Automating of Low Voltage Network Fuse Protection Planning

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Abstract of master's thesis

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Abstract

The planning of electricity networks is time consuming work. The plans may concern huge areas and attention must be paid to the details. Even the smaller plans include various repetitive tasks, which combined increase the time to finish the plan. To get rid of some of the repetitive manual work and to speed up the process, the planners have different instructions and tables. However, the most time savings could be achieved with an automatic planning tool.

The goal of this thesis is to develop an application to plan the fuses of a given low voltage network automatically. To reach the goal, the fuse planning process is examined thoroughly. The studied material includes low voltage networks and fuses before moving on to the fuse protection planning process. The fuse protection was studied from the national standards and with professional planners. The standards were combined with inputs of the planners to create the solution.

As a result, the automatic fuse planning application was successfully developed with the essential features. However, some more advanced topics were left for future development, which will continue. A result network with fuses is introduced in chapter 5.

Keywords Electricity distribution, Low voltage network planning, Fuse protection

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Tiivistelmä

Sähköverkkojen suunnittelu on aikaa vievää työtä. Suunnitelmat saattavat koskea valtavia alueita ja yksityiskohdat vaativat tarkkuutta. Myös pienemmät verkkosuunnitelmat sisältävät toistuvaa käsin tehtävää työtä. Suunnittelijoilla on käytössään erilaisia ohjeita ja taulukoita, joiden avulla päästään eroon joistain toistuvista tehtävistä sekä säästetään aikaa. Suurimmat ajansäästöt voidaan kuitenkin saavuttaa automaattisella suunnittelutyökalulla.

Tämän työn tavoitteena oli kehittää työkalu, joka suunnittelee annetun pienjänniteverkon sulakkeet automaattisesti. Sulakesuojauksen suunnitteluprosessia tutkittiin huolellisesti, jotta tavoite saavutettaisiin. Tämä työ sisältää katsaukset pienjänniteverkkoon sekä sulakkeisiin ennen sulakesuojauksen suunnitteluun siirtymistä. Sulakesuojausta tutkittiin sekä kansallisista standardeista että sähköverkkojen suunnittelijoiden kanssa. Standardien sekä suunnittelijoiden ohjeet yhdistettiin, minkä pohjalta lopputulos syntyi.

Työn lopputuloksena kehitettiin onnistuneesti työkalu sulakesuojauksen automaattista suunnittelua varten. Työkalusta löytyvät olennaisimmat ominaisuudet, mutta joidenkin haastavampien aiheiden käsittely jäi vielä tulevaisuuteen. Kehitystyö kuitenkin jatkuu tulevaisuudessa. Suunnittelutyökalun tuloksena on esitetty verkko sulakkeineen luvussa 5.

Avainsanat Sähkönjakelu, Pienjänniteverkon suunnittelu, Sulakesuojaus

Preface

First, I want to thank Trimble Solutions Oy for offering such an exciting topic for my master's thesis. I also want to thank everyone who has helped me during the process, from gathering the information about fuse protection to putting it all together. Special thanks to my advisor Eero Saarijärvi, who has offered excellent guiding, John Millar from Aalto University, who has helped me to figure out the behavior of Optimizer, and my supervisor, professor Matti Lehtonen, for valuable contribution regarding the writing process of this thesis.

Otaniemi has been an awesome place to study, mostly because of the people I have been spending my time with, so thanks for helping me through my studies. Finally, and most importantly, I want to thank my family, friends and girlfriend for all the support, which has made everything possible.

Otaniemi, 27.11.2019

Jaakko Anttila

Contents

Symbols

C	[€]	lifetime cost
c	[€/a]	cost per year
c_{kW}	[€/kW]	cost per kW
c_{kWh}	[€/kWh]	cost per kWh
c_{max}		voltage factor for maximum short-circuit current
c_{min}		voltage factor for minimum short-circuit current
f	[1/a]	fault frequency
I_2	[A]	current, which ensures the operation of the device in a designated conventional operation time
I_B	[A]	designated current of the circuit
I_k	[A]	short-circuit current
I_{k1min}		minimum single-phase short-circuit current
I_{k3max}	[A]	maximum three phase short-circuit current
I_n	[A]	current rating of a fuse
I_t	[A]	rated current of a transformer
I_z	[A]	current carrying capacity of the conductor
K		coefficient conductor and insulation materials
k_T		temperature dependency coefficient of phase conductor
l	[m]	line length
P_k	[W]	load losses of a transformer
P_{max}	[W]	maximum consumption of a connection point
p	[%/a]	interest rate
R_k	[Ω]	short-circuit resistance of the feeding network
R_{k1}	[Ω]	short-circuit resistance of fault location
R_t	[Ω]	short-circuit resistance of a transformer
R_{t0}	[Ω]	zero-sequence resistance of a transformer
r	[%/a]	load growth
r_0	[Ω/m]	zero-sequence resistance of a line
r_1	[Ω/m]	positive-sequence resistance of a line
r_n	[Ω/m]	resistance of the neutral conductor of a line
S	[mm^2]	cross-section of a conductor
t	[a]	lifetime
t_k	[s]	duration of the short circuit
t_{repair}	[h]	repair time
U	[kV]	phase voltage
U_N	[kV]	rated voltage of a transformer
U_{n2}		rated secondary voltage of a transformer
u_r	[%]	short circuit resistance of a transformer
S_N	[kVA]	rated power of a transformer
X_k	[Ω]	short-circuit reactance of the feeding network
X_{k1}	[Ω]	short-circuit reactance of fault location
X_t	[Ω]	short-circuit reactance of a transformer
X_{t0}	[Ω]	zero-sequence reactance of a transformer
x_{1i}	[Ω/m]	positive-sequence reactance of a line (per length)
x_{0i}	[Ω/m]	zero-sequence reactance of a line (per length)
x_{ni}	[Ω/m]	reactance of the neutral conductor of a line (per length)
Z_k	[Ω]	total impedance seen from the fault location
γ		ratio between load growth and interest rate
κ		discount factor
λ		faults per year

Abbreviations

BF	Brownfield
CIC	Customer interruption cost
DMS	Distribution management system
DSO	Distribution system operator
GF	Greenfield
HV	High voltage
LV	Low voltage
MV	Medium voltage
NIS	Network information system

1 Introduction

The protection of power systems is extremely important, because any neglect could cause danger to life. The low voltage (LV) networks are no exceptions, even though the voltage level is low. In fact, most of the electricity related deadly accidents happen in the LV environment (Lakervi & Partanen 2008). In addition, the faults in LV networks are mostly discovered only after a customer calls that they have no electricity (Löf 2009). For these reasons, a correctly working protection system is essential, to ensure all the electricity users stay safe.

Faults in the electricity networks occur inevitably somewhere at some point. The climate change poses a new threat to the distribution system by possibly increasing the number of faults. Extreme weather conditions may cause widely spread power outages and even the normal conditions are able to cause interruptions of electricity supply. In Finland, the warming climate is expected to increase annual rainfalls and decrease the amount of frost, which could increase the damage caused by wind. (Lehtonen et. al. 2019) As a comparison, in the United States the climate change is expected to increase the frequency of severe storms, which directly affects the damage costs (McKinsey 2019). The role of protection will be emphasized as the number of faults in the network increases.

Network planning is one of the core businesses of distribution system operators (DSO). The lifetime of distribution networks is long, which makes meticulousness a key element in the planning phase. The planning of networks is time consuming and includes various repetitive tasks. When the planning is made manually by humans, the plans may not be as efficient as they could be. Automation of the different manual tasks the planner has to do regularly would save lots of time. Planning the fuses of a network is one of the manual and repetitive tasks, which could potentially be automated.

The planning of fuse protection is part of the network planning. Traditionally, the fuses are planned manually, even though it is a routine task for the planners. The DSOs have their own guides and recommendations, such as tables with maximum fuse size for a certain conductor, which they utilize. Standards exist as a basis for the rules of the DSOs. The fuse planning process follows a regular path consisting of different checks to ensure the fuse is viable for the location. The fuse size must be adjusted to fit within the desired limits. The task of dimensioning the protection devices is important to ensure that the protection is working as intended. It is the responsibility of the planner to take care of the protection matters.

The aim of this thesis is to develop an extension to a network planning application, which automatically inserts correctly dimensioned fuses into the network to each location where they are required. To reach the target, the rules of fuse planning need to be determined with detail to determine how the automating could be completed. To achieve a solution that offers value to the professional network planners, they need to be consulted to some extent. In practice, the research starts from the standards and later moves on to include the inputs of the DSOs. As an important part, the short circuit calculation, which is a prerequisite for the fuse planning, needs to be included as a part of the development before the fuses can be considered.

This thesis consists of six chapters, introduction being the first. The second chapter introduces low voltage networks as a part of the power system. The fuses offer protection for various components of the LV network and understanding the structure, which the fuses are designed to protect, is important as background material. In addition, the causes of faults are identified to know against what the protection is required. Protection of the network also includes other aspects in addition to the fuses, such as earthing. Network planning is briefly discussed as the final part of the chapter.

On the third chapter, fuses, as the protection devices, are thoroughly discussed, to gain information about their abilities. The operation principles, structures, types and important characteristics are valuable information in determining the correct fuse for any situation. The data sheets of fuses offer lots of technical data about them, so they are taken advantage of in this chapter.

The fourth chapter presents the methods and limits for the fuse planning. Most of the equations, which are the core of the planning process, are introduced in that chapter. The relevant standards are also introduced. This chapter also includes theory of short circuit calculation. The protection is divided into two main topics: overload and short circuit protection. Protection of different components is also discussed before the final topic of this chapter, selectivity, is brought up.

The fifth chapter shows how the actual planning process is automated, so the results of this thesis are presented there. In this chapter, the knowledge from the previous chapters is put into use. The chapter is divided into several phases, each representing some important part of the automating process. The most important parts are the initialization of all the needed fuses and then applying the selectivity rules. Additionally, Trimble Network Optimizer, an automatic network planning application, is introduced in this chapter.

The sixth and final chapter is for the conclusions. The automating process is evaluated, and future of the project is briefly discussed.

2 Low Voltage Network

The electricity system of Finland consists of electricity generation, transmission grid, distribution system and electricity consumers. First, the electricity is produced, for example in conventional power plants or from renewable sources, after which the transmission and distribution networks are utilized in transferring the electricity from the generation sites to the various consumption points. Both transmission and distribution grids are utilized to transfer electricity but the main difference between them is that the transmission grid is designed for long transfer distances and the distribution system instead is designed to deliver electricity to the consumers. The transmission grid consists of high voltage (HV) networks of different voltage levels, but the distribution system includes various network types: subtransmission, medium voltage (MV) and LV networks. The different network types exist because of variable requirements of the end users as well as technical limits. Longer distances require higher voltages because the amount of energy losses reduces as the voltage level grows. Additionally, some consumers require different voltage levels than the others. (Fingrid 2019, Lakervi & Partanen 2008)

To offer some perspective, a closer look in the Finnish electricity networks reveals the total lengths of each network type is related to the voltage levels. The transmission grid consists of three voltage levels: 400, 220 and 110 kV, all classified as high voltage. The total length of the transmission lines is over 14 000 km. When it comes to the distribution of electricity, the voltage levels instead vary from HV to LV. First, subtransmission networks are mostly 110 kV networks but older 45 kV networks are also still used. MV networks often have the voltage level of 20 kV but 10 kV networks also exist, because they were popular in the past, especially in cities. A great majority of LV networks are 0.4 kV, but 1 kV could be used in rare situations when neither 20 kV nor 0.4 kV are attractive options. The network lengths by voltage levels are shown in Table 1, which indicates that the total length of one type of network tends to increase as the voltage level decreases. The LV networks represent a substantial share of the whole distribution system because the total length of the 0.4 kV network in 2018 was over 249 000 km. That is considerably more than the total lengths of 1-70 kV networks and 110 kV networks, as they were 152 000 and 9 000 km respectively. (Fingrid 2019, Lakervi & Partanen 2008, Energy Authority 2019)

Table 1. Electricity network length by voltage level in Finland, 2018. (Energy Authority 2019))

Voltage level (kV)	0.4	1-70	110 (subtransmission)	110-400 (transmission)
Network length (km)	249 183.1	151 782.8	9090.8	14 357

Currently the trend concerning new LV networks is constructing more underground network instead of traditional overhead lines. One important driver that has affected the development of LV networks is the legislation concerning electricity market. The law came into effect in 2013 and for the first time stated demands regarding network development and continuity of supply. According to the law, a storm or a snow load must not cause an interruption longer than six hours in urban areas or longer than 36 hours in rural areas. It is important to note, that the limitations are only applied when the cause is a storm or a snow load. However, these are the main causes for outages, especially when a storm causes substantially more damage than usually. For example, 2011 included such a storm and the fraction of storm and snow load caused interruptions out of all the outages was 80 %, which can be compared to the following year, 2012, without such storms when the ratio was 56 %. Exceptions regarding certain customers can be made when they are located on an island without a road or a ferry connection or have not used more than 2500 kWh of electricity during the three previous years if the investments would be too high for the remote distance. The demands must be met in 15 years for the whole network. Milestones include that by the end of 2019 half of the customers except for vacation homes must be protected and by the end of 2023 the fraction should be 75 %. If a distribution system operator must change significantly more than the average amount of overhead lines to underground cables, they can apply for extra time at most until the end of 2036. (Heikkilä 2014)

2.1 Network components

In addition to the actual distribution lines, the distribution system includes other components, most importantly substations and distribution substations. Substations can be viewed as the feeding points of the distribution system along with the electricity generation connected to it. The electricity coming from the transmission grid is transformed to a suitable voltage level at the substations. Similar to substations, distribution substations are used to transform the voltage between MV and LV networks. The distribution substations could therefore be considered as a part of the low voltage system. In addition, the distribution system consists of several other important components including protection devices, energy meters and computer software. The most important protection device regarding the LV networks is a fuse, which will be introduced properly in chapter 3. The computer software refers to the likes of distribution management systems (DMS) or network information systems (NIS), which are vital for the DSOs in keeping track of their assets. (Lakervi & Partanen 2008)

2.1.1 Distribution Substations

The components of a distribution substation include a medium voltage busbar system, at least one distribution transformer, low voltage outputs and a possible auxiliary voltage system. Three main types of distribution substations are being used depending on the type of the network and location. In densely populated city areas, the distribution substations are placed in underground vaults, such as the cellars of buildings, because there is no space to put them elsewhere. As those are located out of sight and out of reach of non-authorized people, they are also secure. Other urban areas have pad mounted distribution substations, which are small constructions, also called kiosks. A picture of such distribution substation can be seen on the left side of Figure 1. Pole mounted distribution are a common sight in rural areas. The right side of Figure 1 shows a pole mounted distribution substation and it also reveals that they are conveniently located in the same structures with the power lines. The pole mounted substation has one major disadvantage, which is the vulnerability to the touch of humans and animals while the pad mounted structure is a safer solution. The rural distribution substations are smaller than the urban ones, physically and by electric power, and thus they are also cheaper, as an increase in the rated power and size tends to directly increase the price. The rated power of pole transformers is up to 315 kVA but commonly only 50 or 100 kVA. Urban transformers are closer to the rated power of 1000 kVA. (Lakervi & Partanen 2008)

Figure 1. Pad mounted (left) and pole mounted (right) distribution substation. (Finnkumu 2019, Järvinen 2010)

2.1.2 Electric lines

The electric lines could be considered as the most important parts of the networks as they connect everything together physically forming the network. The two options affecting the properties of the network are overhead lines and underground cables. Naturally, both options come with advantages and disadvantages compared to the other. The choice of which option should be used is always situational, as the location alone, for example, might determine the type of network. (Lakervi & Partanen 2008) Traditionally, the overhead lines have formed the majority of LV networks, but the construction of underground cables has accelerated, especially in Finland after the new law regarding electricity markets came into effect. For the DSOs the law has in principle meant that they need to replace overhead lines with underground cables, move the overhead lines to roadsides, where less trees might fall on them, or take better care of keeping the forests from growing too close to the lines. The share of underground cables in LV networks was 49.1 % in 2018 (Energy Authority 2019). The percentage is significantly higher compared to the MV networks, of which 31.7 % are underground cables. Comparison to 2014 numbers shows that the cables have replaced overhead lines in a fast pace, as four years earlier 40.8 % of the LV networks and only 16.4 % of the MV networks were underground cables (Energy Authority 2016). The trend of going underground probably continues as it seems to be the most effective way to improve protection against fierce storms which would cause enormous destruction to overhead lines. A problem regarding the transformation towards underground networks comes up with the rural areas that are already dying as the population is moving to cities. Lots of investments might turn out pointless if proper attention is not paid in the rural conditions.

The main benefit of underground cables is that they achieve better reliability than overhead lines. Regarding reliability, the fault frequency is only 10 - 50% compared to overhead lines. Additionally, the underground cables require less space, they do not cause visual pollution to the environment and the energized parts are safe from an accidental touch of a human or an animal. The main disadvantage comes up in fault situations because locating and fixing a cable fault is generally remarkably slower than with overhead lines. Even before the new legislation, the use of underground cables had become more popular, especially in certain situations where the cables are easy to install by plowing. Differences in costs between underground and overhead networks in LV are not as much as in MV. The underground cable is not much more expensive than the aerial bundled cable, which is commonly used in Finnish LV overhead network, and plowing can be cheaper than installing poles. In addition, lifetime of overhead lines is 40 - 50 years and even up to several decades more for underground cables. Therefore, considering the life cycle costs of use and maintenance, installing underground cables can be cheaper than overhead lines in certain situations. Plowing is possible most locations except for areas with rocky ground. Usually the plowing follows roads if possible. (Elovaara & Laiho 1988, Lakervi & Holmes 1995, Lakervi & Partanen 2008)

Moving over to the overhead networks, which overall are not only generally cheaper to construct than underground cables but have multiple other advantages too. One of the reasons behind lower costs is that the total length of underground networks is usually longer compared to overhead networks of the same areas, which stems from the fact that cables are installed to follow roadsides and borders of fields wherever it is possible because the forests are harder areas to work with. The overhead lines are easier to install in forests, so the paths can be straighter. Underground networks are usually easier regarding the land use contracts because of the aforementioned use of areas but overhead networks are more flexible for changes. Adding connections to an existing overhead network is much easier than to an underground network as the cables might be hard to locate and the digging must be performed carefully to avoid any damage. Because of the worse modifiability, underground cables need to be sized for distant future, which brings up the costs. One additional advantage is that the overhead lines also cool down faster than underground cables, so they withstand more overcurrents. In addition, the heating of the underground cables heats and dries the surrounding earth. (Lakervi & Partanen 2008, Elovaara & Laiho 1988)

2.1.3 Cable distribution cabinets

In an underground network, cable distribution cabinets are vital parts regarding fuse protection among other things, such as forming the topology. The distribution cabinets are important nodal points of the network, as they receive one cable, coming from a distribution substation or from another distribution cabinet, as the input and have multiple output cables for the nearby connection points or other cabinets. The underlying logic is to avoid connecting every single connection point to the distribution substation with their own cable or to avoid branching of trunk lines. The distribution cabinets save the DSOs from extra digging and cable length. Additionally, the cross-sections of the cables can be reduced at the cabinets when the flow of current is split between multiple cables. When the cross-sections are reduced, the protection of the cables must be adjusted. Each outgoing feeder is protected at the distribution cabinet. (Hyvönen 2019)

The distribution cabinets are a common sight in urban areas. In the city environment, some of the cabinets stand out because they are sometimes painted to improve the atmosphere of the environment. On the inside, however, they include the LV protection devices. (Hyvönen 2019) The contents of a cabinet are shown in Figure 2. The empty space is present because the cabinets can be modifiable, to allow some flexibility for the planners. The most interesting parts regarding the network protection are the fuse-switches, which are housing for the fuses. The number of the switches is an important parameter in the network planning phase, as the number is limited depending on the structure of the cabinet.

