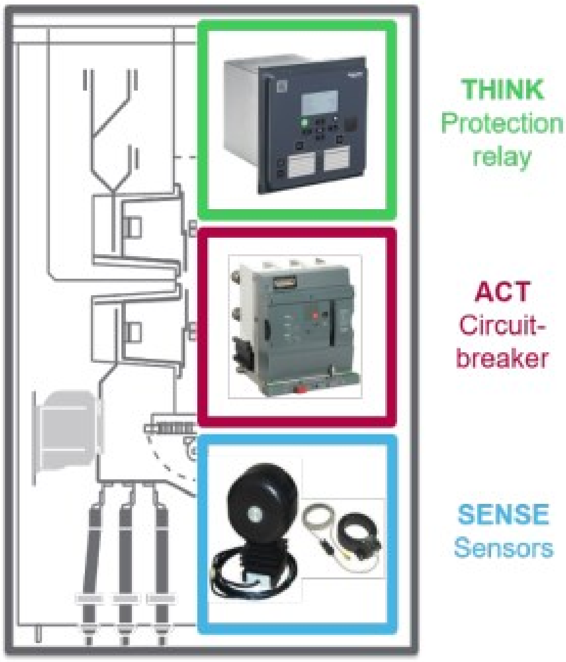

Figure 4 Switchgear protection functionality (Costa & Sagnes, 2018)

Switchgear protection does not necessarily imply electrical protection but can also mean mechanical protection. Evaluated features in Chapter 5 include both electrical and mechanical protection features.

3.3 MV-specification

The MV-specification's main purpose in Wärtsilä is to ease the process of tendering the MV-switchgear. Through this document, the supplier is allowed to submit proposals based on their available solutions or inventory thus increasing their range of choices.

The design and manufacturing, such as functions, measuring, and protection features are specified. But also, ways of manufacturer inspection and testing, and necessary accessories and consumables for operating and maintaining the supplied switchgear up until its warranty expiration are all outlined in the specification. However, this is not the complete list of subjects covered in the MV-specification. (Wärtsilä internal document, 2019)

Compared to previous decades, developed nations are nowadays requiring more complex solutions regarding protection and safety features in their power plants. As Wärtsilä has been expanding business to new countries, the specification has not been properly fit to these new markets and might have been lacking in some respects. (Development Manger, Wärtsilä, 2022)

3.4 MV-switchgear Properties

In this section, events and functions related to the MV-switchgear are described, in such a way that one can continue with the evaluation part in Chapter 5.

3.4.1 Metallic Shutters

The purpose of the metallic shutters is to provide safety by blocking access to exposed components.

Figure 2 shows the circuit breaker compartment, where the circuit breaker (5) is not connected to the bus and cable side due to the shutters blocking it (orange and yellow).

In Figure 3 bus-side is blocked (yellow) and the cable side (orange) is exposed. The metallic shutters are interlocked with the circuit breaker (CB). When moving the CB to test or disconnect position, the shutters close and vice versa thus isolating possible live parts from the open compartment. (Csanyi, Electrical Engineering Portal, 2019b)

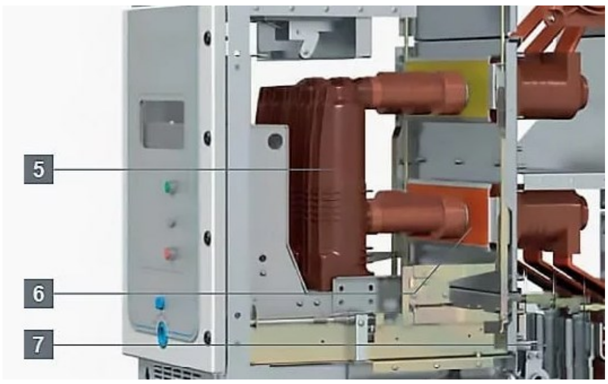

Figure 2 CB compartment (Csanyi, Electrical Engineering Portal, 2019b)

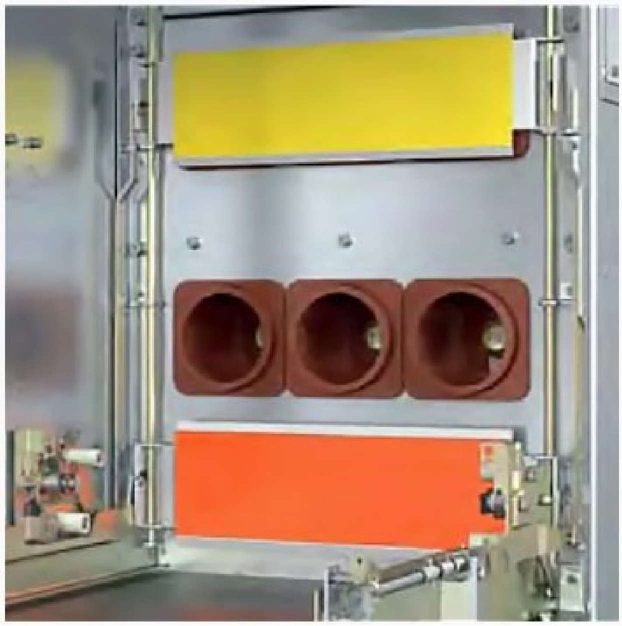

Figure 3 Automatic shutters (Csanyi, Electrical Engineering Portal, 2019b)

3.4.2 Redundant Circuit Breaker Trip Coils

To isolate faults that may occur in power systems and prevent further damage, protection relay functions respond by sending a trip signal to the relevant circuit breaker coil. For safety and reliability, it is preferred to supply the system with redundancy in case of a component failure. Not considering economic reasons, two CBs in series would be a viable option for increased reliability. (Xue et al., 2012)

CBs can fail to trip due to several reasons, for instance, a trip coil failure. To ensure tripping of the breaker nonetheless, a second coil is operated by the same protection functions as the primary, which increases the chance of either one opening the circuit breaker. (Xue et al., 2012)

3.4.3 Trip Circuit Supervision

Usually, disturbance in protection reliability is caused by the CB trip coil not acting when getting a trip signal from a relay. This fault can be prevented by using TCS.

