TAMPEREEN TEKNILLINEN YLIOPISTO
TAMPERE UNIVERSITY OF TECHNOLOGY

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PRIORITIZATION PRINCIPLES FOR THE REINVESTMENT PLAN OF LOW LOADED PARTS OF THE RURAL MEDIUM VOLTAGE NETWORK

Master of Science Thesis

Examiner: Professor Pertti Järventausta
Examiner and topic approved by the Faculty Council of the Faculty of Computing and Electrical Engineering on 8 November 2013.

ABSTRACT

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In the 21th century extreme weather-events have tested the reliability of the distribution networks and caused major disturbances of electricity supply. Major disturbances have raised the improvement of the reliability of distribution networks as an important issue, causing that the demands of reliability improvement were scribed in renewed Electricity Market Act in 2013. The demands will lead to large network investments in the next 15 years. Certain parts of the distribution network are clear targets to be prioritized for renovation due to their criticality, but the majority of the length of the distribution networks in Finland is low-loaded rural network, which prioritization on reliability point of view is no explicit task.

The purpose of this thesis is to create prioritization principles for the reinvestment plan of the low loaded parts of the rural MV network. The prioritization principles are determined by comparing five different prioritization criteria on the reliability and the regulated asset value (RAV) of deconstructed network point of view. The criteria are cabling the oldest parts first, cabling the faultiest parts first, cabling the forest located parts first, starting the cabling from the main lines forward from the primary substation and cabling systematically forward from the primary substation. Four MV feeders, representing the operating area of Elenia Oy, are chosen as the analysis area. Elenia Oy's reinvestment target prioritization, capital reinvestment plan and the decision to raise cabling rate to 70% by 2028 form the basis of this thesis. According to the target prioritization and the capital reinvestment plan the reinvestments of low loaded rural network are scheduled for the period of 2023-2028 in the analysis. The reliability calculations are performed with the RNA-tool of Tekla NIS, which was reparametrized to illustrate a normal year and a major disturbance year. The RAV calculation tool is modified to enable RAV calculations, which follow the annual proceeding of the analysis.

The prioritization principles of the reinvestment plan for the low loaded parts of the rural MV network was created based on the findings of the comparison of the criteria with the emphasis on the reliability demands of the new act. The order of priority is:

1. Cabling main lines forward from primary substation
   1.1. Main lines without backup connection or building backup connections
   1.2. Other main lines starting from feeders, which are located in a forest and have the highest number of customers
2. After main lines are cabled the cabling continues from forest located branches

In addition to the reliability improvement, also keeping the RAV of deconstructed network at a reasonable level are taken into account in prioritization principles. The prioritization principles are generalizable in the operating area of Elenia Oy and provide guidelines for creating the development plan required by the Electricity Market Act. The findings of the analysis can also be utilized for reinvestment target prioritization by other DSOs.

TIIVISTELMÄ

TAMPEREEN TEKNILLINEN YLIOPISTO
Sähkötekniikan koulutusohjelma
HAKALA, TOMI: Pienellä kuormituksella olevan maaseudun keskijänniteverkon uudelleeninvestointien priorisointiperiaatteet
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2000-luvulla sään ääri-ilmiöt ovat koetelleet sähkönjakeluverkkojen luotettavuutta ja aiheuttaneet sähkönjakelun suurhäiriöitä. Suurhäiriöt ovat nostaneet jakeluverkkojen luotettavuuden kehittämisen tärkeään rooliin, minkä seurauksena vaatimukset luotettavuuden kehittämiseksi kirjattiin vuonna 2013 uudistuneeseen sähkömarkkinalakiin. Vaatimukset tulevat johtamaan suuriin verkkoinvestointeihin seuraavan 15 vuoden aikana. Tietyt osat jakeluverkosta ovat selkeästi priorisoitavissa saneerattaviksi kohteiksi niiden kriittisyyden vuoksi, mutta suurin osa Suomen jakeluverkkojen verkkopituudesta on pienellä kuormituksella olevaa maaseutuverkkoa, jonka priorisoiminen luotettavuuden näkökulmasta ei ole yksiselitteinen tehtävä.

Tämän työn tarkoituksena on luoda pienellä kuormituksella olevan maaseudun KJ-verkon osien priorisointiperiaatteet uudelleeninvestointisuunnitelman pohjaksi. Priorisointiperiaatteet on muodostettu vertailemalla viittä eri priorisointikriteeriä luotettavuuden ja purkautuvan verkon nykykäyttöarvon (NKA) näkökulmasta. Kriteerit ovat vanhimmista osista alkaen kaapelointi, vikaisimmista osista alkaen kaapelointi, metsäisimmistä osista alkaen kaapelointi, runkojohdoista alkaen kaapelointi sähköasemalta lähtien ja kaapelointi systemaattisesti sähköasemalta lähtien. Tarkastelualueeksi on valittu neljä KJ-lähtöä, jotka kuvaavat Elenia Oy:n verkkoaluetta. Elenia Oy:n uudelleeninvestointikohteiden priorisointi, vuositason investointien jako ja päätös nostaa kaapelointiaste 70%:iin vuoteen 2028 mennessä ovat tämän työn lähtökohdat. Kohteiden priorisoinnin ja vuositason investointien jaon mukaisesti pienitehoisen maaseutuverkon uudelleeninvestoinnit on aikataulutettu analyysissa vuosille 2023-2028. Luotettavuuslaskelmat on suoritettu Tekla NIS:in RNA-työkalua käyttäen, jolle on määritetty parametrit kuvaamaan normaalivuotta sekä suurhäiriövuotta. NKA-laskentatyökalu on muokattu mahdollistamaan NKA-laskelmat analyysin vuositason etenemisen mukaisesti.

Pienellä kuormituksella olevan maaseudun KJ-verkon osien priorisointiperiaatteet uudelleeninvestointisuunnitelman pohjaksi on muodostettu kriteerien vertailusta saatujen havaintojen perusteella painottaen uuden lain vaatimuksia. Priorisointijärjestys on:

1. Runkojen kaapelointi sähköasemalta lähtien
    1.1. Rungot ilman varasyöttöyhteyttä tai varasyöttöyhteyksien rakentaminen
    1.2. Muut runkojohdot aloittaen sellaisista lähdöistä, jotka sijaitsevat metsässä ja syöttävät suurta asiakasmäärää
2. Runkojen kaapeloinnin jälkeen kaapelointia jatketaan metsäisistä haaroista

Luotettavuuden parantamisen lisäksi myös purkautuvan verkon NKA:n pitäminen järkevällä tasolla on huomioitu priorisointiperiaatteissa. Priorisointiperiaatteet ovat yleistettävissä Elenia Oy:n verkkoalueelle ja tarjoavat suuntaviivat sähkömarkkinalain edellyttämän kehittämissuunnitelman muodostamiselle. Analyysin havaintoja voidaan hyödyntää myös muissa verkkoyhtiöissä uudelleeninvestointien priorisointiin.

PREFACE

This Master of Science thesis was written for Elenia Oy as a part of the research project SGEM (Smart Grids and Energy Markets) and it is included in Task 2.3: Large Scale Cabling. The thesis was carried out during the time between January and December 2013. The examiner of the thesis was Prof. Pertti Järventausta from the Department of Electrical Energy Engineering of Tampere University of Technology and the supervisor was M. Sc. Tommi Lähdeaho from Elenia Oy.

First of all, I would like to thank Tommi Lähdeaho and Elenia Oy for the opportunity to write the thesis about a very interesting and current subject. Thanks to Tommi Lähdeaho also for guidance during the work. Special thanks to Janne Alin, who made the accurate RAV calculations possible. I want to also thank Hannu Leppämäki and the rest of the network planning team, whom I have received advices when needed. I am also very grateful to the examiner Pertti Järventausta, who gave useful feedback and comments during the writing process.

I would also like to thank my girlfriend Annika for all the support given during the work. Last but not least, I want to thank my parents, who have supported and encouraged me throughout my studies and life.

Tampere,
December 19th, 2013

Tomi Hakala

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TERMS AND DEFINITIONS

Symbols

n_j	Number of interruptions experienced by customer j
N_s	Total number of customers
t_{ij}	Duration of interruption *i* to customer *j*
i	Number of interruptions in a certain period of time
j	Number of customers affected by the interruption

Abbreviations

AC	Alternating Current
CAIDI	Customer Average Interruption Duration Index
COC	Customer Outage Costs
CR	Cabling Rate
DC	Direct Current
DSO	Distribution System Operator
EMA	Energy Market Authority
FLIR	Fault detection, Location, Isolation and supply Restoration
LV	Low Voltage
LVDC	Low Voltage Direct Current
MD	Major Disturbance
MV	Medium Voltage
NIS	Network Information System
RAV	Regulated Asset Value
RV	Replacement Value
RNA	Reliability based Network Analysis
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
WACC	Weighted Average Cost of Capital

1 INTRODUCTION

Electricity distribution networks are an important part of society's infrastructure and their reliability has a significant role in the functions of society as well as from households' point of view. In recent years a number of extreme weather-events have tested the reliability of electricity distribution and caused major disturbances of electricity supply. During the major disturbances hundreds of thousands of Finns have simultaneously been without electricity and longest outages have lasted for several weeks at a time. This has raised improvement of reliability of distribution networks as an important issue in social debate. Therefore, demands of reliability improvement, which guide particularly to prevention of long-term interruptions, were scribed in the year 2013 renewed Electricity Market Act. This leads to large investments of distribution system operators (DSO) in the next 15 years.

Since significant amounts will be invested in the distribution network, it is important that the reinvestments are targeted to the most critical sections on reliability point of view. Certain parts of the distribution network, such as urban areas' network and high loaded main lines, are obvious to be prioritized for renovation due to their criticality. However, majority of the length of the distribution network in Finland is low-loaded rural network, the prioritization of which on a reliability point of view is not an explicit task.

1.1 Objective of the thesis

This thesis focuses on the comparison of five different prioritization criteria, which guides reinvestments of low-loaded rural medium voltage (MV) network. The main objective is to find out the differences in development of reliability and regulated asset value (RAV) of network between different prioritization criteria and based on findings create prioritization principles for reinvestment plan of low-loaded rural MV network. Prioritization principles emphasize reliability demands of the new Electricity Market Act, which especially guides in reducing long term outages. Moreover, capital reinvestment plan and principles of planning and reinvestment target selection of Elenia Oy are the main basis of realization of analysis.

Network information system (NIS) Tekla NIS is utilized in the planning of reinvestments of distribution network in analysis of this thesis. Reliability calculations are made using the reliability based network analysis (RNA) tool of Tekla NIS and also the calculations illustrating the development of RAV are based on information provided by Tekla NIS. Calculation tools for reliability and RAV calculations have been modified to meet the needs of analysis of this thesis.

Chapter 2 discusses technology and structure of Finnish distribution network and provides basic principles of distribution business to the reader. Chapter 3 focuses on major disturbances starting from the definition of a major disturbance. It describes the major disturbances which occurred in the 21th century and explains their effects on the DSOs and their customers. The chapter also discusses the probability of the major disturbances in the future and describes the reliability indicators from long-term outages point of view. In turn, chapter 4 introduces the demands of the new Electricity Market Act and their effects on DSOs. Chapter 4 also describes ways to meet the demands of the Act and considers how far the DSOs currently are from the demands. Chapter 5 focuses on reinvestments of the distribution network and their planning. Reinvestment target selection and planning principles are discussed particularly on Elenia Oy's point of view. In turn, chapter 6 introduces the analysis area and the basis for its selection as well as discusses reparametrization of RNA-tool. Chapter 7 describes the principles of analysis, all five different criteria of reinvestment target selection as well as the progression of the analysis. Chapter 8 brings together the results of the analysis. It contains the results of reliability and RAV calculations and their comparison between the prioritization criteria and introduces effects of large scale cabling on structure of distribution network. In chapter 9 prioritization principles for reinvestment plan of low-loaded rural network are created on the basis of results and findings of chapter 8 and the accuracy and generalizability of the results are discussed.

1.2 Elenia Oy

Elenia Verkko Oy covered the operating area of Vattenfall Verkko Oy, which became Elenia Verkko Oy in January 2012 due to a business acquisition. 1.1.2013 Elenia Verkko Oy, Elenia Asiakaspalvelu Oy and Asikkalan Voima Oy were merged together to Elenia Oy. [**1**], [**2**]

Elenia Oy is the second largest DSO in Finland including about 410000 customers in 50000 km^2 geographical area. Market share of Elenia Oy is 12% and it has distribution network of altogether over 65000 km. It consists of 23200 km of 20 kV MV lines and 40600 km of 0,4 kV low voltage (LV) lines. There are also 22732 pieces of 20/0,4 kV secondary substations. The operating area of Elenia Oy is presented in the figure 1.1. [**1**], [**3**]

Elenia Oy has decided to build all new distribution network by cabling starting from the year 2009. Cabling rate of Elenia Oy is at present 15% in MV network and 36% in LV network, which means total cabling rate of 28%. The Elenia Oy's distribution network consists mainly of sparsely populated area, so investments in the low loaded rural network play a significant role. [**2**]

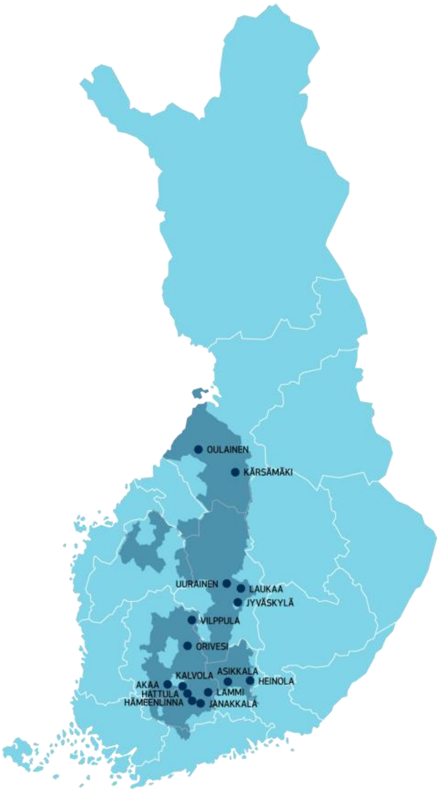

Figure 1.1. *The operating area of Elenia Oy.* [**1**]

2 DISTRIBUTION NETWORK

Distribution networks are significant part of society's infrastructure and their technical task is to move electricity to the customers. This electricity can come through the transmission grid or it can be produced by power plants which are connected directly to the distribution network. Properties of the distribution network affect the customers' power quality and frequency of supply interruptions. Distribution network of a specific area is owned by the regional distribution system operator, which is responsible for its operation, maintenance and development. [**4**]

2.1 Network technology

In Finland the electricity distribution networks are currently based on a three-phase AC voltage with nominal frequency of 50 Hz, which is used at a variety of voltage levels. In this three-phase system the phase voltages have a 120-degree phase shift with respect to each other. Use of AC voltage makes altering the voltage level possible using cheap and simple transformers. When the use of AC technology was decided, system with three phases proved to be the best alternative. One of the benefits is the fact that with three-phase system the same power can be transferred with a smaller need of material and lower costs compared to other AC systems. Moreover, an induction motor works directly connected to a three-phase network. The induction motor is the simplest and most commonly used electric motor. [**5**]

Three different voltage levels are mainly used in the current distribution networks in Finland. These voltage levels are 110 kV, 20 kV and 0,4 kV. The 110 kV voltage level creates the connection between a distribution network and the main grid. Task of the main grid is high voltage (≥ 110 kV) transmission of electrical energy from power plants to closer to the actual consumption areas, where it connects to the distribution network. Extra high voltage (EHV) (>300 kV) of 400 kV is being used for long distance power transmission in Finland. Moreover, the voltage level of 220 kV is also being used for transmission. [**4**], [**6**]

The main distribution voltages are the 20 kV medium voltage and the 0,4 kV low voltage. In the distribution networks there are also other voltage levels of medium voltage than 20 kV, for example 45 kV and 10 kV. However, they are mainly the remnants of the past, when 20 kV had not yet been standardized, and they are usually replaced by 20 kV lines during renovation. However, voltage level of 10 kV is still in use in some big cities of Finland, such as Helsinki and Turku. There is also the newer distribution system based on 1 kV low voltage technology. It is in experimental use in some DSOs and consist of 20/1/0,4 kV AC voltage levels. Figure 2.1 presents the basic structure of the transmission and distribution system in Finland. The analysis of this thesis focuses on MV network. [**4**], [**5**]

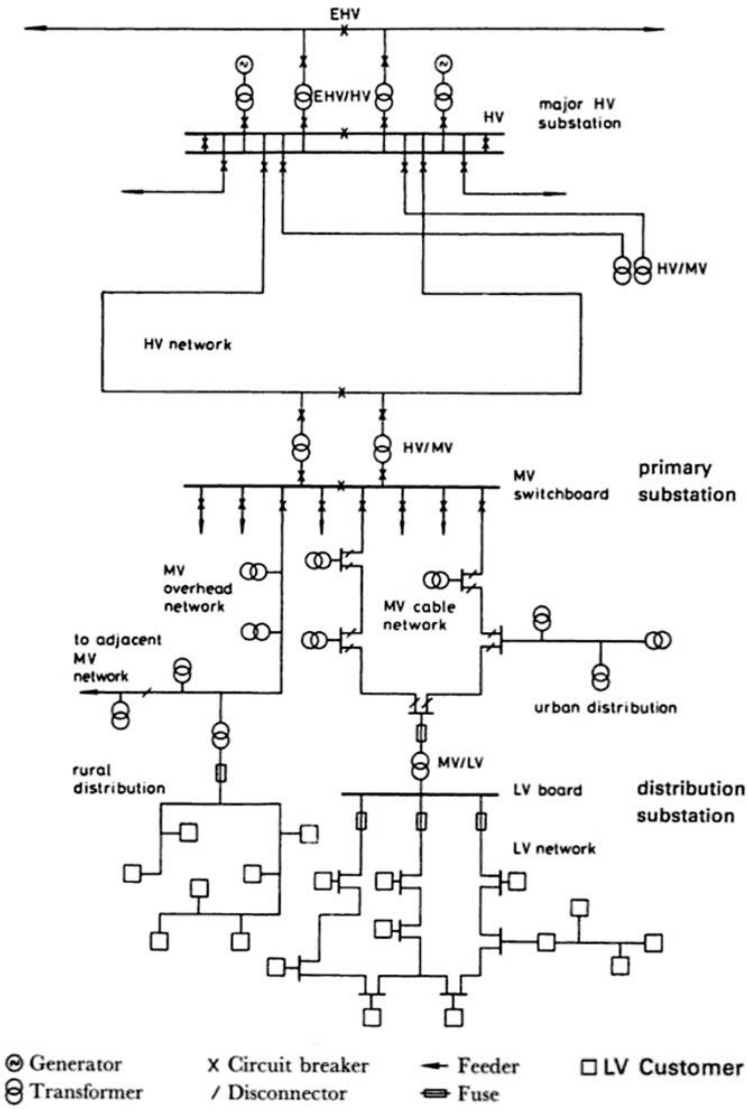

Figure 2.1. *Basic structure of transmission and distribution systems in Finland.* [**6**]

2.2 Structure of the distribution network

Electrical networks can be divided into a radial network and a ring network on the basis of their structure. The loads of the radial network get electricity only via one route. In the ring network the electricity can go through more than one route. The low voltage networks are nearly always built as radial networks. Crucial parts of medium voltage networks are usually built with the ring structure. However, those medium voltage ring networks are operated like a radial network. The ring structure improves the reliability in fault and maintenance situations since it is possible to provide electricity through several routes. With the ring structure the supply interruptions caused by faults and planned power cuts are shorter or interruption can even be completely prevented. [**7**]

Different kinds of structures exist for rural and urban networks (figure 2.1). Urban networks are almost entirely built with ground cable. Also, low voltage networks in the city centers are often built using the ring structure. Often in rural area 20 kV medium voltage branch lines have to be built long, since the customers are scattered and the distances are long. These branch lines increase faults which cause interruptions to a whole medium voltage feeder. [**7**]

Rural medium voltage networks are typically located in forests. The majority of the rural distribution networks were built in the 1950’s – 1970’s. During that time the reliability was not as significant factor as it is nowadays. Minimization of the investment costs and losses were the main factors which directed the planning of the network. This led to a distribution network topology in which the lines were built directly across the forest. About 90% of the present medium voltage network is overhead lines from its structure instead of more reliable cable lines. [**7**]

Over 90% of electricity supply interruptions experienced by customers are caused by outages in the 20 kV medium voltage network. The remaining approximately 10% of interruptions are caused by the 0,4 kV low voltage network, since outages of the main grid are quite rare. Half of all outages are caused by trees reaching the overhead lines due to wind or snow loads. About 90% of the medium voltage network faults are short-term faults which last a maximum of few minutes. High-speed and delayed automatic reclosings are used to remove those faults. [**4**], [**8**]

A significant part of the overhead lines have to be renewed in the near future because of the ageing and reliability demands of the new act (chapter 4.1). This renewal work has two key challenges. First of all, technical solutions which are able to respond to the expectations for the distribution networks for the following 40-60 years are required. That means increase of power transfer capacity, but also significant improvement of reliability. Second, the renovation of the networks should be done as cost-effective as possible, so that the costs to the owners and customers will remain at an acceptable level. This thesis discusses both challenges from the rural network requirements point of view. [**4**], [**9**]

2.3 Distribution system operators and regulation

There are total of 85 distribution system operators in Finland, for which the number of customers and the conditions of the operating areas varies a lot from each other. Operating areas of some DSOs include only urban areas, and thus their entire or almost entire network is built using underground cables. However, operating areas of the other DSOs are entirely in rural area, in which case the cabling rate can be close to zero. Finland’s largest DSO Fortum Sähkönsiirto Oy supplies 440 000 customers, but the smallest DSOs supply less than 1000 customers. The structure of the distribution network depends significantly on the DSO and in which part of country it is located. [**8**], [**10**]

DSOs operate locally and own their distribution network. The DSOs are obliged to maintain, use and develop their distribution network and secure the supply and sufficient quality of electricity to the customers, which as stated in the Electricity Market Act [**11**]. In a power outage situation, the DSO is responsible to repair faults of its distribution network and restore the electricity supply to customers. Therefore, the organization of the DSO must have own repair resources or it has to buy repair services from contractors. [**12**]

With the Electricity Market Act (1995) the electricity distribution has become its own business area, which is separated from the rest of the electricity and energy businesses. Electricity distribution is a monopoly business, in which each DSO has a monopoly in their own distribution region. Therefore, the economic and technical supervision by the electricity market authorities is related to it. The economic supervision implies for instance that a moderate profit margin to be gained from its business operation is defined for a DSO. [**4**]

Based on regulation model of Finnish Energy Market Authority (EMA) major part of profit of DSO is determined on the basis of the RAV of a network and weighted average cost of capital (WACC). Interest of the ten-year Finnish government bond of the May average of the previous year, among other things, has impact on determination of WACC-%. In turn, RAV of distribution network is based on replacement value (RV), age and determined lifetime of its components. The RAV of the component decreases as it ages and ends up in zero at the end of its lifetime. In connection with reinvestments this means that if relatively new network, which has non-zero RAV, is being renovated will investment increase the RAV of a network less than renovating an old network which RAV is zero. If the RAV of deconstructed parts is zero, the RAV of network does not decrease during deconstructing, but will increase due to construction of the new network parts. With this procedure EMA encourages DSOs on long term investments that serve the customers as long as possible. In addition to this, regulation model includes economic incentives for example for improving quality and reliability of electricity supply, cost efficiency and innovation. [**13**]

3 MAJOR DISTURBANCES AND RELIABILITY INDICATORS

In Finland several major disturbances of electricity supply have been caused by extreme weather events in the 21st century, which have caused numerous problems to the society. Modern society and infrastructure are very dependent on electricity, so even the shortest outages can cause harm and even financial losses, especially in the electricity-dependent industries. Extreme weather events will likely increase in the future. Furthermore, the outages will cause more and more harm, since the society's reliance on electronic devices has been growing all the time and will likely continue to grow.