Figure 2. Contents of a cable distribution cabinet. The fuses are part of the fuse-switch-disconnectors. (ABB 2015)

2.1.4 Protection devices

Fuse is the most important protection device of a LV network. Fuses are used as protection against overcurrents, both overloads and short circuits. They are popular because of being simple, at least on a quick glance, as well as reliable and cheap. The operation principle of a fuse is based on a thin metal element, which melts if the current increases too much. Detailed information about fuses will follow in a chapter 3.

Another protection device, which could be used in LV networks, is a circuit breaker. Circuit breakers operate similarly to fuses, breaking the circuit in a fault situation. The difference in operation is that in addition to operating based on thermal properties, a circuit breaker operates also based on magnetic signal. The thermal-trip zone is used for overload protection and the magnetic-trip zone operates on short circuits. A helpful functionality is that the tripping zones are adjustable. Another advantage is resettability, which increases the ease of use. (Morley 2011)

The main advantage of choosing a fuse over a circuit breaker is the price (Electricity Training Association 1995). The operation time of a fuse during high overcurrents is lower than the operation time of a circuit breaker. Fuse is able to interrupt the current in less than one cycle of AC power frequency, which is 0.0083 s. A modern circuit breaker can achieve a fault clearing time of 0.03 s. The ability to limit the fault current is thus better when a fuse is used. (Eduful & Ekowcole 2011) Advantages of circuit breakers include the abilities to adjust the tripping zones, to reset it back to original state and to trip on smaller overloads. With fuses, replacements are required every time they operate and the protection against small overloads is poorer. (Legrand 2009a, Electricity Training Association 1995) One additional factor to consider is that the circuit breakers are safer for the electricians as the dangers of changing the fuse are eliminated (Mörsky 1993).

Circuit breakers could be utilized in areas where faults happen frequently for some reason. In that case, the replacement fuses would take away the initial savings that were achieved by investing in the cheaper protection device. However, fuses are even more obvious choice in areas where the electro-dynamic stress related to the short-circuits causes harm. If the network experiences short-circuit faults frequently, circuit breakers are not the best option as they would also require replacement after certain wear is caused to the contacts. Additionally, because the circuit breakers do not operate as fast as fuses during high overcurrents, the protected equipment might get damaged easier after several faults. (Eduful & Ekowcole 2011) Circuit breakers are often used instead of fuses in distribution boards but the main protection device is still mostly a fuse (Mörsky 1993).

2.2 Structure

The structure of LV networks can be meshed or radial. Meshed network is a structure, in which the distribution substations are connected to each other. Radial networks only have connections from the substations to the consumption points. Both structures are shown in Figure 3. The lines in a distribution network are either trunk lines, which form the core of the network and are the lines between a distribution substation and a cable distribution cabinet or between two cabinets, or supply services, which are the lines that connect the connection points to the trunk network or to the distribution substation. Even though the LV networks can be constructed as meshed, all LV networks are primarily operated radially. In cases of meshed networks, the lines that connect two distribution substations together are not actually connected at both ends, leaving an open point to one end of the line. The open point allows the meshed structure to operate similarly to a radial network. The open points can then be closed in fault situations to allow the restoration of power to as many consumers as possible before the fault is fixed. (Lakervi & Partanen 2008)

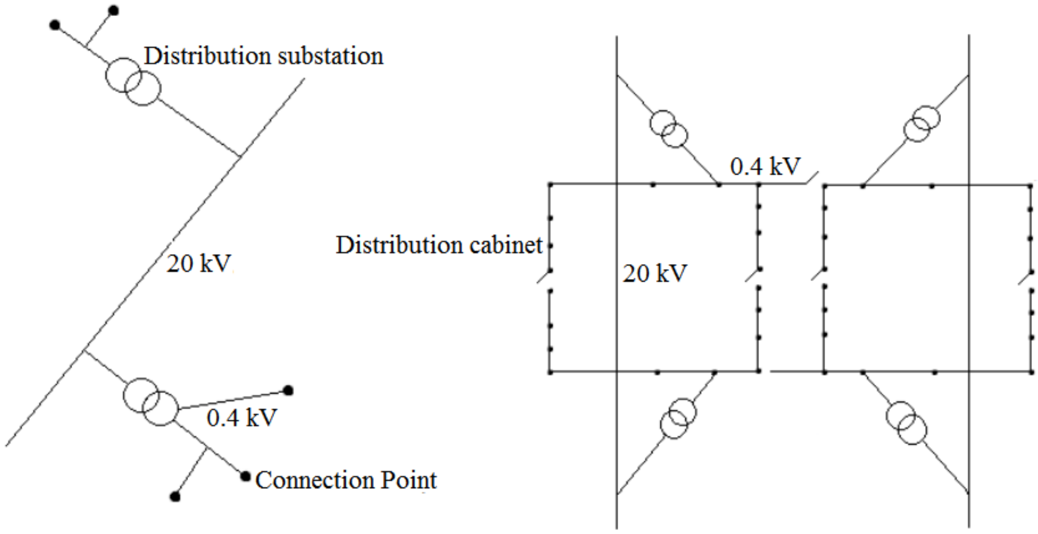

Figure 3. Radial (left) and mesh (right) network topologies. (Lakervi & Holmes 1995)

The topology of a network depends on the area. In a densely populated area, such as cities, where consumption points are close to each other, the networks are often built with backup connections from one distribution substation to another. The meshed structure is essential in reducing outage time of the customers and increasing the security of supply. However, the backup connections are not efficient in rural areas because the distances of the lines would grow to be too long. In such locations, the networks are simply built radial. The outage times are longer, but it would cost too much to reduce them for it being profitable. (Lakervi & Partanen 2008)

Comparing the benefits of the two network types, the radial structure is cheaper to implement, easier to control in fault situations, easier to protect and has lower short circuit currents, while the meshed structure has the ability to massively reduce interruption times during outages in addition to reducing voltage drops and energy losses. The radial topology is simpler than the meshed because electricity is only supposed to flow in one direction. However, exceptions are caused by increasing distributed energy generation, which mixes up the unidirectional flow of current. Thus, an increase of distributed generation supports meshed operation. (Lakervi & Partanen 2008)

2.3 Faults

The possibility of faults is present in every electric network. Faults can be a consequence of multiple different situations, so recognizing the risks is important knowledge when planning the protection of the network. Some situations are more common than the others but even the rare possibilities must be taken into account. For example, weather conditions might be hard or easy to predict, depending on the scale, but a cable having a manufacturing defect is quite impossible to detect after the installment before the fault occurs. The overall situation regarding the faults in the distribution network can be inspected through the statistics provided by Finnish Energy.

Recognizing the role of distribution system faults in terms of customer satisfaction and outage related costs is worthwhile, as out of all consumer experienced power outages, over 90 % are caused because of distribution network faults (Lakervi & Partanen 2008). Most of the distribution system related interruptions occur in the MV networks. In 2018, 81 % of the total interruption time was a result of MV network faults. The share of LV network faults was only 8 % of the total interruption time. The rest of the interruptions were caused by substations and distribution substations. (Finnish Energy 2019)

Even though LV network might seem to be quite insignificant as the cause of interruptions, there is still room for improvement. The 8 % share of LV networks measures up to 0.12 hours per year per customer. Out of the 0.12 h / a, 0.10 h / a was caused by faults and the rest by planned interruptions. The overall interruption time caused by faults was 1.18 h / a per customer in 2018. Significant differences can be spotted between urban and rural areas. In urban areas the total fault interruption time was 0.32 h / a and in rural areas the time was 5.82 h / a. (Finnish Energy 2019)

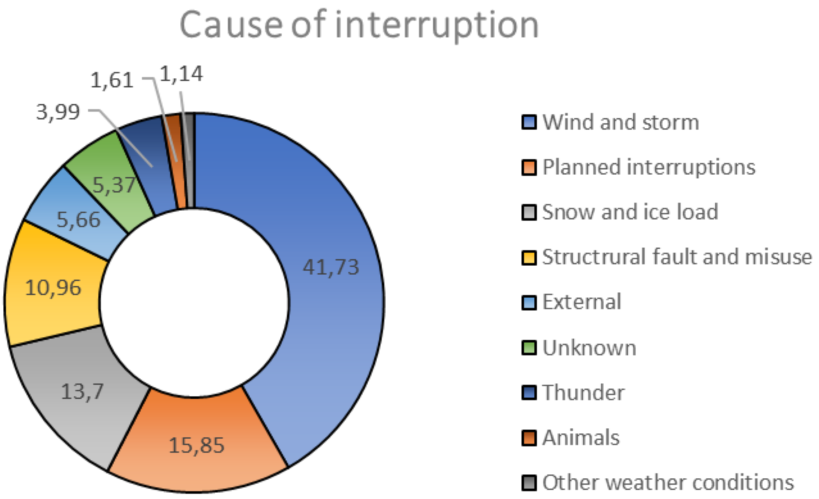

Figure 4. The interruption causes in distribution networks. Values are in percentages. (Finnish Energy 2019)

The interruption statistics also include the causes of the faults. According to the 2018 statistics, which are illustrated in Figure 4, the main causes behind the interruptions were storm and wind, which were responsible for 41.73 % of the total interruption time. Other significant causes were snow and ice loads (13.7 %), structural flaws and misuse (10.96 %) and planned interruptions (15.85 %). Interruptions caused by thunder and animals were quite rare, as their shares were just 3.99 % and 1.61 % respectively. (Finnish Energy 2019)

A significant majority of the fault causes affect mainly just overhead networks as they are so vulnerable to weather conditions. Just the share structural flaws and misuse is easily applicable for underground networks, but at the same time no overhead network is not safe from them. The weather conditions affecting underground cables could be frost or general wetness of the soil. Frost could cause some movement of the cables and if the insulation of the cables fails for some reason, they are left vulnerable for water causing a short circuit in the cables.

A special characteristic regarding LV faults is that they are not directly communicated to the DMS like MV faults. Traditionally customers notify the system operator about faults, which is not the optimal situation. Only a small number of faults can be detected during maintenance or installation processes. To fix a fault after it is recognized, a task can be assigned to the repair team. (Löf 2009)

A clear motivation for the DSOs to keep outage times under control can be found from the legislation. According to the law, consumers are eligible for compensation when an interruption lasts more than 12 hours. The amount of the compensation depends on the duration of the interruption. The maximum compensation is 200 % of yearly distribution service fee or 2 000 € during a calendar year. The whole compensation out of the yearly distribution service fee is following:

- 10 % when the interruption time exceeds 12 hours
- 25 % when the interruption time exceeds 24 hours
- 50 % when the interruption time exceeds 72 hours
- 100 % when the interruption time exceeds 120 hours
- 150 % when the interruption time exceeds 192 hours
- 200 % when the interruption time exceeds 288 hours (Finlex 2013)

In addition to the compensation guaranteed by the law, the DSOs often have their own compensation promises for shorter interruptions (Lakervi & Partanen 2008).

2.4 Protection

Protection is very essential in the sense that an electric network must always be protected to avoid any damage that could result from the faults. The protection must be applied to concern multiple different groups. Humans and animals must be kept safe from energized parts, the network components itself must be protected from to be able to remain working in normal conditions and finally for all other structures, the risk of fire must be eliminated. (Lakervi & Partanen 2008)

According to accident statistics, dangerous touch voltages are in most cases caused by LV networks. Out of all electricity related accidents that have led to a death in Finland, over 60 % have happened in LV environment. Eliminating the danger to life is one of the main purposes of the protection of LV networks, along with keeping the network components safe and neutralizing the risk of fire. Accomplishing each of the above-mentioned requires maintenance of a good earthing in addition to fuse protection. (Lakervi & Partanen 2008)

Protective measures against direct contact include insulation of live parts, barriers, obstacles and out of reach location. Measures against indirect contact contain earthed equipotential bonding and automatic disconnection of supply, insulation, non-conducting location, earth free local equipotential bonding and electrical separation. (Wright & Newbery 2004)

Earthing is a basic safety measurement in LV networks. Three types of basic LV distribution systems exist: TN, TT and IT. The systems are categorized with two letters. The first letter describes the relationship between the power system and earth. The T stands for direct connection to earth while the I stands for isolation from earth or one point connection to earth through an impedance. The second letter describes the relationship between exposed conductive parts and earth. The T, again, means a direct connection to earth while the N means a direct connection to the earthed point of the system. Figure 5 illustrates the different earthing systems. A TN system has at least one part of the source of energy directly earthed and the exposed conductive parts are connected to it by protective conductors. In total, there are three different types of TN systems, described with letters C and S. The C represents a combined protective earthing and neutral conductor and the S tells that they are separated. A TT system has just one part of the source of energy directly earthed and the exposed conductive parts are connected to earth electrodes, which are independent of the source. An IT system has no direct connection between the live parts and earth, but the exposed conductive parts are earthed. (Lakervi & Holmes 1995, Wright & Newbery 2004)

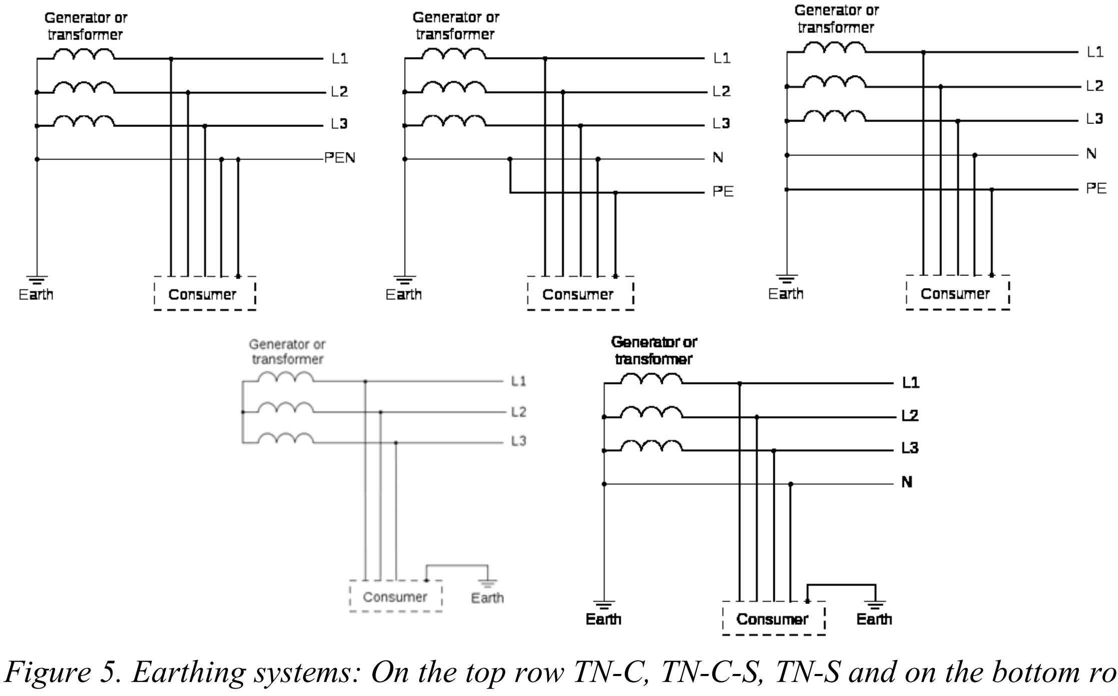

Figure 5. Earthing systems: On the top row TN-C, TN-C-S, TN-S and on the bottom row TT, IT. (Parmar 2011)

In Finland the LV network is a TN-C system, in which there is a combined neutral and protective earthing conductor, also known as a PEN conductor. The PEN conductor in a distribution network must be grounded at the supply point or at most within 200 meters from it. In addition, each line or branch that is over 200 m long must be grounded at the end of the line or at most within 200 m from the end. For overhead network, earthing is recommended at least every 500 meters for working overvoltage protection. If bad earthing conditions prevail, meaning that impedance is not under 100 ohms, earthing is required for each branch, disregarding the 200-meter rule. (Lakervi & Partanen 2008)

During the planning of a protection system, it is important that the protection is technically and economically correctly dimensioned according to protected network and equipment. Interruption costs of LV networks are usually much lower than those of MV networks. For that reason, improving reliability should not be as costly for LV networks as for MV networks. Protection devices should not be as expensive nor as effective. Economic drivers have led to the situation that the most common protection device of a LV network is a fuse. Fuses are placed in each feeder for each phase in a distribution substation. A fuse is dimensioned to withstand the load current but to blow fast enough during a single-phase short circuit occurring at the end of the network. If those terms are not possible, a bigger line or an additional fuse is needed. (Lakervi & Partanen 2008)

In addition to placing fuses to the distribution substation, more are put to other parts of the network to make sure the whole network is safe from overcurrents. The placement of fuses differs with overhead and underground networks. In overhead networks, additional fuses can be placed in each branch, but it is not always necessary. However, in underground networks the branches are directed through the distribution cabinets. In the cabinets, a common practice is to equip each output with fuses. The last fuses are found from the connection points where each one has a main fuse. The fuse protection in detail is covered in chapter 4. (Lakervi & Partanen 2008)

In addition to the overcurrent protection, distribution transformers have overvoltage protection. The goal of overvoltage protection is to cut off the highest peak of, for example, a lightning impulse, so that the voltage level remains under the withstand level of the protected equipment. The protective devices are spark gaps or surge arresters. Small animal protection is also recommended for distribution transformers to stop birds and squirrels and such from getting in touch with energized parts. (Lakervi & Partanen 2008)

2.5 Planning

The long lifetime of distribution networks emphasizes the importance of careful planning. Short term planning for small areas might be an easy task, but the long-term planning of vast areas with great attention to detail is certainly more challenging. Upcoming trends, such as the development of electric mobility or distributed generation, could be hard to predict correctly, but they need to be a part of the decision making. However, the effects of uncertainty on fuse planning are not too severe. Fuses are quite cheap and easy to change, so it is not necessary to think about the distant future. The most important thing in fuse planning is to keep the fuses within the limits that the network puts on them. (Lakervi & Partanen 2008)

In general, distribution network planning consists of many different tasks. The time span of the planning could be as long as tens of years. For example, network reservations for areas that will be built 20 years from now. The various tasks could be categorized as long-term development planning, network planning, field planning, structure planning and working phase planning. The goal in each phase is to find technically feasible solution with minimal lifetime costs. A general plan would include planning, investment, loss, interruption and maintenance costs. The technical boundaries could be: voltage drop in allowed limit, conductors' thermal limits, conductors withstand short circuits, protection orders are fulfilled as well as electrical safety issues. (Lakervi & Partanen 2008) The fuse planning is part of the network planning.