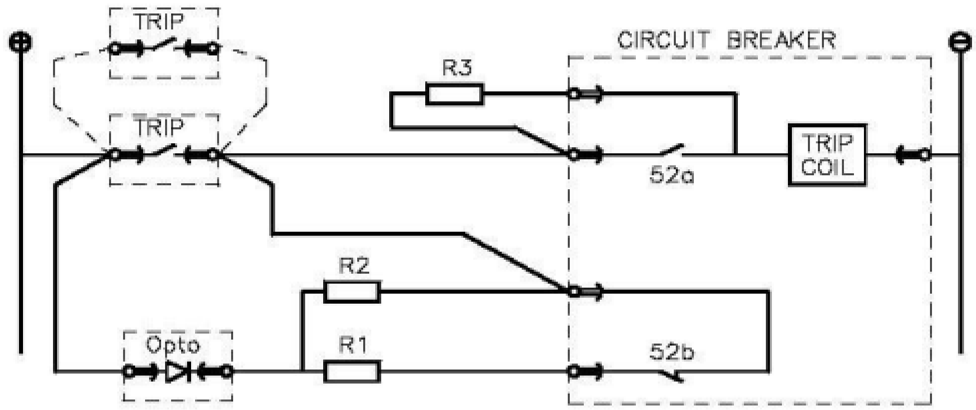

Figure 4 TCS Circuit (Apostolov & Vandiver, 2010)

There are multiple circuit schemes to detect a failure in a trip circuit. Figure 4 represents an example, of the breaker in an open state.

52a (Normally open) respectively 52b (Normally closed) contacts are switched once the circuit breaker state changes.

When CB is closed, 52a and trip contacts are closed and 52b will be open. Hence current will flow through the optocoupler, R2 resistor, and the CB trip coil. And when the CB is open, the trip contacts and 52a will be open, 52b closed, and current will flow through the optocoupler, resistors R1 and R2 in parallel, and finally, the resistor R3 leading to the trip coil. The current flow is monitored and can trigger an alarm. The trip path is continuously supplied with a small supervision current with no dependency on the breaker state.

(Apostolov & Vandiver, 2010)

3.4.4 Interlocking Circuit

Interlocks are necessary to ensure operator and equipment safety, they can be used to disable an action before necessary criteria have been fulfilled or to prevent faulty actions by the switchgear operator. Switchgear apparatuses can be interlocked with access covers or doors to prevent access to live parts, called mechanical interlocks. Electrical interlocks use auxiliary contacts to prevent unwanted actions such as in the Figure 5 circuit, where closing all circuit breakers at once is not possible. (Csanyi, Electrical Engineering Portal,

2023) Metallic shutters described in chapter 3.4.1 is an example of mechanical interlocking. Figure 5 represents a circuit with parallel incoming feed to the common bus. In this case, the left and right incomer cannot be live if the bus coupling breaker is closed, thus interlocks are used to prevent this scenario. There are three possible conditions:

- 1. Q-IL and Q-IR Closed, and Q-BC opened.
- 2. Q-IL and Q-BC Closed, and Q-IR opened.
- 3. Q-IR and Q-BC Closed, and Q-IL opened.

This is achieved by using electrical and mechanical interlocks. (Csanyi, Electrical Engineering Portal, 2023)

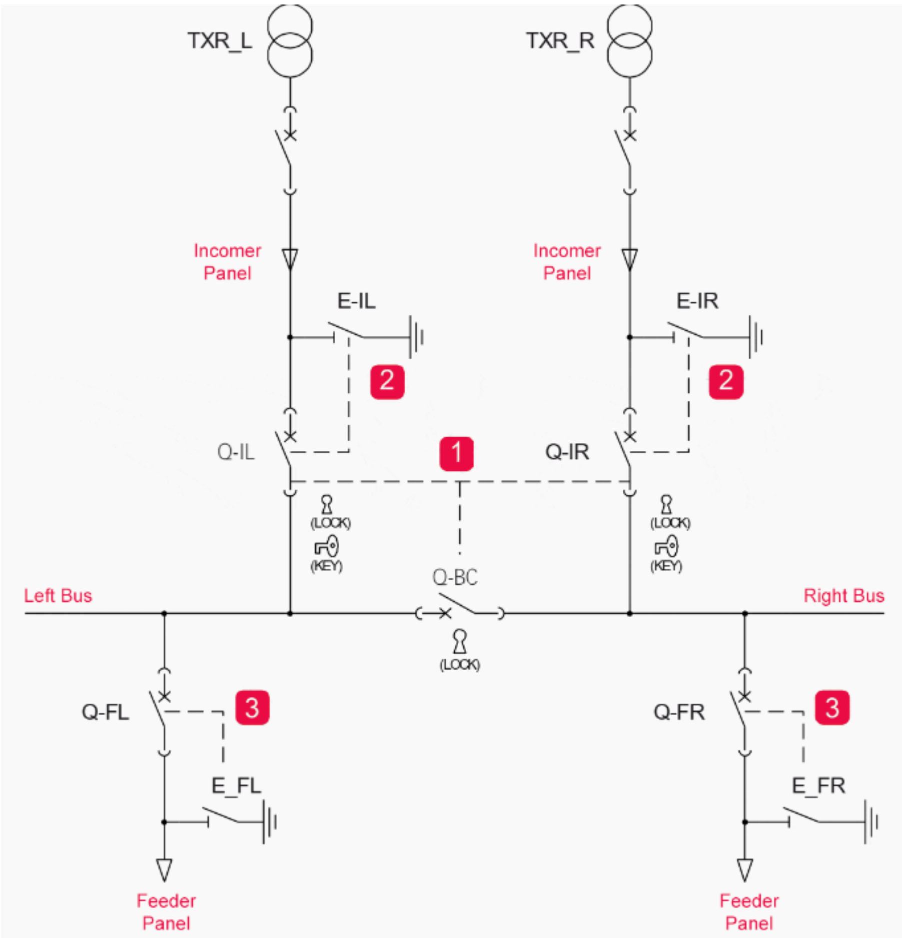

Figure 5 Parallel feeding circuit (Csanyi, Electrical Engineering Portal, 2023)

IEC 62271-200 states a set of rules regarding switchgear interlocking. In switchgear with removable parts, a switching device must be in an open position before withdrawing can be done. One should only be able to manually operate a switching device if it is in the following states: service, disconnected, removed, test, or earthing position. It should not be possible to close a switching device if necessary auxiliary control circuits controlling the opening of the switch are not connected. (International Electrotechnical Commission, 2021a)