3.1 The definition of a major disturbance

The research report [**12**] provides a number of different definitions of the major disturbance and discusses their suitability from the point of view of major disturbances, which occurred during the recent years. The report ended up to the following definition for a major disturbance of electricity supply:

> "Long-term and/or widespread outage of power supply, which results in that in addition to the DSO the emergency services and one or more other public sector department (municipality, police, etc.) need to take steps in order to reduce serious personal injuries and property damages caused by disturbance." [**12**]

The definition covers disturbances caused by problems of both the transmission grid and distribution network. The major disturbances of the electricity supply of the 21th century have been the result of extreme weather events that have caused faults in the distribution network. The transmission grid is built "tree secured" and better resistant against weather events than distribution network, so the weather conditions do not usually cause any problems in transmission grid. Therefore, major disturbances of the transmission grid are rare and are mainly caused by human error or technical defect. Figure 3.1 presents the rough division between the normal electricity supply interruption, major disturbance and national major disturbance by duration and extent of outage. [**12**]

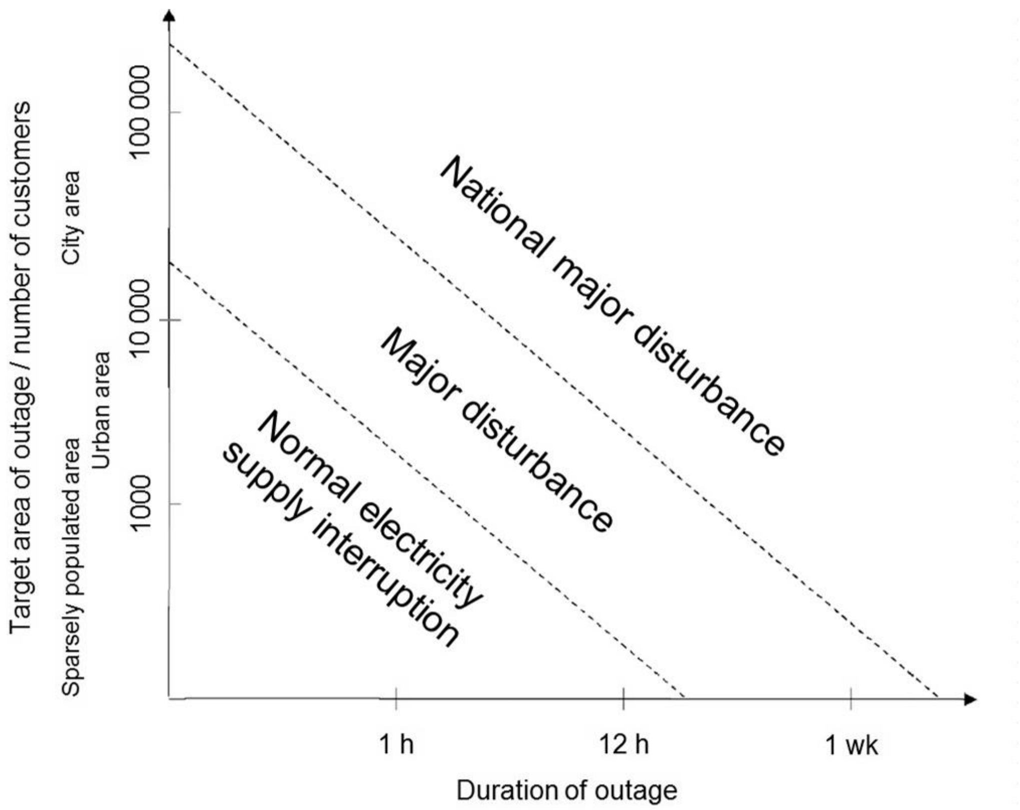

Figure 3.1. *Rough division between the normal electricity supply interruption, major disturbance and national major disturbance by duration and extent of outage.* [**14**]

3.2 Major disturbances in Finland in the 21th century

In November 2001 in the days of Pyry and Janika, storms caused outages of the electricity supply for over 860 000 customers. Strong wind cut down trees and destroyed overhead lines. In the day of Pyry, the outages were also caused by the excessive snow loads. At worst some outages lasted more than a week. As a result of natural phenomena over 7 million cubic meters of wood was cut down of which about 90 000 trees fell down to overhead lines. Thus, 140 kilometers of network had to be rebuilt. The rebuild costs of DSOs were more than 10 million euros. [**10**], [**12**], [**14**]

The thunderstorms Asta (30.7.2010), Veera (4.8.2010), Lahja (7.8.2010) and Sylvi (8.8.2010) caused extensive harm in the summer 2010. Storms caused outages to 481000 customers of which the longest lasted 42 days. 85 percent of the outages were less than 12 hour interruptions, but 6 percent of outages continued for more than 24 hours. A total of 8.1 million cubic meters of wood was cut down. [**10**], [**12**]

In December 2011, storms Tapani and Hannu cut down nearly 3.5 million cubic meters of wood, which caused power outages for a total of 570 000 customers in Finland. Worst damages were caused by Tapani-storm, which mainly striked western Finland. In the next day Hannu-storm made its worst damages in Eastern Finland. In the operating area of Elenia Oy (at the time Vattenfall Verkko Oy) totally 120 000 customers were affected by the storm and at the worst over 101 500 customers were simultaneously without electricity. The figure 3.2 presents the worst situation in Elenia Oy’s operating area during the storm and the figure 3.3 shows the development of the number of customers without electricity. The storms caused 4,5 million euros of fault repairing costs to Elenia Oy. Total costs increased to 10,6 million with standard compensations. [**10**], [**15**]

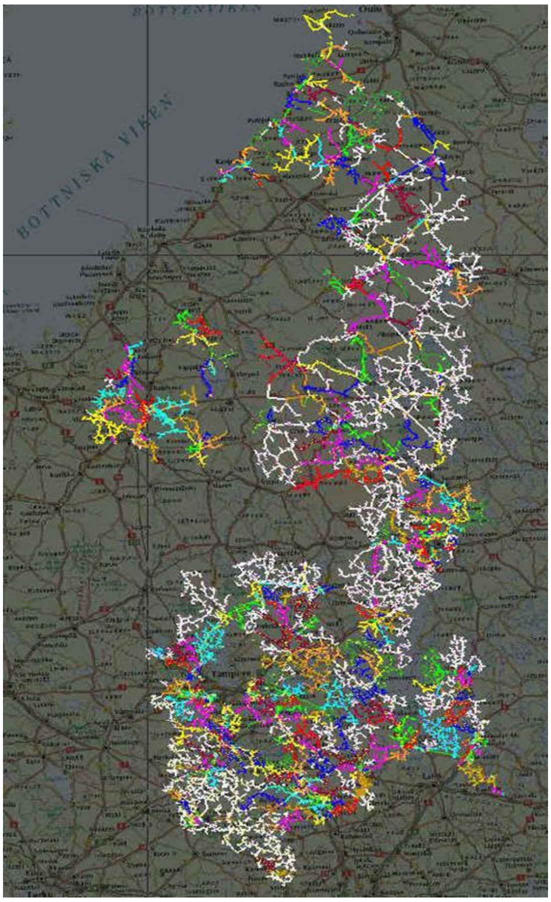

Figure 3.2. *Operating area of Elenia Oy during Tapani-storm. White color presents the network without electricity. At worst, 25 % of customers in distribution area of Elenia were simultaneously without electricity.* [**15**]

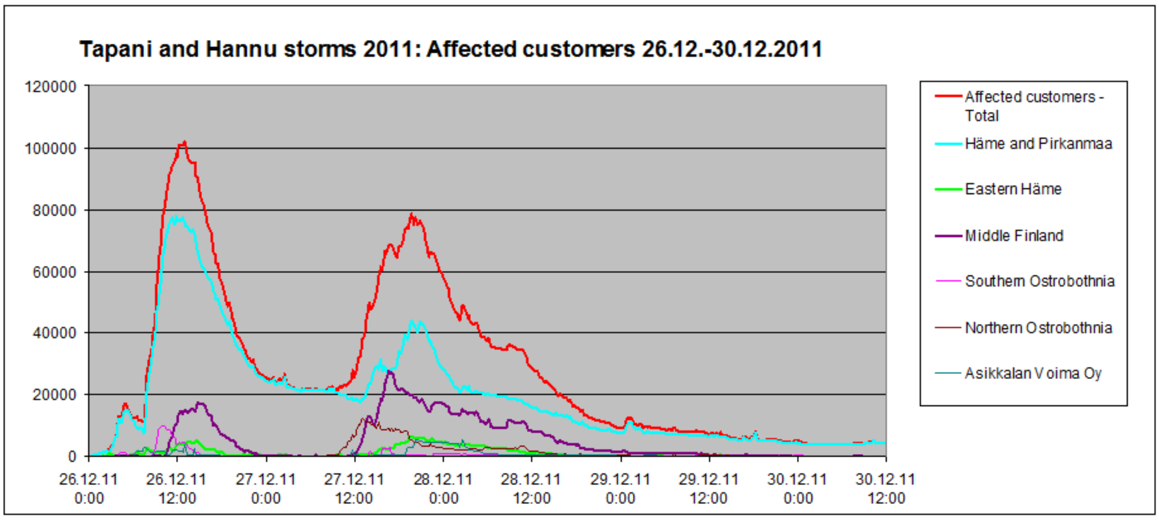

Figure 3.3. *Development of the number of customers without electricity in the distribution area of Elenia Oy during the Tapani and Hannu storms.* [**15**]

Major disturbances of the electricity supply caused outages in communication, mobile and official radio network, among other things. Animal farms had difficulties to distribute food and drinking water, dairy cattle farms were in trouble with milking and milk cooling and the biggest issue on pig farms was ventilation problems, which endangered the health of the animals. There were also problems in the water supply and the elderly had to be evacuated to hospitals and retirement homes. At worst, a major disturbance completely disrupts the functioning of a society. [**12**]

In addition to the major disturbances mentioned above, Finland has had other smaller disturbances caused by storms and snow loads, during which the society has experienced the problems presented in the previous paragraph. For example, Unto-storm in July 2002 and snow loads in the November 2006 and the beginning of 2011 were these kinds of disturbances. [**12**]

3.3 Standard compensations caused by major disturbances

The standard compensation procedure, in which the DSO has to pay compensation to the customer due to electricity supply interruption, was included in the Electricity Market Act in 2003. The amount of compensation depends on the duration of the outage and the amount of the network service fee paid by a customer as follows:

> "The amount of standard compensation is from customer's network service fee of the year:
>
> 1) 10 %, when the outage duration has been at least 12 hours but less than 24 hours;
> 2) 25 %, when the outage duration has been at least 24 hours but less than 72 hours;
> 3) 50 %, when the outage duration has been at least 72 hours but less than 120 hours;
> 4) 100 %, when the outage duration has been at least 120 hours.
>
> The maximum amount of the standard compensation due to electricity supply outage is 700 € per customer " [**11**]

These standard compensation amounts were in force during major disturbances discussed in this thesis. In June 2013 a new Electricity Market Act was approved in Finnish Parliament, which will tighten the demands of reliability and customer compensation due to long outages. The new Electricity Market Act is discussed more in chapter 4.

Standard compensations cause significant costs for DSOs in the event of a major disturbance. Standard compensations share of one Finnish DSO was even 28 percent of its revenue, caused by storms in the year 2010. Between the years 2005-2010 the DSOs in Finland have paid a total of about 18 M€ standard compensations. The division of the standard compensations for the years 2005-2011 is presented in the figure 3.4. In the major disturbance report [**10**] the data was collected from eight DSOs (Fortum

Sähkönsiirto Oy, Kymenlaakson Sähköverkko Oy, PKS Sähkönsiirto Oy, Järvi-Suomen Energia Oy, Savon Voima Verkko Oy, Vatajankosken Sähkö Oy, Parikkalan Valo ja Elenia Verkko Oy), the share of which from the standard compensations of the Asta, Veera, Lahja and Sylvi storms was about 90 percent. Alone the standard compensations paid by those DSOs in Hannu and Tapani storms in the year 2011 were 43,5 M€. [**10**]

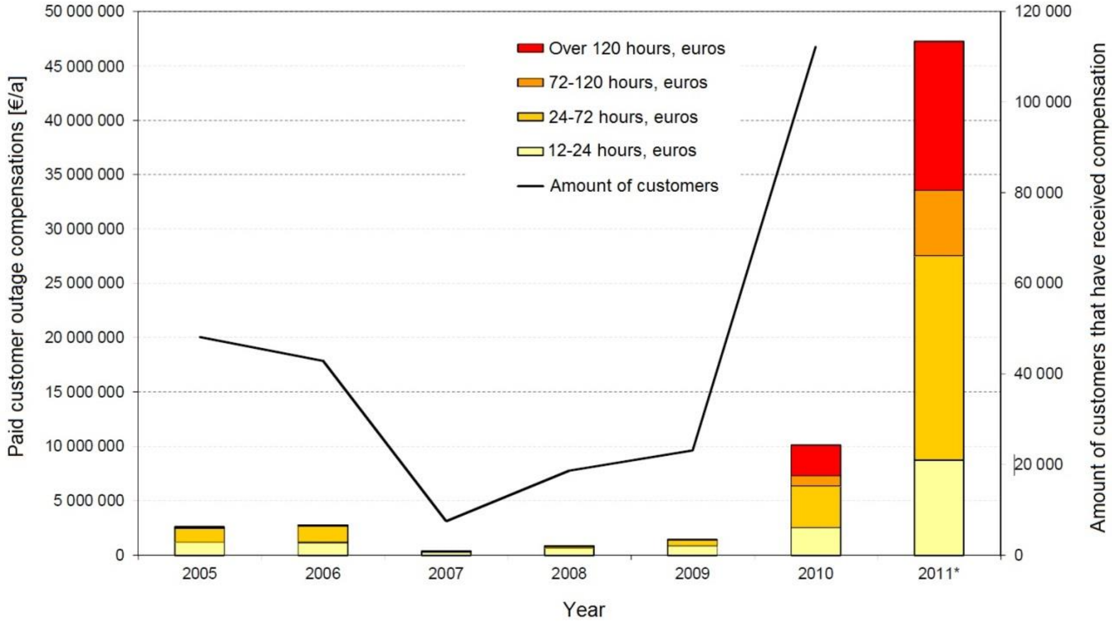

Figure 3.4. *Standard compensations paid during the period 2005-2011. The data of year 2011 is unofficial.* [**10**]

Also, the size of operating area has a major influence on DSOs damages and costs caused by major disturbance. During the storms in years 2010 and 2011 there have been situations, where a storm has caused outages to nearly all customers of some small DSOs. At worst, all customers of a DSO have suffered at least a 12 hour interruption in electricity supply. However, because of the large geographical area, the bigger DSOs have a lower probability that the storm damages the entire distribution network. [**8**]

3.4 Extreme weather event's probability in the future

In contact with a research project of TUT and VTT [**12**] a survey related to major disturbances was made to DSOs. The most common response to the probability of a major disturbance in Finland (31% of responses) was approximately once every two years. The most common estimate of major disturbance hitting the own operating area was approximately once every 10 years (34% of responses) and the second most common estimate was once every 5 years (24% of responses). Furthermore, in the survey the DSO's were asked to estimate the change of probability of major disturbance of the electricity supply in the next 20 years. 43% of the respondents regarded that the probability or major disturbances will grow. Only 12% of the respondents regarded that the probability will reduce and 43% estimated that the probability will remain unchanged.

VTT's research report [**16**] has studied the effects of climate change to electricity network business, which states that overhead line interruptions will increase due to thunderstorms, snow loads and high winds during the years 2016-2045 compared to the reference value of the years 1960-1990. Also, the IPCC Special Report [**17**] and Finnish Meteorological Institute [**18**] predict higher storm winds and increasing of extreme weather events in Finland. Finnish Meteorological Institute predicts that especially the winds during autumn and winter will strengthen.

3.5 Reliability indicators of long interruptions and their definitions

In order to comparably describe reliability of electricity distribution and outages' effect on customers, as well as monitor their development, variety of indicators is needed. From commonly used reliability indicators the best to describe long interruptions of electricity supply are SAIFI, SAIDI and CAIDI, since they do not take into account the effect of autoreclosings. These indicators are defined in standard IEEE 1366-2001 and have been used globally for a long time to describe the reliability of electricity distribution. SAIFI describes average number of interruptions experienced by customers in a certain period of time, for example during a year. In turn, SAIDI describes average duration of interruptions experienced by customers during a certain period of time. Moreover, CAIDI describes the average duration of interruptions in a certain period of time. In all indicators of this thesis the used period of time is one year. Definitions of indicators are [**19**]:

System average interruption frequency index $$SAIFI = \frac{\sum_j n_j}{N_s} \tag{1}$$

System average interruption duration index $$SAIDI = \frac{\sum_i \sum_j t_{ij}}{N_s} \tag{2}$$

Customer average interruption duration index $$CAIDI = \frac{\sum_i \sum_j t_{ij}}{\sum_j n_j} = \frac{SAIDI}{SAIFI} \tag{3}$$

In the equations 1, 2 and 3:

n_j = Number of interruptions experienced by customer j

N_s = Total number of customers

t_{ij} = Duration of interruption *i* to customer *j*

i = Number of interruptions in a certain period of time

j = Number of customers affected by the interruption

Indicators above describe reliability of electricity supply mainly from the distribution system's point of view. They are well-suited to describe reliability level of operating area of DSO and are useful in planning the long-term target of distribution network. However, these indicators do not describe disadvantage caused to customers due to outages of electricity supply very well, since it is also influenced by numerous factors in addition to number and duration of outages. For example, the customer will be able to prepare for a beforehand announced planned outage, so it does not cause as much disadvantage as an entirely unexpected outage. In turn, outages experienced by farms and industrial customers can cause considerable economic disadvantage compared to, for example, a standard household customer. To household customers the disadvantage caused by outages is more a delay of domestic routines than actual financial disadvantage. On the other hand, there are also customers to whom reliability of electricity supply is not very important and even lower quality would be insufficient. Disadvantage caused by outages may also vary greatly with the same customer depending on the interruption's timing during the day and during the year. [**19**]

Because determining the customer outages costs (COC), which describes disadvantage experienced by customer, is very complex and difficult task, there is no widely used and standardized method of calculation of COC. In general, individual disadvantage costs are determined for different consumer groups and / or fault types, which are used for calculating COC ([**4**], [**13**], [**19**], [**20**]). Although the calculation of COC is not an unambiguous task, its meaning is important in describing the effect of outages on customers. Therefore, the COC is also included into regulation model of Finnish EMA, which is used to define the profit margin for DSOs. The COC is taken into account in the calculation of the moderate profit margin as quality incentive, which guides DSOs in reduction of disadvantage experienced by customers. [**13**]

The EMA calculates COC using individual cost coefficients for different fault types, which are unexpected outage, planned outage, time-delayed autorecloser and high-speed autorecloser [**13**]. In addition, the calculation takes into account the consumer price index, which can be used as a general measure of inflation [**13**], [**21**]. In this thesis the COC values are estimated by using the calculations of RNA-tool (chapter 5.1.2).

4 NEW ELECTRICITY MARKET ACT AND ITS EFFECTS TO DISTRIBUTION SYSTEM OPERATORS

The new Electricity Market Act was approved by the Finnish Parliament in June 2013. To improve the reliability of electricity distribution and to prevent major disturbances the schedule and the demands have been scribed in the act. Based on these demands the DSOs must improve their distribution network to better withstand extreme weather events. In practise, that requires a significant growth of the cabling rate in the next 15 years for many DSOs. That will cause large investments, which can clearly be seen in investment amounts of DSOs in the upcoming years.

4.1 The most significant changes to the Electricity Market Act

Major disturbances of electricity supply in the 21th century have caused outages that lasted several days or even weeks. They have got the attention of DSOs as well as society to focus on prevention of large-scale power outages. As a result, the Energy Department of the Ministry of Employment and Economy scribed more stricter demands to improve the reliability of electricity distribution in the new legislative proposal of the Electricity Market Act. The aim is to prevent storm and snow load problems in the overhead network especially in rural and sparsely populated areas, so that major disturbances could be avoided. The new Electricity Market Act was approved in the Finnish Parliament on 19.6.2013 and it came into force in 01.09.2013. [**8**], [**22**], [**23**]

Due to the new demands, the DSOs are obliged to maintain, use and develop their distribution network in such a way that the distribution network failures caused by a storm or snow load do not cause over 6 hour outages to customer living in the urban planned area (covers 75 % of customers in Finland) or over 36 hour outages to customers in other areas. The demands come into force in three stages. The demands have to be met in 50% of customers of DSO at least 31.12.2019 and in 75% of customers of DSO 31.12.2023 at the latest, excluding the holiday apartments. The demands of DSOs have to be met for every customer by 31.12.2028, also including holiday apartments. [**23**]

The demands can be bent, if the customer site is located on an island, for which there is no bridge or other similar fixed link or regular ferry connection for traffic, or the annual electricity consumption of the customer site in the previous three calendar years has been maximum of 2500 kWh and the fulfillment of the demands would require exceptionally large investments due to its distant location. Also, the DSO can get an extension of time for deadlines of the stages of 50% and 75% customer coverage by application for the EMA, if fulfilling the demands will require a significantly higher cabling amount compared to the average cabling amount of DSOs and renewal of a significant amount of distribution network prematurely. With very heavy grounds it is possible to get an extension of time up to 31.12.2036, when the demands must be met for every customer of the DSO. [**23**]

Due to the new act, the network investments of DSOs are monitored more closely. Every DSO has to submit the development plan of distribution network to the EMA, which must be updated every two years. The development plan should include detailed actions divided into periods of two calendar years, which should improve the reliability of distribution network systematically and long-term basis reaching the reliability demands of the act. [**23**]

The new Electricity Market Act also made the standard compensation system more strict. Compared to the previous standard compensation system (chapter 3.3) the new system includes two additional stages (stage 5 and 6), which raise the maximum amount of standard compensation from 100% to 200 % of the customer's annual network service fee. The new stages of standard compensation system are:

> "The amount of standard compensation is from customer's network service fee of the year:
>
> 5) 150 %, when the outage duration has been at least 192 hours but less than 288 hours;
>
> 6) 200 %, when the outage duration has been at least 288 hours" [**23**]

The maximum amount of the standard compensation to the customer is 200% of the annual network service fee or 2000 euros. Therefore, the maximum amount rises 1300 euros from the amount of 700 euros of the previous act. [**23**]

As well as the demands, also the new standard compensation system will come into force in three stages. The maximum amount of standard compensation is 1000 euros, when the outage begins before 1.1.2016 and 1500 euros, if the outage begins before 1.1.2018. After this, the maximum amount of 2000 euros will come into force. [**23**]

4.2 Actions to achieve the demands of the act

DSO's have several different options to improve the reliability of supply, but their effectiveness varies greatly, depending on whether it is a normal situation or a major disturbance. By adding automation solutions, such as pole-mounted circuit breakers, remote-controlled disconnectors and simple primary substations, the reliability of normal situation can be improved at a short notice. They reduce outages experienced by customers as well as reduce durations of the outages in the case of individual faults. However, during a major disturbance the automation solutions have minor effect, because they do not reduce the total number of faults in the network. [**10**], [**24**]

Renovation of low-loaded branch lines by 1000 V low voltage system or LVDC system affects the reliability significantly during a normal situation as well as during a major disturbance. In the solutions MV branch line will be replaced by low voltage cable. Branch lines form their own protection area, which prevents the faults of the branches to cause interruptions to other customers of the MV feeder. However, the renovation of the branches is more time-consuming solution compared to the automation solutions. 1000 V distribution is a relatively new method to improve reliability of low-loaded MV branches and is used by some DSOs in Finland. Elenia Oy does not build 1000 V distribution, so it will not be discussed further in this thesis. For similar purpose Elenia Oy and ABB Oy Drives are developing LVDC distribution. During the writing of this thesis a paper discussing utilization potential of LVDC distribution is written for CIRED 2013 conference [**25**]. Moreover, a wider analysis of utilization potential of LVDC distribution is written on reliability demands of Electricity Market Act point of view, which is awaiting approval for the journal IEEE Transactions on Power Delivery. However, LVDC distribution is not discussed further in this thesis. [**10**], [**24**]

Underground cabling of the MV network is the most effective solution to improve reliability of supply in a normal situation as well as in the major disturbance, because underground cable is not exposed to storm winds or snow loads. However, cabling of the LV network has minor effect in a normal situation, because the low voltage network faults are causing only a small portion of outages experienced by customers (chapter 2.2). Nevertheless, cabling of the LV network has major effect in reliability during major disturbance, since the large-scale damages does not have to be repaired in the cabled LV network side, which reduces the total repairing time significantly. The division of the repairing time of faults of MV and LV networks is discussed more in the chapter 4.3. The solutions have been put in order by time scale of implementation and reliability point of view during a normal situation and a major storm and are presented in the figures 4.1 and 4.2. [**10**]

Because the reliability demands of the new Electricity Market Act have proven to be a problem mainly during extreme weather events, the act guides the development of the network towards the minimization of the risk of a major disturbance. To minimize the risk the best options are cable solutions, of which the most effective one is large-scale cabling of the both MV and LV network. However, large-scale cabling is time consuming and requires plenty of resources. In Finland there are still over 100 000 km of MV overhead lines and over 190 000 km of LV overhead lines. [**8**], [**10**]

With less expensive overhead line solutions the best reliability improvement can be achieved by building the lines on the sides of the roads. By constructing overhead lines as weatherproof as possible, the need of cabling can be reduced. However, overhead solutions are not discussed in this thesis. [**24**]

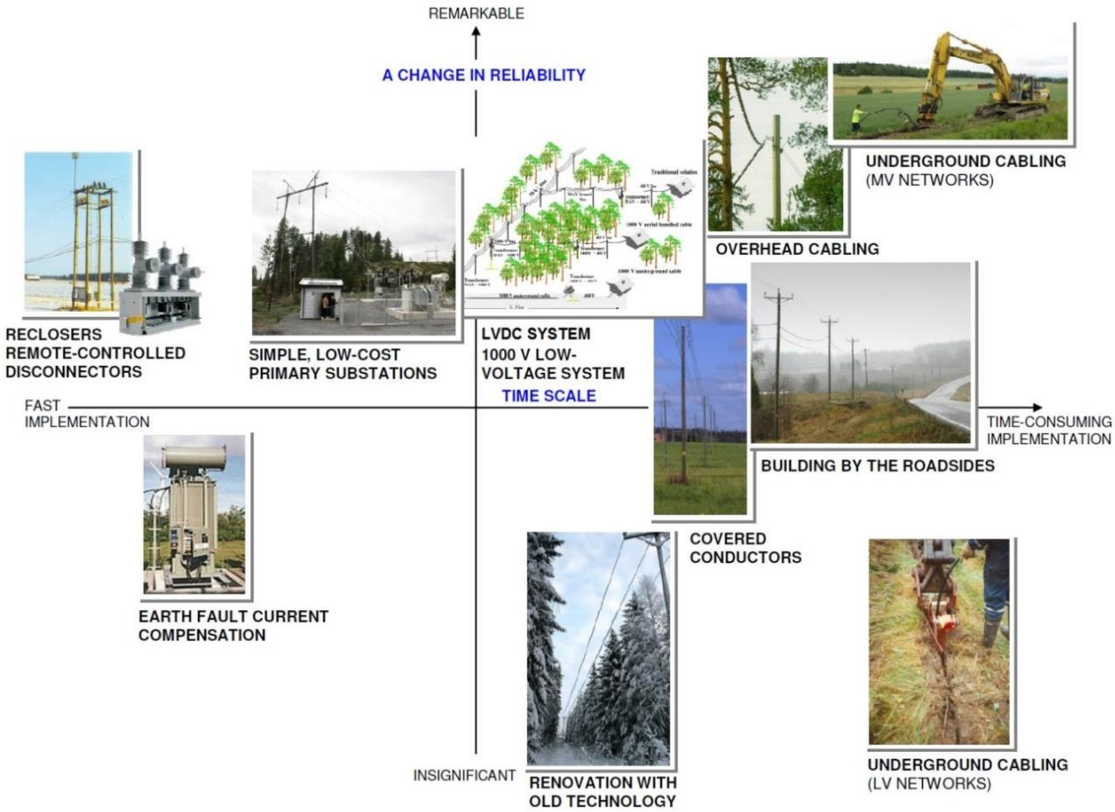

Figure 4.1. *Effects of different network technologies on reliability during a normal situation.* [**24**]

