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AUTOMATIC FAULT MANAGEMENT OF POWER DISTRIBUTION NETWORK USING ENERGY STORAGES

Master's thesis
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TIIVISTELMÄ

Jaakko Niskala: Automaattinen vianhallinta sähkönjakeluverkossa, sähkövarastoja hyödyntäen.
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Sähköistyneessä maailmassamme katkeamaton sähkönsaanti on noussut yhdeksi perustarpeeksi, minkä vuoksi on tärkeää, että sähkönjakelussa esiintyy mahdollisimman vähän katkoksia. Kaikilta vikatilanteilta ei kuitenkaan voida välttyä, minkä takia nopea reagoiminen vikatilanteisiin ja niiden nopea paikantaminen on tärkeää, jotta terveet alueet verkosta saadaan palautettua mahdollisimman nopeasti.

Jakeluverkko on laaja infrastruktuuri, minkä tarkoitus on jakaa sähköä rajatulle alueelle, niin kaupunkiin kuin maaseudullekin. Usein maaseudun lähdöt ovat paljon vikaherkempiä kuin kaupunkilähdöt johtuen pääosin maanalaisen kaapeloinnin yleistymisestä kaupunkialueilla. Maaseutulähdöillä saattaa olla syöttävän aseman ja asiakkaan välillä kymmenien kilometrien matka, jonka varrelle mahtuu tiheästi kasvavia metsiä ja muita vika-alttiita alueita. Tästä syystä maaseutulähdöt ovat vikaherkempiä, mikä yhdessä hankalan maaston ja pitkien välimatkojen kanssa hidastaa työryhmien työskentelyä vikojen paikantamisen ja korjaamisen parissa. Nämä lisäävät manuaalisen vianpaikantamiseen kuluvaa aikaa, eli asiakkaiden sähkötöntä aikaa. Mitä pidempään asiakkaat ovat sähköttä, sitä enemmän tyytymättömiä asiakkaita esiintyy, mikä myös lisää sähköntoimittajien kustannuksia, sillä mahdollisia korvausvaatimuksia saattaa esiintyä katkoksen jälkeen. Näistä syistä on tärkeää, että viat pystytään paikantamaan verkosta mahdollisimman nopeasti, mikä oli yksi päämotivaatioista automaattisen vianhallinnan jatkokehittämiseen.

Yksi tämän diplomityön päätavoitteista oli kehittää Hitachi Energy Finland Oy:lle DMS600 WS ohjelmistoon automaattinen vianhallinnan hallintatyökalu, eli vian paikannus, erotus ja palautus, lyhennettynä FLIR. Ideana oli kehittää toiminnallisuus, jonka tarkoitus on paikantaa viat automaattisesti verkosta kokeilukytkentöjä hyödyntäen. Kokeilukytkennöillä tarkoitetaan sitä, että vika paikannetaan algoritmisella toimintatavalla; missä tiettyjä verkon kytkimiä operoidaan ohjelmiston generoimalla tavalla siihen asti, kunnes vika-alue on saatu paikannettua. Kun vika-alue on paikannettu, se pystytään erottamaan muusta verkosta ja terveet alueet lähdöltä voidaan palauttaa takasyötöistä. Työssä tarkastellaan myös sähköenergiavarastojen mahdollisia käyttötapoja palautuksen yhteydessä.

Suurin osa työhön käytetystä ajasta kului implementointiin, mikä oli itsessään pitkä ja aikaa kuluttava prosessi, mutta siitä jäi käteen paljon hyvää tietoa yleisesti isojen toiminnallisuuden kehittämisestä, kuin myös DMS600 ohjelmistosta ja sen toiminnasta konepellin alla. Implementointi toteutettiin pääosin C++ kielellä sisältäen kymmeniätuhansia rivejä koodia. Työssä esiteltiin MicroSCADA X DMS600 ohjelmistoperhe sisältäen muutama sen keskeinen työssä käytetty ohjelmisto, mistä saatiin hyvä yleisnäkymä, miten ohjelmiston sisäinen kommunikaatio toimii, mitä toiminnallisuuksia on jo olemassa ja mitä oli tarpeen toteuttaa. Toteuttamistarpeen yksi pääsyistä oli se, että olemassa olevaa toiminnallisuutta pystyi hyödyntämään vain kourallisessa vikatilanteista, johtuen sen puutteista. Työssä toteutettu FLIR toiminnallisuus pyrkii toimimaan myös näissä hankalammissa tilanteissa mihin aiempi toteutus ei kyennyt, mikä on suurilta osin kokeilukytkentöjen ansiota.

Avainsanat: Automatic fault management, FLIR, Distribution networks, Energy storages, DMS, MicroSCADA X

ABSTRACT

Jaakko Niskala: Automatic fault management of power distribution network using energy storages.
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In our widely electrified world, uninterrupted power delivery has risen to be one of the basic needs. Therefore, it is important to have minimal interruptions during the power distribution. However, preventing all faults from happening beforehand is impossible, so it is necessary to react quickly to the fault situations and to manage to locate it from the network as quickly as possible so that the healthy parts of the network can be electrified as soon as possible.

Distribution network is a vast infrastructure that's purpose is to distribute electricity around a designed area to customers, that can be in around either in city areas or in more rural environment. Usually, rural feeders are much more prone to faults than city feeder due to plenty of underground cabling. These feeders can cover over tens of kilometres from the feeding substation to the customers, including heavily forested areas and similar more fault prone areas. While these factors make the rural feeders more prone to faults, they also make them harder to access, since difficult terrain also slows down the response time of the repair groups operating on the ground. These combined prolong the time it takes to manually locate the fault, thus prolonging the time customers are without electricity. Longer down times mean more displeased customers and more losses for the supplier due to possible compensation payments requested by the customers. These are the reason that fast fault location is important and one of the reasons that a development is needed for the automatic fault location functionality.

One of the main goals of this master thesis is to develop an automatic fault management functionality; Fault Location, Isolation and Restoration, known as FLIR, for the DMS600 WS software, for Hitachi Energy Finland Oy. Idea is to develop a functionality whose purpose is to automatically locate faults from the network, utilizing trial switching. Trial switching means that the fault is located with an algorithmic way; where certain switches are operated in a specified order generated by the software, until the faulty section can be located. When faulty section has been identified and isolated from the rest of the feeder, electricity can then be then restored to the healthy parts of the network from back-up sources. Back-up sources can either be other substations or distributed generation plants. The thesis looks also into the possibilities of utilizing energy storages as a back-up during restoration.

Most of the work of the thesis went on to developing the implementation part, which was a lengthy process and took its time, but gave a good amount of knowledge of how DMS600 software family works under the hood. Work was done primarily using C++ code and there were tens of thousands of lines of code written for the implementation. The thesis introduced the MicroSCADA X DMS600 software family, including few of its main software that the implemented functionality utilizes. This gave a good overview how the internal communication works between the software and what functionalities they already have and what needed to be implemented. The focus was that the existing fault management functionality could be only utilized in a handful of faults, whereas the new implemented FLIR functionality aims to work around the issues in the old implementations, mainly because trial switching was implemented.

Keywords: Automatic fault management, FLIR, Distribution networks, Energy storages, DMS, MicroSCADA X

PREFACE

This master's thesis was written for Hitachi Energy Finland Oy in Hervanta. It was a challenging and lengthy process, which took its time, effort, and energy, but at the same time it gave so much in return. During the process I've learned a lot of new challenging things that will most definitely be helpful in my future endeavors. Most importantly this is also an end and a beginning of a chapter in my life, where life as a student is finally left behind, and new sights await as the career and life itself progresses forwards.

I would like to thank the examiner Tomi Roinila for helpful tips and information regarding the writing process, my thesis coordinator from Hitachi Energy, Matti Kärenlampi for overseeing and providing helpful information during the process, Jussi-Pekka Lalli for providing the basis and motivation for this work with his own thesis, Esa Korpi for providing valuable deep knowledge about the DMS software and all my co-workers that have provided their support and knowledge during this seemingly never-ending process.

Finally, I would like to thank my parents and family that have provided me with this opportunity to get to this point in life and have always been supportive and understanding, and all my great friends that have kept the work-life balance in check.

In Tampere, Finland, on 9 November 2021

Jaakko Niskala

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ABBREVIATIONS & ACRONYMS

AC	Alternating current
BMS	Battery management system
CB	Circuit breaker
DC	Direct current
DG	Distributed generation
DSO	Distribution system operator
ESS	Energy storage system
HV	High voltage
LESs	Local energy storage system
LV	Low voltage
MV	Medium voltage
NE	(DMS600) Network editor
PCS	Power conversion unit
PV	Photo-voltaic
RES	Renewable energy source
RCD	Remote-controlled disconnector
RCZ	Remote-controlled zone
SoC	State of charge
TESS	Transportable energy storage system
WS	(DMS600) Workstation

1. INTRODUCTION

The modern society applies electricity almost in every application and more and more applications are invented and brought to the consumers constantly increasing the need and dependency of electricity. As this is the case, continuous availability of electricity has become one of the most important aspects in our daily lives. Most of us have faced a power outage at some point of our lives and from experience it is safe to say that it is never a pleasant feeling knowing that the food is spoiling and all the electrical devices that are not equipped with a battery are unusable. Since most people have no idea or do not even want to know the details of how the power is delivered in the distribution network or how different fault situations might occur in the network, the first instinct is to blame the supplier for the outage. This is one of the main reasons why fault situations in the distribution networks should be resolved as quickly as possible, since it improves the customer happiness and reduces the amount of possible costs related to the outages. It might seem that it would be easy to locate and repair the faults quickly without any issues, but most of the distributors have vast networks that cover large areas, leading to the fact that there is a lot that can go wrong. These vast infrastructures of distribution networks have become an essential part of our modernized world. Therefore, it is important to constantly develop the distribution infrastructure to keep up with the rest of the fields that are developing in staggering speeds.

First touches with electricity were made early in the human history by observing naturally occurring phenomena i.e., thunderstorms, but real understanding were first made in the 18th and 19th centuries. Earliest designs of batteries and generators were invented in the early 19th century, and this was the turning point in history that changed the future forever. From then on, the electricity was one of the main points of interest for many of inventors and researchers. Truly the electrification began in the early 20th century. During that century having electricity became more and more common in industrial applications and in normal households [1]. From then on there was no turning back from the electrification of the industrialized countries and this can be seen in our everyday lives as almost everything nowadays utilizes electricity in some way and more and more applications are invented all the time.

Faults are rarer occurrence in city areas where the usage of underground cabling is more frequent, but the rural areas are more prone to faults. According to statistic collected in

Finland, rural areas were at least two times more prone to have an interruption caused by a fault in the network than a city area [2]. Commonly rural feeders can be much longer than in the city areas, and they can cover tens of kilometers from the feeding substation to the consumers, including heavily forested areas and similar more fault prone areas. This makes the rural feeders more prone to faults and the difficult terrain also slows down the response time of the repair groups operating on the ground. These factors prolong the time it takes to manually locate the fault thus prolonging the time customers are without electricity. Longer down times mean more displeased customers and more losses for the supplier due to possible compensation payments requested by the customers. These are the reason that fast fault location is important and one of the reasons that a development is needed for the automatic fault location functionality.

One of the main goals of this master's thesis is to develop an automatic fault management functionality Fault Location, Isolation and Restoration, known as FLIR, for the DMS600 WS software, for Hitachi Energy Finland Oy. The Idea is to develop a functionality whose purpose is to automatically locate faults in the network, utilizing trial switching. Trial switching means that the fault is located with an algorithmic way; where certain switches are operated in a specified order generated by the software, until the faulty section can be located. After the faulty section has been located, the electricity will be restored from an alternative source to the healthy sections of the faulty feeder. The goal is to reduce the time it takes for certain faults to be isolated thus reducing the down time for the customers located in the healthy parts of the feeder. This master's thesis will also investigate the possibilities that energy storages provide in restoring the power back from an interruption, as a sort of back-up route. As smart grids have become more common in the electrical network infrastructure, there is increased amount of energy storages in the system that opens a possibly to use them during the restoration process. This will guarantee more stable overall electricity delivery, since fewer number of customers are affected by the fault situations.

The remainder of the thesis is organized as follows. Chapter 2 covers the theory that is applied in the work; We start the theory section from the beginning of the whole production-distribution chain, where various power generation methods are presented. Then we move on to the electricity transformation, where we present various transformers and focus on the basic principle of transformer operation and related equations. Next up is the transmission where we get to know the basics and we mainly focus on the losses during the transmission and how to mitigate them. The end point of the chain is the distribution, where we present various components of the distribution network and how they are used. Also, faults in the distribution network and fault current calculations are also presented. Lastly, we present various energy storages and present few use cases how they can be applied in the distribution network.

Chapter 3 presents the methods applied in the work; We start by presenting the MicroSCADA X DMS600 software family, which is directly related to the implementation part. Introductions includes some functionalities, communication protocol and interface introductions. Then the existing fault management functionalities of the DMS600 is presented and the development needs of how and why it needs to be improved. Automatic FLIR is introduced, including customer requirements, and expected benefits for the functionality, and the functional requirements.

Chapter 4 introduces the implementation part of the thesis, where the description of the implementation contains class diagrams and flow charts to visualize the implementations better. To close out the chapter, we present the future development needs, which are outside of the scope of this thesis but will be implemented later.

2. THEORY

2.1 Electrical generation, transformation, transmission, and distribution

Electrical infrastructure is a vast and complex system, which main goal is to handle the generated electricity from the generation plants to the customers scattered around the distribution network. This takes a lot of planning and careful construction to get the whole process to work without any issues, which further requires a lot of calculations of different characteristics to get the sizing, protection, and loss mitigations correctly for everything. This chapter is organized as following; Firstly, various electricity production sources are presented, listing their operation principle, possible strengths, and weaknesses, including some real use-cases, also taking in their environmental aspect as well. Then we will present the basics of the electricity transformation, which includes the basic equations related to it. Also, different type of transformers, their use-cases, and rated voltages are presented in a table form. Then we get to the transmission of electricity, where we include some calculations of the transmission losses during the transmission procedure, which can be used to size and plan transmission lines accordingly to the needed characteristics. Lastly, the chapter will present distribution networks, since most of the implementations work in this thesis is done mainly for the distribution network and DMS600 software is a distribution network management system. Distribution networks are first introduced, then various of its components are presented, describing their use-cases and purpose. Also, we present various fault situations that can happen in the distribution network and how the fault currents can possibly be calculated and how they can be utilized when approximating the fault location from the distribution network.

2.1.1 Introduction to electrical networks

Electrical distribution begins from the source of the electricity, generally electricity is converted from potential or chemical energy to electrical energy. There have been various inventions, which use and convert the source of the energy differently. These various types can be divided further to different categories, where two of these are natural and renewable sources. Natural sources include for example, coal, gas, and oil. These are known to produce excessive amounts of carbon, or greenhouse gas emission, which are highly damaging to the environment. Renewable sources include for example, solar, wind and hydroelectricity. These are considered much more favourable for the environment, since carbon emission are only a fraction of what their counterpart natural sources produce. Then there is also nuclear power, that is very effective and carbon emission free, but is also considered somewhat dangerous by various counties, mostly because there have been few bad nuclear disasters in the history. [3,4]

After the electricity has been generated in a power generations plant, the electricity characteristics might need to be modified, so that it would be optimal for transmission. This is where transformers come into the picture. Transformers are devices, whose purpose is to transfer electrical energy between two circuits, utilizing phenomenon called electromagnetic induction. This phenomenon can be used to either increase or decrease the voltage of an alternating current (AC) system. This is a key feature of a transformer, since it allows the universal usages of AC systems with different voltage levels, which further increases the benefits from it. Optimal voltages in various applications are a must in power systems nowadays, since it improves the overall efficiency. [5]

The electricity then needs to be transferred to the customers, which means power transmission. Power transmission means that the power is transmitted via power cables in the transmission network. Distances vary greatly depending on the location and the transmission network, but usually the transmission happens over long distances. Long distances mean that there must be a lot of cable to transfer the power and the longer the cable the greater the losses are. This however can be mitigated by using high voltages during the transfer. This means that the usage of transformers is essential to power transmission, since the voltage is first increased greatly for long distance transmissions and then it can be reduced back to voltage levels that can be used by the customers. Typically, there are three layers of transmission network, these are high voltage (HV), medium voltage (MV) and low voltage (LV) networks. Distribution network usually contains MV and LV networks. [3]

2.1.2 Generation of electricity

As mentioned before there are various ways to generate electricity. These can be further categorized into thermal, hydro, nuclear, geothermal, and other renewable power sources. Thermal power is still the most used, since it has numerous advantages compared to other methods. These advantages include reliability, maturity, and general understanding of the technology. The most common thermal energy fuel is coal, but also oil and natural gas are used rather commonly. Unfortunately, there are major drawbacks regarding thermal energy, which is carbon dioxide, more commonly greenhouse gas or CO_2 emissions. Usage of thermal energy generation furthermore accelerates the global warming phenomena, which in the future could be one of the major issues that humankind must face. [4,6]

Generator is basically an electrical motor, that is run backwards, meaning that the input happens in the output shaft of the electrical motor, thus spinning the motor. This allows the mechanical energy to be converted to electrical energy. There are different designs of electrical motors, varying from direct current (DC) and AC motors. These have all different usages, but most commonly the AC-motors are used. Especially 3-phase-AC-motors are most used in production plants. Basic operation principle of a 3-phase-AC-motor is the following: rotor part of the electric motor is rotated, which then rotates either in magnetic field or rotates magnets that are attached to the rotor, thus generating rotation in the motor. Rotation in the rotor creates induced voltages to the stator coils, which is where the conversion happens from mechanical to electrical energy. [7]

Either steam or gas turbines are used for thermal energy generation. The basic principle of a steam turbine is that the coal or other thermal energy source material is burned inside the furnace, which then heats the water into a high-pressure steam, which then is directed though a series of turbines making the turbine spin. Gas turbine works more like a combustion engine, similar operation principle to a car, where the fuel is combusted with compressed air, creating exhaust gasses that are heated to $1400°C$ or upwards. The higher the output temperature the better the efficiency, so new materials are considered which could withstand more heat. [4,6]

Nuclear power is a different animal when it is compared to more traditional fuels. Nuclear power fuel is, as the name suggests, a reaction between the atomic nuclei. These nuclear reactions are powerful and hard to control, which we have seen in the past nuclear disasters. There are two different methods, which are fission and fusion. Fission is more mature, and it has been in use for a while now. Fusion is still taking its baby steps, but perhaps in the future fusion power might be available. Generally, fission-based nuclear power uses enriched uranium as its fuel, since its radioactive and highly volatile. Nuclear fission basically means that the nuclei of an atom splits into different components, also releasing a lot of energy at the same time. If there are these radioactive atom nuclei close one of others, then a chain reaction occurs, which then spreads rapidly in the material, releasing immense amount of energy in a split second. This needs to be controlled and the reactions need to be held mild, so that the energy can be harvested. This is the basic principle how fission-based power generations works. The enriched uranium is placed in a core where there is a moderator, usually either water, gas, or graphite, which then slows down the reaction and captures part of the energy released from the reaction. This heat then can be used to produce steam, which is then lead to a steam turbine, which then converts the energy from the nuclear reaction to electrical energy. [6]

Hydropower is well known and widely used renewable energy source; water has been harnessed to do work for humans for thousands of years. Hydro power produces almost 20% of worlds energy. Even though hydro power is considered renewable energy, it has more drawbacks when comparing to other renewable choices, since it affects the local ecosystem greatly and lessens the habitability of the rivers and riverbanks for wildlife. Hydro power uses the potential energy of the water as the basic energy source, which is then converted to electrical energy using turbines that then turn large generators. Usually these areas are dammed, to create more potential difference and reserve between the up- and downstream. Technologically hydro power turbines are mature, since they have been actively in use for hundreds of years now, but even though there still are risks linked to the hydro power, including natural disasters and such, which added together with environmental effects and other more minor concerns have decreased the likability of hydro power slightly, which furthermore drives the renewable energy generation to more environmentally friendly solutions. [6]

As mentioned, the hydropower is mature technology, but it has its drawbacks, for these reasons the other renewable energy sources have been lifting their interest. One of which is wind power, which has grown substantially in the last 20 years. Wind power is currently the second most important renewable energy source and according to [8] it produces almost 70% of the total renewable energy production, when traditional hydro power is not included. Wind power has also been around for a while now and has gone through the maturing process like hydro, recently there has been multiple new wind power projects, which have driven the technology even further. Basic principle of wind power is as the name states to convert energy from the moving air to electrical energy. There are multiple designs for wind turbines varying in size, nominal power, and configurations.