It is important to note that the distribution network business is regulated monopoly. The supervisory body is the Energy Authority. Supervision includes economic and technical monitoring. The targets of economic monitoring are profits and efficiency of the DSOs. Each DSO has a maximum profit level that they cannot exceed, or they must pay money back to the customers. That level depends on the value of the network, which has a clear connection with investments. The economic monitoring should drive the DSOs to have careful planning processes of new network to ensure desired profitability. The quality of supply is also a part of the economic supervision as it is linked to the efficiency of operations. Thus, the quality of supply is also directly linked to maximum allowed profits. In Finland also interruption of supply related costs can adjust the profit level of DSOs. (Lakervi & Partanen 2008)

3 Fuses

Fuse protection is not a very recent invention. Thin metallic wires have been used for protection of a circuit at least since 1774, first by Edward Nairne to add a safety element to discharging a capacitor. The demand and use of fuses popularized with the spreading of electrical lighting starting after a demonstration by Joseph Swan in 1878 in Britain. Almost simultaneously, Thomas Edison did the same in the USA. The first patent of fuse, mentioning lead safety wires, was introduced by Edison in 1881. At first, the fuses were designed to prevent the lamps from over-running, not as protection against overloads or short circuits. (Gelet 2007, Wright & Newbery 2004)

Fuses have a vital role in protecting components of electrical networks and ensuring the safety of electricity users by limiting the impacts of inevitably occurring faults. A fuse is such a common device that most electricity users should know about their existence and purpose. For most people, fuses have become familiar thanks to the homes of people where the fuses bring up their existence from time to time by blowing and waiting for replacement. Even though fuses appear to be simple devices, at least for the ordinary electricity user, great attention must be paid in the designing and manufacturing processes, to ensure their performance is at the desired level. Despite simplicity, for example the arcing process still requires more research leading to improvement of the performance of fuses. (Wright & Newbery 2004)

The advantages of fuses forms a long list: high breaking capacity (current interruption rating), simple short circuit calculations, easy and inexpensive to implement in a system with high fault currents, faults forced to be dealt with by the user as fuses are not resettable, reliable with no moving parts or worries of dust, oil or corrosion, cost-effective, compact size, limitation of short-circuit energy and peak currents to extremely low levels, silent, fast operation at high currents, easy coordination, standardized performance, improved quality of power supply as fast operation minimizes voltage dips and no maintenance. The long list of advantages makes a fuse a very attractive protective device. (Wright & Newbery 2004)

In LV networks, the main part of the network the fuses protect are the conductors, but fuses can also be used to protect components such as voltage transformers, capacitors, semiconductor devices, rectifiers, DC thyristor drives, inverters and special applications. (Wright & Newbery 2004) The efficiency of a fuse can be highlighted by stating that a fuse performs the works of relay, breaker, disconnector, telecommunication and instrument transformer, all at the same time, inexpensively and often within technical boundaries (Mörsky 1993).

Fuses can be split into three categories: high voltage, low voltage and miniature. The dividing line between LV and HV fuses is 1000 V AC or 1500 V DC. This thesis focuses on LV fuses because they are the ones used in LV networks. HV fuses can be found, for example, in MV networks and they can also be considered quite important relative to this thesis as the coordination between the LV fuses in the secondary side and the HV fuse in the primary side of a distribution substation is necessary. Miniature fuses are designed for smaller electric applications. (Wright & Newbery 2004)

3.1 Operation

The simple working principle of fuses is that a relatively short and thin strip of conducting material, the fuse element, is connected in series with the circuit. Having such a small cross-sectional area, the element can only carry currents up to a certain limit, after which the element melts. By melting and breaking the current flow, the fuse can protect, for example a cable, which is significantly longer and thicker, from overcurrents. The fault gets permanently cleared as the medium inside the fuse, around the element, turns into a good insulator filling the cartridge. The medium inside the cartridge, commonly silica, can absorb very high energies by fusing and vitrification, further protecting the circuit by limiting energy let-through. After the operation, the fuse cartridge gets destroyed and it must be replaced. However, the fuse is a small sacrifice compared to the long conductor, which could be damaged, and lots of materials are saved. The fuse can be inserted to a selected part of the circuit where protection is needed. (Grigsby 2012, Legrand 2009a, Wright & Newbery 2004)

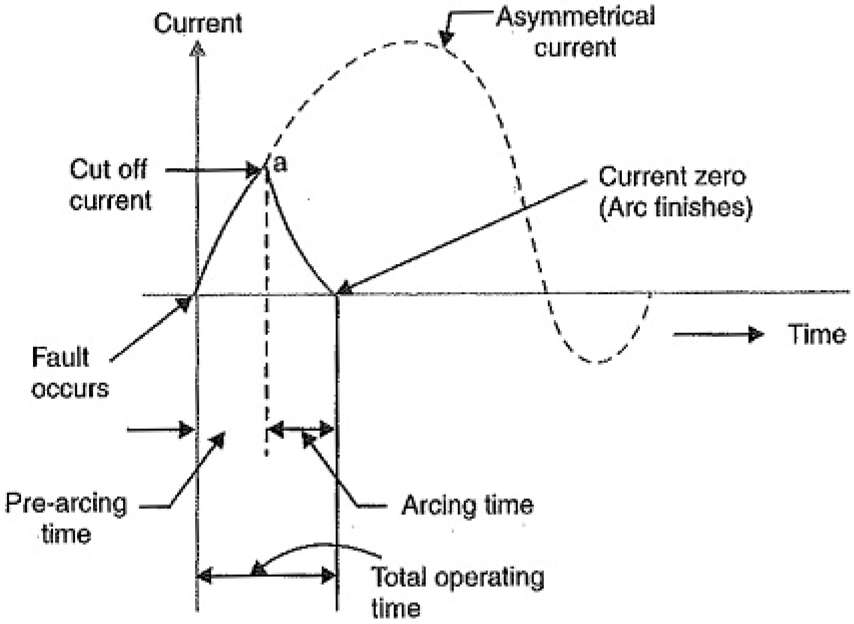

Figure 6. Operation of a fuse illustrated as a function of time and current. (EEEGuide 2018)

The operation of a fuse during a fault situation is illustrated in Figure 6. The operation consists of two phases: pre-arcing, followed by arcing. Pre-arcing stage refers to the time period starting as the minimum energy required by the fuse to start melting is reached and lasting until the fuse element melts and breaks. Arcing supposedly starts when a gap in the fusing element becomes ionized as a result of the rapid buildup of voltage across it. The current limitation properties of a fuse can also be seen from Figure 6, because the maximum value of the current would reach is much higher if the fuse did not exist.

The time of the pre-arcing period depends on the amount of current. The larger the current is, the faster the fuse element melts. It is important to acknowledge that the ambient temperature affects fuse characteristics. A rise in temperature leads to a lower minimum fusing current because the melting temperature of the element is then reached faster. In the same way, cooling of some applications where fuses are used affects the operation time. Thermal stresses play an important role in detailed selectivity analysis. The important thresholds are pre-arcing, arcing and total thermal stresses. The minimum energy required by the fuse to start melting corresponds to the pre-arcing thermal stress. The arcing thermal stress is the energy limited between the end of pre-arcing and total melting. The total thermal stress is a sum of the pre-arcing and arcing thermal stresses. (Legrand 2009a, Wright & Newbery 2004)

When the fuses are not operating, they are just idle components in a network. They are not too harmful in terms of losses because the power consumption of a fuse is quite low. For example, fuses with under 100 A rated currents usually have losses under 10 W and smallest fuses have just losses around 1 W. The power consumption rises along with rated current: 1250 A fuse has a power consumption of about 100 W. The current of the circuit affects the amount of losses. The losses can be cut by choosing a fuse with rated current much larger than the load current or by using special low loss fuses. When a bigger than needed fuse is used, the safety matters need to be checked carefully again. (Mörsky 1993) However, some problems are related to the power consumption of fuses. Because of the number of fuses in a distribution cabinet, low power loss fuse links are preferred to minimize the temperature rise within the cabinet. Additionally, measurable energy savings can be made by cutting the power losses of fuses just based on the number of fuses in the whole network. (Wright & Newbery 2004)

3.2 Structure

The first fuse, similar to the current ones, consisting of a fusible conductor inside a glass tube filled with incombustible, badly conducting materials was patented in 1890 by W. M. Mordey. The fuse element introduced in the patent was made of copper. The filling medium was supposed to be finely divided dry chalk, marble, bath brick, sand, mica, emery or asbestos. The construction of a modern fuse is visualized in Figure 7. In a quick glance, not much has changed in over a century. Today, sand is still the preferred medium to extinguish the arc. During operation, the arc will melt the sand and it turns into a solid pumice, stone like piece after cooling down, which is an excellent insulator. The material forming inside the fuse once it has operated is also called fulgurite. Another unchanged material can be found from the fuse element. According to extensive studies, the best element materials are silver and copper. (Gelet 2007, Wright & Newbery 2004)

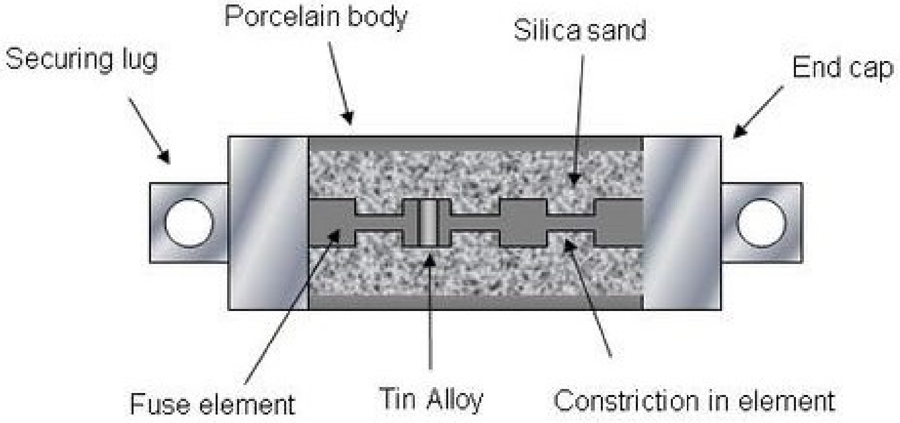

Figure 7. Structure of a fuse including a tin alloy. The element shapes are variable, and a fuse can have multiple elements. (Electronical Concepts 2016)

Even though some components have not changed over the years, development has happened regarding multiple parts of the fuse. The fusing element can be considered the most important part of a fuse because it effectively has the most impact on the performance of the fuse. In the past the fuse elements were just simple wires, but today they are differently shaped and sized metal strips. The modifications in the element design are related to the current rating. The low current ratings require only a single element, but the higher rated fuses consist of multiple parallel connected elements. For further effects, the elements can have holes, cuts and alloys in them, as in Figure 7. The bodies must be good insulators and not let any moisture inside. In addition, good thermal conductivity is desirable along with mechanical robustness, so they do not break from the effects of short-circuit currents. Previously, ceramic and glass were the most popular options, but glass reinforced plastics have gained popularity. The filling material is exclusively chemically highly pure quartz. The grain size can be chosen according to the element thickness and demanded performance. The material also plays a part in conducting heat, in this case from the element towards the body. The packing density of the material must be maintained constant across the production process because it affects the conductivity and arc behavior. In production, the quartz gets poured into the fuse link from an open end. End caps are the connection between the outer circuit and the fuse elements. They are made of plated copper or brass and together with the body, they form a complete enclosure or cartridge. The final phase of assembly is putting the outer end cap on and adding tags. In LV applications, the replaceable fuse link is commonly fitted into a fuse holder, which includes a fuse carrier and a fuse base. (Wright & Newbery 2004)

Instead of a single fusing element, fuse links with high current ratings commonly utilize multiple identical elements connected in parallel. In principle, the current should divide equally among the elements. However, that does not happen in every application. Those situations are important to detect to make sure the fuse still works as intended. Sharing skin effect and the presence of current-carrying conductors near the fuse links (proximity effect) are two possible sources causing the unequal sharing of current. The skin effect causes the current flow to have higher density nearer the surface of the conductor. To eliminate the effect from harming fuses, all elements should have an equal distance from the center, meaning none of the elements should be at the center. The proximity effect grows stronger as the frequencies get higher and will be significant with high currents. Thus, it is necessary to reduce the current ratings of fuse links which are used at high frequencies, to prevent the effects. (Wright & Newbery 2004)

Some fuses have a built-in method, an indicator or a striker, to identify whether a fuse has blown or not for a quick way to see which fuses must be replaced. Indicator and striker rely on the same working principle. A spring that is held back by a wire which melts simultaneously with the fuse element when the fault happens is released. The difference is that the operation of a striker fuse activates a microswitch in the fuse carrier, which communicates the fault with an indicator light and a fuse with an indicator has a disk or a button on the end or the center of the cartridge showing the state of the fuse. (Legrand 2009a, Wright & Newbery 2004)

The material choices are essential as they determine the behavior of the fuse. For example. oxidation must be minimized to avoid weakening of fuses. In the past that was done by using only silver or plated copper. Those materials are unfortunately quite expensive, so plain copper has replaced them. The oxidation has been handled by designing the fuses to operate at lower temperatures. (Wright & Newbery 2004) In normal operation a fuse does not deteriorate. Constant overcurrents, especially near the current limit when the fuse would operate, will affect the fuse, which might lead to maloperation or loss of selectivity. (Mörsky 1993)

The manufacturing of fuses must be very careful and accurate at all stages to ensure even quality of the products. The bodies are tested via pressure, dropping, fast temperature change and crushing. Measurements of the dimensions of the fuses are also checked. End caps are also measured, and hardness and surface finish are checked. Elements are usually bought in strips or wires, so they are also measured carefully. Resistances are also measured to check purity of material. Filling material is checked for purity and grain size. (Wright & Newbery 2004)

3.3 Types of fuses

In Finland, there are two types of LV fuse systems in use. They are D-type fuse system and NH fuse system. The main difference between the two types is that the current rating of D-type fuses is at most 100 A while the limit for NH fuses is 1250 A. (SFS 5490, SFS 5855) The same fuses are used widely in Europe. In addition to having the previously introduced names, fuses can be classified depending on their appearance. The D-type fuses are also known as end-contact fuses, screw-type fuses and bottle fuses, because of their shape, while the NH fuses are blade-contact-type fuses. The letter abbreviations “D” and “NH” come from the German language. Adding to the long list of different names, the “D” can also be called Diazed, which has developed from the words “diametral abgestruft”, which means “diametral steps”. The abbreviation “NH” comes from the words “Niederspannungs Hochleitungs”, which means “low-voltage high-breaking capacity”. (Wright & Newbery 2004)

The D-type fuse system is older than the NH fuse system. Much of the demand for D-type fuses exists because the replacements are still required due to the amount installed in the networks over the years. The D-type fuses are mainly being produced up to 63 A ratings for voltage levels up to 500 V AC. (Wright & Newbery 2004) The breaking capacity of these fuses must be at least 20 kA in 500 V level, but the breaking capacity can reach even 75 kA. Fuses with faster operation have somewhat lower breaking capacities than slower operating fuses. A downside of the fuses comes with the production as satisfactory contacts with the holders are difficult to produce, which leads to the limits in current ratings. Additionally, sometimes the fuse might not be properly in touch with the fuse carrier, which could lead to replacing the fuse. Fuses with blade contacts rarely have such problems. (Mörsky 1993) Similar to the D-type fuses, D0-type fuses also exist. The difference between the two types is that D0-type fuses are physically smaller, so they could fit some applications better. (Wright & Newbery 2004)

For D-type fuses, the elements of the fuse links are strips of copper or silver-plated copper. The fuse links are filled with granular quartz and bodies are ceramic. The bodies can be quite thick to assist with heat dissipation because thermal conductivity of porcelain is higher than that of quartz. The contacts are cylindrical and made of brass, often nickel-plated. The indicators are included as tiny button heads in top contacts. The indicator can be seen through a glass window in the screw cap. As a specialty of the D-type fuses, they have different sized gauge rings to ensure that too large fuses, which would not protect the circuit, cannot be installed. The components required to install D-type fuses are shown in Figure 8. (Wright & Newbery 2004)

Figure 8. D-type fuse fitting example. The screw cap keeps the fuse link in place in the base and the gauge ring ensures the fuse link size is correct. (Eaton 2017)

The NH fuse system is the modern one of the two systems. In addition to being common in power distribution networks, NH fuses can be found from industrial applications and factory distribution systems. As opposed to the bottle shape of the D-type fuses, the shape of the body of NH fuses is rectangular with the blade contacts on both ends, which can be seen from Figure 9. (Wright & Newbery 2004) The breaking capacity of NH fuses must be at least 50 kA in 500 V. However, they can often break a current of at least 100 kA. The NH fuses are a popular option these days as they offer higher current ratings and higher breaking capacities than the D-type fuses. (Mörsky 1993)

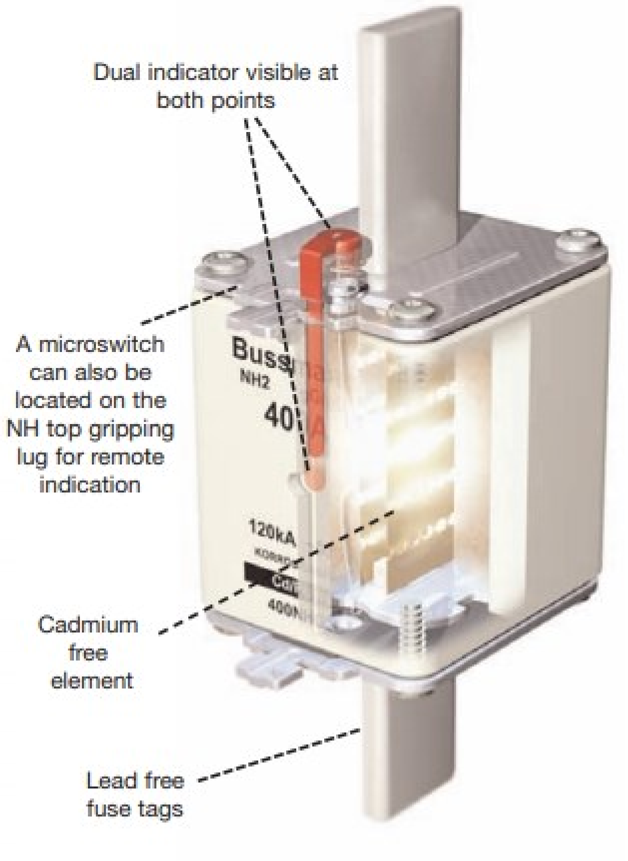

Figure 9. NH fuse link with a dual indicator to declare whether the fuse has operated. (Cooper Bussmann 2009)

For NH fuses, also copper strips are generally used as fuse elements and the body is ceramic or sometimes high-temperature thermosetting plastic. NH fuses are usually equipped with operation indicators, which operate with a small wire that melts as the fuse operates. The breaking of the wire then causes a flag or plunger being pushed out by a spring, indicating that the fuse has blown. The indicator can be in the end plate or at the center of the body depending on which parts of the fuse remain visible after installation. Fuses can also have combined front and end indicators, which is the case in Figure 9, to avoid multiple designs. The structure is highlighted in Figure 9. (Wright & Newbery 2004)