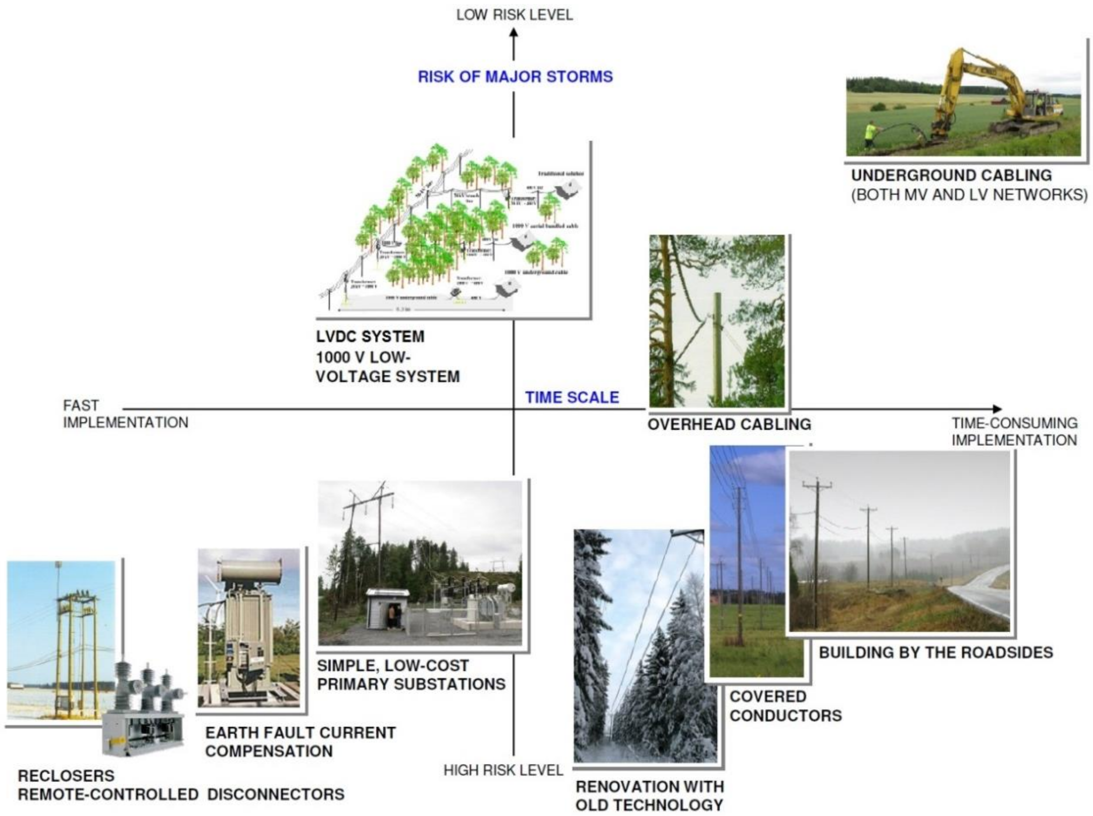

Figure 4.2. *Effects of different network technologies on reliability during major storms.* [**24**]

4.3 The extent of actions in Finnish distribution system operators

Effect of the cabling rate on the outages during major disturbances can be described by the model presented in the figure 4.3. The cabling rate of the MV network has a significant effect on the number of customers without electricity, since one fault of the MV network has more extensive effect than one fault of the LV network has. Therefore, the faults of the MV network are repaired first. The less there are faults in the MV network, the sooner repairing of LV faults can be started and the faster electricity supply can be returned for the last customers without electricity. [**10**]

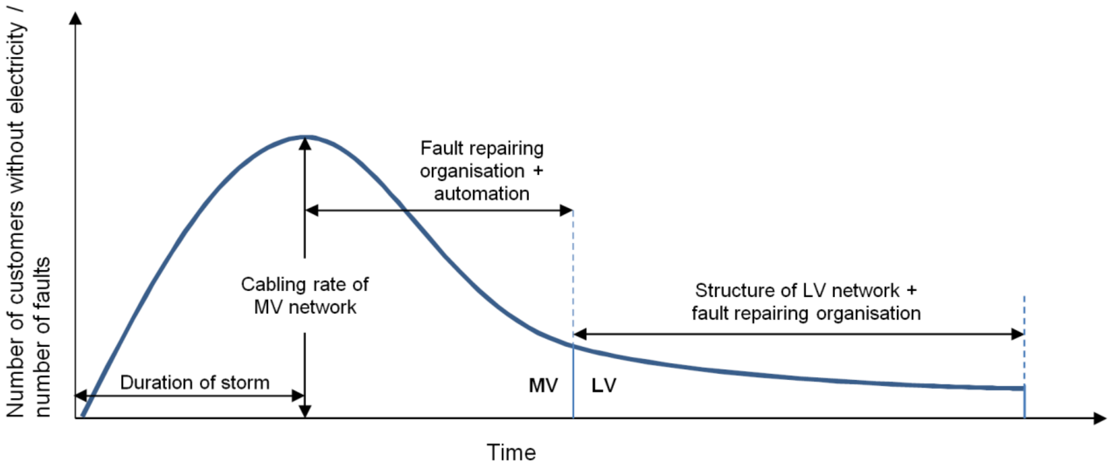

Figure 4.3. *Factors effecting the number of customers without electricity and the number of faults during major disturbance.* [**10**]

In the Major Disturbance Report [**10**], there were eight DSOs which accounted for over 90% of the total standard compensations of the storms Asta, Veera, Lahja and Sylvi. The report examined, among other things, how large MV and LV network cabling rates of the DSOs should have been so that they would have been able to survive the fault repairing during the storms of summer 2010 (Asta and Veera) and winter 2011 (Hannu and Tapani) according to the demand of 36 hours maximum outage time in the sparsely populated area. Figure 4.4 presents the situation for the summer storms and figure 4.5 for the winter storms. For the summer storm the data were received only from five DSOs. In the figures the dots present the existing cabling rate of the DSOs and the line delineates the minimum requirements of the cabling for the specific DSO. [**10**]

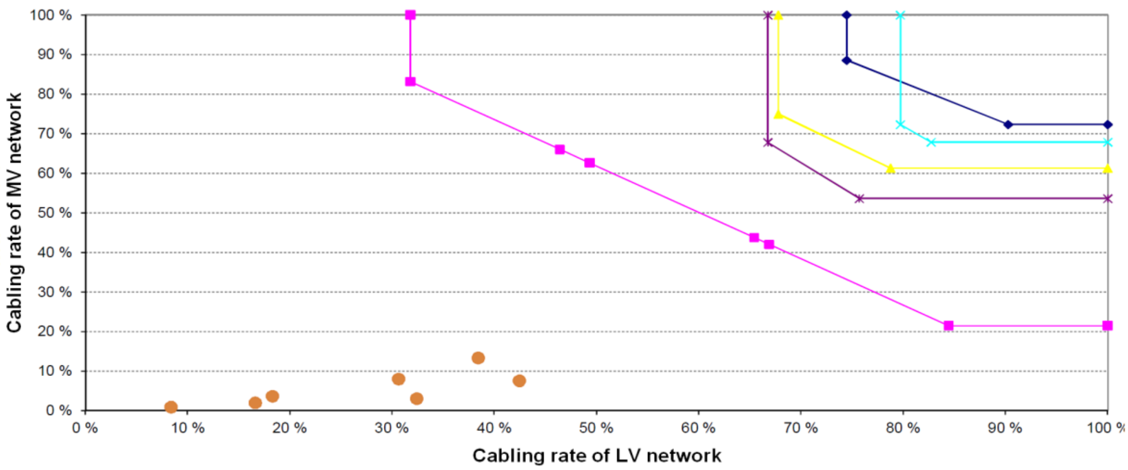

Figure 4.4. *Minimum cabling rates of the DSOs to reach the 36 hours maximum outage limit in sparsely populated area based on the summer storms of 2010 (Asta and Veera). Dots present the existing cabling rate of DSOs.* [**10**]

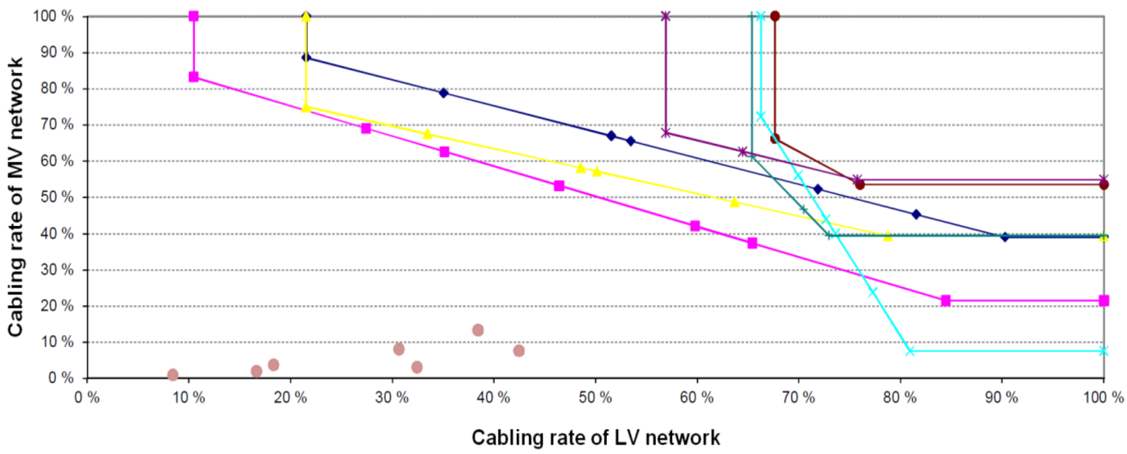

Figure 4.5. *Minimum cabling rates of the DSOs to reach the 36 hours maximum outage limit in sparsely populated area based on the winter storms of 2011 (Hannu and Tapani). Dots present the existing cabling rate of DSOs.* [**10**]

Based on the figures 4.4 and 4.5 can be noticed that sufficient cabling rate of MV and LV networks varies greatly between DSOs. However, it is noteworthy that all DSOs in the report are far below the sufficient cabling rates for achieving the demand of the new act. Also, most of the other DSOs have relatively small cabling rates in the reliability demands point of view. Figure 4.6 shows the LV and MV networks cabling rates in Finland.

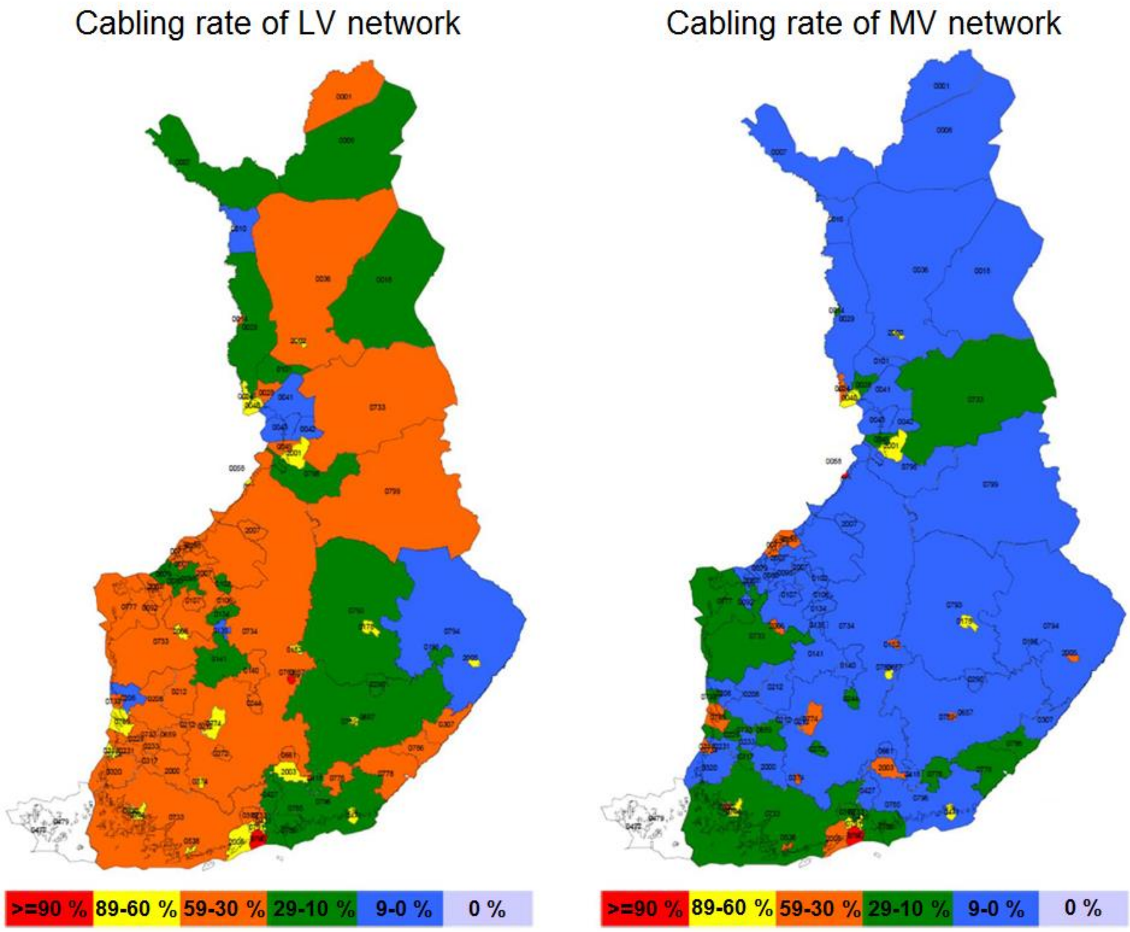

Figure 4.6. *Cabling rates of LV and MV networks in Finland (in the year 2010).* [**10**]

The majority of the Finnish distribution networks are vulnerable to disturbances caused by natural phenomena. However, for example the completely cabled city centers as well as the networks of Lapland, where trees do not cause any problems, do not suffer from winds and snow loads at all. When the starting points and circumstances vary a lot, necessary cabling amount of DSOs also vary greatly. In the report [**10**] has been estimated that on average 50% cabling rate in MV network and 60% cabling rate in LV network would be sufficient to achieve the demand of the 36 hour maximum outage time. Then approximately 70-85% of customers would be supplied through a weather-proof network, when also taken the overhead lines into account which vulnerability has been minimized against weather events. Demands of the year 2019 are estimated to be achievable in most cases in the cabling rate of 20-25%. Figure 4.7 presents development of network investment amount of DSOs up to year 2019. [**8**] [**10**] [**26**]

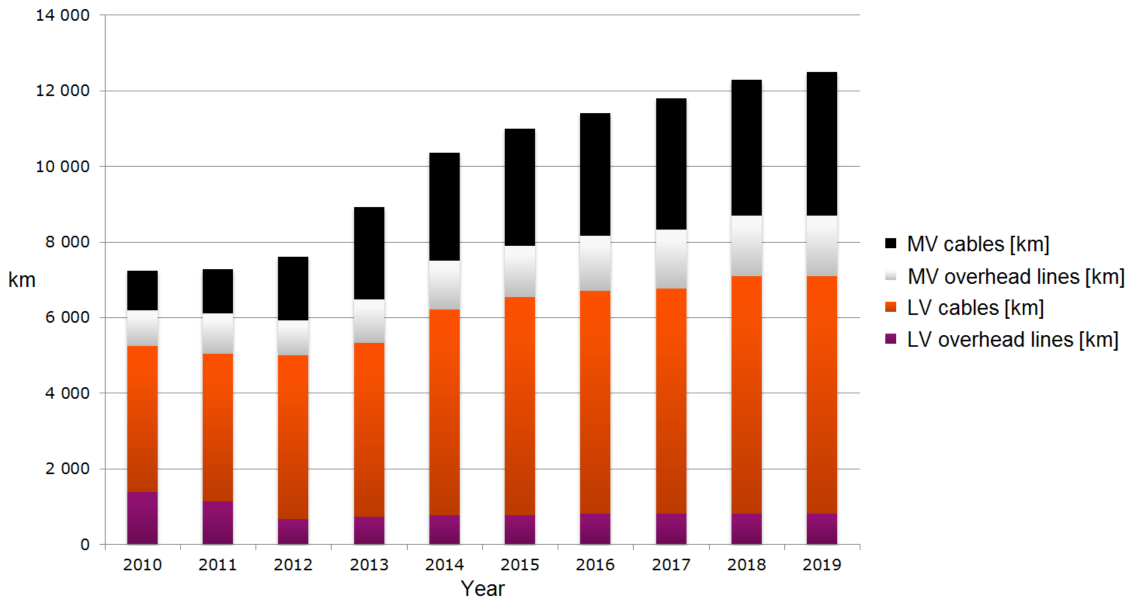

Figure 4.7. *Development of network investment amount of Finnish DSOs. Data based on actual results and estimates for the years 2010-2019 reported by 33 DSOs. Those DSOs covers 62% of total length of the distribution network in Finland. The results are proportioned to total network length.* [**27**]

The figure 4.7 presents an increasing trend of the total network investments, which is mainly due to the increasing amount of underground cables. The steepest growth of network investments amount occurs during this decade, but growth is likely to continue as a gentle slope in the 2020s. Investment division of Elenia Oy differs from the figure 4.7, because Elenia Oy is building all new network by cabling. Based on the demands of the new Electricity Market Act, Elenia Oy has decided to raise its cabling rates of MV and LV networks to 70% by the end of the year 2028, which is one premise of analysis of this thesis. [**27**]

5 REINVESTMENTS OF DISTRIBUTION NETWORK

Because of the demands of the new Electricity Market Act and the aging of the rural area's distribution network, the Finnish DSOs' have to make major network investments during the next 15 years. To meet the demands of the act it is also required that some lines which still have operating life left must be renovated to improve reliability. Due to large investments the long-term investment plan and finding the most critical parts are requirements in developing the network towards long-term goal and implementing them cost-effectively. The best tool for finding the critical parts and planning the distribution network is a modern network information system. Using network data and calculations of the network information system Elenia Oy has made a prioritization of the MV network to guide the network reinvestments and it has also updated the planning principles to meet the reliability demands of the new act.

5.1 Network planning tools

In distribution network planning different systems and information sources are used. Much information is needed from network, supply area of network and area's development, so the new network can be optimized rationally from power transfer capacity, reliability, usability and costs point of view. The most important planning tools regarding this thesis are presented in this chapter. Information sources that support planning are discussed in more detail in the chapter 5.2.2.

5.1.1 Network information system

The most important tool in distribution network planning is the modern network information system (NIS). The network information system contains technical data of both MV and LV network forwards from the customers' connecting point. The modern network information system includes a graphical user interface which enables easy network simulation. The network is modeled at the component level including also the location data of every component and it is displayed on the map. Thus, the user sees the network on the map as it is located in the terrain. Using the network information system it is easy to calculate how the electrical values change when new network is added, the old is renovated or the state of disconnectors are changed, which makes it an excellent planning tool. In addition to network calculations the system checks that the electrical boundary conditions are fulfilled in the simulation situation. [**4**]

Elenia Oy uses Tekla NIS network information system, which includes among other things the data of the customers, the actual measured load curve of each customer based on hourly measured consumption data, maintenance data of the components as well as information on the locations of the faults that have occurred. In addition to electrical calculation of the network the system is able to calculate cost information, such as construction cost, RAV and RV. Moreover, the system is able to calculate the network reliability values, which are discussed more in the chapter 5.1.2.

For the analysis of this thesis a new kind of calculation tool is made, which enables to calculate RAV of deconstructed network in the chosen year from plans of Tekla NIS. Tool determines ages of components for RAV calculation based on their year of construction (filed in Tekla NIS) and chosen deconstructing year, which enables changing the deconstructing year following the analysis annual proceeding. The age of an overhead line section is determined based on the ages of its poles. In the analysis area of this thesis (chapter 6.1) the year of construction can be found from all poles and major part of the other components. If the year of construction of the component is unknown, the tool estimates its RAV as a zero. In the analysis of this thesis it is quite accurate estimate since mainly the oldest components have an unknown year of construction and RAV comparison focuses on years 2023-2028 (chapter 8.2), when the oldest components have exceeded their lifetime. The RV of deconstructed network components and thus their RAV are calculated based on regulation model [**13**].

5.1.2 Reliability based network analysis

It is possible to make reliability calculations using the RNA (Reliability based Network Analysis) tool of Tekla NIS. RNA-tool of Tekla NIS has been made based on the results of the LuoVa-project [**28**], the goal of which was to gather the visions of the reliability based modeling of the distribution network as comprehensively as possible and to create a calculation tool that supports planning, especially general planning (i.e. long-term planning). The project was carried out as a co-operation with several DSOs, IT system suppliers and research organizations during the period of 2002-2005. [**28**], [**29**]

The RNA-tool processes the network at the component level. Fault frequencies and fault repairing times that have been caused by various reasons can be determined for components. Altogether the RNA-tool uses 177 parameters for reliability calculation of a MV network. MV network's reliability calculation gives 208 different values for a MV feeder, which includes the feeder data (i.a. number of customers, length of conductor types and maintenance information), customer outage costs as well as a large number of different fault and reliability indicators, among other things.

The fault frequency parameters of the RNA-tool represent the average fault frequencies, on the basis of which the RNA-tool determines more accurate fault frequency for each line section during calculation. They are affected by the line's location, for example the forest location, among other things. In addition to the line's location the RNA-tool takes into account the condition of the line. One factor affecting the condition of the line is line's age, but in addition it is also affected by maintenance data of poles, which is stored in the Tekla NIS. [**28**], [**29**]

Despite the large number of parameters and calculation results, the RNA-tool is not customizable within the scope of this thesis so that it would be able to calculate whether the MV feeder fulfills the demands of 6 and 36 hours or get a cost estimate based on the new standard compensation system. However, the other reliability values of the MV feeder can be calculated with the RNA-tool, which can be used for comparing different prioritization criteria of reinvestments. Since this thesis discusses prioritization criteria from the new Electricity Market Act's point of view, the most important role is played by the analysis of long-term outages. Thus, the reliability indicators SAIFI, SAIDI and CAIDI (chapter 3.5) have been selected for the analysis of this thesis. The effect of the number of reclosings is not included within the scope of this thesis.

Reliability calculations of this thesis have been made by using the RNA-tool. The utilization of RNA-tool in the analysis and determining the parameters are discussed more specifically in the chapter 6.2.

RNA-tool is most suitable for comparing different options (overhead line, covered line, cable), prioritization criteria and targets. Since Elenia Oy uses other methods (described in the chapter 5.2) when choosing reinvestment targets and has decided to build all new network by ground cabling, the RNA-tool is hardly used in everyday planning in Elenia Oy. Although RNA-tool is not used with planning individual targets, it is used in reliability calculations on a larger scale, for example evaluation of reliability influence of annual reinvestment program, among other things. RNA was also one tool when considering the cabling decision of Elenia Oy.

5.2 Reinvestment target selection of MV network

Primary targets of reinvestment are parts of the network that have to be renovated due to their mechanical condition. However, these targets are only a small portion of the annual network reinvestment targets, so the selection of the targets is mainly based on other criteria. The most important factor that guides network reinvestments in Elenia Oy is the prioritization of the MV network. However, choosing the most important target from the prioritized network is based on evaluating several different factors.

5.2.1 Prioritization of the MV network

Based on the reliability demands of the new Electricity Market Act Elenia Oy has done the MV network prioritization, which guides the reinvestments of the MV network. Prioritized targets of the network are the most critical parts of the network, the cabling of which brings the greatest benefit to reliability. For example, urban areas and their supplying feeders, main lines with at least 200 kW load, bottlenecks of the reconfiguration of primary substations and developing regions are prioritized network. Reconfiguration refers to a situation in which the primary substation or some of its feeders need to be supplied through abnormal route, such as from nearby substation and through its feeders, because of fault situation or maintenance interruption. Elenia Oy’s principle is that all primary substations must be reconfigurable from other primary substations if necessary. Prioritization principles are summarized in figure 5.1.

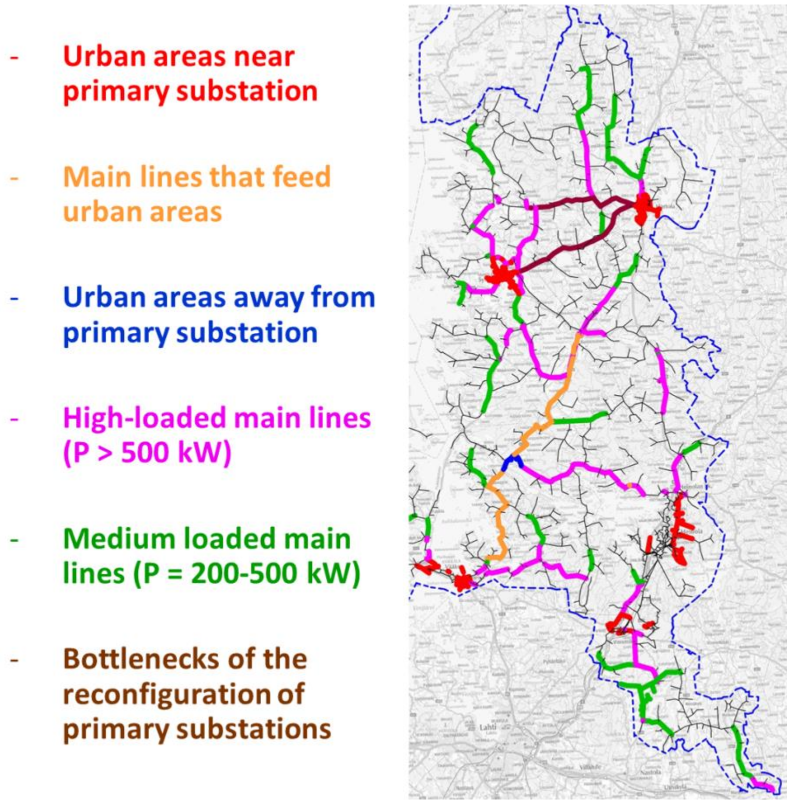

Figure 5.1. *Prioritization principles of MV network. In addition to prioritization criteria of the figure, prioritized network includes also developing areas, the power consumption of which will likely increase significantly in the near future. These do not exist in this example area.*

28 % of the MV network of Elenia Oy is prioritized but it supplies most of the customers. Investment targets are primarily selected from the prioritized parts of the network, so prioritized network will be cabled before un-prioritized network. The most part of the network is un-prioritized (59 %), but it supplies only small amount of the customers. This is due to the fact that the un-prioritized network consists mainly on low-loaded rural network and branch lines. Altogether there is almost 14 000 km of un-prioritized network. In addition to prioritized network, approximately half of un-prioritized network must be cabled by the end of the year 2028 to achieve cabling rate of 70% (according to Elenia Oy’s target, chapter 4.3). Network of one planning area of Elenia Oy is divided into prioritized and un-prioritized network in figure 5.2.