Most commonly the larger ones are 3-bladed horizontal axis turbines, which are usually intended to be built on high towers. There are also vertical axis ones, which are usually used in smaller applications and not necessarily in large wind farms. Turbine blade is connected to a rotor which rotates the generator via a gear box, thus converting the rotation to electrical energy. Recently there has been large offshore wind farm projects, where large wind turbines are being built offshore in the ocean, these wind farms contain multiple wind turbines that collectively produce great amount of energy. Usually, these wind farms have their own power stations and such, which also handle the transforming so it can then be connected to the onshore main grid. [9]

Last renewable that we are going to present at in this chapter is solar energy. The sun is the origin of life, and it grants vast amount of energy to the planet constantly blasting us with solar rays. These sun rays can be harnessed by solar or photo-voltaic (PV) panels, but only a portion of the solar energy can be captured, since average efficiencies are still below 30%. However, this has increased constantly through the maturing process of the technology and there are some promising results. According to [8] best experimental solar panel efficiencies are nearly 50%, which would boost the solar panel production and cost-effectiveness greatly if the same results can be transferred to commercial use. Basic principle of PV energy relies on semiconductors, where the conduction happens only in sufficient circumstances. There are different semiconductor materials available, and each have their own characteristics, but usually these materials are doped to make them more efficient. Doping allows there to be more electron-hole pairs in the conductor, which then allows more absorption of solar rays. When a solar ray hits the solar cell, ray is partially absorbed in the material, which then releases the negatively charged electrons to the conduction band and the positive “hole” moves to the valence band. When these bands are connected the electrons start moving, which then results in electrical current. For solar cells to generate enough electrical energy, there needs to be multiple cells connected to each other, which is then called a solar panel and usually there are hundreds of PV panels in large scale solar plants. [8,10]

Production is generally produced in relative few places compared to the consumers, but it is vastly scattered around the whole network, since there are multiple production plants which are different sizes and are in different locations. These plants feed the transmission network simultaneously, thus a sophisticated control method is required for proper synchronization. Insufficient synchronization might lead to overloading of the network components or destabilization of the other feeding generators. [3]

Even though the distributed generation needs more advanced methods, it has its perks. Since it mitigates the losses that happen during the transmission and this leads to less emissions, since the efficiency goes up. These advantages of distributed generation have driven the electrical generation to be more scattered and closer to the point of usage. [3,11]

2.1.3 Transforming the electricity

Transforming or more commonly changing the electrical characteristics. Can be achieved by utilizing transformers. Transformer itself is not a clever device, it basically contains iron and copper, that do all the work, but there are complex calculations required for it to function properly. Transformers are essential part of the network; they make it possible to transfer electricity with minimal losses and allows the consumers to use electricity with lower voltages. Operation principle is based on common magnetic field between the transformer cores, which can be further explained by electromagnetic induction. This induction links the two connected systems together without changing the frequency, which further enables the usage of universal AC power systems. Basically, the electrical energy is converted to magnetic energy in the primary winding, which is then converted back to electrical energy via induction in the secondary winding. This allows voltage to be transformed during the conversion. [5,12]

Ideal transformer can be used to model the basic physics behind the transformer operation. If we consider an ideal single phase two winding transformer, that has each winding wrapped around a magnetic core, like one that is illustrated below in figure 1.

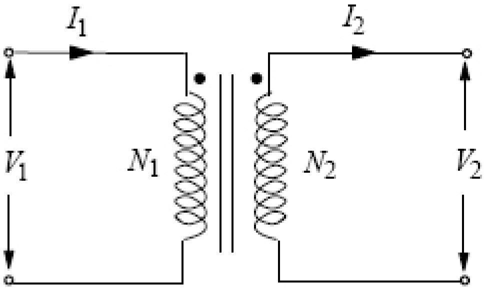


Figure 1. Illustration of an ideal single phase magnetic core transformer. [5]

Ideal transformer can be modelled as the following, the electromotive force in the primary winding can be deduced as [5]

$$e_1 = N_1 \frac{d\phi_m}{dt} \tag{1}$$

where the e_1 is the electromotive force in the primary winding, N1 is the amount of turns in the winding and ϕ_m is the mutual flux in the magnetic core.

As the ideal suggest, the resistive losses can be neglected, thus we get the following formula [5]

$$v_1 = e_1 \tag{2}$$

where the v_1 is the instantaneous applied voltage. Since it is an AC system, the voltage is constantly varying according to the frequency of the system, the mutual flux must vary as well. So, we get the following [5]

$$\phi_m = \phi_{mp} \sin \omega t \tag{3}$$

where the ϕ_{mp} is the peak value of the mutual flux in the magnetic core and the ω can be represented as $\omega = 2\,\pi\, f$. Equation (3) can be then substituted to the equation (1), and it results into [5]

$$e_1 = N_1 \omega \phi_{mp} \cos \omega t \tag{4}$$

where root mean square value of e_1 can be obtained by dividing the peak value of equation (4) by $\sqrt{2}$, and this results in [5]

$$E_1 = 4.44 \phi_{mp} f N_1 \tag{5}$$

Equation (5) is more commonly recognized as the emf equation for transformers. It can be used to deduce the relation between the number of turns in the winding and the voltage that is induced, meaning that the frequency and the flux in the magnetic core is determined by the applied voltage in the primary winding. [5]

Secondary winding can also be modelled similarly to primary winding, since the same mutual flux affects it as well. So, we get the following [5]

$$e_2 = N_2 \frac{d\phi_m}{dt} \tag{6}$$

Then we can derive the ratio between the primary and secondary windings by using (1) and (6), so we get [5]

$$\frac{e_1}{e_2} = \frac{N_1}{N_2} = a \tag{7}$$

where a is the transforming ratio. As we can see, the transforming is related to the number of turns in each winding, thus different voltage levels can be calculated quite easily when we are dealing with ideal transformers. Non-ideal transformers are much more complicated, but the closer look to ideal transformers give a good outline what is supposed to happen inside a transformer and how it works ideally. [5]

Transformers come in a lot of sizes and use-cases, with different conversion voltages in different kind of applications. Table 1 below will describe the different transformers and use-cases.

Table 1: Different type of transformers and their use-cases. [5,12]

Transformer type:	Voltage range:	General use-case:
Generator transformer	11 – 25 kV is stepped up to 220 – 765 kV depending on the region.	Steps up the voltage so it will be suitable for long distance transmission.
Distribution transformer	11 – 25 kV is stepped down to 400 – 460V depending on the region.	Steps down the medium voltage network to distribution voltage for consumer usage.
Phase-shifting transformer	Not specified	Shifts the phase of the voltage, can be used to control the power flow between the transmission lines balancing them.
Station transformer	Not specified	Used for generator start-up operation for multiple auxiliary components in the generation station.
Receiving station transformer	220 kV – 115 kV is stepped down to 66 kV – 33 kV. Also varies depending on the region.	Used to step-down the transmission voltages to primary feeder voltage level.
Autotransformer	Steps interconnecting voltages accordingly. e.g., 400 kV – 220 kV or 345 kV – 138 kV.	Used to interconnect two different transmission networks with different voltage levels.
Grounding transformer	Not specified	Used to provide neutral point to the transmission system, helpful when detecting earthing faults.

Rectifier and inverter transformer	Not specified	Used to counter harmonics due to special design. Usage lessens the stress that different type of harmonics might cause to the system.

Transformers presented in the table are the ones that are mostly found in the whole production-distribution chain. There are others that are somewhat out of this scope so they were left out. Table gives a good overview of each transformer and presents their possible use-case.

2.1.4 Transmission of electricity

Transmission lines are engineered to carry bulk amounts of electricity, which is then distributed accordingly in smaller distribution networks, that feed the consumers. One of these smaller distribution networks might consume only portion of the transmitted electricity, so generally transmission network feeds multiple distribution networks simultaneously. Main objective of the transmission network is to connect the production plants with distribution networks, which then will feed the consumers with electricity. As mentioned in the last chapter, transformers play a vital role in the whole transmission chain, since the long-distance transmission is done in high voltages to mitigate the losses. Depending on the region, the network operates either with 60 Hz or 50 Hz and usually the transmission voltage is from 100 kV up to 500 kV. Usually, transmission and distribution are done in 3-phase-systems, which is a standard in most of the regions. [13,14]

As the electricity is generated, the voltage is generally too low for transmission, so it is required to step-up the voltage for suitable level for long-distance transmission. Generator transformer is used to step-up the voltage to high voltage level, which then can be transmitted through the transmission network, sometimes even hundreds of kilometres. When distances are great, even the tiniest losses add up and lead to great losses if they are not properly mitigated. Losses in the transmission network can be modelled and calculated with various parameters, these are for example, resistance, inductance, capacitance, and conductance. Conductance can usually be neglected in transmission line modelling, since the losses it causes are significantly smaller than others. [13,14]

Resistive losses are due to physical characteristics of the conductor material, which depend on at least the temperature and thickness of the conductor. We get the DC-resistance in the transmission conductor with the following equation [13]

$$R_{DC} = \frac{\rho l}{A} \tag{8}$$

where the R_{DC} is the DC-resistance, ρ is the conductors resistivity in a specific temperature, l is the length of the conductor and the A is the cross-section of the conductor area. [13]

In an AC system, the resistance is affected also by the frequency, which is more commonly known as the frequency or skin-effect. The frequency effect increases the resistance of the conductor, which then lowers the efficiency of the system. This effect is small, but noticeable in long transmission lines. Frequency effect can be modelled as following [13]

$$R_{AC} = R_{DC}k \tag{9}$$

where the R_{AC} is the AC-resistance and k is the estimated correction factor to estimate the effects of the frequency effect has in an AC conductor. This factor can be calculated with complicated differential equations and Bessel functions. According to [13] in 60 Hz systems the k is estimated to be $k = 1{,}02$. [13]

Effects of temperature can also be modelled, since the resistivity changes linearly for conductive materials depending on the operation temperature. This linear increase can be modelled as following [13]

$$R_2 = R_1 \left(\frac{T + t_2}{T + t_1} \right) \tag{10}$$

where the R_2 is the resistance value in the new temperature, R_1 is the original resistance value in the original temperature, t_2 is the new temperature, t_1 is the original temperature and T is the temperature coefficient for the specific conductor material. For typical conductor materials these temperature coefficient values are obtainable from various sources. [13]

Inductive losses happen due to electromagnetic induction, since each conductor that carries current creates a magnetic flux around them, and in an AC-system when the current varies over time, the magnetic flux fluctuates, thus resulting in voltage induction. In order to calculate the inductance in a transmission line, we need to calculate the permeability μ, which can be achieved by finding out the magnetic field intensity H, magnetic field density B and linkage flux λ. [13]

Total inductance of the conductor can be divided to two different calculations, internal and external inductance, which are both required so we can get the total inductance of the conductor. First, so that we can calculate the internal inductance, we need to determine the fraction of the current, which is enclosed in a specific area of the conductor. We get the following [13]

$$I_x = I \frac{\pi x^2}{\pi r^2} \tag{11}$$

where I_x is the enclosed current, I is the total current, x is the enclosed area radius and r is the radius of the conductor. According to ampere's law, the magnetic field intensity is constant along the circle, thus we get the following for the enclosed intensity [13]

$$H_x = \frac{I_x}{2\pi x} = \frac{I}{2\pi r^2}\, x \tag{12}$$

where H_x is the enclosed magnetic field intensity. Then we can obtain the magnetic flux density via the enclosed magnetic field intensity, and we get the following [13]

$$B_x = \mu H_x = \frac{\mu_0}{2\pi}\left(\frac{I_x}{r^2}\right) \tag{13}$$

where the B_x is the enclosed magnetic flux and μ is the permeability for a nonmagnetic material. μ is a constant, thus we get the following. [13]

$$\mu = \mu_0 = 4\pi 10^{-7} \tag{14}$$

Differential flux in the enclosed area, with a certain thickness for a 1-meter part of the conductor can be calculated as following [13]

$$d\phi = B_x dx = \frac{\mu_0}{2\pi}\left(\frac{Ix}{r^2}\right)dx \tag{15}$$

where $d\phi$ is the differential flux in the enclosed area and dx is the thickness of the ring-section. [13]

Differential linkage flux can also be defined as following [13]

$$d\lambda = \frac{\pi x^2}{\pi r^2} d\phi = \frac{\mu_0}{2\pi}\left(\frac{Ix^3}{r^4}\right)dx \tag{16}$$

Then we can integrate the defined differential linkage flux over $x = 0 \; to \; x = r$ and we get the following integral function. [13]

$$\lambda_{int} = \int_0^r d\lambda = \frac{\mu_0}{8\pi} I \tag{17}$$

We can use this to calculate the internal inductance per-unit value, and we get the following equation [13]

$$L_{int} = \frac{\lambda_{int}}{I} = \frac{\mu_0}{8\pi} \tag{18}$$

Now we have defined the equation for the internal inductance, for the total inductance we still need to define the external inductance equations. External inductance can be modelled in a way that we can assume that all the current is stacked in the surface of the conductor, meaning that there is a maximum skin-effect. Equations for external magnetic field intensity comes out as [13]

$$H_y = \frac{I}{2\pi y} \tag{19}$$

where H_y is the external magnetic field intensity, y is the radius of the external magnetic field radius. For magnetic field density we get the following as well [13]

$$B_y = \mu H_y = \frac{\mu_0}{2\pi}\frac{I}{y} \tag{20}$$

where B_y is the external magnetic field density. For the external differential flux, we get the following [13]

$$d\phi = B_y dy = \frac{\mu_0}{2\pi}\frac{I}{y}dy \tag{21}$$

where the $d\phi$ is the enclosed external magnetic field density, dy is the thickness of the magnetic field line ring from point $D_1\ to\ D_2$. For the external differential linkage flux, when the conductor is affected by maximum skin-effect we get the following equation [13]

$$d\lambda = d\phi = \frac{\mu_0}{2\pi}\frac{I}{y}dy \tag{22}$$

We can then integrate the linkage flux over the points of the ring. We get the enclosed linkage flux as following. [13]

$$\lambda_{1-2} = \int_{D_1}^{D_2} d\lambda = \frac{\mu_0}{2\pi}I\int_{D_1}^{D_2}\frac{dy}{y} = \frac{\mu_0}{2\pi}I\ln\left(\frac{D_1}{D_2}\right) \tag{23}$$

Total per-unit length external linkage flux in any point in the external enclosed magnetic field can be calculated with the following. [13]

$$\lambda_{ext} = \int_{r}^{D} d\lambda = \frac{\mu_0}{2\pi}I\ln\left(\frac{D}{r}\right) \tag{24}$$

Internal and external linkage fluxes can be summed together as following. [13]

$$\lambda_{int} + \lambda_{ext} = \frac{\mu_0}{2\pi}I\left(\frac{1}{4} + \ln\left(\frac{D}{r}\right)\right) = \frac{\mu_0}{2\pi}I\left(\ln(e^{\frac{1}{4}}) + \ln\left(\frac{D}{r}\right)\right) = \frac{\mu_0}{2\pi}I\ln\left(\frac{D}{e^{-\frac{1}{4}}r}\right) \tag{25}$$

We can use (25) to calculate the total inductance per-unit length in the conductor as following [13]

$$L_{tot} = \frac{\lambda_{int} + \lambda_{ext}}{I} = \frac{\mu_0}{2\pi}\ln\left(\frac{D}{GMR}\right) \tag{26}$$

where GMR is shortened from geometric mean radius, which is $e^{-\frac{1}{4}}r = 0.7788\,r$. These inductance calculations are done for a basic one-phase conductor, more advanced calculations are needed for 3-phase systems, but a good general picture is achieved from these. [13]

Capacitance is a potential difference between two electrically charged potentials. Since, transmission lines are electrically charged, they have a potential difference, which then appears as capacitance. Usually this happens between the two conductors, thus we need to define the voltage between them and the surrounding electric field strength. We shall look at a simple single conductor case to get an understanding of the capacitance in a transmission line conductor. [13]

If we consider an ideal conductor, where the resistivity is zero, all the charge will be evenly spread through the surface of the conductor. This leads to constant electric field strength to be in the surface of the conductor. If the conductor is positively charged with a charge of $q+$ and it has permittivity of ϵ_0 it can be modelled according to Gauss's law, which tells us that the total electric flux leaving out of the surface of the conductor is the same as the total charge that is enclosed inside the conductor surface. We can define the electric field flux density and electric field intensities in a point P, which is located somewhere outside the conductor. We get the following equation for the flux density in the point P [13]

$$Density_P = \frac{q}{A} = \frac{q}{2\pi x} \tag{27}$$

where $Density_p$ is the flux density at the point P, q is the electric charge in the surface of the conductor, A is the surface area of the cylindrical conductor, x is the radius. Conductor is 1 m long. For the field intensity we get the following equation [13]

$$E_P = \frac{Density_P}{\epsilon} = \frac{q}{2\pi\epsilon_0 x} \tag{28}$$

where E_P is the field intensity, $\epsilon = \epsilon_0 = \frac{10^{-9}}{36\pi}$ is the permittivity of free space, which is assumed to be constant for the ideal conductor. If two points are considered in the electric field, for example P_1 & P_2 with distances from the centre of the conductor x_1 & x_2, their potential difference can be obtained by integrating (28) over the corresponding distances $x_1 \; to \; x_2$, thus we get the following equation [13]

$$V_{P1-P2} = \int_{x_1}^{x_2} E_p \frac{dx}{x} = \int_{x_1}^{x_2} \frac{q}{2\pi\epsilon_0} \frac{dx}{x} = \frac{q}{2\pi\epsilon_0} \ln\left(\frac{x_2}{x_1}\right) \tag{29}$$

where $V_{P_1-P_2}$ is the potential difference between the points. With this we can calculate the capacitance between the points and we get the following equation [13]

$$C_{P1-P2} = \frac{q}{V_{P1-P2}} = \frac{2\pi\epsilon_0}{\ln\left(\frac{x_2}{x_1}\right)} \tag{30}$$

where C_{P1-P2} is the capacitance between the given points. If the second point is in the ground level, we can calculate the capacitance between ground and the conductor, i.e., $x_2 = h$ is the height of the conductor. We get the following equations [13]

$$V_{ground} = \frac{q}{2\pi\epsilon_0} \ln\left(\frac{h}{r}\right) \tag{31}$$

$$C_{ground} = \frac{q}{V_{ground}} = \frac{2\pi\epsilon_0}{\ln\left(\frac{h}{r}\right)} \tag{32}$$

where V_{ground} is the potential difference between the conductor surface and ground and C_{ground} is the capacitance between the conductor surface and the ground. [13]

This was a brief look into the transmission line parameters, which can be used to minimize the losses in each transmission line system. More advanced calculations are needed for 3-phase systems and more accurate real-life utilization, but these give a good heading what are the losses and how they affect the transmission. These calculations can also be used when sizing the proper protection devices, thickness, and material of the transmission lines.