3.4.5 Arcing Faults

Arc-flashes could be described as electrical explosions that can result in severe injuries or death if one would be affected by them. Traditional overcurrent protection such as a circuit breaker is considered ineffective in countering arc-flash accidents, due to the time it takes for it to operate once an arc fault occurs. (Jäntti et al., 2015)

An arc fault occurs the moment when phase-to-phase or phase-to-ground is shorted somewhere in the system such as a cable or bus. Although an arc might start between a small gap, the arc might increase in arc voltage and length thus involving other phases. (Short, 2011)

3.4.6 Power Island (LOM)

A power island can occur when the distribution network section the plant is connected to, gets disconnected from the utility supply. This will result in the plant generating power to the isolated distribution network section, which can be harmful to personnel or appliances. A sudden reclosure of the power island to the utility supply will cause equipment damage due to them being out of synchronization. A loss of mains (LOM) protection prevents this from happening and disconnects the generators from the grid. (Laverty et al., 2015)

Figure 6 represents a scenario with a line fault in which protection A and B operate to disconnect the two sectors, leaving one generator islanded. (Laverty et al., 2015)

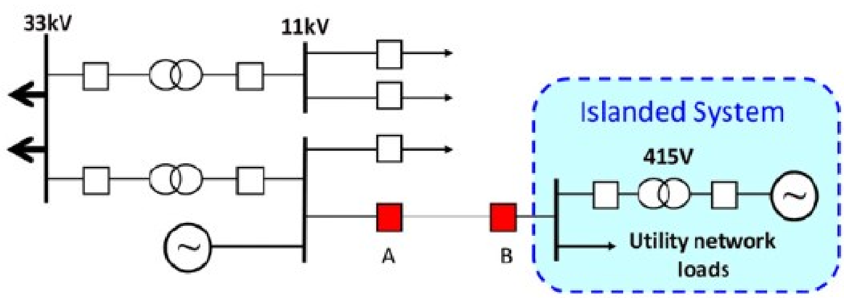

Figure 6 Power Island example (Laverty et al., 2015)

3.4.7 Breaker Failure Protection

Breaker failure protection (BFP) is a protection function utilized when the main circuit breaker fails to open when a fault occurs. When the breaker fails to open, a trip signal to other adjacent breakers upstream or downstream is sent to clear the fault. (IEEE, 2016)

BFP function is identified as CCRBRF1 (IEC 61850), $3I>/I_0>BF$ (IEC 60617), or 51BF/51NBF (ANSI) according to (ABB, 2009).

3.4.8 Synchronize Check

Power system equipment might be damaged if two unsynchronized networks are connected. Before closing the circuit breaker connecting these networks, a synchronize check is needed to avoid equipment damage and power surges. For the two power systems to connect in synchronization, the spinning generator(s) should be connected to the other system when they match phase angle, voltage magnitude, and frequency. (Gross et al., 2007)

3.4.9 Relay Communication

IEC 61850 communication, is a relevant form of technology used in substations to provide communication between intelligent electronic devices (IED), such as devices used for control, protection, measurement, etc.

For grid instability detection and infrastructure protection, electrical utilities are becoming more reliant on exact clock synchronization. A collaboration between IEC and IEEE resulted in PTP (Precision Time Protocol) that was implemented into the IEC-61580 communication standard. It supports seamless redundancy and offers sub-microsecond timing precision. (Kirrmann & Dickerson, 2016)

3.5 Protection Single-line Drawing

Appendix 3 represents a protection single-line drawing. This type of drawing is project specific, and its purpose is to describe how protection relay functions act depending on monitoring and measurement from power generation equipment, and what trip certain functions will cause. Generally divided one section per page, e.g., all gensets on different pages.

Evaluation whereas the overall protection single-line diagram presented in Appendix 2 would be a better approach for creating the drawing in projects with deviating MV-system, where an overall view of the system might be preferable.

4 MV-system Deviation Analysis in Past Projects

In this chapter technical deficiencies linked to the MV-system in past projects are analyzed. One project located in Germany and two projects in Mexico are included in this study. The analysis contains partial interview answers from CPEs (Chief Project Engineers) and an external engineer who is not Wärtsilä internal personnel but has been heavily involved in following projects and assisting with the MV-system. The CPE's main task is to manage the technical aspects of projects.

Technical implementations of the MV-switchgear for respective projects are listed in Chapters 4.1.4 and 4.2.4. Implementations are described and evaluated in Chapter 5.

Exact numbers are not shown in this study as it is confidential information; instead, percentual calculations are used.

4.1 Germany

4.1.1 General Project Information

A grid stabilization CHP plant equipped with black start capability running eight Wärtsilä 31 SG gensets capable of providing 94 MW electrical output and 84 MW of district heating output. (Wärtsilä, 2022c)

The project was signed in December 2018 and handed over in November 2022. The customer is a sub-company to a bigger organization managing electrical and natural gas supply in eastern Saxony, Germany. (Electrical Chief Project Engineer, Wärtsilä, 2022)

4.1.2 Switchgear Setup

Two air-insulated ABB UniGear ZS1s were used in this project, one per engine block connected through a coupling busbar. Each switchgear setup with 14 cubicles, and a voltage level of 10,5 kV. (Electrical Chief Project Engineer, Wärtsilä, 2022)

Customer requirements in the design phase resulted in the addition of cubicles in this specific design. An additional bus-rise and bus-tie cubicle allowed for an extra circuit breaker separating the plant from the grid, allowing the grid operator and the customer to have independently operated circuit breakers. (Electrical Project Engineer, Wärtsilä, 2022) Seen in Appendix 1, cubicles one and three.

The customer requested a 10,5 kV medium voltage level, even though this is not a standardized voltage level listed in Table 2. However, Wärtsilä internal document (2023) also states the following regarding voltage ranges: "If possible, standard design to have option for voltage variation +-10% and frequency variation of +-5%.".

The switchgear cubicle setup is as follows:

- Outgoing grid connection cubicle (1x).
- Bus-tie and bus-rise (connecting bus with breaker) (4x).
- Reserve outgoing cubicle (1x).
- Auxiliary transformer cubicle (1x).
- Generator cubicles (4x).
- Measuring cubicle (1x).
- Earthing transformer cubicle (1x).
- Bus coupler cubicle (to second switchgear) (1x).