Another factor to categorize fuses by type is not by the system but by the application. Different applications set different limits to fuses. To identify the purpose of a fuse, they are categorized with different letters. The codes consist of two letters, of which the first indicates the main operation and the second category of equipment to be protected. The first letter is either a (associated) or g (general). The letter “a” means that the fuse has to be associated with another protection device because it provides only short circuit protection. General purpose fuses provide both short circuit and overload protection. The second letters and what they stand for: G for cables and conductors, M for motor circuits, R and S for semiconductors, Tr for transformers, N for conductors according to North American standards and D for time-delay fuse for protecting motor circuits according to North American standards. A newer addition is class PV fuses, which are specifically designed for photovoltaic system protection (Siba 2012). The mainly used fuse types in low voltage installations are gG and aM. The gG-fuses offer protection against all overcurrents. The aM-fuses offer high overload and short circuit protection for motors. They allow temporary overloads which occur when the motor is started but require some thermal protection device in addition to protect against low overloads. (Legrand 2009a)

Even though LV fuses are the focus of this chapter, HV fuses are also needed very close to the LV networks. The HV fuses used in Europe are cylindrically shaped cartridge fuses. They can be found from the primary side of the distribution transformers. These fuses have current-limiting abilities, which is not to be taken for granted when it comes to HV fuses. The structure is similar to the LV fuses introduced before, only the shape and materials are differing as they are long and thin cylinders and the arc is extinguished by gases, which form during the operation. (Elovaara & Laiho 1988, Mörsky 1993, Wright & Newbery 2004)

Many of the current-limiting HV fuses are not capable of operating at full range of currents but they are still valid for many applications. They can be categorized as partial range or back-up fuses. Many HV fuse links include strikers, which give indication of operation or a command to trip associated switchgear. The tripping command feature is often essential in three-phase circuits because after a single fuse has operated, the other phases might remain energized, which can cause harm. (Wright & Newbery 2004) Small overloads are problematic for current limiting fuses because the fuse element does not melt at once like with high overcurrents. The danger is that the body of the fuse could burst before the fuse blows as a consequence of the extended heating period. The minimum current the fuse can break safely is from 2.5 to 10 times the rated current of the fuse. (Mörsky 1993)

The current limiting HV fuses can interrupt currents as high as 50 000 A. They can be categorized in three types: general purpose, backup and full range. The general-purpose fuses have the ability to interrupt all currents from the rated maximum interrupting current down to the current that causes melting of the fuse element in 1 h. The backup fuses can interrupt all currents from the rated maximum interrupting current down to the rated minimum interrupting current. The full range fuses are capable of interrupting any current that melts the element up to the rated maximum current. (Grigsby 2012)

3.4 Characteristics

Fuses have a variety of parameters, which are essential when the operation of a fuse is observed. A brief introduction of the core parameters follows:

- **Current rating** denotes the value of current which the fuse can carry safely without melting. The current rating is the most referenced attribute of a fuse.
- **Breaking capacity** denotes the maximum current which the fuse is able to safely interrupt at rated voltage.
- **Voltage rating** determines the voltage level for which the fuse is designed to. To ensure a fuse can safely clear any fault up to its breaking capacity, the voltage of the circuit must be equal to, or less than, the voltage rating of the fuse. The voltage ratings are reported as the maximum rms AC voltage or the maximum DC voltage or both if the fuse is eligible to either type. It is important that a correct fuse is selected because no rules exist to apply fuses meant for AC to DC circuits or the other way around. (Littlefuse 2009a, Littlefuse 2009b)

3.4.1 Time-current characteristics

The operation of fuses is usually illustrated with time-current curves, which are displayed in Figure 10. The curve will tell how fast the fuse will operate depending on the current (Legrand 2009a). The time-current characteristics of all fuses are inverse, which means that every fuse has a certain maximum current, below which the temperature will always reach equilibrium and the fuse has no risk of operating. From the characteristics every fuse has currents, with which the operating time is infinite. Because of the infinity, those cannot be tested, so minimum fusing current is expressed with a predetermined time, typically 1-4h, that a certain current requires to cause the operation of the fuse. (Wright & Newbery 2004)

The melting time of a fuse element is adjustable by applying a method of time delay. One method is the M-effect, coming from the name of the discoverer A. W. Metcalf, which consists of adding low melting-point alloy to the surface of the element, where it will dissolve the element material when it melts. The fuse structure in Figure 7 includes an alloy on the element. The point of dissolution can then be chosen along the length of the element. Because the dissolution process requires more time than the melting of an unmodified fuse element with smaller cross-section but the same minimum fusing current, the M-effect can be used to create a time delay with small to medium currents. It thus prevents the nuisance of blowing fuses by surges of current occurring in normal service. Even longer time delay can be obtained by adding a large insert of fusible metal in the element. The insert acts as a heat sink because of added thermal capacity. The amount of time delay is controllable by adjusting the size of the insert. On high overcurrents, the fuse element melts quicker at its weakest point, so the delays will not matter. These techniques allow manufacturers to produce more accurate fuses depending on application. (Electricity Training Association 1995, Wright & Newbery 2004)

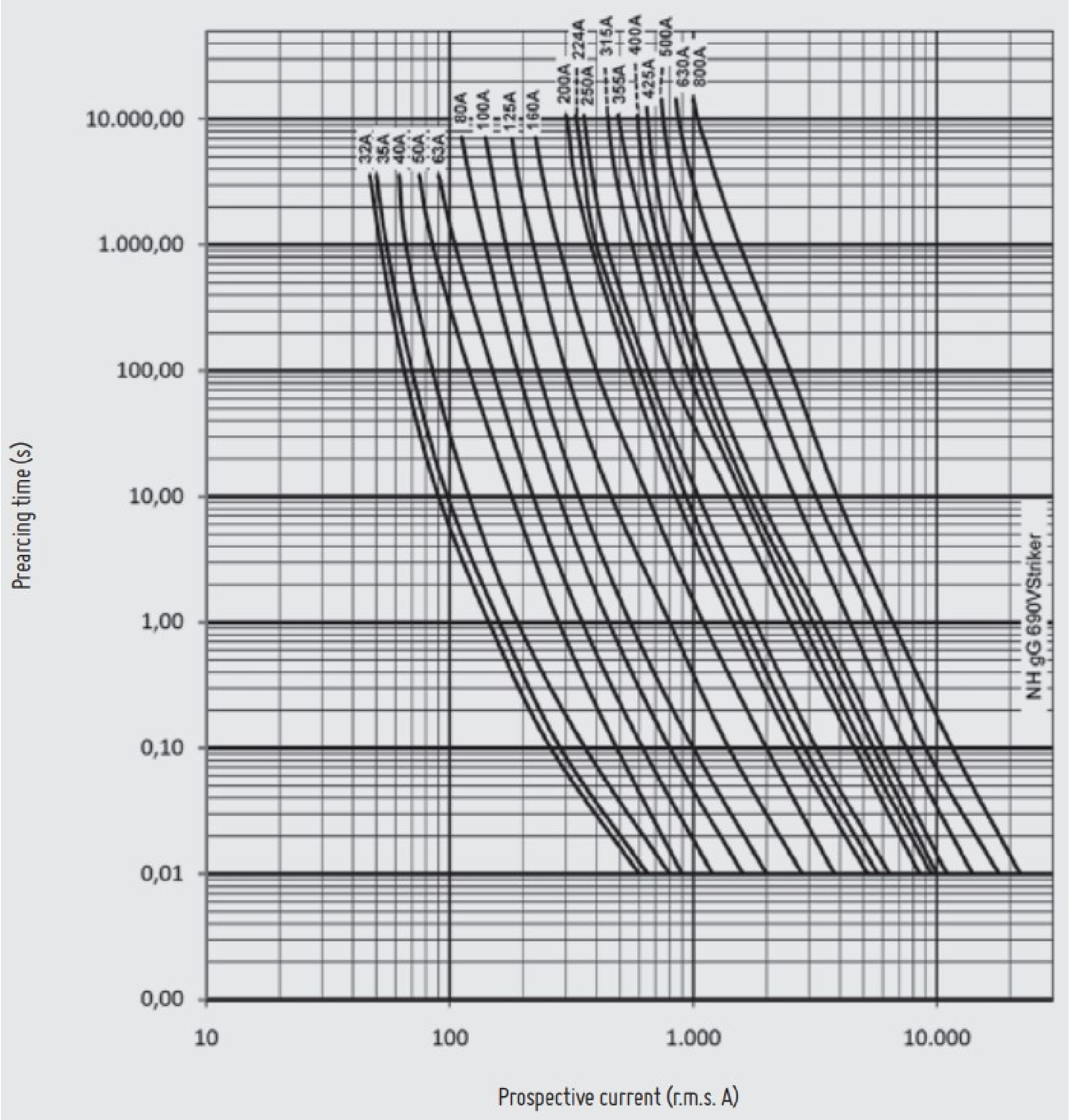

Figure 10. Time-current characteristics of NH gG 690 V fuse links. (DF Electric 2015)

Other factors related to the time-current properties of a fuse are conventional non-fusing and fusing currents. The conventional non-fusing current is the current value, which can flow through the fuse for the conventional time without causing the operation of the fuse. The conventional fusing current is the opposite, referring to the current value, which will cause the operation within the conventional time. (Legrand 2009a) The conventional time depends on the current rating of the fuse. The relations are presented in Table 2 along with the factors to calculate the non-fusing and fusing currents.

Table 2. Conventional non-fusing and fusing currents of gG and gM fuses. (SFS-EN 60269-1)

Current rating I_n (A)	**Conventional time (h)**	**Non-fusing current I_{nf}**	**Fusing current I_f**
$I_n < 16$	1	$1.25 * I_n$	$1.6 * I_n$
$16 \leq I_n \leq 63$	1		
$63 < I_n \leq 160$	2		
$160 < I_n \leq 400$	3		
$400 < I_n$	4		

3.4.2 Current limiting characteristics

A great advantage of fuses is the current limiting effect in fault situations. The prospective current, which would have flowed during the fault, is significantly higher than the current flow with a fuse interrupting the current before the possible maximum value is reached. The higher the prospective current is, the higher also the reduction is in percentages. The current limiting effects can be displayed by cut-off graphs, also known as let-through charts. An example of a let-through chart along with a guide to read them is shown in Figure 11. (Wright & Newbery 2004)

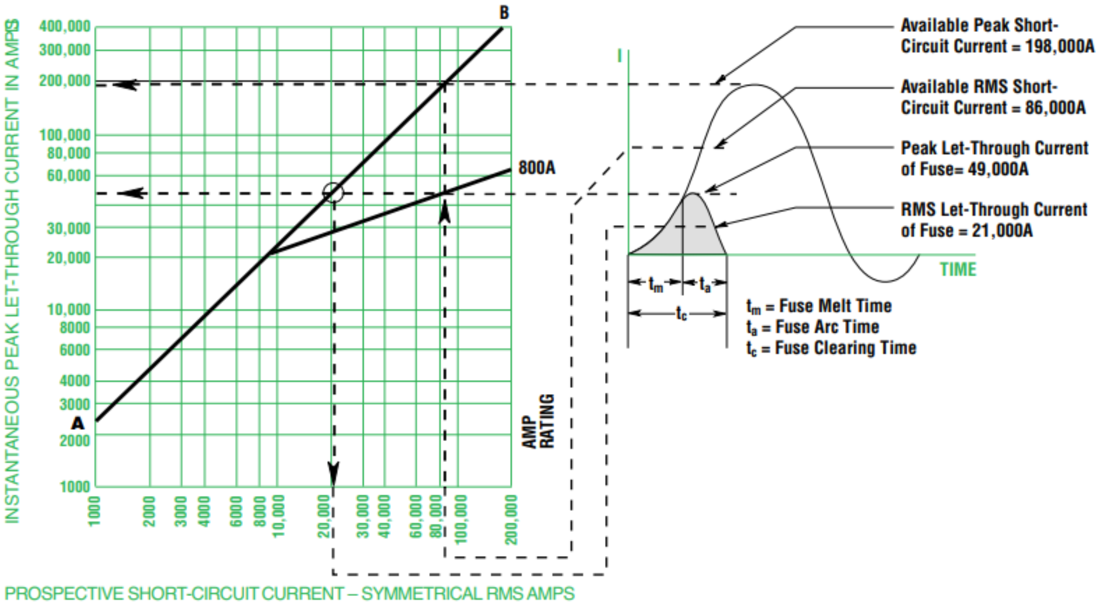

Figure 11. Let-through chart of an 800 A fuse with explanations of the important current values related to it. (Cooper Bussmann 2005)

A significant amount of energy is released during a short circuit. The fuse cartridge reduces the amount of energy to a considerably lower value that is also known as the limited thermal stress, expressed in A^2s. The limitation is vital to prevent destruction of the installation. (Legrand 2009a)

3.4.3 I^2t characteristics

A time integral of the square of the instantaneous current flowing through a fuse link during its operation is called I^2t. It is a more accurate representation of the time-current curves for a quickly operating fuse. The value of the time integral is proportional to the electrical energy that passes through the fuse. However, I^2t is not actually let-through energy, which it is sometimes incorrectly referred as, because it does not contain a resistance component and is thus not in units of energy. If the resistance of the circuit remained constant over the fault situation, I^2t would be proportional to the energy, but the short circuits heat up the components increasing their resistances even quite significantly. (Wright & Newbery 2004) I^2t values are found from the technical data sheets of fuses where they can be expressed only by the numbers or like in Figure 12. The I^2t values are useful to determine accurate selectivity between fuses. In principle, the selectivity means that only the fuse, which is closest to the fault should operate. Selectivity is discussed more in chapter 4.

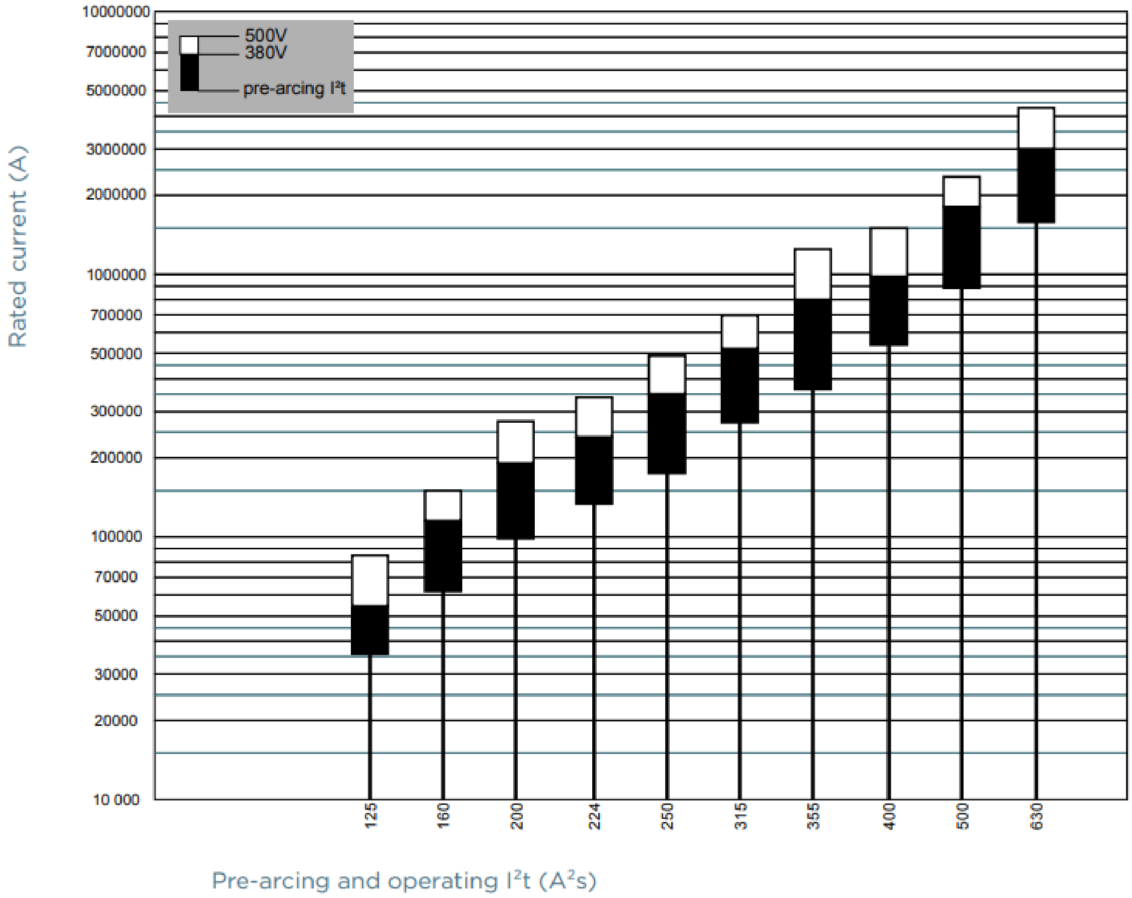

Figure 12. I^2t values illustrated visually. The selectivity is determined by the black (or white) bars: when the bar of the fuse in question is completely below the bar of the other fuse, the fuses are selective. (Mersen 2019)

To determine, whether two fuses are selective, the graph of Figure 12 is useful. When the voltage level is 380 V, only the black bars are used. The lower value of the bar is the pre-arcing I^2t-value and the top value is the total I^2t-value. To achieve selectivity, the total I^2t of the fuse, which should clear the fault has to be lower than the pre-arcing I^2t of the fuse, which is next in line to clear a fault. For example, the graph shows that the 400 A fuse is not selective with the 500 A fuse, but the selectivity is achieved with the 630 A fuse.

4 Fuse protection

The fuse protection of LV networks is a result of applying multiple standards and DSO specific policies together in practice. First of all, short-circuit calculations of the network are required to analyze the fault situations. The standards set limits for the minimum short-circuit currents, according to which the network and the fuses have to be dimensioned. In addition, the DSOs might have certain customers, for which they have set higher minimum values. The values of short-circuit currents are needed to determine how fast the fuses operate. The standards also set the maximum operating time regarding the fuses protecting supply services. Additionally, the DSOs might have their own policies regarding the operation speed of the protection. Generally, the trunk lines and the supply service lines have different requirements concerning the protection, supply services having stricter rules. The fuse protection offers protection from overcurrents, both short circuits and overloads, to the conductors and transformers. Standards advice where overload protection is a must and otherwise it is up to the DSOs to decide whether they think overload protection is important or not. One last aspect of the fuse protection is selectivity, which in practice means that the fault should be cleared by the nearest fuse to limit the effects of the fault as much as possible. Selective protection is desirable but not always possible to implement. Money is an important factor when it comes to the selectivity because larger networks require increasing fuse sizes on every additional distribution cabinet to keep the protection selective. On the other hand, the interruption related costs are quite low in LV networks because the loads are not large. When the target is a minimal cost network, selectivity could be sacrificed to save money.