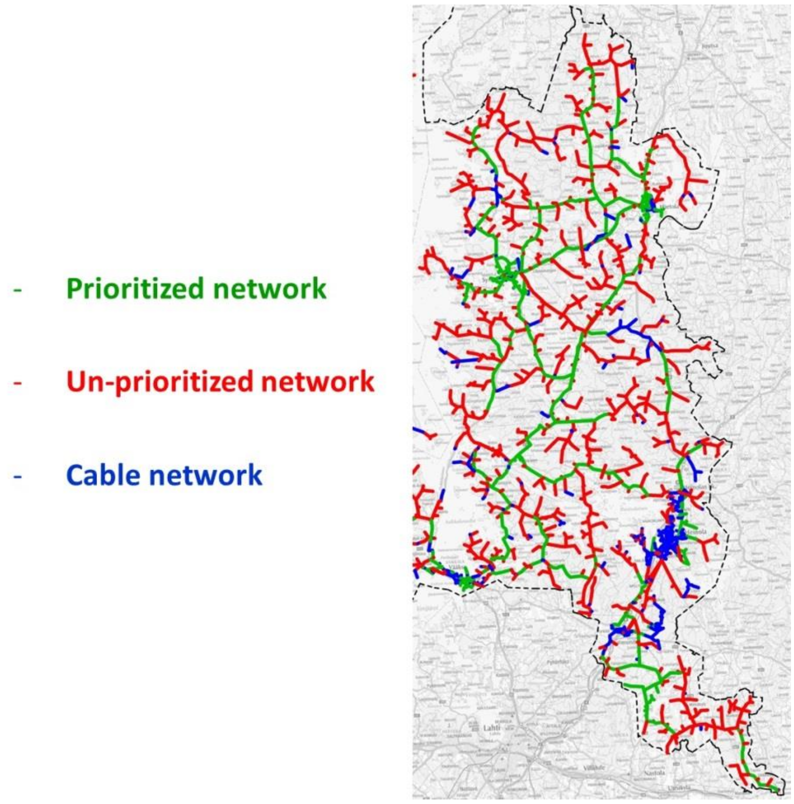

Figure 5.2. *Network of one planning area of Elenia Oy divided to prioritized, un-prioritized and cable network. 470 km is prioritized network (includes 70% of customers) and 820 km is un-prioritized network.*

Because a relatively large amount of un-prioritized network will be cabled, it is very important to know how to choose the right parts of the network, so that cabling will improve reliability as much as possible and it can be realized reasonable and cost-effectively. The renovation of the prioritized network is easily justified as a reinvestment target, because it improves reliability of most critical parts and affects reliability of large number of customers. However, it is more difficult to choose the reinvestment targets from the un-prioritized network, since there are several factors affecting investment target selection, and none of them clearly stands out above the rest. Therefore, more detailed analysis is required for un-prioritized networks part. Reinvestment plan, which prioritizes cabling order of un-prioritized network parts for renovation of un-prioritized network, has not yet been done. The main goal of this thesis is to create the prioritization principles for reinvestment plan by comparing different prioritization criteria of reinvestments. Although there is still a large amount of un-cabled prioritized network, some parts of un-prioritized network must be cabled every year due to the mechanical condition. Therefore, creating the reinvestment plan of the un-prioritized network is already beneficial, as all investments must be done supporting the long-term goal.

5.2.2 Other factors that affect investment target selection

The prioritization principles presented in the figure 5.1 are not in order of importance, but all principles described the critical parts of the network of reliability point of view. Furthermore, there is such a large amount of prioritized network, the cabling of which can not be proceeded in a short period of time. Therefore, the actual selection of the reinvestment targets is based on the expertise of the areas network planner, who defines the most important and critical cabling targets for the year in question. In addition to local knowledge of the planning area the network planner utilizes the network information systems and DSOs inner and outer information sources in choosing the targets.

In Tekla NIS can be found the up-to-date network information, which are network location and conductor information, component data, inspection and maintenance information, age data, consumption data, other calculation data (e.g. ground fault, short circuit and reconfiguration calculation), fault location data, actual reliability level and customer information, among other things. In addition, Tekla NIS offers a variety of map templates, which show i.a. forest areas, fields, plot boundaries and soil properties, such as rocky areas. Evaluating the condition and maintenance needs of the existing network Elenia Oy has the Visimind-tool, which contains photographs of the entire MV network taken by several cameras attached to a helicopter [**30**]. [**31**]

Internal information sources of DSO are experiences, observations and reviews of the staff on critical targets. External sources of information are co-operation stakeholders, contractors and other partners, customers, authorities and the media. Information gathered from co-operation stakeholders such as municipalities, water suppliers, and telephone operators are mainly related to future needs of electricity supply by new municipalities zoning plans or possible co-operation projects, where cabling is done e.g. in connection with the construction of roads or water pipes. Other external sources of information are Google Maps and other map services, which provide information about cabling routes and their circumstances. Based on all this information the network planner evaluates the conditions and criticality of the targets and defines the most important reinvestment targets. [**31**]

5.3 Planning principles of distribution network

The planning of distribution network starts mainly from two different starting points, new network has to be built due to new customer connections or the old network is renovated to improve or maintain the reliability. Network reinvestment project can also be launched from opportunity to network construction in co-operation with one or more stakeholders. Although network construction for new customer connection is usually much smaller work than network reinvestment, the same principles must be taken into account during planning in both cases. Standards give their own demands for electrical dimensioning, but in addition to evaluating the present needs the situation to be evaluated well into the future. The network information system makes it easy to determine the dimensions and protection of the network for the present situation. However, a techno-economically sensible dimensioning requires skills and vision of the area's development from the network planner, since the lifetime of the new cable-network can be even up to 50-60 years.

5.3.1 Long-term planning

Network is built in small parts when constructing new customer connections, but reinvestments of the MV network are also quite small portions when compared to the entire length of the MV feeders, especially the long rural MV feeders. However, every network construction should develop the network systematically towards the same long-term target network. Therefore, before the actual planning of the selected target, the area of the target has to be considered from a long-term planning point of view. Long-term plan of the area may be completed earlier or the consideration is made separately before target planning. [**31**]

In the long-term plan the goal of the MV network is determined further in to the future in such a way, that the location of the network and substations, capacity of the network, consumption growth, necessary back-up connections, disconnector frequency, remote-controlled disconnectors and their locations as well as reconfiguration of the primary substations and MV feeders are taken into account and optimized for future needs (even up to 50-60 years). Long-term planning typically starts from the present network. Depending on the existing network and planning area, the goal may be easily determined by narrow analysis but it often requires a much wider overall analysis, which could cover even the area of several primary substations. [**31**]

In addition to determining the technical goal, scheduling reinvestments and economic analysis are also related to long-term planning. Reinvestments that lead to the long-term goal are generally implemented during several years, even decades. Planning aims to a solution, the long-term total costs of which are as small as possible taking into account investment, loss, outage and maintenance costs. Economically the most sensible solution can be determined by calculating the present value of total costs of different solutions, for example as presented in the book [**4**]. Economic analysis also reveals whether it is better to extend the lifetime of existing network with temporary reinvestments or to do a more extensive and expensive renovation earlier. Many factors affecting the economic issues, such as the construction method and the components being used, can already be decided due to the strategic policies of the DSO, in which case the actual planning can focus mainly on technical issues. Plans that have been made during the analysis of this thesis (chapter 7) are made according to the strategic policies of Elenia Oy. [**4**], [**6**]

The biggest challenges of long-term planning are related to predicting the future. When planning the placement of network and secondary substations, the customer needs should be able to predict for decades to come, which is a challenging task. Essentially municipality zoning plans and the information of the development of the area obtained from the media and stakeholders form the basis for the prediction. In addition to the location of customers the development of the load of the feeders must also be able to predict, since it affects the techno-economically sensible dimensioning of network. However, the dimensioning is made easier by the fact that in general DSOs have only few conductor sizes in use, so the assessment of the magnitude of the load is sufficient. The network planner's local knowledge and vision of the development of the area has a key role in the assessment of the future situation. [**6**]

5.3.2 Planning principles of Elenia Oy

The MV network is built with 20 kV ground cables and LV network with 400 V ground cable throughout the entire operating area of Elenia Oy. All new secondary substations are kiosk type substations. In urban areas the network is primarily planned along the edges of public areas such as streets and parks and in the rural areas along edges of the roads, fields and plots, when possible. Area's development and municipalities zoning plans are taken into account when planning the locations of the cables and substation according to the principles of the long-term planning. [**32**]

In urban areas' cable network disconnectors are planned in both directions of the MV main lines in every substation as well as in the beginning of the branch lines. Remote-controlled disconnectors are planned in nodes of the MV network taking into account the flexible use of different switching situations. [**32**]

In rural areas' cable network there can be a maximum of 200 kVA nominal transform power between disconnectors or one secondary substation, the nominal transform power of which is bigger than 200 kVA. Between the disconnectors there can be no more than 5 km of MV cable. In rural area the remote-controlled disconnectors are planned one for every 10 km or every other disconnector of the network. Remote-controlled disconnectors should be planned in the secondary substation located in the node, when possible. During reinvestment cabling projects the remaining overhead branches should be equipped with remote-controlled disconnectors, when the branch is exposed to faults. When the branch is not particularly exposed to faults, disconnector without remote-control is used. Pole-mounted circuit breakers, which deconstruct because of reinvestment projects, are moved to a natural point of the network to separate the faults of the overhead lines from the cable network. New pole-mounted circuit breakers will not be built, which is a result of Elenia Oy's strategy to develop reliability by cabling. [**32**]

6 SELECTION OF ANALYSIS AREA AND REPARAMETRIZATION OF THE RNA-TOOL

In order for making the comparison of the prioritization criteria of reinvestments as reliable as possible the analysis area and calculation tools have to be suitable for this analysis. Sufficient extent and versatility are important criteria in selecting analysis area, so that the differences of prioritization criteria are clearly displayed. Furthermore, the results of the analysis must be reliably generalized to the entire operating area of Elenia Oy. Of the tools used in analysis, Tekla NIS is excellently suitable for the calculations of this thesis, because the goal is to plan the network again using different prioritization criteria of reinvestments. However, the RNA-tool used to calculate the reliability indicators requires modifying, as it has not been previously used for this type of analysis.

6.1 The selection of analysis area

Due to the wideness of the operating area of Elenia Oy, it is not sensible to perform the comparison of prioritization criteria of reinvestments for the whole operating area, but a smaller analysis area has to be selected. However, the selection of the analysis area was made in such a way that it would represent the average network structure of Elenia Oy as much as possible. Thus, the results can be reliably generalized to the entire operating area.

Although this thesis focuses on comparison of prioritization criteria of reinvestments of un-prioritized MV network, the effect of the cabling of the prioritized network must be found out before this analysis, in order to know the starting point of the un-prioritized network’s reinvestment. Therefore, an area consisting of two urban MV feeders in addition to two rural MV feeders has been selected as the analysis area. Thus, the analysis area represents the average operating area of Elenia Oy as well as possible and the results of cabling of the prioritized MV parts can also be generalized. The selected analysis area is presented in the figure 6.1.

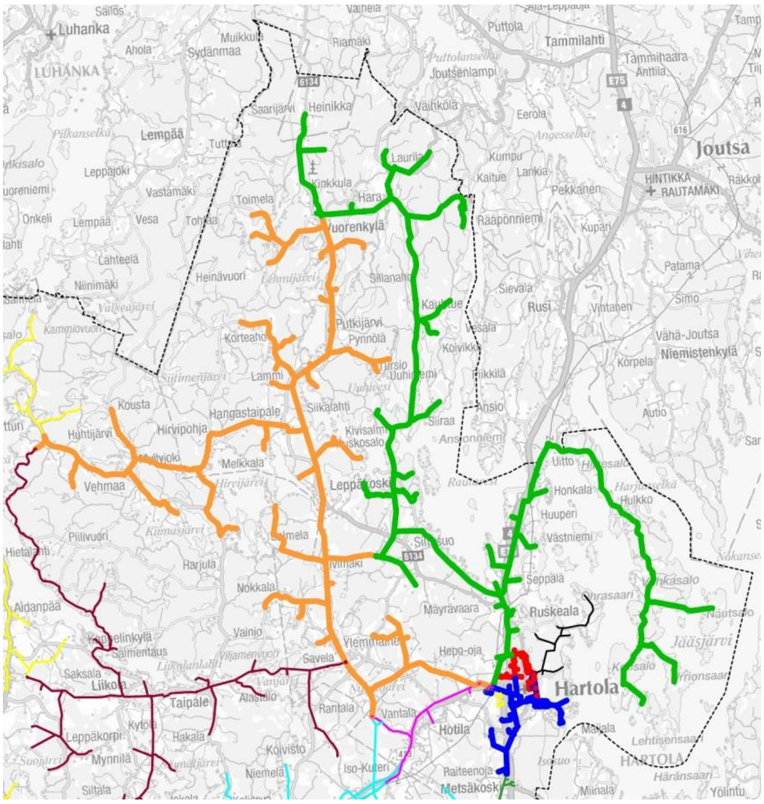

Figure 6.1. *The analysis area, which includes two rural MV feeders (green and orange) and two urban MV feeders (red and blue). Name of the green colored feeder is 05 HRL_RUSKEALA, orange colored feeder 07 HRL_YLEMMÄINEN, red colored feeder 10 HRL_KÄPYKYLÄ and blue colored feeder 06 HRL_HARTOLA.*

The black colored un-prioritized part is separated from the red colored urban feeder. Thus, the comparison of prioritization criteria of reinvestments of un-prioritized network can be focused on the two rural feeders. Figure 6.2 presents the prioritized, un-prioritized and cabled network parts in the analysis area.

In addition to generalization of the results, the versatility of the un-prioritized network is an important issue in selecting the analysis area. The analysis area of figure 6.1 includes a wide range of un-prioritized network of different ages, network parts where many faults have occurred, network parts located in the forest and network parts located in the fields. In addition to the un-prioritized branch lines the analysis area includes un-prioritized main lines. Thus, the analysis area is well suited for comparison of the different prioritization criteria of reinvestments.

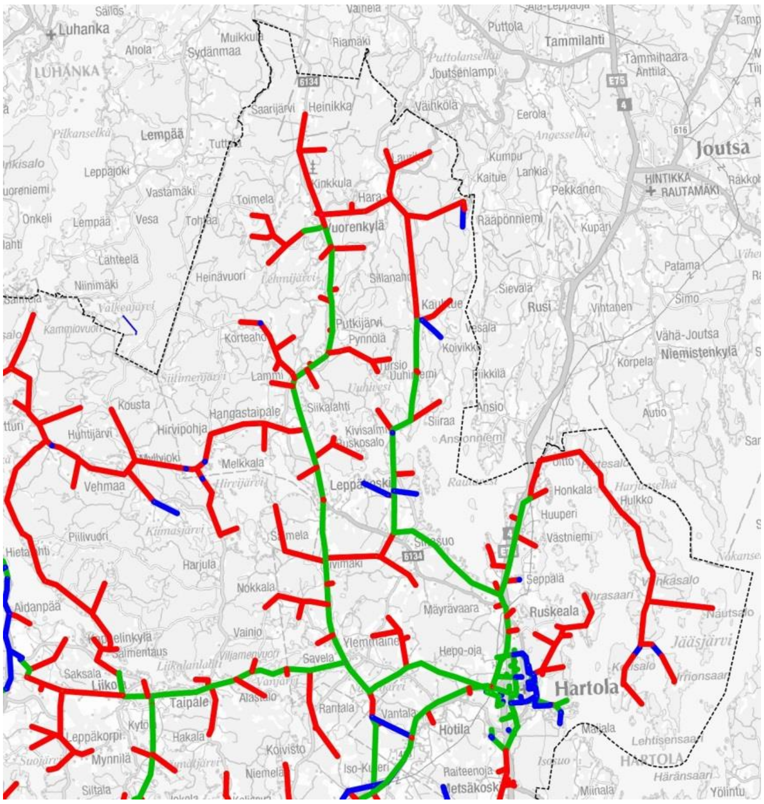

Figure 6.2. The analysis area, in which prioritized, un-prioritized and cabled network are highlighted. Green color represents prioritized network, red un-prioritized network and blue cable network.

6.2 Reparametrization of the RNA-tool

The RNA-tool is made primarily to model the normal distribution situation, since it only processes one fault at a time and thus is not able to model simultaneous faults, in particular major disturbances. However, the failure frequencies of the parts of the network that are sensitive to weather events and average fault repairing times differ between a normal year and a year when major disturbance occurs. By changing the parameters of the RNA-tool these differences can be taken into account. Thus, the proper choice of the parameters enables the modeling of the year when a major disturbance occurs with a sufficient accuracy in analysis of this thesis, because the reliability calculations are used to compare prioritization criteria of reinvestments. Thus, numerical values of reliability indicators are not as important as the indicators' ratio between prioritization criteria. In addition to the reliability indicators of a major disturbance year it is interesting to know the effects of prioritization criteria during the normal situation. Therefore, the different parameters of the RNA-tool are defined for a normal year as well as for a major disturbance year, which enables the comparison of the reliability effects in both situations. [**28**], [**29**]

6.2.1 Parametrization principles

The parameters of the RNA-tool have last been updated in 2009 to be equivalent to an average year based on the current fault statistics at that time. The cable MV network has been built to the rural area on a large scale only in the last few years, so in 2009 there was no comprehensive statistical information to define the parameters of cable network. Therefore, especially the parameters of cable network need to be updated to the parameters of a normal year, because the results of cable network have a high impact on the reliability indicators of the analysis of this thesis. Finally, it was decided that all the key parameters that affect the indicators SAIFI and SAIDI were to be reparameterized for a normal year. In addition the parameters for a major disturbance year were to be determined. The RNA-tool has not been used previously in the analysis of a major disturbance year in such a way that it is used in this thesis.

The RNA-tool is parameterized in such a way that the calculated SAIFI and SAIDI of the analysis area matches the average values of the fault statistics of the operating area of Elenia Oy. The SAIFI and SAIDI of the analysis area are formed by calculating the average of the reliability results of the four feeders of the analysis area weighted with the number of customers of the MV feeder. The average of the values of the years 2007-2009 and 2012 statistics has been used as the values for a normal year. The effect of Tapani and Hannu storms can still be seen in the statistics of January 2012. Thus, the effect of the major disturbances has been excluded from the statistic values of 2012 when calculating the average. The average values of SAIFI and SAIDI of the years 2010 and 2011 statistics has been used as the value for a major disturbance year. Used average values are gathered in the table 6.1.

Table 6.1. *Average values of SAIFI and SAIDI in the distribution area of Elenia Oy. Normal year values are average of the years 2007-2009 and 2012 statistics excluding the effect of major disturbances. Major disturbance year values are average of the years 2010 and 2011 statistics.* [**33**]

Reliability indicator	Normal year	Major disturbance year
SAIFI	3,05	5,64
SAIDI	2,21	9,08

6.2.2 Determination of parameters

Parameters affecting SAIFI

Fault frequencies of secondary substation (animal fault, thunder, other faults) in the RNA-tool are based on the fault statistics of Elenia Oy [**33**]. Parameters for a normal year are determined based on the fault statistics of the year 2007-2009 and 2012 and parameters for a major disturbance year on the statistics of the years 2010 and 2011.

Work frequency of a secondary substation cannot be reliably determined based on the fault statistics of Elenia Oy [**33**] because statistics of work interruptions can be found only from year 2012 onwards. Moreover, based on these statistics work interruption frequency would be really small, only about 0,06 pcs per 100 substations. Thus, the determination of the parameter is based on the fault statistics of Energiateollisuus [**34**]. The fault statistics of Energiateollisuus [**34**] contain annually collected fault statistics from nearly all Finnish DSOs.

Due to the very low amount of cable network faults, very comprehensive data for dividing the fault frequencies cannot be collected based on the fault statistics of Elenia Oy [**33**]. Therefore, in addition to the fault statistics of Elenia Oy [**33**] fault statistics of Energiateollisuus [**34**] of the corresponding years have been used in determining the fault frequencies of different causes. However, the total fault frequencies of cable network are kept in similar values as in the statistics of Elenia Oy.

Reliable values for the fault frequencies of covered MV line were neither found from the fault statistics of Elenia Oy [**33**] nor from the fault statistics of Energiateollisuus [**34**]. Based on both the statistics, the covered MV line would be more reliable than ground cable, even in major disturbance years. This is unlikely the truth, since a large portion of the causes of long-term faults of overhead lines, such as trees fallen on the wire, also cause faults on covered MV lines. Moreover, ground cables are almost completely safe from weather events. The lack of statistics is likely due to the fact that the faults of covered MV lines may be marked incorrectly as faults of overhead line.

Due to the unreliable statistics the total fault frequency of a covered MV line is estimated to be slightly over 2/3 of the total fault frequency of an overhead line on a major disturbance year and a little less than 2/3 of the total fault frequency of an overhead line on a normal year. The division of fault frequencies between ones caused by wind/snow, other faults and work interruptions are made similarly as the division is done for overhead line interruptions. Possible inaccuracy in fault frequencies of covered MV line does not cause a major inaccuracy in the results of this thesis, because the portion of the covered MV lines is only 7,9 % of the total length of overhead lines.

In addition to the above-mentioned parameters, the fault frequencies of overhead MV line affect the SAIFI. They could be determined with fairly reliable accuracy based on the fault statistics of Elenia Oy [**33**], which are also pretty close to the values of fault statistics of Energiateollisuus [**34**]. However, it is found by testing that the RNA calculation gives too small SAIFI compared to the average values of Elenia Oy using fault frequencies of overhead MV line based on statistics. Therefore, the fault frequencies of overhead MV line are increased until the SAIFI of RNA calculation in the analysis area corresponds to the values of table 6.1. The frequency of the most common fault cause of overhead MV line, which is wind/snow, has been raised the most. Although the fault frequencies have to be raised quite a lot compared to the statistics, the parameters of a normal year end up really close to the values, which were determined in the year 2009. Therefore, the corresponding values have also been found in the past to be suited for RNA calculations and the difference is likely due to the method of calculation that the

RNA-tool uses. The parameters determined in the year 2009 have been created in connection with doctoral thesis [**35**].

Parameters affecting SAIDI

The percentage and the duration of short, medium and long faults and the duration of transformer change are obtained directly from the fault statistics of Elenia Oy [**33**]. In addition to these, the duration of a remote controlled disconnection is one factor affecting the SAIDI. The actual statistic do not exist to determine the duration of remote controlled disconnection, but using the experiences of the employees of network control center [**36**] the roughly correct values and the ratio between normal year and major disturbance year have been determined. Elenia Oy has introduced automatic fault isolation and restoration system (FLIR) for rural MV networks in December 2011 [**37**], which speeds up fault isolation especially in the case of multiple faults. More information and experiences of FLIR can be found in [**38**].

In addition to the above-mentioned factors, the duration of MV cable replacement and the duration of a MV fault correction also affect the SAIDI. Total outage times of cable and other MV faults can be found in the fault statistics of Elenia Oy [**33**], but the correction times can not be found directly. Also, testing indicates that the RNA calculation gives too high SAIDI when compared to the average values of Elenia Oy using total outage times of statistics for the duration of MV cable replacement and the duration of MV fault correction. Therefore, the parameters based on the total outage times are decreased, while keeping the ratio between the two constant, until the SAIDI of the RNA calculation in the analysis area corresponds to the values of table 6.1. It can be noticed that also these parameters for normal year are close to the previously determined parameters.

Summary of the fault statistics and the parameters

In tables 6.2 and 6.3 are summarized parameters determined for normal year in the year 2009, values based on fault statistics of Elenia Oy [**33**], values based on the fault statistics of Energiateollisuus [**34**] and parameters determined based on these statistics for normal year and major disturbance year. Using the RNA parameters in table 6.2, the calculated reliability indicators (SAIFI, SAIDI) for present network of the analysis area are equal to values in the table 6.1.