Second switchgear setup with identical cubicle design. Appendix 1 illustrates the MV-switchgear setup simplified to an extent. Not all connections nor apparatus are shown, meaning this is not a 100% accurate representation.

4.1.3 Issue and Impact

Challenges with the MV-switchgear in this project were realized in the design approval stage. After the first design draft was made, the customer requested changes and it was difficult to get approval from the customer during the design process. Eventually, Wärtsilä gave approval to the manufacturer to keep the project schedule feasible. The design requirements were not provided in a comprehensible manner from the beginning of the project, and it was not realized how much the standard solution differed from the required product. (Electrical Chief Project Engineer, Wärtsilä, 2022)

Relative to standard manufacturing time, design phase time went as high as 183% before the purchase was finally made. (Electrical Chief Project Engineer, Wärtsilä, 2022)

Cost impact for additional implemented features relative to standard switchgear cost with 14 cubicles increased by 27% based on calculations from an internal document. Note that this calculation not only includes the features in chapter 4.1.4 but also additional costs such as hours spent for modification and design.

Chapter 4.1.4 lists implemented features in the Germany project that could be considered in standard specifications or as an option according to External Electrical Engineer (2022).

4.1.4 Implemented Features

- Independent securing of circuit breaker compartment shutters
- Two circuit breaker trip coils
- Trip circuit supervision
- Illuminated interlock release indication for earthing switch interlocking circuit
- Illuminated interlock release indication for truck interlocking circuit
- Double pole control of generator circuit breaker (GCB) in BAE and Outgoing CB in BAO

- Capacitive voltage detectors
- Arc protection light and current sensing

4.2 Mexico

4.2.1 General Project Information

The following project was signed in October 2021 and is currently ongoing. The project involves two separate facilities. Facility one with 400 MW electrical output, generated by 24 Wärtsilä 50DF gensets, and facility two with 200 MW electrical output, generated by 22 Wärtsilä 34DF gensets. The customer is a government-owned company, which operates around 50% of the electrical grid in Mexico. (External Electrical Engineer, 2022) This contract represents the biggest generating capacity EPC Wärtsilä has conducted to date. (Wärtsilä, 2021)

4.2.2 Switchgear Setup

Facility one includes four ABB UniGear ZS1s built with five cubicles each, three gensets feeding each switchgear. Facility two includes four ABB UniGear ZS1s where two switchgear is set up with seven cubicles fed by five gensets and the remaining two are set up with eight cubicles fed by six gensets. Wärtsilä standardized voltage level at 13,8 kV (see Table 2) and 60 Hz frequency. (Electrical Chief Project Engineer, Wärtsilä, 2022)

Facility one switchgear cubicle setup is as follows:

- Outgoing cubicle (1x)
- Auxiliary transformer cubicle (1x)
- Generator cubicles (3x)

Facility two, switchgear connected to six gensets cubicle setup as follows:

- Outgoing cubicle (1x)
- Auxiliary transformer cubicle (1x)

- Generator cubicles (6x).

Facility two, switchgear connected to five gensets cubicle setup as follows:

- Outgoing cubicle (1x)
- Auxiliary transformer cubicle (1x)
- Generator cubicles (5x)

4.2.3 Issue and Impact

The switchgear in this project was delivered in two phases, thus phase two was not affected as much as phase one in terms of time delay since the additional requirements were already known once the manufacturing started. (Electrical Chief Project Engineer, Wärtsilä, 2022)

The main issue was that the project specifications were not signed before the project contract was signed. This should have been done as the customer is experienced in power plant operation and grid management and the fact that they had their own specifications on the plants. (Electrical Chief Project Engineer, Wärtsilä, 2022)

Like the Germany project in Chapter 4.1, the MV-switchgear was first planned to be manufactured according to Wärtsilä's standard specifications, however, it was not accepted by the customer and modifications had to be done to the manufactured switchgear included in phase one delivery. Modifications were conducted before delivery to the site. (Electrical Chief Project Engineer, Wärtsilä, 2022)

Relative to standard manufacturing time, manufacturing time rose to 183% for phase one delivery and phase two delivery 133%. (Electrical Chief Project Engineer, Wärtsilä, 2022)

The cost impact for additional implemented features relative to standard switchgear offers increased to about 125% for both phase one and two deliveries. (Electrical Chief Project Engineer, Wärtsilä, 2022)

Chapter 4.2.4 lists implemented features in Mexico projects that could be considered an addition to standard specifications or as an option according to External Electrical Engineer (2022).

4.2.4 Implemented Features

- Independent securing of circuit breaker compartment shutters
- Two circuit breaker trip coils
- Trip circuit supervision
- BAE Voltage transformer supervision
- Loss of mains protection
- Illuminated interlock release indication for earthing switch interlocking circuit
- Illuminated interlock release indication for truck interlocking circuit
- BAO Local control via IED
- BAA Local control via IED
- Breaker failure protection (51BF) from generator protection (higher hierarchy)
- Breaker failure protection (51BF) to generator protection (lower hierarchy)
- Signals from the generator circuit breaker in BAE
- Synchronize check (25C) in BAO
- Double pole control of GCB in BAE and Outgoing CB in BAO
- IEC 61850 standard protocol
- Arc protection light and current sensing
- IED alarm LEDs

5 Evaluation of Technical Features

This chapter evaluates all implemented features from previous projects in chapter 4, but also a few features that according to External Electrical Engineer (2022), would be a beneficial inclusion in the MV-specifications. Sections 5.1 – 5.15 are structured to first give a detailed description of the function, and the latter part of the section gives reasoning for implementing it. In most cases, it is not based on numerical literature analysis, but on expert technical experience.

5.1 Independent Securing of Circuit Breaker Compartment Shutters

Possibility to secure CB compartment shutters independently regarding busbar/cable side with a padlock instead of typically used simultaneous operation.

This is an advantage regarding safety for example if there is a need to keep the busbar alive and the cable side dead in case of maintenance. In addition, to adhere to standard IEC 62270-200 for Loss of Service Continuity (LSC-2B). This feature has no cost impact as it is normally selectable how they shall be operated.

5.2 Two Circuit Breaker Trip Coils

Redundant trip coil on all switchgear circuit breakers. Protection functions from IED trip both coils. Important for generator and outgoing step-up transformer feeders to ensure a faulty coil will not damage equipment downstream.