In the future, distributed generation will complicate fuse protection. Traditionally electricity has been produced in large power plants. However, distributed generation is growing its share because of multiple reasons. The main driver is the will to eliminate carbon dioxide emissions that are coming from fossil fuels burned in the traditional power plants. Distributed generation means for example small scale hydro power, CHP, solar power and wind power. The emissions will drop as clean energy increases its share in the power mix. In addition, the overall efficiency will improve because of lower distribution distances. One more upside is that the distributed generation is easier to build as no huge area is not always necessary. (Lakervi & Partanen 2008)

The concerns regarding the fuses arising from the addition of distributed generation are related to the fault currents. Problems where the fuses do not operate as they were intended to have been recognized and are based on the fact that the distributed generation acts as a new source of short-circuit current, affecting the current fed by the grid. When a new source of fault current is introduced to the network, the already planned protection might not be fit anymore. Blinding of protection and wrong operations of fuses are some examples. (Karppanen 2012)

4.1 Standards

The standards determine the limits within which the low voltage distribution network has to be operated. The relevant standards regarding the fuse protection are are included collection SFS 6000 Low-voltage electrical installations, especially Part 4-43: “Protection for safety. Protection against overcurrent" and Part 8-801: "Supplementary requirements. Public distribution networks". The important standards concerning the fuses are "SFS 60269-1 Low-voltage fuses. Part 1: General requirements", "SFS 5490 Low-voltage fuses. Supplementary requirements for fuses for use by authorized persons (fuses mainly for industrial application). Fuses with fuse-links with blade contacts" and "SFS 5855 Low-voltage fuses. Supplementary requirements for fuses for use by unskilled persons (fuses mainly for household and similar applications). D-type fuses". The SFS 6000 collection is based on corresponding CENELEC HD and IEC standards and harmonized documents (SFS 6000-1).

The most important standard relative to this work is SFS 6000-8-801, which has no international examples. It covers the LV network from the LV contacts of the transformers to the contacts of the main fuse or some other protection device on the connection point. Lots of topics that are relevant to this work are discussed in the standard, including the overcurrent protection, for which the rules are given in the standard. Overload and short-circuit protection are treated separately.

4.2 Short circuit and calculation

Short circuit is an accidental or intentional connection between one or more conductive parts which forces the potential difference between those conductive parts to zero or close to zero (SFS 6000-1). Short-circuit current is an overcurrent occurring during a short circuit. In a distribution network, a short circuit can happen between two or three phase conductors and the short-circuit current is typically greater than the normal load current. The fault can also happen between phase and earth. The faults can cause damage to people and animals, overheating of conductors and other components and interruptions to electricity distribution. In LV networks the damaged part of circuit is disconnected after a fuse operates. (Lakervi & Partanen 2008)

A short-circuit current, as seen in Figure 13, has a decaying DC component, which has an initial value depending on the time of the short circuit and a decaying speed depending on the R/X ratio of the circuit, in addition to the AC component, which might also have a decaying part. The initial symmetrical short-circuit current decays until it reaches the steady-state short-circuit current as a result of increasing reactance during the fault situation. The peak short-circuit current is the value of the first peak of the short-circuit current occurring right after the fault.

Short circuits are not limited to only safety matters, but also the quality of supply suffers. Three phase no load short circuit drops the voltage to zero at the fault location. However, also other feeders experience voltage sags. The size of the sags depends on the location of the fault, the closer it is to the busbar, the worse sags other feeders suffer. (Lakervi & Partanen 2008)

Short circuits have two dangerous effects: electrodynamic and thermal. The electrodynamic effects will cause mechanical damage to the insulation of the conductors depending on the achieved peak current of the short circuit. The thermal effects are able to burn the insulation of the conductors depending on the thermal energy dissipated during the short circuit. Fortunately, fuses limit those effects as much as possible. (Legrand 2009a)

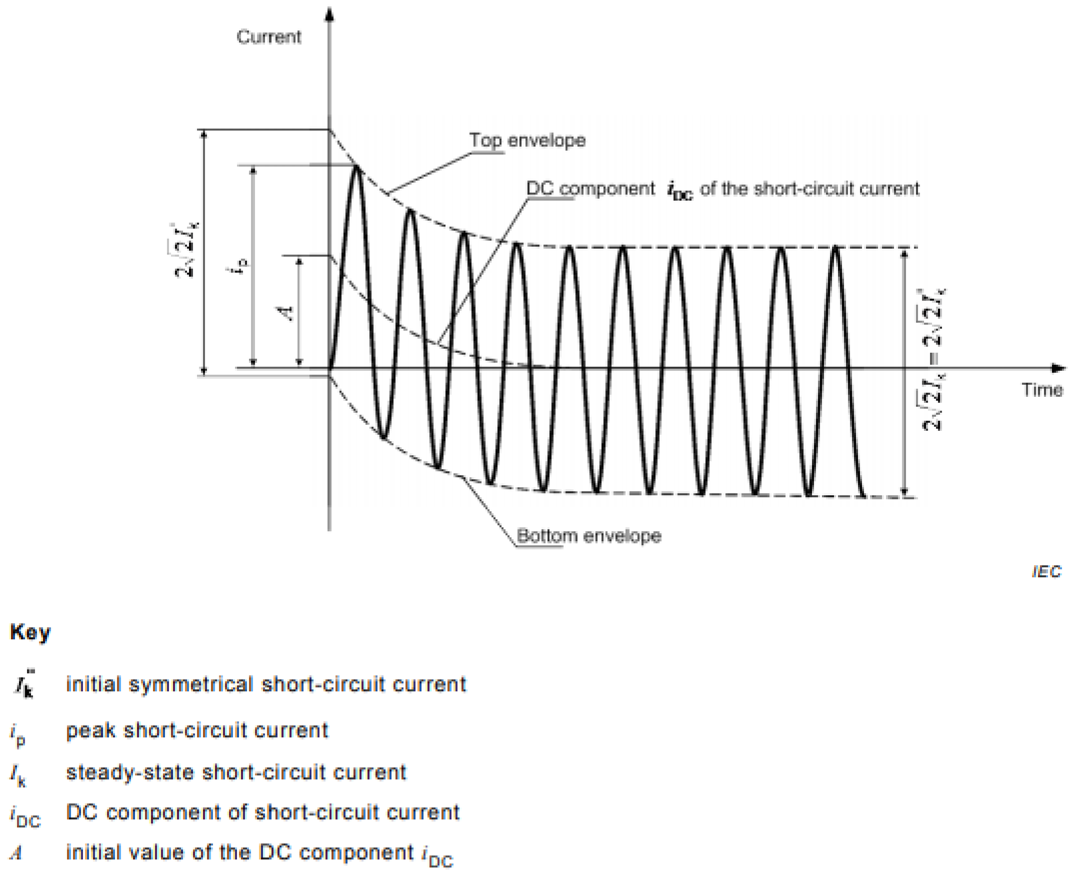

Figure 13. Visualization of short-circuit current when a fault occurs. (IEC 2016)

Calculation of the short circuit currents is essential when determining the right fuse size. For calculation purposes, the components of the distribution system are modeled with equivalent circuits. Regarding the conductors, resistance is obtained from the resistivity of the material, line length and cross-sectional area. Reactance is proportional to magnetic field and depends on the distances of the phase conductors from each other. The reactance for an overhead line is essentially greater than for an underground cable. For transmission lines, resistance could be neglected because of thick lines, but that is not the case for distribution lines. (Lakervi & Partanen 2008)

The largest short circuit currents occur on transformers. The transformers rarely have a given short circuit resistance and reactance, but they usually have short circuit impedance, rated power and load losses. From those values short circuit resistance can be obtained with the following equation:

$$u_r = \frac{P_k}{S_N} \tag{1}$$

where

P_k = load losses
S_N = rated power

After this the short circuit reactance can be obtained with the following equation:

$$u_x = \sqrt{u_z^2 - u_r^2} \tag{2}$$

where

u_z = short circuit impedance

With these values also the resistance and the reactance of the transformer can be calculated with following equations:

$$R_t = u_r * \frac{U_N^2}{S_N} \tag{3}$$

$$X_t = u_x * \frac{U_N^2}{S_N} \tag{4}$$

where

U_N = the rated voltage of the transformer. (Lakervi & Partanen 2008)

For network planning purposes, two types of short-circuit currents are important to determine:

- The minimum single-phase short-circuit current
- The maximum three-phase short-circuit current

The minimum short-circuit current is necessary to calculate for ensuring that each fuse operates in its target time to clear any fault fast enough. The maximum short-circuit current is needed to evaluate whether the conductors withstand such currents without getting damaged and that the fuse is able to break the current without failing.

To calculate the short-circuit current, the voltage and impedance seen from the fault location are needed. (Lakervi & Partanen 2008)

In general, the short-circuit currents can be calculated with the following formula:

$$I_k = \frac{U}{Z_k} \tag{5}$$

where

U = the phase voltage
Z_k = the impedance seen from the fault location (Lakervi & Partanen 2008)

Depending on the fault type, the fault impedance is formed from positive sequence, negative sequence and zero sequence impedances. To calculate the maximum three-phase short-circuit current, the short-circuit impedance is equal to the positive sequence impedance. (ABB 2007) A voltage factor c is used to calculate maximum and minimum values. In LV, values of the factors are for $c_{max} = 1.05$ and $c_{min} = 0.95$. The equation for maximum three phase short-circuit current is:

$$I_{k3max} = \frac{c_{max} * U}{\sqrt{(R_k + R_t + \sum_i l_i * r_{1i})^2 + (X_k + X_t + \sum_i l_i * x_{1i})^2}} \tag{6}$$

where

c_{max} = voltage factor for maximum short-circuit current
U = phase voltage
R_k = short-circuit resistance of the feeding network
R_t = short-circuit resistance of a transformer
r_{1i} = positive-sequence resistance of a line (per length)
l_i = length of a line
X_k = short-circuit reactance of the feeding network
X_t = short-circuit reactance of a transformer
x_{1i} = positive-sequence reactance of a line (per length)

The minimum single-phase short-circuit current is somewhat more complicated. It can be calculated with the following equations:

$$I_{k1min} = 3 * \frac{c_{min} * U}{\sqrt{R_{k1}^2 + X_{k1}^2}} \tag{7}$$

$$R_{k1} = 2 * R_k + (2 * R_t + R_{t0}) + \sum_i l_i * k_T * (2 * r_{1i} + r_{0i} + 3 * r_{ni}) \tag{8}$$

$$X_{k1} = 2 * X_k + (2 * X_t + X_{t0}) + \sum_i l_i * (2 * x_{1i} + x_{0i} + 3 * x_{ni}) \tag{9}$$

where

c_{min} = voltage factor for minimum short-circuit current
U = phase voltage
R_{k1} = short-circuit resistance of fault location
R_k = short-circuit resistance of the feeding network
R_t = short-circuit resistance of a transformer
R_{t0} = zero-sequence resistance of a transformer
l_i = length of a line
k_T = temperature dependency coefficient of phase conductor
r_{1i} = positive-sequence resistance of a line (per length)
r_{0i} = zero-sequence resistance of a line (per length)
r_{ni} = resistance of the neutral conductor of a line (per length)
X_{k1} = short-circuit reactance of fault location
X_k = short-circuit reactance of the feeding network
X_t = short-circuit reactance of a transformer
X_{t0} = zero-sequence reactance of a transformer
x_{1i} = positive-sequence reactance of a line (per length)
x_{0i} = zero-sequence reactance of a line (per length)
x_{ni} = reactance of the neutral conductor of a line (per length) (Trimble 2019b)

4.3 Short circuit protection

Protection devices must be used to break and limit the short circuit currents before thermal and mechanical effects cause harm and danger. Devices being used for protection against short-circuits are fuses and circuit breakers with magnetic relays. In principle, all conductors must be equipped with short-circuit protection, although, some exemptions can be made in certain situations. To protect components from short-circuit, the protection device must have a breaking capacity that is at least equal to the maximum prospective short-circuit current and the breaking time must be low enough, so the conductors do not suffer damage. (Legrand 2009b) The goal of short circuit protection is to prevent damage to lines and equipment caused by the short circuit current and to disconnect the faulty part from the network. The other goal is to assure the safety of the system in fault situations for users and outsiders. (Lakervi & Partanen 2008)

The rules for short-circuit protection are set in the standards. Automatic switch-off time of supply in case of a fault situation can be at most five seconds. The DSO, however, can accept longer switch-off times when they decide the five second rule is not suitable. They can use the information of Table 3 to determine the current rating of the protecting fuse. In the minimum single-phase short circuit calculations, the temperature value must be at least +40 °C. If the short circuits are not protected according to Table 3, the DSO must construct the network in such a way that the voltage during a short circuit does not cause danger. (SFS 6000 801)

Table 3. The minimum short-circuit current, according to which the overcurrent protector for fault protection can be dimensioned. (SFS 600-8-801)

Overcurrent protector	**The minimum single-phase short-circuit current in the distribution network**
gG-type fuse link $I_n \leq 63$ A	$2.5 * I_n$
gG-type fuse link $I_n > 63$ A	$3.0 * I_n$

For the connection points, the five second rule cannot be disregarded. An additional limitation concerns the minimum short circuit current. If the main fuse of a connection point is at least 25 A, the minimum short circuit current must be at least 250 A. If the level of 250 A cannot be reasonably achieved, a minimum short circuit current of 180 A can be accepted. (SFS 6000-8-801)

4.4 Overload protection

An overload is an overcurrent in a circuit with no faults. It is caused by either undersized conductors or oversized load and leads to overheating of the equipment. Protection against overloads is necessary to avoid damage to conductor insulation, connections and surrounding equipment. Devices being used for protection against overloads are fuses, circuit breakers with thermal or electronic release or contactors with measurement relays. (Legrand 2009b)

Overload protection is not required from underground cables, bare overhead lines nor overhead lines with self-extinguishing conductor insulation. Aerial bundled cables must be equipped with overload protection. The overload protection device can be located in either end of the conductor. The main fuses of connection points can act as the overload protection when the sum of the current ratings is at most as high as the maximum fuse size determined by the current carrying capacity of the conductor. (SFS 6000-8-801) Even though the overload protection is not a requirement for every conductor, the DSOs may want to include it in every part of the network to make sure the conductors remain unharmed and functioning.

4.5 Protection of transformers

The protection of distribution transformers is handled with fuses on both HV and LV sides. In a normal situation, the fuses on LV side of the transformer are acting as protection devices for the load circuits and the fuses are dimensioned according to the conductors. In a situation in which the transformers are parallelly connected, the fault current could be fed back into the transformer and the fuses must be dimensioned to protect the transformer in addition to protecting the feeders. The HV fuses on the primary side of the transformer must clear any fault occurring in the transformer. Minimal disturbance to the system as well as limiting the effects of the fault are the driving factors in selecting the right fuse. (Wright & Newbery 2004)

While the total exciting current of a transformer is not much, just 2-3 % of the steady state rated current, the initial transients can reach many times the rated current value in addition to having possibly quite long time constants. The real values of the transients depend on multiple factors, such as the design of the transformer and impedance of the circuit. This affects the fuse protection as the protecting fuse should not operate by the inrush current. In practice, the duration of the initial transient generally increases when the rated power of the transformer grows. However, the ratio of inrush current to rated current generally decreases as the rated power increases. When the actual values are not known, general assumption is that the inrush current ratio to the rated current of the transformer is between 10 and 12, while the duration is 100 ms. (Wright & Newbery 2004)

4.6 Protection of conductors

Protection of the conductors is important to ensure the circuit works as intended. The protection matters regarding the conductors are mostly covered in the standards, so the set of rules applies to every DSO. Short-circuit and overload protection are separated as overload protection is not always necessary. (Wright & Newbery 2004)

To start with the conductor protection, the current carrying capacity of the conductor is very important factor. The capacity is related to the conductor and insulation materials as well as to the cross-section area. Additional properties affecting the capacity are ambient temperature of the surrounding environment and the installation method. (Wright & Newbery 2004)

In practice, to protect the conductors, the current rating of the fuse must be lower than the current carrying capacity and at the same time higher than the maximum load current of the cable. However, conductors are able to carry more current than the capacity implies for shorter periods. To allow this, the fuse should operate only if the higher current level is sustained for an extended period. Frequent overloads, however, are not desirable because they could shorten the lifetime of the conductor. (Wright & Newbery 2004)

The standard SFS 6000-4-43 states that the overload protection of a conductor must fulfill two conditions:

$$I_B \leq I_n \leq I_z \tag{10}$$

$$I_2 \leq 1.45 * I_z \tag{11}$$

where

I_B = the designated current of the circuit
I_z = the current carrying capacity of the conductor
I_n = the current rating of the protection device
I_2 = the current, which ensures the operation of the device in a designated conventional operation time

Figure 14 combines the conditions in one picture for an easier interpretation. The conventional operating times and currents come from the standard SFS-EN 60269-1 and were presented in Table 2.

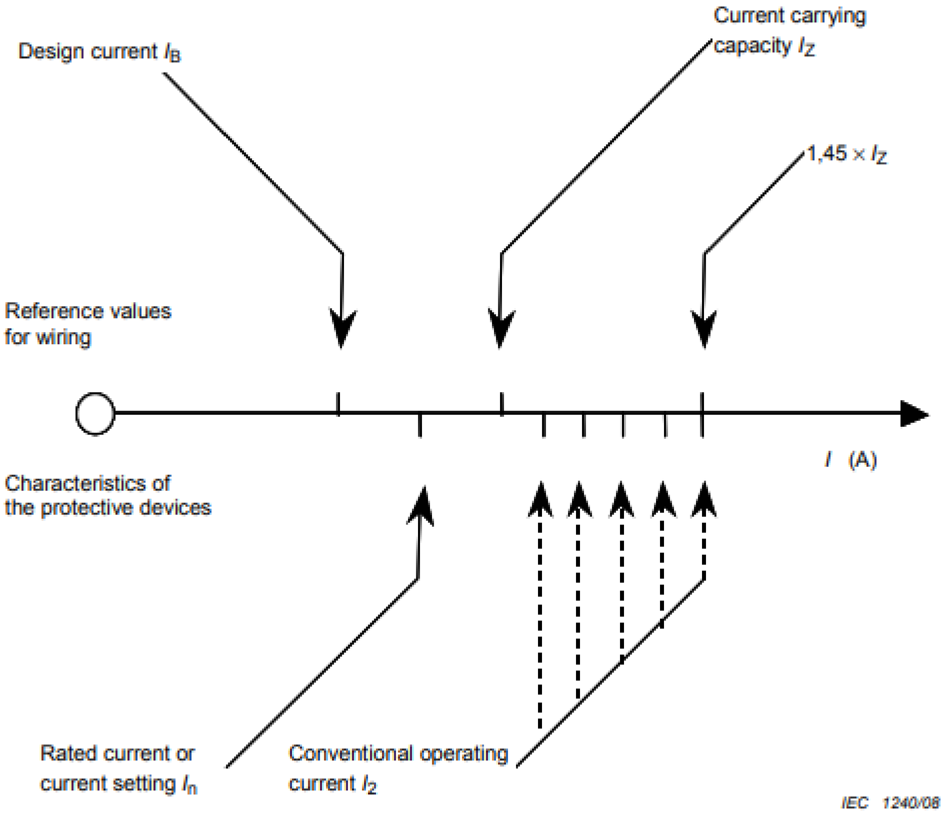

Figure 14. Overload conditions visualized. (IEC 2008)

For conductors, it is important that they can withstand the maximum short-circuit currents. The short-circuit protection of a conductor can be determined with the following formula:

$$t_k = (\frac{k*S}{I_k})^2 \tag{12}$$

where

t_k = duration of the short circuit (s)
S = cross-section of the conductor (mm^2)
I_k = short-circuit current (A) (r.m.s.)
k = coefficient conductor and insulation materials (SFS 6000-4-43)

4.7 Selectivity

Fuses are very often used in coordination with each other. It is important to choose the fuses in a way they operate one at a time, depending on the fault location. Discrimination between fuses can be checked from time-current curves or I^2t-characteristics. The time-current curves should not cross each other, and it is essential to take the pre-arcing periods into account as the curves might only show the total operating times. When the operating times are lower than 100 ms, the curves are not enough but the I^2t values must be compared. The selectivity should be achieved for the fuses, which are consecutive in the network, so the one being closer to the distribution substation can be referred as the upstream fuse, and the fuse further away is then the downstream fuse. For fuses to reach selectivity, the pre-arcing I^2t of the upstream fuse must be higher than the total I^2t value of the downstream fuse. Only then it is sure that the upstream fuse does not operate before the downstream fuse. (Wright & Newbery 2004) According to the standard SFS 6000-8-801, the protection should be selective, but it is not a must. Standard SFS 5855 states that for fuses with current ratings 16 A and more, the selectivity should work when the fuses are from the same series and the ratio of their current ratings is 1:1.6.