Table 6.2 *In the year 2009 determined RNA parameters (Previous), fault statistics of Energiateollisuus (Statistics 1) and Elenia Oy (Statistics 2) and determined RNA parameters for analysis of this thesis affecting SAIFI. Statistics values for normal year (Normal) are averages of the years 2007-2009 and 2012 statistics and values for major disturbance year (MD) are averages of the years 2010 and 2011 statistics.* [**33**] [**34**]

Parameter affecting SAIFI	Previous	Statistics 1		Statistics 2		Determined parameters	
	Normal	Normal	MD	Normal	MD	Normal	MD
Distribution substation, fault frequency, animal faults	0,2	0,115	0,095	0,118	0,081	**0,1**	**0,1**
Distribution substation, fault frequency, thunder	0,25	0,128	0,128	0,061	0,183	**0,06**	**0,18**
Distribution substation, fault frequency, other faults	0,2	0,35	0,4	0,375	0,469	**0,39**	**0,45**
Distribution substation, work interruption frequency	2	0,883	1,275			**0,88**	**1,28**
Total interruption frequency of distribution substation	*2,65*	*1,22*	*1,685*			***1,43***	***2,01***
MV cable, fault frequency, construction	0,5	0,285	0,34	0,165		**0,165**	**0,2**
MV cable, fault frequency, digging	0,25	0,4	0,4	0,289		**0,25**	**0,25**
MV cable, fault frequency, other faults	0,5	0,048	0,095	0,412		**0,315**	**0,4**
MV cable, work interruption frequency	2	0,465	0,455	0,165		**0,3**	**0,3**
Total interruption frequency of MV cable	*3,25*	*0,89*	*0,98*	*1,031*		***1,03***	***1,15***
Covered MV line, fault frequency, wind/snow	2	0,253	0,33			**7,5**	**19**
Covered MV line, fault frequency, other faults	1	0,128	0,175			**1**	**2**
Covered MV line, work interruption frequency	3	0,203	0,23			**3**	**4**
Total interruption frequency of covered MV line	*6*	*0,423*	*0,58*			***11,5***	***25***
Overhead MV line, fault frequency, wind/snow	13	3,645	6,055	2,553	5,659	**13,11**	**28,52**
Overhead MV line, fault frequency, other faults	2	1,508	1,885	1,431	2,326	**2**	**3**
Overhead MV line, work interruption frequency	3	2,49	4,135	0,571		**3**	**5**
Total interruption frequency of overhead MV line	*18*	*6,928*	*11,11*	*4,555*		***18,11***	***36,52***

Table 6.3 *In the year 2009 determined RNA parameters (Previous), fault statistics of Energiateollisuus (Statistics 1) and Elenia Oy (Statistics 2) and determined RNA parameters for analysis of this thesis affecting SAIDI. Statistics values for normal year (Normal) are averages of the years 2007-2009 and 2012 statistics and values for major disturbance year (MD) are averages of the years 2010 and 2011 statistics.* [**33**] [**34**]

Parameter affecting SAIDI	**Previous**	**Statistics 1**		**Statistics 2**		**Determined parameters**	
	Normal	**Normal**	**MD**	**Normal**	**MD**	**Normal**	**MD**
Percentage of short (e.g. 5-8 h) faults (%)	30	2,18	3,6	10,2	11,7	**10,2**	**11,7**
Percentage of medium long (e.g. 8-12 h) faults (%)	8	0,349	0,983	4,56	4,68	**4,56**	**4,68**
Percentage of long (e.g. over 12 h) faults (%)	2	0,262	2,51	2,41	9,13	**2,41**	**9,13**
Duration of short (e.g. 5-8 h) faults (min)	360			371	372	**371**	**372**
Duration of medium long (e.g. 8-12 h) faults (min)	540			576	580	**576**	**580**
Duration of long (e.g. over 12 h) faults (min)	780			1525	3096	**1525**	**3096**
Duration of transformer change (min)	200			193	333	**190**	**330**
Duration of remote controlled disconnection (min)	10					**7**	**12**
Duration of MV cable replacement (min)	240			443	576	**266**	**297,4**
Duration of MV fault correction (min)	125			229	557	**137,5**	**287,6**

Inconsistencies can be noticed in the total values of the fault statistics of Energiateollisuus, since the sum of fault frequencies is not always corresponding to the total fault frequency. This is due to the fact that the information provided by some DSOs have lacked the specified data of the faults. In all cases the division similar to the parameters can not be directly found from the fault statistics, so the divisions are formed on the basis of the given information. [**34**]

Because the RNA-tool is reparameterized to match the average SAIFI and SAIDI of Elenia Oy, the RNA parameters and the calculation results can be kept quite reliable for the present network structure, in which the largest portion of the network consists of overhead lines. However, the suitability of determined parameters for cable network is uncertain. Although the total fault frequency of the cable is accurate, it is not sure whether the RNA calculation processes the cable network completely correctly or whether the parameters need modification like the parameters of overhead network. However, the possible systematic error of the results of the cable network is not a problem in the analysis of this thesis, since in every compared prioritization criteria of reinvestments, the same portion of overhead lines will be cabled. Thus, the RNA-tool is suitable for comparison between the criteria, even if there are some errors in the numeric values of reliability indicators. Suitability of the RNA parameters for calculations of cable network is discussed more in the chapter 9.2.1.

7 PROCEEDING OF THE ANALYSIS AND PRIORITIZATION CRITERIA

The main objective of this thesis is to compare the reinvestment criteria of un-prioritized MV network. However, before the comparison of the criteria the effect of the cabling of the prioritized MV network needs to be solved, in order to know the starting point of the un-prioritized MV network reinvestments. In addition, the year when the prioritized network is cabled must be known, so the reinvestments of the un-prioritized network can be correctly allocated on an annual basis. This chapter describes the principles of the proceeding of the analysis as well as the annual progress of cabling following each prioritization criteria.

7.1 Principles of proceeding of the analysis

Elenia Oy has made a capital reinvestment plan for the next 15 years, in order to reach the cabling rate of 70% by 2028. The cabling of the prioritized (chapter 7.2) and un-prioritized (chapter 7.3) MV network has been done in such a way that the annual reinvestments of the analysis area proceed by following the capital reinvestment plan of Elenia Oy. Capital reinvestments of the analysis area are scaled to match the annual total capital reinvestment amount of Elenia Oy's plan, in order to provide annual results of the cabling which can be generalized as reliably as possible to the entire operating area of Elenia Oy.

All changes in the MV network are planned with Tekla NIS using the same methods as used in planning the real network renovation plans and following the planning principles of Elenia Oy (chapter 5.3.2). Thus, all changes in the network topology due to cabling, such as the growth of network length, the suitable location for cable network and disconnectors as well as the growth of the substation density are taken into account in the analysis as realistically as possible. This also enables using the plans of the analysis as areas long-term plans. However, the supply areas of the feeders are kept similar to the present situation as well as possible during the analysis, so the analysis area and the number of customers of the feeders remain the same.

Currently the analysis area (figure 6.1) includes 181 km of MV network and 185 secondary substations. If the LV network would also be planned in detail in addition to the MV network, the workload within the framework of this thesis would increase too much and the analysis would not be possible to be carried out for such a large area. However, the LV networks share of the annual costs, which is estimated based on the average costs of the renovation projects, are taken into account in the calculations, so the reinvestments can be targeted annually according to the capital reinvestment plan of Elenia Oy. Otherwise the LV network is not taken into consideration in the analysis of this thesis.

SAIDI, SAIFI and COC values are calculated using the RNA-calculation of MV network, in which the LV network is not taken into account except the number and consumptions of customers. The RNA-calculation of the MV network processes such customer information on secondary substation level. Customer information is transferred from the deconstructed substations to the new corresponding substations of the cable network, so that the RNA-calculation would work realistically. The results of the reliability calculations are presented as values which describe the reliability of the entire analysis area, which can be generalized to values representing reliability of the entire operating area of Elenia Oy. This means that the presented SAIDI and SAIFI are averages weighted with the number of customers of the four MV feeders (figure 6.1). In turn, the CAIDI values are calculated based on the SAIDI and SAIFI results using the equation 3. The COC-results of the feeders are added, in order to obtain a value that represents the analysis area. However, the COC-results are presented as a percentage relative to the calculated value of the analysis area in the present situation, because the COC is otherwise difficult to generalize to the entire operating area. Moreover, the most important thing is to find out the changes of COC-results during the progressing of the cabling, rather than the absolute value.

Reliability values as well as the changes in conductor types calculated for each rural feeder by the RNA-tool are presented annually for each prioritization criteria in the table 3 in appendix 1. When cabling un-prioritized network, only the values of the rural feeders change. Appendix 1 also includes the values of the four MV feeders in the present situation, the situation when all prioritized network is cabled and in the starting point of the cabling of the un-prioritized network. Moreover, appendix 1 includes annual results of the RAV and RV of the deconstructed network for each prioritization criteria. The comparison of the financial calculations between the prioritization criteria is not presented in this thesis except for the RAV of the deconstructed network.

7.2 Cabling of prioritized network

The analysis of this thesis focuses on the comparison of the prioritization criteria of the low loaded un-prioritized rural network. Since the prioritized network will be cabled before the reinvestments of the un-prioritized network, the prioritized network of the analysis area must be planned as cable to find out the starting point of the cabling of the un-prioritized network. When the cabling of the prioritized network is planned following the capital reinvestment plan of Elenia Oy, the prioritized network of the analysis area will be cabled during the third quarter of the year 2023. Figure 7.1 presents the situation where the prioritized network of the analysis area is cabled.

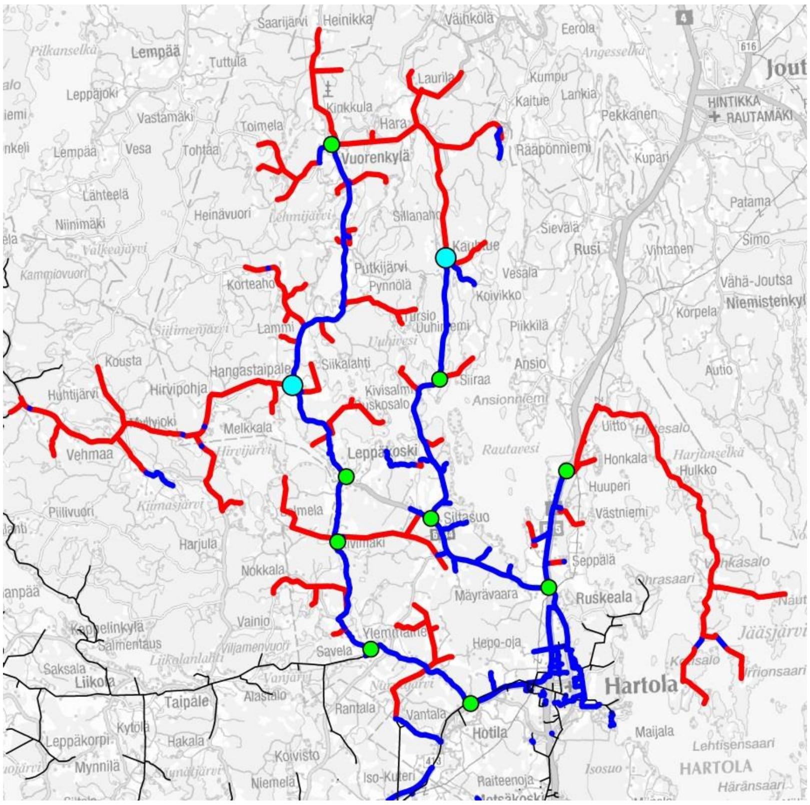

Figure 7.1. *The analysis area, where the prioritized part of the network is cabled. The cable network is highlighted in blue and un-prioritized overhead network of the rural feeders of the analysis area is highlighted in red. Green dots represent remote-controlled disconnectors and turquoise dots represent pole-mounted circuit breakers. A situation, where pole-mounted circuit breakers are replaced by remote-controlled disconnectors is selected as the starting point of cabling of un-prioritized network.*

There is one pole-mounted circuit breaker in the prioritized part of both rural MV feeders, which were relocated on the border of the cable and overhead line network to protect the cable network from faults of the overhead lines following the planning principles of Elenia Oy (chapter 5.3.2). When cabling the un-prioritized parts the pole-mounted circuit breakers would be deconstructed according to some prioritization criteria and would not be deconstructed according to other criteria. Also, the sensible relocating points for the pole-mounted circuit breakers would vary depending on the prioritization criteria. This would cause inaccuracy to the results of the analysis, which focuses on determining the effects of large scale cabling. Moreover, the influence of the pole-mounted circuit breakers is not wanted as a part of the results, because new pole-mounted circuit breakers are no longer being built in the operating area of Elenia Oy (chapter 5.3.2) and, therefore, they do not exist in the long-term target state. For these reasons the pole-mounted circuit breakers are replaced by remote-controlled disconnectors in the starting point chosen for the cabling of the un-prioritized network, as presented in the figure 7.1. Table 7.1 summarizes the SAIFI and SAIDI values calculated from the present situation, when all prioritized network is cabled and in the starting point of the cabling of the un-prioritized network, in which the influence of pole-mounted circuit breakers are eliminated.

Table 7.1. *Calculated SAIFI and SAIDI values from the present network (figure 6.2), when all prioritized network is cabled (figure 7.1) and in starting point of cabling of un-prioritized network without pole-mounted circuit breakers (figure 7.1).*

	Normal year		Major disturbance year	
	SAIFI	**SAIDI**	**SAIFI**	**SAIDI**
Present network	3,05	2,21	5,64	9,08
Prioritized cabled	2,31	1,60	3,94	5,25
Starting point	2,97	1,68	5,23	5,51

The results show, that the cabling of the prioritized network reduces the SAIFI by 24% and the SAIDI by 27% in a normal year. The corresponding values for major disturbance year are 30% and 42%. Thus, cabling of prioritized network reduces the SAIDI value of major disturbance year proportionally the most, which is the most significant reliability indicator from the point of view of the reliability demands of Electricity Market Act (chapter 4.1) point of view. After the removal of the pole-mounted circuit breakers the SAIFI and SAIDI are reduced by 2,5% and 24% in normal year and by 7,3% and 39% in major disturbance year compared to values of the present network. Thus, when pole-mounted circuit breakers are removed, the SAIFI is almost at the same level as in the present situation. The pole-mounted circuit breakers which are located at the border of cable and overhead network have a large influence on the number of outages experienced by customers, since the majority of the faults occur in the overhead network (chapter 2.2). However, the average duration of the faults is not influenced as much by whether the faults of the overhead network are separated from the cable network with pole-mounted circuit breakers or remote-controlled disconnectors.

7.3 Prioritization criteria

The analysis of this thesis compares five different prioritization criteria for the reinvestments of un-prioritized low loaded rural MV network. The prioritization criteria are cabling the oldest parts of the network first, the faultiest parts of the network first, the parts of the network located in a forest first and the parts nearest to the primary substation first with two different methods. The first method is to start cabling from the main lines and then proceeding to the branches nearest to the primary substation. The second method is to systematically cable the main lines and the branches forward from the primary substation. In the later chapters the criteria are discussed numbered:

1) Cabling the oldest parts first
2) Cabling the faultiest parts first
3) Cabling the forest located parts first
4) Starting the cabling from the main lines forward from the primary substation
5) Cabling systematically forward from the primary substation

It is justified that the oldest parts of the network are prioritized to be renovated first, because in general the old lines are in worse mechanical condition than the newer, thus increasing the risk of their failure. However, the location of the line has a great influence on the failure rate, since the most common cause of faults is a tree falling or bending on an overhead line, especially during major disturbances (chapter 3.2). Therefore, it is reasonable to renovate the forested parts of the network first. However, Elenia Oy also has a comprehensive fault location statistic, the basis of which denotes the parts of the network that have had the most faults. Most likely these parts are also liable to failure in the future and, therefore, it is justified that they are to be renovated first. Nevertheless, cabling forward from the primary substation results in a consistent cable network, where the faults of the more vulnerable overhead network are easy to separate with remote-controlled disconnectors. Cabling the main lines first quickly achieves the reliability effects affecting a large number of customers by reducing the failure rate of main lines and by locating the disconnectors sensibly from a cable network topology point of view. In turn, cabling systematically forward from the primary substation results in the most consistent cable network, which can be protected the most effectively from the faults of overhead lines, since there are the minimum number of borders of cable and overhead network.

These five different prioritization criteria are compared by starting the cabling from the starting point's network, in which the prioritized parts of the network are cabled and pole-mounted circuit breakers are removed (figure 7.1). According to each prioritization criteria, overhead network is being cabled following the capital reinvestment plan of Elenia Oy in such a way, that by the end of the year 2028 the cabling rate of the network of the analysis area is 70% (chapter 4.3). Reinvestments in terms of time are divided such that the cabling of un-prioritized network parts begins in year 2023 so that a share of 35% of the total reinvestments of that year is allocated to the cabling of un-prioritized network.

7.3.1 Cabling the oldest parts first

Figure 7.2 presents the starting point network of cabling of un-prioritized network, in which the oldest parts of the un-prioritized network and the cables are shown as highlighted. The ages of the overhead lines are determined based on the ages of the poles.

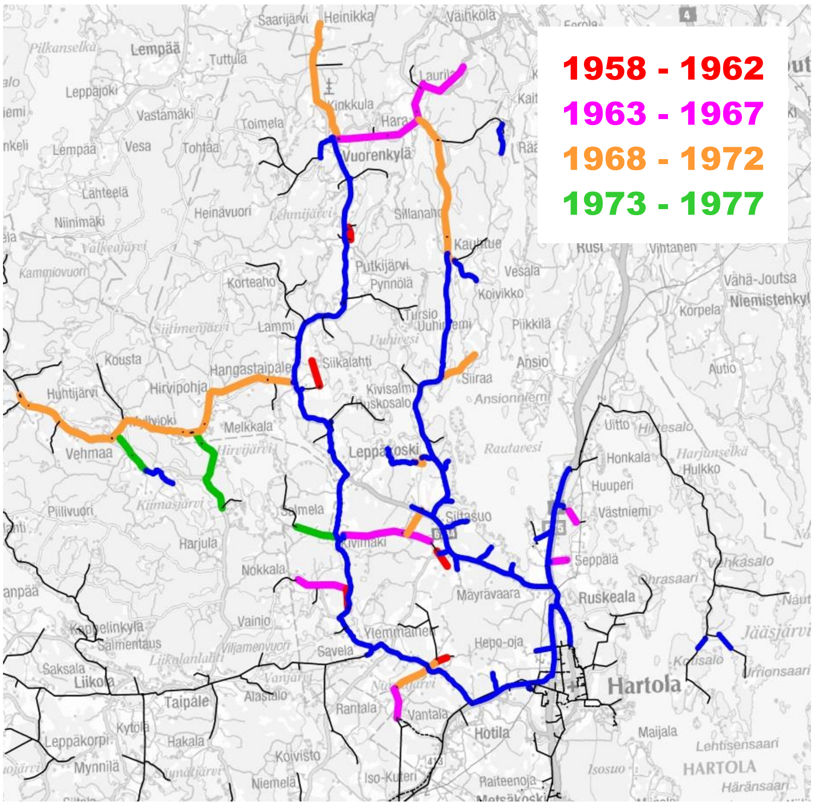

Figure 7.2. *Starting point of cabling of un-prioritized network, in which the cables are shown highlighted blue and the oldest parts of the network in other colors. Each color represents a certain year of construction range.*

Un-prioritized parts of the network are cabled starting from the oldest parts based on the network age analysis as shown in the figure 7.2. Therefore, in the years 2023 and 2024 reinvestments are almost entirely targeted to cabling MV branch lines. Reinvestments of the year 2025 are allocated fairly evenly between the main lines and the branches, but the reinvestments of the years 2026 and 2027 are targeted to main lines. In turn, reinvestments of the year 2028 are once again targeted to branches. The figure 7.3 presents a situation of the year 2028, in which the cabling rate of the analysis area is 70%, cabled starting from the oldest parts of the un-prioritized network.

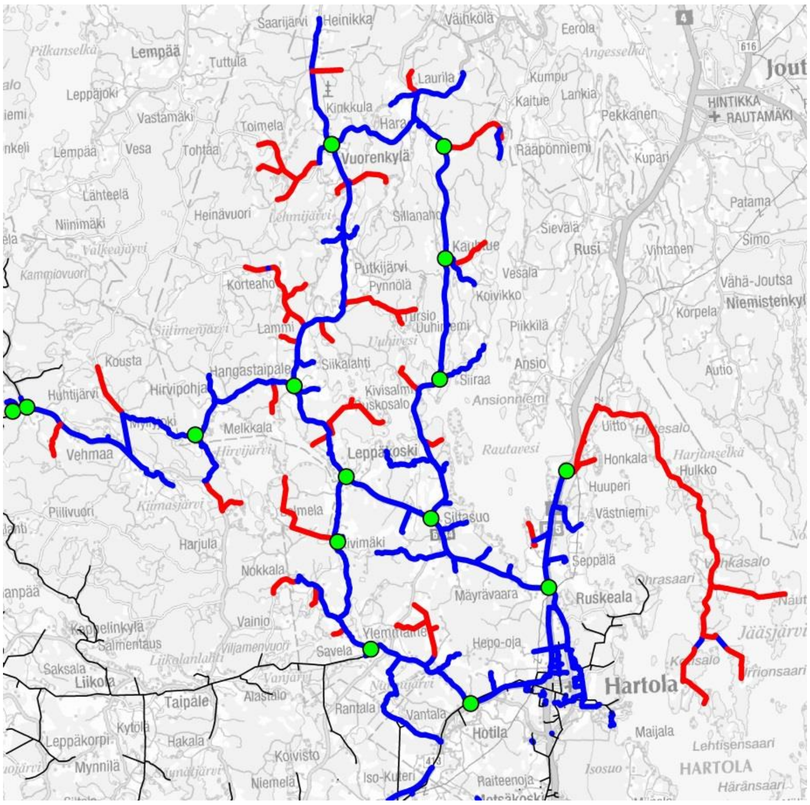

Figure 7.3. *Network of the year 2028, in which the cabling rate of the analysis area is 70%, cabled starting from the oldest parts of the un-prioritized network. Cables are highlighted blue and green dots represent remote-controlled disconnectors.*

The reinvestments of this prioritization criterion are targeted fairly evenly between the branches and main lines of the analysis area. Reinvestments are also divided relatively evenly geographically, with the exception of the east branching main line of the feeder 05 HRL_RUSKEALA, in which the network is more recently built (1991), and therefore is not cabled following this prioritization criterion. All other main lines are so old, that they are cabled. Branches are left un-cabled here and there along the rural feeders, because the branches are built as needed and some branches are thus clearly more recently built than the main line. The PAS sections are not cabled in this criterion at all, since the oldest PAS section of the analysis area was built 1991. By the year 2028 all overhead lines built in year 1974 and before are cabled. Only about one kilometer of overhead line, built in 1975, was left un-cabled from the network built in the 1970s. After that, the next oldest part of network was constructed in year 1983.

7.3.2 Cabling the faultiest parts first

Figure 7.4 presents the starting point network, in which the cables and the fault locations based on fault location analysis of Tekla NIS are shown as highlighted. The fault location analysis shows the actual locations of faults that have occurred in the recent years, based on the fault location statistics.

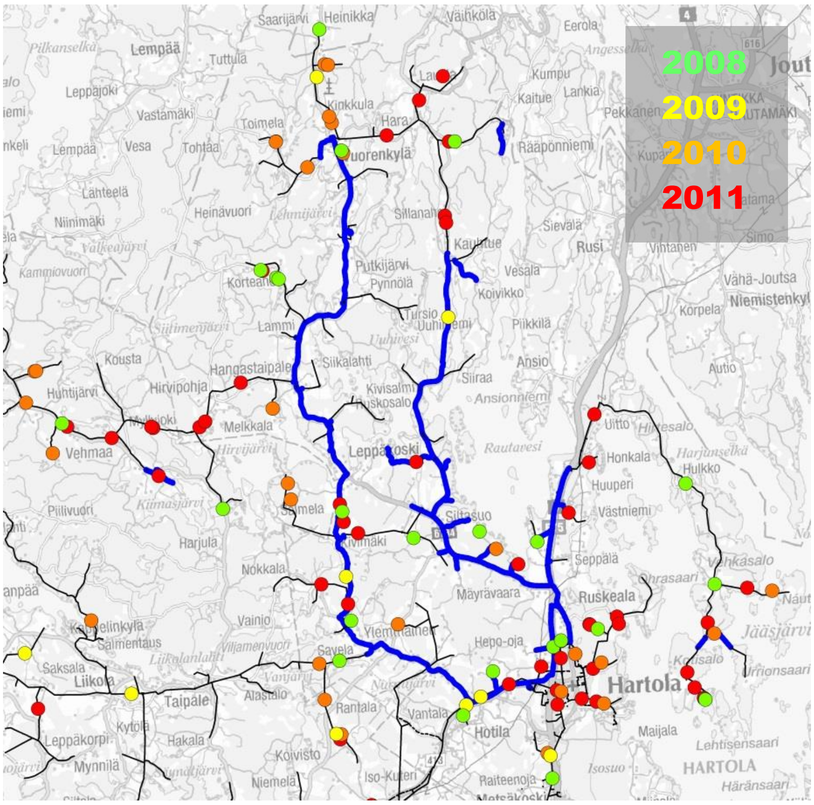

Figure 7.4. *Starting point of cabling of un-prioritized network, in which the cables are shown highlighted blue and the fault locations as dots in other colors. Each color represents a certain year when faults have occurred.*

Un-prioritized parts of the network are cabled starting from the faultiest parts based on fault location analysis of Tekla NIS as shown in the figure 7.4. In the years 2023 and 2024 reinvestments are entirely targeted to the cabling of branches. Particularly notable is the PAS branch located in the end of the feeder 05 HRL_RUSKEALA. There are 6 fault markings in that branch which makes it the faultiest individual section of the entire analysis area. Reinvestments of the years 2025 and 2026 are targeted mainly on the cabling of the west branching main line of the feeder 07 HRL_YLEMMÄINEN. In turn, the reinvestments of the years 2027 and 2028 are targeted in the main lines as well as in the branches so that in year 2027 the main focus of cabling is on the branches and in 2028 on the main lines. Figure 7.5 presents the situation of the year 2028, in which the cabling rate of the analysis area is 70%, cabled starting from the faultiest parts of the un-prioritized network.

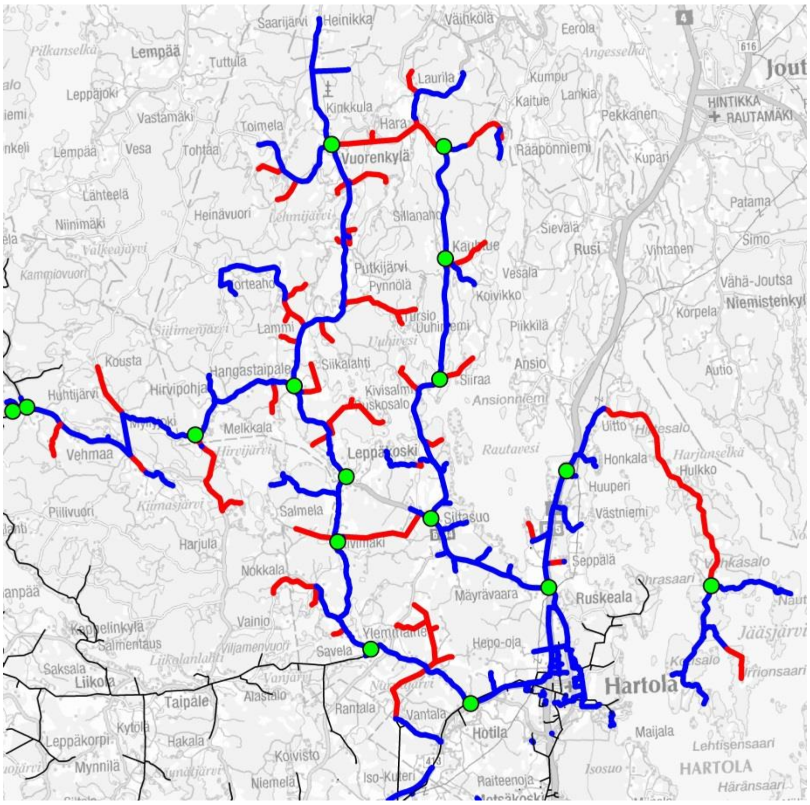

Figure 7.5. *Network of the year 2028, in which the cabling rate of the analysis area is 70%, cabled starting from the faultiest parts of the un-prioritized network. Cables are highlighted blue and green dots represent remote-controlled disconnectors.*

The reinvestments of this prioritization criterion are targeted fairly evenly between the branches and main lines of the analysis area. Reinvestments are divided geographically more evenly than in the prioritization criterion where the oldest parts are cabled first, since reinvestments are also targeted to the east branching main line of the feeder 05 HRL_RUSKEALA and its branches. Prioritization of the faultiest parts leads to a network structure, in which un-cabled overhead line sections are left between cable sections. This results from the fact that, especially a main line, located on the side of a road, has less faults than branches, which are typically located in a terrain which is more vulnerable to natural phenomena. From the 10,7 km of the PAS sections of the analysis area a share of 67% is cabled by the year 2028.