It is common for suppliers to offer CBs with redundant trip coils according to Development Manager, Wärtsilä (2022). Functions requiring high-speed trip outputs for instance arc protection can be problematic to address to both coils, depending on IED output availability. Increases reliability of the overall MV-system, small cost.

5.3 Trip Circuit Supervision

Enabling 74TCS (ANSI) or TCS (IEC) function in protection relays as well as fault indication on local LED and remotely to control system. Combined with the redundant trip coil described in Chapter 5.2, high reliability is insured. Two TCS functions are available on most protection relays nowadays.

5.4 Earthing Switch and Truck Interlocking Circuit, Illuminated Interlock Release Indication

The earthing switch and truck interlock circuit independently have a “Release earthing / Release for truck transfer” button that will activate a time relay whereas the interlock is released if all requirements are fulfilled. During the set time truck transfer or earthing can be performed. An illuminated button also indicates whether all internal mechanical interlocks and external electromechanical interlocking conditions are released.

Will give a clear indication to the operator if the interlocks are released or not.

5.5 Double Pole Control of GCB in BAE and Outgoing CB in BAO

Generator circuit breaker (GCB) control circuit in the generator bay (BAE) and outgoing bay (BAO) to have double pole control, operating + / - simultaneously in case of a double earth fault. An earth fault in the floating DC-system and the MV CB closing control circuit plus pole could otherwise cause the CB to close unintentionally. Safety and reliability improvement.

5.6 Capacitive Voltage Detectors

A portable device for checking voltage before earthing is done is not necessarily a requirement in all projects. As this will impact cost could be included as an option when necessary.

5.7 Arc Protection Light and Current Sensing

To develop concepts and proposals for equipment setups. For different configurations such as only light sensing, both light and current sensing, etc. This would speed up design and discussion in cases where there are more specific arc protection requirements. Regarding project management, this documentation improvement would be beneficial.

5.8 BAE Voltage Transformer Supervision

A signal from the voltage transformer circuit breaker related to the generator feeder. If loss of voltage in a transformer occurs, the wanted outcome is to block specific generator protection functions for example 27 (Undervoltage Protection) / 50AE (Accidental energizing protection). In other words, voltage-dependent functions.

This will include more wiring work and verification that the protection relay has room for more digital inputs. Preparation could be done as standard and activated when needed.

5.9 Loss of Mains Protection

To have LOM protection (78V) moved to BAO, outgoing bay (grid connection point) instead of BAM, measuring bay. Reliability and safety improvement (see chapter 3.4.6).

5.10 BAO and BAA Local Control via IED

Local control via IED allows energizing of busbars. BAO outgoing circuit breaker towards step-up and BAA auxiliary circuit breaker towards LV busbar. Possible if the truck is recognized in the test position. This will allow for testing in the commissioning phase to energize MV-busbar and LV-busbar. Only possible if all generator circuit breakers are confirmed open or in the test position. Would be an advantage during the commissioning phase.

5.11 Breaker Failure Protection (51BF) from and to Generator Protection

Prepare signal from generator protection relay located in genset control panel to generator bay panel (BAE) to make higher hierarchy (e.g., BAO, outgoing) recognize 51BF trip if needed.

Vice versa functionality, a signal from higher hierarchy to generator protection in case of 51BF trip from the higher hierarchy. Safety and reliability improvement.

5.12 Signals from the GCB in BAE

Generator circuit breaker (in BAE) signals to the generator protection apparatus to get readings like CB position (open/closed), truck position (service/test), or truck position extracted.

Allows for timestamp collection from source in case of IEC 61850 communication implementation.

5.13 Synchronize Check (25C) in BAO

Synchronizing check 25C can be activated in an outgoing cubicle. Would be implemented to the last point of the closing circuit.

Ensures connection of two power networks in synchronization to avoid failures (see chapter 3.4.8).

5.14 IEC 61850 Standard Protocol

The IEC 61850 protocol would allow collecting time stamping from various sources like measurement or protection devices. Makes usage of point lists possible with an accurate event and alarm log (see chapter 3.4.9).

5.15 IED Alarm LEDs

Use of LEDs in IEDs for better local indication of faults, for example in Figure 4. Helpful for the operator of the switchgear.

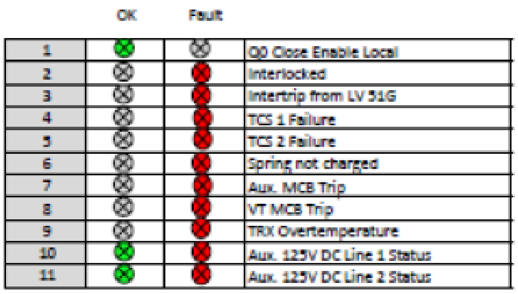

Figure 7 IED led indication (External Electrical Engineer, 2022)

6 Overall Protection SLD

The OP SLD was created by External Electrical Engineer (2022) to achieve a more understandable overview of the protection functions in the MV-system. It is not meant for customer usage, but for internal use, like the project team and site engineers. It can however be used for customer meetings and presentations where protection measures are discussed.

Particularly for projects with switchgear and protection configurations that differ from Wärtsilä's standard medium voltage solutions, the OP SLD could be a good implementation. (Development Manger, Wärtsilä, 2022)

6.1 OP SLD Content

Information related to MV protection such as measuring and monitoring units is displayed. Appendix 2 shows an example from the OP SLD, which includes details on genset protection for one unit and an auxiliary transformer with a corresponding protection unit.

All protection units are displayed with information such as protection functionality, make and model, connection types, and activated functions.

Figure 8 represents how one generator protection unit is connected to the genset in Figure 9. Important aspects of the OP SLD include informing how protection functions interface with systems in an overall display. Colored lines are used to aid in recognition: purple lines represent analog hardwired signals, blue lines represent current transformer connections, etc.

One should not consider the representation of symbols such as transformers in comparison to the original way of preparing it shown in Appendix 3, more the overall representation of the diagram.