Selectivity between the HV and LV fuses is very important to keep the transformer safe and to avoid a single feeder causing fault to the whole substation. That might sometimes be a difficult task because the current ratings of the primary side and secondary side fuses are so far apart. That affects the time-current curves as the steepness of the curves may differ enough for them to cross each other. For selectivity purposes the intersection of the curves should be beyond the maximum fault current of the circuit. In some cases, compromises between sacrificing the selectivity or using unacceptably high current rating fuses on the primary side may need to be done. (Wright & Newbery 2004)

5 Automatic fuse planning

The fuse planning application consists of several phases. Each function has its own purpose and task. The final solution is produced after the functions are run in the correct order. The fuse planning can fail, dismissing the whole network solution when suitable fuses cannot be found. In addition to creating the fuses, the algorithm also forces conductor upgrades in certain situations before failing the solution if the upgrades are not enough. Upgrading of transformer is also one method to increase the maximum fuse size because it may be the limiting factor.

5.1 Trimble Network Optimizer

Trimble Network Optimizer (shortly Optimizer) is a network planning application, which aims to automatically produce a technically feasible, minimum cost network for a given area based on power consumption and location of connection points. The cost minimization takes into account the whole life cycle cost of the network, which include the interruption and maintenance costs and the cost of energy losses along with the initial investment costs. Optimizer is a tool for network planners to help find the most cost-effective network solutions and get rid of recurring manual tasks of the planning process. Additionally, the DSOs can take advantage of the Optimizer by quickly creating target networks for wide areas. Trimble NIS is used with the Optimizer to create the networks. (Trimble 2019a)

The task of the Optimizer is not simple because the number of variables to keep track of is quite high. However, manual planning process is time consuming and the human planner is more prone to errors than a computer software. Another benefit is that the Optimizer can evaluate a huge number of different network configurations during the time it takes the planner to come up with one solution. However, because of some special cases, the Optimizer may not always be a suitable solution for the planning task. The professional planner can be more adaptable to take care of the special situations, but Optimizer will save lots of precious time and money by completing the more regular tasks efficiently.

Optimizer is capable of planning both MV and LV networks. One main difference between the two types is the components of the network. Protection of the network is one of the differences between MV and LV. Where the MV network has various switches, the LV network has fuses. Fuse planning is an essential part of the LV Optimizer alongside cable distribution cabinets, which are not part of the first developed MV environment.

Two different calculation types are possible for the Optimizer, those being greenfield (GF) and brownfield (BF). GF means a completely new network and BF is a new addition to an existing network. GF is a useful tool for planning networks to a completely new area, but BF is more useful for cases where an old network could be utilized in new network plans or when an old network is redeveloped. The development of the fuse planning application leans heavily towards GF networks, because the GF version was developed further than the BF at first. An important part, the BF brings in, are the customer owned lines. They are not planned by the DSOs, but the customer is in charge of their own line. Anyway, the planner must take each of the customer owned lines into account when planning the protection.

Optimizer has a lot of settings for the planner to decide what is needed. The settings can, for example, be related to backup lines or different costs. Fuse planning is one of the more regular tasks, which is repeated for every LV network. At first, the only setting regarding fuses is to decide whether trunk lines are allowed to have a direct busbar connection or short-circuit knives. Other examples for further development could be the overload protection, which is not mandatory by the standards, but some DSOs want each line to be protected, or some special rules related to selectivity, such as using a default fuse wherever possible, because they would be preinstalled in the distribution cabinets.

The networks are formed from nodes, which are the locations of the distribution substations, cable distribution cabinets and connection points. The lines of the network have a node in each end, which are referred as the upstream and downstream nodes. The flow of electricity goes from the upstream node towards the downstream node. In overhead networks, the poles, which are the possible branching points, are also considered as nodes. The fuse planning is focused on underground networks but the fuses for an overhead network can be planned with slight modifications to the initialization phase.

5.2 Requirements

To create an application for automating the fuse planning process, the rules must be first determined carefully. In the start of this project, I met a few professional network planners, who explained the process to me. The information and advices I got formed the basis of the application. It was important to learn the details to make the application as useful as possible for the planners.

A requirement specification regarding the short circuit calculations and the fuse planning was presented as a basis to follow in the developing process. The requirements stated, which abilities are needed, which has been the backbone of this work. Requirements concerning the short-circuit calculation state that the minimum single-phase short-circuit currents must be calculated and the network must be dimensioned according to the connection point specific minimum short-circuit current requirements. Requirements concerning the fuses state that short circuit and overload protection must be available for the whole network according to the rules in the standards. Selectivity is a target, which may not always be realized for different reasons, but it is a desirable feature for every network.

5.3 Short circuit calculation

The short circuit calculations are required to know how fast the fuses operate in a fault situation. It is important that even the smallest fault current causes the fuses in the target time. The short-circuit currents are calculated at each node using the formulas 5-9, which were presented in chapter 4. The maximum three-phase, minimum two-phase and minimum one-phase short-circuit currents are the calculated values. The calculation is done with per unit values, adding flexibility for possible changes in the future.

Special requirements related to the minimum requirement for the smallest fault current at each node are checked and violations are marked to know where improvement should happen. If the minimum short-circuit current at some node is too low, the network components require changes. This is implemented by strengthening the lines of the network to reduce the short-circuit impedance. The strengthening is done by upgrading one line part at a time, starting from the feeder at the transformer. If the minimum short-circuit current is still too low, the next line part towards the fault point is upgraded. The upgrading continues until the minimum requirement is met. After the fault point is reached, the strengthening process starts again from the feeder at the transformer. The loop may continue until no line on the path between the distribution substation and the fault point can be upgraded. If that happens, the whole network solution gets discarded because the basic requirements could not be met. Additionally, the transformer could be upgraded to lower the short-circuit impedance.

5.4 Initial fuses

The fuse planning algorithm starts by adding a fuse to every location that needs one. As the networks are formed from nodes, each fuse is linked to a node to have a location. However, information about the node is not enough because the lines can be protected from either end. To resolve the location of a fuse, it also needs the information about the location relative to the line. The locations of the fuses depend on the network type, because underground and overhead networks have different practices.

The LV switchgear of the distribution substation is a common place for the fuses in every network. Fuses are put in each outgoing feeder of the distribution substation. The next locations are network type dependent. In underground networks, the cable distribution cabinets are the main locations where fuses are placed into. In overhead networks, the fuses do not have a similar structured placement method, but they are placed wherever needed. The placement depends on the load current and minimum short-circuit current, which determine when the previous fuse no longer satisfies the protection targets and a new fuse is required. The differing planning methods complicate the planning algorithm.

The process of determining the maximum fuse size, satisfying the technical limits, for every fuse location is described in the flowchart of Figure 15. The first step is to determine which factor limits the maximum fuse size the most. The three factors are short circuit protection, overload protection and transformer. The maximum fuse size regarding short-circuit protection can be calculated using the equation 12 and comparing the result with the time-current curve of the fuse. However, the Trimble NIS also has technical data about the lines, including the maximum fuse size for short-circuit protection for a trunk line or a supply service. The line data of Trimble NIS are utilized because they are configurable by the user. This way the user has more freedom but has to be sure the values are correct. The maximum fuse size regarding overload protection can be determined with the help of Figure 14. Additionally, the installment conditions have an effect on the ampacity of the line, which have to be taken into account in the planning process. The calculations are not performed in the function, because the line data of the NIS are again utilized. The line data also offer the maximum fuse size for overload protection for a trunk line or a supply service, which is taken advantage of because users have varying line data and might have their own, stricter rules for overload protection.

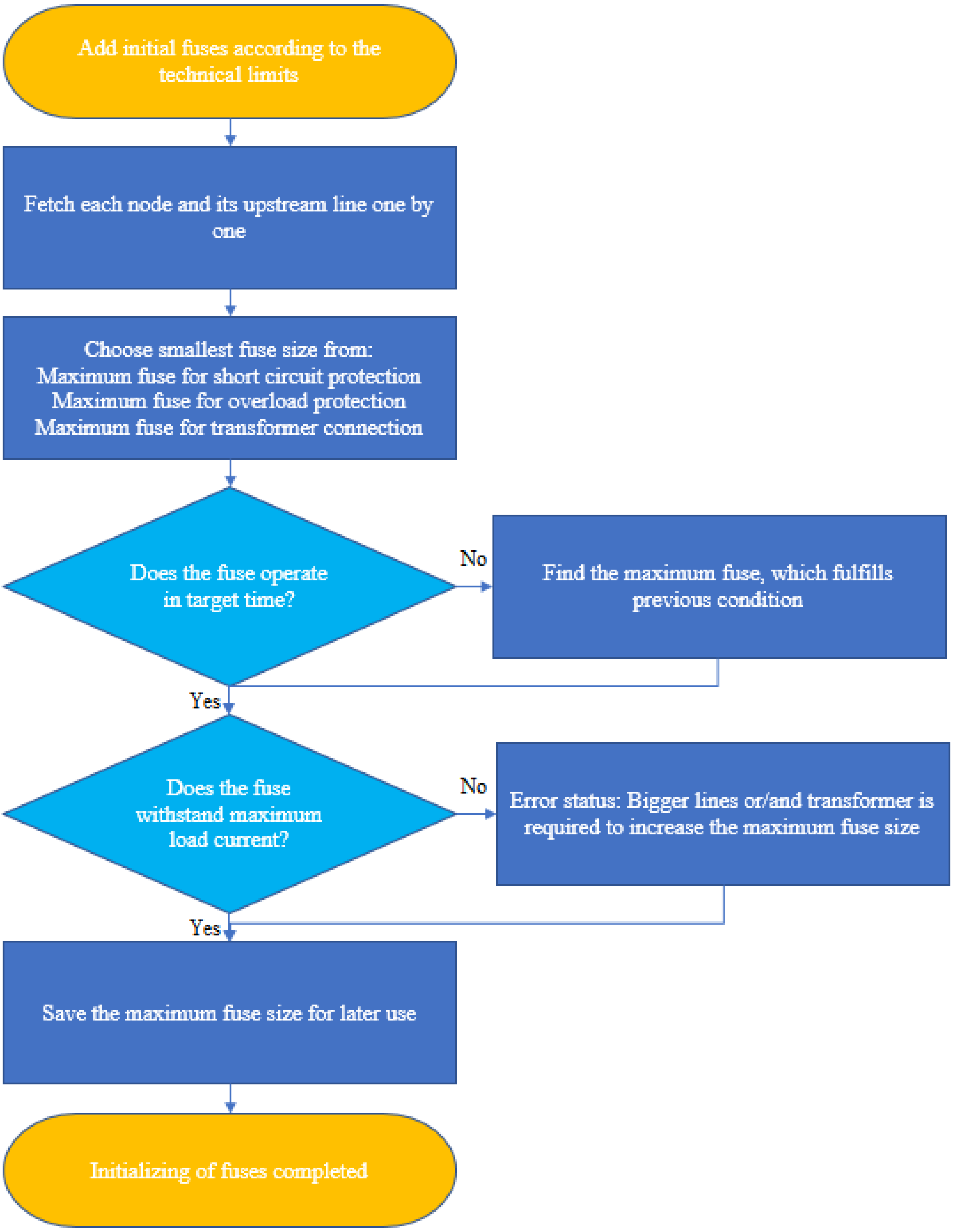

Figure 15. Flowchart describing the logic behind determining the maximum fuses sizes.

The transformers effect on the maximum fuse size is in place to avoid unnecessarily large fuses related to the size of the transformer because they would make the protection slower and their full capacity could not be utilized. The limit for the maximum fuse size for a transformer is determined with the following equation:

$$I_n \leq 1.5 * I_t \tag{13}$$

where

I_n = the current rating of the fuse
I_t = the rated current of the transformer

The rated current of the transformer can be calculated with the following equation:

$$I_t = \frac{S_N}{\sqrt{3} * U_{n2}} \tag{14}$$

where

S_N = the rated power of the transformer
U_{n2} = the rated secondary voltage of the transformer

One more factor, which could limit the maximum fuse size is the operation time condition. The condition is different for a trunk line and a supply service. Both conditions are presented in chapter 4.3 “Short circuit protection”. Most often, the short-circuit current might be the limiting factor in the furthest parts of the network because of higher fault impedance.

The last check before the fuses can be saved for later phases is comparing the current rating of the fuse against the maximum operating current. If the maximum fuse size is lower than the maximum load current, something needs to change in the network. Otherwise, the fuse would constantly operate whenever replaced, constantly disabling the protected network. To solve the situation, the limiting factor or factors must be upgraded to allow the upgrading of the fuse up to a working level. The information about the limiting factor(s), which could be the line(s) or the transformer, is passed on to start the upgrading process. If everything was fine at this point, the maximum fuse sizes are saved for later use and when each of the fuses have been added, the initialization is completed.

5.5 Main fuses of connection points

The main fuses of connection points are an essential part of the fuse planning. The data of the fuses is fetched from the NIS where the main fuses are found from the connection points, which form the initial data for the Optimizer. The main fuses and the connection points are then checked, and necessary warnings are displayed for the user when something is not as it should be.

The flowchart of Figure 16 displays the checks which are performed for the main fuses and connection points. The first check is to compare the current rating of the main fuse against the maximum load current. The same check is performed in the initialization function, but there consequent actions follow. In the case of main fuses, they can only be changed by the planner, not Optimizer. When a warning for this appears, one probable possibility is that the main fuse size is documented wrong in the NIS. Otherwise, the main fuse would need an upgrade, or the consumption should be adjusted. However, those tasks are left to discuss between the DSO and the customer.

Another check, more important regarding this planning algorithm, is whether the main fuse protects the line from overload or not. Depending on the overload protection practices of a DSO, this check might have consequences affecting the conductor sizes. When the overload protection is a requirement everywhere, the other fuses will take care of it. The disadvantage is that selectivity suffers because the fuse protecting the supply service from overload will be smaller than the main fuse, if the supply service cannot be strengthened. The end parts of the supply services often include a customer owned line, which the Optimizer cannot change. When the main fuses are used as the only overload protection, a warning of main fuse not serving as overload protector is necessary. The overload protection requirement could also lead to the need of strengthening the supply service. Often when new network is planned, the fuse protecting the supply service has to be at least equal to the main fuse of the connection point, so the lines might be forced to be bigger than the initial proposal would be.

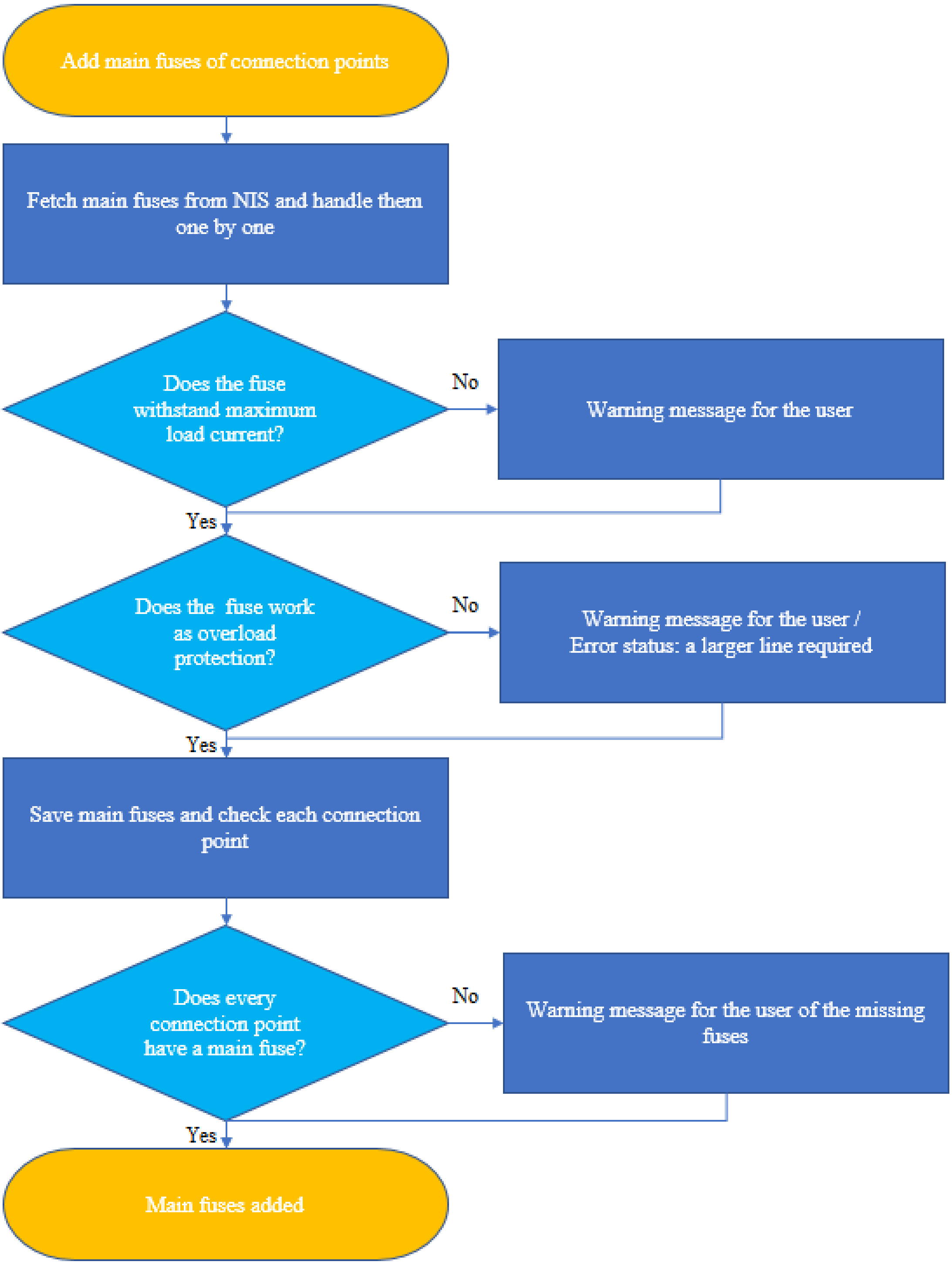

Figure 16. Flowchart describing the logic behind adding the main fuses of connection points

5.6 Strengthening of lines

Strengthening the lines is a vital part of fuse planning. Some situations can only be solved by upgrading the conductor to a larger alternative. An example situation comes up when a conductor is initially selected making sure the current carrying capacity is higher than the maximum load current but the maximum fuse for overload protection is lower rated than the current. In those situations, a larger conductor is required to increase the fuse for overload protection.