7.3.3 Cabling the forest located parts first

Figure 7.6 presents the starting point of cabling of un-prioritized network, in which the cables and the network location information provided by the line surrounding analysis of Tekla NIS is shown as highlighted. The line surrounding analysis indicates the type of terrain where the line is located, based on the terrain map of Tekla NIS.

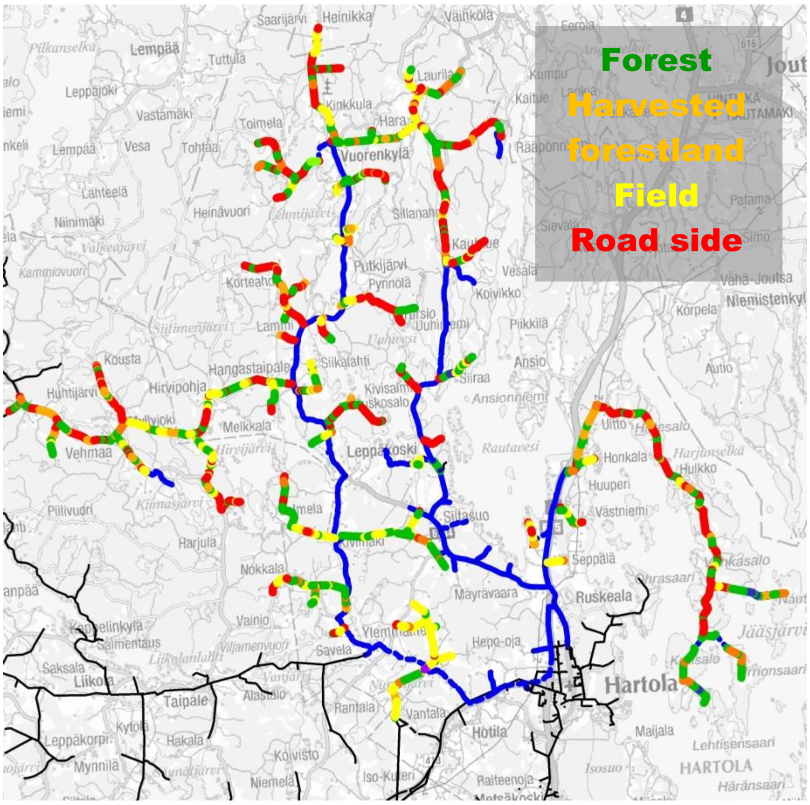

Figure 7.6. Starting point of cabling of un-prioritized network, in which the cables are shown highlighted blue and the locations of the line in other colors. Each color represents a certain surrounding type of line.

As shown in the figure 7.6, forest located parts are highly fragmented across the analysis area and not many significantly clear forest located sections are seen in the analysis area. Un-prioritized parts of the network are cabled starting from the forest located parts in sensible-sized sections. In the years 2023 and 2024 reinvestments are almost entirely targeted to cabling branches. In turn, reinvestments of the years 2025 and 2026 are fairly evenly targeted to branches and main lines. Also in 2027 the branches are cabled, but the west branching main line of the feeder 07 HRL_YLEMMÄINEN has a slightly greater weight than the branches. In the year 2028 quite the same amount of main lines and branches are cabled. Figure 7.7 presents the situation of the year 2028, in which the cabling rate of the analysis area is 70%, cabled starting from the un-prioritized parts located in forest.

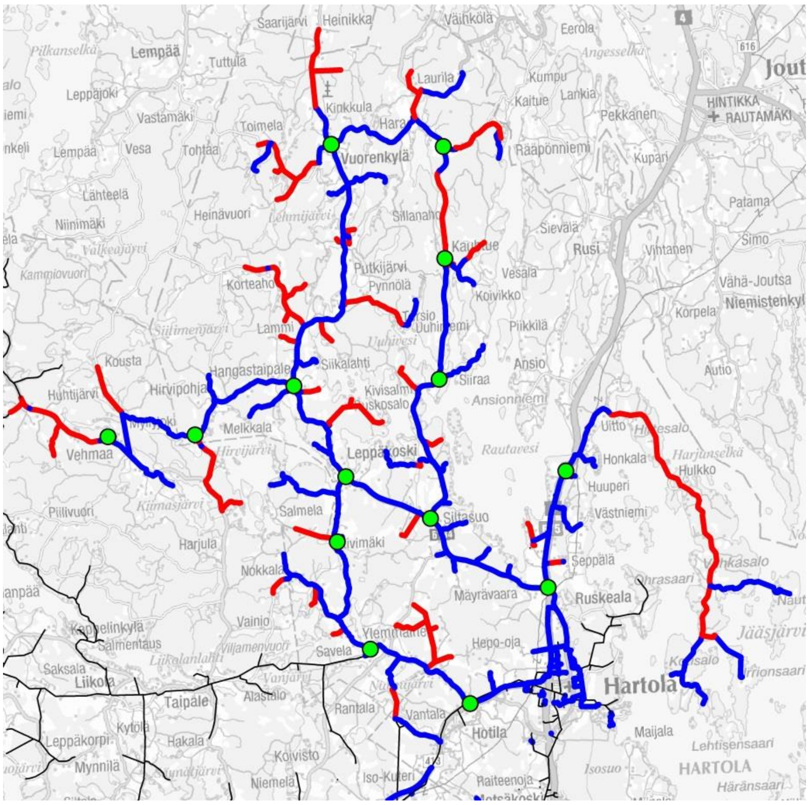

Figure 7.7. Network of the year 2028, in which the cabling rate of the analysis area is 70%, cabled starting from the un-prioritized network parts located in forest. Cables are highlighted blue and green dots represent remote-controlled disconnectors.

The reinvestment of this prioritization criterion are targeted a slightly more to the branches than the main lines. Reinvestments are divided geographically quite evenly. From all of the prioritization criteria cabling forest located parts first leads to the most fragmented network structure, where un-cabled overhead lines are left between the cable sections. This is a consequence of the fact that some parts of the main lines are located on the sides of the roads and part in the forests. Moreover, the most clear forest located parts are focused on branches. From all the prioritization criteria in this prioritization criterion the PAS sections are cabled more than with the other criteria. From the PAS sections of the analysis area a share of 74% is cabled by the year 2028.

7.3.4 Starting cabling from main lines forward from primary substation

In this prioritization criterion the un-prioritized main lines are cabled forward from primary substation and proceeding in such a way, that the nearest un-cabled overhead main lines to the primary substation are cabled in reasonable-sized parts. At the end of the year 2027 the main lines are cabled, so the reinvestments of the year 2028 are targeted to the cabling of branches nearest to the primary substation. Figure 7.8 presents the situation of the year 2028, in which the cabling rate of the analysis area is 70%, cabled starting from main lines forward from the primary substation.

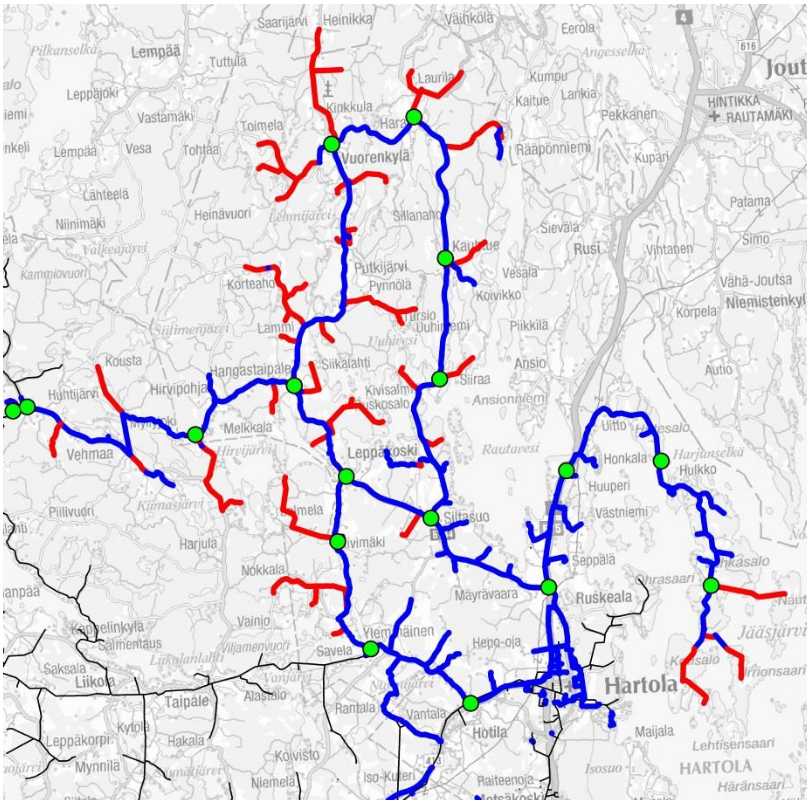

__Figure 7.8.__ Network of the year 2028, in which the cabling rate of the analysis area is 70%, cabled starting from the un-prioritized main lines forward from the primary substation. Cables are highlighted blue and green dots represent remote-controlled disconnectors.

Reinvestments of this prioritization criterion are clearly the most targeted to main lines compared to the other prioritization criteria. Reinvestments are also divided geographically most evenly throughout the analysis area. Following this prioritization criterion the PAS sections are not cabled at all.

7.3.5 Cabling systematically forward from primary substation

In this prioritization criterion un-prioritized the overhead lines are systematically cabled forward from the primary substation in such a way, that the nearest un-cabled overhead line section, branch or main line, to the primary substation is cabled. The goal is to create as consistent cable network as possible.

In the years 2023 and 2024 the reinvestments are solely targeted to the cabling of the branches nearest to the primary substation. Reinvestments of the year 2025 are targeted to the cabling of the backup supply connection between the rural feeders, part of the east branching main line of the feeder 05 HRL_RUSKEALA and approximately the same length in branches. In the years 2026 and 2027 mostly branches are cabled, but also the cabling of the east branching main line is continued. Reinvestment of the year 2028 are entirely targeted to cabling the east branching main line of the feeder 05 HRL_RUSKEALA and the west branching main line of the feeder 07

HRL_YLEMMÄINEN. Figure 7.9 presents a situation of the year 2028, in which the cabling rate of the analysis area is 70%, cabled systematically forward from the primary substation.

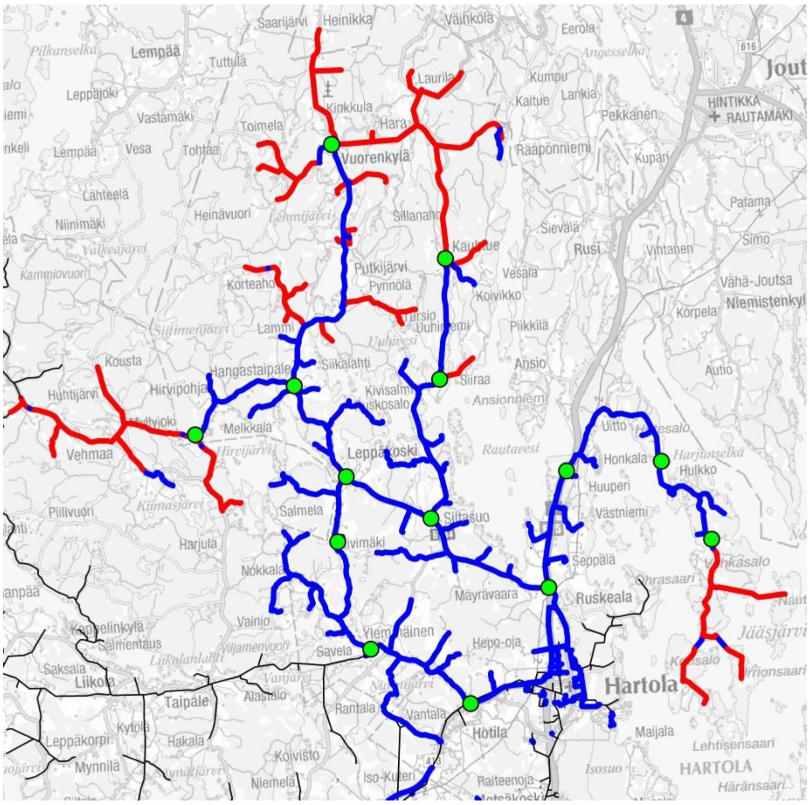

Figure 7.9. *Network of the year 2028, in which the cabling rate of the analysis area is 70%, cabled systematically forward from the primary substation. Cables are highlighted blue and green dots represent remote-controlled disconnectors.*

The reinvestments of this prioritization criterion are more targeted on the cabling of the branches than on the main lines, which is why following this prioritization criterion the shortest length of main lines are cabled compared to the other criteria. Almost all the cabled branches are un-prioritized branches of the prioritized main line. Also, geographically the reinvestments are divided the most unevenly on the analysis area, since the overhead lines nearest to the primary substation are cabled. This prioritization criterion clearly leads to the most consistent cable network, but still some of the branches of the prioritized and cabled main lines are left un-cabled, because the prioritized main lines extend relatively far in both rural feeders. From the PAS sections of the analysis area a share of 28% is cabled following this prioritization criterion.

8 CALCULATION RESULTS OF ANALYSIS AND COMPARISON OF PRIORITIZATION CRITERIA

This chapter presents the reliability results of the analysis calculated with the RNA parameters of a normal year as well as a major disturbance year. Based on those results, the basis for the prioritization principles for the reinvestment plan of low loaded rural MV network is sought by studying the factors affecting reliability. In addition to the reliability results the differences between prioritization criteria are discussed from the point of view of the RAV of the network. Moreover, the chapter presents the effects of large scale cabling on the network structure based on the analysis of this thesis.

8.1 Comparison of the reliability results

This chapter presents the values and the development of the reliability indicators SAIFI, SAIDI, CAIDI and COC following the different prioritization criteria of un-prioritized network reinvestments as described in the chapter 7.3. Reliability values are calculated with the RNA-tool (chapter 5.1.2) using the RNA-parameters for a normal year and a major disturbance year (chapter 6.2). The reliability results of prioritization criteria are presented as values that describe the entire analysis area (chapter 7.1). Therefore, the reliability results, the generalizability of which is discussed in more detail in chapter 9.2, can be used to estimate the annual development of reliability of the entire distribution area of Elenia Oy. The differences in reliability results and their annual development between prioritization criteria are analyzed in an effort to find out the factors affecting reliability and their significance as thoroughly as possible. The numbers representing the different criteria are as follows:

1) Cabling the oldest parts first
2) Cabling the faultiest parts first
3) Cabling the forest located parts first
4) Starting the cabling from the main lines forward from the primary substation
5) Cabling systematically forward from the primary substation

8.1.1 Results of SAIFI

Figures 8.1 and 8.2 present the development of the SAIFI of the analysis area following the different prioritization criteria of un-prioritized MV network reinvestments. SAIFI describes average number of interruptions experienced by customers during a one-year period.

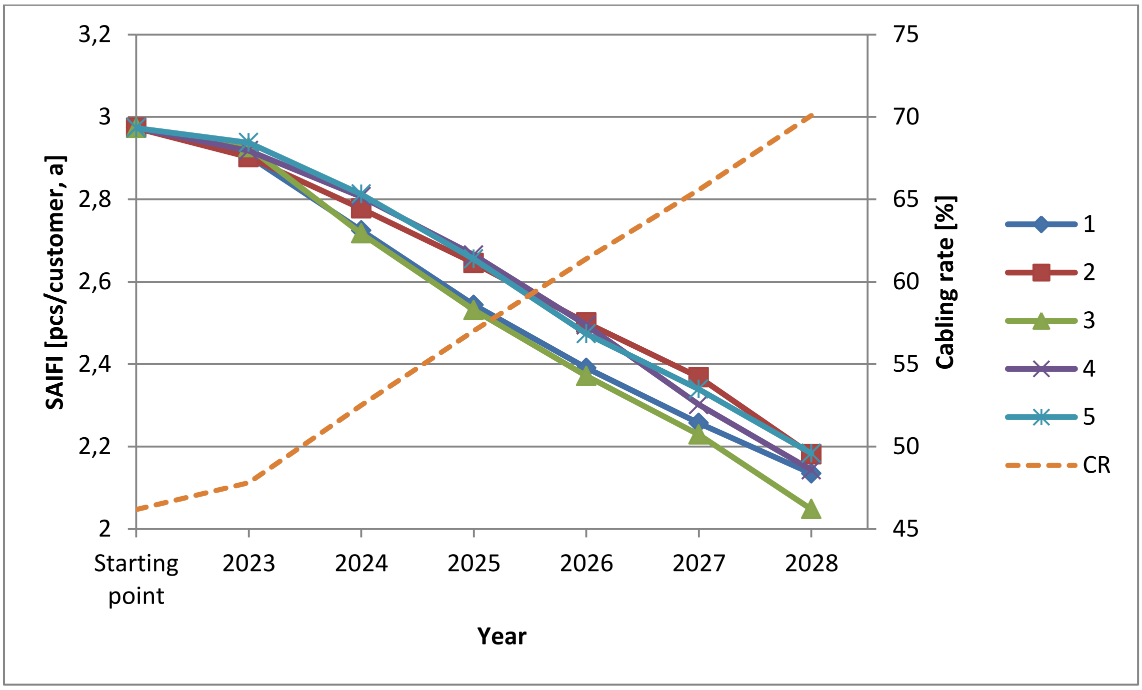

Figure 8.1 *SAIFI results of normal year. CR is abbreviation of cabling rate.*

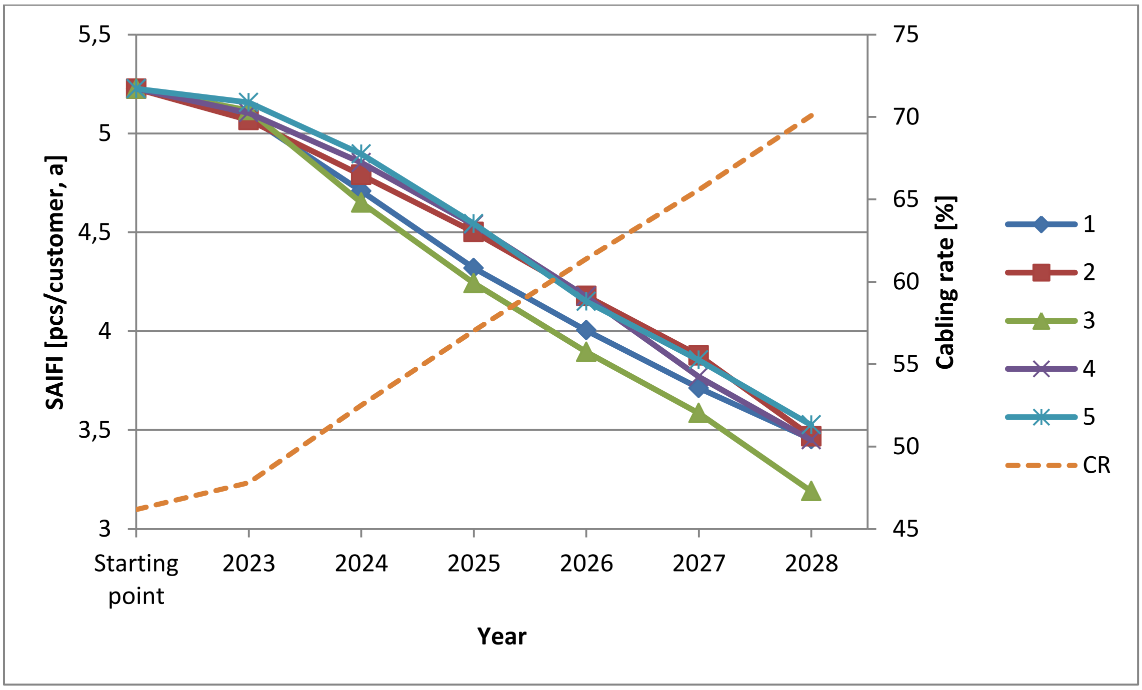

Figure 8.2. *SAIFI results of major disturbance year.*

The starting point of cabling of un-prioritized network (figure 7.1) is scheduled for the third quarter of the year 2023 so that only 35% of reinvestments of that year are allocated to cabling of un-prioritized network (chapter 7.3). As a result, the difference between the SAIFI values of the starting point and the end of the year 2023 is not as great as the difference between the following years when all reinvestments of the year are targeted to un-prioritized network.

As shown in the figures 8.1 and 8.2, there are no major differences between the prioritization criteria on the development of the SAIFI value, but it can be seen that the value decreases fairly linearly as the cabling rate increases, regardless of the prioritization criterion. However, two prioritization criteria stand out over the others, which are the criteria 3 and 1. However, the criterion 3 leads to clearly the smallest SAIFI value when approaching the year 2028 results in both normal year and major disturbance year situations. As shown in the figures 8.1 and 8.2, the difference is greater between the values for a major disturbance year. This is a very logical result, since the most effective way to reduce the number of faults is to cable the most fault vulnerable overhead sections. Due to their location, the forest located overhead sections are the most sensitive to faults caused by natural phenomena. In turn, the oldest overhead sections are on average in weaker mechanical condition, which is also one factor that increases the fault frequency. However, the forest location is a more significant factor from the point of view of fault vulnerability, especially during a major disturbance year.

The RNA-tool takes into account the forest located network parts and the ages of network components when it determines the fault frequencies of network parts during calculation (chapter 5.1.2). However, the RNA-tool does not take into account the fault location statistics (figure 7.4). For this reason, the SAIFI values of prioritization criterion 2 are likely closer to the values of prioritization criteria 3 and 1 than RNA-calculations presented in analysis of this thesis.

The SAIFI values of the two prioritization criteria for cabling forward from the primary substation develop almost evenly for a normal year as well as for a major disturbance year. However, starting from 2027 the prioritization criterion 4 outstrips the criterion 5. However, it is most notable that the prioritization criteria 4 and 5 are very even with the criteria 1 and 2. This holds especially in the situation at the end of the year 2028, even if the prioritization criteria 4 and 5 are not primarily intended to cable the parts with the highest fault frequency. Also, focusing on the cabling of main lines or branches does not bring difference between the SAIFI results, since regardless of where the fault is located on the feeder it will cause an outage for all customers of the feeder, because pole-mounted circuit breakers do not exist. Although, there are no big differences between the SAIFI results of prioritization criteria on the basis on this analysis, it turns out that cabling forest located parts first is the most effective way to reduce the number of faults in the network.

8.1.2 Results of SAIDI

Figures 8.3 and 8.4 present the development of the SAIDI of the analysis area following different prioritization criteria of un-prioritized MV network reinvestments. The SAIDI describes the average duration of interruptions experienced by customers during a one-year period.

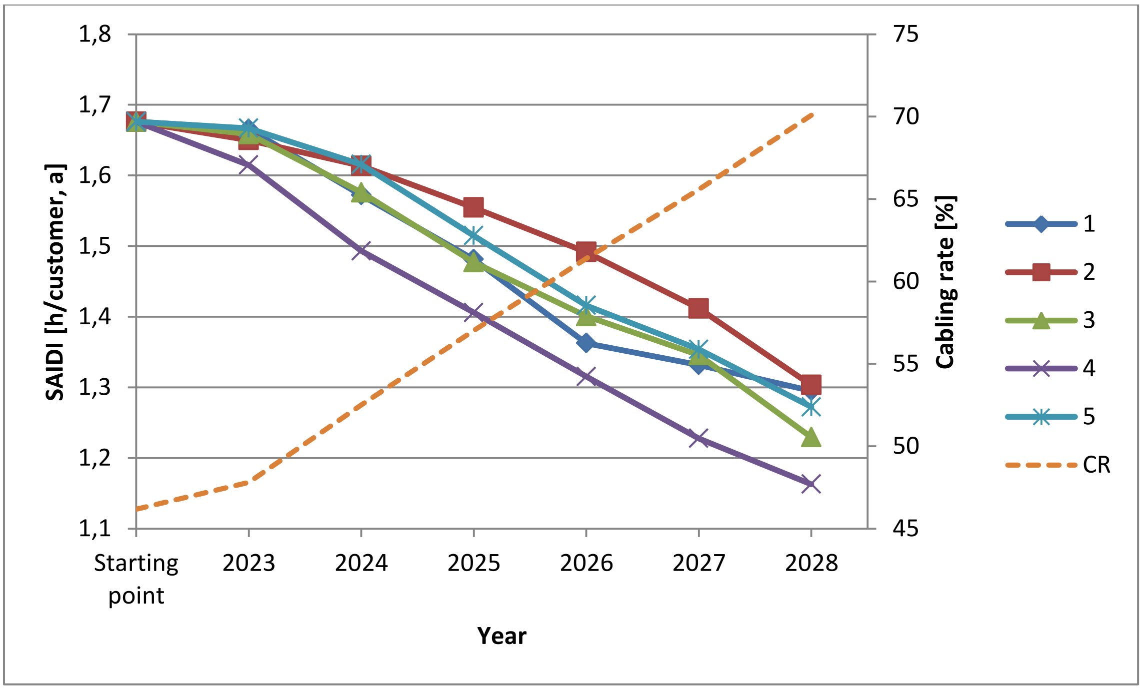

Figure 8.3. *SAIDI results of normal year.*

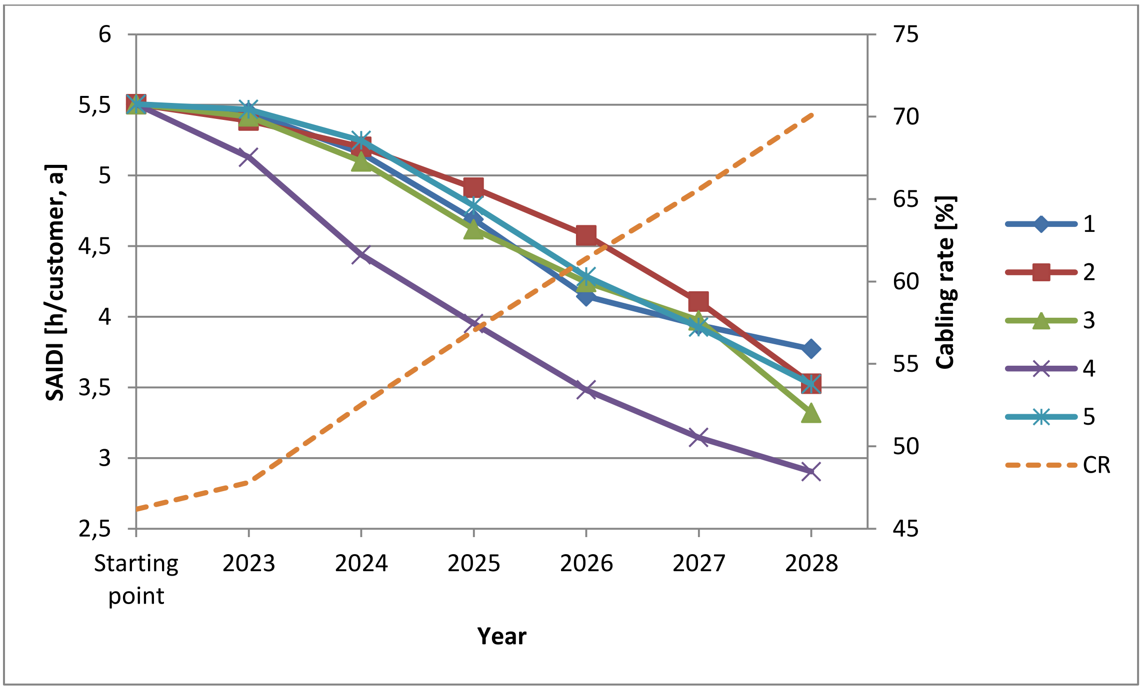

Figure 8.4. *SAIDI results of major disturbance year.*

The most significant reduction of SAIDI values is achieved by the prioritization criterion 4 in the years 2023 and 2024. In the year 2023 a part of the east branching main line of the feeder 05 HRL_RUSKEALA is cabled. In the year 2024 cabling of the east branching main line continues and in addition a part of the north branching main line of the same feeder is cabled. Moreover, remote-controlled disconnectors are built in critical points on both of the main lines, which also have a significant impact on the duration of faults experienced by customers. The remote-controlled disconnectors in the node of the north branching main line enables fast separation of faults of the overhead network from the cable network. In turn, reducing the fault frequency of the east branching main line and sensible placement of disconnectors is particularly significant since there is no backup supply connection on the east branching main line.