2.2 Distribution networks

Distribution network is the last part of the whole production-distribution chain where the electricity is transmitted from the production plants to the consumers. Distribution networks are more localized networks where the goal is to distribute the electricity that has been transmitted via transmission networks to consumers accordingly. Since distributed generation (DG) is increasingly getting more common, there are requirements for interconnecting smaller DG generation plants. Distribution network usually operates with a medium voltage (MV) or low voltage (LV) networks, where the LV-network level is the consumer level and MV-network is used to transmit the electricity inside the distribution network. LV- and MV-network voltages vary from region to region, but in France for example LV-network nominal voltage is 400V and MV-network nominal voltage is 20kV. [11]

When electricity needs to be distributed to all consumers equally, there is a need for longer rural and more complex urban distribution, this leads to lots of distribution lines, which makes the distribution network one of the largest electrical infrastructures in the whole process. More modern distribution networks can have a meshed structure, where there are loops in the distribution network, that allow more continuous power delivery with different feeding options. These modern distribution networks can be operated in a radial- or tree type structure, meaning that there is only one possible path between the feeding substation and a certain node in the network. Distribution networks include multiple substations, transformers, distribution lines, containing LV- and MV- network overhead lines and underground cables and bunch of switching devices and more. [11]

As distribution networks are complex and are in variable locations around the country where the electricity is transmitted, the need of a localized overview is needed. This is where the distribution system operators or DSOs come into the picture. DSOs must be independent from the organizations that handle the transmission and production to ensure that the distribution and competition is fair and thus guaranteeing fair game for all consumers. DSOs are the backbone of the whole transmission network, since they are ultimately the link between the producers and consumers, they ensure that the power is distributed for the consumers with high quality and without major disruptions. One of the main tasks of DSOs are to monitor and control the distribution network, ensuring that there are no active faults and power is constantly distributed to all consumers uniformly. [11] This being one of the main goals of this master's thesis, to decrease the time customers are without electricity during active fault situations. Implemented functionality is introduced later in this thesis.

2.2.1 Components in distribution network

There are various components with different purposes in the distribution network, each doing their own part ensuring that power is delivered with high quality and without breaking anything from the consumers or in the network itself. Brief introduction of most common components is next.

Feeding stations or **substations** are one the bigger “components” in the distribution network, these may contain lots of the components found in the distribution network, including different type of transformers, switching devices and protection devices. Main purpose is to divide the distribution to different feeders, meaning that the distribution network splits, thus feeding different locations. Also feeding protection is considered, including isolations and de-energization of the network if needed. [15]

Various **transformers** are being used in the distribution network. For example, various size power and autotransformers are used for converting the voltage from the transmission voltage level to MV-levels and further MV is converted to LV-level near the consumers. [15]

Busbars are one of the most essential components found in the distribution network. It is designed to interconnect the feeding lines, forming an “bar” that feeds multiple circuits at the same time. There are three main busbar types, which are the following: Rigid, where the busbar is some sort of solid bar, usually aluminium or copper. Tensioned strain, where conductor is a stranded wire which is tensioned. Cable, where stranded conductor is under lower tension, resembling a normal overhead cable. Substation busbars might have dozens of connected feeder circuits. [15,16]

Disconnectors, disconnect switches or isolators are utilized in isolating certain parts of the distribution network. They can either be manually operated, or remote operated. Remote operated are equipped with proper communication equipment and electrical motor, which is used when disconnector is operated. These can also be divided into off- and on-load categories. Off-load means that the switch is meant to be operated only when there is no load in the network, thus the device operation does not have any current ratings. On-load means that switch can be opened against a nominal load current. Switches can be further categorized by the break type, these include vertical, centre, single side, and double side breaks. In addition, these switches can also have interruption capabilities with either buggy whip, gas blast or vacuum interruption devices. Also, some of them are equipped with desired grounding switches, which can be operated with their own separate mechanism to ground the network directly from the switching device, which is useful when maintenance work is done for example. [15,17]

Fuses are commonly used protection devices and they can be found in various sizes in most electrical devices and larger applications such as buildings and found in the distribution network too. Fuses are cheap and simple, which makes them desirable in most applications. Fundamentals of fuse protection is simple, excessive current causes thermal energy to be absorbed in the fuse-element, which then causes the fuse to melt, thus breaking the circuit. By technological advances, fuses have become quicker and safety has increased greatly. Fuses have different characteristics and they are designed to certain overcurrent values and are not configurable afterwards, thus if network characteristics change, the fuses need to be changed also. Fuse has an inverse time-current characteristic, which defines the time fuse needs to be under defined overcurrent to melt, which is not a linear figure. Since fuses do not have any way to trip it by command from outside, like for example a circuit breaker, the fuse must be carefully sized, so that the current limit is not set too high. Too high overcurrent sizing might cause the fuse not to blow in certain earth fault situations, where the fault is located far away in the network because of the losses in the transmission lines. [3]

Circuit breakers are one of the essential components of the distribution network, they are used in load switching and fault current interruptions and are designed to interrupt the fault current of the fed network. Combination of relay and a circuit breaker is a sophisticated protection method, which is widely used since it allows fast tripping of the circuit breaker when a fault occurs in the network. Relay receives information about the network and sends a tripping command to the circuit breaker when an abnormal network state is observed. It can also be used manually from other external signal, either from SCADA or manual human operation. Generally, closed circuit breaker has built in energy storage, for example a charged spring or built-in battery tripping unit (BTU), that is utilized when circuit breaker needs to be opened during a tripping. [3,16]

During relay-circuit breaker combination tripping, the following process is gone through: [3,16]

- Relay receives information about an abnormal network state, which is then analysed and used to determine if the circuit breaker needs to be tripped.
- Relay engages the trip coil, which then engages the trip energy storage.
- Circuit breaker opens its main contacts, thus breaking the circuit.
- Trip coil is then de-energized by opening of the auxiliary contacts.

Circuit breakers have different characteristics, which are important when choosing them for their desired purposes. There are few important protection characteristics. Firstly, tripping time or CB breaking time is the characteristic which defines the time it takes CB to trip from a new fault in the network. We can define the tripping time as following [3,16,17]

$$t_{CB_{trip}} = t_o + t_{arc} \tag{33}$$

where the $t_{CB_{trip}}$ is the total time it takes for the CB to trip, t_o is the opening time and t_{arc} is the arcing time. Opening time is the time it takes for the CB to open after it receives trip command from the relay. Arcing time is the time it takes for the CB to allow completely zero current flow, since there is an arc present through the air during the opening procedure for a while. Total time it takes for the fault to be isolated from the rest of the network can then be calculated by adding the delay from the relay and total CB trip time. Modern CBs total breaker trip time varies around 40-100ms. [3,16,17]

CB breaking or rupturing capacity is one of the important characteristics of an CB. Breaking capacity gives out the nominal MVA-rating. We get the following equation [16]

$$MVA_{rating} = \frac{\sqrt{3}\, V_L\, I_F}{10^6} \tag{34}$$

where the V_L is the voltage of the system and I_F is the fault current. Breaking capacity can be selected to suit needs of the network by calculating the approximates of the actual fault current during fault situations. [16]

Distribution network also has many more useful components that help the distribution to be as smooth as possible, but these are regarded in this chapter since they are not that important in the main scope of the master’s thesis.

2.2.2 Faults in the distribution network

Faults in the distribution network might occur for various reasons, usually between two- or three-line conductors, either as a 2- or 3-phase fault or as an earth current between line conductor and earth. Phase to phase faults might occur for various reasons, which include mechanical damage to the conductor insulation, overheating, voltage surges, insulation deterioration or misuse of equipment. Fault currents are usually enormous compared to normal load situations, which means that if faults are not cleared quickly, it can lead to extensive equipment and conductor damage and otherwise hazardous situations in the network. Faults can be further categorized to be unbalanced and symmetrical. Symmetrical fault includes all three phases, which can cause enormous faut currents and cause major disturbances in the system. Unbalanced faults are not that severe compared to symmetrical fault but can also cause major problems if not cleared quickly. One of the most common fault types is phase-to-ground fault, which is also the least severe of them. Because all possible faults are always severe, it is vital that switching gear is properly rated for each feeder, so that even the worst fault currents can be cleared as soon as possible to mitigate the stress to the system. [3]

Short-circuit currents can be approximated by calculations and they can also be utilized when choosing the switch gear ratings and protection devices to the system. Since we are dealing with AC-systems, we can look at the AC side of things. We start from the fundamental laws, which is of course Ohm's law, and we get the following [16]

$$I = \frac{V}{Z} \tag{35}$$

where I is the current, V is the voltage and Z is the impedance. Since we are dealing with an AC system, we need to use vectors to model them effectively, because there are different phases in the AC system. Vectors can be used to represent the relation between two different voltage or current sources with a common reference base between them, then they are comparable between each other. This representation helps us understand the basics of the AC-systems. For impedance we get the following equation [16]

$$Z = R + jX \tag{36}$$

where the R is the resistance, X is reactance and j is the imaginary indicator for imaginary component. In inductive circuits, the reactance is marked as positive and in capacitive circuits reactance is marked as negative. To further model the reactance, it can be divided as inductive reactance and capacitive reactance. As inductive reactance we get the following equation [16]

$$X_L = 2\pi f L \tag{37}$$

where the f is the frequency and L is the inductance. As Capacitive resistance we get the following equation [16]

$$X_C = \frac{1}{2\pi f C} \tag{38}$$

where C is the capacitance in the system. To find the net reactance of the system we need to calculate them vectorially, thus we get the following equation [16]

$$Z_{tot} = R + (j\ x\ 2\pi f L) - \left(\frac{j}{2\pi f C}\right) \tag{39}$$

Voltage of the system follows the phase of the impedance and current is in phase with the resistive component, which is why in inductive circuits the current is said to be lagging behind the voltage and in capacitive circuits the current is leading the voltage. [16]

To understand the 3-phase faults we will cover over the power and power factor calculations as well. In AC systems, power is measured in volt amperes or VA. For single phase DC systems, the power can be calculated straight forward as the following [16]

$$P = V\ x\ I \tag{40}$$

But for 3-phase AC system, a new factor needs to be introduced. We get the following equation for VA [16]

$$VA = \sqrt{3}\ x\ V\ x\ I \tag{41}$$

where the $\sqrt{3}$ is the factor for 3-phase AC systems. If $V = kV$ and $I = kA$ then we get the following [16]

$$MVA = \sqrt{3}\ x\ V\ x\ I \tag{42}$$

MVA is widely used when doing calculations in the 3-phase AC systems. Now we know the basics of the 3-phase system calculations, so we can get to calculating the short-circuit currents. We get the following for short-circuit MVA equation [16]

$$I_s = \frac{E_p}{X_p} \tag{43}$$

where I_s is the r.m.s short-circuit current, E_p is the voltage per phase and X_p is the reactance per phase. Then we get the following [16]

$$\frac{Short - circuit\ MVA}{Rated\ MVA} = \frac{\sqrt{3}E_p I_s x 10^6}{\sqrt{3}E_p I x 10^6} = \frac{I_s}{I} = \frac{\left(\frac{E_p}{X_p}\right)}{I} \tag{44}$$

Then if both sides are multiplied by $\frac{X_p}{E_p}x100$ we get the following in the end [16]

$$\frac{IX_p}{E_p}\,x100 = X\% \tag{45}$$

where $X\%$ is the reactance per phase. With this we get the following as the short-circuit MVA [16]

$$Short - circuit\ MVA = \frac{100\,P}{X\%} \tag{46}$$

where P is the rated power of the transformer. This can be utilized when calculating fault currents in certain cases where the transformer limits the reactance and as can be seen the value of the X is deciding the short-circuit MVA of the fault when the fault is located after the transformer and not before the generator. With this percent reactance value, the proper rating can be then chosen for the transformer. If we consider the following circuit, where the fault is behind a 10 MVA transformer and the fault is located right next to the switchgear of the transformer where voltage level is 11 kV. We can calculate the fault current utilizing (46) and we get the following. [16]

$$short - circuit\ MVA = \frac{100\,P}{X\%} = \frac{100\,X\,10}{10} = 100\,MVA \tag{47}$$

With (47) we can calculate the fault current in the current situation, and we get the following. [16]

$$Fault\ current = \frac{100}{\sqrt{3}\,x11} = 5.248kA \tag{48}$$

We can calculate the source impedance utilizing the fault current and voltage level by utilizing (35) and we get the following. [16]

$$Source\ impedance = \frac{11}{\sqrt{3}x11} = 1.21\,\Omega \tag{49}$$

For an example's sake, we shall calculate fault current in a situation where the fault is not directly next to the switchgear, thus the losses in the transmission lines affect the fault current. If we have a fault situation which is located after the switchgear, and the total impedance of the transmission lines after that is 1 Ω we get the following equation. [16]

$$Fault\ current = \frac{11}{\sqrt{3}\,x\,(1.21 + 1)} = 2.874kA \tag{50}$$

As can be seen, the fault current is affected greatly by the transmission losses in the transmission lines. This is only one of the ways of calculating the fault current, more of these can be found in [16]. With these faults current calculations, the protection devices can be sized properly. [16]

Fault location is often vital information, since it can be used for isolating the fault from the rest of the feeder. Once fault is isolated, the rest of the feeder can then be re-energized from various back-up connections. There are multiple different existing algorithmic based fault location methods. Most methods are impedance-based that utilize the fault current, voltage, and frequency of the system. These values are usually measured at the local feeding station. These algorithms are used to approximate the fault location based on the source data of the fault. Various DMS systems have built in fault location calculations, which utilize these fault location algorithms accordingly. [18]

For more accurate location information, additional measurements from the feeder can be also utilized in the algorithms. These methods can be utilized either in radial, non-radial or in both types of networks. It is also possible to try to simulate the fault situation, where multiple simulations are run in a way that the recorded characteristics of the fault situation is matched closely as possible. If corresponding characteristics are found, the fault location can be assumed to be in the simulated location. However, definitive location is often hard to obtain, since there are multiple branches, where for example the fault current can be at the same level, or there might be communication issues, or some required measurement data is lost or not even recorded properly. [18]

Whole process from the fault to DMS system, where the fault location calculations are done is presented in the figure below.

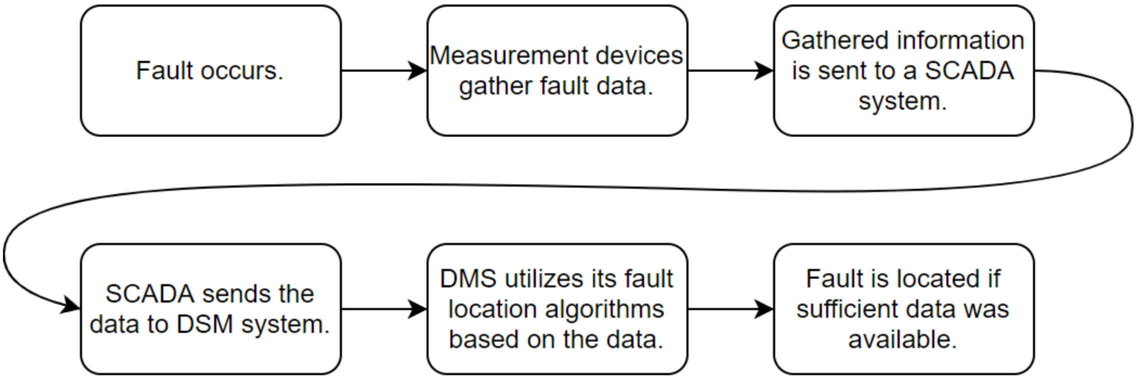


Figure 2. General interpretation of the whole fault location process.

Information for the figure above is gathered from [18]. As can be seen from the figure, the fault data is first measured by various measurements devices, which gather the information about the short-circuit currents, voltages, frequency, switching status and load data. Measured data is then sent to a SCADA system via communication protocols. SCADA then send the gathered information to a DMS system, which then interprets the data further by feeding it to built-in fault location algorithm. Algorithm then utilizes the fault data and calculates the fault location. If fault data is sufficient, the fault location should be then visible for the DMS operators. After fault location has been determined, it can be acted upon either by operator by manually isolating the fault or feeding the information to an automated functionality that handles the fault isolation and restoration. [18]

2.3 Energy storages

Main purpose of an energy storage is to store energy for an indefinite time until it needs to be used later as a need arises. There are various ways of using an energy storage and the applications vary greatly also. Energy can be stored in different forms of energy, depending on the energy storage method, which include mechanical, electrochemical, electrical, and thermal storages. Each of the methods have their own advantages and disadvantages, meaning that they are suitable for certain applications but not necessarily for everything. For example, electrochemical batteries are mostly used in portable devices such as laptops, mobile devices, or electrical vehicles, but they also can be used in bigger applications such as a part of a distribution network. [19]

Chapter is organized as following; First different type of energy storages and their basic operation principles are presented, focusing on explaining the storage method and comparing their differences. Advantages and disadvantages of these energy storages are viewed, also listing their possible applications. Then larger scale energy storages that are being used in distribution networks are presented, including their use-cases and some examples of operations. Lastly, a look into how energy storages can be utilized during distribution network fault situations.