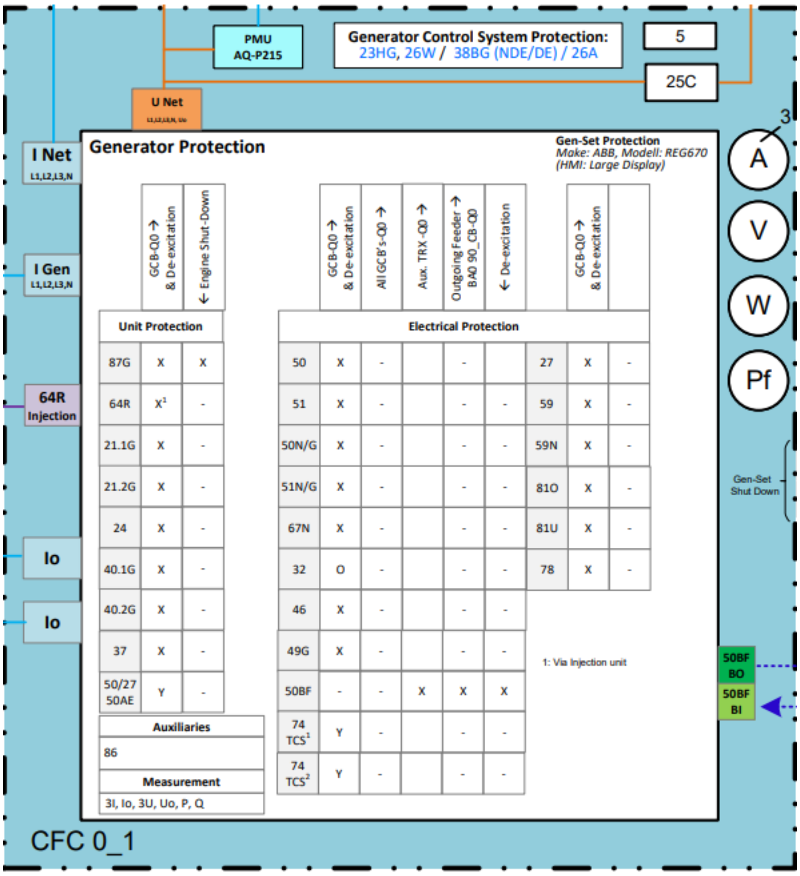

Figure 8 Generator protection (External Electrical Engineer, 2022)

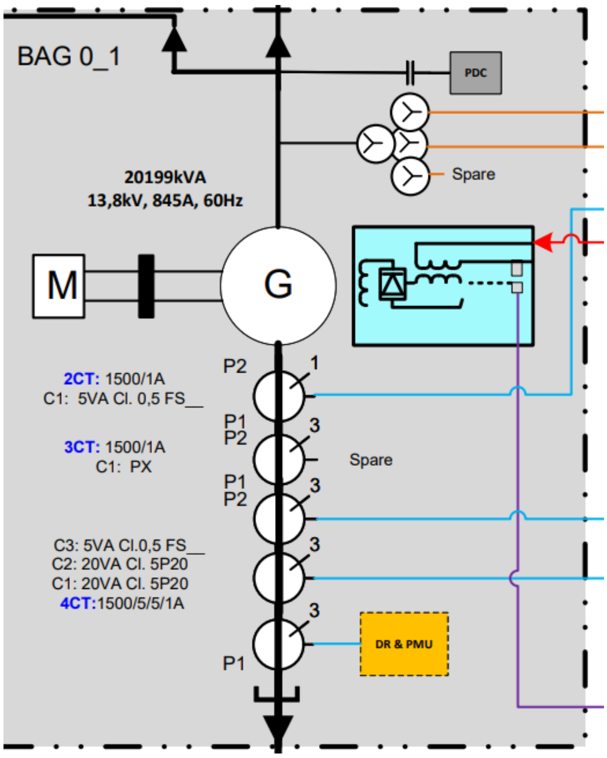

Figure 9 Genset connections (External Electrical Engineer, 2022)

6.2 Feedback

Both the site and office project teams' feedback came back positive after using the OP SLD. It works as an input for those designing the switchgear, and site workers can use this SLD during commissioning. A downside is a need for a printer with large paper printing capability, as the drawing has now been made in A1 size (841 x 594 mm). (External Electrical Engineer, 2022)

6.3 Transition from Visio to AutoCAD

The protection SLD by External Electrical Engineer (2022) has been made in Microsoft Visio. According to External Electrical Engineer (2022), Visio would be the preferred tool for this type of drawing due to the ease of use regarding color, tables, figures, and symbol usage. One criterion for making these drawings is the use of color for quickly distinguishing different wiring types. A change of software to AutoCAD would however be preferable for economical and availability reasons. AutoCAD Electrical is the main tool used for all other electrical drawings that internal personnel are already familiar with, meaning no need to buy new software licenses. Eventual training could be held for creating this type of SLD.

According to Development Engineer, Wärtsilä there should be no issues re-creating this drawing in AutoCAD Electrical. A starting point would be to create a base template that later can be modified into project-specific drawings. By using the XREF (external reference) function in AutoCAD one could save time by referring to other drawings when creating the OP SLD. (Development Engineer, Wärtsilä; Project Engineer, Wärtsilä) "We must manage to make the creation procedure as quick as the old way of preparing the protection single-line diagram, where we print the drawing in an instant." (Project Engineer, Wärtsilä).

7 Conclusions and Future Work

This thesis aimed to analyze projects with MV-systems that deviate from Wärtsilä's standard solutions, evaluate the technical additions made to the MV-switchgear in analyzed projects and consider whether these additions could be beneficial to include in the MV-specification for future tendering. Another task was to analyze the OP SLD for eventual inclusion in future projects.

It is difficult to know exactly what kind of features are to be implemented to minimize the overall challenges in all projects. National-specific grid codes may require certain protection features, or customers may have specifications that they require to be followed. However, some features evaluated in this thesis were required in both analyzed projects located on different continents, implying that some of them might be considered state-of-the-art nowadays. Knowing the project-specific requirements before signing a contract is crucial for avoiding unexpected challenges.

One should consider that by implementing additional standard features to the MV-specification, the manufacturing time and cost will increase. It would be necessary to discuss these matters with switchgear suppliers.

Without further updating of the specification, it would be possible to deliver projects to less-developed nations where requirements are not as strict and where Wärtsilä's typical setup has been found sufficient. However, revising the MV-specification will guarantee more effortless projects in the future in terms of the MV-system.