The influence of cabling the main lines can also be seen in SAIDI results of other criteria. In the years 2025 and 2026 when following criteria 1 and 3 the SAIDI reduces approximately as effectively as with criteria 4 at the same time. During these years plenty of the main lines are cabled with both criteria 1 and 3. In the year 2026 the reinvestments of the criterion 1 are targeted entirely on the main lines, which cause the criterion's SAIDI value to outstrip the SAIDI of criterion 3, the reinvestments of which are targeted approximately evenly between the main lines and branches. However, the SAIDI values of criterion 1 decrease the least compared to the other criteria after the year 2026, as the reinvestments are targeted to branches and the tail of the west branching main line of the feeder 07 HRL_YLEMMÄINEN.

In the years 2025 and 2026 the SAIDI values of criterion 5 decrease also approximately as effectively as in criterion 4. In criterion 5 more branches than main lines are cabled in years 2025 and 2026, but the cabled main line section belongs to the east branching main line of the feeder 05 HRL_RUSKEALA. Moreover, the backup supply connection between rural feeders is cabled.

In the year 2027 the SAIDI values of criterion 4 do not decrease as sharply as before, since the tails of main lines are targeted for cabling. In that case, the effect on SAIDI is mostly the result of the decrease of fault frequency, since new remote-controlled disconnectors are no longer built. Thus, the fault separation is no longer essentially speeded up. In the year 2028 the development of SAIDI value is even slower, when the reinvestments are targeted to the cabling of branch lines.

In 2028 the criteria 2 and 3 improve their SAIDI value remarkably. In the criterion 2 reinvestments are targeted to the north branching main line of the feeder 05 HRL_RUSKEALA and the cabling ends on remote-controlled disconnector. In turn, approximately the same amount of branches and main lines are cabled in criterion 3, but the cabled main line section is the east branching main line of the feeder 05 HRL_RUSKEALA.

The significance of the cabling of the east branching main line of the feeder 05 HRL_RUSKEALA can be more clearly seen when comparing the SAIDI results of individual feeders (appendix 1), especially in the results of criteria 4. In the criterion 4 the reinvestments are targeted on the feeder 05 HRL_RUSKEALA more than any other criteria, since it includes the most un-cabled overhead main lines. Therefore, the superiority of the criterion 4 is due to the development of the SAIDI values of the feeder 05 HRL_RUSKEALA, the SAIDI value of which in 2028 is approximately 50% lower when compared to the other criteria. In fact, the SAIDI of a major disturbance year in criterion 4 is even more than 50% lower when compared to the results of criteria 1 and 5. In addition to the greater targeting of reinvestments to the feeder 05 HRL_RUSKEALA, a significant impact on the big difference of SAIDI values is a result of the cabling of the entire east branching main line in the criterion 4. On the other hand, in criterion 1 all other main lines of the feeder 05 HRL_RUSKEALA except the east branching main line are cabled, leading to the highest SAIDI results of the feeder for all criteria. In all other criteria at least some part of the east branching main line is cabled. Therefore, the cabling of the east branching main line has an especially significant impact on the SAIDI results. Also, the reinvestments of the feeder 05 HRL_RUSKEALA are slightly more efficient than the reinvestments of the feeder 07 HRL_YLEMMÄINEN, due to the 12% larger number of customers. Thus, the reinvestments of the feeder 05 HRL_RUSKEALA improve the reliability of electricity supply for more customers.

A common observation for all criteria is that cabling of the main lines reduces the SAIDI value more efficiently than cabling of branch lines. Moreover, it is also observed that cabling main lines is no longer as efficient, when cabling the last remote-controlled zone of the feeder, because the number of customers isolated by remote-controlled disconnectors no longer grows. Cabling of the east branching main line of the feeder 05 HRL_RUSKEALA has a greater effect on the SAIDI value than cabling of the other main lines, because it has no backup connection. Also, cabling the other parts of the feeder 05 HRL_RUSKEALA seems to be slightly more effective in reducing SAIDI than cabling the parts of the feeder 07 HRL_YLEMMÄINEN due to the larger number of customers.

8.1.3 Results of CAIDI

Figures 8.5 and 8.6 present the development of CAIDI of the analysis area following different prioritization criteria of un-prioritized MV network reinvestments. CAIDI describes the average duration of interruptions during a one-year period.

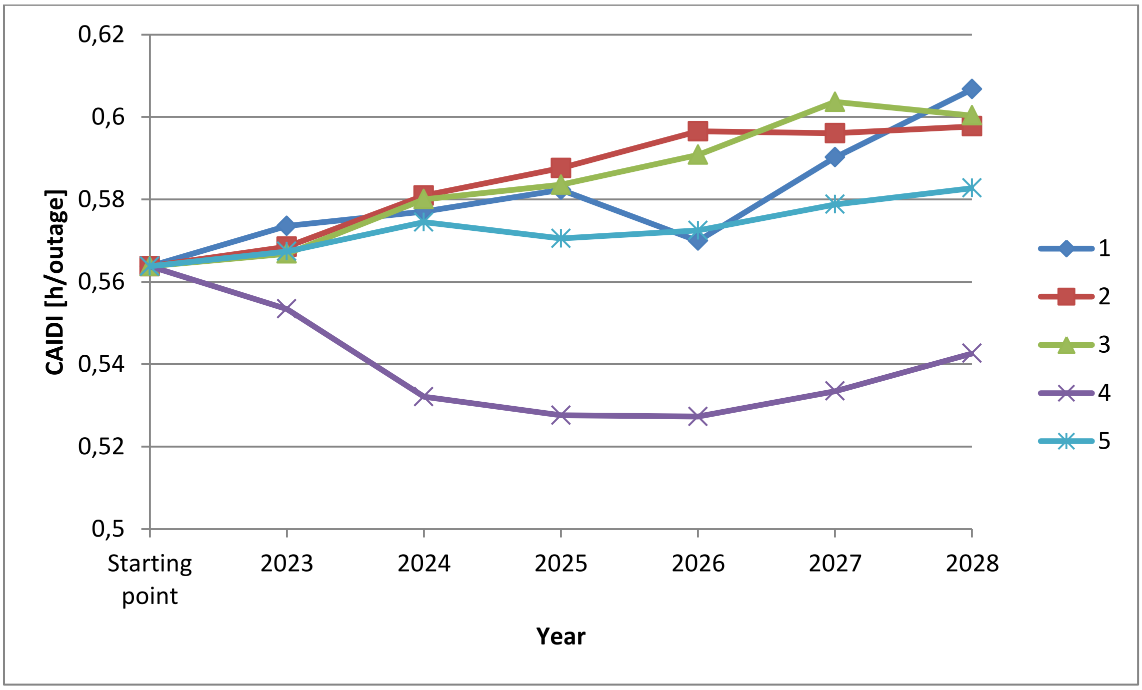

Figure 8.5. *CAIDI results of normal year.*

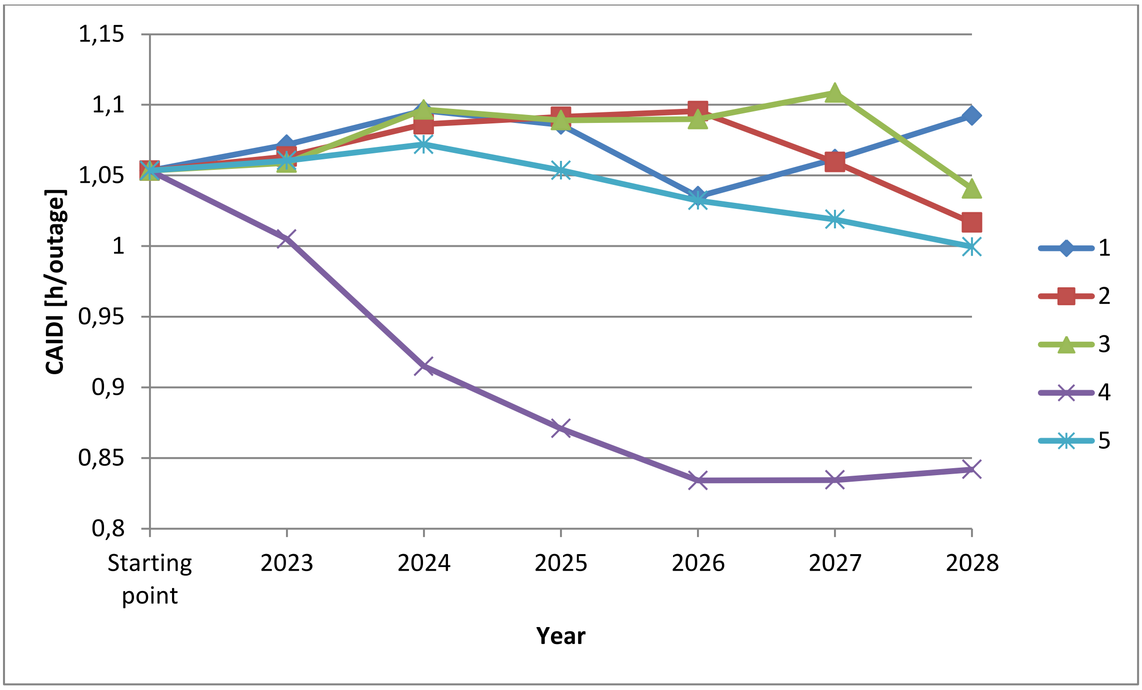

Figure 8.6. *CAIDI results of major disturbance year.*

The CAIDI results clearly develop in a different way than the SAIDI and SAIFI results, and there is no major change in the CAIDI values between the starting point and the situation of the year 2028. This is due to the fact, that the CAIDI is quotient of the SAIDI and SAIFI and it represents the average outage duration time (chapter 3.5). Thus, as the cabling proceeds and the number of customer interruptions as well as the sum of customer interruption durations both decrease quite steadily, the average duration of interruption will therefore stay at approximately the same level. However, the differences in the SAIDI results have the largest effect on the CAIDI curves in this analysis, because the differences between the SAIFI values for the criteria are minor (chapter 8.1.1 and 8.1.2).

There is a rising trend in the CAIDI results for a normal year in the prioritization criteria 1-3 and 5. This is due to the fact that as the cabling rate raises the relative number of faults of the cable network increase when compared to the fault number of the overhead network. Since it takes on average longer to repair a cable fault than a fault in the overhead line (chapter 6.2.2), the increase of cabling rate leads to the raise of the average interruption duration time. However, the criterion 4 behaves conversely and its CAIDI for a normal year is less than at the starting point during the entire examination period. This proves that the improving of reliability and the efficient fault separation of main lines has clearly greater effect on shortening the customer interruption durations than cabling the branches. This can also be seen in the CAIDI results of prioritization criterion 1, which contains an explicit downward spike in the results for the year 2026. The reinvestment of the year are targeted entirely on main lines and mostly on uncabled main line between the cabled sections, which also reflects the importance of consistently cabled main lines.

In the CAIDI results for a major disturbance year the increase of cabling rate no longer causes a rising trend on any of the prioritization criteria, since the ratio of overhead network faults to cable network faults is significantly higher than for a normal year. In addition, repairing the faults of the overhead network takes on average clearly longer than during a normal year, and is thus very close to the repairing time for cable network faults (chapter 6.2.2). Thus, of the results for a major disturbance year, only prioritization criterion 1 has a higher CAIDI value for the year 2028 when compared to the starting point value. However, the difference between the CAIDI values of prioritization criterion 4 and the other criteria is significantly greater for a major disturbance year than for a normal year. For the year 2028 the CAIDI value for criterion 4 has dropped 20% compared to the starting point value and is 16% lower than the value for the next best criterion.

8.1.4 Results of COC

The RNA-tool also calculates an estimate for the COC (chapter 3.5). The cost parameters are not reparameterized as a part of this analysis, but the percentage difference between the present situation and the situations for the year 2028 can be determined relatively reliably, since the parameters of fault frequencies and duration times are determined suitable for analysis (chapter 6.2) and the cost parameters remain constant during the analysis. The development of the COC results compared to the present situation is presented in the figure 8.7.

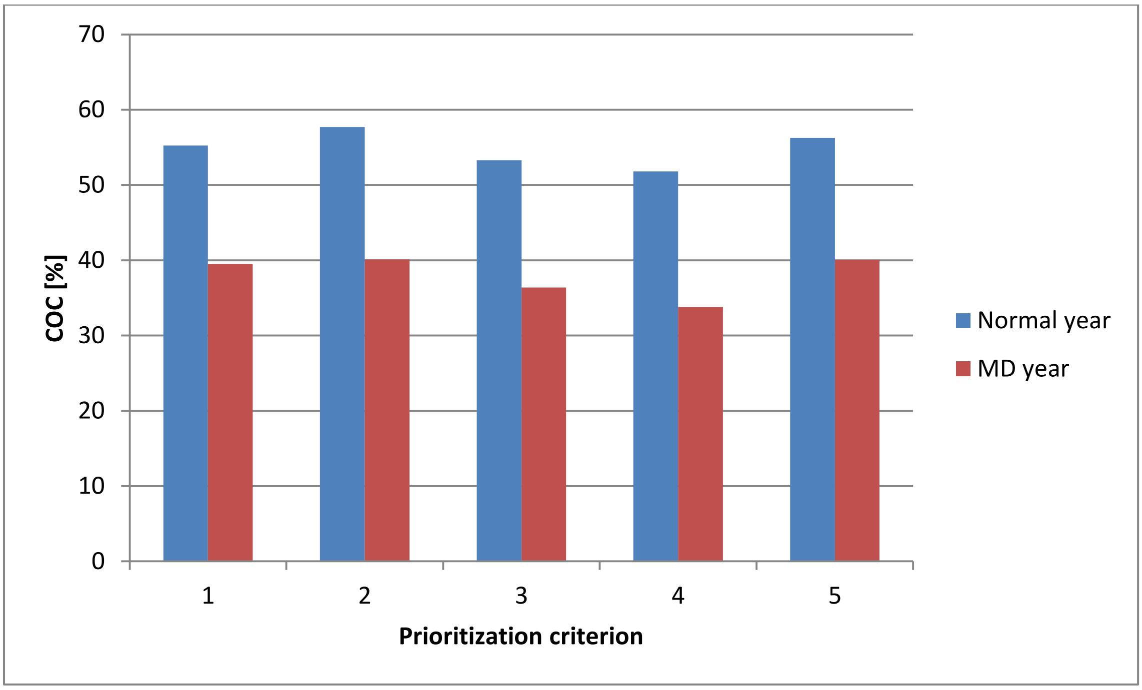

Figure 8.7. *Share of COC results in the final situation of the prioritization criteria in the year2028 in relation to values of present situation. MD is abbreviation of major disturbance.*

As based on the SAIDI results and also the COC values, prioritization criterion 4 appears to lead to the lowest value and prioritization criterion 3 the second lowest. After this the sequence goes in a different order than based on the SAIDI values of the major disturbance year, but between criteria 1, 2 and 5 the COC values differ very little between each other. In the COC values for a major disturbance year the criteria 1, 2 and 5 are all within 0,6 percentage points of each other and in the values for a normal year within 2,5 percentage points of each other. The differences in the COC values between the worst and the best criteria are 6,3 percentage points in the values for a major disturbance year and 5,9 percentage points in the values for a normal year.

8.1.5 Summary of reliability results

In figures 8.8 and 8.9 are summarized the results of reliability calculations. The level of each reliability indicator in year 2028 is presented in percentage of the present situation values.

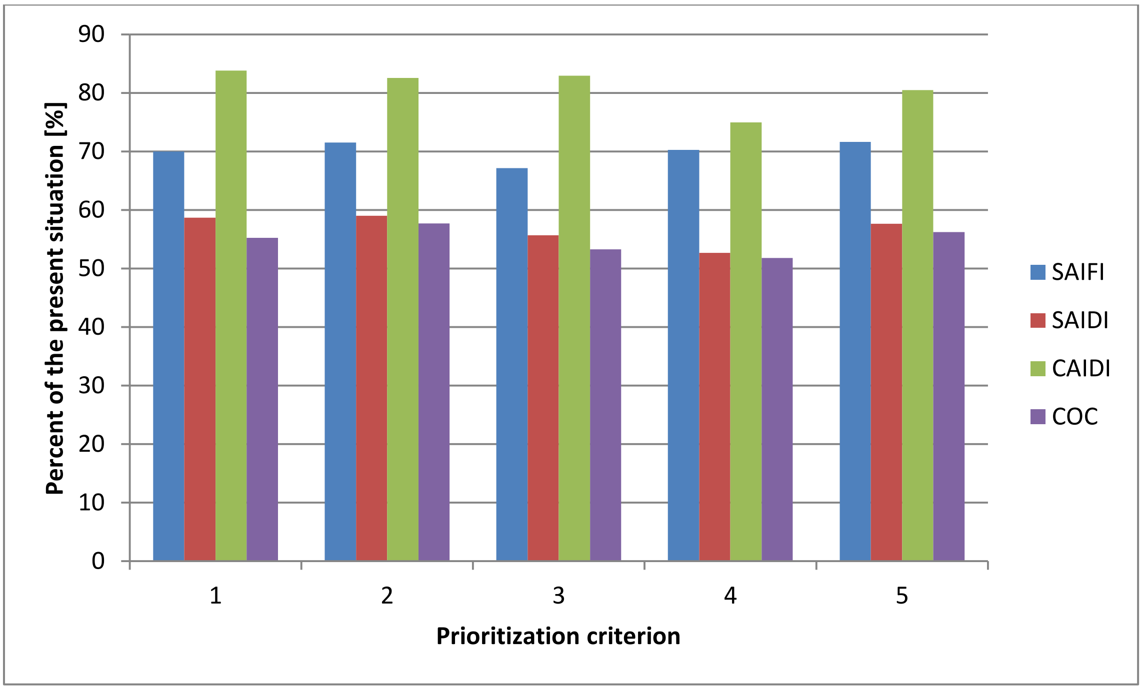

Figure 8.8. *Share of reliability results of the prioritization criteria in the year 2028 in relation to values of present situation calculated with parameters of normal year.*

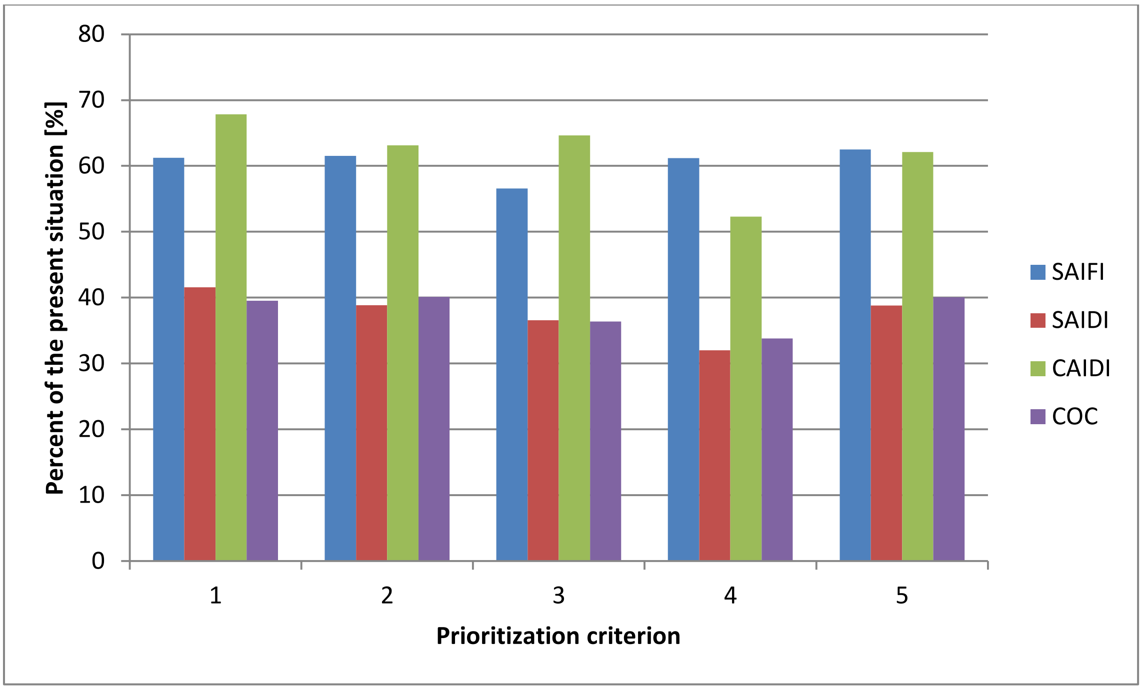

Figure 8.9. *Share of reliability results of the prioritization criteria in the year 2028 in relation to values of present situation calculated with parameters of major disturbance year.*

As can be seen in the figures, the values for a major disturbance year have a higher relative change than the values for a normal year. Cabling has a significant effect especially on improving the reliability during a major disturbance situation, since cables are not exposed to climatic phenomena. Moreover, the figures show that the prioritization criterion 4 ends in the lowest values for all reliability indicators, expect for the SAIFI results, when compared to the other prioritization criteria.

8.2 Comparison of RAV results

In the analysis of this thesis the RAV is calculated with a customized calculating tool, which enables the calculation of the RAV of deconstructed overhead network according to the annual proceeding of prioritization criteria (chapter 5.1.1). Thus, the deconstructing order of the network parts of the analysis area also appear in the results, since the RAV of the deconstructed network part decreases as it ages until it has dropped to zero. The RAV of deconstructed un-prioritized network and their differences between prioritization criteria can be calculated very accurately using the tool.

Figure 8.8 presents the RAV of deconstructed network in relation to the RV of deconstructed network following different prioritization criteria. Height of the bar indicates the percentage of RAV of the RV throughout the time period of the analysis (starting point – year 2028) combined. The shares of the bar present the RAV of deconstructed network for a particular year in relation to other years. These results only include the MV network share, which is the only share that can be calculated accurately in this analysis, since the values of LV network are based on an estimate (chapter 7.1). However, the results also illustrate the LV network results quite well, because the LV network is almost without exception in connection with the MV network from the same era.

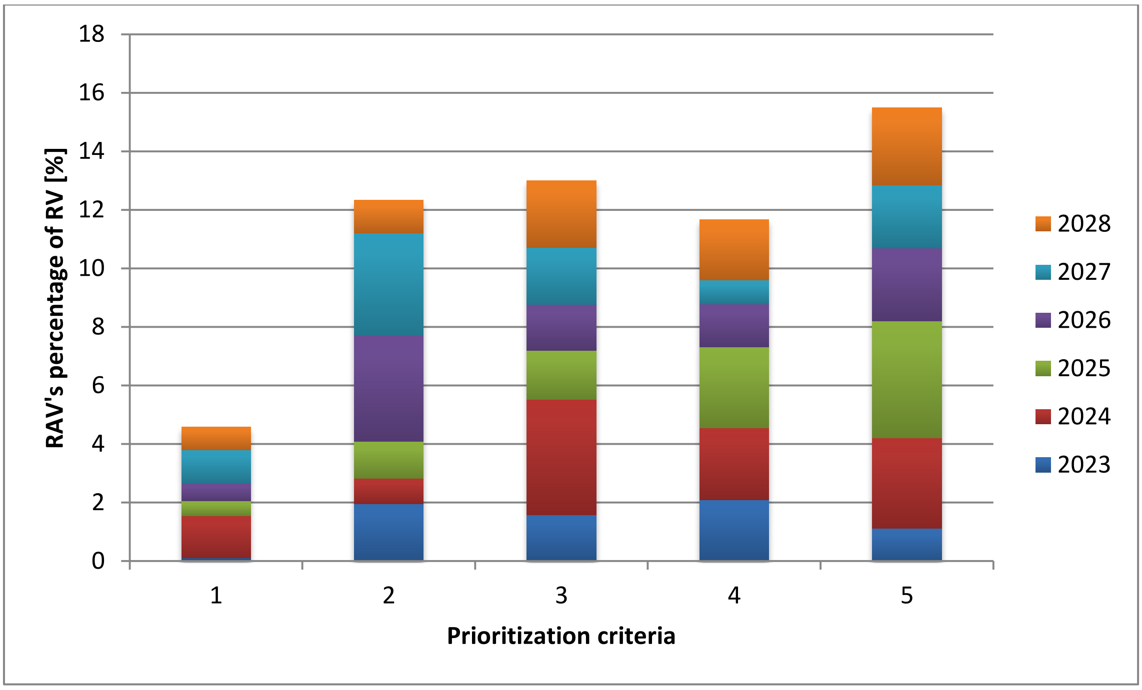

Figure 8.8. *RAV of deconstructed network in relation to its RV. Height of the bar indicates percentage of RAV of RV throughout the time period of analysis (starting point – year 2028) combined. Shares of the bar present RAV development of a particular year in relation to other years. Number 1 represents criteria of cabling oldest parts first, number 2 cabling faultiest parts first, number 3 cabling forest located parts first, number 4 starting cabling from main lines from primary substation forward and number 5 cabling systematically from primary substation forward.*

Clearly the smallest RAV of deconstructed network is achieved by prioritization criterion 1, in which the RAV of deconstructed network is only 4,6% of its RV. This result is a highly expected, since all of the overhead sections deconstructed in prioritization criterion 1 have exceeded their lifetime according to the lifetime intervals set by the EMA, and thus their RAV is zero [**13**]. Thus, only components, such as transformers and disconnectors, which have been built after building the overhead line, have a non-zero RAV. Moreover, small sections of overhead line in which the pole/poles are renewed have a non-zero RAV, since the calculation tool defines the age of overhead line based on ages of its poles (chapter 5.1.1).