2.3.1 Basic principles of different type energy storage solutions

In present day there are different type of ways of storing the energy and each way varies from another in some way. This means that each energy storage has their advantages and disadvantages in certain situations. So as the advantages vary the use cases must vary as well, meaning that each energy storage has their specific case where they are at their strongest. Next a look into the different solutions is presented.

Currently, most used energy storage is the pumped-hydro storage, which consists of 99% of worlds energy storage capacity installed in the electrical networks around the world. The last 1% contain the rest of the solutions, compressed air, flywheel storages and different type of battery storages. This might change in the future as the other technologies mature more. [20]

Hydroelectricity is one of the oldest and most mature way of storing great amounts of energy. The first water storage systems are from 1930s and this method has not vanished anywhere, rather it is still in use and new pumped-hydro storages are being built. [19] The basic principle for generating the energy from the water is like the dams built in rivers, meaning that there is a turbine that the water turns, and the potential energy of the water is converted to electricity via electrical motors that are being used as a generator. Generally pumped-hydro storages contain two different containers, that are built in different elevation levels. This elevation difference allows the energy to be stored as the waters potential energy and by running the water through the turbine attached to the generator the kinetic energy of the water can be transferred to electricity. As the name states, the water is pumped between the lower and the upper containers during times when there is excess amounts of power available in the network and when the need arises the water can be ran through the generator back to electricity [21].

The approximate energy stored in the pumped-hydro storage can be presented as [19]

$$E = pVgH \tag{51}$$

where E is the stored energy, p is the water density, V is the capacity of the reservoir in cubic meters, g is the acceleration caused by gravitation and H is the height difference between the two reservoirs.

This formula can be used to calculate the approximate energy stored to the pumped-hydro storage. This calculation does not take losses into account, meaning that in practise the real energy converted to electricity is slightly lesser due to losses in the system. These losses in the system can be for example evaporation of the water in the reservoirs, friction losses of the water and leakage around the turbine. Efficiency of the pumped-hydro storage is reported to be around 70-80%. [19,21]

Scale of the storage varies greatly depending on the size of the reservoirs, but generally large pumped-hydro storage capacities vary around 1000-3000 MW. As there is a lot of capacity available in the large storages, it can be used to balance the power peaks during the increased demand during the busiest hours. [21]

Compressed air storage or **CAES** is quite like the pumped-hydro storage, the difference is that the energy is stored as compressed air. Basic principle is that a compressor is ran when network is in its non-peak usage and the air is compressed into a large container, usually build in some sort of cave that has been repurposed to be as a compressed air storage and then when need for the stored electricity arises the compressed air is ran through a turbine attached to a generator and the compressed air can be converted to electricity again. [19,21]

When the compression happens, the air warms up during the process according to the basic thermodynamics. Also, as gasses warm up, the density drops, so that is why the air needs to be cooled down to use the storage space most efficiently. Therefore, CAES storages have intercooler circuit for the air to cool down after the compression. Air is compressed to about 75 bars, which means that quite a lot of cooling is required. [19]

The reverse procedure, meaning that when the compressed air is decompressed, the air gets cooler according to the basic thermodynamics. Temperature can drop too low and be harmful for the components in the system, so the air needs to be heated during the decompression procedure. Generally, the heating is done by pre-heating the air from the exhaust gasses produced by the combustion chamber and then injecting small amount of fuel to the air to make fuel-air mixture that is fed to the combustion chamber. This fuel-air mixture is burnt in the combustion chamber and the expanding of the gas turns the turbine attached to the generator. [19]

Ideal gas law [19,21] can be written as:

$$PV = nRT \tag{52}$$

where the P is the absolute pressure, V is the volume, n is the total amount of gas moles, R is the Boltzmann constant, and the T is the temperature of the gas. [19] This can be used to form the equation [19] that gives the theoretical maximum energy stored in the storage

$$W_{AB} = nRTln\left(\frac{p_A}{p_B}\right) \tag{53}$$

where the W_{AB} is the work performed during the isothermal process, from state A to B i.e., from compressed to decompressed. And the $p_A \,\&\, p_B$ are the different state pressures. [19]

In practise there are losses in the system, meaning that the maximum energy is slightly less than the equation theoretically gives. The efficiency of the CAES storages is approximated to be around 27-70 % [20].

Flywheel differs from the two earlier methods, as the energy is not stored into any volume of something rather than it is stored into the energy of a spinning object. Everyday example usage of flywheels can be found in gearbox assemblies in various motorised vehicles. Typical flywheel has few main components including flywheels rotating disk, bearings each side of the shaft, nowadays singular electrical motor/generator and power electronics converters that are used as bi-directional way for the electricity between the storage and the grid. [19] Flywheel's energy capacity is directly proportional to the speed difference between the maximum and minimum angular velocity values [22].

Basic principle according to physics is that the energy is stored as rotational kinetic energy to the flywheel. The basic equation for the rotational kinetic energy [19,22] can be given as

$$E = \frac{J\omega^2}{2} \tag{54}$$

where E is the rotational kinetic energy, J is moment of inertia and ω is the angular velocity. This gives the theoretical maximum energy stored into the rotational mass in the flywheel. As can be deduced from the (54), increasing the angular velocity, which is squared in the equation, is more effective in increasing the theoretical maximum energy stored to the system than increasing the mass of the flywheel. However, increasing the speed of the flywheel increased the frequency of the generated electricity, which is a problem if the power needs to be fed back to the grid. This however can be mitigated by various power conversions utilizing power electronics. [19]

As in everything, there are losses in the system, so in practice the maximum energy is slightly lower than the theoretical maximum value. Major losses in the system comes from the friction losses from the bearings, losses in the electrical motor/generator, the power conversion and form the wind shear that happens when the flywheel rotates. To minimize losses in the system, advanced modern magnetic bearings are used to minimize the friction losses and the flywheel is built into a vacuum, so that the flywheel can spin more freely. There are also modern lightweight materials available to make the flywheel lighter and more robust at the same time. [22]

Flywheel is mostly used as short-term energy storage since the decay of the stored energy can be nearly 20% of the capacity per hour. However, the decay may be high, but the overall efficiency is high, around 90% when operating at its rated power. This means that it is useful as a temporary storage for specific applications, rather than a long-term failsafe storage like pumped hydro for example. Flywheels can be used in various application in the power industry, for example flywheels are being used in some windmill and solar energy plants to compensate the fluctuating power generation of these plants. [19,22]

Capacitor or **supercapacitor** is a short-term energy storage, usually measured in seconds or minutes. Capacitor has positive and negative terminals, and a dielectric material that spits the two terminals. When an electrical potential difference is applied to these two terminals, an electric field appears between the materials, this causes positive and negative charges to gather around their designed terminals, thus increasing the energy stored in the electrical field. [20,21]

Equation for energy stored in a capacitor comes out as the following [21]

$$W_C = \frac{1}{2}\epsilon A \frac{V^2}{d} \tag{55}$$

where ϵ is the permittivity, A is the area of the terminal plates, d is the distance between the two terminals and V is the applied voltage. Permittivity can be further explained as (56) [21]

$$\epsilon = \epsilon_r \epsilon_0 \tag{56}$$

where ϵ_r is the relative permittivity of the material and $\epsilon_0 = 8.854\ x\ 10^{-12}\frac{F}{m}$ is the permittivity of a vacuum. [21]

Capacitors generally have high amount of cycle lives, which makes them good for applications where kind of frequent use is needed, but due to the low energy density they are only sufficient on supplying short bursts of electricity. [20]

Electromagnets or **superconductors** can be used to store the electricity in a magnetic field and can usually hold much more energy when comparing the size to a capacitor. Equation for energy stored in a magnetic field can be given as following [21]

$$W_M = \frac{1}{2}\mu H^2 \tag{57}$$

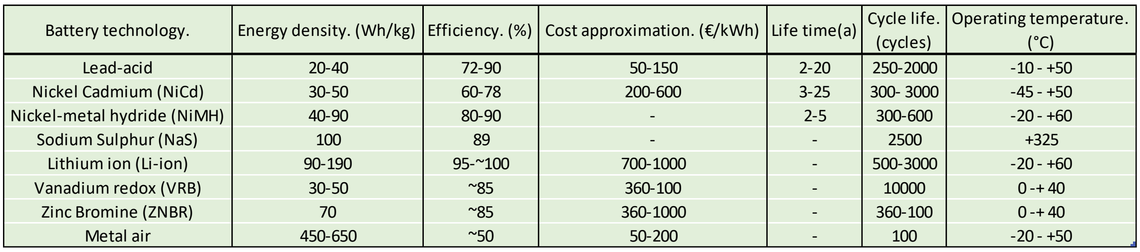
where H is the magnetic field intensity and μ is the permeability. Permeability can be further explained as [21]

$$\mu = \mu_r \mu_0 \tag{58}$$

where μ_r is relative permeability and $\mu_0 = 1.257\ x\ 10^{-6}$ is a permeability of a vacuum. Like a capacitor, the energy stored in a magnetic field is suitable only for supplying electricity only for a short period at a time but can withstand multiple cycles during their lifetime. [21]

Battery storages are a way of storing energy in an electrochemical form. There are various materials that are suitable for battery operation, each have their own characteristics and desired applications. First battery needs to be charged, which requires specific type of charging to be most efficient on each battery type. Charging stores the energy in an electrochemical form, which then can be discharged when needed by reversing the reaction. Basically, electrochemical cells enable the flow of electrons between the two terminals, which then translates to electrical current. Battery storages are suitable for various applications in various sizes, since they can be sized accordingly, thus making them viable for short and long-term applications. Batteries are also highly efficient, which makes them a good choice for long-term use. However, some materials have a limited cycle life, which means that batteries need to be replaced from time to time. [20,21]

Figure below contains a table of different battery technologies, including material, capacity range, efficiency, cost, cycle life and operating temperature. Figure data is gathered from [21,23]



Battery technology.	Energy density. (Wh/kg)	Efficiency. (%)	Cost approximation. (€/kWh)	Life time(a)	Cycle life. (cycles)	Operating temperature. (°C)
Lead-acid	20-40	72-90	50-150	2-20	250-2000	-10 - +50
Nickel Cadmium (NiCd)	30-50	60-78	200-600	3-25	300- 3000	-45 - +50
Nickel-metal hydride (NiMH)	40-90	80-90	-	2-5	300-600	-20 - +60
Sodium Sulphur (NaS)	100	89	-	-	2500	+325
Lithium ion (Li-ion)	90-190	95-~100	700-1000	-	500-3000	-20 - +60
Vanadium redox (VRB)	30-50	~85	360-100	-	10000	0 -+ 40
Zinc Bromine (ZNBR)	70	~85	360-1000	-	360-100	0 -+ 40
Metal air	450-650	~50	50-200	-	100	-20 - +50

Figure 3. Table containing different battery technology characteristics.

Figure above describes the common battery technologies with their characteristics. Brief description of each technology is given next, starting from top to bottom.

Lead-acid battery is really matured technology and it has two viable types, it has lead dioxide in the positive side and sponge lead on the negative side. Flooded lead-acid type uses sulphuric acid solution and during discharge the lead dioxide on the positive terminal reacts with the sulphuric acid forming lead sulphate and negative terminal is oxidized to lead ions also reacting with the sulphuric acid. Second type is a valve regulated (VRLA) lead-acid type, which use the same basic operation principle as the flooded type, but VRLA has a pressure regulation valve and a sealed structure. VRLA does not require any electrolyte filling. [23]

Nickel-cadmium battery is also matured technology and has been around for decades. It has sufficient lifetime and cycle life for many applications. Electrolyte is potassium hydroxide (KOH), which changes its concentration or density depending on whether it is charged or discharged. These batteries are always sealed. Even though, NiCd batteries seem suitable for multiple applications, they are considered dangerous threat to the environment and are quite costly compared to lead-acid batteries, so they are not that desirable in most applications. [21,23]

Nickel-metal hydride (NiMH) has NiOOH in the positive terminal in its charged state and hydrogen on its negative terminal. When oxygen is transported from the positive to the negative terminal during operation, it recombines with the hydrogen and forms water. Due to better characteristics of these NiMH batteries, they replace NiCd batteries in portable applications, but they are even more expensive than NiCd, so they are not suitable for all applications because of this. [21,23]

Sodium sulphur (NaS) is a “molten salt” battery, positive electrode has molten sulphur and negative electrode has molten sodium and electrodes are separated with a solid beta alumina ceramic electrolyte. When electricity is discharged from the battery, sodium ions from negative electrode flow through the electrolyte allowing electron flow in the external circuit. Temperature needs to be kept around 300 Celsius to battery to function properly. NaS is quite well characterized battery, but operating temperature is its major drawback, and that is why it is not suitable for that many applications, making it a less favourable choice for many. [23]

Lithium-ion (Li-ion) has been recently on of the most developed battery technology, it has advanced greatly in the few decades, mostly due to electric cars and mobile devices needing light weight batteries with dense energy densities and now a days this is the case, since nearly all portable devices rely on Li-ion battery technology. Li-ion cathode, i.e., the positive electrode is made of lithium-metal-oxide and anode, i.e., the negative electrode is some sort of graphite carbon with layered structure. There are several Li-ion configurations, which offer little different characteristics for the battery. Ultimately, Li-ion technology is the most promising in solving the issue with battery capacities being too small for example electric vehicles. However, there are drawbacks too, since Li-ion batteries are the most expensive ones of the list and have relatively small cycle lives. [21,23]

Vanadium redox (VRB) is a flow battery, which offers high power, long duration, fast response. But has lower efficiencies than the more traditional. Flow battery means that the electrolytes are circulated in the system when charging and discharging. When battery is not used, the electrolytes are stored separately, which mitigates the self-discharge nearly fully, since they cannot react with each other. Each VRB cell has vanadium redox couples, which are stored in a mild sulphuric acid solution. During the operation H+-ions are exchanged between the two electrolytes, which then allows the electric current to flow. [23]

Zinc bromine (ZnBr) is also a flow battery, where two different electrolytes flow through carbon-plastic electrodes. During charge, metallic zinc is plated into the carbon-plastic electrodes. [23]

Metal-air battery anode is high energy density metal, either aluminium or zinc, which when oxidised, releases electrons to the cathode, which is often porous carbon or some sort of metal-mesh structure. Metal-air batteries have great energy densities compared to other batteries, but cycle life is low, so they are not that suitable for most applications. [23]

There are various choices for battery energy storages to use in various applications, each having their desired applications. In the next chapter, we shall take a closer look into the battery energy storages that are suitable for distribution network storages, either as a back-up storage or as balancing the peak consuming hours.

2.3.2 Energy storages in the distribution network

Since smart grids are more common nowadays, distributed energy storages are also gaining more attraction, since they offer various advantages in technical, economical, and environmental fields. These advantages include various power quality improvements, cost reductions and less emission. This makes energy storage systems (ESS) a desirable investment in the distribution network. However, if ESSs are not planned properly, they can degrade the power quality, so a careful planning and modelling is required. [24]

There are various types of ESSs available, most of these were presented earlier in this chapter. To utilize the ESSs full potential a proper power conditioning is needed, which can be achieved with a proper power conversion unit or PCS. Depending on the type of the ESS, the power conditioning also varies, but the aim is to match the frequency, voltage, and current output as close as possible to the grid values, so that any disruptions to the quality can be mitigated. It is also crucial to consider that there are losses during charging and discharging when these are modelled, so that an accurate model can be created. Most ESSs also have specific self-discharge rates, which causes stored energy to be lost over time even when storages are not being used. Also, battery based ESSs require separate battery management system (BSM), so that the battery can be properly re- and discharged based on the type of the battery. [24-26]

Proper charging and discharging planning are required to get the most benefit of the ESS. This is to prevent charging during peak power hours and discharging when it is not necessary. This is called controlling the state of charge (SoC). Proper SoC needs to be maintained for each ESS depending on the type and appropriate strategies are required to mimic the manufacturer's instructions as closely as possible so that optimal efficiency and desired lifetime can be achieved. [24,26]

Certain ESS charging and discharging strategies are given in [24], which are designed specifically for ESS that are connected near renewable energy sources (RES), for example a PV or wind power systems. [24] We get the following equations

$$P_n^{IN} = \min\left\{(F_n^L - C_{RL}),\ P_{ESS}^{IN}, \frac{(E_{MAX} - E_{n-1})}{\Delta t}\right\} \tag{59}$$

$$P_n^{OUT} = \min\left\{(C_{RL} - F_n^L), P_{ESS}^{OUT}, \frac{E_{n-1} - E_{MIN}}{\Delta t}\right\} \tag{60}$$

where P_n^{IN} is the inputted power, P_n^{OUT} is discharged power, F_n^L is the power flow in the line, C_{RL} is the rated power capacity of the line, P_{ESS}^{IN} is the rated charge capacity, P_{ESS}^{OUT} is rated discharge capacity, E_{MAX} is the maximum limit of energy stored, E_{MIN} is the minimum limit of energy stored, E_n is energy stored in the current step, Δt is the step of the simulation. Each variable with an *n* as a subscript means that the value is at a specific step *n*. [24]

Based on the charging strategy in (59) the ESS will be charge only when there is additional power flow in the grid, i.e., it is above the rated value $(F_n^L - C_{RL}) > 0$ with the charge rate that is defined by P_{ESS}^{IN}. Discharging strategy in (60) is utilized when there is not enough flow in the grid, i.e., it is below the rated value $(F_n^L - C_{RL}) < 0$ with the discharge rate that is defined by P_{ESS}^{OUT}. These strategies are designed to help with the peak load shaving. [24]

With carefully planned placement, correct sizing and proper utilization of charging and discharging strategies positive results can be achieved. These are for example increased power and voltage qualities, especially during peak load situations, since production can be shifted more to the off-peak-hours when charging the ESSs and then during peak-load hours the productions does not need to be run on such high percentages. Also, ESSs allow better utility system reliability, they reduce power losses slightly and they can also relieve the distribution congestion. [24,26]

2.3.3 Usage of energy storage as a back-up feed

Usage of energy storages as a back-up feed has gained attention increasingly during the recent years. ESSs can be utilized for supporting the restoration after a full blackout or during other interruptions. The main advantages of these are that they improve the security, reliability, and power quality in the connected distribution network. Therefore, DSOs have increasingly added ESSs along their distribution networks due to their many advantages and conveniences. However, some electricity market rules are still strict about the ESSs usage but are evolving in preferable direction. [27]

Allowing ESS to be used in an island mode, i.e., ESS is feeding parts of the grids during an interruption or a blackout, will allow ESSs to be used to improve the restoration quality by keeping the balance between the demand and the supply of power or feed the part of the network as a back-up feed. Reference [28] proposes a restoration strategy which utilizes different type of ESS as a back-up feed for parts of the distribution network that are left out without power after a fault in the network. First, the strategy is to supply network islands by feeding them from distributed generation (DG), usually PV or wind power, and then considers power restoration with local ESS (LESs) or transportable ESS (TESS) combined with DG. TESS can be a truck containing ESS, that can be connected to a desired part of the grid. This presented optimization strategy tries to achieve an optimal combination of ESS usage combined with different energy sources, in a way that optimal load, balance and power constraints can be kept during and fault situation even though parts of the feeder is fed in an island mode. [27,28]

3. METHODS

In this chapter the methods applied in this work are presented; We start by presenting the MicroSCADA X DMS600 software family. . Introductions includes some functionalities, communication protocol and interface introductions. More detailed presentation is given for DMS600 NE, DMS600 WS and SYS600, listing some of their functionalities. Then the existing fault management functionalities of the DMS600 is presented and the development needs of how and why it needs to be improved. Lastly, we introduce the implementation part of the thesis, where we first present the customer requirements and expected benefits for the functionality, then the functional requirements and lastly, the description of the implementation containing class diagrams and flow charts to visualize the implementations better. To close out the chapter, we present the future development needs introducing some of the modifications that needs to be done to the functionality for it to be more effective, but these are outside of the scope of this thesis and will be implemented later.