The OP SLD could be utilized in future projects when a way of working is clarified. Creating the drawing from scratch every time would take too much time and is not feasible.

7.1 Future Work

The main future objective is to include necessary changes to the MV-specifications regarding MV-switchgear technical requirements, to be based on the analysis that has been conducted in this thesis and during the development project meetings. A detailed manufacturing time increase and cost increase analysis could further be done with the suppliers.

For personnel to start implementing the OP SLD in future projects, first is needed that training is held and a template is made in AutoCAD.

Typical drawings were discussed to be a useful basis for designing project-specific systems in the future. Examples of such drawings could include relay configurations, cause-and-effect diagrams, and arc-protection designs. A development project was decided will be held for the low voltage system, as similar problems have been noted.

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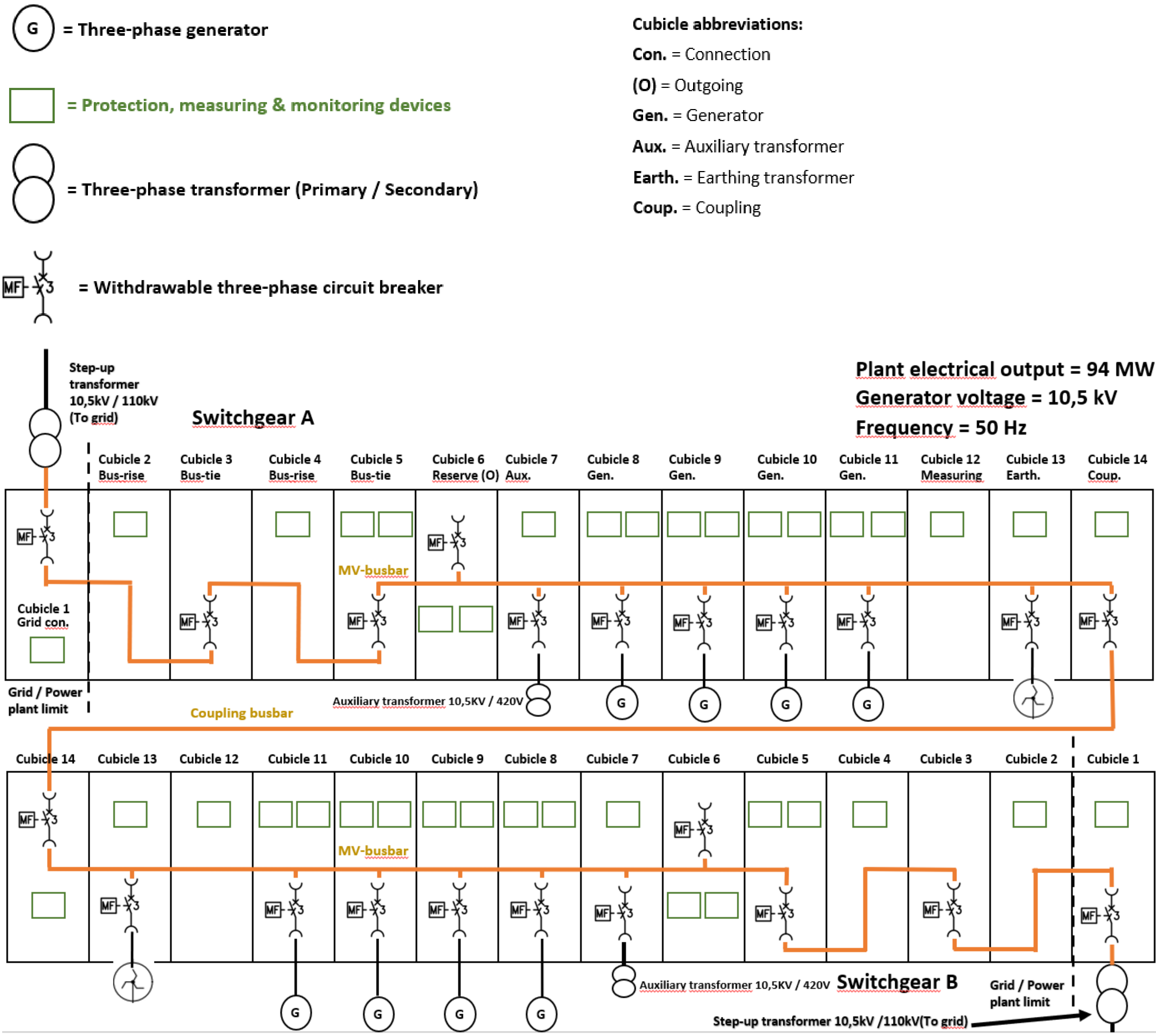
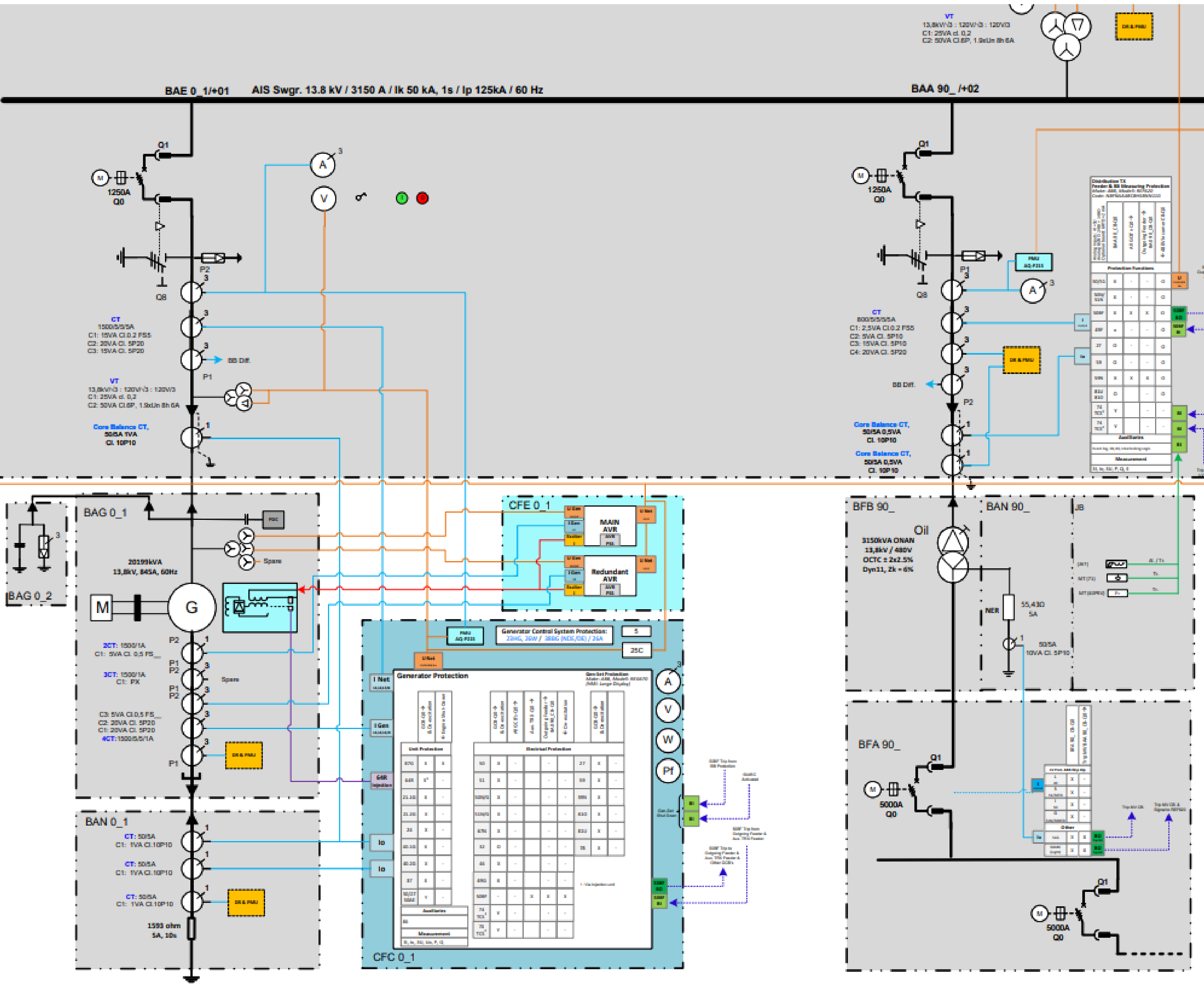
APPENDICES