Prioritization criteria 2-4 all have a result close to 12%, of which criterion 4 has the lowest RAV of deconstructed network with the result 11,7%. Criterion 5 has the highest RAV of deconstructed network with the result of 15,5%. Thus, prioritization criteria 2-5 have a significantly higher RAV of deconstructed network than criterion 1. Even criterion 4, which has the second lowest RAV, has a 2,7 times higher result compared to the criterion 1. The reason for the prioritization criterion 4 ending up with slightly lower

RAV result than criteria 2, 3 and 5 is that the criterion focuses on the cabling of main lines and the PAS sections located on branches are not cabled at all. Moreover, on average the main lines are built slightly before its branches, since branches are also built when needed at a later time after building the main lines. However, it is notable that with all prioritization criteria a lower RAV of deconstructed network is achieved than in the cabling of prioritized network, in which the RAV's percentage of its RA is 16,4%. This results from renovating prioritized network before un-prioritized network and the higher average age of rural network compared to the prioritized urban network.

In the annual comparison renovating the east branching main line of the feeder 05 HRL_RUSKEALA and the PAS sections stand out clearly, since they have a high RAV. The east branching main line of the feeder 05 HRL_RUSKEALA was built in 1991 and thus is newest main line of the analysis area. In turn, the PAS sections were built in the years 1991-2002. Furthermore, the PAS lines have a higher RAV compared to overhead lines of the same age [**13**]. Taking into account, that of the reinvestments of the year 2023 only 35% are targeted to un-prioritized network, the largest values of annual RAV of deconstructed network are in the criterion 4 and 2 in the year 2023. In that year the reinvestments of the criterion 4 are entirely targeted on east branching main line of the feeder 05 HRL_RUSKEALA and the reinvestments of criterion 2 are mostly targeted to PAS sections built in the years 1991 and 1992. High results of RAV of deconstructed network can be seen also in prioritization criterion 3 in the years 2023 and 2024, in prioritization criterion 5 in the year 2025 and in prioritization criterion 2 in the years 2026 and 2027. Common to all these are that in those years either the PAS sections or the east branching main line of the feeder 05 HRL_RUSKEALA are being cabled.

8.3 Changes in network structure caused by cabling

For the realization of the analysis of this thesis 365 km of new MV cable network was planned. On the basis of the results of renovation of overhead lines this chapter discusses the chances in network structure caused by large scale cabling and today's planning principles (chapter 5.3). The greatest relative change is in the growth of the number of disconnectors, which is about 2,9 times higher compared to the old overhead network, when lines are renovated by cabling. The number of remote-controlled disconnectors grows 1,9-fold and the number of manual disconnectors 3,7-fold based on the analysis of this thesis. In addition, the number of secondary substations and the length of the network will change.

Based on the analysis of this thesis the number of secondary substations increases slightly over 1,6-fold, when overhead lines are renovated by cabling, which is caused by several factors. First of all, the planning principles have changed from the overhead line construction times, when generally more than kilometer long LV feeders were built due to scattered location of customers. Today the target is to build no more than 800m long LV feeders. Therefore, when deconstructing the secondary substations with long LV feeders, it has to be replaced by two or even more secondary substations depending on the situation and terrain, because substations are built closer to customers.

The growth of network length when cabling the overhead network also increases the number of secondary substations, since almost without exception the renovated overhead feeder is shorter than new cable feeder. The reason for this is that both LV and MV overhead lines are generally built in a straight line across fields and forests (chapter 2.2), but ground cable is built on the side of the roads and fields (chapter 5.3.2). According to the analysis of this thesis building substations closer to customers as well as the change in the location of the network causes an average 1,3-fold growth in the length of the MV network, when overhead line is cabled. In addition to these reasons the number of substations increases a little due to the fact that in cable network kiosk type substations are used in branching of MV cable network, since necessarily there are no customers nearby every network node.

9 PRIORITIZATION PRINCIPLES FOR REINVESTMENT PLAN AND GENERALIZATION OF RESULTS

In this chapter the prioritization principles for the reinvestment plan of low-loaded un-prioritized rural MV network are created based on the results and findings presented in the chapter 8. The reliability demands of the new Electricity Market Act are chosen to be the most significant guiding factors in creating the reinvestment plan. The accuracy of the reliability calculations is also estimated by comparing the reliability results for cable network to statistics. In addition, the generalizability of prioritization principles is discussed.

9.1 Prioritization principles of un-prioritized MV network

Prioritization principles to guide the reinvestments of low-loaded un-prioritized rural MV network are created from point of view of the reliability demands of new Energy Market Act, which especially guides to the prevention of long-term outages experienced by customers (chapter 4.1). The longest outages are caused by faults of the distribution network due to major disturbances caused by extreme weather events (chapter 3). Of the reliability indicators of this thesis, the SAIDI and CAIDI for a major disturbance year are the most suitable to describe the development of fault interruption time during major disturbance. However, the long-term outages during a major disturbance are the result of a large number of simultaneous faults, for the repairing of which a limited amount of resources is available. For this reason, the SAIFI results for a major disturbance year, which describes the number of faults, are also weighted. Since the reduction in the absolute values for the SAIDI and SAIFI is more significant than their ratio, the CAIDI, are the prioritization principles created based the most on the findings from the SAIDI results and the second most on the findings from the SAIFI results (chapter 8.1.2 and 8.1.1).

Prioritization principles for the reinvestment plan of low-loaded un-prioritized rural MV network in the order of priority:

1. Cabling main lines forward from primary substation
   1.1. Main lines without backup connection or building backup connections
   1.2. Other main lines starting from feeders, which are located in a forest and have the highest number of customers
2. After main lines are cabled the cabling continues from forest located branches

Point 1.1 is the result of the finding that the cabling of the east branching main line of the feeder 05 HRL_RUSKEALA, which does not have a backup connection, clearly has the greatest impact on the development of SAIDI. In turn, point 1.2 is the result of the finding that the cabling of the main lines proved to be more effective in decreasing SAIDI, and also CAIDI and COC, than the cabling of branches. By cabling main lines located in a forest the reduction in the number of faults of the network is achieved faster. Moreover, by starting the cabling from feeders which have a higher number of customers the SAIDI improves faster, because the reinvestments affect the reliability for a larger amount of customers. Since keeping the cabled main line consistent is beneficial based on the results on SAIDI and CAIDI should the steps 1.1 and 1.2 be implemented by cabling the feeders forward from the primary substation. Point 2 is due to the fact that cabling branches forward from the primary substation does not bring noticeable advantage in improving the reliability. Thus, after cabling all the main lines it is reasonable to focus on cabling forest located branches, which has the greatest impact on decreasing the SAIFI.

Of the prioritization criteria, criterion 4 ends up closest to the final result of the above-described prioritization principles for reinvestment plan. In the situation of the year 2028 the only difference is that the reinvestments of the last year in criterion 4 are targeted on the cabling of branches forward from the primary substation. By focusing the reinvestments of the last year on forest located branches, the final situation of the year 2028 of the criterion 4 corresponds to the prioritization principles. The reliability values of this situation are presented in table 9.1.

Table 9.1. *Reliability values of analysis area according to prioritization principles for reinvestment plan. COC values are presented in relation to the present situation.*

Normal year			Major disturbance year		
SAIFI	**SAIDI**	**COC (%)**	**SAIFI**	**SAIDI**	**COC (%)**
2,09	1,14	50,3	3,28	2,77	31,6

From the table 9.1 it can be seen that by cabling forest located branches in the year 2028, the SAIFI for a major disturbance year reduces 5,0% more and the SAIDI 4,5% more compared to prioritization criterion 4. The corresponding reduction in SAIFI for a normal year is 2,7% more and in SAIDI 1,5% more. Moreover, the COC values are 2,2 percentage points lower for a major disturbance year and 1,5 percentage points lower for a normal year.

From point of view of the maximum utilization of network lifetime the prioritization principles do not end up with the most optimal solution, since it leads also in the cabling of rather new overhead lines. However, from the point of view of reliability cabling the oldest parts first is not rational, since it leads to the highest SAIDI value for a major disturbance year (chapter 8.1.2). Since the prioritization principles for the reinvestment plan are very close to the prioritization criterion 4, which has the second lowest RAV of deconstructed network (chapter 8.2), it can be noted that reinvestment plan also realizes maximum utilization of network lifetime on a moderate level.

9.2 Reliability and generalizability of the results

This chapter discusses the reliability and generalizability of the calculation results and findings. Successful definition of the RNA parameters and the functionality of the RNA-tool have the largest effect on the accuracy of the reliability calculations of this thesis. This chapter also discusses the generalizability of prioritization principles for the reinvestment plan to the entire operating area of Elenia Oy and utilization potential of findings from the point of view of other DSOs.

9.2.1 Assessment of uncertainty of the analysis

The RNA parameters of overhead network are determined reliably, since the parameters are determined based on the network of the present situation so that the SAIFI and SAIDI values match the average values of Elenia Oy. However, from the point of view of the cable network the functionality of the parameters was somewhat uncertain. Table 9.2 summarizes the reliability results of urban feeders after cabling and as a reference the average values of city area as provided by the fault statistics of Energiateollisuus [**34**]. The statistical values for a normal year are the averages of the years 2007-2009 and the 2012 statistics and values for a major disturbance year are averages from the statistics of the years 2010 and 2011.

Table 9.2. *Reliability indicators of urban feeders after the cabling of prioritized network and the average values of city area based on fault statistics of Energiateollisuus* [**34**] *in the situation of a normal year and a major disturbance year.*

		06 HRL_HARTOLA	10 HRL_KÄPYKYLÄ	Fault statistics
Cabling rate (%)		93	99	>75
Normal year	SAIFI	0,64	0,32	0,23
	SAIDI	0,74	0,23	0,16
Major disturbance year	SAIFI	0,81	0,34	0,30
	SAIDI	1,48	0,34	0,17

Based on the table 9.2 it can be noted that the RNA-tool calculates the SAIFI and SAIDI values too high for urban feeders when compared to the fault statistics, especially when taking into account the very high cabling rates of the urban feeders. However, most likely the parameters of the cable network are quite sufficient and the main difference between the reliability indicators is due to the too high parameters for distribution substations. The RNA parameters can not be determined individually for overhead network's substations and kiosk type substations but the RNA-tool uses the same average fault parameters for both substation types. Since the RNA parameters are determined based on the present network, the fault parameters correspond much better with the values of overhead network's substation than the values of a more reliable kiosk type substation. Therefore, when the cabling rate increases, the real average fault frequency of substations decreases even though the RNA parameters remain the same. The increase in the number of secondary substations to 1,6-fold, when the overhead network is cabled, increases the influence of parameters' error even more.

In addition, the reduction in average fault duration times, when the cabling rate increases, is one of the factors that increase the SAIDI values compared to statistics. Especially in major disturbance year the average fault duration times are reduced when the total number of faults is reduced, since it also reduces the simultaneous faults and the faults are thus faster to repair. Thus, the RNA parameters should be determined separately for each year by taking into the account cabling rate of the moment in order for the RNA-tool to calculate the reliability indicators of cable network correctly. Thus it can be noted that the cabling most probably decreases the SAIFI and SAIDI values more than based on the results in chapter 8.1 and also the differences between the prioritization criteria are likely to be greater. Therefore, also the COC values are reduced more than based on the results in the chapter 8.1.4.

In the prioritization criteria of the analysis of this thesis the same amount of network is cabled, so from the point of view of reliability the error in the results of the cable network does not affect the ranking of the prioritization criteria, since the error is the same for all criteria. Moreover, the comparison of the RAV of deconstructed network shows the differences between the criteria reliably, since the calculation tool modified for the RAV calculations enables achieving very accurate results. Thus, it can be concluded, that the findings based on the comparison of the prioritization criteria are correct.

9.2.2 Generalization of the results

The analysis area represents the average operating area of Elenia Oy quite well. PAS-lines' share of the MV network of the analysis area is 7,9%, while the corresponding percentage for the entire operating area is 8,8%. Furthermore, the average age of the network of the analysis area corresponds well to the average age of Elenia Oy's network. The factor that differs the most is the cabling rate of MV network, which is 8,4% for the analysis area and 15% for the operating area of Elenia Oy. The cabling rate of the present situation affects the most in determining the RNA-parameters (chapter 6.2). Since the parameters are determined based on the fault statistics of the years 2007-2011 and the cabling rate of Elenia Oy's network has increased rapidly in the last couple of years, corresponds the cabling rate of 8,4% the situation of the years 2007-2011 very well. Thus, it can be noted that also the cabling rate of the analysis area of the present situation is fairly ideal for the analysis of this thesis.

As presented in the chapter 9.2.1, from the point of view of reliability and the RAV of deconstructed network the findings based on the comparison of the prioritization criteria are reliable. Because the analysis was proceeded for an area characterizing Elenia

Oy’s average operating area with basis of Elenia Oy, it can be noted that the findings and thus also the prioritization principles for the reinvestment plan are reliably generalizable to the entire operating area of Elenia Oy.

In addition to the generalizability of the results of the analysis of this thesis in the operating area of Elenia Oy, the results can also be utilized more widely. Although the analysis is realized based on the planning principles and the capital reinvestment plan of Elenia Oy and thus of the construction methods improving reliability only cabling is discussed, the results can also be utilized by other DSOs. Although a construction method for improving reliability of rural network would be some other than cabling, for example building the overhead lines on the sides of the roads, it is very likely more efficient to improve the reliability and usability of main lines than renovate branches in order to reduce the outage times for customers. Other findings for the prioritization of reinvestment targets will also almost certainly apply regardless of the construction method.

10 CONCLUSIONS

The purpose of this thesis was to create prioritization principles for the reinvestment plan of low loaded parts of the rural MV network of Elenia Oy. The prioritization principles were determined by comparing five different prioritization criteria from the point of view of the reliability and the RAV of deconstructed network. The prioritization criteria were:

1) Cabling the oldest parts first
2) Cabling the faultiest parts first
3) Cabling the forest located parts first
4) Starting the cabling from the main lines forward from the primary substation
5) Cabling systematically forward from the primary substation

Elenia Oy's reinvestment target prioritization, capital reinvestment plan and the decision to raise cabling rate to 70% by 2028 on the basis of the reliability demands of the new Electricity Market Act were the basis of this thesis. According to the reinvestment target prioritization the most critical MV network parts, such as urban area's network and high and medium loaded network, are cabled first. When reinvestments of analysis area were divided into annual level based on the capital reinvestment plan, the reinvestments of low loaded rural network are scheduled for the period 2023-2028.

Four MV feeders, which together represent the average operating area of Elenia Oy as accurately as possible, were chosen as the analysis area of this thesis. Areas two rural feeders include a wide range of different types of low loaded rural network from the prioritization criteria point of view, so the area was suitable for the analysis of this thesis very well. The reliability calculations were performed with the RNA-tool of Tekla NIS, which was reparametrized to meet the requirements of the analysis in such a way that the present situation's SAIFI and SAIDI results of analysis area match the average values of the operating area of Elenia Oy. For the analysis, parameters characterizing a normal year and a major disturbance year were created. Parameters are one part of the results of this thesis and are presented in tables 6.2 and 6.3. The RAV of the reconstructed network was calculated with calculating tool, which was modified for this thesis. The tool allows the calculation of RAV results following the annual proceeding of analysis.

Only clear advantage can be achieved by cabling forest located parts from the development of the SAIFI result point of view. In turn, the most effective way to reduce SAIDI value turned out to be cabling main lines, especially main lines without backup connection. Also, cabling feeders including larger number of customers proved to be more effective than cabling feeders including a smaller number of customers. In comparison the criterion 4 led to clearly smaller values of CAIDI than the other criteria. Improvement of the usability of a main line due to proper placement of disconnectors gives advantage, which could be seen most clearly in CAIDI results. Criterion 4 turned out to be the most effective criterion also in reducing COC, second most effective was criterion 3. As a summary of the reliability comparison between the criteria was noted that criterion 4 ends up in lowest values, except in SAIFI results. Relative change between reliability values was greater in major disturbance year than normal year. Also differences between criteria were clearer in values of major disturbance year.

On the basis of results of RAV of deconstructed network naturally the lowest value was achieved by following criterion 1, for which the RAV of RV of deconstructed network is 4,6%. Second lowest value was reached with criterion 4, for which the result was 11,7%. Also criteria 2 and 3 are in the same range with results 12,3% and 13,0%. Criterion 5 ended up in the highest result of 15,5%.

Prioritization principles for the reinvestment plan of low loaded parts of the rural MV network were created based on the reliability results and findings of the comparison of criteria with emphasis on the reliability demands of the new Electricity Market Act:

1. Cabling main lines forward from primary substation
   1.1. Main lines without backup connection or building backup connections
   1.2. Other main lines starting from feeders, which are located in a forest and have the highest number of customers
2. After main lines are cabled the cabling continues from forest located branches

As the prioritization principles for reinvestment plan are closest to prioritization criterion 4, which has second lowest RAV of reconstructed network, it can be noted that at a moderate level it also supports the target of long term use of network components.

Due to the limitations of the RNA-tool, it can not be parameterized in such a way that calculation would provide absolute correct reliability values regardless of cabling rate of network. Thus, parameters determined based on the present network lead to slightly too high values of reliability indicators when the cabling rate is high. Therefore, the absolute values of reliability indicators likely decrease even more when cabling rate rises than in the calculation results of this thesis. However, the differences between the prioritization criteria observed during analysis are reliable, since the cabling rate of comparable criteria develops identically. Prioritization principles for reinvestment plan are thus reliably generalized to the operating area of Elenia Oy. The findings in development of reliability and RAV values can also be utilized by other DSOs and with other construction methods than cabling.

The new Electricity Market Act requires DSOs to make a detailed development plan, which should improve the reliability of their distribution network systematically and long-term basis reaching the reliability demands of the act. Prioritization principles for reinvestment plan created in this thesis provide guidelines for creating development plan for low-loaded rural network.

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APPENDIX 1: MORE DETAILED RESULTS OF CALCULATION

Abbreviations used only in the tables of appendix 1:

05	05 HRL_RUSKEALA
06	06 HRL_HARTOLA
07	07 HRL_YLEMMÄINEN
10	10 HRL_KÄPYKYLÄ
N	Normal year
MD	Major disturbance year

Table 1. *Length of the line's type and the reliability results of each feeder in the present situation, when all prioritized network is cabled and in the starting point of the cabling of the un-prioritized network.*

	Present network				Prioritized cabled				Starting point			
Feeder	**05**	**06**	**07**	**10**	**05**	**06**	**07**	**10**	**05**	**06**	**07**	**10**
Customers (pcs)	595	959	533	547	595	959	533	547	595	959	533	547
Overhead (m)	65736	11093	72598	3310	42018	1176	52790	53	42018	1176	52790	53
PAS (m)	7009	0	5497	634	6376	0	4328	0	6376	0	4328	0
Cable (m)	5776	3633	1449	4347	37280	14715	32212	7357	37280	14715	32212	7357
SAIFI_N	5,45	1,19	6,10	0,73	4,42	0,64	5,03	0,32	5,96	0,64	6,58	0,32
SAIDI_N	4,45	0,97	3,44	0,73	3,52	0,74	2,43	0,23	3,69	0,74	2,61	0,23
SAIFI_MD	10,39	1,94	11,72	1,04	7,77	0,81	9,00	0,34	10,77	0,81	12,01	0,34
SAIDI_MD	19,96	2,94	15,10	2,13	12,73	1,48	8,73	0,34	13,31	1,48	9,34	0,34

Table 2. *Annual results of the RAV and RV of the deconstructed network for the prioritization criteria according to EMA unit prices* [**39**].

Year	Criterion	1	2	3	4	5
2023	**RAV (€)**	1695	28310	22788	29837	16056
	RV (€)	120861	125238	76390	89284	113439
2024	**RAV (€)**	20490	12616	56443	34927	44050
	RV (€)	278291	211066	282211	214639	281576
2025	**RAV (€)**	7091	18066	24215	39450	56994
	RV (€)	279367	227913	274892	234016	253108
2026	**RAV (€)**	8759	52598	22489	20898	35487
	RV (€)	243852	287445	268188	266654	264663
2027	**RAV (€)**	16168	50356	28093	11496	30834
	RV (€)	251182	290316	272445	275132	252650
2028	**RAV (€)**	11404	16284	32813	29478	37730
	RV (€)	256131	304124	263124	344260	262079

Table 3. *Annual development of the length of the line's type and the reliability results of each rural feeder following the different prioritization criteria.*

	Criterion	1		2		3		4		5	
Year	**Feeder**	**05**	**07**	**05**	**07**	**05**	**07**	**05**	**07**	**05**	**07**
2023	**Overhead (m)**	40656	51182	41959	51443	42018	51451	38938	52790	42018	49280
	PAS (m)	6376	4328	4440	4328	6376	3291	6376	4328	6376	4328
	Cable (m)	39026	33909	40077	33416	37280	35461	40431	32212	37280	35586
	SAIFI_N	5,80	6,43	5,82	6,38	5,96	6,34	5,71	6,58	5,96	6,40
	SAIDI_N	3,67	2,58	3,64	2,53	3,69	2,52	3,41	2,61	3,69	2,56
	SAIFI_MD	10,42	11,72	10,41	11,61	10,77	11,46	10,22	12,01	10,77	11,66
	SAIDI_MD	13,18	9,22	13,07	9,02	13,33	8,88	11,64	9,34	13,33	9,13
2024	**Overhead (m)**	38643	43628	37131	49155	40672	46300	32160	52790	40080	43002
	PAS (m)	6376	4328	4107	4328	4747	2300	6376	4328	6376	3981
	Cable (m)	43999	39972	46003	37712	41322	41582	50828	32212	39566	43795
	SAIFI_N	5,64	5,70	5,40	6,23	5,69	5,61	5,22	6,57	5,84	5,91
	SAIDI_N	3,43	2,39	3,56	2,44	3,52	2,30	2,88	2,61	3,62	2,39
	SAIFI_MD	10,06	10,24	9,50	11,26	10,13	9,87	9,11	12,00	10,54	10,62
	SAIDI_MD	12,58	8,45	12,67	8,54	12,84	7,85	8,58	9,33	13,03	8,36
2025	**Overhead (m)**	31572	41824	36977	42016	35781	43605	28153	49497	36420	39682
	PAS (m)	6376	4328	4107	4328	4107	2300	6376	4328	6376	2268
	Cable (m)	53135	41991	46176	47689	48330	44597	56727	36374	45263	48972
	SAIFI_N	5,02	5,50	5,40	5,57	5,15	5,29	4,87	6,27	5,55	5,46
	SAIDI_N	3,10	2,30	3,57	2,14	3,17	2,20	2,65	2,43	3,25	2,30
	SAIFI_MD	8,72	9,80	9,49	9,85	8,93	9,19	8,29	11,36	9,88	9,62
	SAIDI_MD	10,87	8,03	12,68	7,11	11,15	7,36	7,19	8,49	11,42	7,88
2026	**Overhead (m)**	28015	37472	35238	38116	32379	40025	23767	46232	31149	36590
	PAS (m)	6376	4328	3709	2480	2607	2300	6376	4328	6376	1872
	Cable (m)	57437	47430	48797	54891	54647	49052	61931	41180	51696	52233
	SAIFI_N	4,66	5,11	5,20	5,08	4,77	4,93	4,40	5,94	5,07	5,10
	SAIDI_N	2,72	2,14	3,44	1,97	2,97	2,05	2,33	2,34	2,91	2,19
	SAIFI_MD	8,07	8,97	9,04	8,75	8,06	8,45	7,31	10,66	8,83	8,85
	SAIDI_MD	9,22	7,17	11,96	6,24	10,14	6,64	5,52	8,03	9,69	7,34
2027	**Overhead (m)**	27006	31001	31308	35435	31464	34867	21195	39850	26961	33611
	PAS (m)	6376	4328	1741	2300	756	2300	6376	4328	6376	1872
	Cable (m)	58529	55494	55399	58090	58018	55974	65027	47077	57903	55541
	SAIFI_N	4,64	4,51	4,81	4,86	4,59	4,43	4,11	5,32	4,77	4,77
	SAIDI_N	2,75	1,95	3,17	1,88	2,90	1,85	2,09	2,17	2,71	2,10
	SAIFI_MD	7,92	7,70	8,13	8,27	7,64	7,39	6,68	9,36	8,13	8,16
	SAIDI_MD	9,15	6,24	10,33	5,75	9,75	5,73	4,72	7,25	8,49	6,90
2028	**Overhead (m)**	21297	28693	22413	34826	25696	32330	17196	32985	24656	28566
	PAS (m)	6376	4328	1234	2300	436	2300	6376	4328	6376	1379
	Cable (m)	64713	58645	64551	58751	64410	59128	69667	53272	61277	62209
	SAIFI_N	4,24	4,35	4,02	4,82	4,01	4,18	3,77	4,91	4,54	4,25
	SAIDI_N	2,68	1,85	2,70	1,86	2,50	1,72	1,91	2,05	2,57	1,86
	SAIFI_MD	7,05	7,38	6,41	8,18	6,36	6,86	5,99	8,55	7,63	7,09
	SAIDI_MD	8,77	5,83	7,85	5,64	7,40	5,12	4,10	6,75	7,70	5,79