3.1 MicroSCADA X DMS600

MicroSCADA X DMS600 is the software family that Hitachi Energy Finland Oy is currently developing. There are multiple branches in the whole family, but in this chapter a more detailed look is taken into the DMS600 side of things, because the implementation is made for the DMS600 software. DMS600 can be further divided into two software, the Network editor, or NE and workstation or WS. Since FLIR implementation was mostly done to the WS side, it is covered in more detail, including existing fault handling and related features. Family also includes the SYS600, which handles SCADA communication and operates as its interface. SYS600 also contains various features which are covered later in this chapter, but one of the focus points is the sequencer feature, which is used at least in the first phase of the FLIR functionality. DMS is shortened from distribution network management system and DMS600 is a geographical presentation of the distribution network, which provides distribution network data as an accurate representation as geographical network view. Software provides network component data management and modeling and gives an overview of the whole network with topological coloring. DMS600 can be used in tandem with a SCADA software or without one by utilizing OPC Data Access interface. DMS600 can be customized according to customer needs, by choosing different optional modules for it. DMS600 utilizes SQL database for storing and reading the stored data. In addition to these programs, there are multiple background processes that have their own desired purposes. [29]

For a proper operation, proper communication between the programs is needed. DMS600 utilizes three different communication interfaces. These are visualized in the figure below. Information for the figure is gathered from [29].

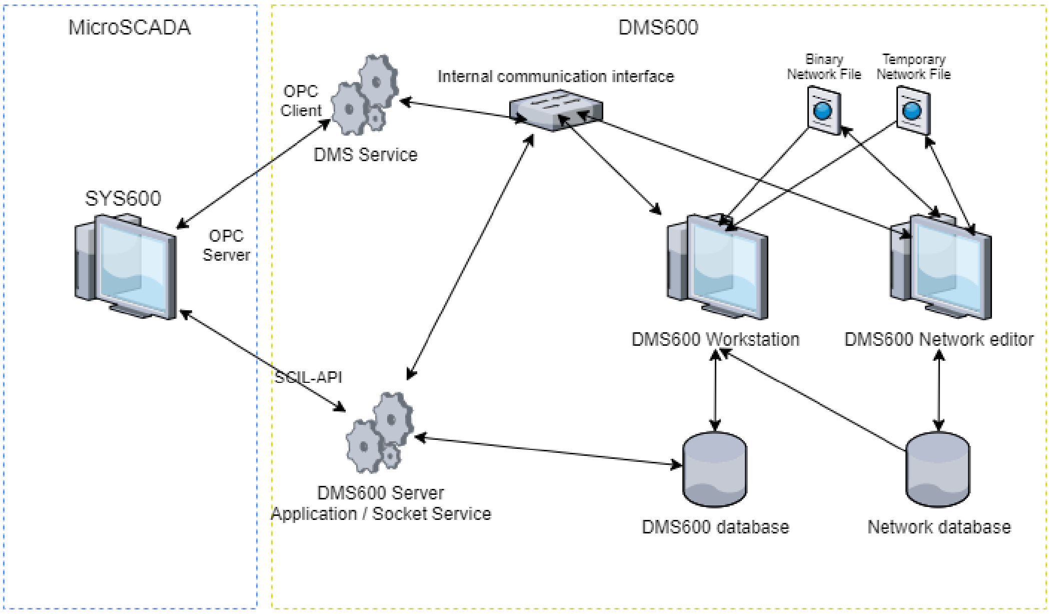


Figure 4. Communication and database interface of MicroSCADA DMS600.

Figure above shows the communication interfaces and their relations. Background services communicate with SYS600 via OPC connection and with SCIL-API. DMS600 has built in internal communication interface which handles the internal communication between the instances and other modules. Figure includes also the database interface of the DMS-side, which includes both databases and binary network files. Binary network file contains the data of the whole network, including the nodes and node-sections for example. Binary network data can be generated using NE.

3.1.1 DMS600 Network editor

Network editor or usually shortened as just NE is mainly used for generating the distribution network model, which is then saved to the network database in the primary fileserver and can be generated to a binary network file for WS to use. NE works also as an administrator tool for the whole DMS software package, since it is used for various configurations and settings. DMS can handle both medium and low voltage network modelling, meaning it can be used to generate the network from the feeding substation to the consumers. NE is also used for background map initialization, various symbol definitions, network model binary file generations and other configurations for the communication between the MicroSCADA and DMS600 software. Figure below shows the overview of the NE. [29]

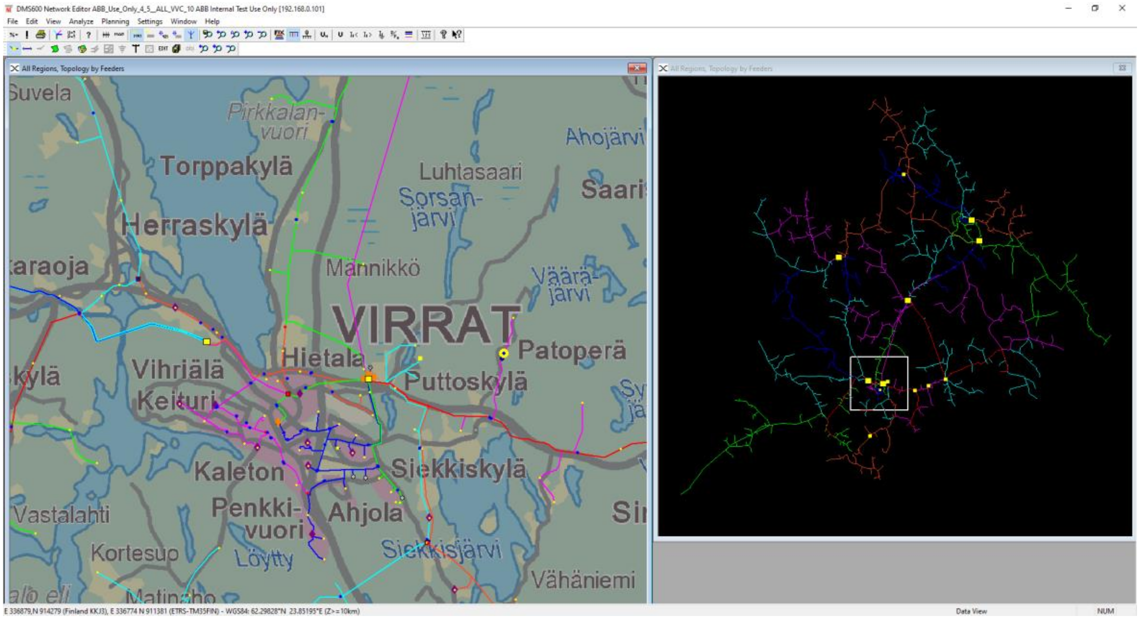


Figure 5. Overview of the DMS600 NE interface.

As can be seen from the figure above, the software offers various options and configurations for the user, including network node and node section editing, various components, including circuit breakers, disconnectors, fuses and much more. These various components and network models can be configured individually so that the network model can be kept accurate as possible. User can pan and zoom the network to their liking and design and modify the network to their liking accurately. It is possible to integrate satellite images to the background images for more accurate designing. NE also has possibility to create different type of network models, including for example a radial, schematic, semi-schematic or connecting lines views.

3.1.2 DMS600 Workstation

Workstation, usually shortened as WS is the tool that the operators mainly use for overviewing the whole distribution network. WS allows the users to monitor and operate the network basically in real time, since state of switches and such are obtained via socket communication. WS has topological colouring of the network, which shows the user whether the network is electrified or not. Different colouring options are also available, for example feeder based, main transformer based and few more specific options. Figure below gives and overview of the WS interface.

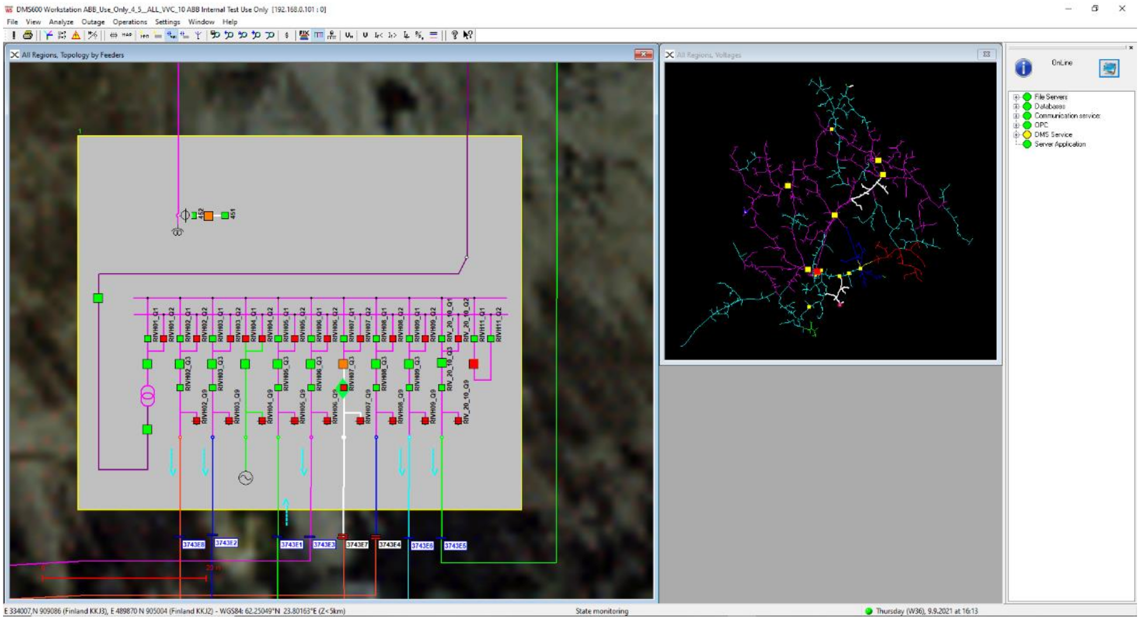
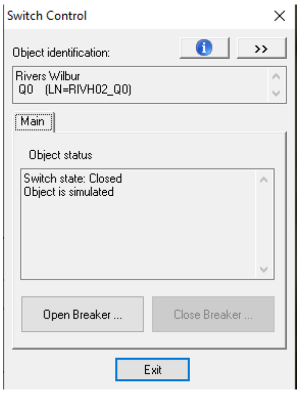


Figure 6. Overview of the DMS600 WS interface.

Figure above has an overview of the DMS600 WS interface. As can be seen WS has two different main views just like NE that was described earlier. Network window on the left is the one that is used as more accurate monitoring and operations, since user can pan and zoom it freely. When user selects a component from the network view, a component specific dialog is opened, which then shows the stored data for each component accordingly. Helpful symbol and colour legend dialogs can be separately opened, which helps the user identifying different components in the view and differentiates what the different colours mean. Colouring is utilized in network colouring and for switch states, alarms and so on. Background symbols also differentiate different statuses of the components. These are all described in the symbol legend dialog. One the right side of the overview, there the connectivity status bar, which tells the user whether the important background processes are running correctly. [29]

When a switch is clicked on the network view a control dialog is opened. Dialog opened depends on whether the switch is remote controlled or not and whether there is a SCADA connection available. Following figures are for remote and manually controlled switches.

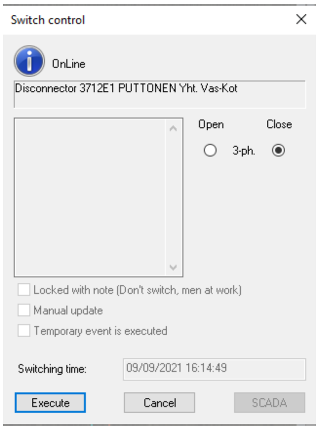


Object identification:
Rivers Wilbur
Q0 (LN=RIVH02_Q0)

Switch state: Closed
Object is simulated

Figure 7. Switch control dialog for remote controlled SCADA switches.

Figure above has the control dialog for remote controlled SCADA switches, it contains the switch specific information and status. Also, warnings about switch state are given if there is some error present. If user presses Open breaker button, an open command is sent to SCADA which then sends it further to the physical switch via communication protocols and if there are no error in the communication the switch should open almost in real time. There are communication delays in the real-world applications as always.



OnLine
Disconnector 3712E1 PUTTONEN Yht. Vas-Kot

Open ○ 3-ph. ● Close

☐ Locked with note (Don't switch, men at work)
☐ Manual update
☐ Temporary event is executed

Switching time: 09/09/2021 16:14:49

Figure 8. Switch control dialog for manually controlled switches.

Figure above has the control dialog for manually controlled switches which are not remote controlled. These can be used to keep the state of the network up to date manually.

Dialog also contains the information and it also can be used to set switches in to forced manual and locked states. Switching can be done with different ways, either from SCADA, which updates the status in the WS also, or manually using the dialogs in the figures above or operators can schedule switching operations by creating switching plans using manual or remote switches, this plan can then be given out to ground operating work crew and then updated manually to the network.

WS also has various other functionalities which include the following [29]

- Alarming
- Fault management, with fault location calculations based on fault current and fault detector data
- Restoration
- Switching planning
- Fault and outage reporting and management
- Field crew management
- Load estimation and overviewing
- Customer service, including calls received and such reports.
- Documenting, including printing, archiving and notes.

Some of these functionalities are behind a specific license that DSOs need to order for them to be active, but most basic functionalities are included in the basic license.

3.1.3 SYS600

MircoSCADA X SYS600 is the SCADA interface of the software package. It offers various functionalities regarding communication, control, and analysis of the distribution network. Program has several displays and smaller applications, which can be used to monitor and control the distribution network. Figure below contains the process display; it contains substation diagrams and their simplified connections. [30]

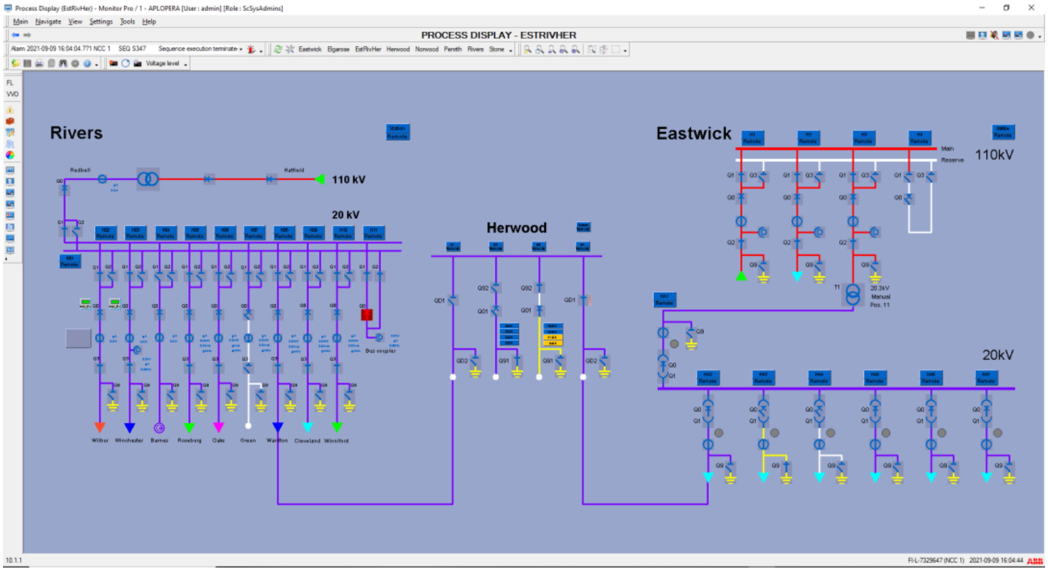
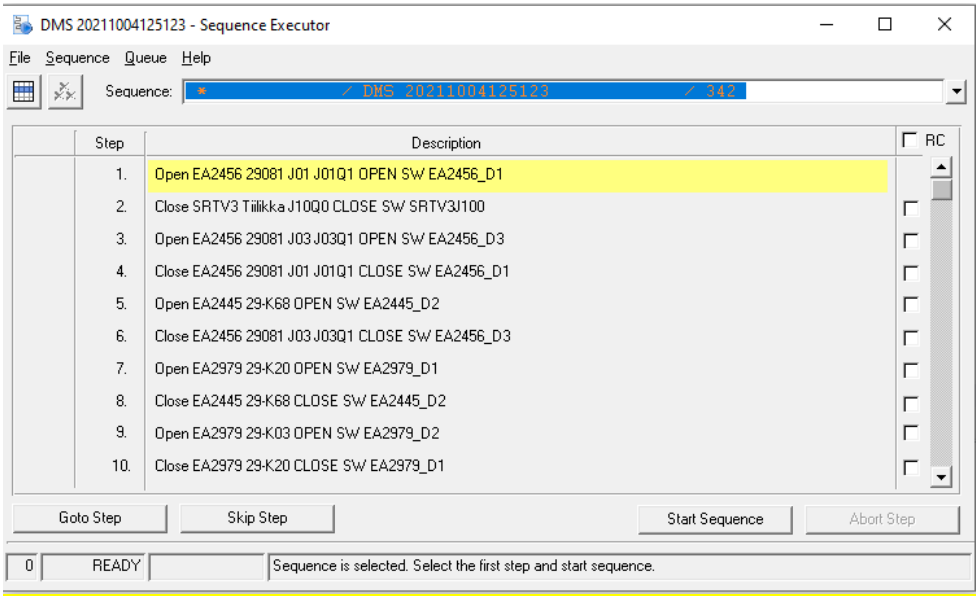


Figure 9. Overview of the SYS600 process display interface.