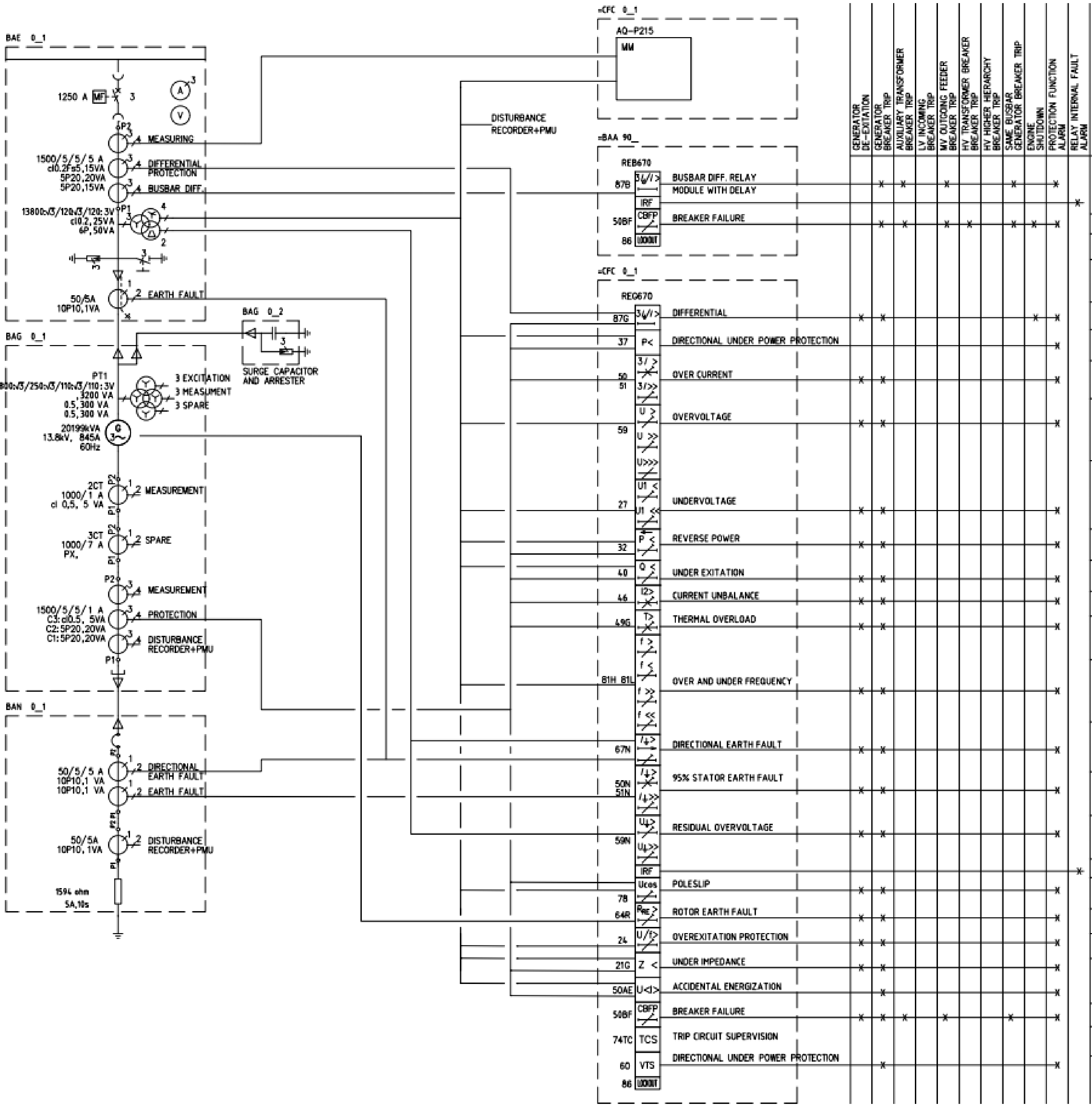
Appendix 1. Simplified MV-switchgear SLD setup



Appendix 2. Overall protection SLD example



Appendix 3. Standard protection scheme example



Appendix 4. Wärtsilä EPP overview