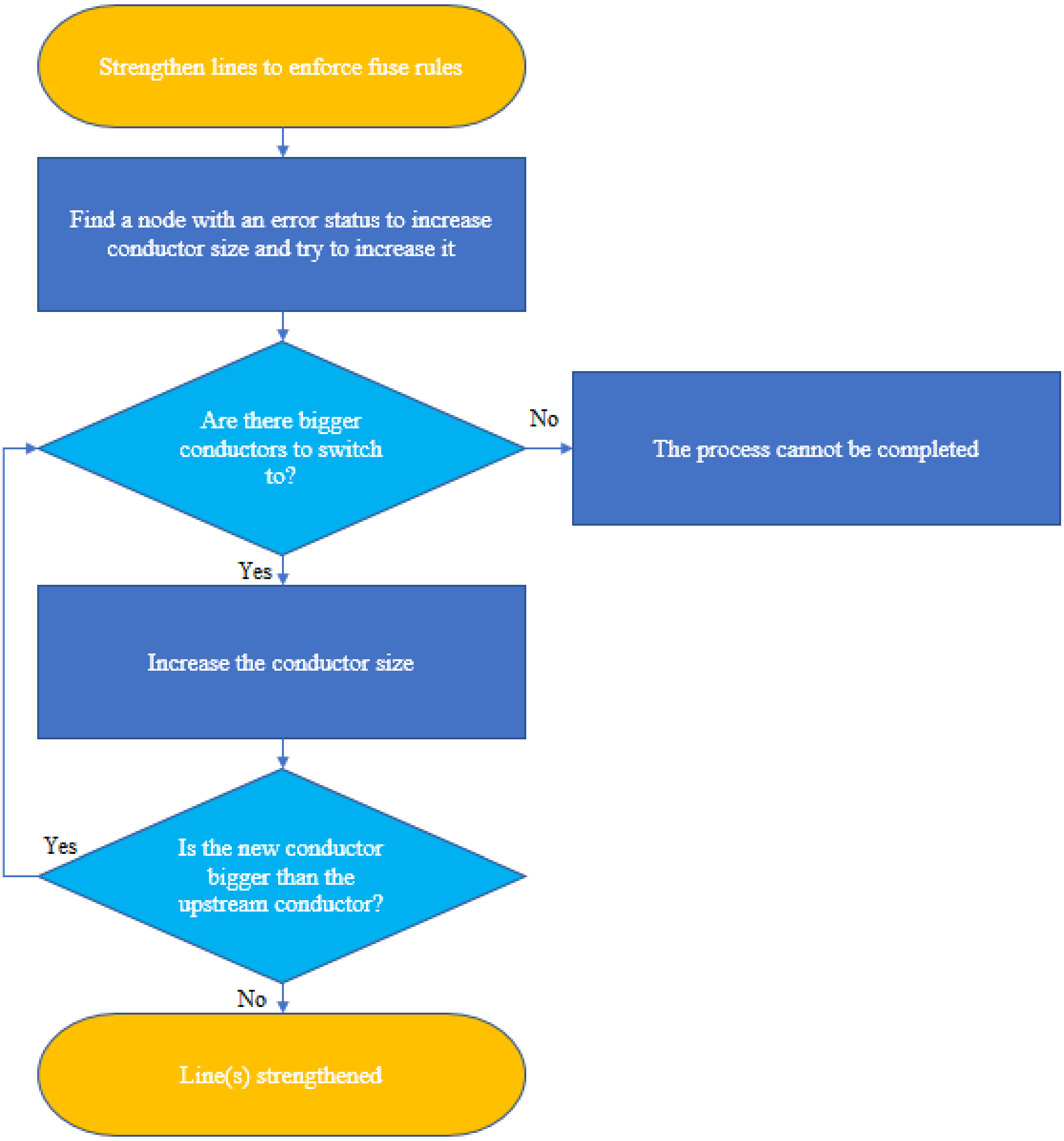

Figure 17. Flowchart to describe the logic behind increasing the conductor size(s) to allow the increase of fuse size.

Figure 17 displays a flowchart describing the line strengthening process. On the contrary to the strengthening process related to the short-circuit currents, the fuse related strengthening starts from the line part where the problem occurs. The first conductor to be upgraded is the one associated with the problematic fuse. When a conductor is upgraded, it is important to keep track of the upstream conductor too. The upstream line must be upgraded too, if the downstream line grows to be larger than it. Otherwise, the lines cannot be used to their full capacity, when the limiting factor is found from the smaller upstream line. Thus, the strengthening process moves to the opposite direction than with short-circuit currents, where the feeder connected to the transformer gets upgraded first.

Another case, when the line strengthening is necessary, is related to the main fuses. The main fuses at connection points are sometimes larger than the consumption would require. As the lines are initially dimensioned according to the consumption data, the maximum fuse of the supply service could end up being lower than the customer main fuse. In those cases, the lines require upgrading to accommodate larger protective fuses. The minimum requirement for new network usually is that the supply service fuse is at least the same size as the customer main fuse.

In situations with customer owned lines, upgrading is not possible. Thus, situations where the customer main fuse cannot be fully utilized because of smaller fuse in the network side are possible. The customer owned lines may still require overload protection according to the policies of the DSOs, which has to be taken care of at the other end of the line, when the customer main fuse does not provide the protection.

5.7 Selectivity

Selectivity is the most complicated part of the fuse planning because of the different possibilities. In an optimal situation, consecutive fuses leave one possible fuse size unused to achieve a ratio of 1:1.6 between the rated currents of the fuses, but a limited number of fuse sizes complicates the situation in larger networks. The most important location, which should be selective is a cable distribution cabinet and the supply services connected to it. The selective configuration secures that a fault in the supply service does not cause the operation of a trunk line fuse. If that happened, a lot of connection points could be left without electricity because of wrong protection configuration.

5.7.1 Full selectivity

The target selectivity is achieved by leaving one fuse size between consecutive fuses. In principle, the rule seems easy to enforce. In reality, the available fuse sizes might not be enough. Up to a certain point, the selectivity could be ensured by increasing the line cross-sections or the transformer size to increase the amount of available fuse sizes. In the end, for a large enough network, even with the largest conductors, the desired selectivity cannot be reached. Additionally, the costs would increase quite a lot if the desired selectivity level was always enforced. For smaller networks, the desired selectivity is reachable.

The flowchart of Figure 18 shows the actions behind making a network selective. The first step is to start from the connection points and move gradually from the furthest points towards the distribution substation. Each fuse is changed to be two sizes larger than the largest consecutive downstream fuse. Then the technical limits are checked to find out if the change is permissible. If any conflicts exist, the fuse size is increased or decreased back within the technical limits. After each fuse is handled, the selectivity, depending on the network, is achieved or not. When the selectivity is not achieved, more actions are taken to improve the partial selectivity to cover the best possible areas.

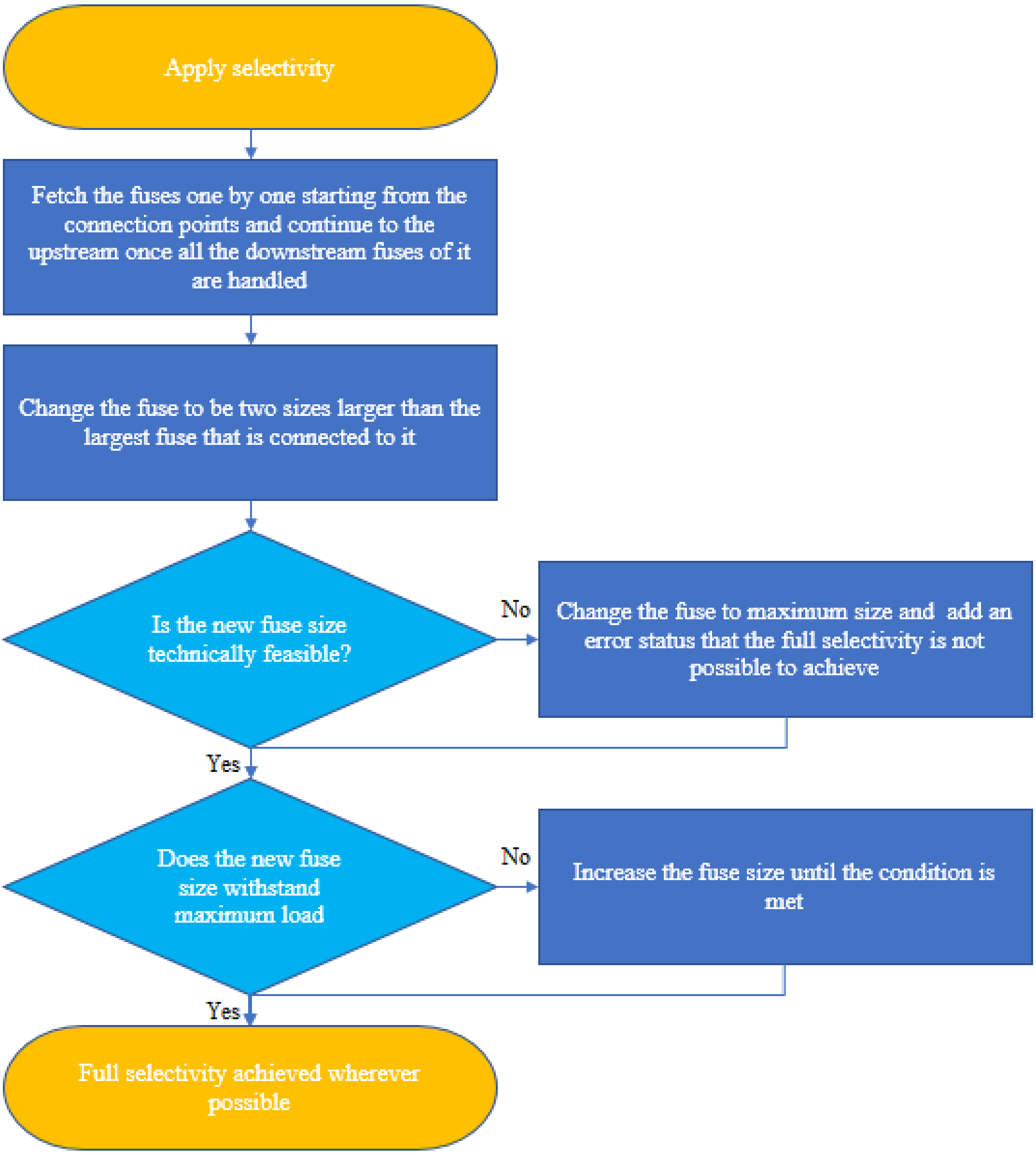

Figure 18. Flowchart describing the logic behind the initial selectivity measures

5.7.2 Best possible selectivity

The goal of adjusting the selectivity to a better direction is to cover as many connection points as possible under the selectivity. When full selectivity, meaning one size in between consecutive fuses, cannot be achieved, the goal is to achieve partial selectivity, which means setting consecutive fuses to have consecutive fuse sizes. When partial selectivity is not a possibility, the upstream fuse has to be at least equal to the downstream fuse. In addition, when the consecutive fuses are equal, the one in the downstream can be changed to short-circuit knives or a direct busbar connection, leaving out the fuse completely.

The process of adjusting the selectivity is illustrated in the flowchart of Figure 19. The previous selectivity function might leave consequent fuses to be equal, but the downstream path could have places with full selectivity. The adjusting here only concerns the fuses between distribution cabinets, so supply service fuses remain untouched. The first step is to find the consecutive and equal fuses and then check if some downstream fuses could be decreased to balance the selectivity to be overall more consistent. The next step is to check if selectivity has differences somewhere in the network. If some differences exist, the aim is to move the most selective parts where most connection points are affected. In practice, the effectivity of selectivity is calculated for each distribution cabinet. It is done by counting how many connection points would lose electricity if during a fault in the downstream line from the cabinet the fuse of the upstream line operated. While the fuses are changed, it is important to ensure that the selectivity between a trunk line and a supply service fuse does not suffer during the process.

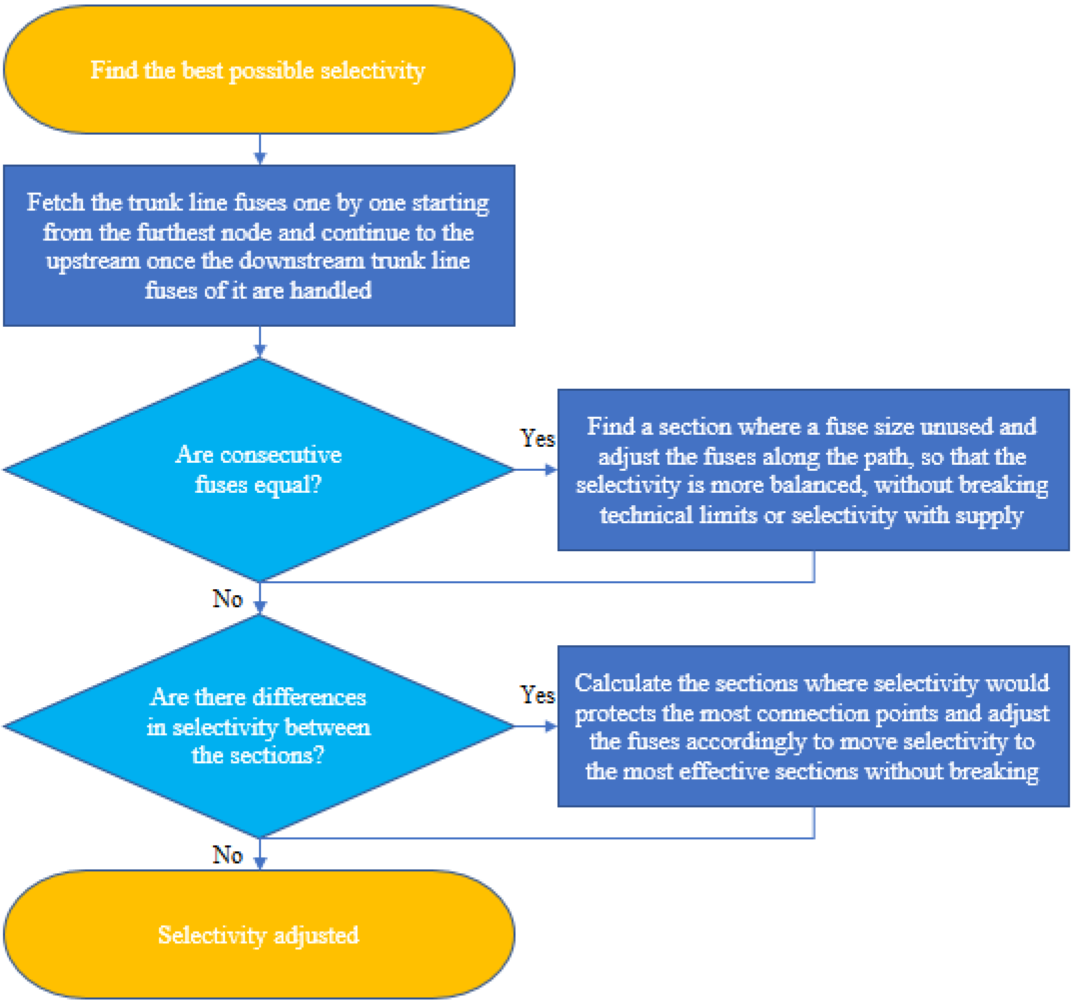

Figure 19. Flowchart describing the logic behind completing the selectivity measures

The process to find out the best locations for the limited selective sections starts from forming distribution cabinet paths from each last cabinet. Then the selective sections are tried to be moved to the cabinets where selectivity would offer most protection. This is not always possible, because every time a fuse is tried to be changed for a bigger or a lower alternative, the technical constraints and the supply service fuses are checked. Those factors may cause a conflict for the changing process and the possibility is discarded.

5.7.3 Selectivity rating

An evaluation of the effectivity of the selectivity should be possible to be performed. This evaluation offers information about the state of the selectivity of the network. The results of the evaluation could be used to push the final network towards better selectivity by associating a cost component related to the selectivity. Again, the DSOs could have differing opinions on how they value the selectivity of the network. Figure 20 explains how the evaluation of selectivity is implemented.

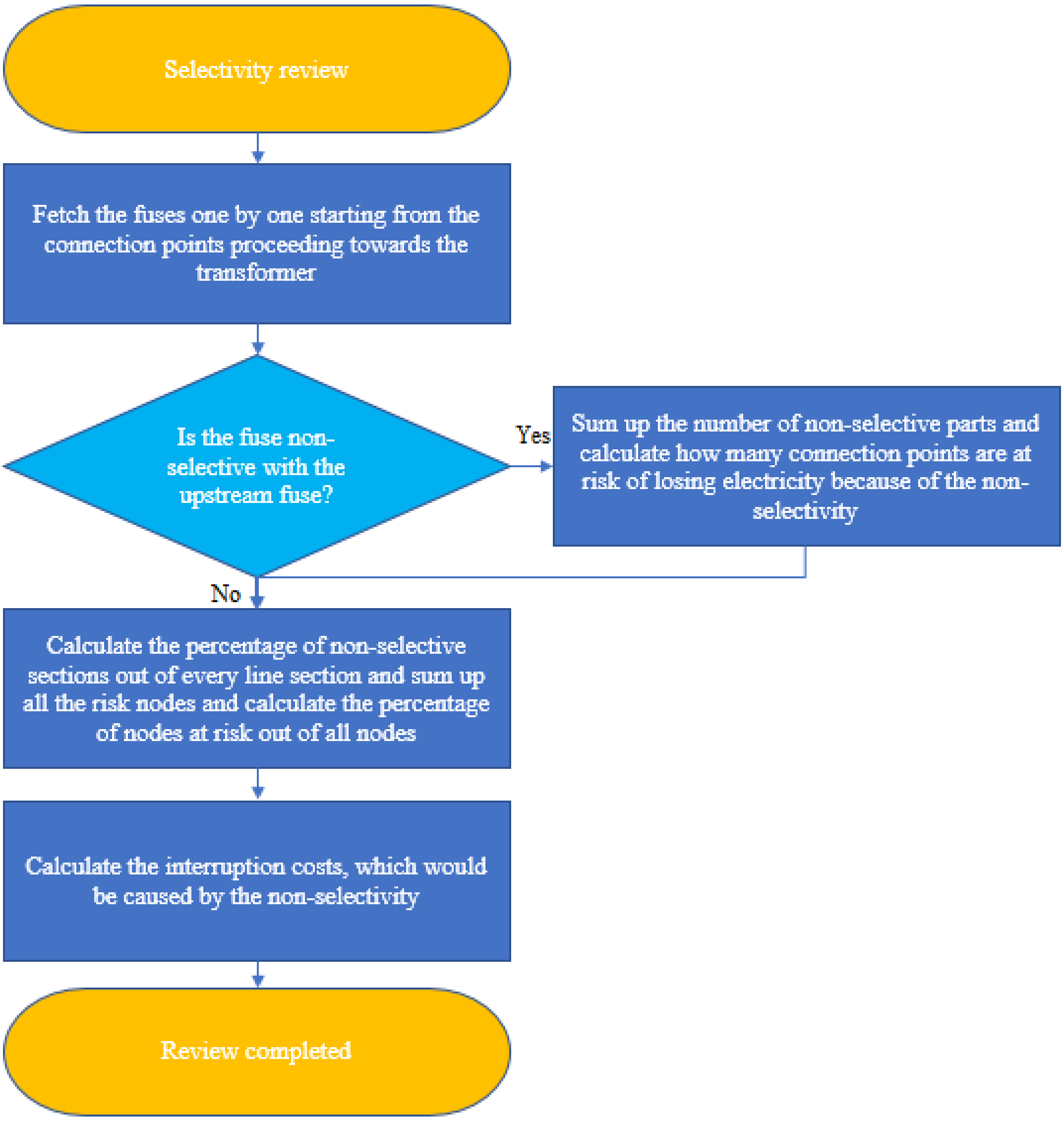

Figure 20. Flowchart describing the logic behind evaluating the effectiveness of the selectivity

In the Optimizer, the implementation is completed by starting from the non-selective parts of the network. Every non-selective part of the network is identified and a percentage value of non-selective parts of all the line sections is calculated. The share can be utilized in the evaluation of the state of the selectivity of the network. Additionally, when a line section is identified to be non-selective, the damage, which could be caused by the non-selectivity, can be evaluated by counting the number of connection points, which would lose electricity as a result of wrong fuse operating. After all the connection points at risk are summed up, their share compared to the total number of nodes is calculated to express how severe consequences the non-selectivity could cause. To emphasize the effects of the non-selective parts, the share of connection points at risk can be over 100 % as each connection point can be counted multiple times, if multiple non-selective parts put the same point at risk. The overall effectivity of the selectivity could be evaluated based on the shares.