User can operate the remote-controlled switches from the SYS600 process display, which opens same dialog that is shown in Figure 7. It also shows possible alarms, locked states, faults and more. SYS600 contains also many other built-in processes and procedures, one of which is the SYS600 sequencer. The sequencer is being used in the first phase of implementation of the FLIR, since it is used for checking and running the generated sequences by DMS600 FLIR instance. Figure below shows the sequencer with a FLIR isolation sequence.



Sequence: * / DMS 20211004125123 / 342

Step	Description	☐ RC
1.	Open EA2456 29081 J01 J01Q1 OPEN SW EA2456_D1	
2.	Close SRTV3 Tiilikka J10Q0 CLOSE SW SRTV3J100	☐
3.	Open EA2456 29081 J03 J03Q1 OPEN SW EA2456_D3	☐
4.	Close EA2456 29081 J01 J01Q1 CLOSE SW EA2456_D1	☐
5.	Open EA2445 29-K68 OPEN SW EA2445_D2	☐
6.	Close EA2456 29081 J03 J03Q1 CLOSE SW EA2456_D3	☐
7.	Open EA2979 29-K20 OPEN SW EA2979_D1	☐
8.	Close EA2445 29-K68 CLOSE SW EA2445_D2	☐
9.	Open EA2979 29-K03 OPEN SW EA2979_D2	☐
10.	Close EA2979 29-K20 CLOSE SW EA2979_D1	☐

0 READY

Sequence is selected. Select the first step and start sequence.

Figure 10. SYS600 Sequencer interface.

Figure above shows the interface for the SYS600 Sequencer functionality, where a FLIR isolation sequence has been inputted by WS. This interface can also be used when checking the sequences that the FLIR WS generates for each fault but use of this is not necessary when operating the functionality normally. In this example, there is an isolation switching inputted to the sequencer, which would be operated step by step, so that the faulty remote zone can be located from the feeder. This requires constant communication between the sequencer and WS. This is one of the reasons why this type of automatic operation might be kind of slow from time to time. Major drawback of the sequencer is that only one sequence can be operated on, thus preventing parallel operations.

3.2 Fault management in DMS600

DMS600 workstation can be utilized in fault management. Faults will be noticed from the physical network when for example the feeding circuit breaker trips from the feeding station and part of the feeding network is de-energized as a result. This triggers a set of events that in the end notifies the DMS600 WS to create a new fault ticket for the operators to see, also updating the network status to correspond the real-life situation.

For there to be a fault there must be an event for the tripping that can then be handled by SCADA. Various protection units can be used to generate the tripped message, this is then sent to MicroSCADA for further processing. Event is saved to the process database, which is then checked by SCADA and set of command procedures are run that's purpose is to collect the fault and possible reclosing data. Collected data is then sent to DMS background service called DMS600 SA. DMS600 SA service takes a snapshot of the fault and reclosing data, which is then saved to the DMS600 database. Socket message is then sent to all current DMS600 WS instances, thus notifying them that there is a new fault in the network. DMS600 WS then reacts to this new fault by reading the fault data and performing the fault locations algorithms. Finally, the new fault is then created for the users to see in the fault management dialog. [29]

Fault locations algorithm utilizes various variables for the calculations. These are the following:

- Measured fault current, either short-circuit or an earth-fault current.
- Impedance or reactance between the relay and the fault location.
- Type of the fault, either 2- or 3-phase short circuit or a 1- or 2-phase earth fault.
- Measured feeder load moments before the fault.

Short-circuit currents can be measured from the protection terminal of the faulty feeder or directly from the busbar protection. [29]

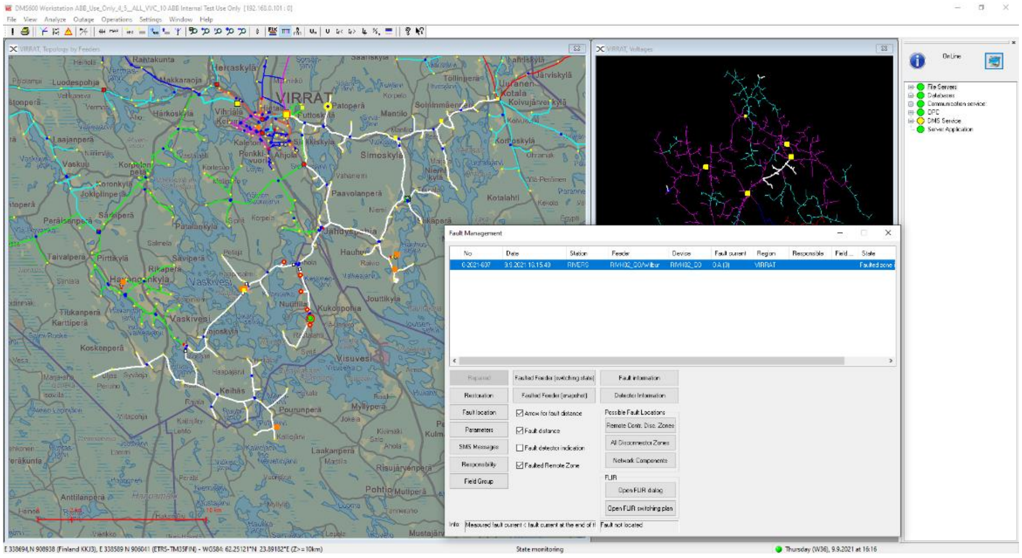
3.2.1 Existing fault management functionality in DMS600 Workstation

Fault management functionality main purpose is to help the operator in dealing with fault situations in the distribution network. It visualizes the fault situation in the geographical presentation and gives the fault data for the operator to overseer. Operator can then either deduce the fault location using calculated fault locations by the algorithm if there was enough data available or manually by trial and error using their own knowledge. Existing functionality allows management for multiple simultaneous faults. The main fault management functionalities are the following: [31]

- Visual geographical and data presentation.
- Fault location calculations and visualization.
- Option to configure GSM messaging to customers.
- Planning fault isolation and restoration switching.
- Isolation and restoration switching execution.
- Fault reporting and archiving.

These functionalities are mainly for managing the MV-network, but an LV-network fault management is also possible, even though it is not automized and must be done manually by operators. [31]

Upon WS obtains a new fault ticket from the SA service, the fault management dialog is opened for operators to see. Figure below shows the interface with an active fault.



No	Date	Station	Feeder	Device	Fault current	Region	Responsible	Field ...	State
0-2021-607	9.9.2021 16.15.40	RIVERS	RIVH02_GO/Wilbur	RIVH02_DO	0 A (3)	VIRRAT			Faulted zone

☑ Arrow for fault distance
☑ Fault distance
☐ Fault detector indication
☑ Faulted Remote Zone

Info: Measured fault current < fault current at the end of t
Fault not located

State monitoring
Thursday (W36), 9.9.2021 at 16:16

Figure 11. DMS600 WS interface with an active fault.

As can be seen from the figure above, fault management dialog is opened, thus operators notice that there is a new fault situation present in the distribution network. Depending on the settings, the fault can be automatically zoomed to the main view so the operator can quickly see which part of the distribution network is affected. White colour in the topological colouring tells which parts of the network is de-energized for the fault. There also are different fault colouring options available.

Existing fault management functionality allows the users to set the WS instance to automatic fault isolation and restoration mode, which tries to deduce the fault locations by utilizing fault location calculations. If fault can be definitely located for a single specific zone, in a way that it is in configurable parameters, the automatic isolation is started automatically for the fault in question. Automatic isolation sequence is then generated for the specific remote-controlled zone or RCZ, then it is sent for execution to SCADA. SCADA then performs checks for the selected switches and returns check results back to DMS. If all checks are ok, then the automatic isolation is started. If all goes as planned, the faulty RCZ is isolated from the rest of the network and restoration sequence can be then generated for possible back-up connections. Restoration sequence goes through the same checks as the isolations went and then electricity is restored to the rest of the network before and after the faulty RCZ. Resulting situation is that the fault is isolated in the specific RCZ and rest of the customers along the feeder are electrified. If automatic instance is not running, the functionality can also be used to generate the isolation and restoration sequences manually by using it from the fault management dialog. However, if fault location is inconclusive for some reason, fault current could not be measured or there are no fault detectors installed in the feeder, the fault location logic cannot deduce the location, thus the automatic isolation is not possible. [31]

3.2.2 Development needs of the fault management functionality

As stated earlier, when automatic isolation and restoration mode is enabled and new fault with insufficient fault location data is acquired, the current implementation cannot deduce the fault location in the network. In practice the current functionality functions only in the simplest of cases, when the fault location can be defined only in one specific RCZ. Thus, a need for more advanced methods appears. This is the reason more advanced version of the fault location, isolation, and restoration (FLIR) functionality is needed to be developed. Fault cases where the fault information is not definitive is common, thus the existing logic does not even try to isolate the fault, thus rendering it less useful than it could be. Therefore, trial switching utilization is needed for more reliable isolation and restoration. Which is one of the main reasons that this master's thesis was done on the subject, since large part of the thesis was developing the FLIR functionality that utilizes the trial switching logic for faults in the distribution network.

Scope of this thesis was to implement robust FLIR trial switching functionality with good configurability. Idea is to get it through most of the simplest fault situations and help the operators handle them. In the future, more advanced features shall be added, which include parallel isolation and restoration, more complex usage of fault pre-conditions and more optimizations for isolation and restoration sequences. These future development needs are presented later in this thesis.

3.3 Automatic FLIR with trial switching

In this chapter a detailed view of the implemented automatized fault location, isolation, and restoration functionality (FLIR) is given. Several customers around Finland were interviewed by Jussi-Pekka Lalli for his master's thesis [32], where he gathered information about the requirements and the expected benefits for the automatic FLIR functionality with trial switching.

This gathered information was used to create the separate functional specification document that specifies most of the interfaces and functionalities for the software implementation. This chapter will consist of the requirements and expected benefits that the customers aim to benefit from, the somewhat shortened functional specifications that were specified in the separate document, description of implementation that will contain the how and why the software was developed such way and lastly the test results from the implemented functionality and the future development needs.

Fault location is deduced by trial-and-error method, thus the name trial switching. Algorithmic switching logic needs to be developed, so that these trial switching sequences can be created to different feeders automatically without the need of a human operator. This also makes the fault isolations and restoration quicker, but also relieves the work burden of the operators in situations when there are multiple simultaneous faults active.

Implementation of this functionality was made to the DMS600 software family, more specifically to the workstation or WS. Most of the work was done using C++ language and, in the end, it resulted in tens of thousands of new lines of code to get this to work as intended. There were a lot of new additional dialogs added to the existing software, including new interfaces for the configurations, FLIR specific settings, new management dialog to easily overseer the FLIR operations, FLIR switching plan dialogs and more. Sequence generation logic and its handling was also implemented along the way. Some additions to the socket communication were made, for internal FLIR communication.

3.3.1 Customer requirements and expected benefits

Jussi-Pekka Lalli conducted DSO interviews about the requirements and expected benefits that were used as the basis of this FLIR project and collected them in his own thesis. By using the data gathered from these interviews, the functionality got general borderlines for the implementation. This chapter will cover over the main points of those interviews.

Since we are dealing with automation that switches physical devices on and off, that have high voltage and current running through them, it is essential that safety is considered every step of the way, so that nothing dangerous can be done by the automation. This was one of the main points that was pointed out by the DSOs during the interviews. It was crucial that FLIR does not do anything that it has not been configured to do, so in the interviews it was pointed out that it should be easily configurable which feeders are selected for FLIR operation also including different configurations for these feeders, including for example back-up usage. These configurations ensure that the FLIR does not operate on feeders that are not suitable. For example, if most of the feeder is underground cable network, the trial switching could stress it too much or feeder can have an essential customer which should not experience multiple interruptions in short time span, like for example a hospital. [32]

Even though safety is highly prioritized, the FLIR can operate independently when all configurations have been done correctly. Interviewed DSOs pointed out that automation should be able to operate independently without disrupting the situational awareness of the network. In other words, the automation should not disrupt the work of the operators that are handling the faults in parallel with the FLIR functionality. This creates a requirement of its own, meaning that developed software should not cause too much disturbance to normal use of the product for other users. Also, since network can be operated simultaneously from multiple open instances, it is sufficient that user is notified if FLIR has reserved certain switches for its operations. Thus, it should be prevented that operator would operate the same switches that the automation without noticing it and causing a possible safety issue. [32]

When switching is done remotely to RCDs, there is always varying delay in the real world, since communication can have lengthy delays especially in rural feeders where the RCDs are located far away from the feeding station. According to the interviews communication delay may vary between 2-30s before status indication can be interpreted. Therefore, DSOs stated that the automation should not give right up if successful connection was not achieved straight away. Also, if for some reason switching device is in some sort of abnormal state, the automation should abort the operation and it should be handled back to operator, so that electrical safety is not compromised. [32]

In conclusion, requirements that were gathered from the DSOs via the interviews emphasized heavily on safety and configurability, so that nothing that isn’t desired is done by the automation and for safety reason, operation should be disabled as default for all configurable feeders and feeding stations. This gives out the general borderline for the implementation, which is that safety is prioritized as much as possible.

During the interviews, DSOs also pointed out their desired expectations regarding to FLIR functionality. Mainly it was expected that FLIR could perform trial switching, with little pre-data of the fault, meaning that it should perform trial switching whether fault current is available or not. This was one of the main issues regarding the existing fault handling functionality, since it would often fail to interpret the definite fault location and it would fail to do anything, so this is one of the core features that this new FLIR functionality offers. [32]

DSOs also pointed out that in the first implementation the FLIR should focus on operating reliably on the simpler fault cases rather than try to cover all more difficult cases. These can be left for the operators to handle. More advanced handling can be implemented later when general operation is verified to be robust. It should also be possible for FLIR to handle multiple feeding stations at the same time. [32]

4. IMPLEMENTATION

FLIR functionality was implemented with mainly using C++-code added to the existing DMS600 software. There were multiple new additions to the software functionalities, including new dialogs, additions to socket communication, switching sequence generation and execution logic and much more. This chapter is going to cover the implementation and open it up how and why it was implemented in a way it was.

DMS600 already had an implementation for more basic automatic fault handling functionality, but it had major drawbacks and could usually only point out the faulty zone in the most basic cases. This was an issue for most of the DSOs that have used it, since it was unable to locate most the faults. There was a need for a functionality that can determine the faulty location by trial and error-based method. Which is where the current FLIR implementation comes in. Parts of the already existing method was used in the current implementation and a good basis could be formed out of it, but most of the implementation needed to be done from a scratch.

4.1 Description of implementation

So that a good idea of how the whole process works can be obtained, a process flowchart is a good way to illustrate it. In the figure below, FLIR process flowchart is introduced. Flowchart tries to illustrate the operation process generally as best as possible including sequence generation and communication between SYS600 sequencer.

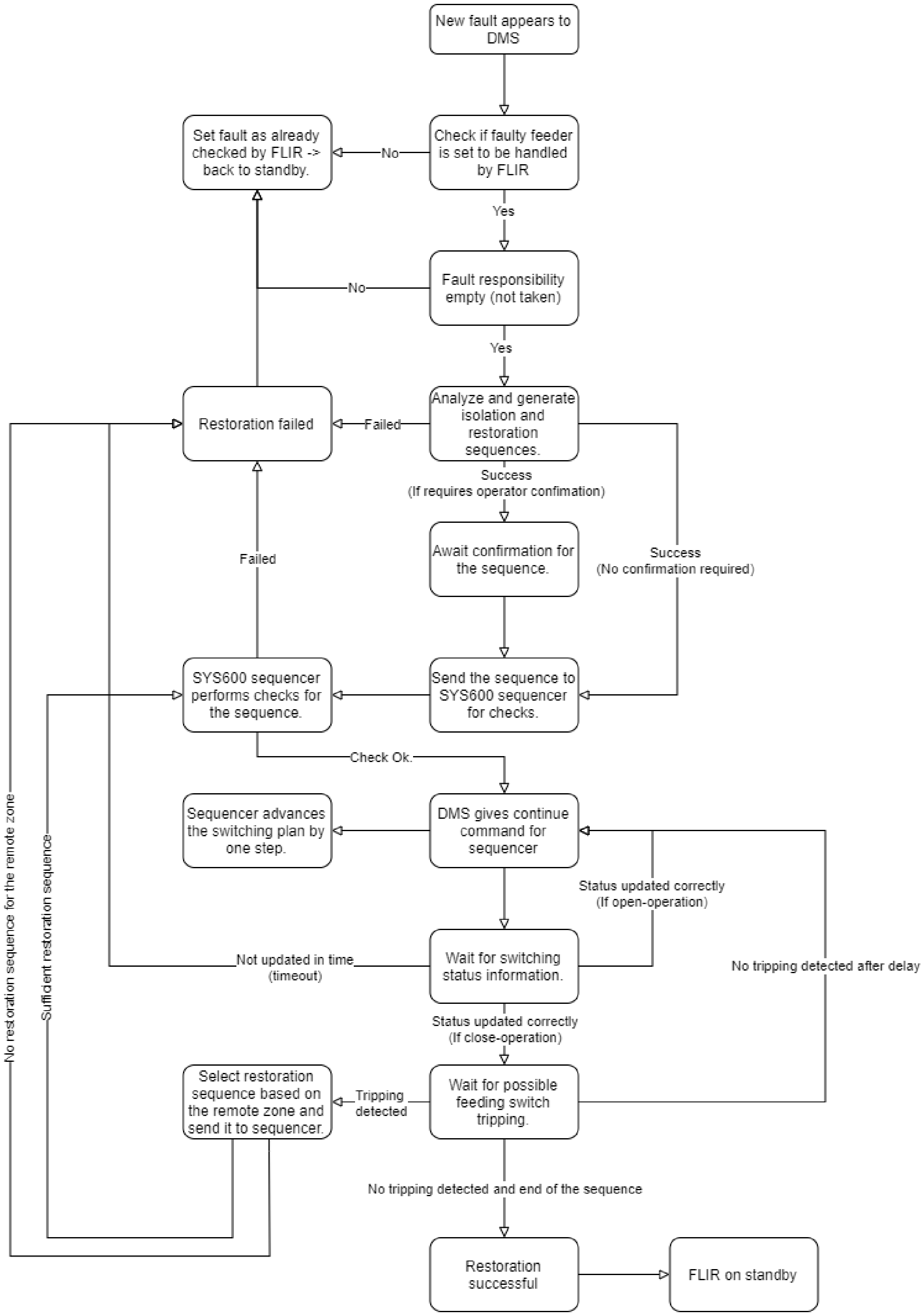


Figure 12. FLIR process flowchart.

Figure 12 illustrates the flowchart of the FLIR operation process. There are various checks that need to be done before switching can be executed. As a new fault-package appears to DMS, FLIR WS instance will check if faulty feeder is configured to be under FLIR operations and that the responsibility has not been taken yet by anyone. If these checks are passed, FLIR will start generating the isolation and restoration sequences for the fault, by first analysing the fed network, then generating sufficient sequences for isolation and restoration. If sequence could be generated without any issue, FLIR WS will proceed to the next phase of operation, which depends on which mode it is configured to run. If confirmation is required, FLIR WS will wait for operator to confirm the sequence before sending it to the SYS600 sequencer. If automatic mode is used, no confirmation is needed, and this step can be skipped. FLIR WS sends the generated sequence to SYS600 sequencer as a SCIL-script, which needs to be checked first. All switching devices will be checked for controllability and the result will then be sent back to FLIR WS. If all the checks were ok, FLIR WS will then send a continue command for SYS600 sequencer to proceed the plan by one step. Each step is then monitored by FLIR WS, by first waiting that the status information of the operated switch updates correctly and then proceeding accordingly. If switch operation is opening, there is no need to wait for the feeding switch tripping, so a new continue command can be sent straight away when the status information is received. If switching operation is closing, FLIR WS will need to wait for a configurable time for the feeding switch trip. If trip happens during that time, FLIR WS will deduce that the fault must be in the remote zone that was just closed on the last step and will send restoration sequence for the SYS600 sequencer, if a suitable one has been generated. Restoration sequence will have the same controllability checks done for it and FLIR WS will handle it the same way as isolation sequence. If either isolation or restoration sequence is managed go to the end without detecting tripping, it can be assumed that the restoration has been successful. FLIR WS will then go back to standby mode and either select a new fault from the fault list or wait for new faults to appear.

Implementation consists of few bigger classes that handle the management, communication, settings and sequence creation and execution. The image below contains a class diagram that shows the relations between the classes and some of the memory variables and methods that the classes have. Most of the not so important variables and methods are redacted to make the class diagram more compact.

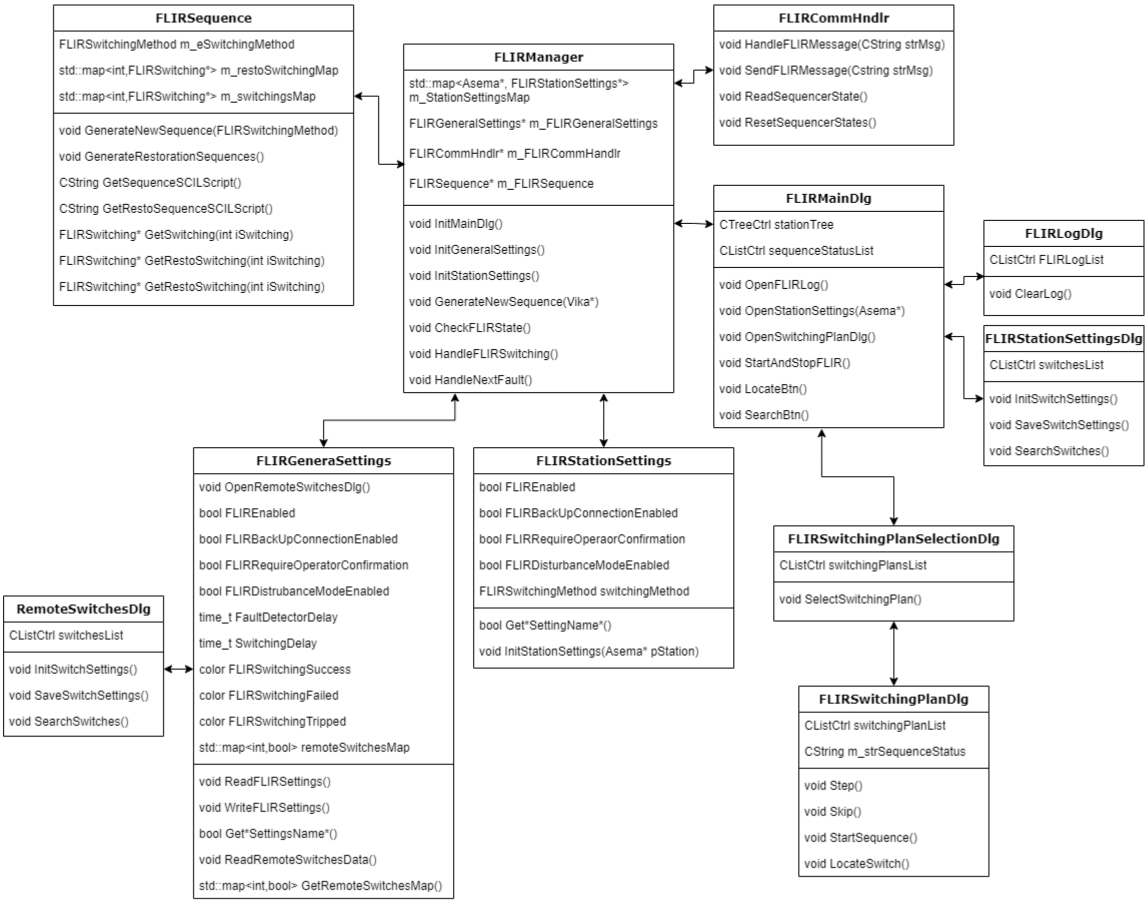
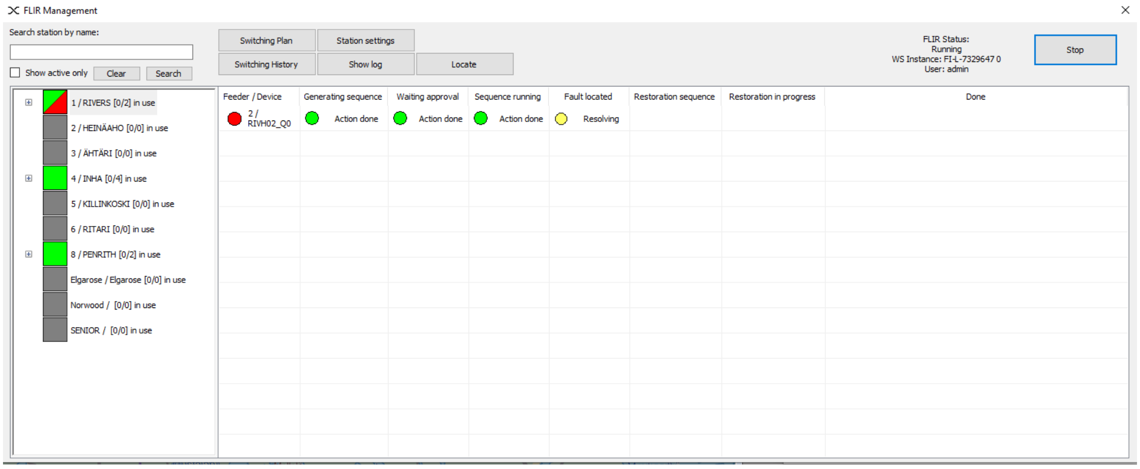


Figure 13. FLIR implementation class diagram.

As can be seen from the figure above, FLIR has multiple new classes implemented for the functionality. Brief presentation of these classes is given. FLIRManager is the mainframe of the functionality, it handles the managing between the classes and is used when initializing all the settings and configurations related to it. FLIRManager is also utilized when a new FLIR fault needs to be handled, GenerateNewSequence(Vika*) will create a new FLIRSequence object, which will handle the isolation and restoration switching generation, by first analysing the faulty feeder by going through the network and creating a tree-structure of the possible remote-controlled switches. If network is properly analysed, isolation switching can then be generated after. FLIRSwitchingMethod specifies which type of isolation switching is utilized, currently there are three distinctive methods. If isolation switching sequence is successfully generated, then restoration switching sequence for each remote zone is generated also. When generation is completed, FLIRManager notifies FLIRMainDlg to show the correct status of the specific sequence and depending whether the FLIR is in automatic operation mode, the sequence is either sent to the SYS600 sequencer or is put on hold to wait for the operator confirmation.

FLIRCommHandlr handles the communication between the DMS600 WS instances, including sending the FLIR messages and parsing them and handles the sequencer state reading and state resetting.

FLIRMainDlg is the main user interface that shows active FLIR faults and can be used to navigate in different FLIR related dialogs and menus. FLIR is started from this dialog also. Figure below shows the FLIR management dialog with an active FLIR fault situation.



☐ Show active only

FLIR Status:
Running
WS Instance: FI-L-7329647 0
User: admin

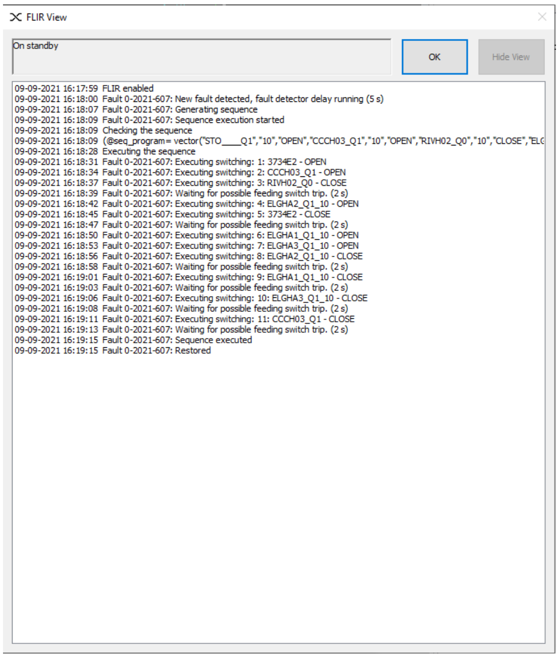
1 / RIVERS [0/2] in use
2 / HEINÄAHO [0/0] in use
3 / ÄHTÄRI [0/0] in use
4 / INHA [0/4] in use
5 / KILLINKOSKI [0/0] in use
6 / RITARI [0/0] in use
8 / PENRITH [0/2] in use
Elgarose / Elgarose [0/0] in use
Norwood / [0/0] in use
SENIOR / [0/0] in use

Feeder / Device	Generating sequence	Waiting approval	Sequence running	Fault located	Restoration sequence	Restoration in progress	Done
● 2 / RIVH02_Q0	● Action done	● Action done	● Action done	○ Resolving			

Figure 14. FLIR management dialog.

Figure above shows the FLIR management dialog. On the left side of the dialog, there is a list of all the stations in the network, which can be used with the FLIR. These are colour coded, so that if they are greyed out, there are no feeders that the FLIR is monitoring for faults, green means that there is at least one feeder that has FLIR enabled and red/green means that there is currently an active fault situation in the station. This list can be filtered and searched using the search bar in the top left corner, also allowing filtering the unused stations from the list for easier monitoring. FLIR-enabled feeders per station can also be set to be visible by clicking the tree structure open further. List on the right is the FLIR status list, which shows status of each fault that the FLIR has operated on and where the FLIR is currently operating it. If operation fails, the step that has failed is shown on the status list also. Top right of the dialog has the start and stop button, which sets the specific FLIR instance to be on standby mode. Status of the specific FLIR instance is also shown on the top right. Management dialog also has few buttons to navigate the different FLIR dialogs, including settings for stations, switching plans, switching history and FLIR log.

FLIRLogDlg is a separate dialog for logging the FLIR operations. It has the time stamps for each FLIR event and can be used to monitor the FLIR operations further. Following figure shows the FLIR log with prints from a fault isolation sequence.



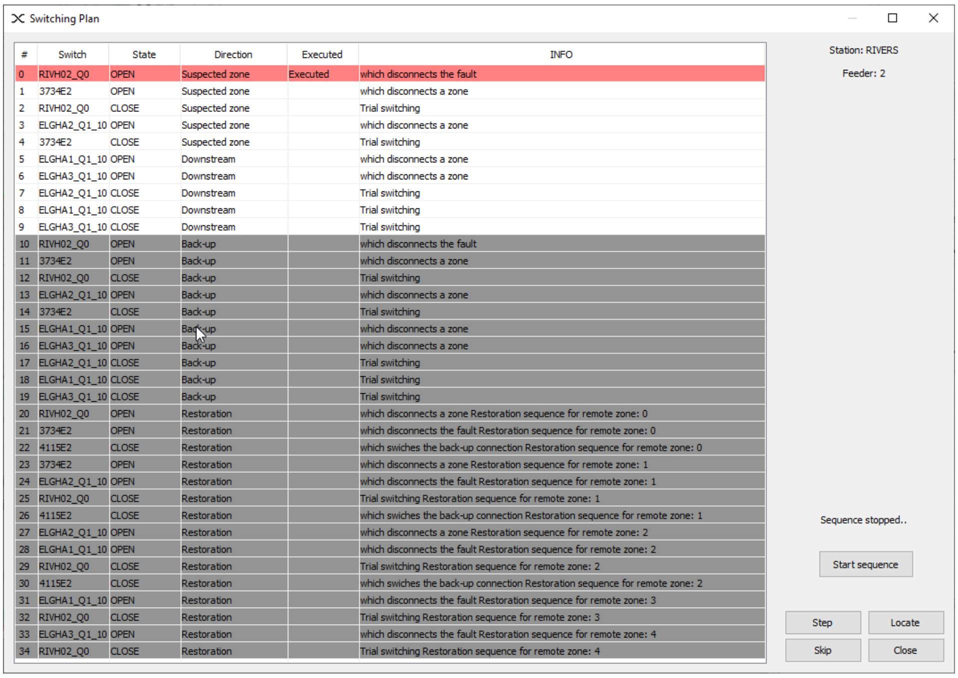
On standby

```
09-09-2021 16:17:59  FLIR enabled
09-09-2021 16:18:00  Fault 0-2021-607: New fault detected, fault detector delay running (5 s)
09-09-2021 16:18:07  Fault 0-2021-607: Generating sequence
09-09-2021 16:18:09  Fault 0-2021-607: Sequence execution started
09-09-2021 16:18:09  Checking the sequence
09-09-2021 16:18:09  (@seq_program= vector("STO____Q1","10","OPEN","CCCH03_Q1","10","OPEN","RIVH02_Q0","10","CLOSE","EL
09-09-2021 16:18:28  Executing the sequence
09-09-2021 16:18:31  Fault 0-2021-607: Executing switching: 1: 3734E2 - OPEN
09-09-2021 16:18:34  Fault 0-2021-607: Executing switching: 2: CCCH03_Q1 - OPEN
09-09-2021 16:18:37  Fault 0-2021-607: Executing switching: 3: RIVH02_Q0 - CLOSE
09-09-2021 16:18:39  Fault 0-2021-607: Waiting for possible feeding switch trip. (2 s)
09-09-2021 16:18:42  Fault 0-2021-607: Executing switching: 4: ELGHA2_Q1_10 - OPEN
09-09-2021 16:18:45  Fault 0-2021-607: Executing switching: 5: 3734E2 - CLOSE
09-09-2021 16:18:47  Fault 0-2021-607: Waiting for possible feeding switch trip. (2 s)
09-09-2021 16:18:50  Fault 0-2021-607: Executing switching: 6: ELGHA1_Q1_10 - OPEN
09-09-2021 16:18:53  Fault 0-2021-607: Executing switching: 7: ELGHA3_Q1_10 - OPEN
09-09-2021 16:18:56  Fault 0-2021-607: Executing switching: 8: ELGHA2_Q1_10 - CLOSE
09-09-2021 16:18:58  Fault 0-2021-607: Waiting for possible feeding switch trip. (2 s)
09-09-2021 16:19:01  Fault 0-2021-607: Executing switching: 9: ELGHA1_Q1_10 - CLOSE
09-09-2021 16:19:03  Fault 0-2021-607: Waiting for possible feeding switch trip. (2 s)
09-09-2021 16:19:06  Fault 0-2021-607: Executing switching: 10: ELGHA3_Q1_10 - CLOSE
09-09-2021 16:19:08  Fault 0-2021-607: Waiting for possible feeding switch trip. (2 s)
09-09-2021 16:19:11  Fault 0-2021-607: Executing switching: 11: CCCH03_Q1 - CLOSE
09-09-2021 16:19:13  Fault 0-2021-607: Waiting for possible feeding switch trip. (2 s)
09-09-2021 16:19:15  Fault 0-2021-607: Sequence executed
09-09-2021 16:19:15  Fault 0-2021-607: Restored
```

Figure 15. FLIR log.

As can be seen from the figure above, each FLIR event is logged in the FLIR log with time stamps, which helps the operators to monitor what the FLIR has done, also showing whether the sequence has been executed successfully or not. If isolation and restoration has been successful, the fault can be stated to be restored by FLIR. Logged information is also saved to a separate .txt file, so that the logging information is not lost when the log is closed.

FLIRSwitchingPlanDlg is used when FLIR has successfully generated a new switching sequence for a specific fault, operator can then view the switching plan by using the switching plan dialog. It has all the planned switching laid out for viewing, containing information about the switch and whether the switch is opened or not. This is useful when using the FLIR in the require- confirmation-mode but can also be used to overseer where a specific isolation sequence is currently at. Switching plan dialog can be seen below with a DEMO-environment switching case.



Station: RIVERS
Feeder: 2
Sequence stopped..