As the previous method offers no immediate impact on the cost of the network, a cost function would be required if selectivity was wanted from the network. Based on the nodes at risk, interruption related costs can be calculated to add a cost component for non-selectivity. The first step is to determine the number of faults per year based on the line length (km) and fault frequency (faults per 100 km per year).

$$\lambda = f * l \tag{15}$$

where

λ = faults per year
f = fault frequency
l = line length

The second step is to determine the cost per year based on the customer interruption cost (CIC) values, the number of faults and the maximum consumption of each affected connection point.

$$c = \lambda * \sum_i (P_{max,i} * (c_{kW} + c_{kWh} * t_{repair})) \tag{16}$$

where

c = cost per year
$P_{max,i}$ = maximum consumption of a connection point
c_{kW} = cost per kW
c_{kWh} = cost per kWh
t_{repair} = repair time

The final step is to calculate the lifetime interruption cost with the following formulas:

$$C = \kappa * c \tag{17}$$

where

C = the lifetime cost
κ = discount factor

$$\kappa = \gamma \frac{\gamma^t - 1}{\gamma - 1} \tag{18}$$

where

γ = the ratio between load growth and interest rate
t = lifetime

$$\gamma = \frac{100+r}{100+p} \tag{19}$$

where

r = load growth (% per year)
p = interest rate (% per year) (Lakervi & Partanen 2008)

The interruption costs for LV networks are very low compared to the investment costs, so the non-selectivity does not have much weight behind to cause changes to the final network structure. An additional factor should be added to represent the probabilities of how often the non-selectivity actually leads to the upstream fuse operating before the downstream fuse. That would make the selectivity even less important.

5.8 Leaving out fuses

Short-circuit knives and direct busbar connections are alternatives for fuse links. In areas, where the use of short-circuit knives or direct busbar connections is permitted by the DSOs practices, they can replace the fuse links in certain situations. The skipping of fuses is utilized in situations where the consecutive fuses would be equal. The downstream fuse does not offer much additional protection compared to the fuse in the upstream because the upstream fuse can operate before the downstream fuse due to the fuses sharing the operation zones. For that reason, the use of short-circuit knives or a direct busbar connection is justifiable.

The short-circuit knives are only a solid link, which offers no protection. The direct busbar connections also are a solution without any protection. In these situations, the upstream fuse is in charge of the protection. The use of short-circuit knives or direct busbar connections depends on the DSO, because they may have different rules where the use is appropriate.

5.9 Special requirements

The DSOs may have special wishes regarding the fuse sizes. For example, they could use predefined distribution cabinet configurations, which come with certain fuses already pre-installed. These wishes are important to acknowledge because the goal is to automate the planners manual work. However, every fuse that meets the selected conditions is not automatically updated. The technical limits and selectivity are still checked and only the fuses, which are eligible for update, will get a new value.

The most used case has so far been upgrading 50 A fuses, which protect the supply services, to 63 A fuses, which are more commonly used. In this situation, the 50 A fuses protecting the supply services are a result of 25 A main fuses. The majority of the 50 A fuses can be upgraded to 63 A fuses, only affecting the protection time, which still remains within the limit. However, when the upstream trunk line is protected only with an 80 A fuse, and it is not possible to increase it or the other upstream fuses, which would also require an upgrade along with the 80 A fuse, by one size, the update process will fail. The possible upstream fuses are also updated if it is necessary to keep the original selectivity. Selectivity is never sacrificed in this case. The other probable limiting factor is the minimum short-circuit current. In the furthest parts of the network, the short-circuit current may be just above 250 A, which is the requirement. A 63 A fuse, however, requires a current of 320 A to operate in 5 seconds (SFS-EN 60269-1). Also, in those situations, the update process will fail.

5.10 The use of subterminals

A common practice is to use subterminals of the fuse-switches in the distribution cabinets. It means that two conductors are protected by the same fuse, to which both are connected to. The important factor to keep in mind when considering the use of subterminals is to make sure the combined maximum load current does not exceed the current rating of the fuse.

The implementation can be done in a few phases. First, every fuse of a distribution cabinet is fetched. Then the fuses are matched with other equal fuses if any exist. After the matching fuses are found, the fuses will be paired with each other, if it is possible. If the combined maximum load current of the two conductors is lower than the current rating of the fuse, the pairing can be completed. The other thing is to check if the conductors physically fit under the same fuse, which depends on the structure of the distribution cabinet.

5.11 Results

The results of the fuse planning application appear to be consistent. As the development of the Optimizer has continued along with the fuse planning, restructuring and redeveloping were constantly required to tie everything together. The changes have often caused bugs, which have been fixed continuously. However, the Optimizer will head into customer testing in the near future, including the fuse planning as an essential part, which will certainly cause feedback.

One great example result network is presented om Figure 21 to display the final results of this thesis. Similar additional results could be displayed but there is nothing, which could not be explained with the selected network. The final result is presented with a network and the fuses. The numerical data behind the fuse planning process are presented in Tables 4, 5 and 6. Full selectivity was not achievable for the network because of the network size. The selective sections are located on the most efficient locations. The result showcases well the different aspects of the fuse planning application.

Analysis of the results could be started from the connection points and supply services. The main fuses are located at the connection points and the fuses displayed above the node and main fuse information are located in the distribution cabinets where the supply services are connected to. The example includes four different main fuse sizes: 25 A, 35 A, 63 A and 100 A. There are also four different fuse sizes to protect the supply services: 50 A, 63 A, 80 A and 100 A. At first each supply service fuse has been set to the maximum fuse size based on the line specific limits and the short-circuit current. Each supply service line in this case, except for one, is 25 mm^2, which has a maximum overload fuse size of 80 A. The supply service of node 14, however, has been strengthened due to the larger main fuse size. The rule for new network states that the supply service fuse has to at least match the main fuse size, if nothing blocks that. The blocking could be caused by a customer owned line with lower line specific maximum fuse size than the main fuse is. Because of the rule, the supply service fuse of node 14 is 100 A, which in this case is the maximum fuse for the 35 mm^2 cable and on the same level as the 100 A main fuse. After the maximum fuses are added, each supply service fuse gets a fuse that is two sizes larger than the main fuse. However, that is not always possible for the larger main fuses, which are rated 63 A and 100 A. Initially the 25 A main fuses get a 50 A supply service fuse and the 63 A fuses are used with the 35 A main fuses. As a final step, the 50 A fuses are upgraded to 63 A fuses wherever possible, because those are the default fuses in many distribution cabinets. The upgrade requires that the selectivity does not get worse from the initial situation. The trunk line fuses will also get upgraded in the process, for example from 80 A to 100 A and the upstream fuses also by one size, if it is technically possible and does not negatively affect selectivity. In the example network, only the supply service fuses of nodes 12 and 13 do not get upgraded, because the 80 A trunk line fuse cannot be increased without breaking the selectivity, which already is not ideal.

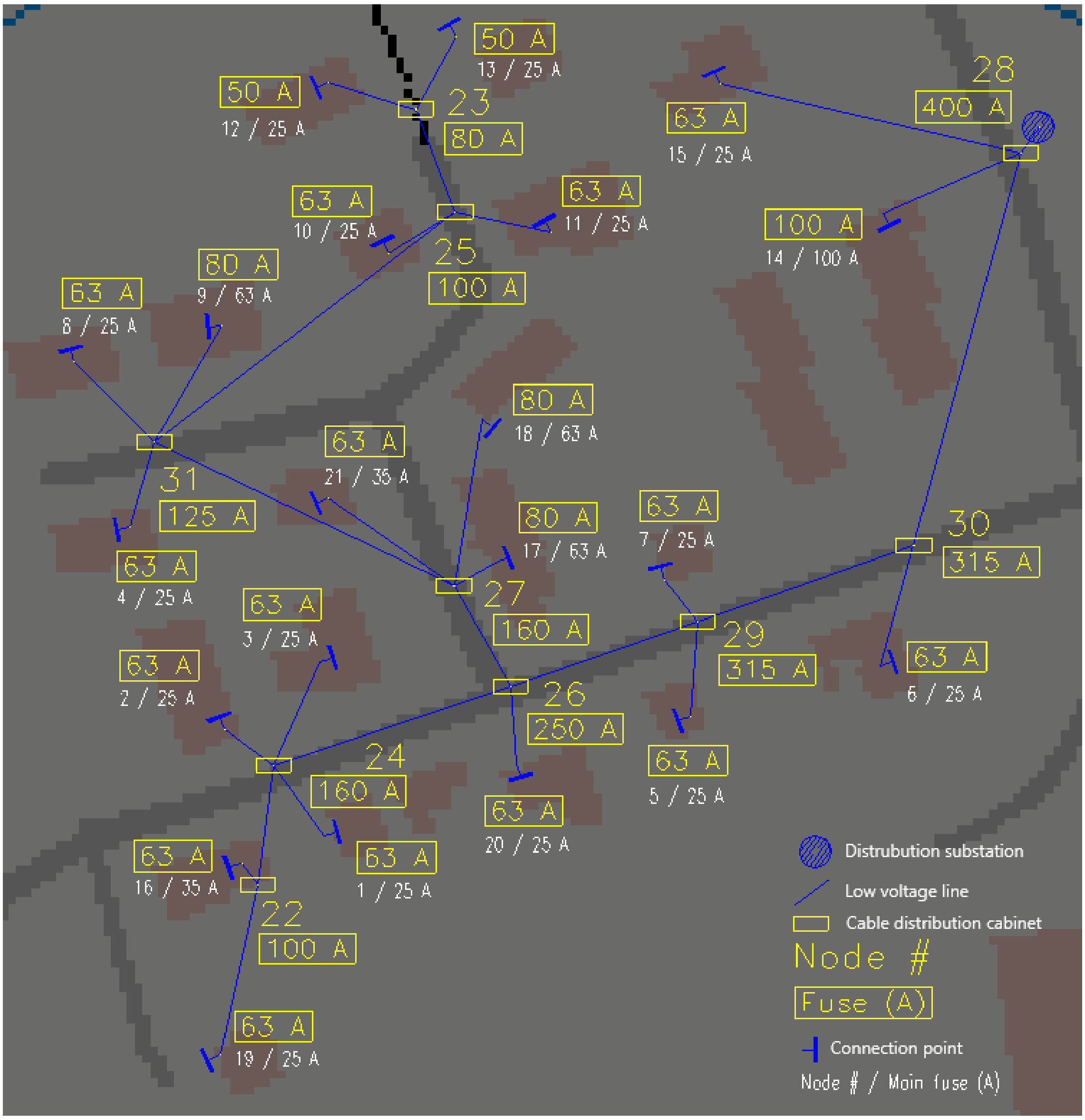

Figure 21. Results of the fuse planning completed by the Optimizer in Trimble NIS.

The trunk line fuses, which are visible at each distribution cabinet, are in reality located in the beginning of the lines at the previous distribution cabinets. The trunk line fuses are initially added as the maximum allowed fuses. The second step is first enforcing the full selectivity rules, which in this example are not enough. Selectivity is the key when the trunk line fuses are observed, because the selectivity gets adjusted to make the most out of it. Most importantly, the selectivity between a supply service fuse and a trunk line fuse should be the first priority. In the example, each of those sections are selective. The trunk line fuse after 50 A supply service fuses is 80 A, for the 63 A supply service fuses it is at least 100 A, for the 80 A supply service fuses it is at least 125 A and the 100 A supply service fuse is in downstream of 400 A trunk line fuse. The next step is to analyze the selectivity between the trunk line fuses. The fuse at the distribution substation is 400 A, which is the maximum fuse size of the network. It is connected to node 30 which is protected by a 315 A fuse. Node 29 has to also have at least a 315 A fuse, because of the maximum load current. In this case the one step selectivity is more efficient between nodes 28 and 30 because it somewhat protects the two connection points connected to node 30 instead of being between nodes 30 and 29, where it would just protect one connection point. Node 26 must have at least a 250 A fuse, so the one step selectivity is offering some protection. Selectivity is at the desired level between nodes 26 and 24, and nodes 24 and 22. After the initial selectivity was applied, those fuses have not changed.

The distribution cabinets 27, 31, 25 and 23 are interesting in terms of how to adjust the selectivity. There is room for full selectivity between two cabinets, while the other sections are left with one step selectivity. The ideal location for the selective line section is between nodes 26 and 27, because if the fuse protecting node 26 operated first, the whole other branch with distribution cabinets 24 and 22 would lose electricity because of bad selectivity. The selectivity between nodes 26 and 27 offers protection for six connection points. If the full selectivity was at any other line section along the path, the maximum number of connection points, which could be secured, would be at most three. Fortunately, the maximum load current at node 27 is 151 A, which is just below the 160 A fuse.

The selectivity review for this network reveals that the cost is quite low. The non-selective parts of the network are between the trunk line fuses. When the selectivity is only one step, for example between nodes 25 and 23, and a fault occurs in the line between them, the fuse protecting node 25 and line between nodes 31 and 25 could operate before the fuse protecting the node 23 and the line where the fault occurs. If this happened, the connection points 10 and 11 would lose electricity because of the selectivity conditions. By this logic, every non-selective section is evaluated, and the possible interruption costs are calculated. In the example network, the six non-selective sections are between 23-25, 25-31, 31-27, 26-30, 29-28 and 30-28. Calculated with formulas of chapter 5.7.3 “Selectivity rating” the selectivity rating is 81 %, risk rating is 76 % and combined rating 5 %. The total cost of the non-selectivity is 476,76 € with faults per 100 km being 5 and repair time being 6 h. With a more reasonable repair time, the cost would be even lower.

Table 4. Maximum fuse sizes for overload protection for various sized conductors. (NIS)

Conductor size (mm^2)	Max fuse, OL, trunk (A)	Max fuse, OL, supply (A)
25	100	80
35	125	100
70	200	160
120	250	200
185	315	250
240	400	315
300	400	315

Table 5. The numeric values upon which the fuse selection is based on.

Node	**I_{max}**	**I_{k1min}**	**Conductor size**
0	0	12,9	0
1	10	1,84	35
2	12	1,83	25
3	9,83	1,44	25
4	11,9	2,03	70
5	12,5	2,27	25
6	11,4	2,14	25
7	3,92	2,7	25
8	12,5	1,55	25
9	17,4	1,27	25
10	15,2	1,29	35
11	8,85	1,08	25
12	13,7	0,916	25
13	20,4	0,967	25
14	24,9	3,3	35
15	13	1,2	25
16	36	1,34	25
17	20,6	2,39	25
18	19,3	1,35	25
19	18,1	0,945	25
20	2	2,21	25
21	11,3	1,44	25
22	54,1	1,46	25
23	34,1	1,17	25
24	86	2,42	120
25	58,1	1,58	120
26	239	3,35	300
27	151	3,06	300
28	305	11,9	300
29	255	3,98	300
30	267	5,06	300
31	99,9	2,36	300

Table 6. The current which causes the fuse operation in 5 s. (SFS 60269-1)

Fuse Size	**I (5s)**	**Fuse Size**	**I (5s)**
16	65	**100**	580
20	85	**125**	715
25	110	**160**	950
35	165	**200**	1250
50	250	**250**	1650
63	320	**315**	2200
80	425	**400**	2840

6 Conclusions

The goal of this thesis was to develop a method to automatically plan the fuse protection of LV networks. The automated fuse protection planning was developed as a part of Trimble Optimizer, which is an application producing network plans automatically for a given set of consumption points. During this thesis, the guidelines of the fuse protection were determined from the national standards and with the help of the consultation from professional network planners, the planning process was examined. The next step was to put all the information into use and the automated fuse planning application was developed.

The implementation was done according to the Finnish standards and the needs of DSOs. The basis behind the logic of the implementation was presented in chapter 4. Even though the standards state the minimum requirements, some DSOs might have stricter approaches to keep their networks safe. For example, the conductor specific maximum fuse sizes could be different for different companies, which is the reason for using user configured line data in determining the maximum allowed fuses. As the practices can differ between users, the discussions with them have been vital for this work.

The automating of the fuse planning process starts from initialization of the fuses. The locations for the fuses are set along and the maximum size of each fuse is determined. The maximum fuse size is limited by the conductor it is protecting, the size of the transformer and the value of minimum short-circuit current. The minimum size comes from the maximum load current. Also, the main fuses of the connection points checked and together with the minimum short-circuit current, they determine if the network has to be strengthened. The next important phase is applying the selectivity rules. Selectivity is a desired feature, but not always a real possibility. When the desired selectivity level is not reached, the selectivity is set to offer protection for the maximum number of connection points possible. As the final measures, some adjustments can be made, depending on the settings the planner wants to use, but selectivity must not suffer from any changes.

As a result of this thesis, the automating of fuse protection planning was completed, and the results are showcased in chapter 5 with the planned fuses in an example network. The results are consistent and promising, although the development will continue. Most of the problems along the development were related to the selectivity, because of the high number of possible configurations and situations. More issues are likely to be revealed as the development continues, especially concerning the existing overhead network, because the development has mostly relied on new cable network. Additionally, after the initial version is ready and the customers get to start their testing, more wishes related to the development may arise. Some topics are still left for the future, such as the situation of parallel lines, which complicate the short circuit calculation and fuse protection. The parallel lines are a common structure in city networks, where loads are high, so they will be a part of the application eventually.

Overall, the process of developing the automatic fuse planning application went well. One sign supporting that is continuation of the development after this thesis, which will concern the more advanced configurations. The basic requirements have been met with the work done in this thesis.

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