#	Switch	State	Direction	Executed	INFO
0	RIVH02_Q0	OPEN	Suspected zone	Executed	which disconnects the fault
1	3734E2	OPEN	Suspected zone		which disconnects a zone
2	RIVH02_Q0	CLOSE	Suspected zone		Trial switching
3	ELGHA2_Q1_10	OPEN	Suspected zone		which disconnects a zone
4	3734E2	CLOSE	Suspected zone		Trial switching
5	ELGHA1_Q1_10	OPEN	Downstream		which disconnects a zone
6	ELGHA3_Q1_10	OPEN	Downstream		which disconnects a zone
7	ELGHA2_Q1_10	CLOSE	Downstream		Trial switching
8	ELGHA1_Q1_10	CLOSE	Downstream		Trial switching
9	ELGHA3_Q1_10	CLOSE	Downstream		Trial switching
10	RIVH02_Q0	OPEN	Back-up		which disconnects the fault
11	3734E2	OPEN	Back-up		which disconnects a zone
12	RIVH02_Q0	CLOSE	Back-up		Trial switching
13	ELGHA2_Q1_10	OPEN	Back-up		which disconnects a zone
14	3734E2	CLOSE	Back-up		Trial switching
15	ELGHA1_Q1_10	OPEN	Back-up		which disconnects a zone
16	ELGHA3_Q1_10	OPEN	Back-up		which disconnects a zone
17	ELGHA2_Q1_10	CLOSE	Back-up		Trial switching
18	ELGHA1_Q1_10	CLOSE	Back-up		Trial switching
19	ELGHA3_Q1_10	CLOSE	Back-up		Trial switching
20	RIVH02_Q0	OPEN	Restoration		which disconnects a zone Restoration sequence for remote zone: 0
21	3734E2	OPEN	Restoration		which disconnects the fault Restoration sequence for remote zone: 0
22	4115E2	CLOSE	Restoration		which swiches the back-up connection Restoration sequence for remote zone: 0
23	3734E2	OPEN	Restoration		which disconnects a zone Restoration sequence for remote zone: 1
24	ELGHA2_Q1_10	OPEN	Restoration		which disconnects the fault Restoration sequence for remote zone: 1
25	RIVH02_Q0	CLOSE	Restoration		Trial switching Restoration sequence for remote zone: 1
26	4115E2	CLOSE	Restoration		which swiches the back-up connection Restoration sequence for remote zone: 1
27	ELGHA2_Q1_10	OPEN	Restoration		which disconnects a zone Restoration sequence for remote zone: 2
28	ELGHA1_Q1_10	OPEN	Restoration		which disconnects the fault Restoration sequence for remote zone: 2
29	RIVH02_Q0	CLOSE	Restoration		Trial switching Restoration sequence for remote zone: 2
30	4115E2	CLOSE	Restoration		which swiches the back-up connection Restoration sequence for remote zone: 2
31	ELGHA1_Q1_10	OPEN	Restoration		which disconnects the fault Restoration sequence for remote zone: 3
32	RIVH02_Q0	CLOSE	Restoration		Trial switching Restoration sequence for remote zone: 3
33	ELGHA3_Q1_10	OPEN	Restoration		which disconnects the fault Restoration sequence for remote zone: 4
34	RIVH02_Q0	CLOSE	Restoration		Trial switching Restoration sequence for remote zone: 4

Figure 16. FLIR switching plan dialog.

Switching plan dialog in the figure above contains information about the isolation and restoration switching that FLIR has generated for the faulty feeder. Station and feeder name can be seen in the upper right corner of the dialog and bottom right corner has button for stating the sequence, when FLIR is operated in the require-confirmation-mode. There is also a possibility to operate the plan manually by stepping or skipping certain switching. Configurable colour coding is used for easier recognition of what is planned to be done when confirming the sequence, as can be seen that most of the switching are greyed out because these are only for back-up or used as a restoration sequence if required. When the switching plan is advanced, either automatically with the SYS600 sequencer or manually by stepping the one at a time, the list is updated to be kept up to date with the existing switching state. A green colour is then shown on the executed rows as a default colour, but it is also configurable. This same dialog is utilized when viewing historical FLIR switching.

This implementation is only for the first phase of FLIR, biggest downside to this is that sequencer can only handle single sequence at a time, so no parallel fault handling can be achieved. This will be changed in the future as second phase is already being planned and sequencer is then discarded. There is going to be also various minor changes and improvements, but these are not yet defined entirely. More of the future development needs later in this chapter.

4.2 Test results acquired from test environment

Lots of internal testing was required to find out most of the bigger issues regarding the integration of the FLIR functionality to the existing DMS600 software functionalities. This was also a lengthy process, which was done alongside the implementation. There were some issues to get the SYS600 sequencer to work alongside with the new FLIR functionality and there are still some active bugs. Next, we shall present an isolation and restoration case from a DEMO-environment, which is a rather simple feeder, thus easily followable.

At first, we get an imaginary fault in the DEMO-network, which is fully simulated and is not connected to real-world devices. Figure below illustrates this kind of situation.

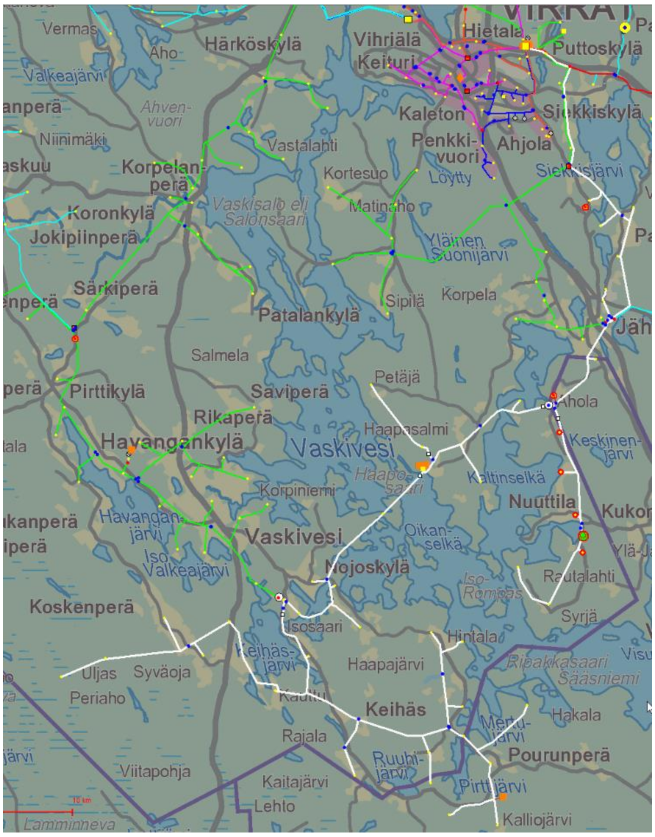


Figure 17. New fault has appeared in the DEMO-network.

As can be seen from the figure above, the faulty network is presented as not electrified, i.e., colouring is white for the whole feeder. This feeder contains only few RCDs, which means that there aren't that many possible RCZs where the fault can be located. But for examples sake, we input it to be in the second RCZ.

When FLIR is up and running on its specific instance, the FLIR instance is constantly looking for new faults to appear. When a new fault appears and FLIR is configured to handle the faulty feeder, the FLIR will take the responsibility of the fault. First, FLIR will analyse the faulty feeder and find all the remote-controlled switches. These remote-controlled switches are then added to a tree-structure, which is used when generating the isolation and restoration sequences. When the analysis is completed, sequence is then generated with all the required switching. Illustration of the completed sequence can be found in the Figure 16.

When sequence generation is completed successfully, it can be then sent to the SYS600 sequencer by sending a specific SCIL-script containing all the switching devices and specific operations. Sequencer will perform certain checks to the inputted sequence and if all goes well, it will send an ok signal back to the FLIR instance, which will then give a go signal for the execution of the sequence to begin. When sequencer is executing the sequence forwards, it will stop on each step and communicate with the FLIR instance between the steps to check that it is still okay to proceed. FLIR WS is constantly looking for the trip of the faulty feeder between the steps, and when the trip happens, the fault can be then determined to be between two RCDs. This can be then used to send correct restoration switching to the sequencer. If all goes well, the result should look like this.

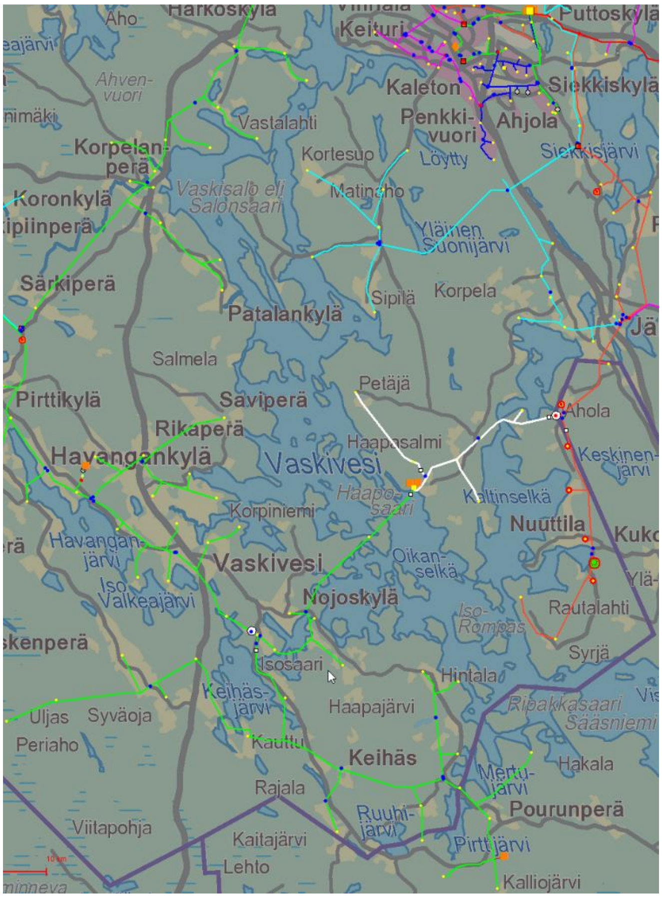


Figure 18. Fault has been isolated between two RCDs.

In the figure above, the fault is isolated between two RCDs and electricity for the rest of the feeder is restored. Upstream from the faulty RCD is restored from the feeding switch and downstream is then restored from an alternative source. FLIR will only use specifically configured alternative sources in the restoration sequences so unwanted stress can be prevented. Also, there is a possibility that the alternative source feeding switch also trips, if there are multiple simultaneous faults in the feeder. This however is not in the scope of the implementation done for this thesis, but more of this in the future development chapter.

When fault is successfully isolated, and electricity has been restored in the parts of the feeder that were possible, then the FLIR can release the responsibility. In the FLIR log the output looks something like the output seen in Figure 15. Also, FLIR fault status in the management dialog changed to done, and the feeder in the list can be changed back to green, since the fault situation was handled successfully by FLIR. After one fault has been operated on by FLIR, if will choose new fault from active faults if there is any, otherwise it will go on a standby and wait for new faults to appear.

4.3 Future development needs

Implementation was divided into two phases, where the first phase of implementation was included in this master's thesis, but there are development needs in the future so that a more satisfying operation results can be acquired.

One of the main improvements that needs to be developed is parallel FLIR sequence operation. This requires work on the SCADA side, which was the limiting factor in the phase 1 implementation, since sequencer could only handle single switching sequence at a time. New command procedures need to be created that allow parallel sequence operation, with similar switch controllability checks. Figure below introduces the FLIR process flowchart in phase 2. Idea is to allow multiple parallel sequences to be executed at the same time.

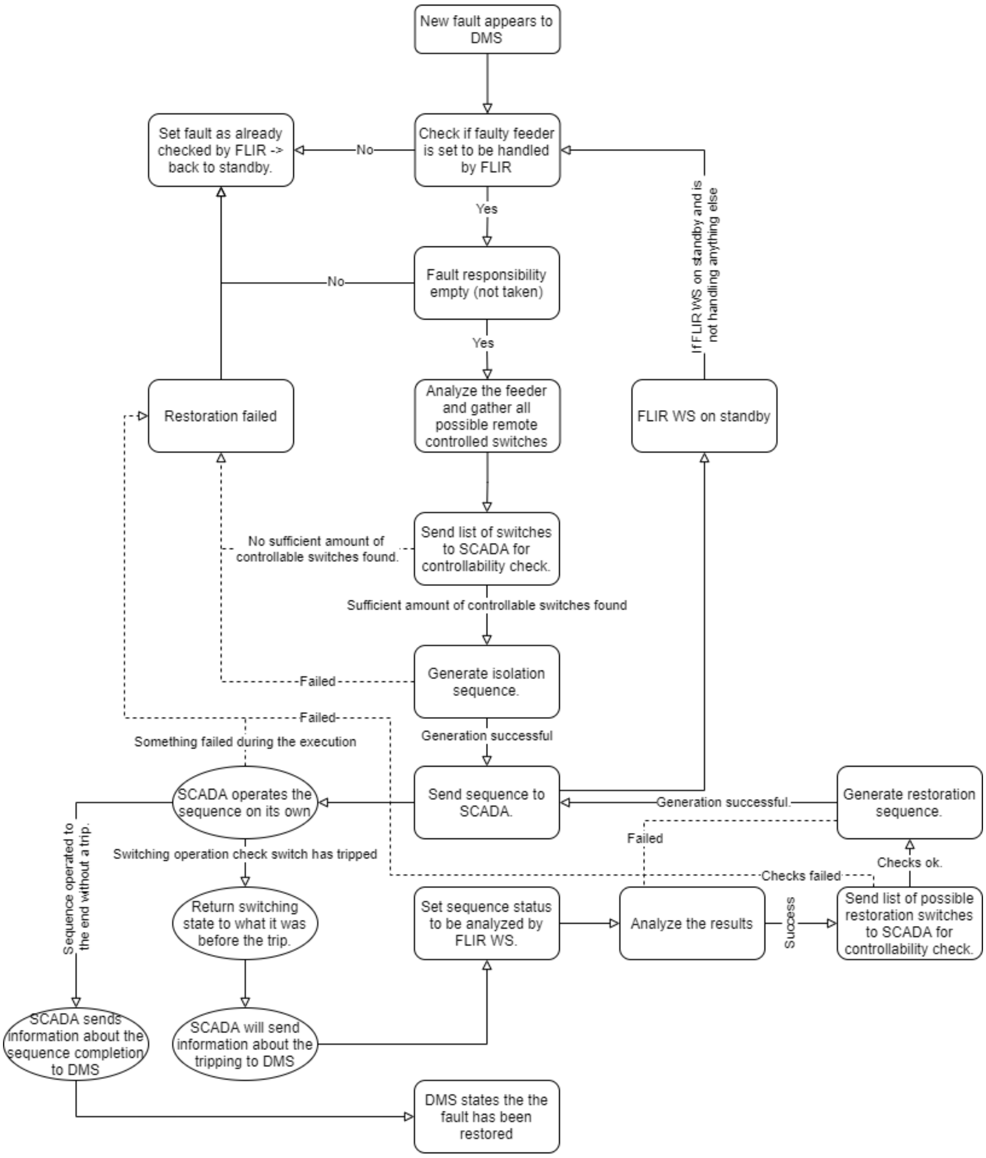


Figure 19. FLIR operation process flowchart for phase 2.

Figure above introduces the possible operation process flowchart for FLIR in phase 2. This is still a work in progress. Major difference to the flowchart in Figure 12 is that the sequencer is no longer used for the sequence execution and restoration sequence is generated after isolation sequence tripping has been detected. Basic operation principle stays the same, but improvements and changes are needed. One addition is that switches that are alongside the feeder are gathered first for controllability checks and if some of the switches fail the controllability check, they are left out and switching sequence can then generated with the switches that could be operated. If sequence is generated successfully, it will then be sent to SCADA as a SCIL-script for execution. Execution is done in SCADA side without communication between FLIR WS and SCADA, since SCADA will now handle the monitoring of the sequence. If something fails, SCADA will send failed message for the specific sequence. If sequence is executed to the end without detecting tripping, SCADA will send sequence restored message and lastly, if tripping is detected during the execution, SCADA will send the switching number and tripped switch information to DMS. FLIR WS will then add it to the handling queue, which will be handled as soon as possible. First an analysis is needed to properly determine the faulty remote zone, then restoration sequence will be generated for the fault in question. New controllability checks will also be done here and if there are no issues with it, it will be sent to the SCADA again. If restoration is then successful, the sequence can be stated to be restored in DMS and FLIR WS will change the sequence status as so, but if restoration fails for tripping, FLIR WS will not do anything for it anymore and sequence can be stated to be failed.

Phase 2 aims to be more efficient when sequence is generated, thus restoration is only done if the feeding switch tripping is detected. Idea is to allow multiple switches to be monitored during the SCADA operation, so possible back-up feeding switch trips can also be noticed and handled. The main advantage of phase 2 implementation is going to be the parallel switching in the SCADA, meaning that DMS can generate isolation sequences for faults that appear simultaneously or during multiple sequence operations. This is possible since lots of processor time can be achieved when sequence operation monitoring is done in the SCADA side.

5. CONCLUSION

The whole production-distribution chain of electrical energy is a vast infrastructure which feeds millions of people with electricity allowing our modernized world to be the way it is. Nearly everything nowadays is somehow electrified, and there are constantly new inventions being developed around the world. It might seem easy to just produce the electricity in one place and then use it in another, but it requires immense amount of careful planning, various calculations, and effort to get it to the consumers while still maintaining high power quality, well mitigated losses, and constant supplying. As is in everything, there is always a possibility that something might go wrong, and when this happens it causes disruptions to our everyday lives. Which is why it is important to be prepared properly in these situations when the unexpected happens, thus a need for proper fault handling is necessary.

Main purpose of this thesis was to design and implement automatic fault management functionality, FLIR, for DMS600 software. Designing and implementations were based on interviews conducted in [32], which was the basis of this whole thesis. Thesis started the theory from the beginning of the production-distribution chain of electrical energy, introducing relevant things along the way of how to keep the quality of the chain as best as possible. In the beginning various power production methods are introduced, listing their advantages, disadvantages, and use-cases to get a good overview of how electricity is produced. Then to move on to the next part of the chain is the transforming of electricity, introducing basic transformer related calculations and how the electricity characteristics are affected. Transmission losses and proper sizing were emphasized next. Then closer look for the end of the chain was given, where distribution network is introduced as a whole entity, including various components and how they are utilized in the network. Then we get to the one of the main points of the thesis, which is faults in the distribution network and how to handle them. Lastly, look on various energy storages were given and how they possibly can be utilized in distribution network.

Most of the work of the thesis went on to developing the implementation part, which was a lengthy process and took its time, but gave a good amount of knowledge of how DMS600 software family works under the hood. The work was done primarily using C++ code and there were tens of thousands of lines of code written for the implementation. The thesis introduced the MicroSCADA X DMS600 software family, including few of its main software that the implemented functionality utilizes. This gave a good overview how the internal communication works between the software and what functionalities they already have and what needed to be implemented. The focus was that the existing fault management functionality could be only utilized in a handful of faults, whereas the new implemented FLIR functionality aims to work around the issues in the old implementations, mainly because trial switching was implemented.

The implementation was thoroughly introduced, including flow chart of the operation logic, class diagram of the newly implemented C++ classes and their relations, and most of the newly added dialogs to the DMS600 WS were introduced also and how they are supposed to be used. During this whole process, the scope of the work shifted a little, when new desires arose and new issues were found from the intended functionalities that were to be used. The biggest issue was the sequencer, when it could not operate parallel switching sequences, thus a different approach needs to be used in the future. This was also part of the thesis, since there are already plans on how the implementations is developed in the future.

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